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Orbit Determination Adaptations for the Cassini Grand Finale

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The Cassini spacecraft has been operating in orbit around Saturn since 2004, during which time it has executed over 150 satellite encounters. Over this period, there have been several papers describing the orbit determination process and performance up through 2016 [1-5]. In April of 2017, Cassini will enter its Grand Finale mission phase when it will traverse the gap between the D-ring and the Saturn atmosphere twenty-two times before plunging deep into the atmosphere to end the mission. The lack of targeted satellite encounters during this period necessitates updates to the nominal Cassini Orbit Determination (OD) process. This paper describes these planned adaptations for the operation of the Grand Finale. During the Equinox and Solstice Mission Phase (2008-2016), navigation analysis has been divided into segments focused on two particular targeted satellite encounters, called an "arc". Maneuvers in an arc were usually targeted to encounter B-plane position and time, so the OD state and covariance were mapped forward to the B-plane of the encounter within the arc. Trajectory dispersions during the Grand Finale need instead to be mapped to equator crossings and targeted Cartesian positions. In addition, trajectory arcs have typically covered a few orbital revolutions (~2-8 weeks), in order to span the time between two encounters. However, the Grand Finale will encompass five months of time without an encounter which necessitates an adjusted arc strategy. A modified arc strategy was developed based on OD behavior during long multi-rev periods between encounters in the year leading up to the Grand Finale. The OD covariance study conducted for the Grand Finale mission phase will also be examined.

Key Words: Cassini, Orbit Determination, Grand Finale

1. Introduction

The Cassini spacecraft was launched in 1997 and arrived at Saturn in 2004. It has since completed more than 260 orbits around the planet, 126 flybys of Titan, 22 flybys of Enceladus, and many other icy satellite encounters. Cassini has now completed its prime mission, 1st extended Equinox mission, and nearly all of its 2nd extended Solstice mission. The names of the extended missions correspond to their applicable Saturnian seasons. Figure 1 shows the Cassini Solstice mission trajectory color-coded by mission phase.

On April 22, 2017 Cassini will complete its last targeted flyby of Titan and enter the Grand Finale phase of its mission. For twenty-two orbits it will pass between the D-ring and the Saturn atmosphere, ending with a final plummet into the Saturn atmosphere to be burned up. This final mission phase presents unique challenges to the Orbit Determination team. The six months of the Grand Finale phase will present a drastically different mission compared to the previous thirteen years of operations around Saturn which were focused on satellite encounters. There will be substantial impacts to software, product exchanges, and communication of these changes with other subsystems. The current OD software has been developed and improved upon over thirteen years, and modifications to the system will need to be completed in much less time. This paper describes the major modifications planned for conducting orbit determination during the Cassini Grand Finale and describes results from the covariance analysis performed for the final mission phase.

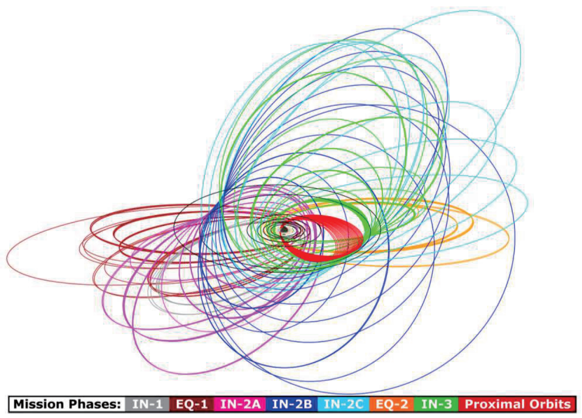

Fig. 1. Solstice mission Saturn-centered trajectory oblique view. [6] The coloring scheme represents the various phases of the trajectory, either at inclination or in the equatorial region. The small red set of orbits corresponds to the Grand Finale phase.

2. Navigation Overview

The Cassini Navigation operations guiding concept is to return the spacecraft to a 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. An important secondary goal is to maintain ephemeris knowledge to the level required to acquire spacecraft signal from Earth at any time.

Cassini's orbit determination is dependent on 2-way X-Band Doppler and range tracking data acquired via NASA's Deep Space Network. The radio-metric data are calibrated to remove the measured variability of the Earth's ionosphere and troposphere effects on the data. Corrections to Earth's polar motion and timing are also applied to the measurement models. Errors due to station locations, troposphere, ionosphere, and Earth orientation are all considered in the OD filter. The spacecraft state, orbit trim maneuvers (OTMs) parameters, parameters for small burns from turns and momentum management, acceleration from Radioisotope Thermoelectric Generator (RTG) 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. This process is conducted using JPL's python-based Mission-design and Operations Navigation Toolkit Environment (MONTE) software. [6]

There are extensive product exchanges between the Attitude & Articulation Control Subsystem (AACS) and Nav teams for ingesting small forces, from activities such as turns for OTMs, health and safety checks, or science related turns, and the process has been refined over the years. Small force biases are induced by such turns due to execution errors and small imbalances in the Reaction Control System (RCS) thrusters. In their paper presented in 2008, Ardalan et al also explained how telemetry was adapted to better suit navigation needs. [7] The improved modeling has allowed better estimation of small force delta-v and are fed back as calibration data for the RCS thrusters. The calibrations mean that small forces can be characterized well, even without bracketing tracking data.

Navigation analysis has been divided into segments focused on a particular targeted satellite encounter, called an "arc". Each arc consisted of an initial encounter (the previous arc's targeted counter) and the targeted encounter. Overlap between two adjacent arcs reduces trajectory discontinuities from one arc to the next. Arcs are named by the number of Saturnian orbital revolution and number of the targeted flyby. For example, arc 251T126 represents an arc which begins on the 251^{st} orbital revolution of Saturn and targets the 126^{th} flyby of Titan (T).

Prior to the Grand Finale mission phase, Cassini maneuvers were generally targeted to the B-plane position and time of the next satellite encounter in the arc. Thus, the OD state and covariance were mapped forward to this encounter B-plane. The B-plane is the plane perpendicular to the asymptote of the incoming trajectory, with the B-vector defined as the vector which joins the body center and the point where the asymptote meets the B-plane. Figure 2 shows the B-plane geometry. Three coordinate vectors are also defined: S along the incoming asymptote, 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.

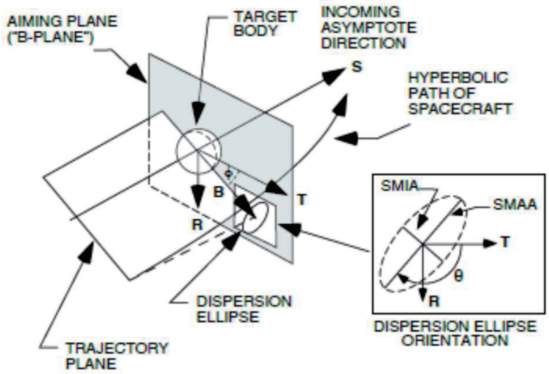

Fig. 2. B-plane Geometry

Figure 3 shows the B-plane at T126 for OD solutions shortly after Orbit Trim Maneuver (OTM) number 468a was executed (February 22, 2017). The blue ellipse indicates the Cassini OD solution using data up to February 26 2017, representing the 1-sigma OD uncertainty. The purple and red ellipses represent solutions with data cutoffs on March 2, 2017 and March 4, 2017, respectively. The ellipse size shrinks slightly from one solution to the next as more data is used in the solution. The ellipse centers also shift by a few km with each new solution. The changes are small relative to the uncertainty in the solution represented by the ellipses. As the data cutoffs come closer to the T126 encounter, the ellipse size will continue to shrink, typically down to sub-km level by the time of the final pre-encounter maneuver.

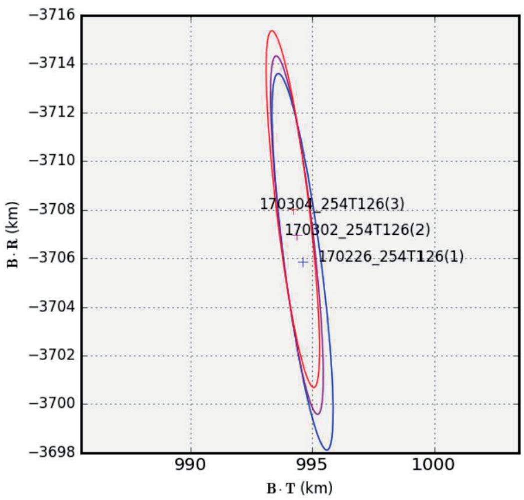

Fig. 3. T126 B-plane Uncertainty

3. Treatment of Trajectory Arcs with Many Revolutions

Trajectory arcs have typically covered a few orbital revolutions (~2-8 weeks), in order to span the time between two encounters. Inputs of a typical OD solution, in addition to radiometric tracking data, include media calibrations, data weight updates, small forces (on or off-Earth-line biases), maneuvers, Earth orientation, and spacecraft attitude. Among estimated parameters, the spacecraft state, OTM and small forces parameters, acceleration for the RTG, and zero-mean stochastics are estimated. The a priori values of the Cassini state and RTG parameters are constrained using the previous arc, whereas the small forces and OTM predictions are external to the OD process, from the Attitude control sub-system (AACS) or the flight path control group of the navigation team. The Saturn system and its satellite parameters have been periodically updated and delivered to the Cassini navigation team by the JPL Solar System Dynamics (SSD) group. The Cassini OD team used to estimate the Saturnian system, but in recent years, the team had been considering those parameters' error contributions. Since the summer 2016, Saturn's harmonics, GM, and ten of Saturn's moons states and GMs are also estimated. The strategy for integrating satellites during arcs is further discussed in Reference [8]. The Saturn system apriori values and covariance are based on the 389th delivery by the SSD, or sat389 [9].

However, the Grand Finale will encompass five months of time without an encounter which will necessitate an adjusted arc strategy. A modified arc strategy was developed based on OD behavior during long multi-rev periods between encounters in the year leading up to the Grand Finale.

In particular, the 240T123, 244T124 and 251T126 arcs included a second arc with an epoch after the first or second periapsis following the first encounter. In doing so, the Cassini state, satellite states and GMs, and Saturn's harmonics and pole parameters were advanced to this new arc epoch, with their respective covariance. This new arc also constrains those parameters' estimation to their nominal values to avoid possible deviation from the iterated solution on which the new arc is based on.

4. Updates to Trajectory Dispersion Mappings

During the Grand Finale, there will not be any targeted satellite encounters to map the OD state and uncertainties to. Instead, they will be mapped to Saturn periapsis and ring plane crossings. Certain Saturn periapses will be used as control points, and the ring plane crossings are events with high scientific interest [10]. Thus, knowledge of trajectory uncertainty at these points is important. The periapsis and ring plane crossing mappings were implemented and tested during the arc associated with the final satellite encounter, 251T126. Figure 4 shows the ring plane crossings and periapses during the 251T126 arc. The timing of maneuvers, targeted and untargeted encounters are also shown on the plot for reference. The reference trajectory values are also plotted, but the difference between reference and OD prediction is too small to be seen at this scale. Small jumps in radius from one set of periapsis and crossings to the next are caused by the gravity of distant untargeted Titan flybys on the orbits. The vertical purple line represents the data cutoff (DCO) time for the OD solution.

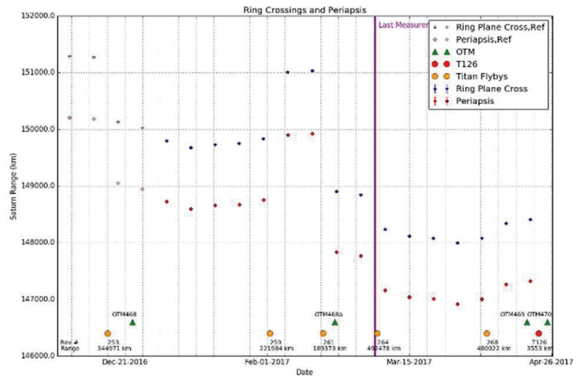

Fig. 4. 251T126 Arc Ring Plane Crossings and Periapsis

Figure 5 shows the difference between the OD prediction and reference trajectory timing at periapsis and ring plane crossing. The data cutoff time for this plot was on February 16, 2017, just before OTM468a. The timing difference between the predicted solution and reference grows larger as time from the last measurement increases since OTM468a is not modeled in this OD solution. The large deviation from the reference trajectory is representative of the maneuver not being executed. Figure 6 shows the same plot with solutions from February 24 and 28, 2017, after OTM468a has been executed. The timing difference with the reference decreases after the maneuver. The error bars represent 1-sigma uncertainties in the predicted OD solution. These errors grow larger with time from the data cutoff as expected.

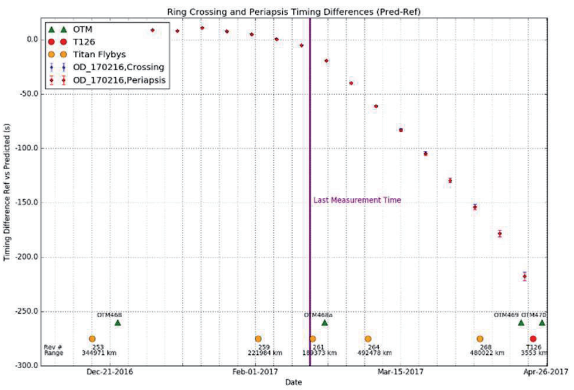

Fig. 5. 251T126 Arc Ring Plane Crossings and Periapsis Timing Difference (Predicted vs Reference) with data cutoff on February 16, 2017

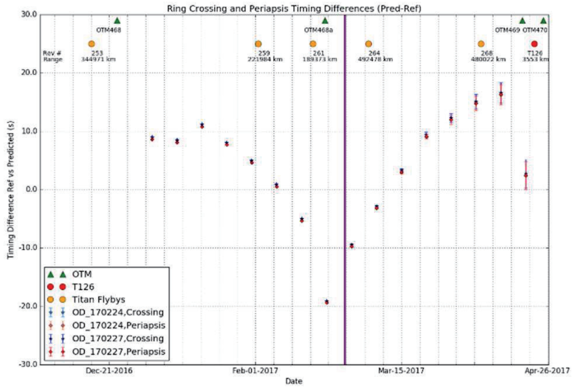

Fig. 6. 251T126 Arc Ring Plane Crossings and Periapsis Timing Difference (Predicted vs Reference) for solutions with data cutoff times on February 24, and February 28, 2017

Figures 7 and 8 similarly show the difference between the OD prediction and reference trajectory radius at periapsis and ring plane crossing for the same data cutoff dates. In this case, performing the OTM468a increased the radial difference between the OD solution and reference trajectories by a few km. This small increase is more than offset by the large reduction in the timing difference. Thus, the maneuver had the desired effect of bringing the predicted trajectory closer to the reference.

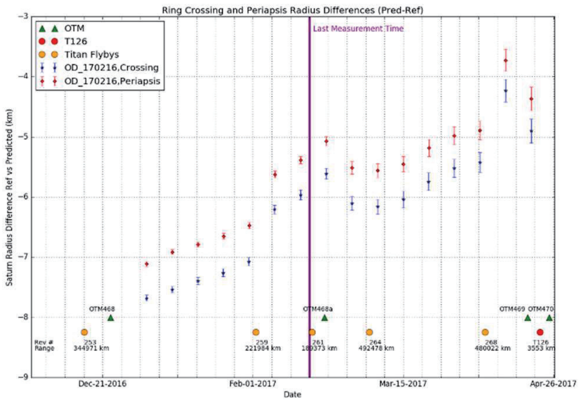

Fig. 7. 251T126 Arc Ring Plane Crossings and Periapsis Saturn Radius Difference (Predicted vs Reference) with data cutoff on February 16, 2017

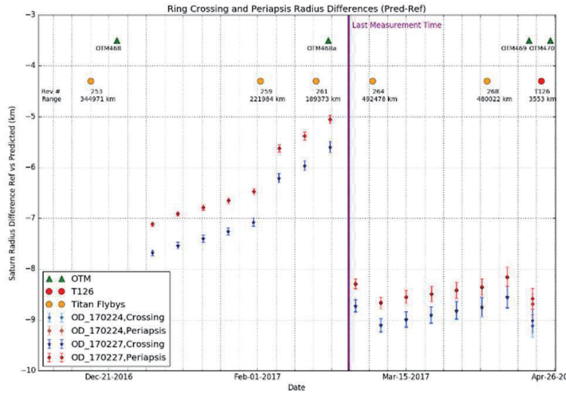

Fig. 8. 251T126 Arc Ring Plane Crossings and Periapsis Timing Difference (Predicted vs Reference) for solutions with data cutoff times on February 24, and February 28, 2017

Plots such as these are useful in quantifying how closely the current OD solution follows the reference trajectory over the period of an arc. However, they are difficult to use to judge the small changes typical from one OD solution to the next (excluding before/after maneuvers). In order to better display such solution history for OD verification it is necessary to focus on one ring plane crossing or periapsis at a time. Figures 9 and 10 show the radial and timing difference with the reference trajectory for multiple OD solutions, zoomed in to one ring crossing or periapsis (Periapsis on February 28, 2017 in this case). In these plots, the x-axis shows timing difference with the reference, while the y-axis shows the radial difference. The changes from one solution to the next are small, as expected (unless an un-modeled maneuver is executed in between the solutions). The error bars represent 1-sigma uncertainty levels. The uncertainties can be seen to decrease with each new solution as more data is included. The majority of the decrease in uncertainty is in the timing.

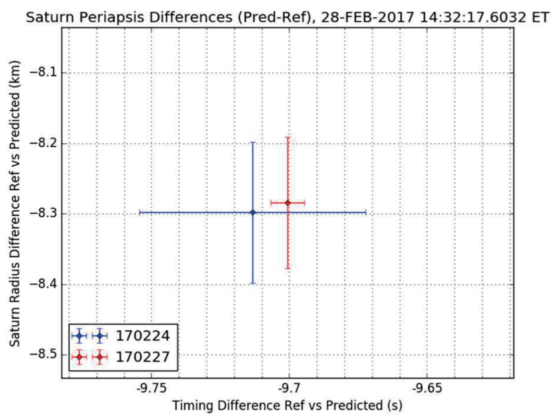

Fig. 9. Radial and Timing Difference (Predicted vs Reference) for Ring Plane Crossing on February 28, 2017 with solutions with data cutoff times of: February 24, and February 27, 2017.

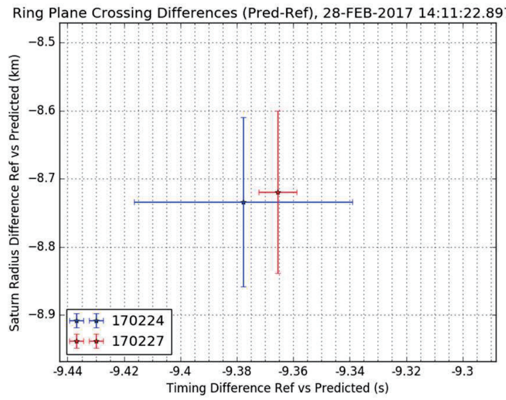

Fig. 10. Radial and Timing Difference (Predicted vs Reference) for Saturn Periapsis on February 28, 2017 with solutions with data cutoff times of: February 24, and February 27, 2017.

The development of these plotting tools during the 251T126 arc allow for better tracking of uncertainties and shifting OD solutions during the Grand Finale. A preview of what such figures will look like for the Grand Finale based on results from a covariance study will be shown in Section 5.

5. Grand Finale Covariance Study

A covariance study was conducted for the Grand Finale mission phase in order to predict the OD uncertainties to be expected during mission operations. Tracking data was simulated until the end of the mission according to the current tracking schedule. The small force biases induced on the spacecraft due to RCS events are accounted for up until July 12, 2017. These events are still being finalized for the final few months of the mission. As mentioned in an earlier section, planned maneuvers have typically targeted a satellite encounter B-plane. However, the Grand Finale mission phase does not include targeted satellite encounters. The maneuvers in the Grand Finale instead target Cartesian XYZ position of the reference trajectory at certain times to reduce trajectory dispersions. The three maneuvers in the Grand Finale were designed to target reference positions at the following times:

OTM470 – 3rd Periapsis of the Grand Finale + 2 hours (May 9, 2017)
OTM471 – 13th Periapsis of the Grand Finale + 2 hours (July 12, 2017)
OTM472 – 16th Periapsis of the Grand Finale + 2 hours (August 1, 2017)

The project also has three more contingency maneuvers, OTM473 – OTM475, that would either lower the following periapsis passage for science observations, or increase the periapsis for spacecraft safety. The target for those maneuvers depend on the density of Saturn's atmosphere, to be determined from the previous periapsis passages. More information about the maneuver strategy for the Grand Finale can be found in Reference [11].

Figure 12 shows the expected timing and radial uncertainty of the OTM470 target based on data cutoffs at each time along the plot. The plot shows a large decrease in timing and radial uncertainty with the first tracking pass after the T126 encounter, after information about the encounter is processed. There are also further dips after small biases are executed, and their execution errors are better accounted for with tracking data. The uncertainties decrease steadily as more tracking data is processed, with a short spike at the execution time of the maneuvers. The radial and timing uncertainties are sub 1km and just over 1s, respectively, at the time of the OTM470 data cutoff.

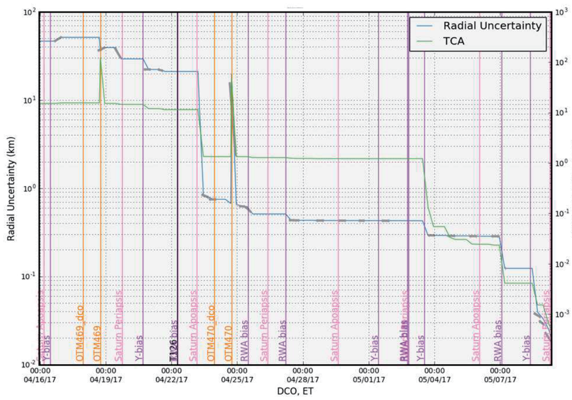

Fig. 12. Radial and Timing Uncertainties for the OTM470 Target vs Data Cutoff Time

Figures 13 and 14 show the same uncertainty plot for the OTM471 and OTM472 targets, respectively. They show similar decreases in uncertainty with time as small biases are executed and more tracking data is processed. As of the writing of this paper, bias events are only known up to July 12, 2017, so information after that date is not considered to be reliable. The plots will be updated with the rest of the bias events when they become available. The radial and timing uncertainties are predicted to be sub 1km and a few seconds, respectively, for both targets before their maneuver's DCO.

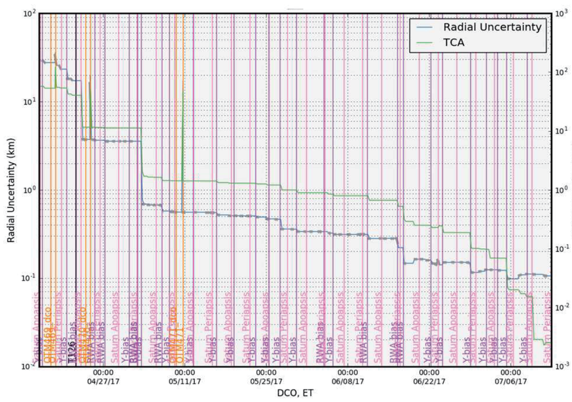

Fig. 13. Radial and Timing Uncertainties for the OTM471 Target vs Data Cutoff Time

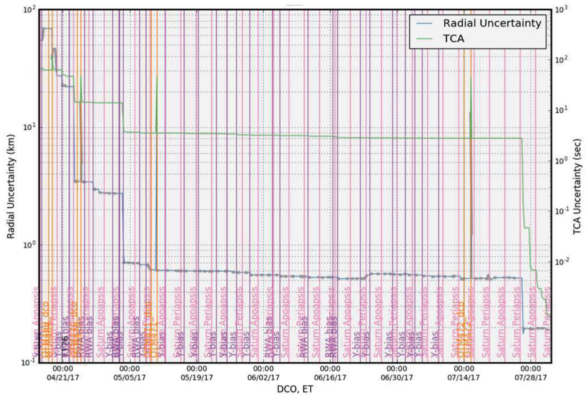

Fig. 14. Radial and Timing Uncertainties for the OTM472 Target vs Data Cutoff Time

Figure 15 shows a plot of periapsis and ring plane crossings for the Grand Finale mission phase based on covariance prediction and reference trajectory data. The maximum radius which would cause spacecraft tumbling and permanent capture into the Saturn atmosphere are marked on the plot. These are based on current estimates of Saturn's atmospheric density. The final periapsis and ring crossings on September 15, 2017 are only shown for the reference trajectory and are well below the atmospheric capture radius. The covariance prediction includes an updated Saturn atmospheric model with a higher density than that included in the reference trajectory, so a final periapsis is not defined (the spacecraft orbit degenerates due to drag effects and is captured). All of the periapsis before September 15 are above the tumbling radius and the covariance predictions match the reference values well. The timing of maneuvers, targeted and untargeted encounters are also shown on the plot.

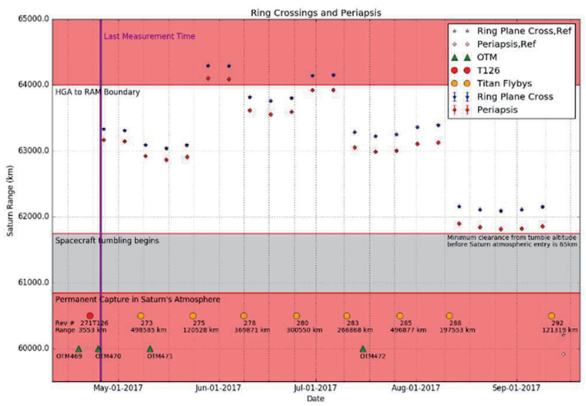

Fig. 15. Grand Finale Ring Plane Crossings and Periapsis Radius

The timing and radial uncertainties can also be viewed as mapped to each periapsis and ring plane crossing for a single data cutoff time as shown for the T126 arc in Section 4. Figures 16 and 17 show the expected radial and timing difference with the reference trajectory for each periapsis and ring plane crossing based on a data cutoff on April 26, 2017. The error bars represent the radial and timing uncertainties at the periapsis and ring plane crossings. As expected, the difference with the reference and the predicted errors both increase with time away from the data cutoff.

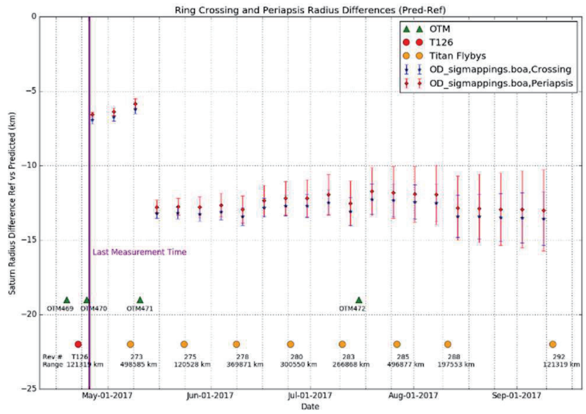

Fig. 16. Grand Finale Ring Plane Crossings and Periapsis Radius Difference (Predicted vs Reference) with data cutoff on April 26, 2017

Figure 17 shows the timing difference with the reference reduce to nearly zero for the three targeted periapsis points (May 9, July 12, and August 1). The timing difference then grows steadily after the last maneuver target on August 1st, up to just over 150s off from the reference at the final periapsis before Saturn atmospheric entry. The larger differences in the last few revolutions are within the acceptable range for this phase of the mission.

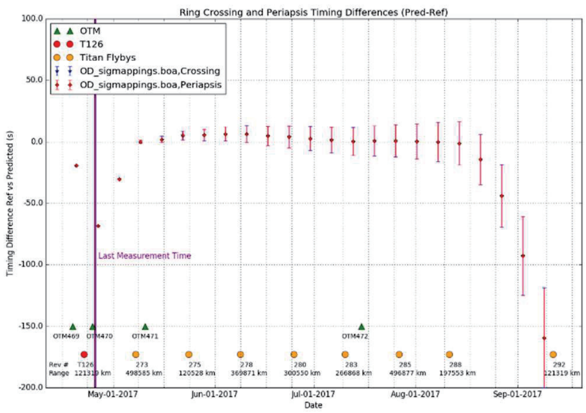

Fig. 17. Ring Plane Crossings and Periapsis Timing Difference (Predicted vs Reference) with data cutoff on April, 2017

In order to judge how well the covariance study is predicting the final plunge into the Saturn atmosphere, uncertainties are mapped to the moment the spacecraft reaches the Saturn radius currently predict to cause spacecraft tumbling (61372km). Figure 18 shows the timing and radial uncertainty mapped to this point based on data cutoffs throughout the arc in a similar way to Figures 12-14. It shows that the uncertainties remain flat for most of the arc at just below 20s and 8km for timing and radius, and then drops after the second to last untargeted Titan encounter in the middle of August. It then continues to drop as more tracking data is received after the encounter, with a final plunge after the last untargeted Titan encounter. As mentioned previously, bias events after July 12, 2017 are not included and this plot will be updated as those become available. The uncertainties shown at the last control point before OTM472 are within the acceptable range to ensure a successful plunge into Saturn to the end the mission.

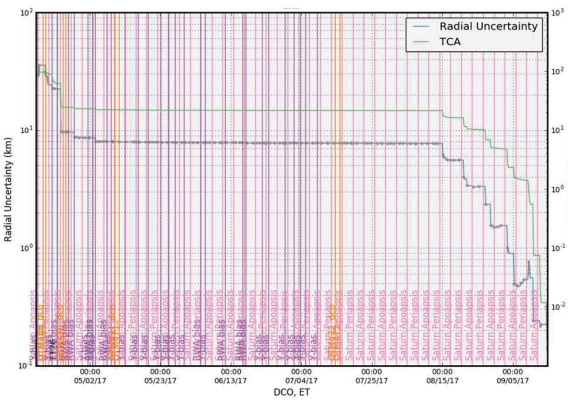

Fig. 18. Ring Plane Crossings and Periapsis Timing Difference (Predicted vs Reference) with data cutoff on April, 2017

6. Conclusion

The Cassini spacecraft has been operating in orbit around Saturn since 2004 and has gone through several different mission phases. In April of 2017, Cassini will enter its final mission phase (the Grand Finale) which will pose unique navigational challenges. The planned modifications described in this paper will allow the orbit determination team to meet those challenges and successfully end the Cassini mission science.

Acknowledgments

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References

1) 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

2) 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

3) 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 Cassini-Huygens Mission", *SpaceOps 2008 conference*, AIAA 2008-3433, 2008

4) 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

5) J. Bellerose, S. Nandi, D. Roth, Z. Tarzi, D. Boone, K. Criddle, and R. Ionasescu, "Cassini Navigation: The Road to Consistent Sub-Kilometer Accuracy Satellite Encounters", AAS 16-142, *2016 AAS GN&C Conference*, Breckenridge, CO, February 5-10 2016

6) S. Evans, et al. "MONTE: The Next Generation of Mission Design & Navigation Software." *The 6th International Conference on Astrodynamics Tools and Techniques (ICATT)*, Darmstadt, Germany. 2016.

7) 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.

8) D. Boone, J. Bellerose, D. Roth, "Resolution of Orbit Determination Prediction Instabilities at Titan During Cassini's Solstice Mission", *International Symposium on Space Flight Dynamics (ISSFD)*, Matsuyama, Japan, June 2017

9) JPL Solar System Dynamics group, ssd.jpl.nasa.gov, last modified 2015

10) Cassini Solstice Mission Navigation Plan, JPL Internal Document D-11621, 2010

11) M. Vaquero, Y. Hahn, D. Roth, M. Wong, "A Linear Analysis for the Flight Path Control of the Cassini Grand Finale Orbits", 26th *International Symposium on Space Flight Dynamics (ISSFD)*, Matsuyama, Japan, June 2017