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# Resolution of Orbit Determination Prediction Instabilities at Titan During Cassini's Solstice Mission

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The Cassini spacecraft has been in orbit about Saturn since 2004. Exploration of the Saturn system is driven by gravitational flybys of the moon Titan which alter the spacecraft trajectory. The Cassini Navigation Team receives regular updates to the Saturn satellites ephemeris from JPL's Solar System Dynamics group. The difference between subsequent ephemeris deliveries can be hundreds of meters in the position of Titan at the time of a flyby. Errors in Titan's position propagate downstream to the next flyby through the estimated spacecraft trajectory. Prior to 2013, the Cassini Orbit Determination Team estimated the Saturn satellite ephemeris parameters and used the *a posteriori* states and covariance of an operations arc as *a priori* inputs to subsequent estimation arcs. Since 2013, the OD Team has only been considering errors in the ephemeris and not estimating a correction to the satellite positions. The T119 Titan flyby exhibited a 3D miss distance of 2.44 km and the following T120 flyby yielded a smaller miss of 1.06 km at the $2.9\sigma$ error level. These discrepancies between pre-flyby prediction and post-flyby trajectory reconstruction were due to errors in the Titan ephemeris. In order to improve the targeting of Titan in future flybys, the team restarted the satellite ephemeris estimation process for orbit determination solutions. Subsequent flybys had target misses of less than 1 km at the sub-3 error level. This paper describes the method of scaling the *a priori* satellite ephemeris covariance in the orbit determination process to allow larger corrections to the satellite system and improve the prediction of the spacecraft's Titan-relative position at the time of encounters.

**Key Words:** Cassini, Titan, navigation, orbit determination, satellite estimation

## 1. Introduction

The Cassini spacecraft launched in 1997 and arrived at the Saturn system in 2004, where it has been in orbit for its Prime Mission, and Equinox and Solstice Extended Missions. Exploration of the Saturn system is driven by gravitational flybys of Saturn's moon Titan which alter the spacecraft trajectory. The Cassini navigation team receives satellite ephemerides to predict the location of Titan and Saturn's other moons from JPL's Solar System Dynamics Group. During Prime Mission, the *a priori* satellite uncertainties were on the order of tens of kilometers; with subsequent refinement from Cassini data, these uncertainties are tens of meters for Titan and on the order of kilometers for the icy satellites. This reduction in uncertainty led the Navigation Team to stop estimating corrections to the satellite ephemeris for navigation operations during the Solstice Mission and instead consider this uncertainty in the navigation filter [1]. This approach gave good results in terms of flyby performance initially, but in the summer of 2016 larger target misses at Titan encounters began to occur. This work discusses the Cassini orbit determination strategy and the reintroduction of satellite ephemeris estimation in navigation operations. The necessity of scaling the formal uncertainty of the *a priori* satellites covariance is shown and estimation results for several orbit determination (OD) arcs are presented.

## 2. Navigation Operations Overview

The Cassini reference trajectory is designed to return to designated target points at close encounters of Titan and other moons [2]. The actual trajectory is allowed to deviate from the reference away from these targets. Figure 1 shows the Cassini reference trajectory for the Solstice Mission.

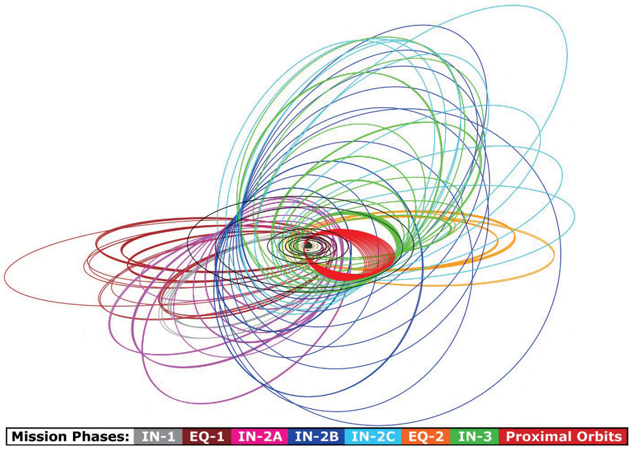

Fig. 1. Solstice mission Saturn-centered trajectory oblique view. The coloring scheme represents the various phases of the trajectory, either at inclination or in the equatorial region. The small red set of orbits corresponds to the Grand Finale phase.

Radiometric tracking data is processed by the OD team to produce a best estimate of the current trajectory and the corresponding uncertainties. This solution is used by the

Maneuver Team to design Orbit Trim Maneuvers (OTM) that target the desired upcoming encounter state. Typically there are three maneuvers between encounters; two deterministic maneuvers targeting the encounter state and a statistical approach maneuver three days prior to encounter which corrects for the execution error of the two deterministic maneuvers. Flyby targets are usually defined in terms of the B-plane. The B-plane forms a set of coordinates in the plane passing through the target body center and perpendicular to the incoming velocity asymptote as in Figure 2. The B.T and B.R vectors describe the in-plane component of the target and a third timing component completes the system. The uncertainty at the time of the encounter is expressed as a 2D error ellipse in the B-plane along with a timing error component. Errors in the OD solution used for OTM design or execution error from thruster firing can result in some 3D target miss error at the encounter. This error then propagates downstream in the trajectory and can result in poor science results at encounter and increased future maneuver sizes.

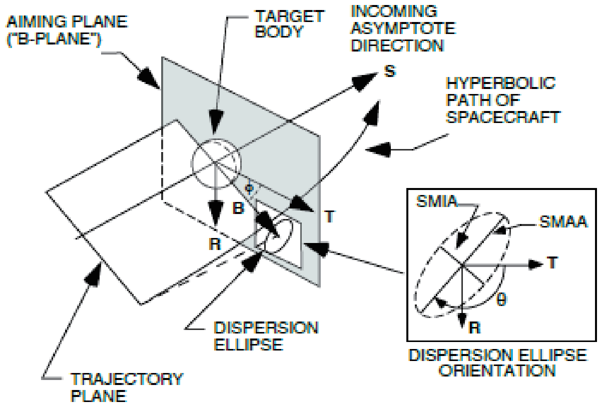

Fig. 2. Description of B-plane Geometry

## 3. Orbit Determination Filter Setup

Trajectory arcs that transfer from one encounter to the next typically cover several orbital revolutions about Saturn and are deignated by the "rev" number, a letter corresponding to the target body, and the number of targeted flybys for that body. For example, the 231T116 arc is the 231st rev about Saturn and the 116th targeted flyby of Titan. Radiometric tracking data in the form of Doppler and range measurements are accumulated in a least squares navigation filter to provide a best estimate of the spacecraft position and corresponding covariance. Table 1 shows the parameters [2] that have corrections estimated in the filter and the parameters whose uncertainty is considered in the covariance [3]. The maneuver execution error model for OTMs implements fixed errors regardless of burn magnitude and errors proportional to the maneuver size [4]. Two sets of maneuver errors are given based on engine configuration; execution on the Reaction Control Subsystem for smaller burns and Main Engine configuration for larger burns. Stochastic accelerations in eight hour batches are estimated to ensure unmodedeled accelerations do not alias into the spacecraft state, OTMs, or small forces estimates. The *a priori* error of the satellite ephemerides varies based on the particular delivery from JPL's Solar System Dynamics Group and is discussed in the next section.

Table 1. OD Filter Setup.

| Parameter | Unit | Est/Cons | 1-sigma error |
|---|---|---|---|
| Epoch S/C state | km, cm/s | Estimated | <5 pos, <20 vel |
| RCS OTM | %, mm/s | Estimated | 0.02% prop., 3.5 fixed |
| ME OTM | %, mm/s | Estimated | 0.4% prop., 0.5 fixed |
| Small Forces | mm/s | Estimated | 0.25-1.20 |
| Stochastic Accelerations | km/s$^2$ | Estimated | 5x10$^{-13}$ |
| Transponder Range Bias | m | Estimated | 500 |
| Satellites Ephemeris Sys. | km,km/s | Est / Cons | varies by set |
| DSN Station Locations | cm | Considered | 2-5 |
| Earth Media Calibrations | cm | Considered | 1-5 |
| Earth Pole Orientation | cm | Considered | 10 per axis |
| Saturn Ephemeris | km | Considered | 0.2 |

The satellite ephemeris system is reintegrated during each iteration and then the states and gravitational parameters (GMs) along with Saturn's pole and zonal harmonics are corrected in the navigation filter.

## 4. *A priori* Satellite Ephemerides

A satellite delivery satXXX consists of trajectories of Saturn's moons and the correlated error covariance of their epoch states, GMs, and the pole and zonal harmonics of Saturn to degree eight. When estimating corrections to the satellites, all satellite trajectories are adjusted as well as each parameter in the correlated covariance. Each new satellites delivery includes the most current spacecraft data from Cassini as well as incorporating past Earth and spacecraft- based measurements. Figure 3 shows the differences in Titan position in radial, along-track, and cross-track coordinates between several satellites deliveries and an estimated solution from Cassini operations, referenced to the most recent delivery of sat389 [5]. The sat358 to sat375 ephemerides are tightly clustered in terms of their Titan trajectories.

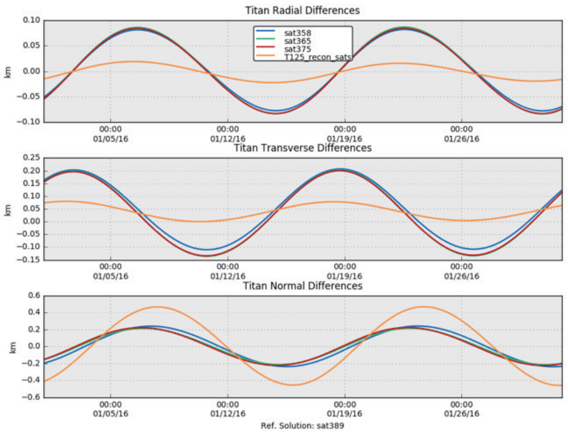

Fig. 3. Comparison of Titan position in the RTN frame for different satellite ephemeris deliveries referenced to sat389. The purple curve shows a corrected Titan ephemeris estimate from Cassini operations.

However, they differ significantly from the sat389 delivery and the Cassini solution estimated from a sat389 *a priori* also differs, most significantly in the normal or out of plane direction. These differences in Titan's position affect targeting future flybys of Titan and cause difficulty fitting the Cassini trajectory to tracking data near a past Titan flyby. The formal 1-σ error on the Titan ephemeris of these satellites deliveries is on the order of tens of meters, reducing by an order of magnitude between sat358 and sat375, while the absolute difference between delivered ephemerides is on the order of hundreds of meters in Titan position. The Saturn pole modeling has also changed over those past deliveries, from a linear to a trigonometric model, with tight 1-σ error but wider absolute difference between deliveries, affecting the satellite ephemerides. This contributes error to the OD solution when not estimating corrections to the satellite trajectories in the filter. The current satellites delivery used as *a priori*, sat389, has increased 1-σ error on Titan state and the Saturn pole paramters compared to sat358 and sat375, and includes a linear pole model for Saturn.

## 5. Titan Encounter Performance

The measure of how well the navigation team predicts a Titan encounter is evident from comparing the spacecraft trajectory solution at the last control point or approach maneuver prior to the flyby, to the reconstructed trajectory estimate using data past the flyby. Table 2 shows the 3D error and corresponding sigma level for Titan flybys near the time that larger Titan errors began to occur.

Table 2. Titan Encounter Performance Summary.

| Titan Flyby | Altitude (km) | 3D error (km) | 3D sigma level |
|---|---|---|---|
| T115 | 3548.1 | 0.54 | 2.5 |
| T116 | 1400.0 | 2.29 | 4.8 |
| T117 | 1018.0 | 0.35 | 2.2 |
| T118 | 990.0 | 0.41 | 0.9 |
| T119 | 971.0 | 2.44 | 5.8 |
| T120 | 975.0 | 1.06 | 2.9 |
| T121 | 976.0 | 0.77 | 2.8 |
| T122 | 1697.7 | 1.11 | 0.5 |
| T123 | 1773.9 | 0.14 | 1.6 |
| T124 | 1584.8 | 0.37 | 1.2 |

A recent Cassini OD paper covered Titan flybys up to the 229T115 arc [1]. The 3D error is computed by differencing the pre- and post-flyby solutions of the spacecraft state at the flyby. The 3D error sigma is a measure of how many standard deviations the 3D error vector is away from the mean of the covariance distribution, referred to as the Mahalanobis distance. For the flyby arcs in the table up until T121, the satellite ephemerides were held fixed and their error was considered in the navigation solution. The large flyby errors at the T116 and T119 flybys led to investigation of possible error sources in the OD solution. Figure 4 shows the B-plane solutions for T116 with the last control point solution used for approach maneuver design in blue and the trajectory reconstruction solution shown in red. The reconstruction solution includes data past the targeted flyby and has its error ellipse significantly reduced. The difference between the ellipse centers accounts for most of the 2.29 km miss shown in Table 1. The delivered OD solution in this case did not estimate corrections to the satellite ephemeris system but considered the satellite uncertainty in the error covariance. The filter solution also produced multi-sigma corrections in magnitude and pointing of the main engine maneuver targeting the T116 flyby. Spacecraft telemetry from the main engine firing is used to constrain the burn pointing in right ascension and declination when fitting the maneuver, so multi-sigma corrections are generally not expected [6].

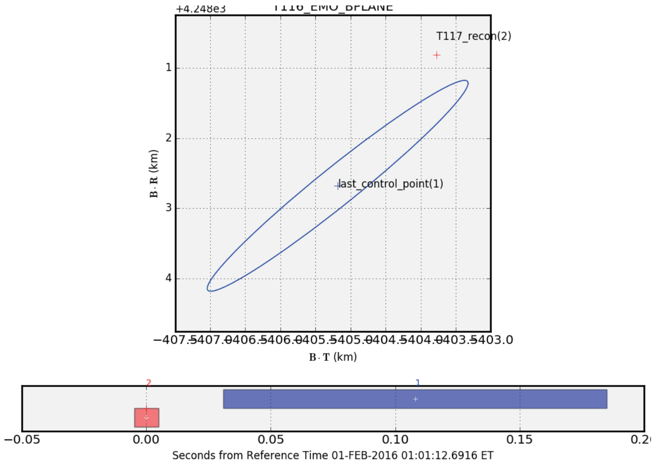

Fig. 4. Comparison of B-plane solutions for T116 between the targeted ellipse (blue) and the reconstructed trajectory with data past the flyby (red).

For the Titan encounters with large 3D target misses, the filter computed large corrections to the targeting maneuver pointing in order to best fit the tracking data. This is because the targeting maneuver size in those cases were on the order of meters per second, representing the largest dynamic event while in Saturn orbit other than a satellite flyby. When the navigation team began estimating corrections to the satellite ephemerides, these unusual corrections to the targeting maneuver estimates were mitigated.

## 6. Satellite System Covariance Scaling Results

Since the nominal filter configuration produced unexpected maneuver corrections and the T116 and T119 encounters produced larger target misses than were in line with recent performance, the OD team experimented with again using satellite estimation in the filter. Up until the T93 Titan flyby, a raw covariance delivery satXXX would be estimated with a scaling factor of 3 applied to the formal covariance. The OD team iterated several solutions with different scaling factors applied to the current sat389 formal covariance to investigate whether a stable solution existed with a data cutoff prior to each targeted flyby. Figure 5 shows B-plane solutions for the T119 encounter with the same data cutoff but different scaling factors applied to the formal satellites covariance, in addition to a solution where the error in the satellites covariance is only considered. The data cutoff for these solutions was the final tracking pass prior to approach maneuver design. Any error in the OD solution would be passed on to the Titan encounter. The blue solution labeled “satconsider_x3” was the delivered solution used for maneuver design which led to the target miss. The other three solutions move toward the top right corner of the B-plane as the scaling factor on the covariance is increased.

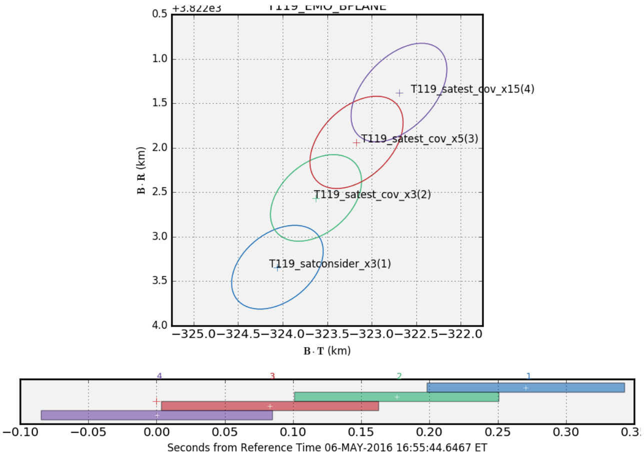

Fig. 5. B-plane solutions for T119 using satellite estimation with different scaling factors applied to the formal satellites covariance.

As the filter was given more freedom to adjust the satellite ephemeris based on the first Titan flyby in the arc, T118, the multi-sigma corrections to the maneuver targeting T119 were reduced. Figure 6 shows the T119 B-plane for solutions with and without satellite estimation. The solutions are labeled by data cutoff “1, 2” representing the two tracking passes prior to the approach maneuver design and “est/cons” showing whether the satellite ephemerides are estimated or considered. The two “est” solutions in red and purple show a stable solution using satellite estimation with a scaling factor of 15 applied to the formal covariance. The consider solutions labeled “1/2_cons” which do not estimate satellite corrections move away from the satellite estimation solutions as more tracking data is accumulated.

The approach maneuver to the T119 encounter was designed based on the “2_cons” solution and the maneuver target is shown in black, with the “J” label representing an executed backup maneuver opportunity. The trajectory reconstruction including data past the T119 flyby is within the “1_cons” blue ellipse. The maneuver was intended to shift the B-plane solution from the “2_cons” ellipse to the black target ellipse (red arrow). The trajectory reconstruction shows that the true solution was closer to the “2_est” satellite estimation solution, since the downward motion in the B-plane due to the maneuver brought the solution from the “2_est” ellipse to the small “T119_recon” error ellipse (green arrow).

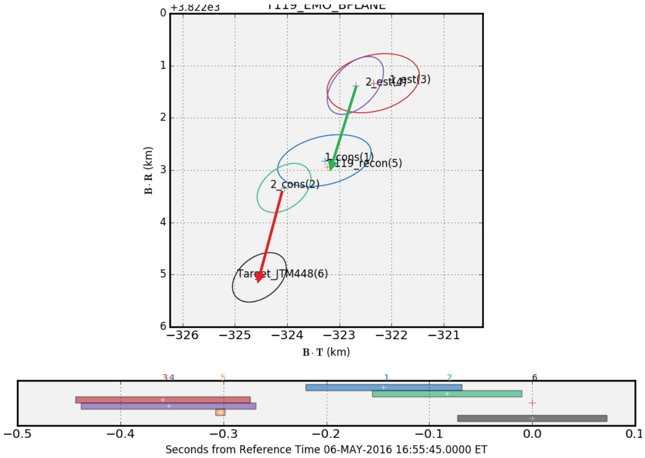

Fig. 6. Comparison of T119 B-plane solutions using satellite estimation and considering satellite error. The maneuver target in black was designed using the “2_cons” consider solution. The reconstructed trajectory solution in orange is within the “1_cons” blue ellipse.

Applying the scaling factor to the formal satellites covariance allowed the Titan ephemeris to correctly fit the first flyby in the arc, and propagate that solution to a more accurate target at the second encounter in the arc. Figure 7 shows the estimated Titan ephemeris represented in radial, along-track, and cross-track coordinates for the arc spanning T118 to T119 for different levels of covariance scaling. The largest correction is in the out of orbit plane normal direction, on the order of hundreds of meters from the nominal. This correction is much larger than the ~30 meter formal uncertainty on the sat389 Titan epoch state. Scaling the covariance allows the filter to make corrections more on the order of the difference between Titan states in subsequent satellite ephemeris deliveries.

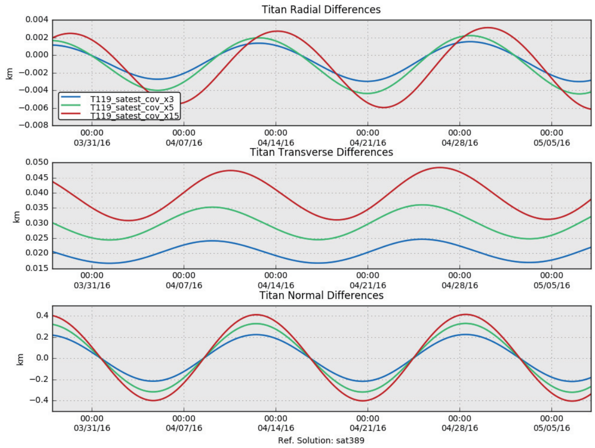

Fig. 7. Comparison of Titan ephemeris in radial, transverse or along-track, and normal or cross-track coordinates referenced to the delivered sat389 ephemeris. As the covariance scaling factor increases, the filter makes larger corrections to the Titan state, most visible in the normal direction.

Changing the location of the first Titan flyby in the arc modifies the computed Cassini spacecraft trajectory and allows for a more accurate second flyby in the arc. Since the data after the first Titan flyby in an arc has so much leverage to adjust the spacecraft trajectory estimate, the filter does not estimate large corrections to the maneuver targeting the subsequent flyby to better fit the mid-arc tracking data.

Simiar behavior is found for the T116 encounter which exhibited a 2.29 km target miss. Figure 8 shows a series of B-plane solutions with two data cutoffs for each of the satellite estimation and consider strategies for the T116 Titan encounter. The consider solutions move from the “1_cons” ellipse to the “2_cons” ellipse by advancing the data cutoff one day. The estimated satellites solutions reduce their uncertainty from the “1_est” to “2_est” ellipses while remaining colocated. The JTM439 backup maneuver implemented was intended to shift the B-plane solution from the “2_cons” ellipse to the black target ellipse (red arrow). The orange cross at the tip of the green arrow shows the final trajectory reconstruction solution is at the edge of the black target ellipse, a miss of 2 km. This shows that the true solution was closer to the purple “2_est” satellite estimation solution and the final reconstruction of the flyby included some maneuver execution error and OD error within that ellipse (green arrow).

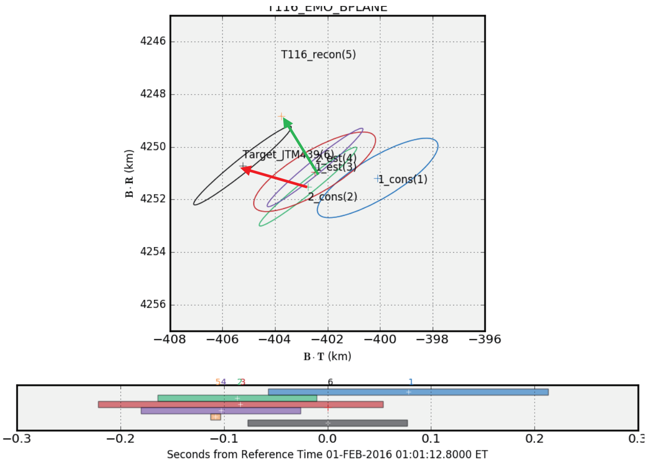

Fig. 8. Comparison of T116 B-plane for solutions with and without satellite estimation. The maneuver target in black was designed using the “2_cons” consider solution. The final trajectory reconstruction lies at the tip of the green arrow.

In this case, more so than the T119 encounter, the addition of tracking data forces the solutions from the two strategies closer together. The filter compensates for the lack of satellite ephemeris correction by modifying the mid-arc targeting maneuver and spacecraft trajectory states.

With the evidence from the T116 and T119 Titan encounters supporting the use of satellite ephemeris estimation, the navigation team began delivering OD solutions with estimated corrections to the satellite system in the arc targeting T121 in the summer of 2016. Figure 9 shows B-plane solutions for the T121 Titan encounter using satellite estimation at three data cutoffs prior to approach maneuver design. The three solutions are colocated since the satellite estimation corrects the first Titan flyby in the transfer, allowing a better fit of the spacecraft trajectory through the arc. The final reconstructed trajectory solution lies just at the edge of the 1-σ target ellipse. The 0.77 km target miss for T121 is attributed to pointing error in the approach maneuver.

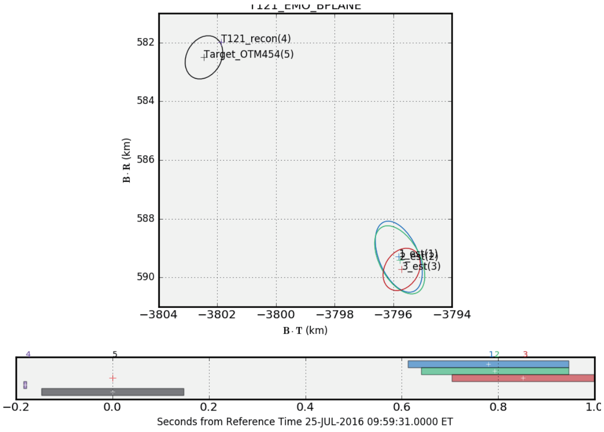

Fig. 9. B-plane solutions for T121 using satellite estimation. The three solutions prior to approach maneuver estimation are colocated in the bottom right corner. The reconstruction of the flyby is at the edge of the target, due to maneuver execution error.

Subsequent flyby encounters are targeted using satellite estimation OD solutions. For T122, a 1 km target miss is attributable to cancellation of the approach maneuver, due to a neglibible penalty in ΔV cost. The T123 flyby yielded a 0.14 km target miss along with the next two encounters falling under 500 meters in encounter error as shown in Table 2.

## 7. Conclusion

The Cassini navigation team has restarted estimating satellite ephemeris corrections in the orbit determination solution in response to larger than usual encounter target misses. These differences in encounter performance only stand out since the Cassini navigation team has routinely delivered sub-kilometer target misses at Titan. The T116 and T119 encounters demonstrate the accuracy of satellite estimation solutions and the solutions delivered since the estimation process was restarted have target misses of 1 km or less. The actual errors of the delivered trajectory still provided adequate flyby performance to meet science experiment objectives at these flybys. Additional potential error sources under study include unmodeled tidal forces and an incorrect representation of Saturn’s pole rate. The Cassini Grand Finale trajectory begins after the final targeted flyby of Titan T126 and will take the spacecraft between the rings and atmosphere of Saturn. Details of the Cassini navigation team’s adaptations for this mission phase can be found in References [7] and [8].

## Acknowledgments

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