Orbit Determination Processes for the Navigation of the Cassini-Huygens Mission

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

Deep space navigation, particularly the Orbit Determination (OD) operations of Cassini at Saturn, cannot easily be automated due to the complex dynamical environment in which the spacecraft flies; however several sub-processes are automated. The Cassini OD operations are often faced with unique challenges that require more than routine procedures. The OD Team is staffed appropriately to meet the demanding schedules and allow some level of flexibility. This paper will discuss how the OD processes are developed and the seven-member OD team is scheduled to support efficient and accurate Cassini navigation operations. Also discussed will be the requirements of the radio-metric Doppler and range tracking data acquired via the Deep Space Network and the optical navigation images of the satellites to support the daily OD operations. Furthermore, the reliability of the OD solutions, which is ensured within the framework of the OD processes, will be explained.

I. Introduction

After launch of the joint United States National Aeronautics, Space Administration, European Space Agency and Italian Space Agency (NASA/ESA/ASI) Cassini-Huygens mission in October of 1997 and a seven-year interplanetary journey, the combined Cassini/Huygens spacecraft (S/C) entered into Saturn orbit on June 30, 2004. Since then the project released ESA's Huygens probe on December 25, 2004, which entered the opaque atmosphere of Saturn's largest moon, Titan, and successfully landed on its surface on January 14, 2005. The "prime mission", four-year, seventy-orbit tour of the Saturnian system was designed to satisfy the mission science objectives to determine the composition, structure and dynamical processes of Saturn's atmosphere, magnetosphere, rings, and satellites[1]. The Cassini S/C trajectory of the prime mission was designed to perform 53 close-targeted flybys of Saturn's largest moons, of which 45 of these are of Titan while 3 are of the icy satellite Enceladus, and 5 are of each of the icy satellites Dione, Rhea, Hyperion, Iapetus and Phoebe. At the time of this conference, the Cassini S/C will have flown through 99% of the designed prime mission. A two-year "extended mission" (XM) has recently been approved by NASA to further investigate the Saturnian system in more detail. This extended mission will include 26 additional close flybys of Titan, 7 of Enceladus, 1 of Rhea and 1 of Dione.[2]

A. Navigation Objectives

Consistent, accurate, and efficient Orbit Determination (OD) processes are important elements to successful satellite tour navigation. The challenge for the Cassini navigation team is to accurately fly the designed tour within minimal propellant cost while meeting requirements for science observations often under tight time restrictions. Figures 1 & 2 shows the relationship between the components of the Navigation Team, Trajectory Design, Optical Navigation, Orbit Determination and Maneuver Design Teams. Navigation begins with the design of the spacecraft reference trajectory by the Trajectory Design Team. The Optical Navigation team plans and processes images of the satellites as viewed from Cassini. These images along with 2-way Doppler and range radio metric data from the NASA's Deep Space Network antennas are processed by the Orbit Determination Team to determine Cassini, Saturn and its satellite orbits. Once these orbits are determined, the Maneuver Team then designs one or more maneuvers using either Cassini's Main Engine (ME) or the smaller Reaction Control System (RCS) thrusters to optimally target the next satellite encounter. Close cooperation with the Attitude and Articulation Control Systems (AACS) and Propulsion Teams is required to implement the commands that are uplinked to the S/C to perform the maneuver. A lead Systems Engineer oversees the planning, design and implementation of every maneuver and the maneuver is then approved by Project Manager, Navigation and Spacecraft Engineering !map. Over 150 trajectory correction maneuvers are planned and performed to achieve the navigation objective of keeping the S/C on the designed trajectory in the prime mission. These are planned to target close (50 – 11,000 km) altitude satellite flybys. The free-energy exchanges from gravity assists of specific Titan flybys are also utilized in the tour design to alter the S/C's path for exploration of different longitudinal and latitudinal regions of the Saturnian system. Maneuver design requires accurate OD of the S/C's predictive path and those of the satellites. A little over one maneuver per week may be required depending on the phase of the mission such as in several series of sixteen-day Titan-to-Titan orbits. These periods, and especially the delivery of the Huygens probe to Titan, are particularly labor intensive and depend on quick OD operations. Williams, et al, discuss the maneuver design processes for Cassini.[3]

As shown in Fig. 2, three Orbit Trim Maneuvers (OTMs) are generally planned per targeted encounter. The deterministic targeting maneuver (usually near apoapsis) realigns the trajectory to maintain the designed upcoming encounter flyby conditions. Next, the statistical approach maneuver takes place approximately 3 – 6 days before the encounter to correct the trajectory from maneuver and OD dispersions. Finally, the clean-up maneuver executes 3 days (or more) after encounter to compensate for flyby errors and is often optimally combined with the following apoapsis maneuver to target the next encounter. Details of the maneuver design strategy are described in the Cassini Navigation Plan.[1] OTMs are performed on either the S/C's 445 N bi-propellant ME or on the four 0.9 N monopropellant RCS thrusters (co-aligned with the ME).

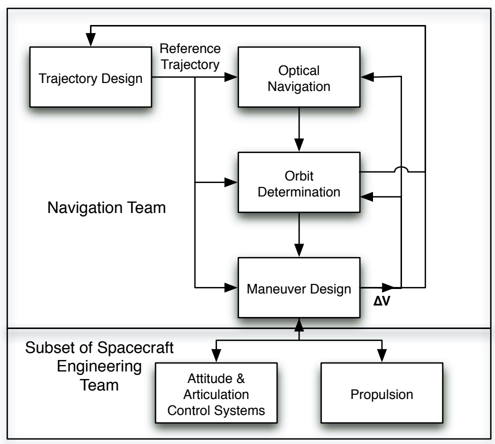

Figure 1. Relationship of the Navigation and Spacecraft Engineering Teams.

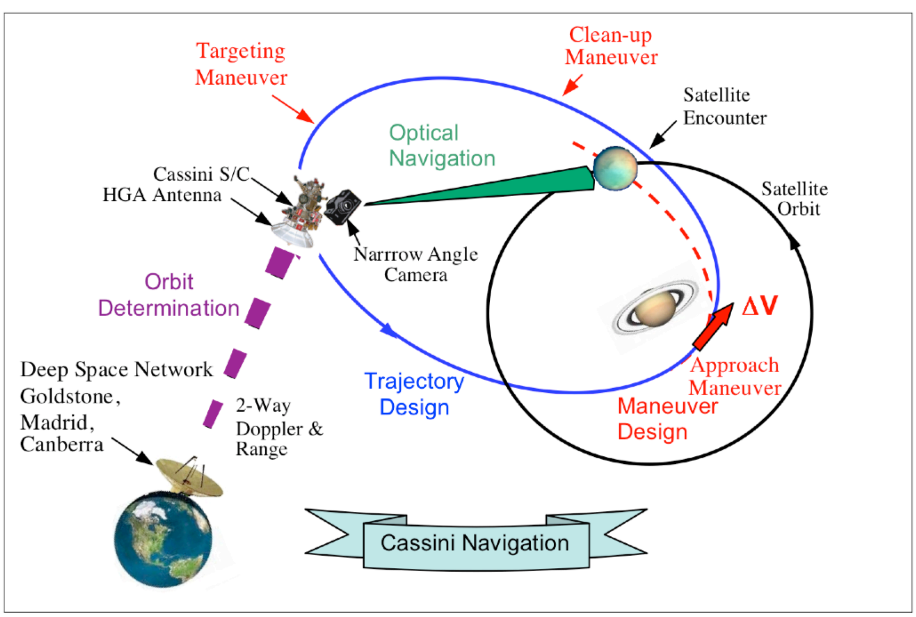

Figure 2. The functions of the Navigation Team for flying the designed reference trajectory.

B. Orbit Determination Objectives

Three main objectives of the OD Team are: 1) to perform covariance studies for satellite tour designs or redesigns in order to determine navigational capabilities of meeting science requirements, 2) to routinely estimate and improve the predictions of the S/C trajectory as well as the ephemerides of Saturn and the major Saturnian satellites to support the maneuver designs that keep Cassini on the reference trajectory, 3) to reconstruct the S/C, Saturn and the satellite ephemerides and gravity after the fact for the Science Teams' precise analysis of their instrument observations. The major satellites in order of distance from Saturn include the nine moons, Mimas, Enceladus, Tethys, Dione, Rhea, Titan, Hyperion, Iapetus and Phoebe.

Satellite ephemeris errors were the major navigation error source prior to Saturn orbit insertion (SOI). The improvements in the estimates of the satellite ephemeris, Saturn and satellite masses, Saturn zonal harmonics, and Saturn pole vector are major objectives for the OD Team as these parameters are important for navigating the tour. The major satellite orbits were only known to a few thousand kilometers in orbital positions before Cassini's final approach to Saturn. These errors had to be reduced for the mission to be successful. Several months from SOI, an optical navigation (opnav) image campaign of the satellites began to reduce their uncertainties through the OD process. Navigation of the prime mission has been a tremendous success as can be seen in the OD results that have been documented in several papers. Roth, et al[4], discuss the OD results during the final approach to Saturn, the Phoebe flyby and SOI. Roundhill, et al[5], Stauch, et al[6], Antreasian, et al[7,8], and Criddle, et al[9], review the results of the first two Titan encounters after SOI, all the encounters leading up to the 11th Titan encounter and the Hyperion encounter. Bordi, et al[10] discuss the OD strategy and results which led to the successful Huygens probe landing on Titan, January 14th, 2005.

II. Orbit Determination

In general, orbit determination is the process of estimating the spacecraft's state (position & velocity) by minimizing (in a least squares sense) the residuals of tracking data observables to the *computed* observables based on a dynamic model of the S/C's motion described below. A measurement model also described below must additionally be used to adjust these *computed* observations to closely match the real world. A depiction of the general process of orbit determination is given in Fig. 3. The equations of motion that model the S/C, planet and satellite orbits cannot exactly match the truth and the parameters such as Saturn gravity, or thrust, for example, thereby have some level of uncertainty associated with them and thus need to be estimated in the OD filter.

A. Dynamic Modeling

Primarily Kepler's laws of orbital motion and Newton's law of gravity govern the S/C's motion around the Saturn barycenter where Saturn's point source gravity is the dominant force. This motion is perturbed in order of significance by thrusting events from maneuvers or "small forces" such as those that result from its RCS which controls the attitude or biases the reaction wheels, gravity due to the satellites, sun's gravity, oblate gravity of Saturn, internally generated thermal radiation pressure, solar pressure, relativity, Jupiter and other 'third bodies'. At Saturn's distance from the sun, it's interesting to note that the force caused by the thermal emission of internally generated heat from the S/C is an order of magnitude greater than solar pressure. Within one to two hours during close satellite encounter, the satellite's point source gravity may become the greater force than Saturn's depending on the flyby distance. Figure 4 shows the significant forces acting on Cassini during a low Titan flyby of 950 km (T16 on July 22, 2006). As shown in Fig. 4 for Titan encounters, atmospheric drag (during low Titan flybys, altitudes < 1300 km) and Titan's oblate gravity become significant perturbations on the S/C's motion. These forces comprise the spacecraft dynamic model and are dependent on the planetary and satellite ephemerides, and masses, and the S/C attitude.

B. Observations

Cassini's orbit determination is dependent on 2-way X-Band Doppler and range tracking data acquired via NASA's Deep Space Network (DSN) and onboard optical navigation images (opnavs) of the major Saturn satellites against a background of known stars. The Doppler measures Earth-line-of-sight velocity of the S/C relative to the tracking station while range measures its Earth-relative distance. Opnavs are a two-dimensional measurement of the apparent satellite's position based on the locations of the stars in the camera's focal plane. Gilliam, et al[11] discuss the optical navigation procedures and results during the Cassini prime mission.

C. Measurement Modeling

The 1993 versions of the International Earth Rotation Service (IERS) Terrestrial and Celestial Reference Frames (ITRF93 and ICRF93) define the Earth-fixed and inertial radio frames used for deep space navigation.[12] The third-body gravitational perturbations caused by the sun and planets are determined from the positions derived from the Jet Propulsion Laboratory (JPL) Development Ephemeris, DE410, which is aligned with ICRF93.[13] The latest timing and polar motion data delivered as the Earth Orientation Parameter (EOP) file from the Time and Earth Motion Precision Observation group at JPL are used to relate the Earth-fixed frame to the inertial radio frame. This data set includes daily differences in Universal Time 1 (UT1) that accounts for polar motion, International Atomic Time (TAI), and geodetic pole motion. The DSN station locations are measured in the Earth-fixed frame and have errors less than 5 cm in each coordinate direction with linear continental plate motion applied. The measured variability of Earth's wet and dry troposphere and day and night ionosphere components is used to calibrate the radio-metric data.

D. Filter Model

The Orbit Determination Program (ODP) pseudo-epoch state estimation filter is used to estimate the S/C epoch state and the corrections to the Saturn ephemeris, the satellite states, their masses, the Saturn pole, and Saturn oblate gravity terms J_2, J_4 and the system mass. Thermal radiation pressure is estimated as well as maneuver parameters of magnitude and pointing, and RCS thrusting events. For low altitude Titan flybys, the coefficient of atmospheric drag is estimated. Background stochastic accelerations are also estimated to account for errors in solar pressure or other small forces. The RCS activity during these flybys is estimated by using a set of stochastic acceleration batches. Low degree and order gravity harmonic terms (J_2, C_{22}) are estimated for cases when radio-metric data is obtained during satellite passes. Errors in parameters that cannot be easily estimated are considered in the filter. These errors contribute to the uncertainties in the estimated parameters, yet their values are not estimated; these include errors in station locations, troposphere, ionosphere, polar motion, UT1 and future RCS thrusting events.

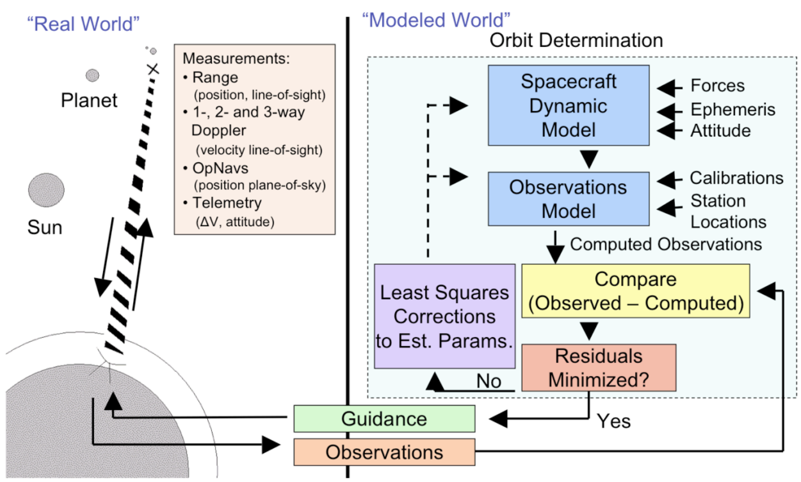

Figure 3. The process of orbit determination.[14]

E. Orbit Determination Requirements

The predicted S/C, Saturn and satellite ephemerides are provided to the project, Deep Space Network, Science and Nav Teams for designing OTMs, computing tracking antenna frequency predicts, or planning sequence updates. Occasionally, these predictions are used to update the tour reference trajectory. In order to verify the feasibility of these reference updates, a covariance study like those described below are performed.[15,16]

The science teams' desired observations of Saturn, its moons and rings require precise pointing predictions of Cassini's science instruments. Precise instrument pointing to targeted and non-targeted satellites levy requirements on the orbit determination of Cassini and the satellites to achieve predicted 1-sigma accuracies at better than 1.02 mrad for flyby altitudes between 20,000 – 30,000 km and 0.79 mrad for altitudes greater than 30,000 km.[1] Generally, five days prior to encountering the target satellite a final approach maneuver is designed to correct the S/C trajectory and realign it to the designated flyby conditions. For each flyby, a S/C onboard sequence of science observing activities including instrument pointing is based on the latest navigation reference trajectory at the time of its inception. These are programmed several months before the targeted encounter and remain somewhat inflexible to inevitable changes in the estimates of the S/C trajectory and satellite ephemeris. Because of this, the Navigation objective is to fly as close as possible to the designed tour, which in general means that the aim points of the targeted flybys must remain unchanged. Occasionally, when there are small target errors, it is found by the Maneuver Team that either a maneuver is too small to execute, there is no substantial mission cost penalty to reduce the target miss by canceling the approach maneuver or there is a overall mission cost savings.[3] To overcome this, there are strategic opportunities for updating the instrument pointing vectors prior (5 days or more) to an encounter or occultation (ring or atmosphere). OD solutions with the latest data up to the 5-day requirement are delivered to support these 'live' updates. The latest S/C to satellite (or Surn) pointing vectors are compared to those from the reference trajectory used to build the sequence and the latest dispersions are computed. These dispersions are tracked (comparing current ops solutions to covariance studies) as shown in Fig. 5 in order to identify times when a pointing update is meaningful, that is, when the dispersion is generally less than the correction. If the instrument pointing vectors for the Titan observations in Fig. 5 are not updated, there's a greater than a 67% probability of not meeting the requirements. The pointing of the science observations is then evaluated by the science teams to either accept the deviation from the reference or update the instrument pointing vectors in the active sequence onboard the S/C. Predictions of how the 1-sigma pointing dispersions for Saturn and the satellites will vary depending on the data cut off for the three maneuvers per arc are presented at the Encounter Strategy meeting described below.

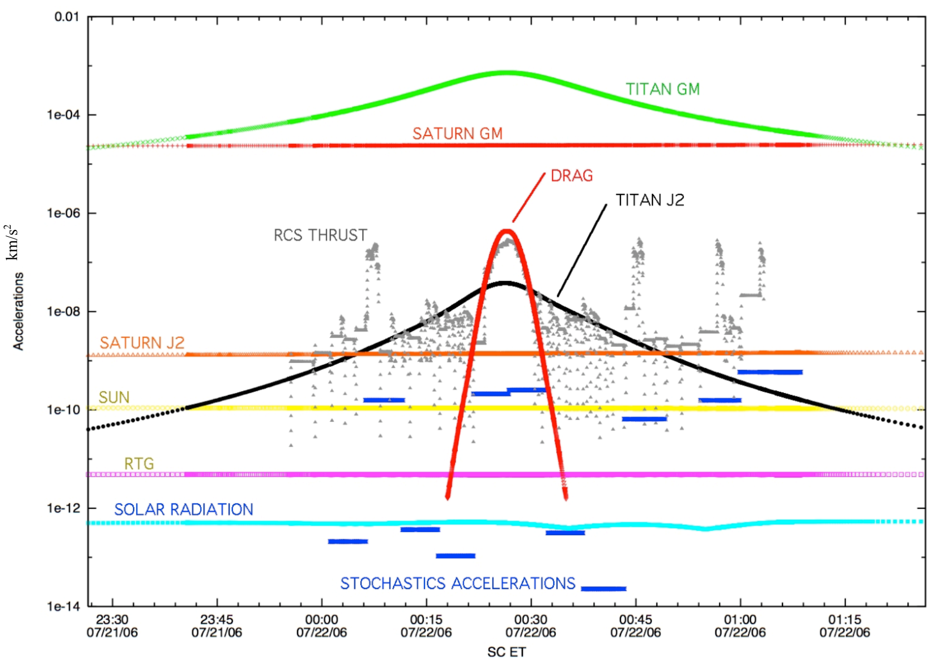

Figure 4. The major forces (accelerations) acting on Cassini during a low altitude Titan flyby (950km).

Table 1. Frequency of Encounters and Orbit revolutions per year not counting the Phoebe flyby or SOI.

Year	Span	Number of Encounters	Number of Revs
1	July 04 – July 05	8	12
2	Aug 05 – July 06	13	14
3	Aug 06 – July 07	18	22
4	Aug 07 – July 08	13	22
	Total	52	70

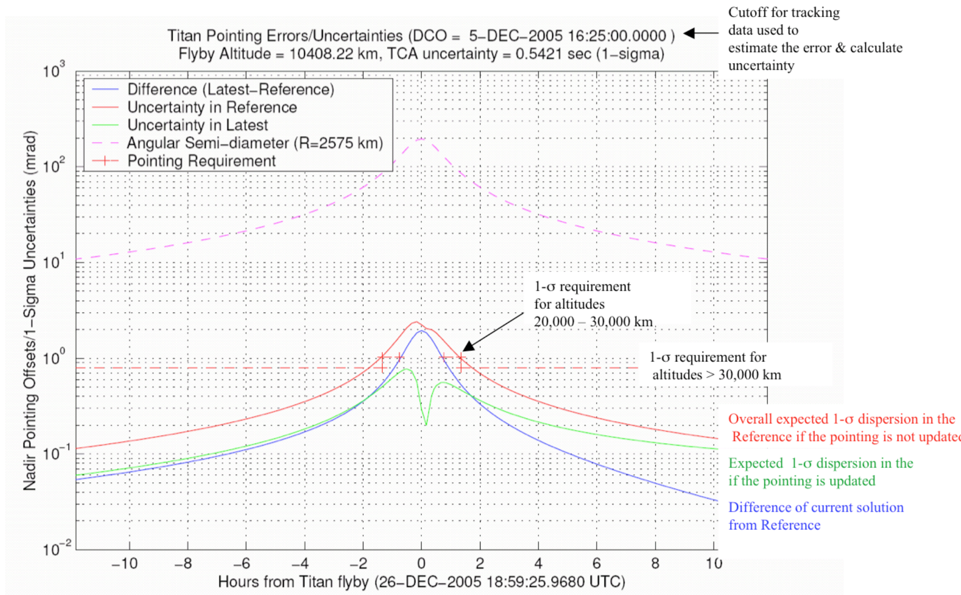

Figure 5. Example of predicted S/C – Titan pointing plot.

F. Tracking Requirements

1. Radio-Metric

The radio-metric tracking requirements for Cassini have been established to ensure robustness to loss of data in the event of tracking station outages or erroneous data. These include:

- One tracking pass per day scheduled coincident with downlink of science data. Usually acquired from the northern hemisphere since southern hemisphere stations cannot support a six-hour coherent pass due to the S/C's high declination.
- Daily pass should acquire at least six hours of 2-way Doppler and three hours of 2-way range data.
- Tracking from second DSN complex at least four times, distributed, between targeted encounters.
- Because the science instruments are fixed-mounted to the S/C bus, radio-metric data are not acquired up to twelve hours before and after targeted encounters since the observing geometries preclude pointing the S/C's High Gain Antenna (HGA) to Earth for telecommunications unless the flyby is specifically designated as a radio science gravity experiment.
- Also, because of the HGA mount, no tracking data are acquired during maneuvers.
- Coherent tracking within 4 hours of a maneuver, at least two hours of coherent tracking before and two more hours after the maneuver.
- At least three range data points acquired after a maneuver to help determine maneuver timing.
- If possible, schedule RCS thrusting events to bias reaction wheels in the middle of the six-hour pass.
- In general OD deliveries are not vulnerable to the loss of a single tracking pass.

2. Optical Navigation

The opnav schedule was also designed to ensure a high level of robustness to loss of data. The requirements on the opnav schedule include:

- To acquire good coverage of all major satellites using Cassini's narrow angle camera (Titan images were later removed from the schedule after the first year due to poor center-finding caused by its atmosphere and due to the fact that the Titan ephemeris was well determined within the first year.) Phoebe imaging after SOI was also substantially reduced.
- Shutter at least three frames per day on approach through the 3rd flyby (TC) to converge satellite ephemeris determination

- Reduce shutter rates to 1.7 frames per day through the first year in orbit at Saturn. (In operations, three to six opnav images were actually shuttered per day.)
- Further reduced to 0.5 frames per day to maintain satellite ephemeris.
- Opnav images must contain at least two known stars of appropriate magnitudes (~10.5 – 8).
- Images of the satellites shall be taken at phase angles below 120˚.
- Images shall be shuttered using the clear filter.

Table 2. Periods of high activity and sixteen-day Titan-to-Titan transfers.

Period	Span (Weeks)	Number of Encounters	Number of Maneuvers	Rate of Maneuvers
Dec 04 – Jan 05*	5	2	6	1.20/week
Aug 05 – Nov 05†	14	5	16	1.10/week
Sep 06 – Nov 06	8	4	10	1.25/week
Dec 06 – Feb 07	10	4	12	1.20/week
Feb 07 – Jul 07	20	9	27	1.35/week
Nov 07 – Jan 08	8	4	10	1.25/week

*Huygens probe delivery period
†Icy satellite phase

III. The OD Team & Staffing

A. Staffing

A relatively large OD team of six to seven members and a lead is staffed to meet Cassini's demanding schedule in the prime and extended missions. Table 1 shows the number of encounters and orbital revolutions per year of the 4-year tour. The schedule to support the Huygens probe delivery was particularly intensive. Several activities during this period included maneuvers to target the probe for delivery, the probe separation, reconstruction of probe release and retargeting the orbiter for receipt of the probe's signal during its Titan atmospheric entry. A complete timeline of the activities and processes that the OD team were responsible for are explained by Bordi et al.[10] Table 2 lists other periods of high activity, especially during the sixteen-day Titan-to-Titan revs and the icy satellite encounter phases. The teams must support the maneuver designs that are quite frequent at up to 1.35 maneuvers per week during these multiple-month phases. The staffing is designed to provide reliability, redundancy and allow some level of flexibility for vacations or sick leave. It is inevitable that the busy satellite tour schedule occasionally requires members of the OD team to work weekends, holidays and late nights or early mornings.

B. Education, Skills

The OD team is primarily composed of engineers who have earned advanced degrees (PhD, MA/MS) in Aerospace Engineering, Mathematics or Physics. Many have had several years experience in astrodynamics, spacecraft orbit determination and estimation before joining the Cassini OD Team. The team is required to know how to run the JPL ODP software on the Linux or Unix computer operating systems. The majority of the team is proficient at programming in matlab, perl, FORTRAN, and python. These skills are required to develop, maintain and troubleshoot programs and scripts that help the OD processes become more efficient. Often Team members are faced with unique challenges that require significant evaluation and troubleshooting. Team members are also expected to have good communications and writing skills as they have ample opportunity to present results to the Nav Team and Project.

C. The Data Arc

The planning and implementation of OD for a particular targeted encounter requires a great deal of focused attention which precludes planning for subsequent encounters. Therefore, the team is split up into three teams of two OD analysts (a lead, and a back-up). Each team is responsible for a particular encounter or a series of orbits in the case of *empty* Saturn revs (which do not include targeted encounters).

When the data arc length is expanded to include two or more close satellite encounters, the numerical accuracy of the OD solution degrades significantly. Ill-conditioned information matrices, integration errors and partial derivative numerical precision limit the data arc length to reliably span two close satellite flybys. This is typically about 1.5 revs. Thus, as shown in Fig. 6, each team fits data starting with the epoch established near the Saturn apoapsis prior to the first encounter and continues through the next encounter 1.5 revs later. Data arcs can, however, span multiple empty Saturn revs without these problems.

D. OD Team Processes

Given the limitation of the data arc, each two-member OD team's activities progress through the following phases: Planning and covariance analyses, arc setup and going *online*, going into operations, going *offline* or into reconstruction, and documentation. The planning phase consists of acquiring the schedules of events, tracking, maneuvers, small forces, S/C attitude, etc. These events are input into the High Fidelity (HiFi) covariance study described below and these results are used to prepare for the upcoming operational data arc. Once the epoch of the data arc is reached, the online phase begins. The operational data arc is established and the first few tracking passes are added to the OD solution. This arc is then used to help the Maneuver Team plan for the subsequent post-encounter, clean-up maneuver. The OD deliveries of this arc during this phase allow for testing of the maneuver processes.[3] Eventually, this data arc goes into operations mode where the S/C, satellite and Saturn ephemerides, maneuvers, etc are estimated on a daily basis. Periodically, during this phase the solutions are delivered to the Nav Team or Project for maneuver designs, live science pointing updates, or DSN frequency predicts. Once the next team goes operational (typically after the second flyby), the data arc goes *offline* into reconstruction. During reconstruction, the entire data arc is refitted with the best a priori models available (which may include telemetry) to determine the best estimates of the S/C, Saturn and the satellite ephemerides, their masses and gravity terms, Saturn pole, maneuvers, and other parameters. These reconstruction products are delivered to the Project for the science teams to base their observations with. OD performance is also tracked by comparing the pre-flyby predictions to reconstructed results. A summary of these processes is:

- Planning/Covariance Studies
    - Prepare for next rev data arc
    - Predict uncertainties as function of data cut off
    - Used as comparison for operational data arc statistics
- Going online
    - Establish epoch, file setup
    - Generate next-arc OD deliveries for post-encounter maneuver design for testing/setup
    - Solutions are used as a comparison for operational data arc.
- Operations
    - Maintain daily estimates of S/C, Saturn, satellite ephemerides, masses, maneuvers, etc
    - Deliver OD solutions for maneuver designs, science pointing updates, DSN frequency predicts
    - Monitor tracking quality
- Going offline/Reconstruction/Documentation
    - Determine best estimates for S/C, Saturn, satellite ephemerides, masses, maneuvers, etc
    - Deliver reconstruction solutions to Project for basis of science observation results
    - Summarize OD solution estimates, and OD performance in reconstruction memo

In Fig. 6, a team becomes *operational* immediately after the first flyby which means that they are responsible starting with the +3-day clean-up maneuver design for the events leading up to the second encounter in the arc. Their first tasks are to reconstruct the flyby events using the post-encounter tracking pass; this then precisely determines the target miss distance and reduces the S/C state uncertainties significantly. Usually, there's only time for one or two tracking passes (2 days) after the encounter to include in the OD delivery to support the clean-up maneuver. Shortly after the time the *operational* team supports the apoapsis maneuver design and the maneuver executes, the next team comes *online* usually setting the epoch of their arc shortly after this maneuver. This allows overlap in the data arcs (*operational* = long arc and *online* = short arc) for any given targeted approach. The overlapping arcs provide a validation to the final OD deliveries for maneuver designs. The *operational* team then supports the final approach maneuver, which executes approximately three days before the next encounter. It should be noted here that depending on the phase of the mission satellite encounters can take place during the S/C's inbound approach to Saturn periapsis, or outbound from Saturn periapsis.

E. Responsibilities

Figure 7 further illustrates the time line of activity that takes place during the satellite tour for the three OD teams. The example in Fig. 7 was taken from a multiple sixteen-day Titan-to-Titan phase of the mission from March – April 2007. As shown in Fig. 7, the 3 teams overlap responsibilities. Each team begins with performing the HiFi covariance analysis (described below) of the upcoming arc. At the time Cassini reaches apoapsis, the HiFi covariance analysis is finished and its results are presented at the Encounter Strategy meeting which takes place for the Project to review the expected navigation, engineering and science activities for the upcoming rev and encounter. At this time, this arc goes *online* (as discussed above), and after its first flyby it becomes *operational*. Finally, after the next team becomes *operational* following the second satellite encounter, this team and their data arc go *offline* into reconstruction mode. During reconstruction the entire data arc (ending approximately 2 days beyond the second flyby) is re-fit with best possible model parameters. Only the first orbit (apoapsis to apoapsis) is delivered to the Project as the 'gold bar' for science evaluations. Figure 7 shows the tight turn-around for the maneuver implementation, which usually follows the OD Data Cut Off (DCO) by 1 – 2 days. The colors in Fig. 7 match the color of the team responsible.

For every planned maneuver there are at least five meetings that the operational OD team needs to support either by delivering updated OD solutions, presenting OD results, or attending for awareness of issues pertaining to the maneuver. These meetings include the Maneuver Preparation, Preliminary & Final Design Nav Reviews, Maneuver Approval and finally the post-maneuver Wrap-up meetings as shown in Fig. 7. Williams, et al, discuss more details on these meetings.[3]

The OD Team Lead is responsible for scheduling the team members to satisfy the needs of the Nav Team, overseeing the daily operations, covariance analyses, assigning tasks, mentoring the team and reporting to the Nav Team chief. Occasionally, the lead performs special studies or steps in to perform deliveries if needs arise.

As shown in Fig. 7, the team members lead and backup roles change after going *offline*. The backup for one arc becomes the lead on the next arc going into the HiFi covariance phase. The lead finishing reconstruction of the prior arc then joins this team as the backup. This allows for everyone on the team to take responsibility, gives them opportunity to manage the arc and present their reports. This also allows for team members to work and learn with other members.

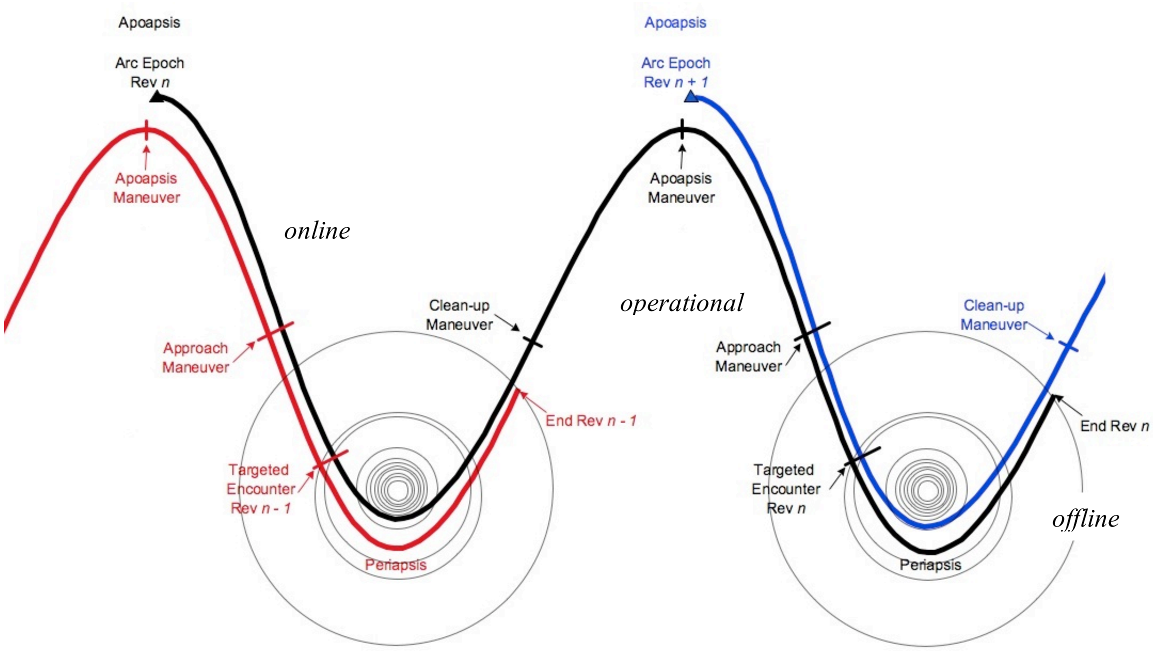

Figure 6. OD arc spans spread out in a time progression for illustrative purpose.

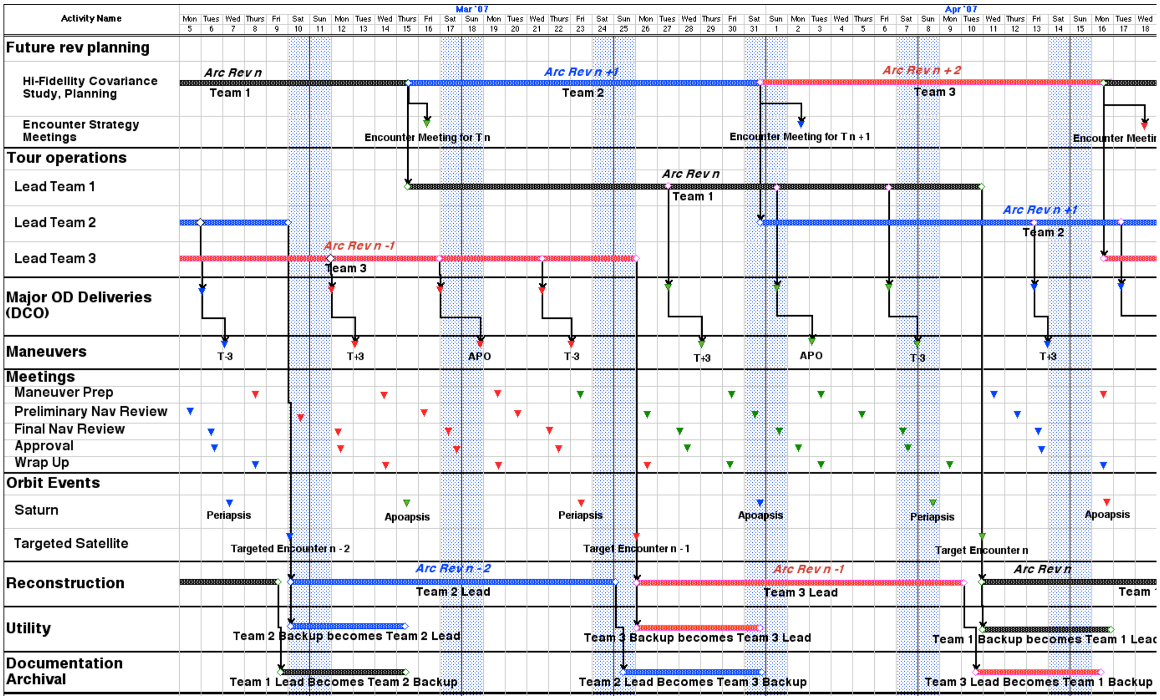

Figure 7. An example of the demanding OD Team schedule during the sixteen-day back-to-back orbits.

IV. OD Processes

A. Computer Systems and Software

The JPL's legacy orbit determination program, the Multi-Mission Navigation Orbit Determination Program–Double Precision Trajectory program (MMNAV ODP-DPTRAJ) is at the heart of Cassini's OD process. It is run on a network of Linux workstations interconnected on a gigabit ethernet backbone to a network attached disk array used for storage of OD data. This fault-tolerant, six terabyte, high-availability disk array is devoted to the OD team for daily operations and file deliveries to the other parts of the navigation team.[17] Built on top of this software is the JPL *navshell* system that helps automate and tie together essential pieces of the ODP and other software tools into an efficient, robust, and flexible system. Deep space navigation, particularly the OD operations of Cassini at Saturn, cannot easily be automated due to the complex dynamical environment in which the S/C flies; however several of the sub-processes are automated. These automated processes including reporting tools (that help build memos and presentations), new arc setup, and input manipulation tools are needed for quick turn around of products.

The OD work environment on the Cassini Nav computer network attached disk array is designed to promote efficiency, consistency, and traceability especially for a large team. Any particular OD solution requires thousands of parameter inputs and it is the OD analyst who is responsible that these inputs are correct for their OD solutions. This environment allows teams to share resources, minimize redundant operations and redundant input files. The directory structure is set up for common files that are used for all arcs and those that are arc-specific. The operation solutions are performed in arc-specific areas designated by the rev number/target name and OTM; daily OD solutions are performed in separate directories designated with the date. The start of daily solutions begins by using the *newdir* utility which copies over any local files and links the last converged case solution files, so that the OD analysts needs to only iterate from the previous day's solution to be current, otherwise it may take several iterations (10 – 30 minutes each) before the solution reaches the converge state. With such a large team using shared resources and input files, quick and efficient communication of input changes, or file updates to the entire team are necessary. This is achieved by automatic email notifications when key files or procedures are updated or downloaded or through a system 'message-of-the-day' feature built into the *navshell* software which sends current messages to the computer screen for all current users running OD solutions. All OD procedures, papers and memos are documented on the Cassini Nav "wiki" web page (JPL internal web page) for the team to peruse for quick reference.

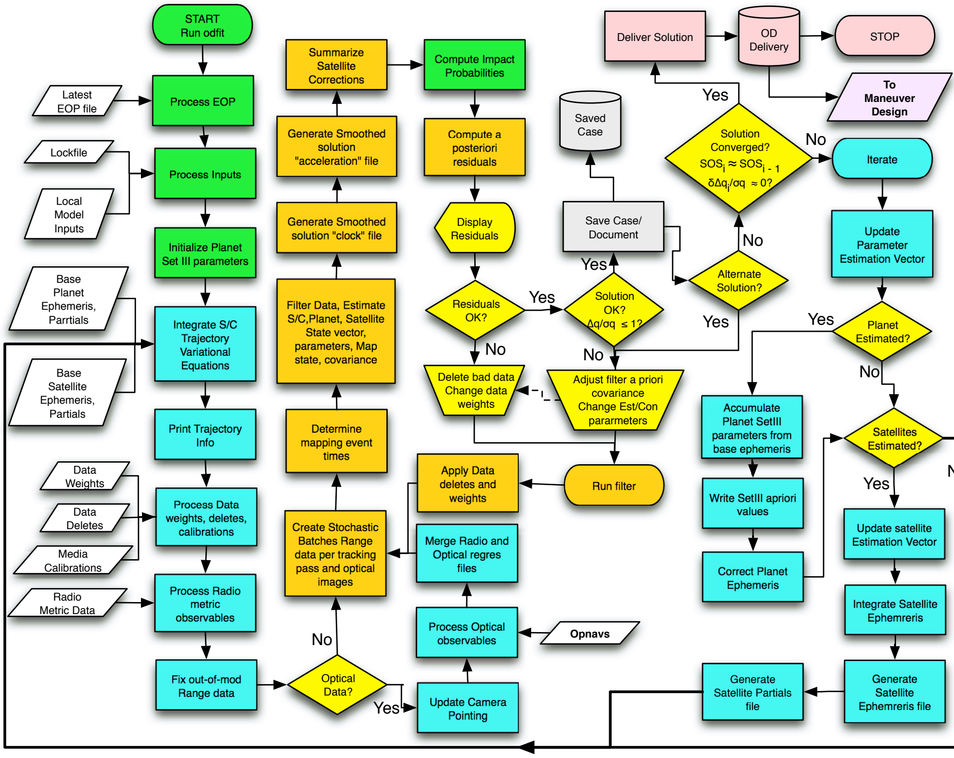

Figure 8. The Orbit Determination process flowchart for Cassini operations.

B. The OD flowchart

Figure 8 shows the flowchart of the various functions and activities, which produce the OD solutions and deliveries. The process to perform an OD solution begins with the green *odfit* sub processes in Figure 8 and includes all the inputs on the left of the figure. The *odfit* processes include all the activities (blue and orange) leading up to "Display Residuals". The yellow diagrams indicate manual intervention by the OD analyst for evaluation, editing and decisions. If there are changes such as data edits or changes in data weights or filter parameter settings, then the *filter* path is exercised until the solution satisfies the OD analyst (i.e. filtered parameters are within their a priori uncertainties, tracking residuals and stochastic accelerations exhibit near zero mean without structure). When the solution is satisfactory it is saved. Then the solution is converged by the *iterate* process at the right (blue then orange). The *iterate* process begins by updating the estimate vector parameters with the corrections from the previous case. Then the Saturn and satellite ephemerides are updated if they were estimated in the previous case. Once these are updated, the path follows back to the original *odfit* processes, starting at the S/C integration step. The solution is iterated in this fashion until the corrections in the estimated parameters are very, very small and the pre-fit tracking residuals sum-of-squares closely match that of the post-fit residuals. Once converged the solution is delivered to the Maneuver Team for the design of the upcoming trajectory correcting burn.

C. Advancing the OD data arc

The S/C state epoch for each new arc that is coming *online* needs to be established with from *operational* OD solution by estimating S/C, satellite, and Saturn ephemerides to convergence using tracking data up to the desired new epoch. In this *filter* run the S/C state is mapped to this new epoch. The post-fit state and satellite covariances from the converged solution are used to define the *a priori* covariances for the new arc and the post-fit S/C state is used as the new arc's initial conditions. The iterated satellite and Saturn ephemerides are then used as inputs in Figure 8.

D. Daily OD operations

The operational team is responsible for keeping the OD of Cassini up to date. Figure 9 shows the daily activity that is required in most cases to keep the solution up to date for converging the OD for a maneuver design. The daily OD fit begins by creating a new directory with the best solution from the previous day as the case to be iterated from. All file updates, new radio-metric and opnav tracking data, media calibrations, EOP and small force predictions are downloaded and the input files are updated. If there were new dynamic events such as small forces or maneuvers, the inputs are updated with the models and parameter partial derivatives. The *iterate* process is performed from this case to bring the solution up to date with the new tracking data added. The radio-metric tracking data is then weighted according to a scaling of its fit root-mean-square (rms) statistics. The *filter* process is then run until the solution is satisfactory for reasons given above and iterated through the *iterate* process also mentioned above. The OD delivery (described below) is then made to the Maneuver Team. The Maneuver Team's processes produce the latest maneuver design that satisfies the targeting of the upcoming encounter. They deliver to the OD Team inputs of the maneuver parameters (execution time, thrust, ΔV, and direction) maneuver error model based on the Gates execution model.[18] In their process, RCS thrusting events to spin down the reaction wheels before the burn and back up after the burn are produced and delivered to the OD team. These events depend on the latest S/C conditions for the burn and thus they need to be updated in the beginning stages of the maneuver design (darker blue processes). Based on the maneuver design and its expected dispersion, the OD team is required to compute the differences in the S/C – satellite pointing vectors of the updated trajectory from the reference and their expected dispersions. The new maneuver design and its execution error covariance must be added in the OD solution to carry out this task. This process starts at the verify maneuver step (light blue and blue path). The process ends with the comparison of this solution's results to the desired aim point and dispersion in the encounter B-plane. If the maneuver achieves the designated target then the pointing errors of this updated trajectory to the reference are computed (pink).

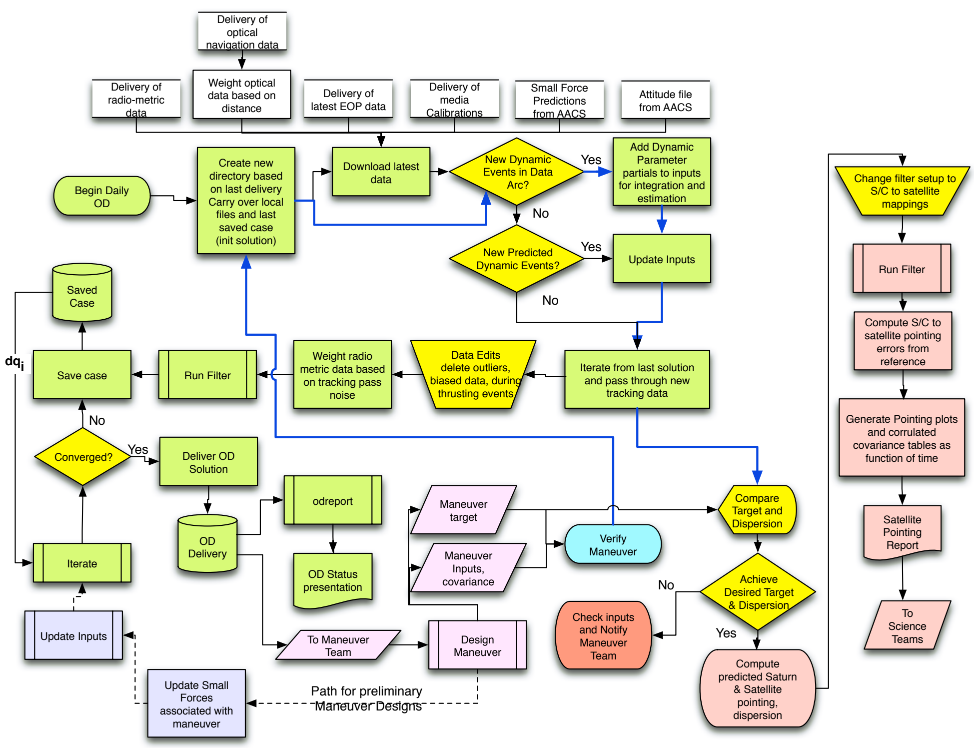

Figure 9. Daily Orbit Determination activities.

E. OD Deliveries

OD deliveries include the updated general input file which includes the converged filtered estimates, the converged S/C trajectory, satellite ephemeris, Saturn ephemeris, S/C attitude and smooth acceleration files. These files are necessary for the Maneuver Team to recreate the S/C trajectory, so they can design the next burn. A summary of the solution parameters, S/C state mappings at the first and second encounter target B-plane and a summary of the tracking data used in the fit. The delivery is documented with a file release form that includes the list of inputs used in the solution and a 'Readme' file that contains comments on the solution strategy and assumptions. The *odreport* process shown in Figure 9 produces the OD report that is delivered with the OD solution and presented at all the meetings mentioned beforehand. It contains plots and tables of items referred in the Verification of OD list below. Other delivered files include the 'light-time' files that are fed into the real-time display of Doppler and range data being acquired at the DSN station. All files inputs used to create the solution are also delivered in the case of needing further analysis.

F. Covariance Studies

The predicted tour covariance analysis as specified in the Nav Plan forms the basis of navigation performance and capability.[1] This study and updates to it,[15,16] which were completed before tracking schedules and detailed dynamic events were known, made somewhat conservative assumptions on the OD filter models, radio-metric and opnav tracking schedules and data quality. Before a segment or data arc begins, a high-fidelity (HiFi) covariance study is performed using the latest tracking schedules, updated dynamic models, and latest OD filter assumptions. As this new data arc becomes operational, these covariance analyses help track the OD convergence of orbit errors and provide a map to track operational OD performance as a function of time leading up to each targeted flyby. The main product of these covariance analyses is the mapping of the S/C dispersions to the encounter B-plane as a function of DCO. The B-plane semi-major and semi-minor axis dispersions are computed as well as the uncertainty in the time of closest approach (TCA). To show how the tracking data is converging or reducing the S/C mapped uncertainties, all thrusting events and filter parameters are included in the filter at each DCO; down-stream events except OTMs are included as considered errors since the mapped OTM dispersions to the encounter B-plane are typically much larger than the OD errors and thus would mask the OD convergence. Instead these OTM events are included into the filter at their execution times. Their contributions to the OD errors are shown in Fig. 10 by the relatively large spikes in these plots. It is also shown how these dispersions are reduced as the post-burn data is fed into the filter. The covariance studies help the Nav Team:

- Establish maneuver DCO's
- Verify the navigation capabilities
- Identify DCO's which can meet pointing requirements
- Verify that opnav and tracking schedules are sufficient to meet required accuracy
- Highlight any particularly critical tracking passes

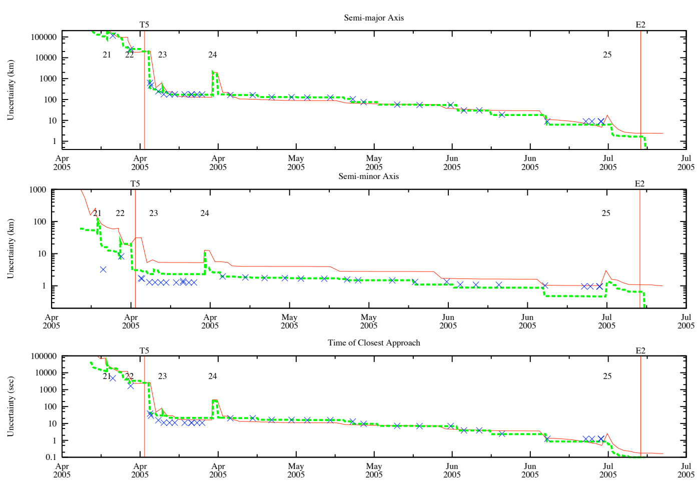

Figure 10. Example of monitoring statistics of daily operation solutions against Nav Plan and HiFi covariance studies.

These rev-by-rev high-fidelity covariance analyses are generally performed one and one half orbit revolutions before each encounter (see Fig. 7). During the progression or evolution of the data arc for a particular targeted encounter, the current OD statistics are routinely plotted in Fig. 10 (designated by the X symbols) against the HiFi and Nav Plan covariance studies to ensure that the OD is converging (errors are declining) as expected from these studies. As shown in Fig. 10, the HiFi analyses typically show better statistics than the Nav Plan. This is expected and is directly attributed to the conservatism in the Nav Plan study. Departures in actual operation solution statistics shown in this figure can be attributed to the following: the late addition or removal of RCS ΔV events, optical or radio data outages, and changes in satellite covariance scaling.

The covariance results of the HiFi study are summarized in the OD Encounter Strategy presentation. The package summarizes the dynamical events important to OD during the arc with a diagram showing the orbital S/C locations of these events and a table listing them chronologically. Also, shown in this package are the expected target B-plane dispersions as a function of time and these values at the DCO's for the maneuver designs. Expected satellite and Saturn pointing dispersions are shown for these DCO's.

G. Satellite Ephemeris Development

One of the major challenges to the OD processing for Cassini is the estimation and integration of the satellite ephemeris. The OD team on a rev-by-rev basis generally improves the satellite ephemeris, however, this processing may not accurately represent the long period satellite-satellite interactions. Therefore, periodically, a large scale development of the satellite ephemeris is performed offline by Jacobson et al.[19] based on all of Cassini's radio and optical data as well as radio and optical data from the flybys of the Voyager and Pioneer 11 S/C, and Earth-based US Naval Observatory, Hubble, and Table Mountain astrometric observations and historical observations dating back to the 1960's. The large data set used to estimate the satellite ephemeris is important to determine the long period dynamical interactions. In addition to the Saturn ephemeris, this environment includes the Saturn pole position at epoch, the masses (GM) of the satellites, Saturn, the oblate gravity and zonal harmonic terms (J_2, J_4, J_6, J_8) of Saturn. Through the large data set, meaningful or significant correlations between these parameters are formed in the covariance and provide the mechanisms that allow some parameters to be improved based on the observability of another.

H. The Verification of OD solutions

The OD team performs several evaluations on near daily basis to insure the accuracy or quality of the OD solutions. Below are a few checks that are done when new tracking data, or model inputs are added before an OD solution is delivered.

- Pass new tracking data through yesterday's OD solution to see how well it is predicting
- Track daily parameter estimates
- Determine the effect of predicted dynamic model changes in target B-plane
- Determine causes to aim point movement
- Solutions are routinely compared against a wide set of filter strategies
- Compare to last delivered solution in terms of how many standard deviations each parameter differs between the two solutions
- Determine if parameter estimate changes exceed their *a priori* uncertainties

The following checks are integrated into the OD reports as a set of plots that are shown in presentations of the solutions to the Nav team and Project for the Preliminary & Final Maneuver Design Reviews and Approval Meetings. Among the items that are routinely covered by this reporting include the following:

1. Monitor of DSN tracking quality
    a. Data loss, noise are reported and problems are noted
    b. A discrepancy report is issued if there was a significant outage or problem
2. Monitor RWA bias predictions
    a. When the 2-way Doppler determines these and their errors exceed a 2.5 mm/s threshold an Incident Surprise Anomaly is issued.
    b. The pedigree of the predict is also tracked through a comment field in the table showing the file used. This helps to identify predictions that need to be updated.
3. Monitor background stochastic accelerations
    a. These estimates measure the quality of the parameter estimates in the arc – large excursions relative to their *a priori* 1-sigma uncertainties raise concerns of miss-modeling, tracking data quality, or over-constrained parameter a priori uncertainties.
    b. Generally estimates should have zero mean
4. Monitor stochastic tracking pass range biases
    a. These also monitor the quality of the tracking pass
    b. Also raises concerns stated in number 3 and also should exhibit zero mean estimates.
5. Monitor stochastic opnav pointing estimates
    a. These monitor the quality of the opnav images

    b. Outliers may be indicative of erroneous stars were used
6. Monitor convergence of data (Doppler & range) through plots of pre-fit data residuals
    a. The excursion of the residuals from zero mean is indicative of solution convergence problems
    b. As long as these remain small, usually less than 10 m for range, there should be no concern
    c. Symptomatic of numerical accuracy in state dynamic partials after close encounters.
7. Monitor satellite ephemeris differences in Saturn-centered Radial-Transverse-Normal frame
    a. Large differences are cause for concern
    b. Trending in one direction such as in the down track may signify problems in achieving best estimate
    c. Helps check the efficacy of opnavs or close satellite encounters on their determinations
8. Monitor daily maneuver estimates
    a. Helps team understand OD solution trending
    b. Reports maneuver performance
    c. Usually telemetry-pointing values are also used and compared to designed values
9. Monitor Titan drag pass estimates
    a. Helps team understand OD solution trending
    b. The equivalent density estimates are reported to Project and compared to the AACS estimates, which are computed through the computation of drag torques on the S/C and the science instrument measurements at regular Titan Atmospheric Team Working Group meetings. The deviation of results from these other teams raise concern to the quality of the OD fit.
    c. Significantly lower or higher estimates may signify miss-modeling of RCS flyby events
10. Monitor opnav quality and performance
    a. Part of this is done through the stochastic opnav pointing estimates above
    b. Large residuals are either indicative of systematic biases, possible center-finding errors or satellite ephemeris errors
    c. Recent large residuals of Enceladus were indicative of large ephemeris down track error and over-constrained satellite covariance
11. Compare predicted RCS thrusting profile for low altitude Titan flybys to telemetry
    a. Gives assurance to the quality of telemetry, the predict and the confidence of the OD solution.
    b. Shows if there are telemetry outages
12. Monitor stochastic accelerations during flyby
    a. These are used to cover errors in the telemetry or prediction
    b. Relatively large excursions from zero mean could be indicative of miss-modeling of the flyby dynamics
13. Monitor OD solution in target B-plane
    a. History of solutions help to signify the quality of the OD solution
    b. Large 1-sigma excursions warn team of possible unresolved errors in the filter set up, unobservable filter parameters or erroneous tracking data
    c. Linear drift again warns team to possible unresolved filter set up errors, unobservable filter parameters or erroneous tracking data
14. Monitor OD solution B-plane dispersion convergence against HiFi covariance.
    a. Departures in operation solution statistics should be explained by the addition or cancellation of RCS events, maneuvers, tracking data losses, changes in a priori satellite covariance or use of pointing telemetry in maneuver estimates (pointing uncertainties may be substantially deferent from designed.
    b. If a source cannot be found then HiFi study needs to be reevaluated and differences must be tracked down and reported

I. Maneuver Wrap Up

The maneuver wrap-up meetings require quick evaluation of maneuver performance to the Project for quality assurance. At least the maneuver tracking pass of coherent data is used for this quick-look OD solution. The OD wrap-up procedures include a report that contains the following plots and tables that give confidence in the maneuver performance as well as confidence in the post-burn OD solution. These include:

- A plot as shown in Fig. 11 showing the real-time display 2-way Doppler residuals of the pre- and post-burn data relative to the annotations of events and the expected 1-sigma dispersion of the burn in the Earth-line.
- The target B-plane diagram showing the maneuver target and expected dispersion, the quick-look OD solution and the deviation from the target due purely to maneuver execution errors. The difference in the OD solution and the maneuver execution error is a result of OD errors.

- The Earth-line maneuver error breakdown of the quick-look estimate and the uncertainty.
- Maneuver ΔV, pointing and start time estimates
- The performance of the RCS reaction wheel spin up/down event predicts is also reviewed.

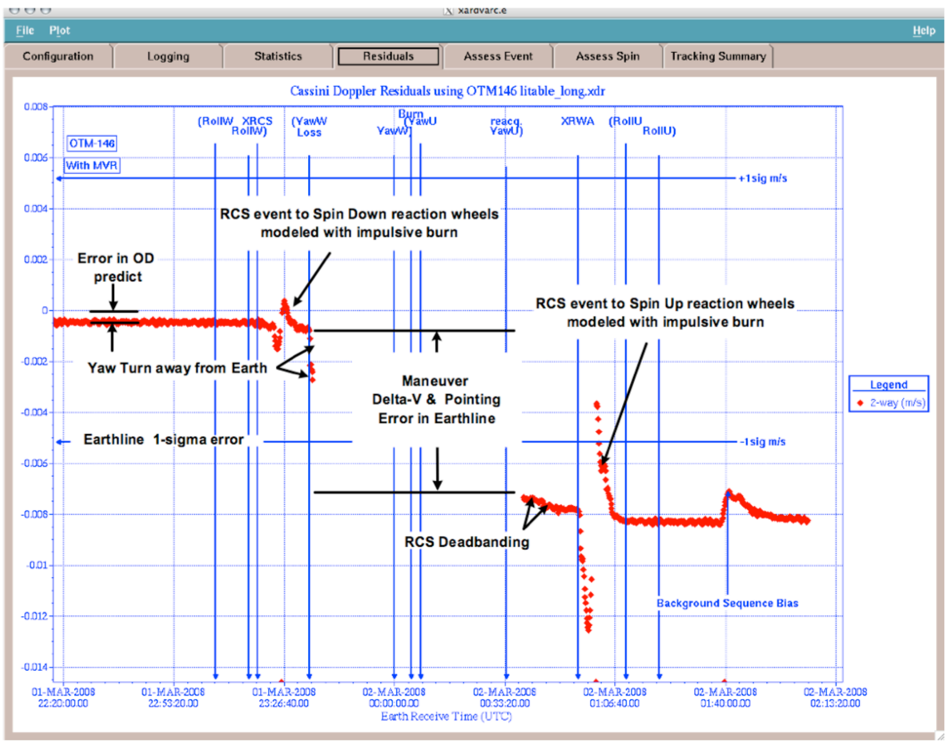

Figure 11. Real-time 2-way Doppler display of a maneuver.

V. Lessons Learned

In order to satisfy the demanding maneuver design schedule of the prime and extended missions, the Nav Team requires a big OD Team. With such a relatively large team planning for future revs, or running simultaneous solutions, quick and efficient communications are vital to keeping the team up to date on updates in procedures, files or procedures. Since dynamical events are continuously taking place on Cassini, there is a short time constant to the knowledge of the current state of the Cassini's orbit. The OD Team needs to be on top of the solution and can't afford to fall behind. Comparing the actual aim point dispersions on a daily basis to those predicted in covariances analyses helps the team to identify possible problems in their arc filter setup. The comparison of the reconstruction to the predicted solutions in the target B-plane provide a metric for determining how well the OD processes are performing. Updates to the models can be modified if necessary. The rotation of duties for each member of the OD Team helps keep the people fresh and trained. Having two people or two pairs of eyes on the solutions at any given time aides in catching potential errors and allows for additional analysis to verify OD quality. The varying OD conditions (short orbits (8 – 12 days) versus long orbits, multiple revolutions, probe delivery) require flexibility in the OD processes.

Acknowledgments

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]Cassini Navigation Plan, JPL Internal Document D-11621, August 1, 2003.

[2]Cassini Extended Mission Navigation Plan, JPL Internal Document D-11621, March 1, 2008.

[3]Williams, P.N., et al., "Orbit Control Operations for the Cassini-Huygens Mission," *SpaceOps Conference*, Heidelberg, Germany, Paper 2008-3429, May 12-16 2008.

[4] Roth, D., P. Antreasian, J. Bordi, K. Criddle, R. Ionasescu, R. Jacobson, J. Jones, M. Meek, I. Roundhill, J. Stauch, "Cassini Orbit Reconstruction From Jupiter To Saturn," *AAS /AIAA Astrodynamics Specialist Conference*, Lake Tahoe, CA, August 7-11, 2005.

[5] Roundhill, I.M., P. G. Antreasian, K.E. Criddle, R. Ionasescu, M. C. Meek, J. R. Stauch, "Orbit Determination Results for the Cassini Titan-A Flyby," AAS Spaceflight Mechanics Meeting, Copper Mtn, CO, Paper AAS 05-113, Jan 2005.

[6] Stauch, et al, "Preparing for the Huygens Probe Mission, Cassini Orbit Determination Results for the First and Second Targeted Titan Encounters," *6th International ESA Conference on Guidance, Navigation and Control Systems*, Greece, October 2005.

[7] Antreasian, P. G, et al., "Cassini Orbit Determination Performance During the First Eight Orbits of the Saturn Satellite Tour," *AAS/AIAA Astrodynamics Specialist Conference*, Lake Tahoe, California, U.S.A., Paper AAS 05-312, 7-11 Aug. 2005.

[8] Antreasian, P. G, et al., "Cassini Orbit Determination Performance During the Saturn Satellite Tour from August 2005 through January 2006," *AAS/AIAA Astrodynamics Specialist Conference*, Mackinac Island, MI, U.S.A., Paper AAS 07-253, 19-23 Aug. 2007.

[9] Criddle, K.E., et al, "Cassini Orbit Determination: The Only Targeted Hyperion Flyby of the Prime Mission," *AAS 29th Annual Guidance and Control Conference*, Breckenridge, CO, AAS Paper 06-082, Feb. 4-8 2006.

[10] Bordi J., et al., "Orbit Determination Results and Trajectory Reconstruction for the Cassini/Huygens Mission," *3rd International Planetary Probe Workshop*, Anavyssos, Attica, Greece, 27 June - 1 July 2005.

[11] Gilliam, S.D., et al, "Optical Navigation for the Cassini/Huygens Mission," *AAS/AIAA Astrodynamics Specialist Conference*, Mackinac Island, MI, U.S.A., Paper AAS 07-252, 19-23 Aug. 2007.

[12] Boucher, C., Z. Altamimi, L. Duhem, "Results and analysis of the ITRF93," IERS Technical Note 18, Observatoire de Paris, 1994.

[13] Standish, E.M., "JPL Planetary Ephemeris DE410," JPL IOM 312.N-03-009, April 24, 2003.

[14] Thorton, C.L., Border, J.S., *Radiometric Tracking Techniques for Deep-Space Navigation*, Wiley, Feb. 2003.

[15] Ionasescu, R., "Cassini Navigation Plan Update for T13 to T45 with New OPNAV Schedule," JPL IOM 343J-06-020, August 1, 2006.

[16] Ionasescu, R., "Cassini Navigation Plan Update for T25 to T45 with Reference Trajectory 070209," JPL IOM 343J-07-012, June 1, 2007.

[17] Beswick, R.M., et al, "Navigation Ground Data System Engineering for the Cassini/Huygens Mission," *SpaceOps Conference*, Heidelberg, Germany, Paper 2008-3247, May 12-16 2008.

[18] Wagner, S.V., et al, "Cassini-Huygens Maneuver Experience: Second Year of Saturn Tour," *AIAA/AAS Astrodynamics Specialist Conference*, Keystone, CO, AIAA Paper 2006–6663, Aug. 21-24, 2006.

[19] R. A. Jacobson, et al, "The orbits of the major Saturnian satellites and the gravity field of the Saturnian system. BAAS, 37(2):524, 2005, *The 36th Annual Meeting of the American Astronomical Society Division on Dynamical Astronomy*, Santa Barbara, CA.