FLYING BY TITAN

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Abstract

The Cassini spacecraft encounters the massive Titan about once every month. These encounters are essential to the mission as Titan is the only satellite of Saturn that can provide enough gravity assist to shape the orbit tour and allow outstanding science for many years. From a navigation point of view, these encounters provide many challenges, in particular those that fly close enough to the surface for the atmospheric drag to perturb the orbit. This paper discusses the dynamics models developed to successfully navigate Cassini and determine its trajectory. This includes the moon's gravity pull with its second degree zonal harmonics J2, the attitude thrust control perturbations and the acceleration of drag.

1 Introduction

The multiple close-encounters of the Cassini-Huygens spacecraft with Saturn's largest moon Titan presents new challenges for the navigation team at NASA's Jet Propulsion Laboratory. In order to meet the numerous goals of the mission, the spacecraft has to fly many close encounters (< 1300 km altitude) with Titan. Table 1 shows all the low-altitude Titan encounters of Cassini's prime tour, from October 2004 to June 2008. From a scientific point of view, the close encounters are the best opportunity to study Titan up close and determine, amongst other objectives, the composition of its thick atmosphere, the surface topography and the extent of its gravity field. But getting close to the moon is not only a scientific objective, it is also a necessity for the navigation engineers. Cassini's trajectory is designed to visit a satellite of Saturn every

Enc	Date	Altitude (km)	Lat (deg)	Lon (deg)
TA	26-Oct-04	1200	39	88
TB	13-Dec-04	1197	59	84.2
T5	16-Apr-05	1025	74	272.5
T7	7-Sep-05	1025	-67	308
T16	22-Jul-06	950	85	318
T17	7-Sep-06	1000	23	59
T18	23-Sep-06	960	71	359
T19	9-Oct-06	980	61	0
T20	25-Oct-06	1030	6	46
T21	12-Dec-06	1000	43	267
T23	13-Jan-07	1000	31	360
T25	22-Feb-07	1000	30	18
T26	10-Mar-07	980	32	0
T27	26-Mar-07	1010	41	0
T28	10-Apr-07	990	50	0
T29	26-Apr-07	980	59	1
T30	12-May-07	960	69	1
T32	13-Jun-07	965	84	4
T36	2-Oct-07	975	-60	111
T37	19-Nov-07	999	-21	119
T39	20-Dec-07	970	-70	179
T40	5-Jan-08	1010	-12	133
T41	22-Feb-08	1000	-35	154
T42	25-Mar-08	1000	-27	159
T43	12-May-08	1000	18	139

Table 1: Cassini prime mission tour low altitude Titan encounters (altitude less than 1300 km)

month on average. This high science return is possible only with the help of Titan's gravitational pull, which is used to periodically reshape the trajectory. Gravity assists from Titan each provide Cassini with some 800 m/s change in velocity, roughly equivalent of about 800 kg of the bi-propellant fuel on board the spacecraft. For comparison, Cassini's fuel tank was left with less than 1200 kg of bi-propellant after the Saturn orbit insertion burn.

To correctly re-aim the spacecraft after each encounter and to provide scientists with the most precise trajectory reconstruction data, navigators pay close attention to the perturbing forces acting on Cassini during an encounter. While the methodology is similar to that of other deep space missions, the uniqueness of the Cassini-Huygens mission requires more refinement in the modeling of the dynamics at Titan. To achieve suitable orbit determination (OD) results, all known perturbing forces acting on the spacecraft need to be modeled and estimated. This paper will discuss how both science and engineering data are used to develop and periodically refine the models.

2 Force Models

For an orbital dynamicist, a Titan encounter is a mixture of gravity and perturbing forces. Gravity is what makes the orbit possible, modeled starting with a point mass Saturn to a more complicated perturbing model, such as third body effects and gravity zonal harmonic J2. Non-gravitational forces are also present, from either the spacecraft's activity or the environment. Following is a list of all the forces that the navigation team models during a typical orbit of Cassini that encounters Titan:

- Gravitational Terms
  - Saturn Point Mass
  - Saturn J2
  - Third Body Gravity (Sun, Jupiter)

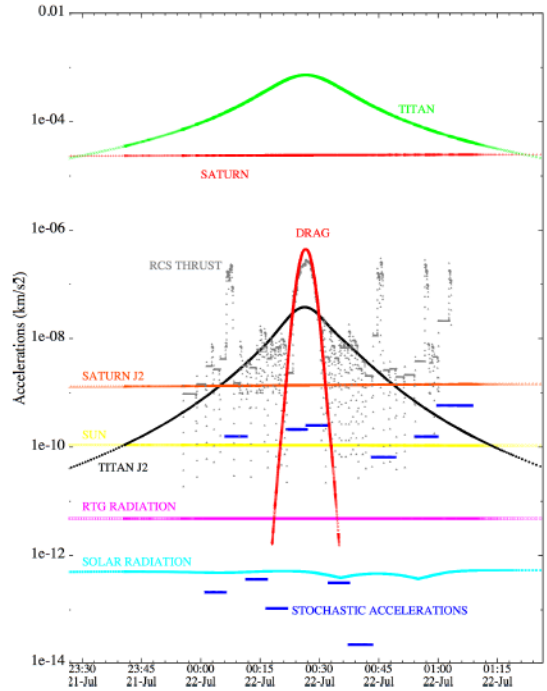


Figure 1: Accelerations Acting on Cassini during the Titan-16 Encounter (22 July 2006)

  - Titan Point Mass
  - Titan J2
- Non-Gravitational Terms
  - Titan Atmospheric Drag
  - Reaction Control System (RCS) Thrust
  - Radioisotope Thermoelectric Generator (RTG) Radiation
  - Solar Radiation Pressure

Figure 1 is a plot (log scale) of the magnitude of all accelerations during a typical Titan encounter. The data correspond to the Titan-16 encounter, which occurred on July 22, 2006. The closest approach altitude with Titan was 950 km. Note that for a period of 2 hours, Titan's gravitational pull dominates over Saturn's (see the top Saturn and Titan curves). Of all these accelerations, Titan's J2, the RCS thrust and the atmospheric drag offer the biggest challenges and at the same time are the most interesting cases to investigate in conjunction with

other teams on the Cassini project. These 3 cases are discussed in more details in the following sections.

Reconstruction of the trajectory during a Titan encounter is possible thanks to radio metric tracking data (range and Doppler) acquired by the Deep Space Network (DSN). Coherent data is available daily for approximately 6 hours, with a gap on the day of the Titan encounter [1]. Figure 2 shows the converged prefit residuals of 4 passes of radio metric tracking data around the Titan 16 encounter.

Since perfectly modeling the dynamics in such a complex scenario is nearly impossible, OD analysts use a set of stochastic accelerations to take into account any modeling error. These are modeled as white noise and batched roughly every 5 minutes with an *a priori* uncertainty that correspond to a percentage of the RCS thrust recorded. The strategy behind the stochastic acceleration batches is further discussed later in this paper. The stochastic accelerations lines shown in the lower part of of Figure 1 (blue) are the post-fit estimated acceleration batches obtained after processing the radio metric data. The fact that these accelerations are roughly 2 orders of magnitude less than the RCS thrust, drag and Titan J2 curves shows that the filter is happy with the force model used and we can therefore look at the estimated parameters with confidence.

2.1 Titan J2

Titan's gravity field is irregular enough to cause gravitational anomalies to the orbit of Cassini. Typical to any OD problems, the Cassini navigation team uses spherical harmonics to represent the gravity field a celestial body. The second degree zonal coefficient (J2) is by far the strongest perturbation. Navigation currently estimates Titan's J2 value at 36.7×10^{-6}, as reported by Iess *et. al* [2].

This value results from an ongoing investigation of Titan's gravity field, which is conducted concurrently by Cassini's radio science and navigation teams. Note that the value reported above is tied to a 3×3 gravity field model that was obtained after the processing of radio metric data during Titan-11, Titan-22 and Titan-33. These three encounters were allocated to radio science, during which the DSN tracked Cassini during the closest approaches to collect coherent Doppler and ranging data. The altitudes at closest approach for the 3 encounters were chosen such that Cassini stayed above Titan's ionosphere and thus minimizing the perturbations from the atmosphere. Also, the spacecraft attitude control system was able to use the reaction wheels to maintain the pointing of the High Gain Antenna to Earth, giving a clean pass without any thrusting perturbations from the RCS. This aspect is discussed in details in the next section.

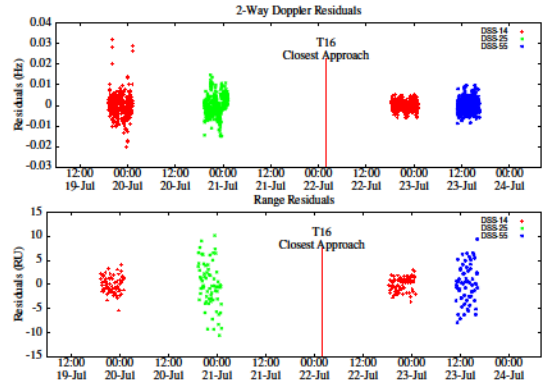


Figure 2: Doppler and range tracking data residuals around the Titan 16 encounter. DSS-14 and 25 are located in Goldstone, California. DSS-55 is in Madrid, Spain

Though a 3×3 field has been estimated, only J2 is significant enough to play a role in the short term navigation goals. As seen in Figure 1, Titan's J2 acceleration becomes significant during a close approach and ignoring it would degrade the reconstruction of the other encounter parameters.

Because the subject of gravity estimation is vast and tied to the estimation of a more complete gravity harmonics set, the J2 value reported above is provided as a reference point

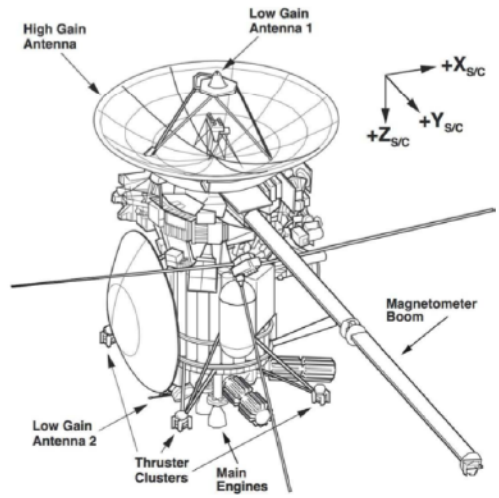
only. The determination of Titan's gravity field involves more detailed discussions on Titan's internal structure and its rotation pole and is clearly outside the scope of this paper. The subject is being investigated thoroughly and preliminary results have been reported by Tortora in 2006 [3] and Iess in 2008 [2]. For the purpose of navigation, having a good estimate is sufficient to isolate the J2 perturbation from the other models.

2.2 RCS Thrust

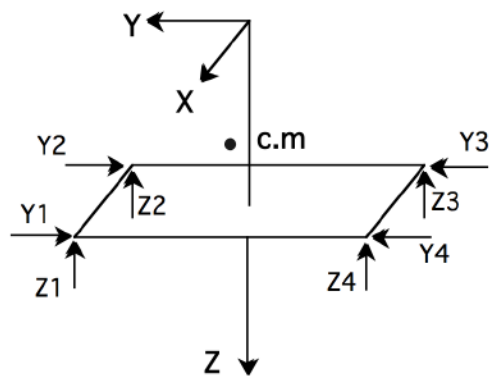
Cassini's attitude is controlled with either the Reaction Wheel Assembly (RWA) or the Reaction Control System (RCS). The RWA is composed of 3 main wheels and one backup wheel. Because it is required to slew the spacecraft rapidly during a close encounter[1], the Articulation and Attitude Control System (AACS) transitions to RCS control during that period. The location of the RCS thrusters on Cassini are depicted in Figure 3(a). As mentioned, the RCS thrust is an important source of perturbation to the trajectory. This is because z-thrusters that slew the spacecraft about the x and y axes are uncoupled, as seen in Figure 3(b). As a result, the thrust also accelerate the spacecraft in addition to producing the desired torque to turn the spacecraft.

Prior to a Titan encounter, the planned RCS thrust is modeled with calibrated flight simulator data, provided to Navigation by the AACS team. The main source of error in the predictions comes from the difficulty to estimate the amount of atmospheric drag the spacecraft will sense, and thus how much thrusting will happen to counteract it. In Figure 1, one can notice that the RCS thrust acceleration pretty much follows the drag acceleration curve during the peak period, and both perturbation are on the same order of magnitude. It is hard, however to get a good estimate of the drag acceleration

[1]Typically < 1300 km; The spacecraft has to make quick turns to accommodate the various surface observations or occultations that are going on.



(a) Spacecraft View, showing 3 of the 4 thruster clusters on Cassini



(b) Thruster directions, showing uncoupled Z-axis thrusters.

Figure 3: RCS Thrusters Configuration. Z-axis points down towards the main engines. [4]

before the fact. The data shown in Figure 1 correspond to post-encounter reconstructed data.

Fortunately, predicted errors in the AACS and drag models don't have a major impact in the Navigation's capability to correctly target the encounter, because the perturbation are localized at the very end of the targeted path. On the other hand, an accurate modeling is more crucial for the targeting of the next encounter. For that reason, Navigation uses the

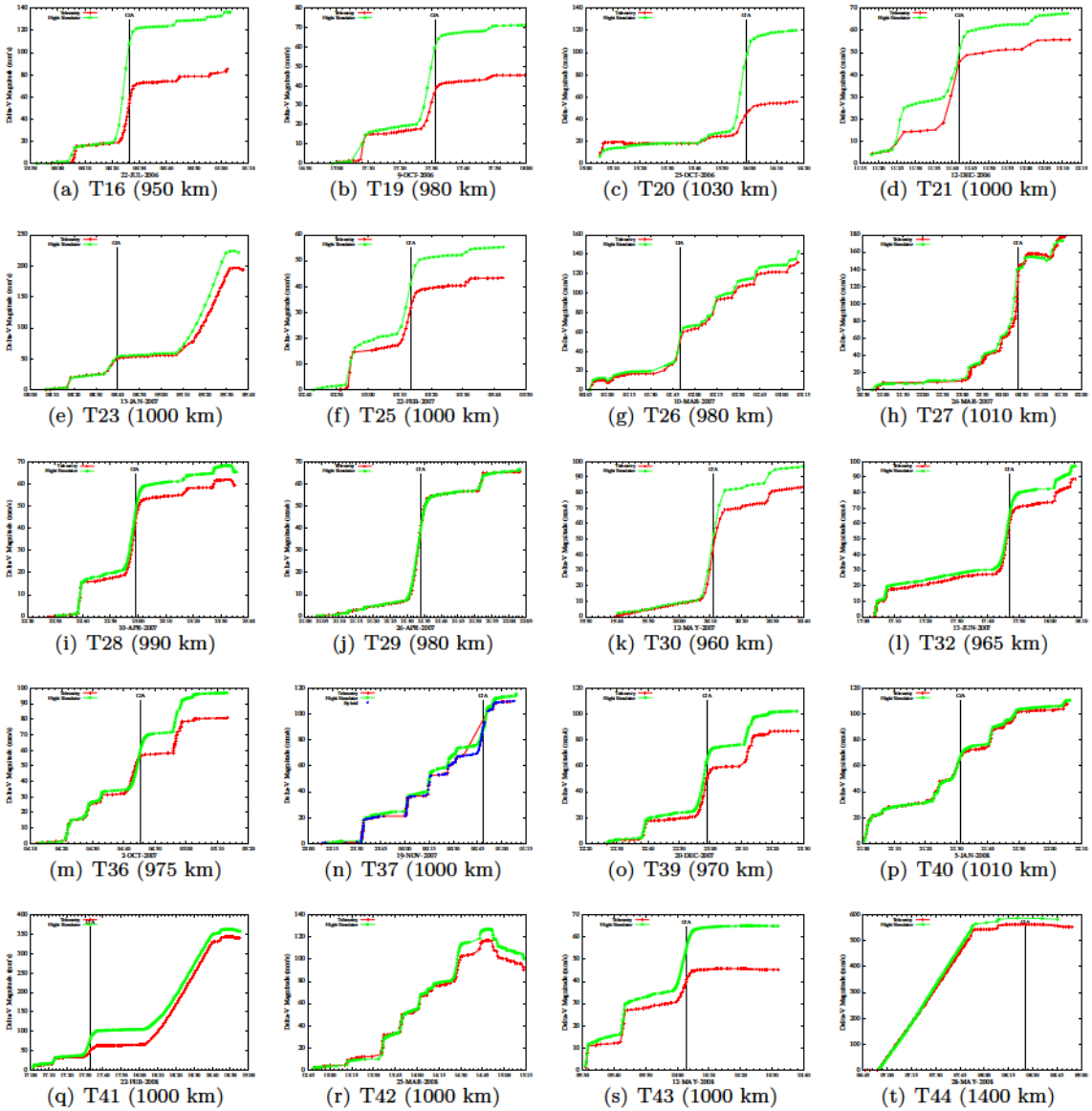

(a) T16 (950 km)
(b) T19 (980 km)
(c) T20 (1030 km)
(d) T21 (1000 km)
(e) T23 (1000 km)
(f) T25 (1000 km)
(g) T26 (980 km)
(h) T27 (1010 km)
(i) T28 (990 km)
(j) T29 (980 km)
(k) T30 (960 km)
(l) T32 (965 km)
(m) T36 (975 km)
(n) T37 (1000 km)
(o) T39 (970 km)
(p) T40 (1010 km)
(q) T41 (1000 km)
(r) T42 (1000 km)
(s) T43 (1000 km)
(t) T44 (1400 km)

Figure 4: RCS thrusting prediction vs. telemetry for most of the low altitude Titan encounters of Cassini's prime mission

thrust profile that is recorded bt Cassini's on-board computer, which available after the fact from telemetry downloads.

The telemetry data comes to OD analysts as an accumulative ΔV table. This table represents periodic velocity increments in meters per second that is caused by the z-axis thrusters. More details on the AACS models and the use of telemetry data can be found in Ardalan *et al.* [4] and Roth *et al.* [5]. RCS encounters show total velocity changes anywhere from 50 to 600 m/s. The resolution on the telemetry

data is 0.4 mm/s [5].

The plots in Figure 4 show comparisons between the AACS predictions and the telemetry data for most of the low altitude encounters of the prime mission. Note that T16 was one of the first encounter to use telemetry during operations, reason why no data is reported on the first few encounters before. As discussed by Roth *et al.* [5], a higher resolution on telemetry data was requested in May 2005, at which point the data could be used by the Navigation team. Subsequent to that date, the next low altitude Titan encounter was Titan-7, which occurred in september 2005, followed by Titan-16 in July 2006. Between those dates, much improvement was made in all aspect of the OD, and telemetry became an important element of the Navigation starting with T16.

As seen from the plots, the AACS team does a good job in general at predicting the science slews, though the predictions around the closest approaches is tainted by the variability in Titan atmospheric density.

On special occasions, part of the telemetry playback was lost due to a transmission fault, causing the OD team to rely partly on the flight simulation data. Fortunately, we were able to minimize the impact by by constructing hybrid models, where the flight simulator data is used to complement the telemetry. Titan-37 is a good example, as shown in Figure 4(n). For about 15 minutes, telemetry was lost, as indicated by the red curve, which corresponds to the period around closest approach, where the spacecraft encounters the peak of the drag acceleration. To overcome this issue, the flight simulator profile (green curve) was superimposed on the telemetry to provide a realistic ΔV profile (blue curve). Note that although not a low altitude encounter, the comparison for Titan-44 was included (Figure 4(t)) since it represents a rare case of a high altitude encounter on RCS control. The ΔV is also the highest to date, at about 550 m/s. This encounter was dedicated to a RADAR pass, where high z-axis thrust was required to scan the surface of Titan. The lack of atmospheric drag for that pass allowed a very good prediction of the ΔV.

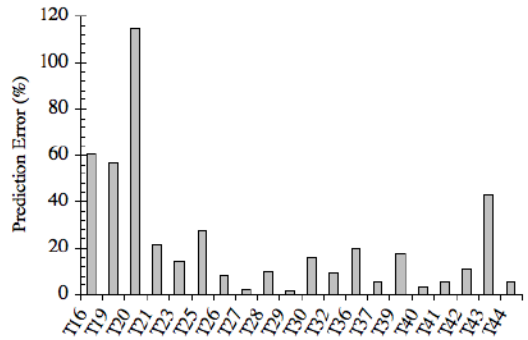


Figure 5: Error in the RCS thrust prediction from the flight simulator. Expressed in percentage away from telemetry data.

Figure 5 summarizes the capability of AACS to predict the RCS thrust during a Titan encounter. In general, the prediction improved considerably as the mission evolved from more than 60% to less than 20%. From the plots, the variability of the atmospheric density is clearly what is holding off the numbers. Using telemetry is thus more reliable as not only does it improve the models, but also can prevent oversights in the simulation, as it was the case for Titan-43 (Figure 4(s)).

In order to use the data in the OD software, the ΔV information is transformed into an acceleration table. Because of software limitations and the desire to limit computation time, the data is sampled such that the acceleration increments are applied only when a certain ΔV threshold is met. This threshold will depend on how long the thrusting last and how much thrusting is going on, but in general it is set to less than 1 mm/s. Figure 6 shows an example for T37, where the hybrid model has been used. The modeled acceleration is shown by the top curve in red. Uncertainty in the model is corrected with the use of stochastic accelerations. Because the RCS thrust is the main source of error during the encounter, the *a priori* uncer-

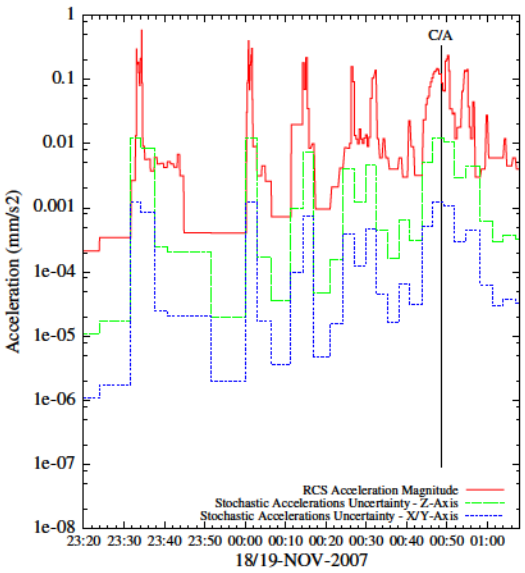


Figure 6: Example of an RCS acceleration model (red) with corresponding stochastic uncertainties (green and blue). The data correspond to the Titan-37 Encounter (19 November 2007)

tainty in the stochastic accelerations is built from its profile, even though they are meant to take into account any errors in the force models. From experience, telemetry data is believed to be accurate to about 5% of the thrust in magnitude and about 0.5% in pointing [4]. The stochastic model use for T37 is shown in the figure by the green (z-axis) and blue (x/y-axis) curves. Those represent a scaled average of the RCS thrust. It is important to note that the stochastic acceleration estimates will also be influenced by other sources of errors, such as the gravity force and the drag force, even though an uncertainty is applied to those parameters as well.

2.3 Atmospheric Drag

The atmosphere of Titan is so dense that an encounter with a closest approach at one thousand kilometer altitude is enough to cause a velocity change of about 70 mm/s. The thick atmosphere of Titan, about 10 times denser than Earth's, is composed of 95% nitrogen, while the remainder 5% is composed of methane, cyanide and other hydrocarbons.

Both the science and engineering teams of Cassini-Huygens have paid close attention to Titan's atmospheric density since the beginning of the mission. The Ion and Neutral Mass Spectrometer (INMS) on board Cassini is collecting data to determine the composition and structure of positive ions and neutral particles in the upper atmosphere of Titan [6]. Not only is it a science objective to better understand the atmosphere's composition and density, it is also critical for the project to determine how low the spacecraft can safely dip the atmosphere without risking the spacecraft to loose control and tumble. The project formed the Titan Atmospheric Working Group (TAMWG) for this very purpose, for which the INMS and AACS teams are the principal contributors. AACS is able to derive the density from the amount of thrusting the attitude control system has to perform in order to counteract the drag torque on the spacecraft [7, 8].

The navigation team has also been watching closely the TAMWG discussions as we directly benefit from it and we can also provide valuable data to compare with. Having a more accurate density model allows us to better estimate the acceleration of drag and it helps the orbit determination problem. Though short in time, the drag is the third most prominent force acting on the spacecraft after the gravity of Saturn and Titan (see Figure 1). In fact, it has been realized early on in the tour that the drag acceleration simply couldn't be ignored to properly fit the radio metric data [9].

One difficult problem to deal with is the large variability in the density estimates. Navigation sees this by measuring the amount of deceleration our filter estimates for each encounter. These data are shown in Figure 7. The plot on the left shows the drag acceleration expressed in total ΔV as a function of the closest approach altitude. It corresponds to the change in the spacecraft velocity that

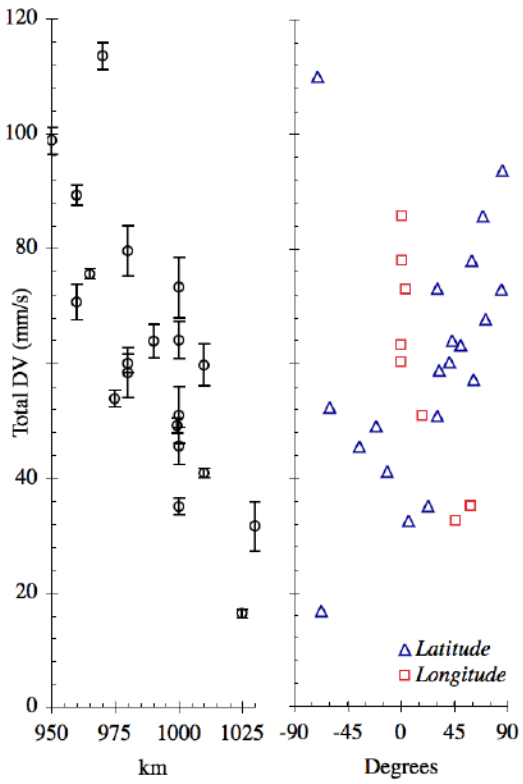


Figure 7: Atmospheric drag ΔV acting on Cassini as a function of closest Approach altitude and Titan local latitude and longitude

the drag acceleration caused, which is what the orbit determination process can observe. The error bars shown correspond to the 3-σ formal statistical error. The plot shows that for any given altitude, various ΔV values were observed, which translates to a variety of density estimates. The plot on the right demonstrates that this variability cannot be attributed to a latitudinal nor a longitudinal dependence. Up to this point, no correlation has been made with any geometric and temporal variations, which makes the prediction of the density a difficult task.

Note that in terms of variability, both the AACS and INMS data are consistent with these results. The mean values, however, differ by quite a bit. At 1000 km, the density values recorded by INMS ranges from about 2.4×10^{-10} to 4×10^{-10} kg/m^3 [?]. This averages to $(3.2 \pm 0.8) \times 10^{-10}$ kg/m^3. The AACS estimates range between 6.5×10^{-10} to 11.1×10^{-10} kg/m^3, an average of $(8.8 \pm 2.3) \times 10^{-10}$ kg/m^3 [7]. The AACS values are about 3 times higher than INMS, adding to the uncertainty in density profile of Titan's atmosphere.

This wide range of values, together with the large scale factor between INMS and AACS is one of the reasons that the navigation team started participating in the TAMWG. As stated above, Navigation is able to measure a perturbing acceleration of drag by making sure that all the other dynamic perturbations to the orbit are modeled. As it was shown in Figure 2, the orbit is tied to the radio metric data collected prior and after the encounter. The small level of uncertainty that we allowed gives us confidence in our models (Figure 6). The drag acceleration is modeled in the OD software with the drag equation [9]:

$$\mathbf{a_D} = -K \frac{\rho V^2}{2\mathrm{m}} C_D \Sigma A_i \hat{V} \tag{1}$$

Values for the spacecraft mass (m), the total cross sectional area (A), the coefficient of drag C_D and the spacecraft relative velocity V are either a direct input to the software or they are being computed internally. The density ρ is profiled with a tabular exponential model. Because we don't have tracking data during the encounter, there is no point to try to estimate any parameters of the equation, and thus only the scale factor K is estimated. The *a priori* uncertainty for K is set to a large number like 5.0 in order to allow the filter to adjust the drag acceleration as it sees fit.

In order to compare our values with the TAMWG, the acceleration results can be transformed back to density values:

$$\rho = \frac{2m}{V^2 C_D \Sigma A_i} \mathrm{a_D} \tag{2}$$

The main drawback with this method is the fact that we have to rely on some density pro-

file in order to estimate a scale factor, which makes our density solution dependent on that model. The density estimates obtained by this method are compared to INMS and AACS results in Figure 8 for most of the low altitude Titan encounters of the prime mission. Note that the error bars shown on the navigation (NAV) data correspond to 3-sigma values and are a direct function of the post-fit uncertainty observed in the scale factor K. In most cases, the post-fit uncertainty in K was less than 0.1 (1-sigma).

On average, the scale factor is 2.7 between NAV and INMS and 0.8 between NAV and AACS. Clearly the NAV results show better agreement with AACS. It is interesting to note that even when using the AACS density profile for a specific encounter as the *a priori* model, the OD filter still wants to estimate a scale factor less than 1 (These results are not shown).

While the density investigation isn't complete, the estimation of a drag acceleration scale factor is adequate to meet the navigation objectives of Cassini. The time spent in the atmosphere is short and changing the shape of the acceleration curve with a more accurate density profile would not change the orbit determination solution by a noticeable amount.

Considering the science objectives of the mission, however, it would be interesting to investigate further and shed some light to the large discrepancy between the INMS and AACS numbers. The authors of this paper recently proposed a possible scenario that would allow the navigation team to come up with an independent density estimate. If selected, this investigation would happen in the extended-extended mission of Cassini. This is discussed further in Section 4.

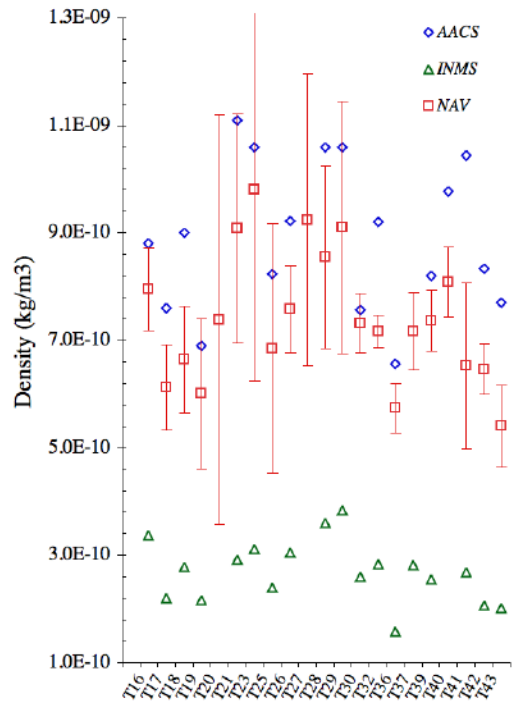


Figure 8: Atmospheric density estimates at 1000-km altitude for low altitude Titan encounters. Navigation results are the red squares with 3σ error bars. INMS results are the green triangles, courtesy of B. Magee and H. Waite [10]. The AACS results are the blue diamonds, courtesy of S. Sarani and A. Lee [7].

3 Models performance

The models described above are used for every low altitude Titan encounters. The OD tasks include the integration of the spacecraft and satellite states with partial derivatives, the formation of computed observables that are compared with the tracking data to form residuals and a filtering technique that minimizes the residuals by estimating and considering various parameters. The list of parameters include the spacecraft state, the Saturn and satellite states, gravity terms, the drag scale factor, maneuver parameters, radiation acceleration terms, Earth orientation and atmospheric biases, ground station locations and stochastic parameters. All this is better described in [1] or [11].

The ability to model the dynamics at Titan is measurable by the level of stochastic accelerations that OD estimates. These are introduced to allow some flexibility in the models and ensure that a suitable orbit determination

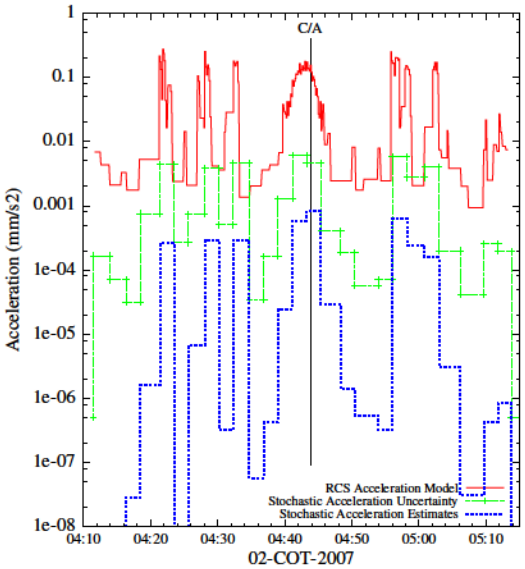


Figure 9: Example of an RCS acceleration model performance. The data correspond to the Titan-36 Encounter (2 October 2007, with the thrust model in red. The estimated stochastic acceleration (blue) are compared with corresponding stochastic uncertainties (green).

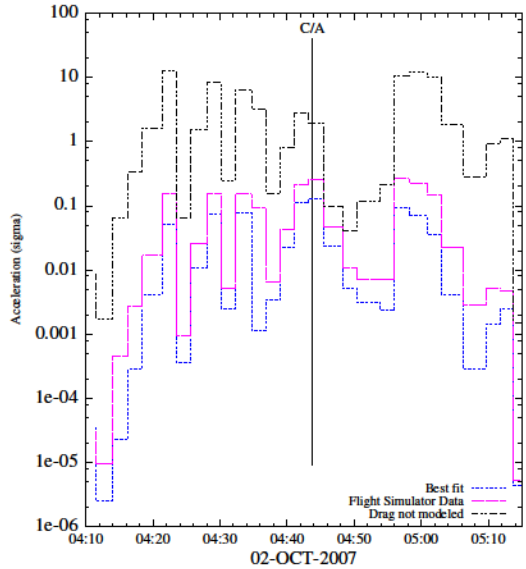


Figure 10: Example of stochastic acceleration estimates for various models used at Titan-36. The best fit curve (blue) correspond to the telemetry RCS model with J2 and drag being estimated. The purple curve shows the performance when the thrust model is built from the flight simulator data. The black curve shows the estimated stochastic acceleration when the drag model is left out.

solution is obtained. The level of stochastic accelerations was diminished considerably since the beginning of the Saturnian tour in 2004, meaning that the models are becoming more and more accurate. Because the drag and the gravity terms are being estimated separately, the stochastic accelerations pretty much take into account the uncertainty in the RCS thrust alone.

Figure 9 shows the RCS model for Titan-36 (in red), along with the estimated stochastic accelerations (in blue). As one can see, these are always less than the one-sigma uncertainty (green curve), which represents the 5% average of the thrust profile from telemetry.

For comparison, a similar OD was performed for Titan-36 using 2 alternate models. In Figure 10, the blue curve labeled "Best fit" correspond to the nominal results, as presented in Figure 9, except that the accelerations are expressed in the number of sigma, equivalent to dividing the blue curve in Figure 9 by the green one. The purple curve in Figure 10 shows the results when the flight simulator data is used to model the RCS thrust. Clearly, the use of telemetry data improves the fit and most likely gives a better estimate of the drag acceleration as well, since part of the true drag might be aliased in the stochastic acceleration. The black curve shows what could be expected should the drag acceleration be completely ignored in the models. It is obvious from that plot that modeling the drag is important, as the stochastic acceleration are sometimes greater than 10 sigma! A good reconstruction of the encounter with a relatively tight level of uncertainty would not be possible without a good understanding of the dynamics involved.

While this paper does not present the results for all the low altitude Titan encounters, the results that have been presented for Titan-36 are representative of the overall performance of the Cassini navigation OD.

4 Extended Mission

The Cassini mission just finished its 4-year prime mission tour of the Saturnian system in June 2008. NASA has already approved a budget for a 2-year extension, for which Cassini will have 17 additional low altitude Titan encounters [12]. In fact, the spacecraft is doing so well that the project is planning to extend the mission further, possibly for 7 more years. The additional data will undoubtedly be used to refine all the acceleration models used in the prime mission. Though the 17 new encounters have already been designed to accommodate specific science objectives, more Titan encounters are expected before the end of Cassini, possibly allowing new types of investigations.

In light of the results presented in this paper, the lead author has proposed to the project to dedicate one of those future Titan encounter to the atmospheric density problem. The proposed method would allow OD to measure the drag acceleration piecemeal with Doppler data, leading to an independent estimate of the density. With the right geometry, Cassini could be tracked from the DSN during the entire closest approach period where it goes in the atmosphere of Titan. This would be much like an encounter dedicated to radio science, except that in this case the spacecraft would be able to go low lower than 1300 km altitude and be controlled by the RCS thrusters. We now know that the thrusting error can be minimized by the use of telemetry with the method described in this paper.

With Doppler tracking during closest approach, the drag acceleration profile can be directly measured. Because we have good understanding of the spacecraft mass, area, velocity and coefficient of drag [7], a series of density values at various reference altitudes can be estimated rather than the overall scale factor.

To prove this method, a study was performed using the Titan-16 encounter. 2-way X-band Doppler data was simulated during the closest approach period and weighted by 0.1 mm/s, which is typical of what is observed with Cassini [11]. The density model was constructed in multiple layers of growing altitude. Those were spread apart by a 60-sec flight time. Because the spacecraft travels exponentially with respect to altitude, the first layer is 20 km and the last one larger at 200 km. This was done to ensure a constant sampling of Doppler points per layer, which maximizes the reduction of the density uncertainties. The layers corresponding to the T16 simulation are shown in Figure 11. The first layer ranges from 950 to 970 km and the last one from 1200 to 1400 km. The data was sampled every 10 seconds since smaller rate has increased noise and round off error problems. The *a priori* uncertainty in the density model was assumed to be 100 %, to clearly rule out any dependance on any given model.

The simulation shows promising results: In the plot, the green curve (triangles) shows the improvement as seen for the nominal Titan-16 encounter, i.e. without tracking data. The improvement is only 70% in the first layer, rapidly increasing back to 100% at higher altitudes. This lack of improvement is what made us choose to simply estimate a scale factor. The simulation with additional Doppler data, however, shows that the density in the first layer is reduced to 3% and that a 20% confidence level is expected up to 1100 km altitude (See the blue circle curve).

While the strategy of layers modeling and data sampling rate will be revisited in order to optimize the data reduction, the study demonstrated that the concept of estimating the atmospheric density with Doppler tracking data is feasible. At this point, the proposition has been presented to the project and science planners are currently evaluating it.

5 Conclusion

The understanding of the forces acting on the Cassini spacecraft during a close Titan encounter have been refined over the years to

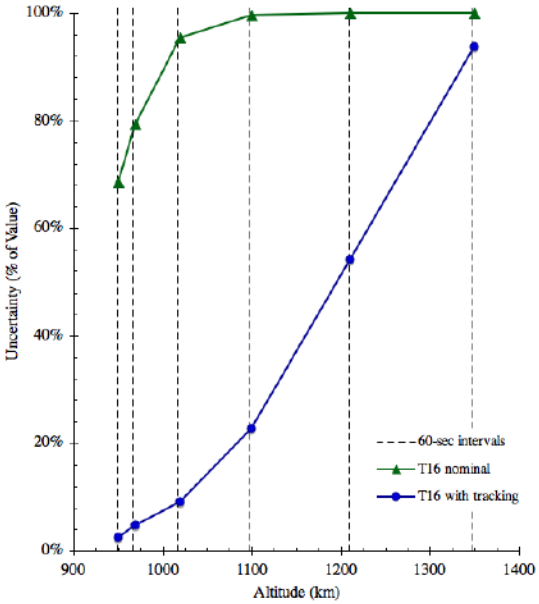


Figure 11: Simulation results showing the atmospheric density uncertainties after the reduction of simulated Doppler data. The simulation was performed with the Titan-16 encounter for which the closest approach altitude was 950 km. The *a priori* uncertainty is 100% for each layers. The green curve is the results with nominal tracking and the blue curve with the additional track during the closest approach.

not only allow better navigation results, but also play a role in many science investigations. Gravity science is in itself tied to navigation, especially for a complex mission like Cassini, where all perturbing forces need to be estimated to determine the spacecraft state. The same can be said about Titan's gravity, though in this case the radio science team plays a significant role. The drag acceleration is also a significant perturbation to the orbit and it forces the navigation team to investigate the density of Titan's upper atmosphere. With all this in mind, additional thrusting from the reaction control system needs to be modeled, and thanks to a good collaboration with the attitude control team and the availability of telemetry data, the impact of this error source has been minimized.

One way to measure the performance of the navigation solutions is by the level of stochastic accelerations estimates, which allow some flexibility in the models. The level of stochastic accelerations was diminished considerably since 2004, meaning that the models are becoming more and more accurate. Results shown in this paper indicate that using telemetry data with valid models for gravity and drag allows a proper trajectory reconstruction with stochastic accelerations with uncertainties of only 5% of the thrust.

For more details on the orbit determination performance during the Cassini prime tour, the reader is invited to look at the papers by Antreasian *et. al* [11, 13, 14].

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