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CASSINI MANEUVER EXPERIENCE: LAUNCH AND EARLY CRUISE

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Abstract

The Cassini mission to Saturn was launched in 1997. It is an international effort to study the Saturnian system. Cassini's interplanetary cruise, which will deliver the spacecraft to Saturn in 2004, is making use of many propulsive maneuvers, both statistical and deterministic. The first few of these maneuvers have been executed and are reported on herein. The system has performed quite close to the pre-launch expectations and requirements. Additionally, two maneuvers have already been dispensed with, saving fuel and flight team effort. The analysis that led to the cancellation of these maneuvers is also summarized here, followed by some comments on upcoming maneuvers.

Introduction

The Cassini project is an international effort to study the Saturnian planetary system utilizing the largest, most capable spacecraft ever sent to another planet. This is the first mission to visit Saturn since the flybys made by the two historic Voyager spacecraft in 1980 and 1981. Cassini will arrive at Saturn in 2004, and will deliver the European Space Agency's (ESA) Huygens probe to Saturn's moon Titan. Previous papers [1,2] reported prelaunch plans for both the primary (97 VVEJGA) and backup (98 VEEGA) launch opportunities. Now that the launch has occurred, the early experience of the Cassini mission is reported, with a focus on trajectory correction maneuvers (TCMs). The first four maneuvers are the focus herein, although plans and strategies for future maneuvers are mentioned as well. The experiences of the Orbit Determination group (OD) of the Navigation team are reported in a separate paper. [3]

Interplanetary Trajectory Optimization

A short history of the development of optimization methods to design fuel efficient interplanetary trajectories is given here. Then the techniques used to design this particular trajectory are described. Early single-planet encounters relied on computer generated charts of launch energy requirements (expressed as C3, defined as the square of the required Earth departure velocity V_∞) plotted versus the launch and arrival dates.[4,5,6] These are the well known "pork chop" charts, named for their typical shape. They made it easy for a mission designer to pick efficient transfer trajectories for a single encounter. As multiple planet flybys such as MVM 73 (Mariner Venus Mars 73), Pioneer 10-11, and Voyager were first designed, methods were developed for connecting together more than one planetary encounter. Several different computer programs were developed at JPL for this purpose, some of which were reported on in a special issue of the Journal of the Astronautical Sciences.[7] One of these computer programs is MIDAS (Mission Design & Analysis Software).[8] MIDAS optimizes the total trajectory to conserve fuel usage, solving a sequence of two body problems using conic trajectories for propagation. The Galileo[9,10] and Cassini[2] interplanetary trajectories were designed using a least squares technique and multiconic propagation methods in a computer program called PLATO (Planetary Trajectory Optimization).[11] A new improved version of this, called CATO (Computer Assisted Trajectory Optimization) which uses trajectory integration for the propagation has recently become available.[12] MIDAS is still used extensively, especially in the proposal and early project stages where its short execution time facilitates extensive mission studies. Output from MIDAS is often used as an initial guess for PLATO or CATO. And, in fact, even with such powerful software, the old "pork chop" charts are still invaluable.

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Trajectory Design for Cassini

The interplanetary trajectory which Cassini is following to Saturn requires four gravity-assist swingbys, two with Venus, one with Earth, and another with Jupiter. This trajectory, referred to as 97 VVEJGA, is depicted in Figure 11, for launch on October 15, 1997 at the opening of that day's launch window, 8:27 AM UTC – the time at which launch actually occurred.

make possible an energy gain on both the first and the second Venus swingbys. Thus, for the first Venus swingby the hyperbolic excess speed, V_∞, was 6.03 km/s and after the DSM of 452 m/s (which will make an energy change of only -8.5 km^2/sec^2) the V_∞ for the second Venus swingby will be about 9.41 km/s.

The second technique is a carefully chosen phasing of the Earth swingby shortly after the second Venus swingby, so that trajectory bending around the Earth completes a total energy gain that would not have been

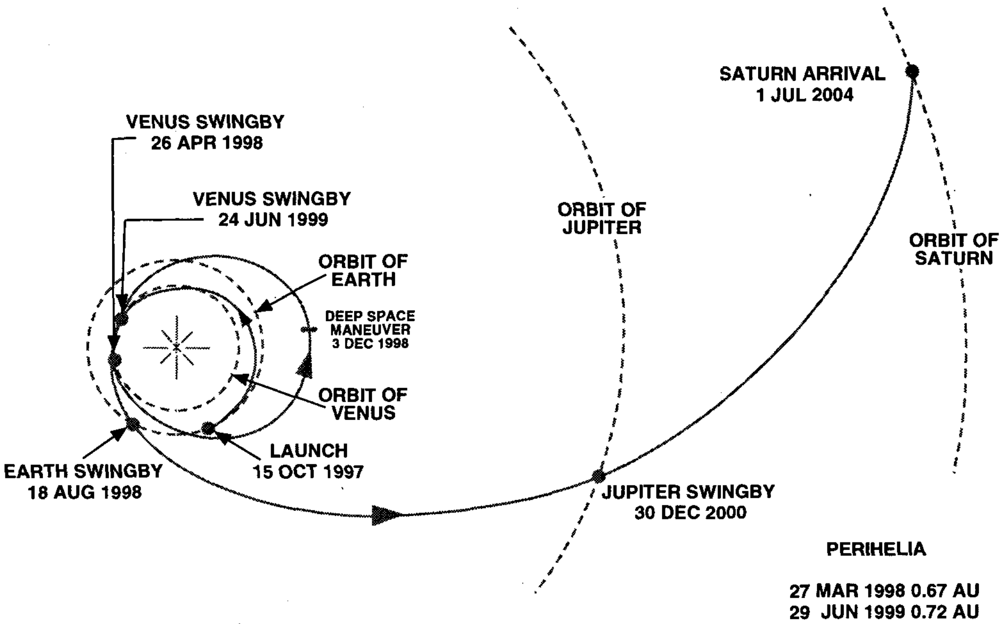

Figure 1: Interplanetary Trajectory

There are approximately seven years between launch and arrival at Saturn. This includes roughly 6.5 months between launch and the first Venus swingby, 14 months between the two Venus swingbys, and 55 days between the second Venus swingby and the Earth swingby. The Jupiter swingby is about two-fifths of the way into the remaining 4 years of cruise. Although no science investigations are planned to date, there are many activities to be accomplished within this time, including the execution of 22 trajectory correction maneuvers (TCMs).

Two techniques were used to design the required energy gain into the interplanetary trajectory. The first being a repeated flyby of the same planet, with the DSM performed between the two flybys. The DSM will be performed near aphelion to lower the perihelion of the trajectory. This changes the subsequent swingby geometry and raises the Venus-swingby velocity to

possible with the second Venus swingby alone. The spacecraft Earth-relative hyperbolic excess speed will be roughly 16.01 km/s. This dramatic increase in the approach speed with each swingby is associated with a corresponding increase in the spacecraft orbital energy relative to the sun. Each swingby has been designed to use the bending of the spacecraft trajectory to place the direction of the outgoing asymptote more in line with the planet's own velocity vector than the corresponding spacecraft incoming asymptote direction. Figure 22 shows the total specific energy (the sum of kinetic and potential energy per unit mass) versus time for the interplanetary trajectory.

The Jupiter swingby is also used to add some energy to the trajectory, but as seen in Figure 22 the amount of that gain is relatively small (*very* small given the large size of Jupiter). However, the Jupiter swingby (and to some extent the Earth swingby) has an additional benefit beyond the immediate rise in specific energy because it circularizes the orbit, thus lowering the V required for the SOI maneuver.

Cassini's three energy-altering propulsive maneuvers are all energy-*reduction* maneuvers. Although too small to see in Figure 22, TCM-1 causes the trajectory to curve inward to the first Venus swingby. Next, the DSM lowers perihelion for a later Venus swingby. Finally, the SOI, not included in Figure 22, reduces the spacecraft's speed to put it into orbit around Saturn.

Not until the Saturn encounter does the spacecraft have the specific energy to escape the solar system (specific energy > 0 relative to the Sun). By comparison, the Voyager spacecraft were launched on direct orbits to Jupiter, and had the specific energy to exit the solar system after that encounter.

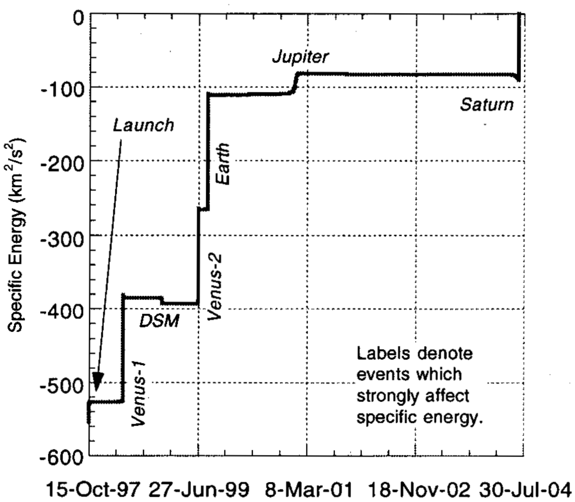

Figure 2: Specific Energy versus Time - Interplanetary Trajectory

Maneuver Design

Small perturbations that occur early in the trajectory can prevent, or undesirably modify, arrival at Saturn. Such undesired deviations, along with planned trajectory modifications, necessitate the execution of TCMs. The Cassini mission scheduled 22 TCMs.[1] Each has a specific purpose. By and large, they are used to fine-tune the trajectory so that the spacecraft arrives at Saturn as close to the targeted conditions as possible. On the other hand, several TCMs are to make required changes in the trajectory. These TCMs are said to have deterministic components, viz. a non-zero mean **V** vector. They are listed in Table II alongside the magnitudes of their deterministic components.

The first maneuver, TCM-1, was to correct for errors due to launch asymptote approximations. These approximations were used in order to simplify launch operations. A launch asymptote target was calculated for the time partway into each launch day's launch window. Therefore, launch at any other time would be targeted to a slightly non-optimal asymptote.

The four maneuvers following the Venus-2 swingby are the Earth-bias-removal maneuvers. They remove a deliberate bias which was built into the trajectory so as to ensure that the probability of an Earth-impact does not exceed 10^{-6}.[13]

Table I: Deterministic Maneuvers (Pre-launch Design)

Event	ΔV (m/s)
TCM-1	1.4
Deep Space Maneuver (DSM)	451.8
Earth Bias Removal 1 (V2+10d), TCM-9	42.3
Earth Bias Removal 2 (E-30d), TCM-10	4.9
Earth Bias Removal 3 (E-15d), TCM-11	36.9
Earth Bias Removal 4 (E-6.5d), TCM-12	13.0
Saturn Orbit Insertion (SOI)	622
Periapsis Raise Maneuver (PRM)	335
Orbit Deflection Maneuver (ODM)	49.5

The last three maneuvers listed in Table II form the junction of interplanetary cruise and the Saturnian satellite tour. The SOI maneuver will remove enough kinetic energy from the spacecraft so that Saturn's gravity captures it. Therefore, SOI is a mission-critical maneuver. The Periapsis Raise Maneuver (PRM) will target the orbiter & probe to the first Titan flyby, setting the stage for final probe-targeting and the release of the probe towards Titan. The Orbit Deflection Maneuver (ODM), will be executed after the release of the Huygens probe, targeting the orbiter away from Titan and onto a trajectory favorable for the relay of data from the probe and the beginning of the tour.

Maneuvers are targeted to the B-plane conditions at the upcoming swingby. These conditions (**B•R**, **B•T**, and time-of-periapsis) are listed in Table IIII. The aimpoints and dates of execution for the Earth-bias-removal maneuvers are listed as well.

Table II: Planetary Swingby Target Conditions (pre-launch design)†

Event	Date & Time		B•R (km)	B•T (km)
Launch	15-Oct-1997			
Venus-1 Flyby	26-Apr-1998	13:44:46	-1910	12302
Venus-2 Flyby *(Earth-relative)*	24-Jun-1999	18:24:17	3322 *150078*	-9084 *57510*
TCM-9 (V2+10d)	4-Jul-1999		14400	57510
TCM-10 (E-30d)	19-Jul-1999		2400	57510
TCM-11 (E-15d)	3-Aug-1999		6960	10390
TCM-12 (E-6.5d)	11-Aug-1999		173	8954
Earth Flyby	18-Aug-1999	3:03:22	173	8954
Jupiter Flyby	30-Dec-2000	10:35:21	132767	10896274
Saturn Encounter	1-Jul-2004	8:39:44	-217939	393160

Earth Bias Strategy

The design of the Earth-bias-removal TCMs was reported earlier in Ref. [1]. The aimpoints during the Earth-approach, depicted in Figure 33, are such that the aimpoint shifts do not point toward the Earth. The aimpoints listed in Table IIII, are plotted in Figure 33. The maneuver magnitudes are listed in Table II

This design, along with the Earth swingby altitude above 1,150 km, assures that the probability of an Earth-impact does not exceed 10^{-6}.

Maneuver Execution Errors

The model for maneuver execution errors is taken from Gates[14]. This model has four independent, Gaussian-distributed error sources: fixed magnitude, proportional magnitude, fixed pointing, and proportional pointing – here, the terms *magnitude* and *pointing* are relative to the total desired TCM $\Delta \mathbf{V}$ vector. The project-levied requirements on standard deviations for each system are given in Table IIIIII, below, at the three-σ level.[15]

Maneuver Experience

The Cassini project has executed the first two maneuvers (TCM-1 & TCM-2) and canceled the second two (TCM-3 & TCM-4). The results from the first two maneuvers are summarized below, followed by a summary of how the cancellation of the latter maneuvers came about. However, before delving into the maneuver details, it is necessary to review how the maneuvers are executed.

†PRM and ODM targets not listed because their targeting strategy has not been finalized.

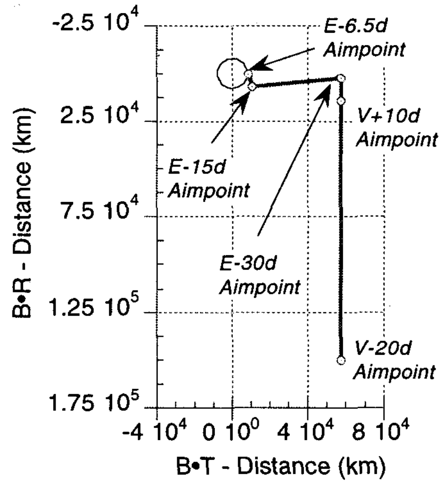

Figure 3: Aimpoint Biasing Strategy for Earth Swingby

Maneuver Execution

Cassini's maneuvers are executed in a turn-and-burn mode. The spacecraft, depicted in Figure 44, is three-axis stabilized and, for maneuvers, thrust is always to be applied approximately along the spacecraft's -Z-axis. To orient this thrust in the desired direction, the entire spacecraft must be rotated, resulting in the following sequence of events: turn (or *wind*), burn, and turn back (or *unwind*).

Rotations are accomplished with the Reaction Control Subsystem (RCS), viz. 4 hydrazine thruster clusters – a total of 8 primary and 8 backup thrusters. These small, monopropellant thrusters supply 0.98 Newtons each when fully pressurized and an I_{sp} of about 195 seconds. They are denoted in Figure 44.

Table III: TCM Error Requirements (3σ)

	Magnitude		Pointing	
System	Fixed[‡]	Prop. (%)	Fixed	Prop.
RCS	10.5	6	10.5	25.5 mrad
MEA	30[§], 50[**]	1[§], 3[**]	52.5[§], 105[**]	30 mrad

The thrusters may be grouped into two sets. One set of RCS thrusters faces the ±Y spacecraft directions; it is used to make balanced turns about the Z-axis (roll turns). The other set faces the -Z-axis. It is used to make unbalanced turns about the X-axis (pitch turns) and/or Y-axis (yaw turns).

The RCS is used for small maneuvers, e.g. less than 1 m/s. Large maneuvers are to be executed with the main engine or bipropellant system, which has two redundant systems (MEA, MEB). The two nozzles are mounted side by side along the Y-axis, which can be seen in Figure 44. Since either of these must thrust toward the spacecraft center of gravity, the resulting thrust direction has a small offset from the -Z-axis direction (approx. 7.2° or 0.13 rad). When fully pressurized, this system has a thrust of 445 Newtons and an I_{sp} of about 304 seconds.

All TCMs in the interplanetary portion of the mission are to use a roll wind turn followed by a yaw wind turn to reach the desired burn orientation. The unwind turns are equal, opposite, and in the reverse order. These turns help minimize heating on the spacecraft because the large high gain antenna is sun-pointed before and during the roll turn while the Huygens Probe partially shields the spacecraft from the Sun during the yaw. The yaw turn causes a net **V** on the spacecraft; the roll ideally would not. These turn- and burn- **V**s are accounted for in planning and analyzing TCMs.

Launch

The Cassini spacecraft was launched on October 15, 1997 by a Titan IV/SRMU rocket (Solid Rocket Motor Upgrade) with a Centaur upper stage. Together, these vehicles provided a launch energy (C3) of 16.640 km^2/s^2. The launch date was near the middle of the primary launch period which opened on October 6, and thus had one of the lowest launch energy requirements of that launch period. After separation from Cassini, the Centaur executed a collision and contamination avoidance maneuver (C/CAM). The C/CAM ensured that the Centaur flew by Venus days later and thousands of kilometers further away than Cassini did.

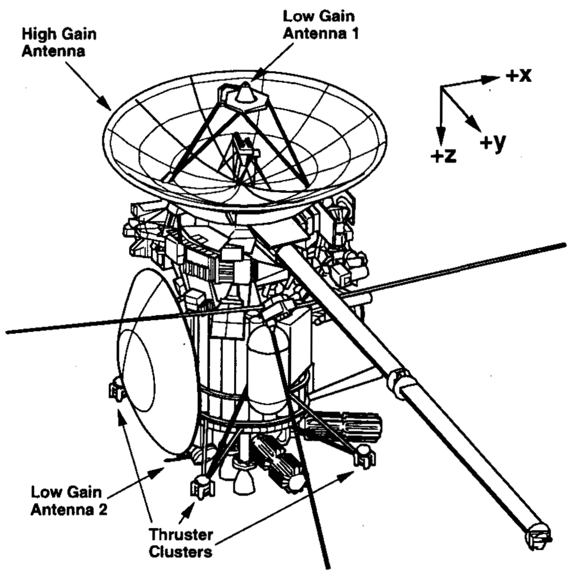

Figure 4: Cassini Spacecraft Diagram

The Cassini spacecraft was delivered on a trajectory very close to desired. Table IVIV lists estimates of the post-C/CAM Venus B-plane encounter conditions.

Table IV: Post-C/CAM Estimates of Venus Encounter Conditions*

	Periapsis	B•R (km)	B•T (km)
Centaur	29-April 02:42:47	-4.495×10^6	7.672×10^7
Cassini S/C	26-April 15:51:35	-1.730×10^4	1.033×10^5

It is important to note that the launch vehicle was targeted to one launch asymptote per daily launch window. There was, therefore, one target for each day of the launch period. These targets were optimized for a launch time 40 minutes into the respective day's ~110 minute launch window. Since Cassini was launched at the opening of October 15th's window, a deterministic correction was required in order to attain the desired Venus flyby conditions.

‡Given in mm/s
§Uncalibrated (TCM-1, TCM-2, and SOI)
** Calibrated

* Given in the Venus-Centered, Earth Mean Orbit of 2000 coordinate system (EMO2K); Time in UTC

TCM-1

The primary purpose of the first trajectory correction maneuver was to correct for the launch target bias (described above) and launch errors. TCM-1 was scheduled to be executed 25 days after launch; it was targeted to the Venus flyby conditions in Table IIII. Furthermore, since it was the first maneuver, it gave the flight team valuable data and experience in operating the spacecraft and its propulsion system.

TCM-1 was designed with the *Launch + 15 day* (LP15D) OD estimate made on October 30, 1997 and was executed on November 9, 1997 at approximately 8 PM UTC. The desired total V was 2.746 m/s. The designed turn-ΔV and burn-ΔV are listed in Table VV, below. The desired burn V of 2.731 m/s was expected to require a main-engine burn lasting approximately 34.25 seconds. The *a priori* TCM-1 delivery dispersion, based on LP15D, is shown in Figure 66.

Table V: TCM-1 Designed ΔV (m/s)[††]

	Wind	Burn	Unwind	Total
X	-2.861×10^{-3}	0.4307	-2.861×10^{-3}	0.4250
Y	-8.851×10^{-3}	-2.450	-8.851×10^{-3}	-2.467
Z	9.807×10^{-5}	1.128	9.807×10^{-5}	1.128
t		34.25 sec		

The turns required for TCM-1 consisted of a -35.77° roll (around +Z) and a -70.64° yaw (around +Y) wind turn. The unwind turns had a symmetric design.

Estimates of the actual maneuver have been produced independently by the Navigation (NAV) team (on the ground) and by the Attitude and Articulation Control Subsystem (AACS) flight software (on board).

Spacecraft range and Doppler measurements were used by the OD group to estimate the actual burn-ΔV; the estimate indicated a 1.7% overburn (2.776 m/s), along with a pointing error of 0.61°. Table VIVI lists the details of this estimate.

The NAV wind and unwind turn **ΔV** estimates were deemed controvertible for two reasons. First, one would expect them to be roughly equal, but they were not; second, the uncertainties in these estimates were too high. This simply due to the fact that not enough data was taken during the maneuver to resolve the estimate to that detail. However, the estimate of the burn **ΔV** was deemed accurate enough for meaningful analysis.

Table VI: TCM-1 NAV-Est. ΔV (m/s)[‡‡]

	Wind	Burn	Unwind	Total
X	-1.028×10^{-3}	0.4665	-3.187×10^{-3}	0.4623
Y	-9.694×10^{-3}	-2.488	-8.762×10^{-3}	-2.507
Z	1.770×10^{-4}	1.140	2.815×10^{-4}	1.141
t		35.05 sec		

The AACS estimate is given in Table VIIVII.[16] That estimate indicates a 0.80% overburn and a 0.29° pointing error. It should be noted that the AACS on-board estimator has a 4 mm/s discretization. Therefore, all values in the table may be considered to have at least a ±2 mm/s uncertainty[§§].

Table VII: TCM-1 AACS-Est. ΔV (m/s)

	Wind	Burn	Unwind	Total
X	-0.004	0.420	-0.004	0.412
Y	-0.012	-2.472	-0.012	-2.496
Z	-0.004	1.136	0.000	1.132
t		34.596 sec		

Comparing these estimates to the levied error requirements (see Table IIIIII) yields some interesting results.[17] The requirements in Table IIIIII indicate that a 1% overburn is a one-σ error for this maneuver, so the NAV 1.7% overburn estimate and the AACS 0.80% overburn estimate represent 1.7-σ and 0.8-σ performance, respectively.

Pointing errors are also of great interest. Figure 55 depicts the error estimates, uncertainties, and requirements in the pointing plane. The pointing plane is perpendicular to the desired burn **ΔV** vector. In depicting this plane, it is convenient to project the S/C X- and Y- axes, as oriented during the burn, onto the pointing plane because maneuver **ΔV**'s are always roughly parallel to the S/C Z-axis.

Figure 55 shows that although the formal NAV and AACS uncertainties are both small, their mean pointing error estimates are in conflict. The pointing error estimates, 13 mm/s (0.29°) by AACS and 29 mm/s (0.61°) by NAV, are in opposite directions. However,

[††]All following **ΔV**'s are listed in the Earth Mean Equator of 2000 coordinate system.

[‡‡]Each turn **ΔV** was estimated, but sum is listed.

[§§]AACS' estimate uncertainty is likely larger than this, but it has yet to be quantified.

since both are well within the pointing error requirement the difference is not significant.

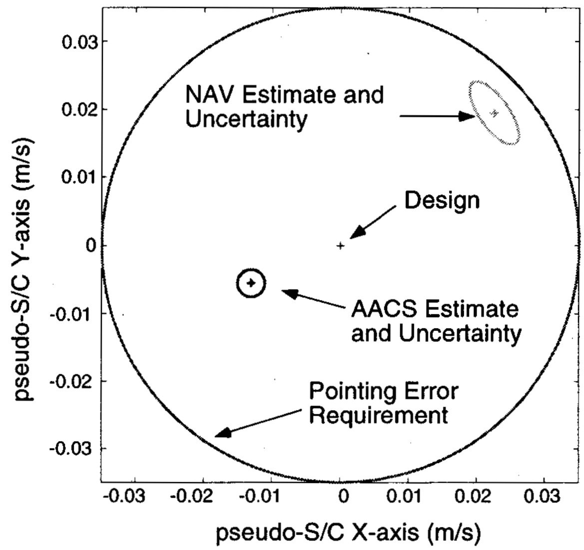

Figure 5: TCM-1 Burn-ΔV Pointing Error Estimates and Uncertainties (1-σ)

Post-execution analysis revealed that the major contributing factors to the execution error were as follows:

- Small errors in the location of the spacecraft center of gravity. This contributes as follows: during a burn, a control loop searches for the correct main engine gimbal setting to prevent the spacecraft from rotating. Once the correct setting is found, a slower guidance loop rotates the spacecraft to align the resulting thrust direction with the desired burn direction. A minute is typically required for the outer guidance loop to correct the thrust direction, so this error was only partly compensated for by the end of the 35-second burn.

- Improvements in the precision of the accelerometer scale factor calibration (m/s per pulse) were not yet complete. Since the on-board software cuts-off the burn based on data from the accelerometer, this clearly contributed to the magnitude error. Analysis by the flight team found that the scale factor was 1% too small. Accounting for the scale factor, the AACS-estimate is 1.8% which is very close to the Navigation-estimate of 1.7%.

Navigation predictions of the Venus flyby conditions were updated repeatedly. As of the *Launch + 47 day* (LP47D) OD estimate, shown in Figure 66, swingby conditions were within the Venus capture radius, see Figure 66. Clearly, another maneuver was required!

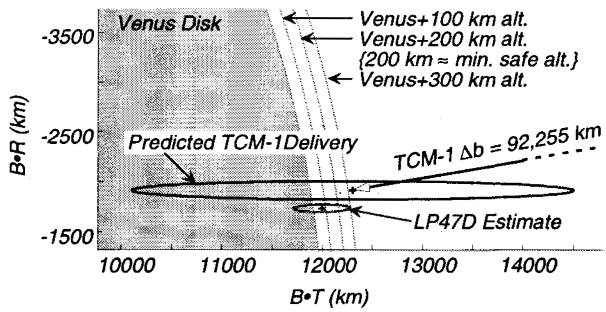

Figure 6: Venus B-Plane, *pre-* and *post-* TCM-1 estimates (one-σ ellipses)

TCM-2

Designed to clean-up after TCM-1, TCM-2 was scheduled about 108 days later – February 25, 1998. After the execution of TCM-1, a new OD solution indicated that a 185 mm/s maneuver would be required to tweak the trajectory so that the desired swingby conditions would be achieved (and Venus-impact avoided). With such a small **ΔV**, the RCS was deemed the appropriate system to use. Furthermore, a Monte Carlo simulation showed that execution of TCM-2 would probably eliminate the need for TCM-3.

TCM-2 was designed on February 13, 1998 to have the parameters listed in Table VIIIVIII, below. This design requires a 118° roll wind turn and a -161° yaw wind turn. The design and predicted delivery (1-σ), as shown in Figure 88, was based on the *Venus-1 - 69 day* (V1M69D) OD estimate.

The maneuver was executed as planned, on February 25, 1998 at approximately 8 PM UTC. Initial observations of the maneuver and estimates derived from ensuing ranging and Doppler data indicate that the executed maneuver was quite close to the design, underburning by a small amount. With additional post-maneuver tracking, more accurate estimates of the magnitude and pointing errors have been made.

Unlike the analysis that was carried out for the previous maneuver, turns and burn are not separated here. Individual turn and burn components could not be estimated by the OD process since, for maneuvers, like this one, which rotate the antenna far from the Earth-line, lock with the spacecraft receiver is lost shortly after the start of the yaw wind turn and not reacquired until after the end of the roll unwind turn. (Such a loss of lock does not affect Navigation performance.)

Table VIII: TCM-2 Design ΔV's

	Wind	Burn	Unwind	Total
X	0.8962	-160.9	0.8962	-159.1
Y	0.1778	45.16	0.1778	45.52
Z	2.180	78.51	2.180	82.87
t		269.7 sec		

Range and Doppler data have been used to produce the NAV estimate of TCM-2 **ΔV**. Compared to the design, this estimate shows a 3.5% underburn and a 0.51° pointing error. Based on the model in Table IIIII, the mean estimate in Table IXIX has a 1.3-σ magnitude error and a 0.43-σ pointing error.

Table IX: TCM-2 NAV-Est. DV's

	Wind	Burn	Unwind	Total
X	*n/a*	*n/a*	*n/a*	-152.7
Y	*n/a*	*n/a*	*n/a*	44.27
Z	*n/a*	*n/a*	*n/a*	81.29
t		*n/a*		

Figure 77 depicts Navigation's and AACS' estimates in the pointing plane[18], alongside the design. The execution error model from Table IIIII (1-σ), Navigation's one-σ covariance, and the AACS ± 2 mm/s uncertainty, are included as would map to the pointing plane. Here, the pointing plane is defined perpendicular to the designed, *total* **ΔV** as opposed to the *burn* **ΔV** for TCM-1.

Table X: TCM-2 AACS-Est. ΔV's [19]

	Wind	Burn	Unwind	Total
X	4.000	-160.0	4.000	-152.0
Y	0	44.00	0	44.00
Z	0	80.00	4.000	84.00
t		292.25 sec		

Both Navigation's and AACS' estimates have mostly -X-direction errors; AACS' estimate is about 2.7 mm/s further out along -X. On the other hand, the two uncertainty ellipses overlap; therefore, there is a rather high probability that the actual error is close to both. The two estimates also share very small Y-direction errors, each less than 0.5 mm/s. This clearly indicates that Navigation and AACS estimated very similar directions for the pointing error. Taken together, these observations lend credence to the assertion that AACS and Navigation have, in fact, reported consistent estimates of maneuver execution errors.

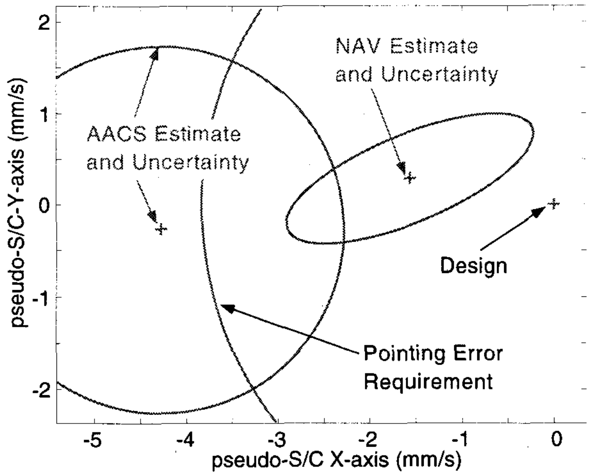

Figure 7: TCM-2 Pointing Error Estimates and Uncertainties

The final Venus swingby aimpoint estimate is shown in Figure 88, below, alongside the pre-TCM-2 estimates.

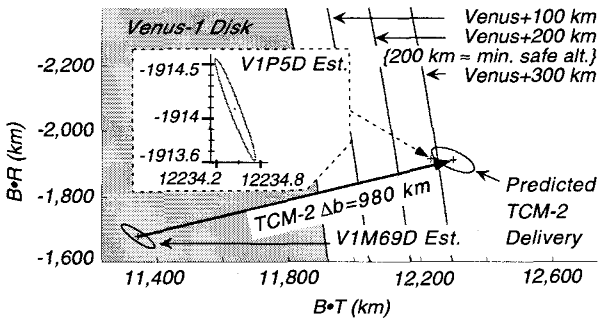

Figure 8: Venus B-plane, *pre*-TCM-2 and *post*-Venus-1 estimates

TCM-3, TCM-4, and Trajectory Update

TCM-3 was scheduled to be executed on April 8, 1998, which was 18 days before the Venus-1 swingby. With pre-launch estimates, the maneuver was expected to be 60 mm/s, but likely, i.e., with 95% confidence, to be no more than 130 mm/s.

TCM-4 was scheduled for May 15, 1998, or 18 days after the Venus-1 swingby. With pre-launch estimates the maneuver was expected to be 0.47 m/s, but not likely, i.e., with 95% confidence, to be more than 1.25 m/s.

The Navigation team proposed a change to the maneuver plan: the cancellation of TCM-3 *and* TCM-4 via a update of the post-Venus-1 trajectory. This update would, of course, be based on the Venus-1 swingby reconstruction.

The formulation of this proposal required a study of the cost associated with the nominal plan, described earlier, versus the update.[20]

Currently, JPL has two software tools available for this sort of trajectory analysis/update. CATO[12] (Computer Algorithm for Trajectory Optimization) uses numerical integration and a variation of multiple-shooting while LAMBIC[21] (Linear Analysis of Maneuvers with Bounds and Inequality Constraints) uses a linear analysis centered about a nominal trajectory. (LAMBIC is also used to perform Monte Carlo simulations of future maneuvers to facilitate maneuver design).

Twenty-five (25) cases, evenly spaced on a rectangular grid in the B-plane, were studied with these tools. Figure 99 depicts the chosen trade-space, the size of which was driven by a desire to cover even unlikely events. A 30 km uncertainty is depicted for comparison. (Also shown is the V1-40d OD solution, *which was the most current information* when this proposal was made.)

Time-of-periapsis variations were not considered because the TCM-4 ΔV was relatively insensitive to them – roughly 0.1 m/s per minute variation in time-of-periapsis.

JPL's DPTRAJ (Double Precision TRAJectory) software[22] was used for high-precision simulation of the 25 non-nominal Venus-1 swingbys. The post-Venus-1 states from DPTRAJ were used in CATO as initial-state constraints. Furthermore, the date of the DSM was fixed as were the aimpoints of the Earth Swingby Plan, above. The Venus-2 and Earth swingby altitudes were limited to be at least 300 km and 800 km, respectively.

The results, depicted in Figure 1010 and Table XIXI, show that the ΔV penalty for skipping TCM-3 would not exceed 5 m/s even for very large misses at Venus-1. The nominal total mission ΔV was 548 m/s.

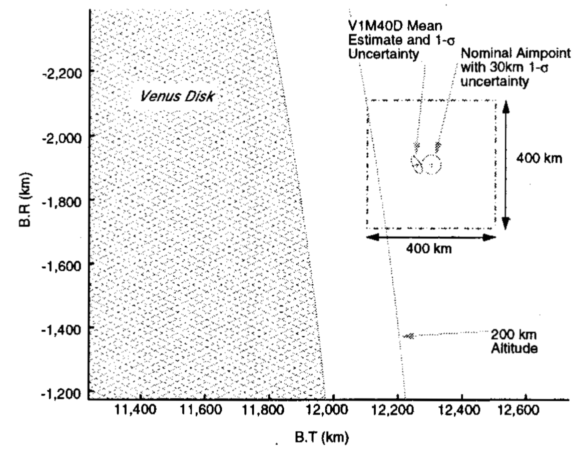

Figure 9: Venus 1 B-Plane and Trade Space, centered at Nominal Aimpoint

In Table XIXI, the left-most entry is the nominal aimpoint; the others are the four corners of the box in Figure 99. From the TCM 4 row, which is essentially zero, it is clear that the trajectory update after skipping TCM-3 does not require TCM-4, either. This, then, motivates the cancellation of both maneuvers.

Venus-2 swingby altitudes in these trajectories range from 450 km to 800 km, always above the 300 km constraint; the time-of-periapsis varies by up to a half-day in either direction.

Table XI: Deterministic Delta-V's for Updateed Trajectories (m/sec)

B•R	0	-200	200	200	-200
B•T	0	-200	-200	200	200
TCM-4	1.15×10^{-3}	6.59×10^{-3}	1.11×10^{-3}	1.07×10^{-3}	1.85×10^{-3}
DSM	450.39	453.92	450.16	454.61	451.70
V2+10	42.80	42.79	42.78	42.81	42.84
E-30	4.98	4.98	4.97	4.99	5.00
E-15	37.03	36.94	36.75	37.11	37.30
E-6.5	12.39	12.33	12.20	12.45	12.58
Total	547.59	550.96	546.86	551.97	549.42

The Earth swingby altitudes range from 1150 km to 1225 km, always above the 800 km constraint with up to 3-hour shifts in time-of-periapsis.

It should be noted that these variations in swingby conditions represent smaller changes than the variations in these parameters over the launch space. In other words, had the launch taken place later on a different day in the launch period, the 'nominal' Venus/Earth flyby conditions might have differed by even larger amounts.

The same analysis was performed with LAMBIC (linear technique). Table XIIXII shows the differences in total mission ΔV ($\Sigma\Delta V_{CATO}$ minus $\Sigma\Delta V_{LAMBIC}$) for the 25 trajectories. As can be seen in this table, the linear technique can produce results less than 0.5 m/s in error out of a total of approximately 550 m/s, which is fairly accurate.

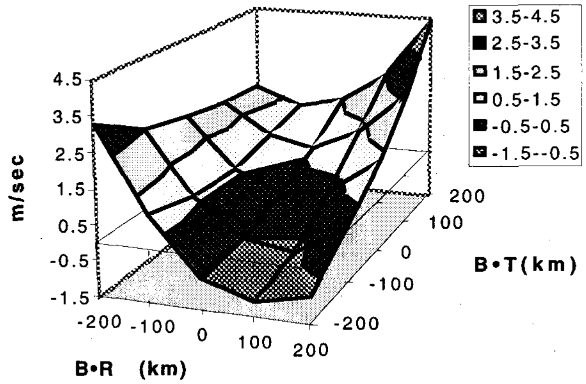

Figure 10: Total Cruise ΔV Cost for Venus-1 Non-nominal Swingbys with Post-Swingby Trajectory Update (See 400 km box in Figure 99)

Table XII: Comparison of Solutions for Total Mission ΔV (m/s) (CATO vs. LAMBIC)

R\T	-200	-100	0 km	100	200
-200	-0.15	-0.15	-0.09	-0.17	-0.49
-100	-0.15	-0.14	-0.06	-0.03	-0.24
0 km	-0.34	-0.21	-0.03	0.01	-0.19
100	-0.32	-0.28	-0.09	-0.04	-0.22
200	-0.29	-0.25	-0.14	-0.18	-0.24

Venus-1 Swingby

With the decision to update the trajectory, skipping TCM-3 and TCM-4, non-nominal Venus-1 swingby conditions became nominal. The flyby was about 5 seconds earlier and about 67 km closer to Venus in the B-plane (Δ**B•R**=-4 km, Δ**B•T**=-67 km) which gives a closest-approach of 283.7 km (pre-launch design: 330 km). Hyperbolic excess speed (V), relative to Venus, was about 0.171 m/s faster than the anticipated 6.030 km/s. The geometry of the first Venus flyby is shown in Figure 1111 from a viewpoint above the trajectory plane, translating with Venus.

The spacecraft, moving outward from the Sun, approached Venus only 25° from the Sun direction. Then, Venus' gravity bent the trajectory forward into the direction of Venus' own velocity, so that the spacecraft's velocity became almost perpendicular with the direction from the spacecraft to the Sun. This flyby geometry is quite efficient in adding energy to the spacecraft trajectory.

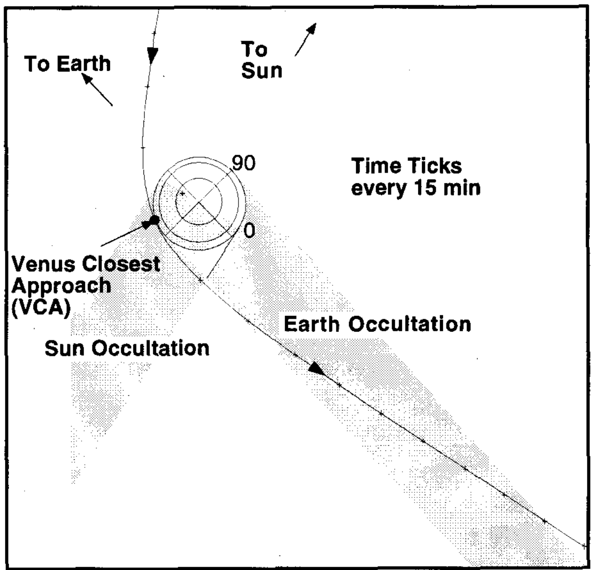

Figure 11: Venus 1 Flyby Geometry (Venus-centered)

Trajectory Update and Future Maneuvers

The update of the nominal trajectory is currently in progress. However, the update does not significantly affect the size of most maneuvers. The next maneuver will be TCM-5t in the early part of November, 1998; it is referred to as the "test maneuver" because it will be used to characterize the propulsion system by simulating conditions that will be seen later in cruise. The TCM-5t design has been fixed at 9 m/s, its direction will be determined as part of the trajectory update effort. Following TCM-5t, the DSM will be executed on December 3, 1998. Like TCM-5t, the DSM design will be fixed by the update, well in advance of execution. TCM-6 is the next targeted maneuver. It is scheduled for January 28, 1999, 147 days before the Venus-2 swingby. TCM-6 is intended to 'clean-up' the execution errors from the DSM. It is expected to be about 8 m/s. TCMs 7 and 8 are scheduled for 77 days and 21 days before the Venus-2 swingby, respectively. These are expected to be small maneuvers about 150 mm/s and 60 mm/s, respectively.

Conclusions

The first two maneuvers of the Cassini mission have been executed rather smoothly. The detailed maneuver analysis performed after TCM-2 demonstrated that both TCM-3 and TCM-4 could be skipped at minimal ΔV cost. This analysis also provided the first in-flight experience for the Cassini Navigation team in comparing trajectories generated by linear mapping and numerical integration. The excellent agreement between LAMBIC and CATO indicates that these two tools can be used to complement each other, the former to quickly generate a large number of data points and the latter to refine/confirm a subset.

Early orbital experience with the Cassini Spacecraft has been very successful and should lead to exciting science investigations of the Saturn planetary system. Maneuver performance thus far has been in the nominal range, and the team fully expects mission success to follow.

Appendix: B-plane Description

Planet or satellite approach trajectories are typically described in aiming plane coordinates referred to as "*B*–plane" coordinates (see Figure A-11).[23] The B-plane is a plane passing through the planet center and perpendicular to the asymptote of the incoming trajectory (assuming 2 body conic motion). The "B-vector" is a vector in that plane, from the planet center to the piercing-point of the trajectory asymptote. The B-vector specifies where the point of closest approach would be if the target planet had no mass and did not deflect the flight path. Coordinates are defined by three orthogonal unit vectors, ***S***, ***T***, and ***R***, with the system origin at the center of the target body. The ***S*** vector is parallel to the incoming spacecraft V vector (approximately the velocity vector at the time of entry into the gravitational sphere of influence). ***T*** is arbitrary, but is typically specified to lie in the ecliptic plane (the mean plane of the Earth's orbit), or in a body-equatorial plane. Finally, ***R*** completes an orthogonal triad with ***S*** and ***T***.

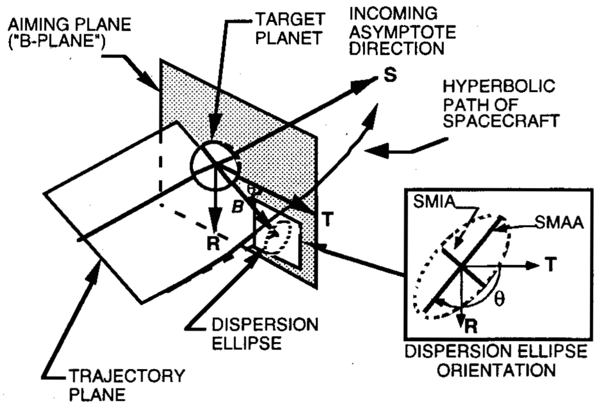

Figure A-1: Aim Plane Coordinate System

Trajectory errors in the B-plane are often characterized by a one–σ dispersion ellipse, shown in Figure A-11. SMAA and SMIA denote the semi–major and semi–minor axes of the ellipse; θ is the angle measured clockwise from the **T** axis to SMAA. The dispersion normal to the B-plane is typically given as a one-σ *time-of-flight* error, where time-of-flight specifies what the time to swingby (periapsis) would be from some given epoch if the magnitude of the B-vector were zero. Alternatively, this dispersion is sometimes given as a one-σ distance error along the ***S*** direction, numerically equal to the time-of-flight error multiplied by the magnitude of the V vector.

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