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CASSINI INTERPLANETARY TRAJECTORY DESIGN

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The Cassini mission to Saturn will start a second phase in the exploration of the Saturnian system, after the historical Voyager flybys of Saturn in 1980 and 1981. The Cassini primary mission is scheduled to be launched in October 1997 by the Titan IV/Centaur. Cassini uses four planetary gravity-assist flybys to gain the energy necessary to reach Saturn in July 2004. This arrival date at Saturn provides a unique opportunity for a flyby of Saturn's outer satellite Phoebe on the final approach. This paper provides an overview of the processes involved in the interplanetary trajectory design and analysis of the Cassini mission to Saturn.

Keywords: Cassini, Interplanetary Trajectory.

1. INTRODUCTION

The Cassini primary mission is scheduled for launch in October 1997 using the Titan IV/Centaur, with an Upgraded Solid Rocket Motor (SRMU) launch vehicle. The Venus-Venus-Earth-Jupiter Gravity Assist (VVEJGA) trajectory, shown in Figure 1, compensates for the necessary energy to reach Saturn, requiring a deterministic or Deep Space Maneuver (DSM) throughout the launch period. This maneuver will be executed after Venus 1 (April 1998) to lower perihelion (the closest point with respect to the Sun) and place the spacecraft on the proper course to encounter Venus for a second time in June 1999.

After the Earth flyby in August 1999, the Cassini spacecraft will be on its way to the outer planets, flying by Jupiter in December 2000. The fortuitous geometry of the VVEJGA trajectory provides a unique opportunity of a double gravity-assist flyby, Venus 2 to Earth within 56 days, reducing the total flight time to Saturn to 6.7 years. The scientific information obtained during the interplanetary cruise phase is limited primarily to gravitational wave searches during three successive Sun oppositions, beginning in December 2001.

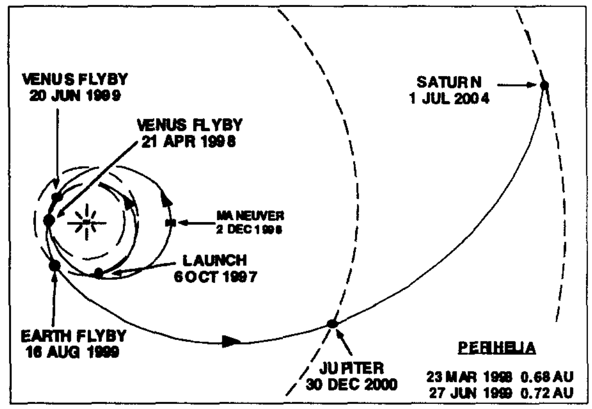

Fig. 1. Cassini-VVEJGA October 1997, Interplanetary Trajectory.

2. INTERPLANETARY TRAJECTORY

2.1 *Primary Trajectory Launch Period*

The current nominal launch period of the primary mission opens on October 6, 1997, and closes on November 4, 1997, providing a 30-day launch period. A contingency launch period is extended beyond the nominal launch period to November 15, 1997, to increase the chances of mission success although degrading to some extent the scientific accomplishments of the nominal mission. The opening and close of the nominal launch period are chosen such that the launch vehicle's capabilities are not exceeded, and the mission performance[1] and operational requirements are met. Launch dates which minimize the interplanetary cruise duration are a function of the Saturn arrival date which is constrained by launch vehicle performance, trajectory characteristics, and mission requirements placed on both the Orbiter and the Probe.

Table 1 provides a summary of events that apply only to the reference trajectory, i.e., the trajectory for the opening of the nominal launch period of the primary trajectory. Other trajectories within the launch period are characterized by differences in flyby parameters such as flyby dates, altitudes, maneuver dates and magnitudes.

2.2 *Trajectory Design and Analysis Tools*

The design of the VVEJGA trajectory is accomplished using two trajectory optimizer programs developed at the Jet Propulsion Laboratory. MIDAS (Sauer, 1990) is used to perform preliminary studies to identify the prospective trajectories, to undertake feasibility studies, and to determine fundamental trajectory characteristics such as the sequence of flyby bodies. MIDAS models spacecraft trajectories using patched conics. The output information provided by MIDAS is then used as initial conditions to the PLAnetary Trajectory Optimization (PLATO) program, (Peralta, 1993). PLATO uses multi-conic propagation methods to model the trajectory dynamics more accurately, and employs a more sophisticated optimization scheme. However, PLATO requires a good guess at the initial conditions in order for convergence to occur. PLATO is first used to corroborate the results obtained by MIDAS, and then to develop a set of trajectories that further enhances the understanding of the behavior and peculiarities of the interplanetary trajectory, not only for one particular launch date but also with variations in launch and arrival dates.

A complete study of all possible trajectories, launching in the September-October-November 1997 range and arriving at Saturn from April 2004 to December 2005, was carried out as part of the launch/arrival trajectory analysis process to identify the optimal trajectory for each launch date within the launch period. As a result of this analysis a launch period strategy was incorporated to maximize mission success. The resulting set of trajectories is guaranteed to meet the injection capability of the launch vehicle.

Optimizing an interplanetary trajectory means minimizing a cost function[2] which in this case is the total deterministic post-launch ΔV required. Variables to consider are the launch energy, the times of the deterministic maneuvers, and the planetary flyby parameters (including: the altitude, flyby geometry, and the times of each planetary gravity-assist flyby). These independent variables are allowed to change, subject to upper and lower limits that may be placed on any or all of the variables. These parameters may be subject to constraints arising from mission operations, such as the time or direction of a maneuver. Other constraints come from scientific considerations or are physical in nature. For example, a lower limit on flyby altitude is specified so as to prevent the spacecraft from impacting the flyby planet or entering its atmosphere. It is important to mention that changing the boundaries imposed on the flyby parameters might alter the behavior of a multiple gravity-assist trajectory, thus providing a new family of solutions.

The solution for an optimized Cassini VVEJGA trajectory usually contains one or more deterministic maneuvers which are non-zero ΔV's. Other maneuvers are statistical and are nominally zero, but in actual flight become non-zero due to maneuver execution errors, orbit determination errors, and planetary ephemeris uncertainties. For example, the first trajectory correction maneuver, performed about three to four weeks after launch, is a statistical maneuver to correct for the injection errors of the Centaur upper stage.

2.3 *Trajectory Space Characteristics*

The design and analysis of the Cassini trajectories is a complex and time-consuming process that requires a high level of human interface. For example, the VVEJGA reference trajectory was the first type of solution discovered for this trajectory. However, in the course of trying to develop a launch period for this solution, difficulties were encountered. Beyond a launch date of October 23, the launch energy per unit mass (C_3) increases dramatically in order to reduce the post-launch ΔV. The C_3 increased well beyond the maximum capability of the launch vehicle. Further analysis was required to realize that another family of solutions existed for this trajectory, with much higher values of C_3. By launching at a substantially increased C_3, it is possible to eliminate the large DSM between Venus 1 and Venus 2

[1] Mission performance is measured in terms of end of mission (EOM) fuel budget, defined as the potential velocity increase achievable with the bipropellant remaining in the tanks after the completion of the four-year satellite tour.

[2] Launch energy is not included in the cost function in the normal mode of operation, so the trajectory set obtained is independent of the selection of the launch vehicle.

altogether, resulting in a ballistic trajectory to Saturn. The higher launch C_3 is used to depress the perihelion of the trajectory initially, which results in a later Venus 1 arrival date. After Venus 2, the two types of solutions have very similar heliocentric trajectories. This second family of solutions is called the "global optimum family," and the original family is called the "local optimum family."

Table 1. Mission Events

Mission Events	Start Date	Days from Launch	Comments
Launch	**6-Oct-97**	0	C3 = 18.1 km^2/s^2
Aphelion	1-Nov-97	26	Sun range = 1.02 AU
• Conjunction	9-Feb-97	126	Inferior conjunction
Deep Space Maneuver	16-Mar-98	162	$\Delta V = 0$ m/s; $\Delta V>0$ for launch dates after 10/25/97
Perihelion	23-Mar-98	169	Sun range = 0.68 AU
Venus 1 flyby	**21-Apr-98**	197	Altitude @Periapsis = 300 km; Velocity @ periapsis = 11.8 km/s
Deep Space Maneuver	2-Dec-98	423	$\Delta V = 466$ m/s
Aphelion	4-Dec-98	424	Sun range = 1.58 AU
High Gain Antenna	16-Dec-98	436	25 day instrument checkout
• Opposition	2-Jan-98	453	
Low Gain Antenna	10-Jan-99	461	Probe thermal constraints restrict High Gain Antenna usage
Venus 2 Flyby	**20-Jun-99**	622	Altitude @Periapsis = 2267 km; Velocity @ periapsis = 13.0 km/s
Perihelion	27-Jun-99	629	Sun range = 0.72 AU
• Conjunction	16-Aug-99	679	Inferior conjunction
Earth Flyby	**16-Aug-99**	679	Altitude @Periapsis = 500; Velocity @ Periapsis= 19.1 km/s
• Opposition	13-Sep-99	707	
Enter Asteroid Belt	12-Dec-99	797	Sun Range = 2.2 AU
High Gain Antenna	29-Jan-00	845	No constraints after this date
Exit Asteroid Belt	10-Apr-00	917	Sun Range = 3.3 AU
• Conjunction	13-May-00	950	
• Opposition	28-Nov-00	1149	Gravity Wave Opportunity
Jupiter flyby	**30-Dec-00**	1181	Altitude = 139 Jupiter Radii; Velocity @ periapsis = 11.5 km/s
• Conjunction	7-Jun-01	1340	
• Opposition	16-Dec-01	1532	Gravity Wave Experiment opportunity ± 20 days
• Conjunction	21-Jun-02	1719	
SCIENCE ON	1-Jul-02	1729	Cruise science begins SOI-2yrs
• Opposition	27-Dec-02	1908	Gravity Wave Experiment opportunity ± 20 days
• Conjunction	1-Jul-03	2094	
• Opposition	4-Jan-04	2281	Gravity Wave Experiment opportunity ± 20 days
Phoebe Flyby	12-Jun-04	2441	Distance = 52,000 km
Saturn Orbit Insertion	**1-Jul-04**	2460	$\Delta V = 613$ m/s
• Conjunction	8-Jul-04	2467	
Periapsis Raise Maneuver	12-Sep-04	2533	$\Delta V = 333$ m/s
Probe Separation	6-Nov-04	2588	
Orbit Deflection Maneuver	8-Nov-04	2590	$\Delta V = 48$ m/s
Probe Entry	27-Nov-04	2609	
Titan 1 flyby	**27-Nov-04**	2609	Altitude @Periapsis = 1500 km; Velocity @ periapsis = 5.9 km/s
• Opposition	13-Jan-05	2656	
End Of Mission	**1-Jul-08**	3921	End of 4-year tour

Unfortunately, the values of C_3 required for the global optimum solutions lie between 35 and 55 km^2/s^2. In order to launch with a C_3 of 35 km^2/s^2. using the Titan IV, it would be necessary to off-load over 1100 kg of propellant. This would not leave enough propellant to perform the Huygens Probe delivery, or the four-year Saturn tour. Therefore, the global optimum solutions are not practical for Cassini.

However, it is possible to find useful, flyable solutions for days after Oct. 23. By fixing the C_3 to a specified value, an intermediate family of solutions was discovered which lies between the local optimum and the global optimum families in terms of C_3. In fact, there is a continuum of such solutions, with Venus 1 arrival dates lying between the local and global optimums, and the values of C_3 spanning the full range from 17 to 40 km^2/s^2. These fixed C_3 solutions display complicated behavior across the launch period. Depending on the launch day and the fixed C_3 selected, an intermediate solution can resemble either the local or the global optimum family. Therefore, in addition to studying the local optimum family wherever it exists, it is also necessary to study the entire launch period at several fixed values of C_3, in order to capture these intermediate solutions.

Figure 2 shows these curves for intermediate solutions with values of C_3 ranging from 16.5 km^2/s^2 up to the ballistic solution which occurs at a C_3 of 46 km^2/s^2. This chart shows, as stated earlier, that off-loading bipropellant in order to fly on a higher C_3 trajectory to reduce the post-launch ΔV is inefficient. This is due to the fairly slow decrease in the post-launch ΔV with increase in C_3. This fact became a pattern throughout the entire launch period.

2.4 *C_3 Variations*

Before trying to understand the relationships of these different types of solutions as a function of launch date, it is useful to study their behavior as a function of C_3 for a single, fixed launch day, Oct. 19. Figures 3 and 4 each show curves representing three different quantities of interest used to identify feasible trajectories for the VVEJGA mission.

1. Injection Margin - The difference between the maximum launch vehicle injection capability and the required injected mass.
2. Interplanetary ΔV - Total deterministic ΔV (not including Saturn Orbit Insertion, (SOI)).
3. End of Mission ΔV - Total ΔV capability of the excess propellant remaining upon completion of the nominal mission.

Figure 3 adds the local optimum solution to Figure 2, and zooms in, excluding the higher C_3 intermediate solutions and the global optimum solution. The nature of the local optimum becomes apparent in this figure. The family appears as a small, parabolic

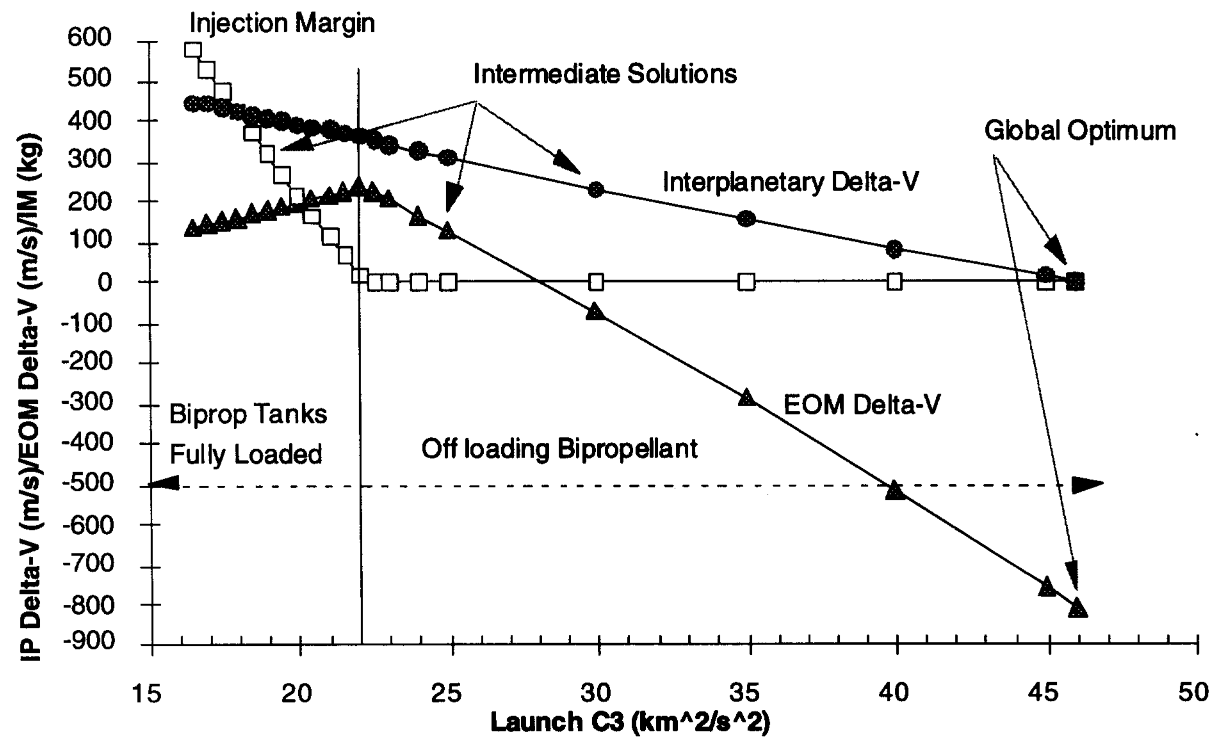

Fig. 2. Injection Margin, Interplanetary Delta-V, and Delta-V at End of Mission versus C_3 for Launch on 10/19/97, Arrival on 7/1/04.

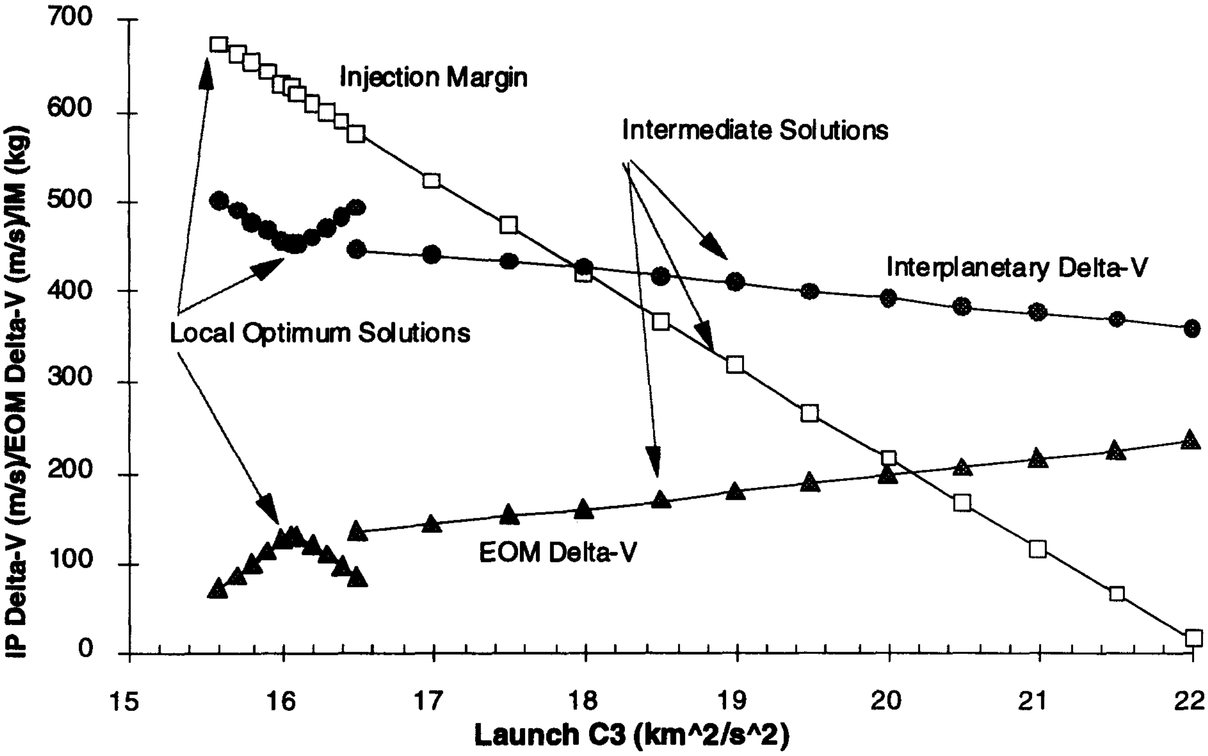

Fig. 3. Injection Margin, Interplanetary Delta-V, and Delta-V at End of Mission versus C_3 for Launch on 10/19/97, Arrival on 7/1/04.

curve lying at the low C_3 end of the intermediate solutions. It is this characteristic shape of the local optimum which makes it possible for the software to converge to a free C_3 solution without jumping up to the global optimum. The existence of the local optimum can most likely be attributed to the fact that the local optimum has at least one flyby on a lower bound for every day that it exists. The existence of these constraints restricts the options available to the software in its optimization, thereby limiting the number of paths that the optimization can take through the parameter space. It can therefore be impossible to reach some lower ΔV solutions due to the location of the initial guesses.

From Figure 4, it is clear that two distinct families do exist in this region. For values of C3 between 16 and 16.5 km^2/s^2, two solutions are shown, with identical values of C_3 and completely different flyby altitude profiles. However, it can also be seen that as the C_3 of the intermediate solution approaches the C_3 of the local optimum, its flyby altitude profile becomes more like that of the local optimum as well. In some sense, the intermediate solution can be said to "fall into" the local optimum as it approaches in C_3.

Looking back at Figure 2, it might seem that the best performance, as judged by end of mission ΔV, will always occur at the point where the injection margin goes to zero. This appears to be due to the fact that for this launch day a very small increase in C_3 along the intermediate solution is all that is required to provide an improvement in performance over the local optimum, and further increasing the C_3 continues to yield better performance until the maximum launch vehicle capability is reached. In other words, the neighborhood for which the local optimum is optimal is very small. This is not always the case, however, as will be demonstrated when other launch days are considered.

Summary of Variations due to Launch Date and C_3. The key concepts that should be noticed with respect to the variation in launch date and C_3 are the following:

1. Interplanetary ΔV is lowest in the middle of the launch period and rises at either end due to flyby altitudes hitting constraints.
2. The local optimum solutions provide the best available performance at the beginning of the launch period, then disappear towards the end.
3. The C_3 of the local optimum solutions varies as a function of launch date.
4. The intermediate solutions provide the best performance starting in the middle of the launch period and continuing until the end.

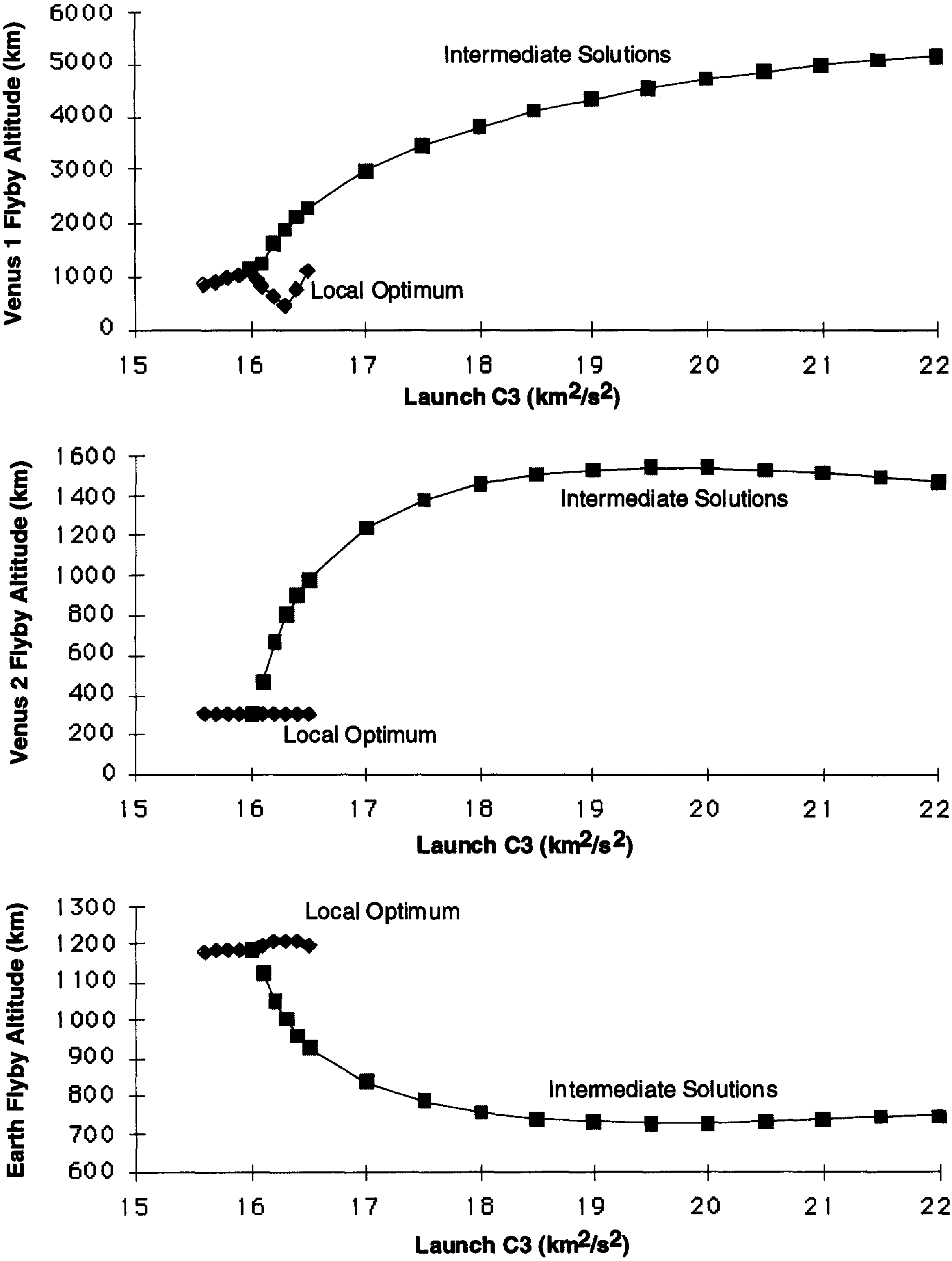

Fig. 4. Venus 1, Venus 2, and Earth Flyby Altitudes versus C_3 for Launch on 10/19/97, Saturn Arrival on 7/1/04.

3. ARRIVAL DATE ANALYSIS

As mentioned previously, Cassini's nominal arrival date, July 1, 2004, was selected because it provides an opportunity for a Phoebe flyby. Cassini will never have an opportunity to perform a close flyby of Phoebe during the four-year tour, since Phoebe's distant orbit around Saturn places it well outside Cassini's apoapses. Phoebe is of particular interest to astronomers due to questions concerning its origin. These factors combine to make it highly desirable to maintain the nominal arrival date.

However, more important than maintaining the nominal arrival date is guaranteeing a launch during the October 97 opportunity. The penalty for missing this launch opportunity is severe. Therefore, any alternatives that have the potential to make a launch in October 97 more likely must be explored. For example, reducing the required total ΔV might be necessary in order to respond to spacecraft mass increases. Extending the flight time is one of the few means by which this sort of mission resiliency can be provided. The ΔV savings is almost entirely in the Saturn Orbit Insertion maneuver. The inner solar system segments of the trajectory require complex phasing, in effect "pinning down" the trajectory, and are affected only slightly by changes in the flight time.

Extending the flight time can also potentially have an impact on the duration of the launch period. It was previously stated that the open of the launch period is strongly influenced by the fact that the Earth flyby altitude is on the lower bound of 500 km for all days prior to October 6 for the nominal arrival date of July 1, 2004. Moving the arrival date approximately one year later, to June 10, 2005, causes the Earth flyby to come off of this bound nearly 5 days earlier. It is not possible, however, to move the close of the launch period by changing the arrival date.

4. SECONDARY AND BACKUP TRAJECTORIES

To enable recovery from possible extreme launch delays, the Cassini project has selected a set of secondary and backup mission opportunities. These missions make use of the Venus-Earth-Earth Gravity Assist (VEEGA) trajectory concept. Secondary missions are allowed to have a launch date less than six months after the primary mission. This mission protects against launch slips that occur after hardware delivery, and can be diagnosed and fixed within a short time, but not quickly enough to meet the primary launch schedule. Scientific returns can be degraded slightly in the light of the competing pressure to launch the spacecraft if a problem delaying the primary mission is identified and solved. Backup missions are required to be launched at least six months after the primary mission opportunity, and to have the same scientific return profile as the primary. Backup missions are kept in the mission set to protect against launch slips from programmatic or technical issues that cause a long launch delay.

The current trajectory set contains a secondary mission opportunity. This mission launches on a VEEGA trajectory in December 1997, shown in Figure 5. A deep space maneuver is executed after the first Earth flyby to properly phase the spacecraft for the second Earth flyby, finally arriving at Saturn on October 13, 2006. Unfortunately, the cruise time for the secondary mission is two years longer than the primary after a launch delay of about one month.

The backup mission opportunity launches on a VEEGA trajectory in March 1999, shown in Figure 6. A deep space maneuver is executed after the first Earth flyby to properly phase the spacecraft for the second Earth flyby, arriving at Saturn on December 22, 2008.

The secondary and the backup trajectories have enough ΔV performance to carry out the mission with no degradation to the scientific return. The significant difference between these missions and the primary is a longer interplanetary cruise time. However, the longer cruise times cause a change in the power available, due to the degradation of the Radioisotope Thermoelectric Generator power source. The available power level for the backup mission at Saturn arrival is roughly equal to that available for the primary mission at the end of the mission, July 1, 2008. This would result in fewer instruments being allowed to operate at a given time, or less engineering support to suit all the instruments.

The extensive analysis described previously for the VVEJGA trajectory was also carried out at the Jet

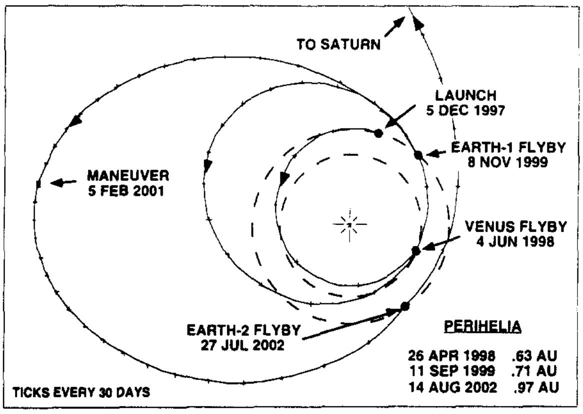

Fig. 5. VEEGA97 - Inner Solar System Trajectory.

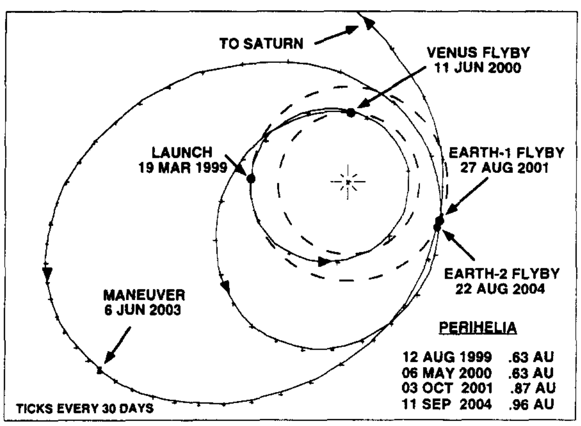

Fig. 6. VEEGA99 - Inner Solar System Trajectory.

Propulsion Laboratory for the secondary trajectory, The extensive analysis described previously for the VVEJGA trajectory was also carried out at the Jet Propulsion Laboratory for the secondary trajectory, so as to fully understand the behavior of the trajectory and to define the launch/arrival space where the secondary trajectory is feasible. No multiple trajectories were found for the secondary mission, as opposed to the primary one.

5. ACKNOWLEDGMENTS

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