

Cassini 1997 VVEJGA Trajectory Launch/Arrival Space Analysis Abstract

Steven Flanagan
Member Technical Staff, Jet Propulsion Laboratory, California Institute of Technology

INTRODUCTION AND PROBLEM DEFINITION

The current baseline trajectory for the Cassini mission to Saturn is a Venus-Venus-Earth-Jupiter-Gravity-Assist (VVEJGA) launching in October of 1997 on a Titan IV (SRMU)/Centaur launch vehicle. The nominal flight time for this trajectory is 6.7 years, arriving at Saturn in June of 2004. This circuitous route to Saturn is necessary in order to reduce the required launch energy, or C_3 , to fit within the launch vehicle's projected injection capability. The minimum C_3 required for a direct trajectory to Saturn launching in 1997 is $108 \text{ km}^2/\text{s}^2$. A Jupiter-Gravity-Assist trajectory (JGA), would require a C_3 of $83 \text{ km}^2/\text{s}^2$. The maximum C_3 available for Cassini, assuming full propellant tanks and the nominal launch vehicle, is approximately $22 \text{ km}^2/\text{s}^2$.

The primary goal of the Cassini launch/arrival space analysis is to determine the optimal feasible trajectory for any launch/arrival date combination. The selection of an optimal trajectory should take into account launch vehicle limitations, spacecraft AV capability and navigation considerations. Towards this end, a comprehensive database of trajectory information is being developed. This database will also facilitate increased understanding of the variation of trajectory characteristics with launch date, arrival date, and C_3 . Of particular interest is the total interplanetary deterministic AV required. The Cassini project recently underwent a major redesign with the goals of reducing spacecraft mass and mission costs. As a result, the bipropellant tank size has been reduced from 4300 kg to 3000 kg. It is therefore of primary importance to determine the AV-optimal trajectory which is within the launch vehicle performance constraints for each day of the prospective launch period.

OCTOBER '97 VVEJGA TRAJECTORY ANALYSIS

The VVEJGA trajectory uses a type 111 transfer to Venus after launch. The first Venus flyby (Venus1) is used to place the spacecraft into a resonant two Venus-year loop. Near

¹A type 1 trajectory has a heliocentric transfer angle between 0° and 180° , type II is between 180° and 360° , and so on.

aphelion of this loop, a large (~ 400 m/s) **deep-space** maneuver (DSM) is performed, which lowers the perihelion of the trajectory, thereby increasing the spacecraft's V_∞ relative to Venus. This is analogous to the aphelion maneuver performed in the AV-Earth-Gravity-Assist (AVEGA) type trajectory. This DSM also establishes the appropriate phasing required for the next leg of the trajectory. The second Venus flyby (Venus2) sets up a very quick transfer to Earth, with a flight time of just 8 weeks. "This extremely fortuitous planetary phasing eliminates the need for an additional trajectory loop in the inner solar system by imparting to the spacecraft the energy needed to reach Jupiter, where a final gravity-assist sends it on to Saturn (Figure 1).

Two distinct families of solutions for the October '97 VVEJGA trajectory have been identified with C_3 's in the range of interest. The first is a locally optimal family of trajectories with C_3 's which vary from $15.9 \text{ km}^2/\text{s}^2$ to $19.9 \text{ km}^2/\text{s}^2$ for the launch days studied. In the course of working with this trajectory, it was also discovered that a purely ballistic solution exists, requiring no deterministic DSMS, but with a C_3 of approximately $48 \text{ km}^2/\text{s}^2$. This is clearly a globally optimal solution for the VVEJGA from a AV standpoint, but is not practical given launch vehicle performance. The second family of feasible solutions is found by starting from the ballistic solution and reducing the C_3 into the desired range. The result is a family of trajectories that is markedly different from the local optimum for identical launch/arrival date combinations. The variation of trajectory characteristics as a function of C_3 can be plotted for both of these families (Figures 2,3). Comparing these curves then makes it possible to determine which trajectory will provide superior performance for a given point in the launch/arrival date space. However, this process is complicated by the fact that these two families exist as distinct solutions only for a subset of the space being examined.

LAUNCH PERIOD VARIATIONS

Although Cassini's nominal launch period is only 25 days long, beginning on Oct. 6 and ending on Oct. 30, the launch date portion of this analysis examined a range of launch dates covering 41 days, from Sept. 27 to Nov. 6. The characteristics of the VVEJGA trajectory, such as flyby altitudes, flyby dates and DSM magnitudes and times, vary greatly with changes in launch date (Figure 4). All trajectories with a feasible launch C_3 require the large aphelion DSM on the Venus1-Venus2 leg mentioned above. Also, an additional DSM appears on the Launch-Venus1 leg towards the beginning and end of the range of launch dates studied, causing a significant increase in total AV. The appearance of this DSM is generally associated with a flyby altitude hitting a lower bound².

²Flyby altitudes are constrained to remain above 300 km in order to prevent damage to the spacecraft and to avoid exacerbating navigation difficulty.

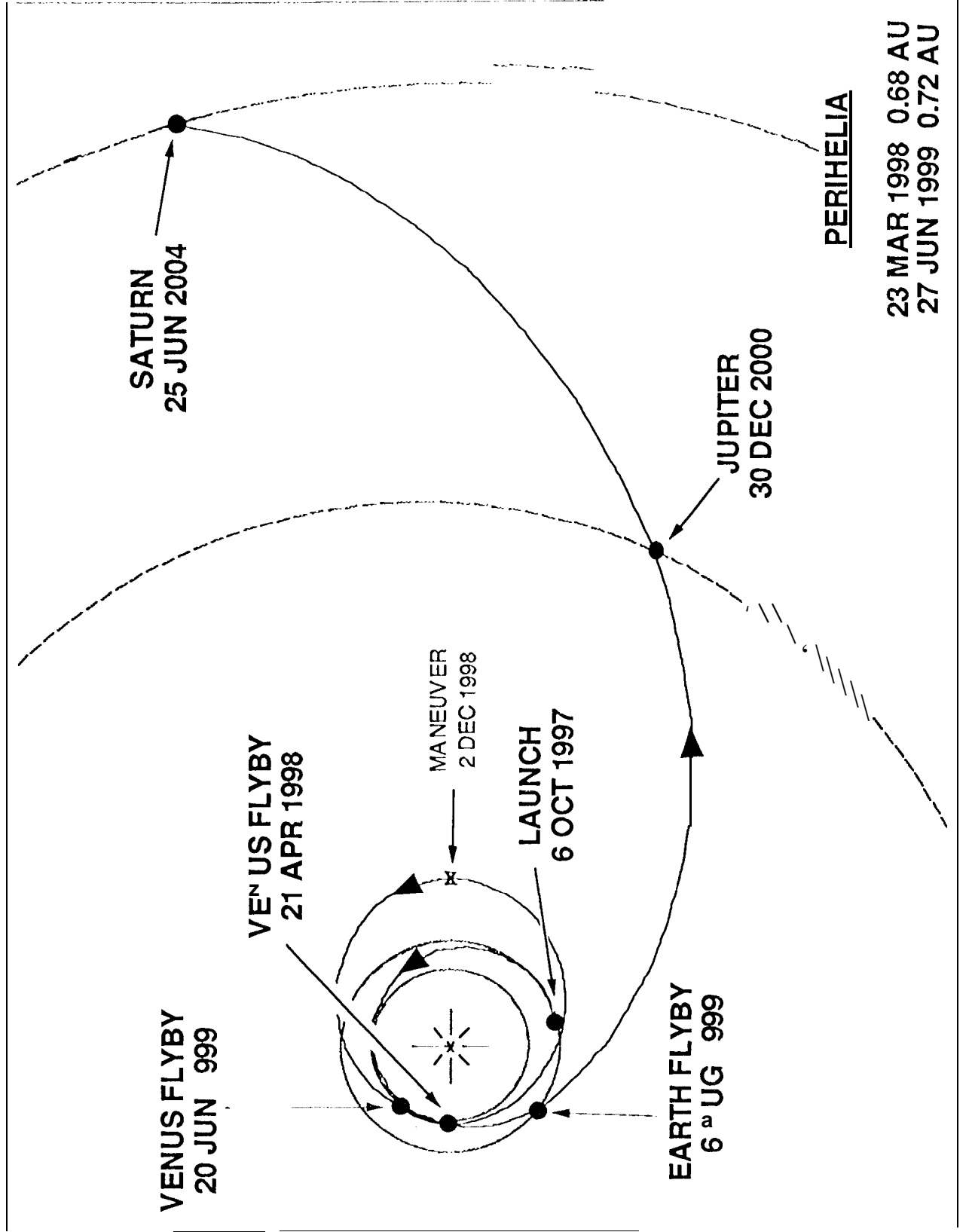
ARRIVAL DATE VARIATIONS

Although the arrival date portion of this study has not yet been completed, it is possible to make several statements based upon previous work that has been done with this trajectory. It is expected that the effect of arrival date variations will be relatively small when compared to that of launch date variations. Two characteristics of the VVEJGA make this likely. First, the very rapid Venus2-Earth transfer restricts the amount of variation of flyby times that can be tolerated in the inner solar system segments. This quick transfer in effect "pins down" the trajectory. Second, the Jupiter flyby is able to compensate for changes in Saturn arrival date. If an early arrival date is selected, the spacecraft will fly by Jupiter at a greater distance, receiving less bending and following a more direct trajectory from Jupiter to Saturn. The opposite is true for later arrival dates. The spacecraft will fly by closer to Jupiter, receive more bending, and arc gradually out to Saturn's orbit. The primary expected impact of arrival date changes is in the magnitude of the Saturn Orbit Insertion AV. Earlier arrival dates will approach Saturn with a substantially higher V_{∞} than later arrival dates. This is a significant impact, but more predictable than launch date dependent variations,

SUMMARY

The Cassini launch/arrival space analysis will result in the development of a database which will greatly simplify the mission design process. Expected products derived from this database include plots of propellant-optimal C_3 and propellant margin as a function of launch/arrival date, and of AV as a function of C_3 and launch or arrival date (Figures 5,6). In addition to enabling trajectory designers to select an optimal launch period utilization strategy, these tools will allow quick answers to questions concerning potential mission alternatives.

Fig.1
CASSINI OCT 1997 VWEJGA



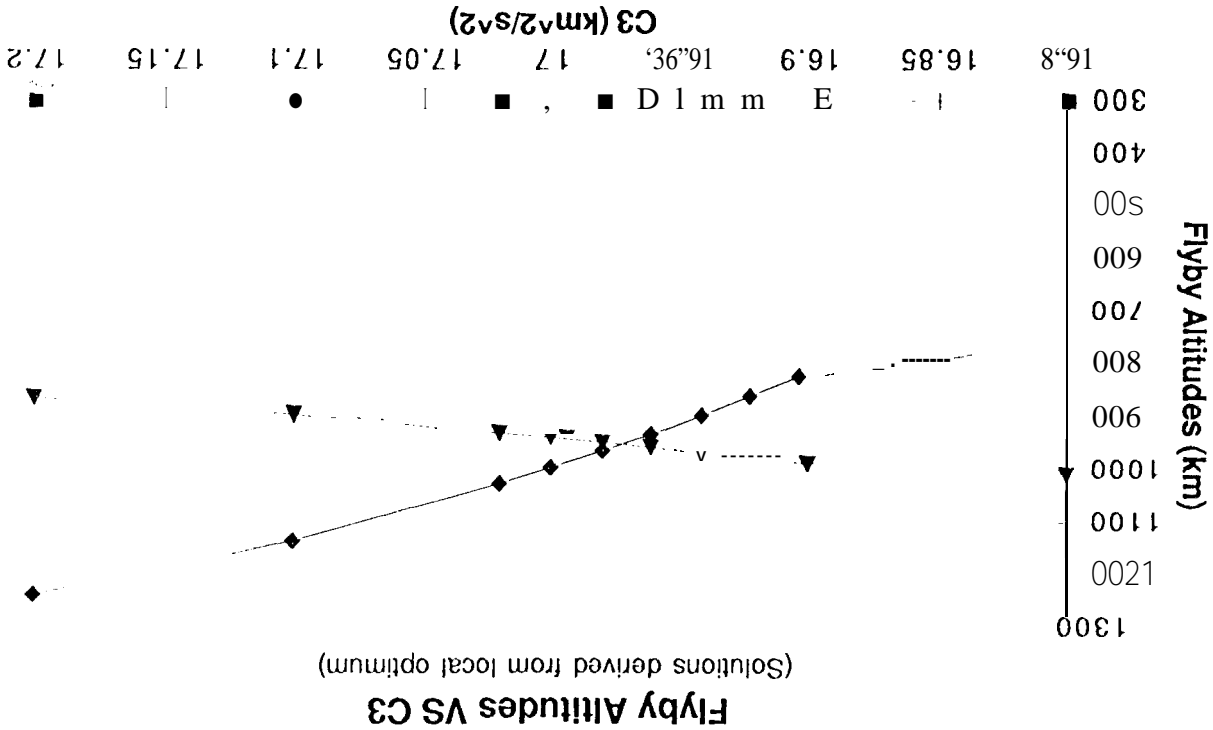
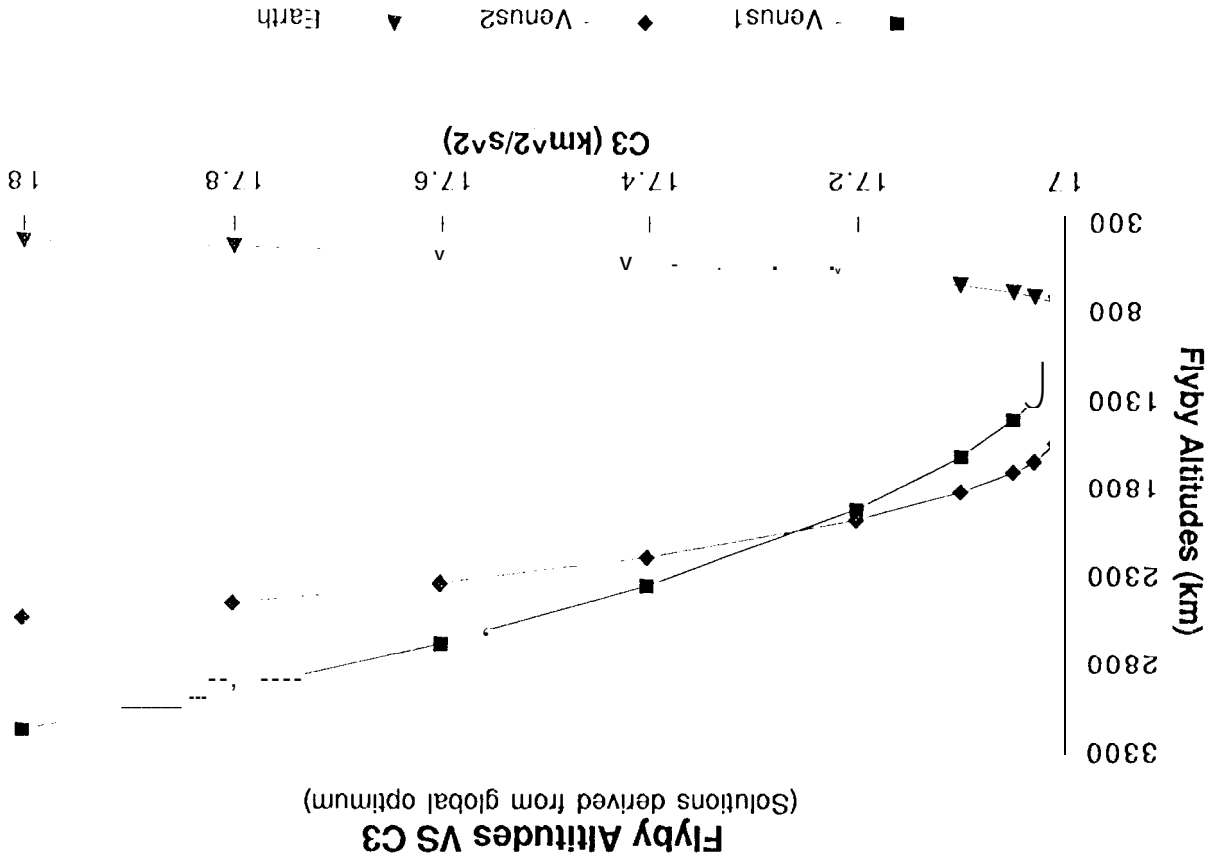


Fig. 2

Fig. 3

Interplanetary ΔV vs C3 For VVEJGA

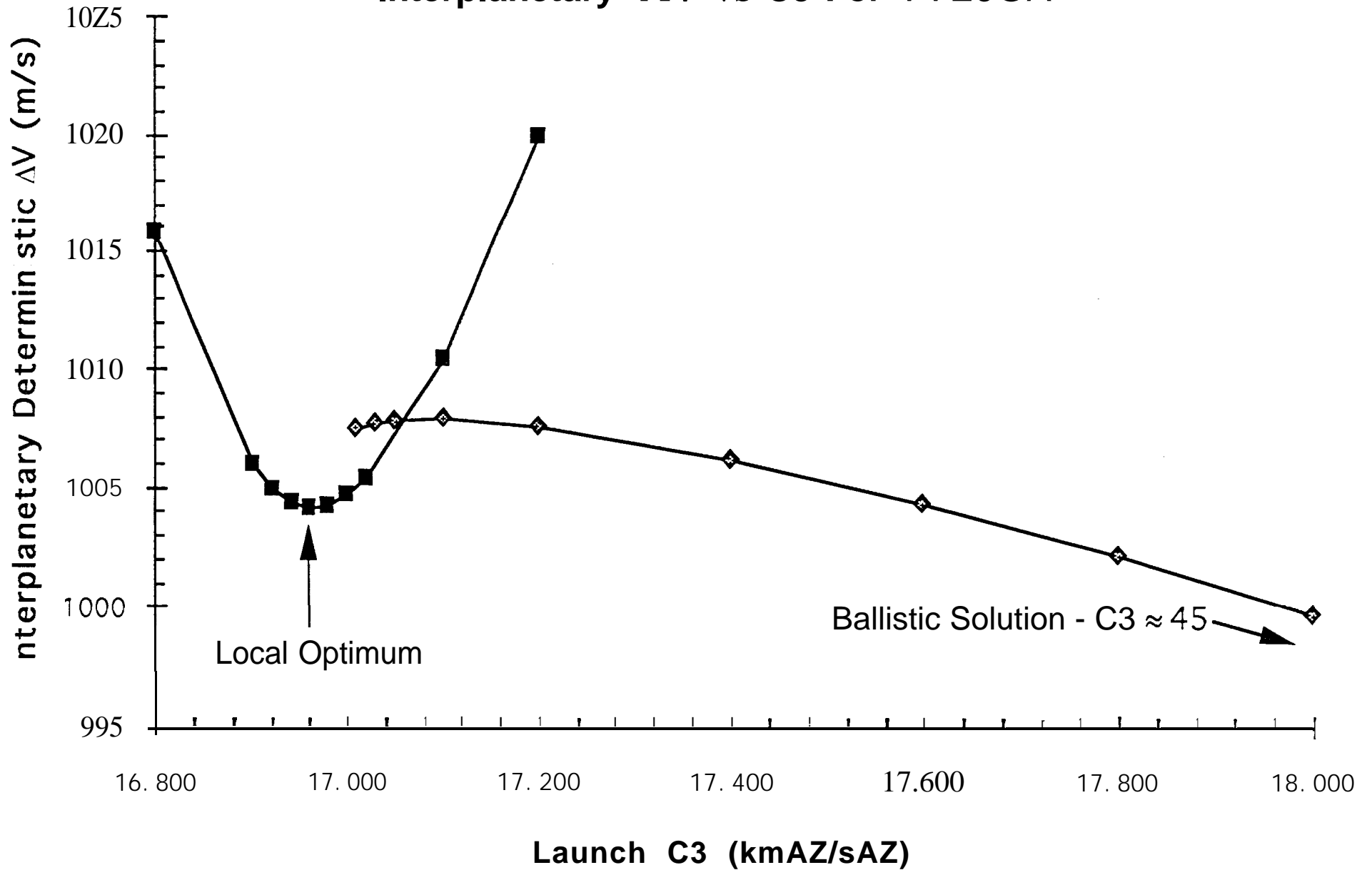
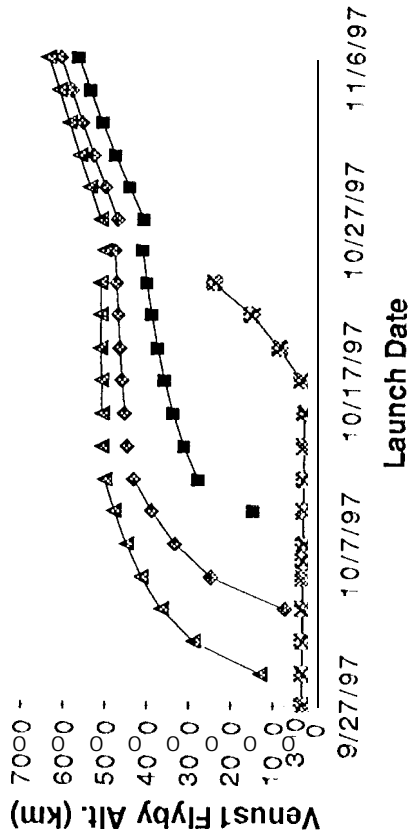
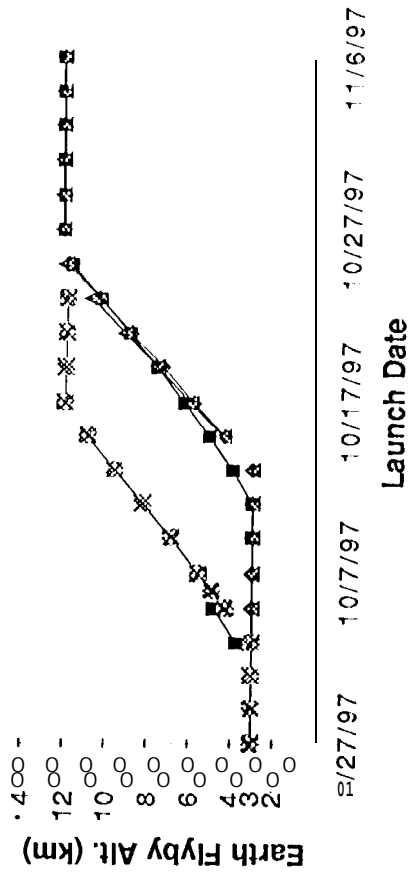


Fig. 4

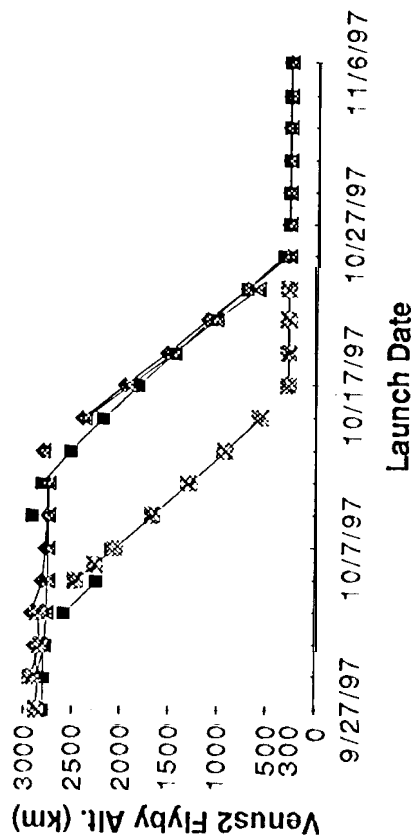
Venus1 Flyby Alt. VS Launch Date



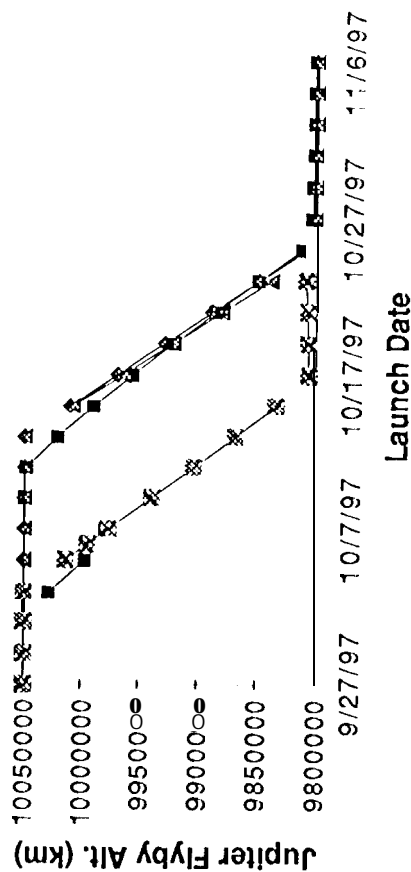
Earth Flyby Alt. VS Launch Date



Venus2 Flyby Alt. VS Launch Date



Jupiter Flyby Alt. VS Launch Date



—■— C3=18

—◆— C3=20

—▲— C3=22

—✕— Local Opt. (C3 varies)

Fig. 5
Interplanetary Delta-V (m/s) VS Launch Date

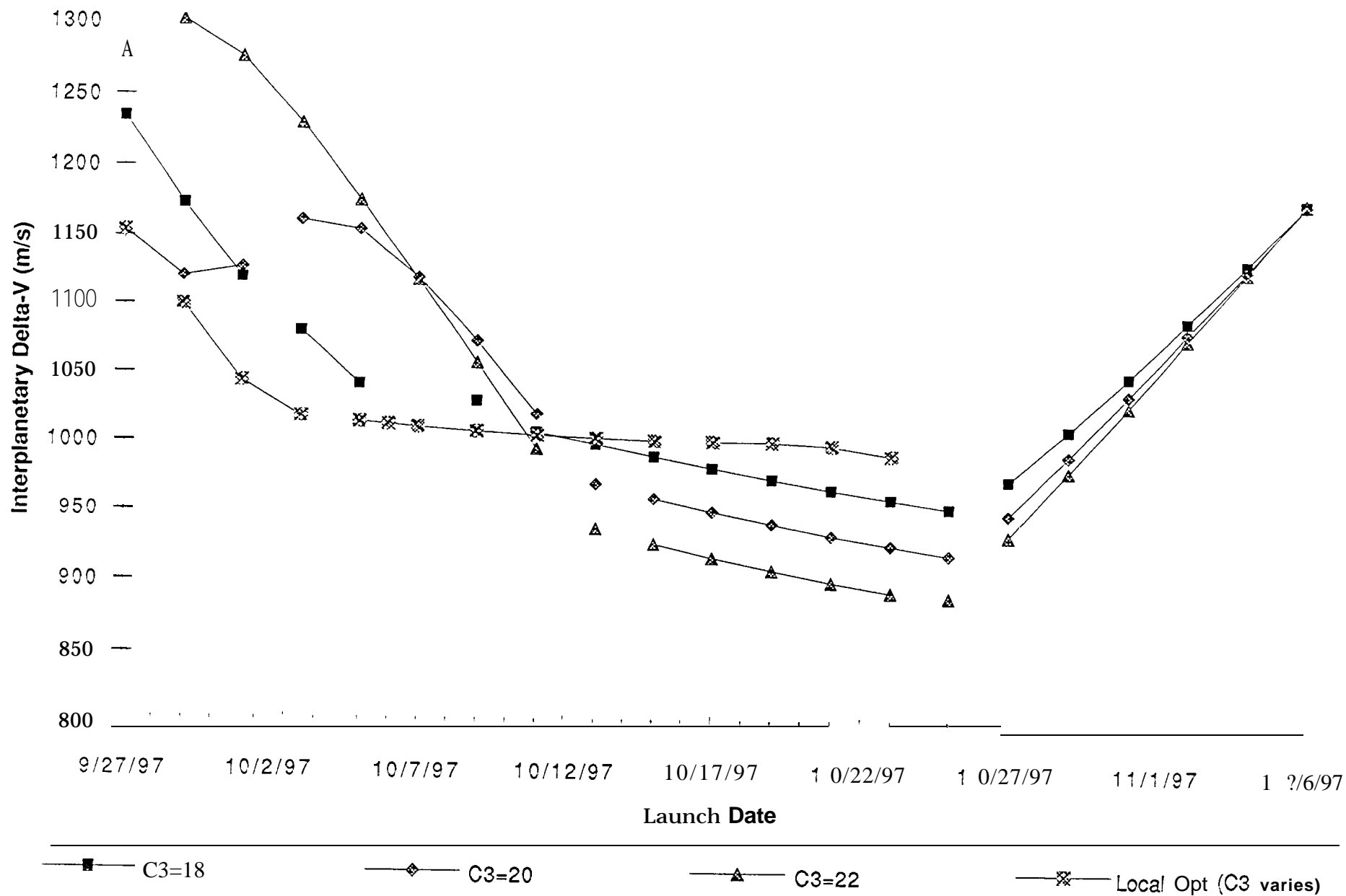


Fig. 6

Post Launch Delta-V as a Function of Launch Date and Launch C3

