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FLIGHT PATH AND MISSION STRATEGIES TO SATISFY OUTER PLANET QUARANTINE CONSTRAINTS

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FLIGHT PATH AND MISSION STRATEGIES TO SATISFY OUTER PLANET QUARANTINE CONSTRAINTS*

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The quantitative results of an investigation of the effect of a planetary quarantine constraint on a typical 1977 Jupiter-Saturn-Pluto mission are presented. Optimum biasing strategies are investigated and fuel loading penalties are determined. Navigation characteristics of multiple outer-planet missions where planetary quarantine constraints are imposed are described. The results indicate that two aim-point biases are required: (1) an injection aim-point bias, requiring ~20 meters/second change in velocity to remove, and (2) a final Jupiter aim-point bias, requiring ~10 meters/second to remove.

I. INTRODUCTION

The importance of planetary quarantine considerations for outer planet missions was discussed in Ref. 1. Preliminary results have shown that for a typical Jupiter-Saturn-Pluto (J-S-P) mission launched in 1976 or 1977, the planetary quarantine constraints at both Jupiter and Saturn would be violated under the assumption that a large body impact produces planetary contamination. One method of satisfying the planetary quarantine constraints when they otherwise would be violated is that of biasing the aim-points of the maneuvers that produced this violation. The biased aim point must be far enough from the impact zone corresponding to the planetary quarantine constraints that the spacecraft would not accidentally find itself inside that zone because of navigation errors. This biasing method was used for both the 1969 and 1971 Mariner Mars missions. Biasing an aim-point results in spacecraft fuel loading (ΔV) penalties in terms of additional fuel required to remove the bias, i.e., to return the spacecraft to its desired trajectory.

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This paper presents some quantitative results of an analysis performed on a typical 1977 J-S-P trajectory, in order to determine such fuel loading penalties as well as to investigate optimum biasing strategies and overall characteristics of outer-planet navigation where planetary quarantine constraints are imposed.

II. MIDCOURSE MANEUVER PLAN AND IMPACT PROBABILITY ALLOCATIONS

The 1977 J-S-P trajectory selected for analysis is the same as the one presented in Ref. 1. A TITAN III D (7 segment)/Centaur 2300/Burner II launch vehicle was assumed, with a spacecraft weight of 659 kg. A nominal trajectory, selected in the middle of the launch period, is shown in Table 1.

The midcourse maneuver plan for the mission (Fig. 1) was assumed to be similar to the one presented in Ref. 1. Also, the planetary quarantine impact probability sub-allocations presented in Ref. 1 were used here as initial values. These are shown in Fig. 2.

III. EARTH-JUPITER LEG

A detailed analysis was performed on the Earth-Jupiter leg of the selected 1977 J-S-P trajectory. The study was performed with particular attention to parametric behavior rather than specific targeting specifications.

A. Launch Vehicle Sub-allocation

The launch sequence of the TITAN III D/Centaur/Burner II ends with the burnout of the Burner II, at which point final injection is achieved. Approximately 100 seconds past this point, the spacecraft is separated from the Burner II, and about 400 seconds after separation, the Burner II will be deflected with a retro firing. It can be seen, therefore, that at injection both the Burner II and the spacecraft have the required energy to reach Jupiter. The Burner II is deflected after separation to reduce its probability of impacting Jupiter, which would violate the planetary quarantine constraints if any microorganisms survived through atmospheric entry.

In order to study the probability of Burner II impact quantitatively, certain numerical values have to be known, such as the reliability of the Burner II/spacecraft separation maneuver, its magnitude and direction, the reliability of the retro maneuver (Burner II deflection), its magnitude and direction, and other parameters and constraints. Since most of these values are not available at present, both Viking and Mariner Mars 1969 values were used as guidelines. The total sub-allocation to the impact probability of Burner II (1.03×10^{-5}) and the spacecraft at injection (2×10^{-5}) (see Fig. 2) is 3.03×10^{-5}. One of the main functions of this analysis was to determine how this total allocation should be divided between Burner II and the spacecraft.

A computer program devised for the Mariner mission's injection aiming point selection was used. The results showed that, considering the above-mentioned assumptions, the total constraint for injection should be divided between the spacecraft and Burner II in the ratio of 2 to 1. This was a significant result, since it departs greatly from previous Mars missions, in which the sub-allocation for the launch vehicle was a very small percentage of the total injection allocation.

The following statements can be made pertaining to launch vehicle planetary quarantine allocation for a Jupiter mission:

(1) The probability that the launch vehicle (Burner II) impacts Jupiter is very large compared to that for a Mars mission.

(2) In order to alleviate this condition, the Burner II separation and deflection ΔV should be increased and the reliability of its execution improved.

(3) From a planetary quarantine point of view, these conditions must be taken into consideration when sub-allocation is performed between the spacecraft and the launch vehicle.

(4) Two additional assumptions were made in order to perform this preliminary analysis: (a) the probability that the launch vehicle impacts Saturn is zero, and (b) ejecta efflux from the launch vehicle may be neglected. Future studies should re-examine these two assumptions.

B. Injection and Midcourse Maneuvers

The objectives of this task were a quantitative investigation of the Earth-Jupiter leg of a multiple planet mission, including determination of the fuel loading penalties resulting from biasing and the selection of optimum aim-point strategies.

Figure 2 shows that the planetary quarantine allocation for trajectory aiming errors has to be apportioned among injection and maneuvers 1, 2, and 3 for the Earth-Jupiter leg, injection and maneuvers 1 through 6 for the Jupiter-Saturn leg, and injection and maneuvers 1 through 8 for the Saturn-Pluto leg. This is the proper breakdown, since even injection errors will result in a finite probability of impacting Pluto. For the purposes of this analysis, the planetary quarantine allocation for trajectory aiming errors was apportioned among injection and maneuvers 1 and 2 for the Earth-Jupiter leg. It is, therefore, assumed that errors in maneuver 3 will not affect an impact at Jupiter, but will affect the impact at Saturn (since maneuver 3 becomes equivalent to the injection maneuver for the Jupiter-Saturn leg). This assumption, at present, seems reasonable; however, further investigation should be performed, as will be discussed in Section V. The important maneuvers for each leg in terms of contributing towards the probability of impacting each target planet are assumed to be those shown in Fig. 2 in undotted boxes.

The problem, therefore, is reduced to the study of an Earth-Jupiter trajectory that has an injection and two midcourse maneuvers. The effect of biasing these maneuvers and determining the optimum biasing strategies will now be investigated.

It was assumed that maneuvers 1 and 2 will be performed at launch + 20 days and at Jupiter encounter minus 20 days, respectively. The midcourse maneuver execution errors were not available for a multiple outer planet spacecraft, so the Viking worst-case values were assumed. These were fixed errors of 0.0667 meters/second and were considered only for the first midcourse maneuver. Orbit determination errors at the first maneuver were neglected. For the second maneuver, the execution errors were neglected (since in 20 days they do not propagate to a large error at Jupiter), and a 3σ orbit determination error ellipse of 2000×400 km with the major axis along the T-axis of the $\overline{B}$-plane was assumed. (The $\overline{B}$-plane is a plane perpendicular to the incoming asymptote, where the T-axis is parallel to the ecliptic plane.)

Numerous computer runs were made to determine (a) the effect of the choice of biasing strategies and (b) the effect of planetary quarantine constraint apportionment among injection and maneuvers 1 and 2. Three aim-point selection strategies were considered in the analysis. One strategy was directed at maximizing the probability of being within the final navigation success zone at Jupiter after the first midcourse maneuver. The other two strategies were directed at minimizing the expected value of the square of the miss distance and minimizing the expected value of the square of the magnitude of the next midcourse velocity correction, respectively. An iterative technique was used to optimize the choice of strategies.

The following results were obtained:

(1) Only the injection maneuver had to be biased to satisfy the planetary quarantine constraint. Maneuvers 1 and 2 can be aimed at the desired point without violating the constraint.

(2) The nominal value of the ΔV required to correct the injection bias at maneuver 1 was approximately 18.5 meters/second.

(3) This ΔV value was relatively insensitive to the value of the impact planetary quarantine constraint apportioned to the injection maneuver. In other words, when the apportionment was changed to tighten the constraints on maneuvers 1 and 2 and to loosen them for injection, the 18.5 meter/second bias penalty was reduced to 18.3 meters/second.

(4) The value of 18.5 meters/second was obtained using a biasing strategy for injection that minimized the square of the magnitude of the next midcourse maneuver. If the strategy that minimizes the expected value of the square of the miss distance were used, the ΔV penalty would be approximately 20 meters/second. The biasing strategy for injection that maximizes the probability of being in the final navigation success zone will produce a ΔV penalty of 57 meters/second.

(5) The maneuver execution errors, even when increased slightly, did not propagate into large enough errors at Jupiter encounter to violate a reasonable planetary quarantine constraint allocation.

IV. JUPITER-SATURN LEG

A. Probability of Saturn Impact

It is assumed that the last pre-Jupiter maneuver (M3) is performed 5 days before encounter (at a range to the planet of 7.3 million km). A 6-arc-second error in the optical approach guidance instrument will result in a 300-km miss at Jupiter, which, when mapped to the Saturn $\overline{B}$-plane, will result in an orbit determination error ellipse of 325,000 $\times$ 304,000 km, with the major axis along the T-axis of the $\overline{B}$-plane.

When the error ellipse at Saturn is known, probabilities of impact for various aim-points can be determined, and contours of constant impact probability can be constructed. This was done, and Fig. 3 shows the Saturn aim-plane with impact contours of 1×10^{-2}, 1×10^{-3}, and 1×10^{-4}. The impact (capture) radius of Saturn and the desired aim-point, for which the probability of impact is 2.7×10^{-2}, are also shown.

B. Optimum Biasing Strategy

As seen from Fig. 2 (and Ref. 1) the probability of impact constraint that has to be satisfied at Saturn must be 1×10^{-3} or less (assuming that the probability of performing maneuver 4, given that maneuver 3 has been successfully performed, is 0.97). This means that in order to satisfy the planetary quarantine constraint at Saturn, the Jupiter aim-point has to be biased so that the aim point at Saturn would fall on the 1×10^{-3} contour (Fig. 3). The effects of this bias of Jupiter's aim-point will be removed in maneuver 4 after Jupiter encounter. It is desirable, therefore, to develop a strategy of determining the biased Saturn aim-point (produced by a biased Jupiter aim-point) which will result in a minimum ΔV required to remove that bias in the post-Jupiter maneuver.

This optimum biasing strategy is relatively simple to achieve because the post-encounter ΔV required to correct a pre-encounter displacement error (ΔB) is a function of the magnitude of $|\Delta B|$. Therefore, in order to minimize the magnitude of the ΔV penalty, $|\Delta B|$ has to be minimized. Circles around the Jupiter aim-point can, therefore, be mapped into ellipses in the $\overline{B}$-plane of Saturn until the ellipse that is tangent to the impact constraint is achieved. This point of tangency in the Saturn $\overline{B}$-plane represents the optimum biased aim-point and is shown in Fig. 3. The required $|\Delta B|$ bias at Jupiter is 485 km in order to satisfy the Saturn planetary quarantine constraint of 1×10^{-3}, which will require a post-Jupiter ΔV of 11 meters/second to correct.

V. SATURN-PLUTO LEG

The planetary quarantine constraint at Pluto was studied in the same way as was done at Saturn. In other words, a 6-arc-second uncertainty in the celestial pointing direction of the approach guidance instrument at Saturn was mapped to Pluto. This resulted in an error ellipse at Pluto of 793,000 × 778,000 km, with an orientation angle of 55° with respect to the T-axis of the $\overline{B}$-plane. This ellipse produced an impact probability of 0.5×10^{-5}. Assuming that the probability of performing maneuver 6, given that maneuver 5 was successfully executed, is 0.97, then the sub-allocation to maneuver 6 in Fig. 2 should be 0.015×10^{-5}. Such an allocation can be performed without violating the planetary quarantine constraint. In other words, Pluto's planetary quarantine constraint is not violated if Saturn's aim-point is achieved with the expected accuracy.

In order to achieve a reasonable degree of mission success, the post-Saturn maneuver 7 must be used to aim the spacecraft at the ultimately desired aim-point at Pluto. Therefore, the principal portion of the planetary quarantine allocation for impact should be given to this maneuver, at least until future analyses indicate otherwise. Currently, the significant factor in determining the navigation errors is the uncertainty in the position of Pluto. A better understanding of Pluto's ephemeris is needed before more thorough navigation analyses can be performed.

VI. CONCLUSIONS

The trajectory and navigation analyses described herein lead to the following results based on the assumptions made and our current state of knowledge of the outer planet mission and spacecraft characteristics:

(1) If the magnitude of the separation velocity between the spacecraft and the launch vehicle would be similar to that for Mars missions, the probability of impact of Jupiter by the launch vehicle is of the same order of magnitude as that for the spacecraft.

(2) The only maneuvers that require biasing are: (a) the injection maneuver in order to satisfy the planetary quarantine constraint at Jupiter; and (b) the Jupiter aim-point in order to satisfy the planetary quarantine constraint at Saturn.

(3) The ΔV penalties for removing the injection bias are about 20 meters/second, and for removing the biased Jupiter aim-point, about 10 meters/second.

(4) The optimum biasing strategy (in terms of fuel penalty) determined for injection was that which minimized the square of the magnitude of the next midcourse maneuver (maneuver 1); for the pre-Jupiter maneuver (maneuver 3), a strategy which minimized the ΔV directly was selected.

The total ΔV biases are relatively large and could become larger if the 7.1×10^{-5} planetary quarantine constraint for Pluto would require additional ΔV penalties.

Future analyses by the planetary quarantine community should include investigation of possible spacecraft microbial burden reduction by the planetary and interplanetary natural environments. These include atmospheric entry heating, Jupiter's radiation belts, and the interplanetary thermal, vacuum, and radiation environments.

REFERENCE

1. Stavro, W., and C. Gonzales, "Planetary Quarantine Considerations for Outer Planet Missions," Preprint No. AAS-71-122 presented at the 17th annual meeting of the American Astronomical Society on the Outer Solar System, July 28-30, 1971.

Table 1. Characteristics of selected 1977 J-S-P trajectory

Planet encounter	Encounter date	Altitude at closest approach, km	Planet aiming plane parameters		Hyperbolic excess velocity V_∞, km/sec	Hyperbolic bending angle, sec
			B, km	θ, deg		
Jupiter	Dec. 21, 1978	152,094 (2.13R*)	593,170	3.4	13.7	97.4
Saturn	June 8, 1980	310,315 (5.14R*)	468,575	65.2	18.5	26.6
Pluto	Apr. 3, 1985				21.3	

Launch Date = September 4, 1977.

Launch Energy = 126.4 $km^2/sec^2 = C_3$.

R* = Planet geometric radius.

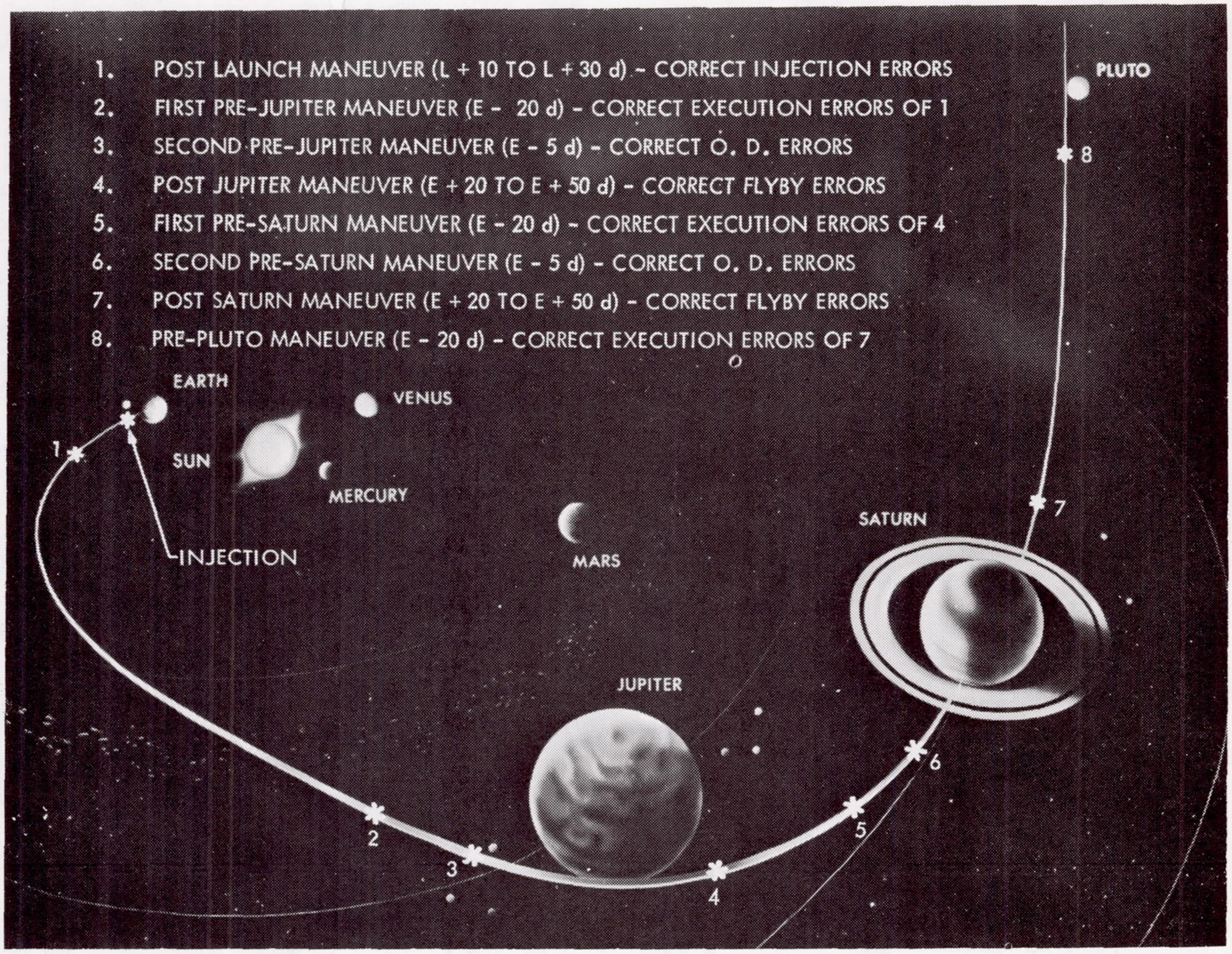

Fig. 1. Midcourse maneuver plan for a J-S-P mission

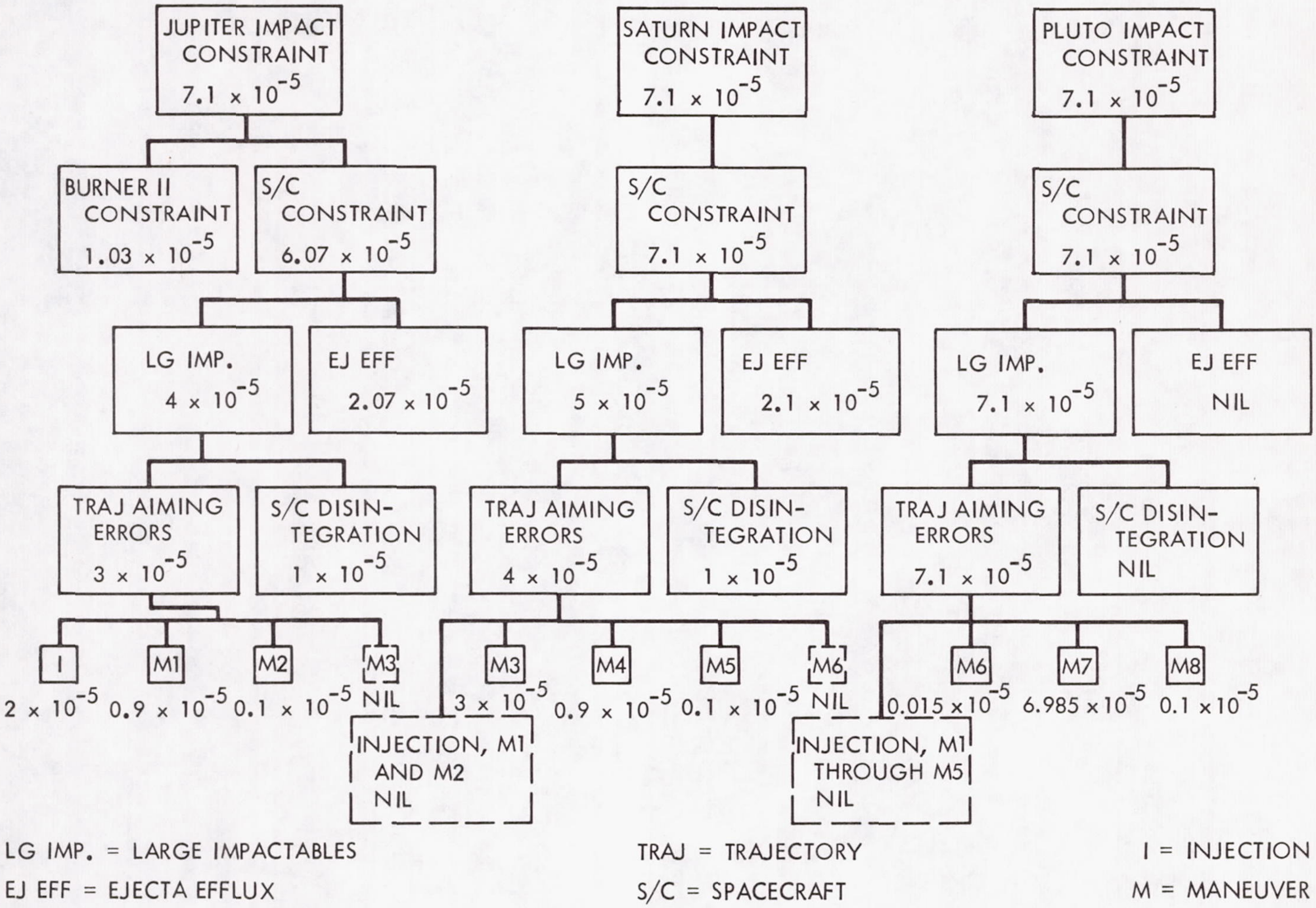

Fig. 2. Impact probability allocations for a J-S-P mission

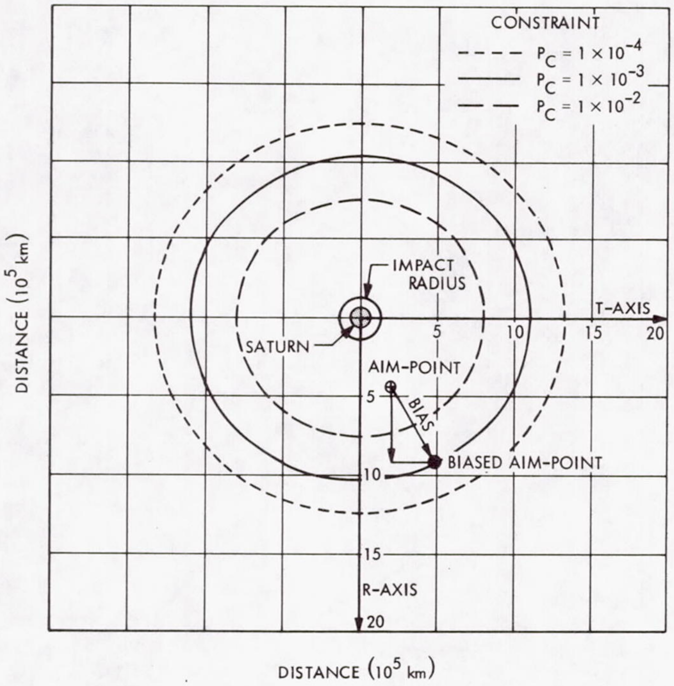

Fig. 3. Impact probability contours at Saturn aim-plane, due to swing-by error at Jupiter, 1977 J-S-P