AAS/AAAS
SPECIAL ASTRONAUTICS
SYMPOSIUM

AMERICAN ASTRONAUTICAL SOCIETY

December 29, 1965
RECENT DEVELOPMENTS IN SPACE FLIGHT MECHANICS

TRAJECTORY DESIGN FOR PLANETARY MISSION ANALYSIS

by

Stanley E. Ross

National Aeronautics and Space Administration
Office of Manned Space Flight
Washington, D.C.

AAS Preprint
No. 65 - 130

TRAJECTORY DESIGN FOR PLANETARY MISSION ANALYSIS

Stanley Ross*

ABSTRACT. A brief survey of current and very recently disclosed work on trajectory design for planetary mission analysis. Topics covered include researches on the Venus-swingby mode; flyby missions past Jupiter to the planets beyond; solar probes which employ close approaches to Jupiter or Venus to favorably modify their trajectories; application of major impulsive maneuvers during planetary passage, or during heliocentric mission phases; and a recently proposed composite flyby-lander mode for Mars exploration. Also discussed are some mission-oriented computer programs which are used to generate planetary flybys automatically; which automatically plot trajectory parameter contours; and which automatically perform complete mission and systems tradeoff analyses.

Trajectory Design for Planetary Mission Analysis is a subject which traces its modern evolution from the late 1950's, and mirrors its growth in the writings of Lawden, of Ehricke, of Battin, of Edelbaum, of my colleagues Breakwell and Gillespie along with me, and of many others who, during the intervening years, have helped to set the analytical and computational framework for a great emergent body of technical literature devoted to the analysis of planetary missions. I will not attempt today to present any sort of complete introduction or historical background to the subject beyond that which we will touch upon in passing. Instead, I would prefer to have the present paper serve as a sort of informal survey of current work in this area, and to cover a number of studies either still in progress or else very recently completed. You will note, in several instances, my references to current works which may not have been published as yet, or which may be scheduled for delivery at meetings which have

---

*Office of Manned Space Flight, NASA, Washington, D. C.

yet to occur. I have sampled these studies, hoping to whet your interest in what other investigators are doing and in what they themselves are soon to present in much more complete treatments. If you find any of the subjects of interest then, you will have the opportunity of hearing the detailed presentations when they are more fully described by the individual authors. I would like very much to acknowledge the kind cooperation and the courtesy extended by these individuals; the release of as yet unpublished information on their private researches represents to me a true indication of the genuine spirit of scientific cooperation which has been extended to us by them.

The labors of several of my colleagues and myself during the years of 1962 and 1963, and of the group at J.P.L. under Clarke during the same period resulted in the publication of a series of volumes comprising two planetary flight handbooks (1, 2), one devoted to the planning of manned flyby and landing flights to Mars and Venus, the other to unmanned probe missions to these same planets. Together, these handbooks blocked out and charted what we then considered to constitute all worthwhile mission areas for flights to the two nearest planets during the rest of this century. But the picture suddenly changed with the disclosures by Hollister (3) and by Sohn (4), in independent and almost simultaneous works, that the strong synodic fluctuation in mission requirements for fast round trips to Mars could be greatly reduced by employing close approaches to Venus enroute, causing its mass to modify nominally unacceptable trajectories to our favor (Fig. 1). Almost immediately, widespread attention was focused upon the "Venus swingby mission" (as Sohn called it), and results of subsequent studies by Sohn himself and by Deerwester were soon forthcoming. Sohn's note (5) examined some representative swingby trips applied to nonstop as well as stopover missions over a span of years between 1970 and 1999 and firmly established the feasibility and the desirability of employing this mission mode. Deerwester's paper (6) embodied two important contributions, the first of which was his exhaustive exploration of two sample swingby opportunities, and the second his method of graphical presentation of the results which makes them compatible in format with the direct flight curves presented in the NASA Planetary Flight Handbook, SP-35. Using this manner of presentation it is possible to match homebound swingby trajectories with direct outbound flights and vice versa, and to then analyze complete missions on a common graphical basis (Fig. 2). Deerwester's study, which in addition encompassed representative missions from other launch year opportunities, confirmed what Sohn and Hollister had stated earlier: namely that in many instances the Venus swingby trips would require considerably less initial mass than would be associated with equivalent direct trips, especially so in many of the "unfavorable years," when the Martian orbital eccentricity serves to make short, direct flights prohibitive by raising terminal speeds beyond reasonable limits. The swingby trips generally involve only modest terminal speeds, they are not unduly long in their execution and they do not require navigational capabilities any more severe than what in any event would be required to return a crew capsule to Earth at the termination of a Mars mission.

Now, possibilities for employing the Venus swingby mission are bound up quite intimately with the orbital geometry of the three planets involved. The eccentricity of Mars' orbit leads to significant variations in trajectory requirements, further complicating the physical problem and virtually precluding any sort of serious attempt to formulate a generalized theory of such missions. So, while studies of specific groups of trajectories, such as the ones mentioned above, can serve to demonstrate the feasibility of such flights, it still remains for the execution of a comprehensive, detailed study of the entire time period of interest to produce the quantitative data necessary to locate all trajectories which might be profitably exploited. With this in mind, Gillespie and I have been attempting to investigate and to catalog all useful swingby trajectories, both outbound and homebound, for the remainder of the century. We have to date generated some two hundred thousand of these trajectories and expect to present the results of our studies in complete detail next January (7). In this connection, I would like to briefly summarize a few of our conclusions here. To begin with, the planets Earth, Mars and Venus have a composite periodicity of about 6.4 years, as is well known. Therefore, the characteristics of trajectories which involve these three planets will also (at least qualitatively) experience a similar periodicity. Within any

6.4 year period, it turns out that only three each of a possible total of seven outbound and seven homebound swingby opportunities warrant serious study (Fig. 3). Further analysis has shown that one group of these three, which we call Type I swingby trajectories, involving total trip times of the order of 600-650 days, are virtually impracticable in almost every case because of the relatively high terminal speeds involved and, further, because of the fact that many of even these trajectories would have to pass beneath the surface of Venus to produce the required amount of planetary bending of the passage hyperbolas. In only one case, that occuring during the 1974 outbound launch opportunity, were we able to locate even a small group of not unreasonable swingby trajectories of this type.

A second group of trajectories however, which we refer to as Type III swingbys, appears to hold great promise during every opportunity in which these trips are to be found. The Type III swingbys involve trips of 500 to 550 days' duration and almost always are associated with tolerable speeds of departure and arrival. The third and last group of worthwhile trips, which we refer to as Type V swingbys, are only marginally acceptable and even then only in some years can we find reasonable cases. Generally speaking, these trips involve total mission times of about 450 days or more in duration, although the speed requirements for Type V swingbys are about as low as one can find in Hohmann trips between Earth and Mars. A number of detailed contour maps pertinent to these trip types will be presented in the forthcoming paper mentioned above, and we hope also to include as a new volume within the SP-35 series (8) a complete set of contour maps and accompanying numerical tabulations of all swingby flights for the remainder of the century.

However, Venus swingby missions have not solely occupied the attention of planetary mission analysts during recent months. Gaining confidence in the capabilities of present and near-term systems, analysts have recently been turning their attention to the study of flights which involve the outer planets. During the course of a detailed systems study on missions to Jupiter and selected asteroids (9), Deerwester compiled tables of direct-flight trajectories to Jupiter and to the two asteroids Ceres and Vesta, valid for the time period between 1970 and 1980. Contours relating to these flights, as well as numerical data supporting the contour maps, are contained in another volume of the Planetary Handbook series, SP-35, which is scheduled to appear shortly (10). Increasing attention also has been turned toward the use of Jupiter's very large mass in producing deflections of vehicle trajectories so that, in some cases, they would pass still other planets, such as Saturn, Uranus, or Neptune; or, in other cases, they might approach the Sun very closely; or, in still other cases, their paths might be deflected out of the ecliptic plane. In one such study recently completed, Flandro quantitatively investigated Jupiter flybys to Saturn, to Uranus and to Neptune (11). He concludes that the latter part of the next decade, between 1977 and 1980, abounds in interesting multiple planet opportunities because of the similar heliocentric longitudes of the outer planets during this time period. For, since a trajectory to Jupiter will be of comparatively long duration by itself, it is important that any additional mission segments beyond it be reasonably direct and not add appreciable time to the total flight; hence the importance of the relatively close alignment of the outer planets with Jupiter. Flandro's sensitivity studies on launch velocity requirements show that the best opportunities for missions past Jupiter to Saturn occur during 1979, and that the most favorable opportunities for trips past Jupiter to either Uranus or Neptune also occur during 1979. Many of these trajectories eventually escape from the solar system after passing the final target. The most favorable launch opportunity for trips past Jupiter to Pluto, on the other hand, occurs slightly earlier, in 1977, according to Flandro's results. One of the highlights of his study is the spectacular trajectory which he located passing Jupiter, Saturn, Uranus and Neptune all on a single flight (Fig. 4), the total trip time being under eight years.

In some of Deerwester's most recent work (12) there was also conducted an investigation of missions past Jupiter to the planets beyond it. Deerwester confirms Flandro's conclusions that the most favorable opportunities for such flights will occur in the late 1970's and he also points out that such favorable opportunities will not occur again for quite some time because of the relatively long mutual synodic periods among the outer planets (Fig. 5). In still another study (13), Niehoff also investigated the use of Jupiter's gravitational perturbation for sending probes to Saturn. He again concludes that favorable opportunities for such flights will present themselves in the late 1970's. Niehoff also discusses the use of Jupiter for performing gravity-assisted solar probe missions. He recognizes the long trip times (up to three years in duration) which are inherent in this method, but points out that when missions to within 0.1 AU are considered, it appears that the only route available using conventional propulsion systems is via a Jupiter flyby. Moreover, Niehoff notes the ideal velocity requirements with Jupiter's gravity assist are almost the same whether one wishes to go to 0.1 AU or, in fact, to impact the Sun. The use of Jupiter for solar probe missions is also discussed at length by Porter, Luce and Edgecombe (14), whose conclusions agree with Niehoff's, although a sensitivity study conducted in Ref. 14 shows that these total mission times could be reduced to slightly over two years if one were willing to pay the penalty of increased propulsion beyond the minimum-energy value for trips to Jupiter (Fig. 6). A very detailed study of solar probe trajectories via Jupiter was also conducted recently by Minovitch (15), who presents tabulated flight parameters pertaining to such trips during the years between 1967 and 1978. One further point in connection with the use of trajectories past Jupiter is the possibility of using it to perturb trajectories out of the ecliptic plane for scientific observations which require the probe to reach high celestial latitudes. In Ref. 14, Porter, Luce and Edgecombe explore this possibility and discuss two different types of Jupiter flybys out of the ecliptic plane, the first involving a perturbation which rotates the plane of the probe's orbit perpendicular to the ecliptic after the encounter with Jupiter, while the second deflects the post-encounter orbit in such a way as to maximize the component of spacecraft velocity normal to the ecliptic plane (Fig. 7). Therefore, although the former type of trajectory will pass directly over the Sun, the second type will generally pass further out of the ecliptic plane at its point of maximum heliocentric latitude. On this subject also Minovitch (15) presents a large amount of detailed numerical data on launch opportunities and trajectories for out-of-ecliptic probe missions via Jupiter during the years 1967 through 1978, these particular trajectories all involving post-encounter inclinations of 90 degrees. As Porter, Luce and Edgecombe (14) point out, a minimum-energy orbit to Jupiter can be deflected to produce a post-encounter orbit inclined only somewhat beyond 23 degrees to the ecliptic plane. Launch velocities for probes whose trajectories are deflected perpendicular to the ecliptic plane must therefore assume values beyond minimum energy values to Jupiter. In a similar connection, Minovitch points out that the planets Mars and Venus can be used to deflect probe orbit inclinations to values of about 10 to 15 degrees from the ecliptic plane.

One further point in this connection deserves attention and this is the fact, as Niehoff argues, that during many different types of missions past Jupiter the vehicle spends a good deal of the flight within the confines of the asteroid belt. Although, as he remarks, this places the spacecraft in a potentially hazardous environment, nevertheless, many experiments designed to obtain data on asteroids could be conducted during the flight as a secondary objective of the mission. This point does in fact comprise the subject of a paper to be presented shortly by Bender (16) in which he suggests that such asteroid encounters might deliberately be sought in the planning of manned missions to Mars. Recognizing that the predicted positions of many asteroids may have larger uncertainties than the closest distances desired, he states that any search for close encounters would only be expected to yield a list of most-likely candidates for encounters, such as are shown in Figure 8, taken from his work. The final determination of such possibilities will probably require new observations of the candidates and a corresponding improvement in our knowledge of their orbits.

Returning now to the use of close flybys of the planet Venus, this time in order to improve solar probe performance, I should like to mention the recent paper by Casal and myself (17) in which we attempted to improve the projected performance of Venus-flyby solar probes. We discussed a special class of such missions on which the probe is made to pass Venus twice, each passage of Venus further reducing the perihelion distance attained. The double passage is performed by forcing the vehicle to follow an initial solar orbit and a post-Venus-encounter orbit, both of whose periods are commensurate with the orbital period of Venus itself (Fig. 9). In this way, a missed encounter with Venus would still provide further opportunities for flybys each time the relative commensurability of the probe's orbit and Venus' orbit brings these bodies into close proximity. Using such a mission profile, we found that, using an Atlas/Agena/X259 or an Atlas/Centaur/X259 combination,* either 600 or 1100 lbs. (respectively) of gross spacecraft weight could be injected onto an orbit which would, in 1-1/2 to 2-1/2 years, reach within 0.2 AU of the Sun. The Saturn IB/Centaur could be expected to deliver 6000 lbs. to this distance and, by using a Pershing upper stage on top of this combination, we might expect to bring the same 600 lbs. mentioned above to within about 0.1 AU from the Sun.

Not only the Sun but even Mercury could serve as the eventual target for a Venus flyby mission. A fine paper by Sturms and Cutting (18) was devoted to just such a study. They concluded that under certain assumptions they might expect a payload of about 1150 lbs. to be delivered to Mercury by an Atlas/Centaur combination. This figure is in good general agreement with the payload estimates made by Casal and myself in the study previously referenced. The paper by Sturms and Cutting concentrated primarily on the navigational requirements for a particular mission in 1970 to Mercury via Venus. In it they found that the mission could be accomplished with existing Earth-based radio guidance techniques, the probe executing planned correctional maneuvers at about six days after injection, about six days prior to the Venus encounter, and at about eight days after the Venus encounter, the total rms. requirement for all three maneuvers

---

*The X259 (Antares) is a storable solid kick-stage.

being estimated at approximately 69 meters/second. From this they concluded that the engineering feasibility of the Earth-Venus-Mercury mission studied had been established.

One extra bonus involved in passing any planet, I should note, is the fact that quite a good deal of useful information about the fly-by planet itself could be obtained during the flyby maneuver, although the skills of the spacecraft designer and experiment integration specialist would be challenged by the requirement for providing a set of payload packages able to function in two distinctly different environments (17).

A detailed study of missions to Mercury by way of Venus was performed in Niehoff's paper (13), the study having been aimed primarily at defining trajectory and mass tradeoff requirements for the missions, as contrasted with the paper of Sturms and Cutting mentioned earlier, which was principally concerned with navigation and guidance requirements for such missions. Figures presented in Niehoff's paper describe the tradeoffs among close approach distance at Venus, total trip time to Mercury and departure velocities required for the trips (Fig. 10). Niehoff also compares Venus flyby modes for Mercury missions against equivalent direct flights, considering Mercury to be either at its aphelion or at its perihelion point and, in so doing, he brackets the performance estimates for such flights. As an example of the energy savings forthcoming from the Venus flyby mode, Niehoff states that the minimum ideal velocity required for the direct trip to Mercury at perihelion differs from an equivalent trip using an intermediate Venus flyby by some 2700 ft. per sec. velocity requirement in favor of the latter flight profile. With the gravity assist from Venus, Mercury can be reached in 170 days with ideal velocity of about 41,500 ft. per sec.; for this mission the Atlas/Agena launch vehicle has a payload capacity of 580 pounds, while the Atlas/Centaur could provide a payload of 1900 pounds. One set of conclusions seems to be forthcoming from all three studies mentioned, viz. (13, 17, 18), and that is that gross spacecraft weights of the order of 600 pounds and of about 1500 pounds seem reasonable estimates for performing various missions within the Earth's orbit using currently available booster combinations.

Now, as regards the application of impulses during flyby maneuvers, this question has interested quite a number of analysts during the past few years. Perhaps one might, as I did originally, feel that there should be missions on which the vehicle's performance could be substantially improved in some sense by the application of thrust impulses at some advantageous point during the passage of an intermediate planet. However, my own experience in this matter, which was admittedly a rather superficial one conducted as part of a larger study about two years ago, led to the conclusion that on round-trip flybys passing Mars or Venus, since we were in most cases operating in regions close to minimum terminal speeds, there was no appreciable gains in either departure or arrival speeds, there was no application of an impulse during planetary passage. The only improvement which appeared worthwhile seemed to be the possible lengthening of launch windows. Recently, however, Titus (19) reopened the question of possible advantages to be gained by applying an impulse during Martian passages on round-trip flybys. His paper represents a rather comprehensive study of such maneuvers. While my own investigations (20) were based on a linearized approximation to the equations entering into the impulse optimization problem, Titus quite neatly formulated a solution to the exact set of equations and carried out a numerical study on a comprehensive scale to determine the positions and directions as well as the magnitudes of the optimally applied impulses. He found that the application of impulses could be used either to reduce initial masses or the total trip times required for Mars round-trip flyby missions (Fig. 11), if one were willing to assume the existence of an entry system for performing returns from speeds of as high as 65,000 ft./sec. at Earth. In order to reduce reentry speeds, which sometimes were higher than this value, to the 65,000 ft./sec. limit, he investigated four methods for reducing speed prior to Earth entry. These were (1) a retro-maneuver prior to the entry, (2) a perihelion retro-impulse, (3) the use of non-optimal powered flybys and (4) a Venus swingby enroute, finding the first of these alternatives to be the most favorable operationally. He also suggested that the capability for performing the impulse maneuver during Martian passage could be used, if necessary, for an abort maneuver on the escape hyperbola from Earth, a consideration which by itself might be a strong factor for providing a post-injection impulse capability on any Martian mission.

Hollister and Prussing (21) also investigated the application of impulses during planetary flyby. In their case, the technique was applied to Venus swingby missions between Earth and Mars. However, they found that, as a general rule, although the use of thrust during the flyby of Venus does offer some savings over the pure flyby without thrust, still, from a practical point of view, the savings do not appear to be significant. When unpowered Venus swingby trajectories require passages below the surface of Venus, the application of an impulse might serve to raise the passage height above Venus surface. Nevertheless, they remark that, even then, direct flights which do not pass Venus at all would still be more attractive than the thrusted flybys because of shorter trip times which result in the former mode, without any additional cost in terms of velocity. I should note, however, that the negative results which emerge from a study such as this provide us with as much information and as much of a qualitative understanding of the problem as a positive result might have. The authors are to be commended for this penetrating exposition of a very important question.

But what of the apparent contradiction between the conclusions of Titus, who finds worthwhile gains possible using in-flight impulses near the planets, and those from the Hollister-Prussing study, which draws the opposite inference? I think that, as usual, the answer is to be found in the system performance characteristics assumed by the authors in each case. Thus, while Hollister and Prussing deal largely with flights whose return speeds lie below 45,000 ft./sec., Titus postulates the availability of a more ambitious system capable of hyperbolic entries at speeds of up to 65,000 ft./sec., during the time period when such missions are to be performed. As is always the oase, it remains for the individual analyst to choose those performance assumptions, optimistic or conservative, which most closely relate to the problem at hand, although I might comment here that a very favorable systems performance which is predicated on optimistic assumptions can often stimulate such a strong case for itself that these same assumptions will form the basis for future hardware design specifications--and this, perhaps, is one of the most useful products we can derive from any mission analysis effort.

Still on the subject of near-planet impulses, I should like to describe a rather ingenious mode for manned Mars exploration missions, suggested by Titus, which he will himself present in greater detail shortly (22): An interplanetary spacecraft leaves Earth for Mars on a nonstop round-trip flyby trajectory (Fig. 12). Approaching Mars, a small excursion module separates impulsively from the spacecraft and races ahead to perform a capture maneuver there. After a brief stay at Mars, the excursion module departs from the Martian parking orbit and rejoins, with a hyperbolic rendezvous, the main spacecraft as it swings onto its inbound trajectory leg towards Earth.

As a plan for executing a minimal capture mission, this proposal shows extraordinarily great merit. There is no need to brake the entire spacecraft at Mars; in fact, the only major propulsive maneuver applied to it occurs at departure. Only the small excursion module must be captured at Mars and subsequently injected from the parking orbit. From extensive calculations, Titus shows the following advantages for the so-called "FLEM" (Flyby-Landing Excursion Mode): (1) much lower mass requirements; (2) mass requirements more stabilized throughout the opposition years; (3) FLEM provides a natural abort mode with no mass penalty (see p. 14, line 16); (4) high probability of mission success; and (5) stopover missions which are a natural extension of flybys.

Finally, I should make note of an exhaustive study of powered maneuvers for interplanetary missions. Recently completed by Ehricke (23), in which he studied several important types of maneuvers and their implications on manned planetary mission possibilities. In particular, he treated six basic types of heliocentric maneuvers, these being perihelion maneuvers, aphelion maneuvers, heliocentric retro-maneuvers, heliocentric acceleration maneuvers, heliocentric plane-change maneuvers and heliocentric planet approach retro-maneuvers. These maneuvers, Ehricke points out, can have one or a combination of the following objectives: (1) reduction of the hyperbolic entry velocity at Earth return by means of a maneuver requiring less velocity than a geocentric Earth approach retro-maneuver; (2) reduction of velocity requirements for planetary capture or powered flyby; (3) widening of planet departure windows; or (4) to permit the deployment of propulsion systems which yield the highest specific impulse for a larger number of maneuvers or a larger amount of velocity changes during the mission. The ultimate, underlying objective is, in all cases, to reduce the orbital departure weight of the heliocentric interorbital space vehicle, for a given payload. He illustrates his arguments with results of comprehensive numberical studies of perihelion braking maneuvers applied to transfers from Mars to Earth, from Jupiter to Earth and from Saturn to Earth. A wealth of data accompanies the expository treatment and provides the reader with definitive information to support the arguments presented in the paper.

Based on the foregoing discussion and from the descriptions of the complex and varied types of planetary flyby missions which one encounters, it is quite clear that enormous physical labors are involved in calculating these trajectories. One naturally tends to turn towards automated techniques for finding flyby trajectories by matching the proper approach and departure conditions at the passage planets and for automated methods of presenting results which are produced during mission analyses. At the Lockheed Missiles and Space Company, a digital computer program designed by Krop and Deerwester (24) has been applied to the automatic generation of single-planet flyby round-trip trajectories as well as Venus swingby missions. Input to the program consists of departure, passage and arrival planet names, a range of departure, passage and arrival dates plus increments for each, and the maximum and minimum tolerable passage distance at the intermediate planet. The computer program searches for the proper passage date, given the departure date and the arrival date. When a solution is recognized to exist between two adjacent passage dates, a linear interpolation determines the proper passage date and recalculates the two trajectories which meet at the intermediate planet. A check is performed on incoming and outgoing hyperbolic excess speeds at the passage planet and if these speeds differ by more than a specified tolerance a parabolic curve fit is then performed. A new passage date is found, a new pair of trajectories is computed and the process is repeated. A feature is included which can calculate corrected pericenter passages: if the computed pericenter at the passage planet lies outside the range of interest, then the pericenter is held at an appropriate value and the velodity increment necessary to rotate the departure asymptote by the proper amount is computed. A modified version of this program has very recently been developed in which it is possible to compute the position, magnitude and direction of an optimal impulse applied during planetary flyby. This program will surely result in a savings of many hundreds of manhours for each group of missions studied in the future.

Still another computer program (25) has been developed at TRW by a group under Lascody. This program accepts output data from a Venus-swingby generation program which we developed at NASA Headquarters and, by interpolation produces from them a tape which controls an automatic plotter. The program can be used to display velocity and/or date contours for various groups of missions (Fig. 13). Considering the labor involved in the presentation of numerical data, as well as in the generation of it, this program also represents a substantial savings in time and in effort required for this work. It is my personal opinion that a new era in mission analysis is dawning, now that truly powerful computing hardware and correspondingly rapid means for displaying the results of these computations are at hand.

Lastly, I would like to dwell briefly on a computer program we have been developing at NASA Headquarters which is intended to analyze complete missions automatically. Underlying the design philosophy of the program was our realization that any mission analysis, regardless of whether it aims at sizing a Mars spacecraft or, perhaps, at planning a Ranger flight to the Moon, involves groups of calculations which pertain to various mission phases such as, say trajectory analysis, propulsion system performance, life support system evaluation, reentry, and so forth. Each group of calculations within the series is generally simulated by a special purpose computer program, the entire set of programs being performed in some sequence appropriate to that particular mission. Each program receives some of its input data directly from the analyst, other inputs in the form of output from previously executed programs.

Now, the greatest expenditure of time and human effort which enters into any mission analysis generally arises from having to manually relay and transcribe data between programs such as these. Suppose that we could store on magnetic tape a library of mission-oriented computer programs and thereby preserve a repertoire of useful analysis tools. If we then could develop a control program which accepts as subprograms each of the functional calculation programs mentioned above; which chains them together in any arbitrary sequence; and which executes the entire chain for all combinations of sequences of values for the externally supplied input data, then we would have a truly general system for automatically performing any type of mission or systems sensitivity analysis (Fig. 14).

A prototype program of this nature developed at the National Bureau of Standards by Dr. R. J. Arms in collaboration with me is now in operation at NASA Headquarters. Fig. 15 shows some preliminary results from a sample problem which was recently analyzed using the program. In this case a launch weight sensitivity analysis of flyby round trip missions past Mars in 1971 was attempted. The vehicle is injected from a given parking orbit around Earth towards Mars and, upon approaching Earth at the end of the mission, it is captured onto another parking orbit, arbitrarily chosen. A range of eleven departure dates and five different passage heights at Mars were specified. For each of the 55 combinations of these inputs, the program analyzes the entire mission. Internally stored flyby contour map tables are consulted and interpolated two-dimensionally using the input values given. Passage and return dates (among other quantities) are then output to a common storage area in core. These values are picked up by another subprogram, which separately generates the appropriate outbound and homebound heliocentric trajectories. Outputs from this latter program, which include the hyperbolic excess departure and arrival vectors at Earth, are then picked up as inputs to a subprogram which calculates the injection and capture velocity increments necessary at the terminal parking orbits. These velocity increments constitute inputs to a mass-calculation subprogram which delivers such outputs as initial mass, stage masses, and volumes, weights and tank sizes for the fuels and oxidizers used. In this particular instance, almost 250 individual output items of interest are generated for each input combination. These are stored and recorded on an archive tape which may then be selectively interrogated at later occasions to examine the mission parameters to any depth desired. A magnetic tape which drives the electronic plotter used to produce Fig. 15, (or plots of any of the recorded variables) is also generated internally during the run, via data cards included within the input deck.

Of significance is the fact that a mass-calculation program written at the Martin Company, a trajectory program developed at Lockheed, an interpolation program from the National Bureau of Standards and a parking-orbit velocity increment program from NASA Headquarters, all directly coupled and working in concert via the executive control program, were used to perform the total mission analysis. For the problem described above, the total running time consumed some seven minutes, and ran completely automatically from the input of data to the generation of output tapes for the printer and plotter.

In a larger sense, such a control program could very well serve as practical focus towards which we might direct efforts at standardizing mission-related computer programs of all types. A system of such modular, compatible programs, quickly and easily able to cover the widest ranges of mission possibilities would permit the treatment of problems whose scope and complexity currently place them beyond practical approach. It would, I believe, bring such flexibility and power to bear that present techniques of planetary mission analysis would be rendered obsolete within a few short years.

REFERENCES

1. Space Flight Handbooks, Vol. 3 - Planetary Flight Handbook, NASA SP-35, prepared for the George C. Marshall Space Flight Center, 1963.

2. Earth-Venus Trajectories, Vols 1-5, V. C. Clarke, Jr., et al., TM 33-99, Jet Propulsion Laboratory, Pasadena. Also, Design Parameters for Ballistic Interplanetary Trajectories - Part I, One-Way Transfer to Mars & Venus; TM 32-77, Jet Propulsion Laboratory, Pasadena.

3. The Mission for a Manned Expedition to Mars, W. M. Hollister, ScD. Thesis, MIT, Cambridge, Mass., 1963.

4. "Summary of Manned Mars Mission Study," by R. L. Sohn, Part 5 of Proceedings of the Symposium on Manned Planetary Missions, 1963/1964 Status; NASA TM-53049, June 12, 1964.

5. "Venus Swingby Mode for Manned Mars Missions," R. L. Sohn, Jour of Spacecraft & Rockets, Vol. 1, No. 5, Sept-Oct. 1964.

6. "Initial Mass Savings Associated with the Venus Swingby Mode of Mars Round Trips," J. M. Deerwester, AIAA 2nd Aerospace Sciences Meeting, Paper No. 65-89, 1965.

7. "The Venus Swingby Mission Mode and Its Role in the Manned Exploration of Mars," by Rollin Gillespie & Stanley Ross, to be presented at AIAA Aerospace Sciences Meeting, Jan. 19, 1966.

8. Space Flight Handbooks, Vol. 4 - Planetary Flight Handbook (Venus Swingby Mission Data), NASA SP-35. To be published, 1966.

9. "Asteroid Belt & Jupiter Flyby Mission Study," M-49-64-2, NASA, Wash., D.C., Sept. 15, 1964

10. Space Flight Handbooks, Vol. 5 - Planetary Flight Handbook (Trajectories to Jupiter, Ceres & Vesta), NASA SP-35. In press, 1965.

11. "Utilization of Energy Derived from the Gravitational Field of Jupiter for Reduction of Flight Duration to the Outer Solar System," by Gary A. Flandro, JPL SPS 37-34; also a more complete version in JPL TR 32-858; both in press. Pasadena, 1965.

12. Jerry M. Deerwester, Lockheed Missiles & Space Company, Sunnyvale, Calif. Personal communication. Submitted for presentation.

13. "An Analysis of Gravity Assisted Trajectories in the Ecliptic Plane," by J. Niehoff, IIT Research Institute Report No. T-12, May 25, 1965.

14. "Gravity - Assisted Trajectories for Unmanned Space Exploration," by R. F. Porter, R. G. Luce, and D. S. Edgecombe, Battelle Memorial Institute, Report No. BMI-NLVP-FTR-65-1, Sept. 23, 1965.

15. "Utilizing Large Planetary Perturbations for the Design of Deep-Space, Solar Probe, and Out-of-Ecliptic Trajectories," by M. Minovitch, JPL TM 312-514, Feb. 15, 1965.

16. "Asteroid Encounters on Mars Missions," by David F. Bender, North American Aviation, S&ISD. Personal communication. Submitted for presentation.

17. "The Use of Close Venusian Passages During Solar Probe Missions," by Federico G. Casal & Stanley Ross, AAS Preprint 65-31, Feb. 1965.

18. "Trajectory Analysis of a 1970 Mission to Mercury Via a Close Encounter with Venus," by Francis M. Sturms & Elliott Cutting, AIAA Preprint No. 65-90, Jan. 1965.

19. "Powered Flybys of Mars," by Richard R. Titus, AIAA Preprint No. 65-515, July 1965.

20. Final Report: A Study of Interplanetary Transportation Systems Phase III, Lockheed Missiles & Space Company, Report No. 3-17-64-1, April 30, 1964. Prepared for George C. Marshall Space Flight Center, Huntsville, Ala.

21. "Optimum Transfer to Mars Via Venus," by Walter M. Hollister & John E. Prussing, AIAA Preprint No. 65-700, Sept. 1965.

22. "FLEM - Flyby Excursion Landing Mode," by Richard R. Titus, to be presented at AIAA 3rd Aerospace Sciences Meeting, Jan. 24, 1966.

23. "Interplanetary Maneuvers in Manned Helionautical Missions," by Krafft A. Ehricke, AIAA Preprint No. 65-695, Sept. 1965.

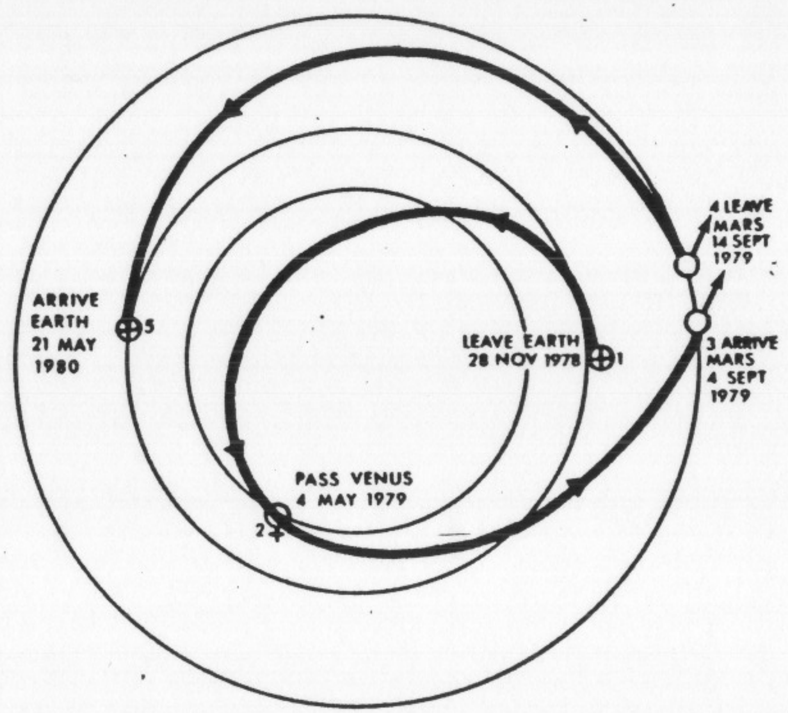
24. Personal communication. Courtesy Lockheed Missiles & Space Company; Sunnyvale, Calif.

25. Personal communications. Courtesy TRW Systems, Inc., Redondo Beach, Calif.

REPRESENTATIVE
OUTBOUND SWING BY 1980

(AFTER DEERWESTER-REF 6)

FIG. 1



NASA MT65-11,980
12-8-65

MARS STOPOVER-1980 OUTBOUND VENUS SWINGBY
(AFTER DEERWESTER-REF 6)

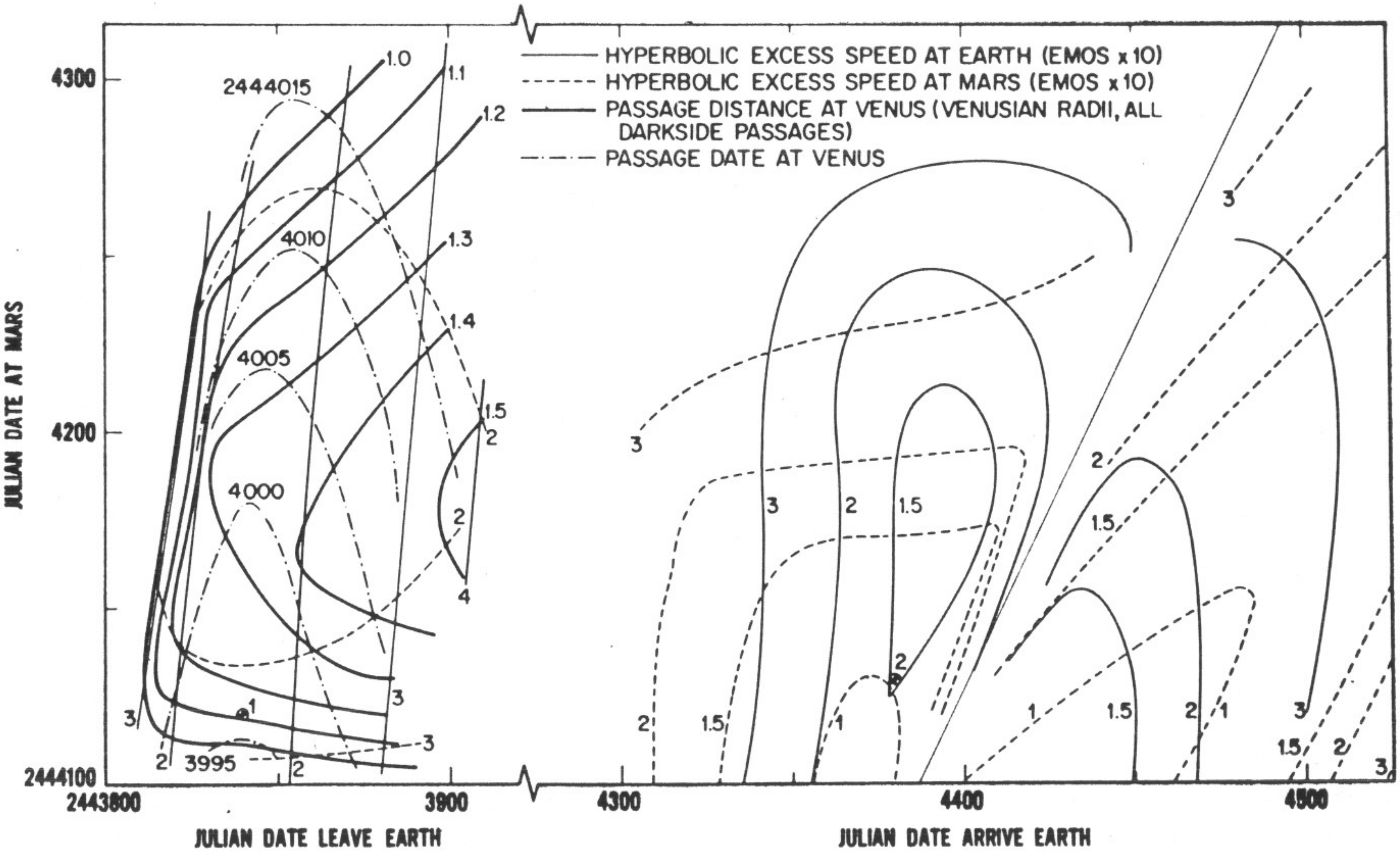


FIG. 2

NASA MT65-11,993
12-8-65

GROSS CHARACTERISTICS OF THE SEVEN BASIC VENUS SWINGBY MISSION TYPES

(REF-7)

VENUS SWINGBY TYPE	COMMENTS	TOTAL TRIP TIME (DAYS)	STOPOVER TIME (DAYS)	HOMEBOUND*		LAUNCH-YEAR OPPORTUNITIES	
				DEPARTURE SPEEDS (EMOS)	RETURN SPEEDS (EMOS)	OUTBOUND	HOMEBOUND
I	UNREASONABLE TRIPS	600-650	0-200	0.2-0.25	0.3-0.4	1980,1987	1980,1987
II	TIMING MISMATCH AT VENUS; NO TRIPS EXIST						
III	ALWAYS GOOD	550	0-60	0.15-0.2	0.13-0.16	1985,1991	1982,1989
IV	TIMING MISMATCH AT VENUS; NO TRIPS EXIST						
V	LOW SPEEDS, BUT OFTEN REQUIRE LONG SWINGBY/SWINGBY COMBINATIONS TO MEET TIMING RESTRICTIONS	450-500	0-50	.15	.15	1982,1989	1984,1991
VI	TIMING MISMATCH AT VENUS; NO TRIPS EXIST						
VII	NOT COMPETITIVE WITH COMPARABLE DIRECT/DIRECT (OPPOSITION-CLASS) TRIPS						

*FOR OUTBOUND TRIPS, INTERCHANGE THESE TWO COLUMNS

[illegible]
12-8-65

PLANETARY CONSTELLATION FOR 1979
EARTH-JUPITER-SATURN-URANUS-NEPTUNE MISSION

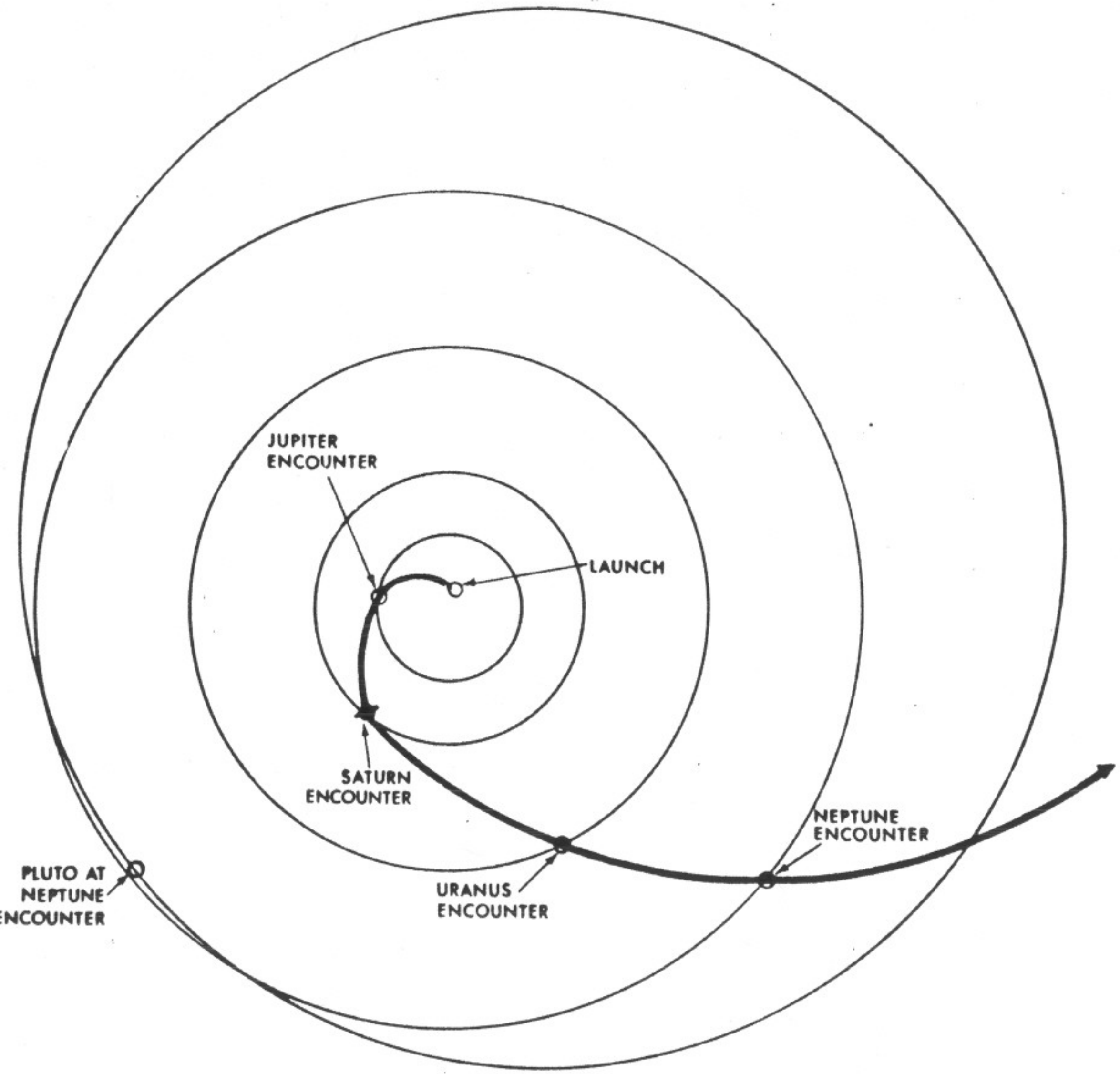


Fig. 4

NASA [illegible]

Fig. 4

EARTH JUPITER - URANUS SWINGBY

(AFTER DEERWESTER-REF 12)

LEAVE EARTH 1979

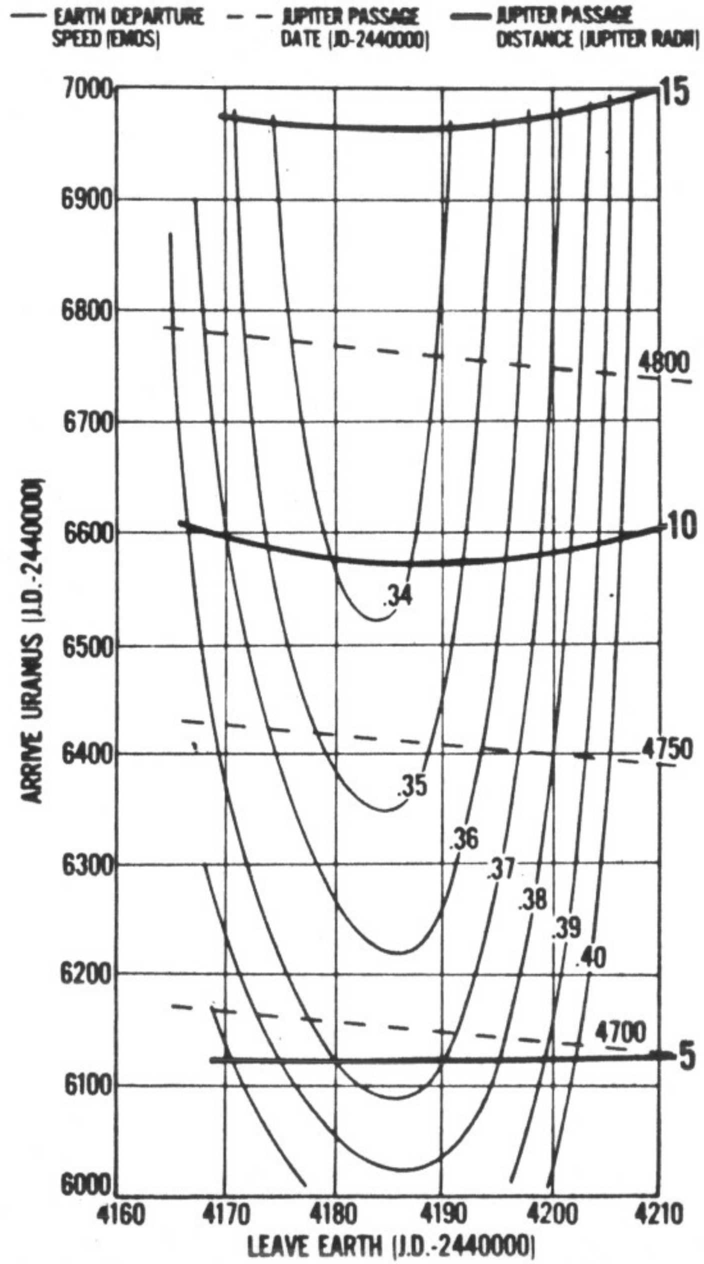


Fig. 5

NASA MT65-11,996
12-8-65

VELOCITY-FLIGHT TIME TRADE-OFF FOR SOLAR IMPACT PROBES USING JUPITER ASSIST

AFTER PORTER, LUCE & EDGECOMBE-REF 14

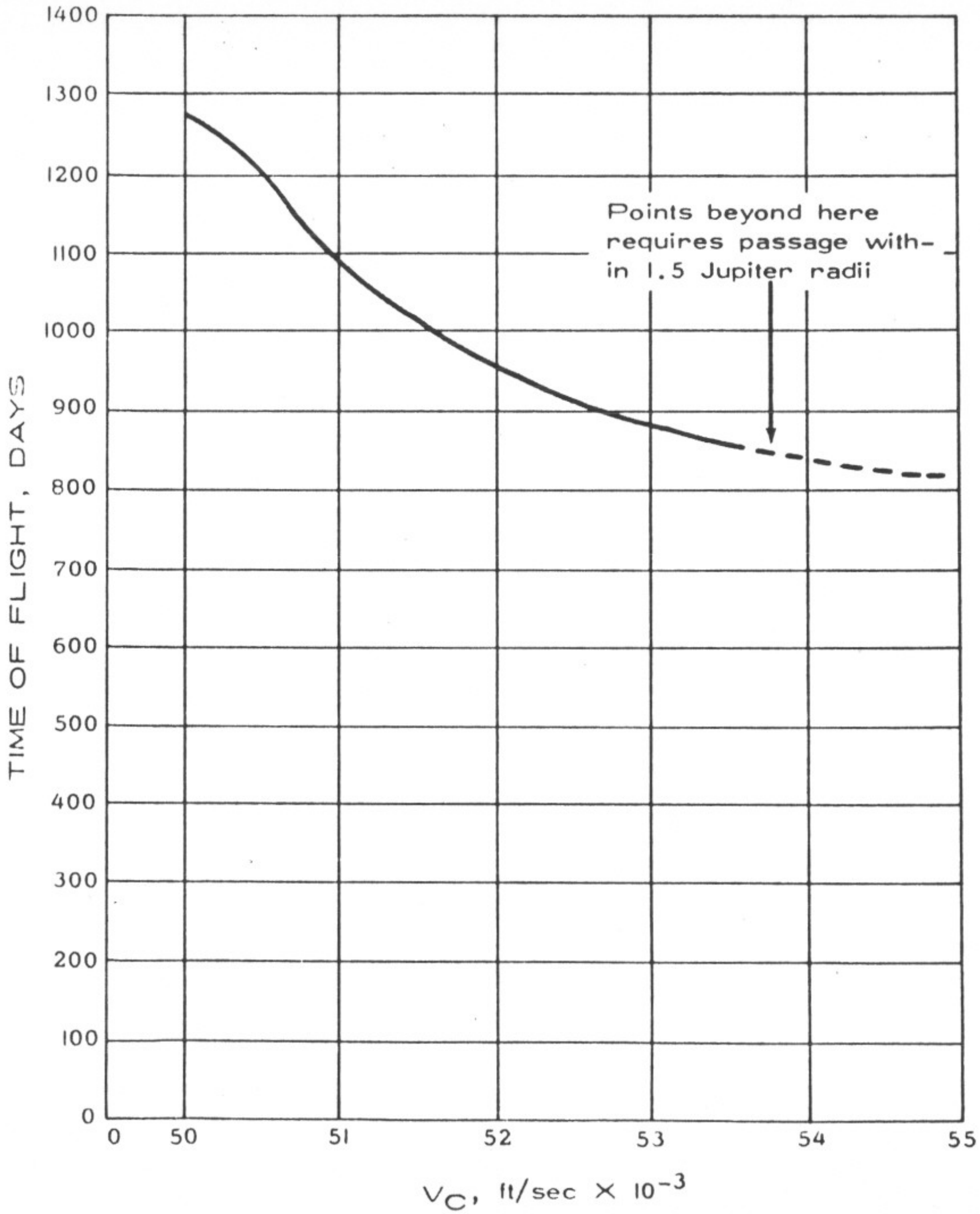
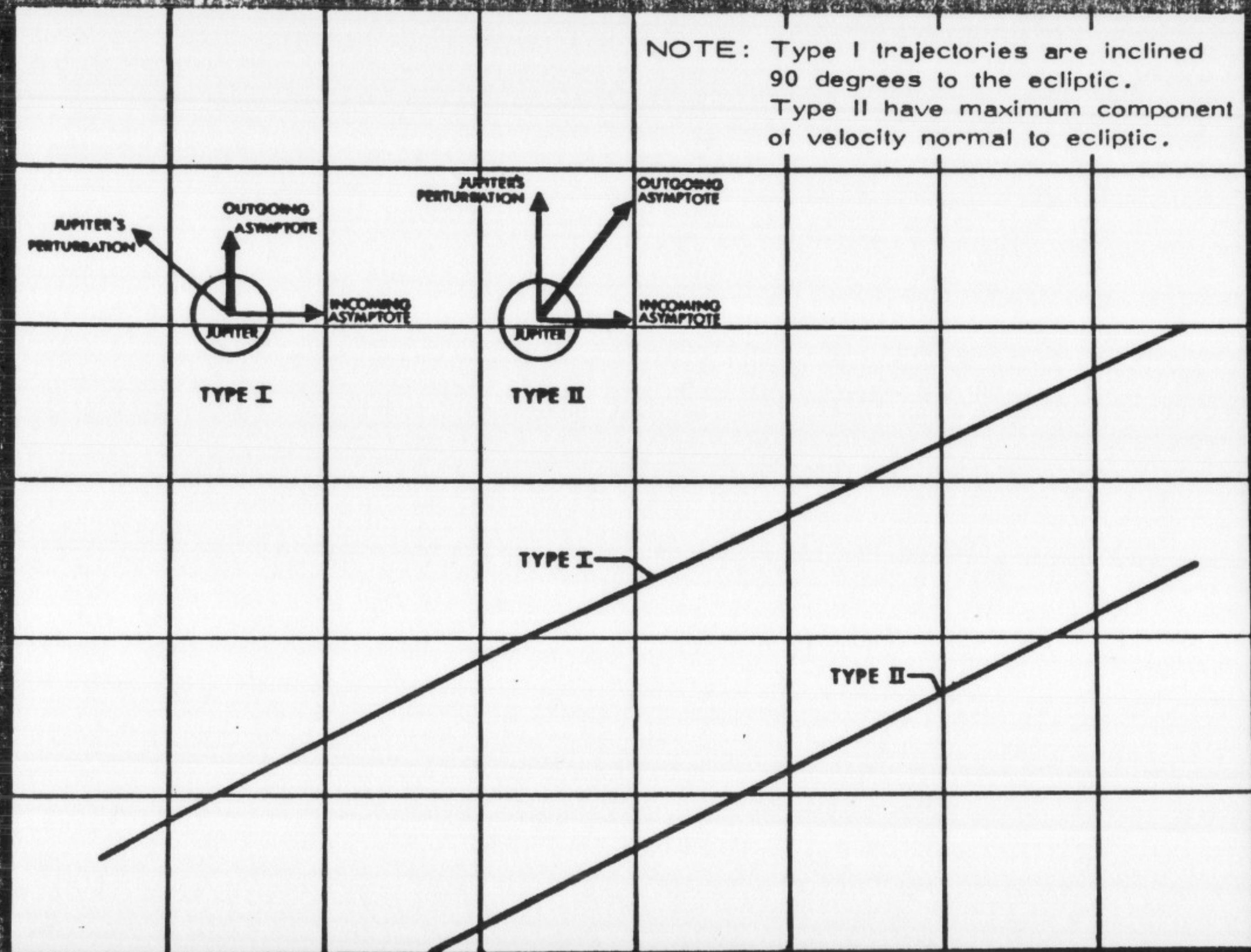


FIG. 6

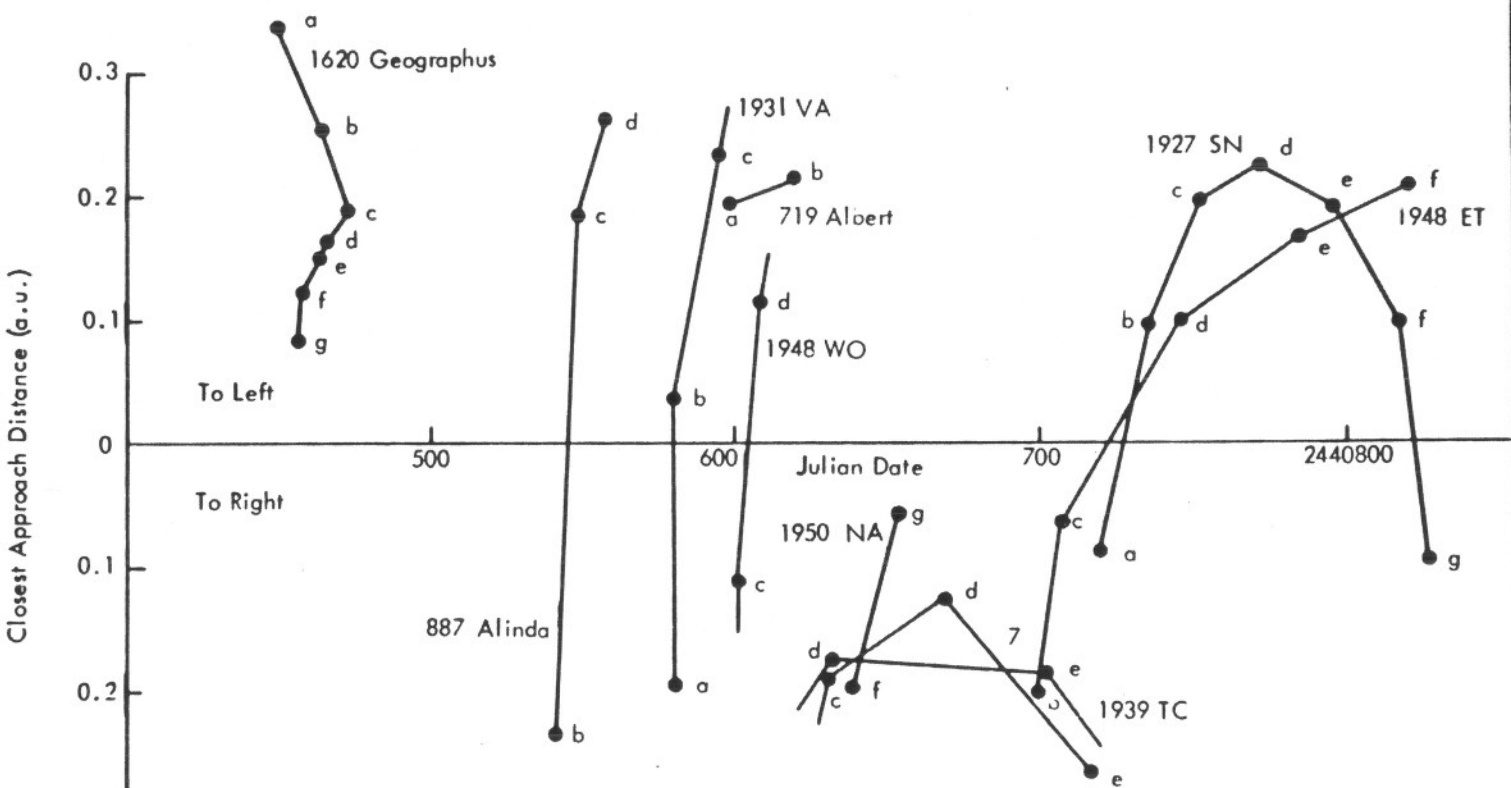
NASA MT65-11,978 12-8-65

V_C, ft/sec × 10⁻⁵

DISTANCE FROM ECLIPTIC AT SUN PASSAGE (AFTER PORTER, LUGG & EDGECOMBE-REF 14)



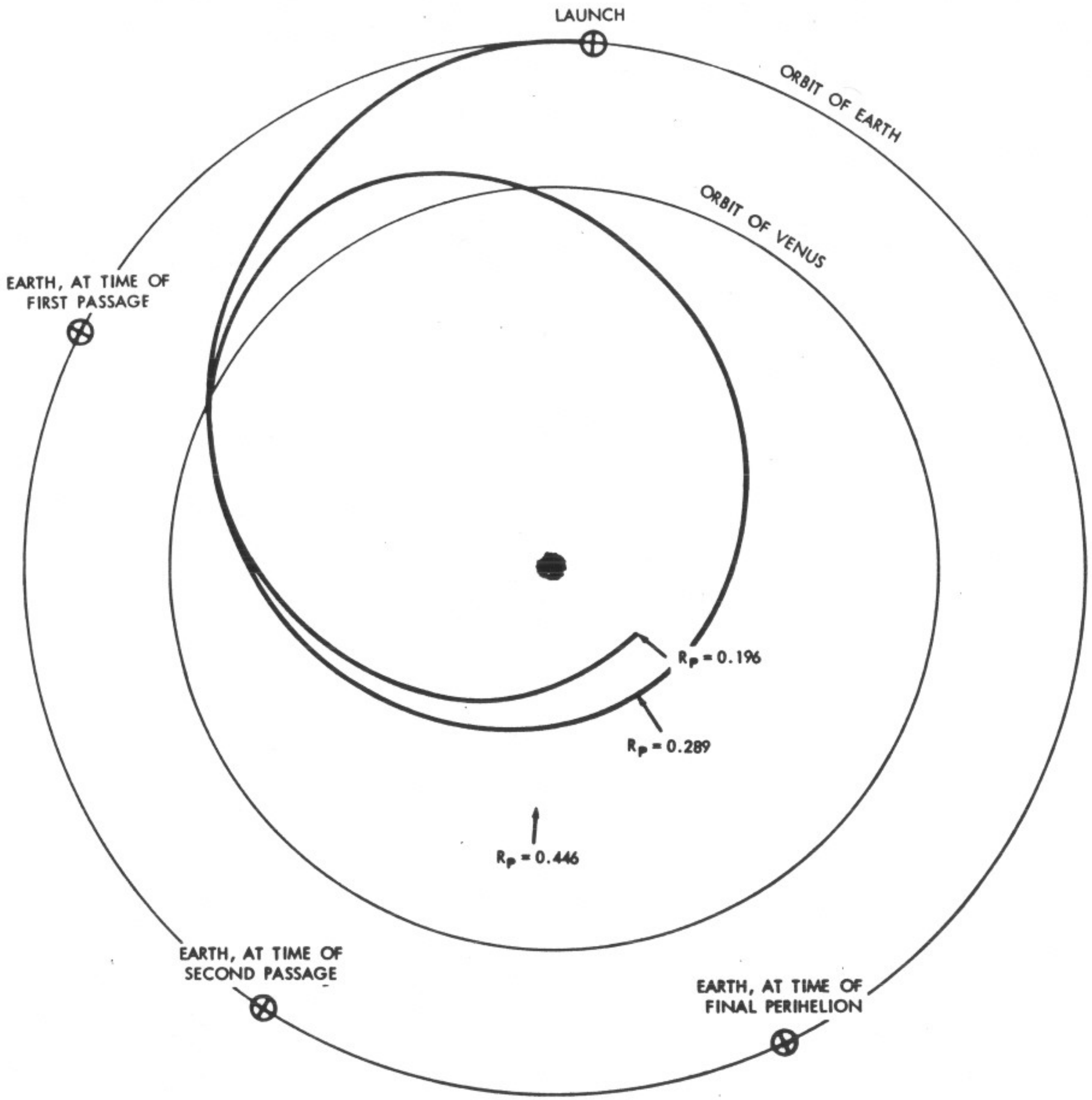
ASTEROID CANDIDATES FOR CLOSE APPROACH TO SPACE SHIP LONG FLIGHTS TO MARS 1969-70 (AFTER BENDER-REF 16)



Space Ship Depart Earth — Arrive Mars

	Depart Earth		Arrive Mars
a	2440330	-	650
b	0350	-	700
c	0370	-	750
d	0390	-	800
e	0410	-	850
f	0430	-	900
g	0450	-	950

12-8-65



FLIGHT PROFILE FOR A SOLAR PROBE EMPLOYING TWO PASSAGES OF VENUS (AFTER CASAL & ROSS-REF-17)

Figure 9

"DATA" GRAPH: EARTH-VENUS-MERCURY (0.31 AU)

AFTER NIEHOFF-REF 13

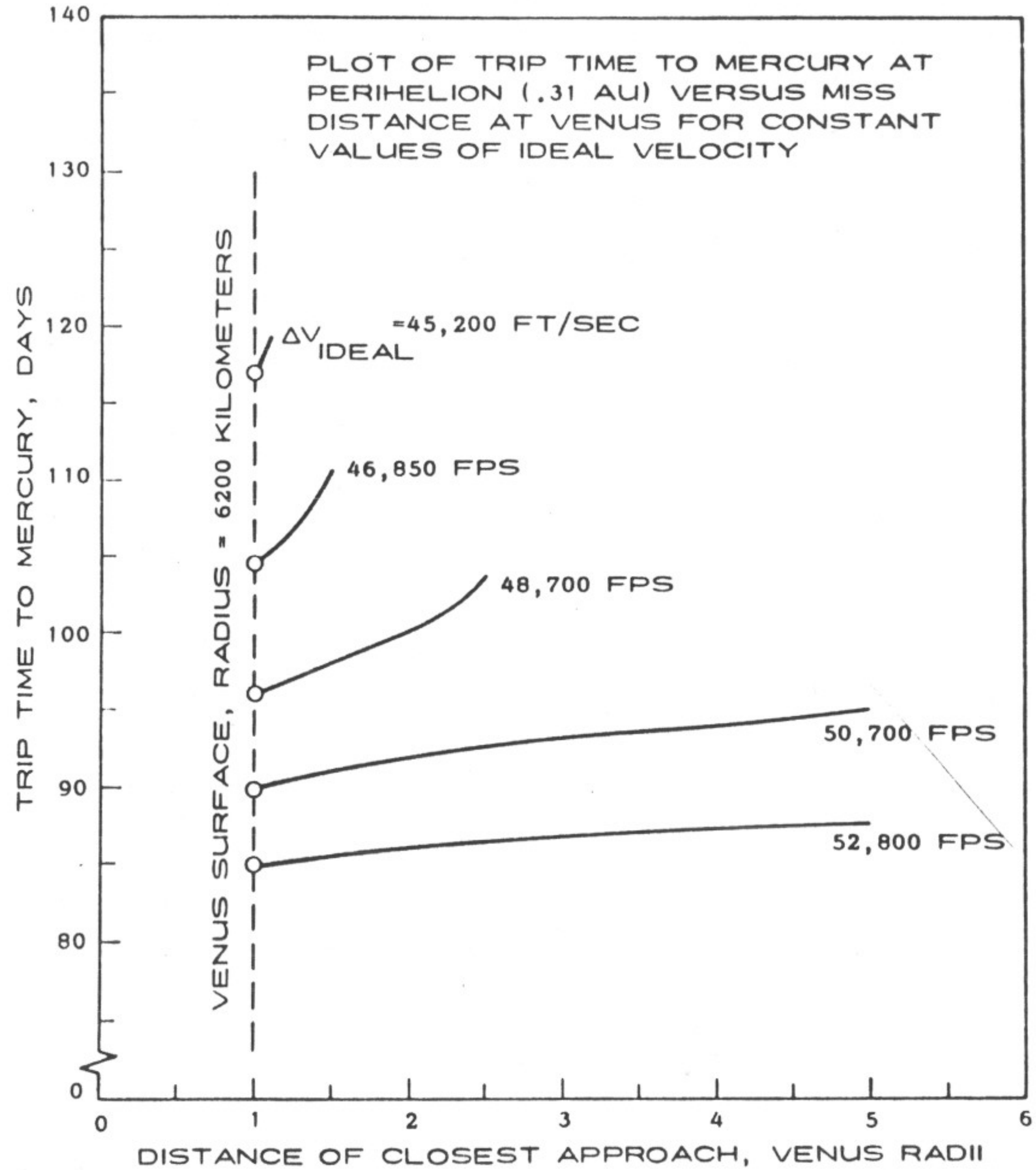


FIG. 10

NASA MT65-11,976 12-6-65

COMPARISON OF BALLISTIC & POWERED FLYBYS
AFTER TITUS REF-19

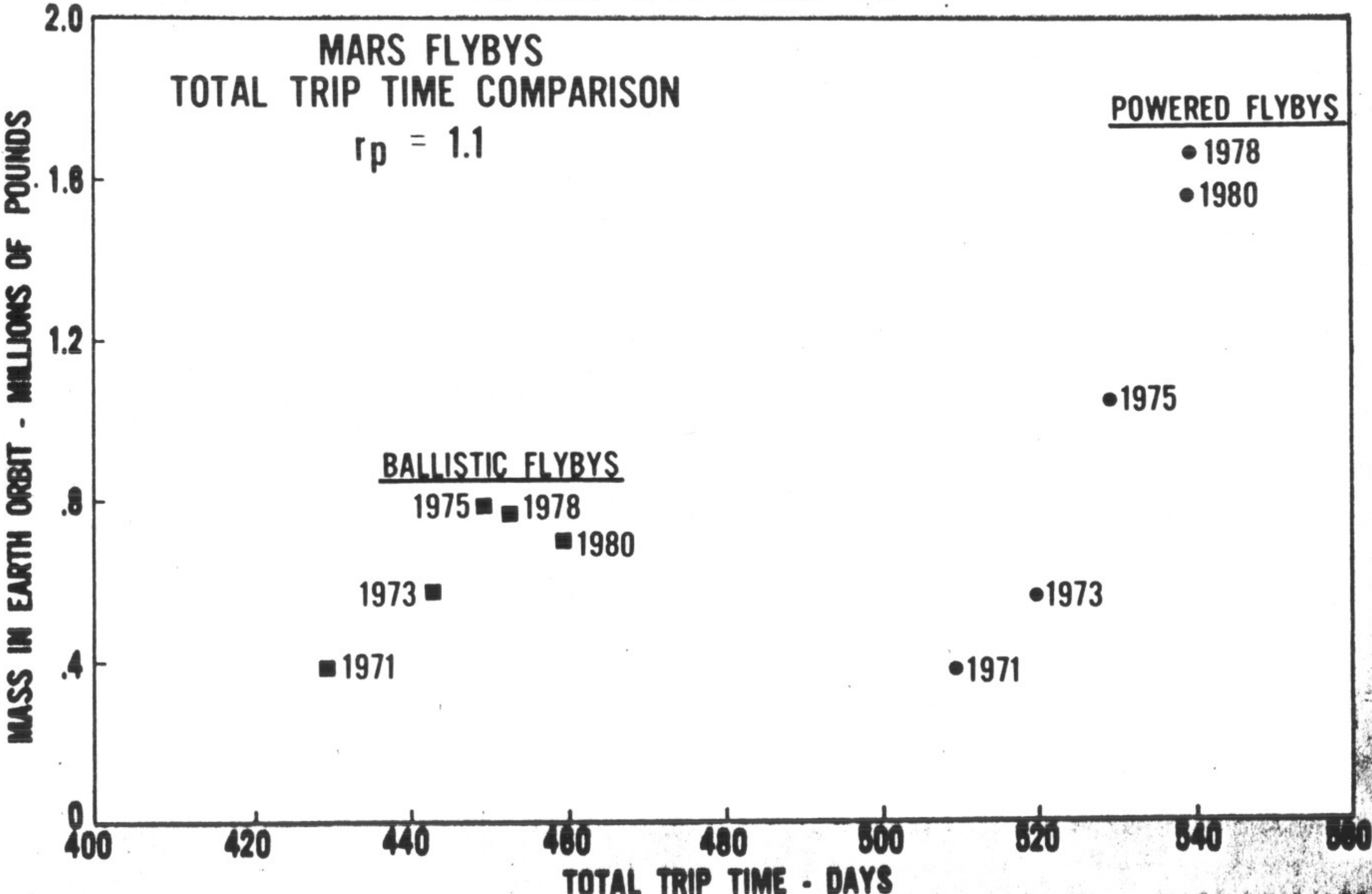


Fig. 11

NASA MT65-11,997
12-8-65

FLYBY-LANDING EXCURSION MODE: "FLEM"

(AFTER TITUS-REF 22)

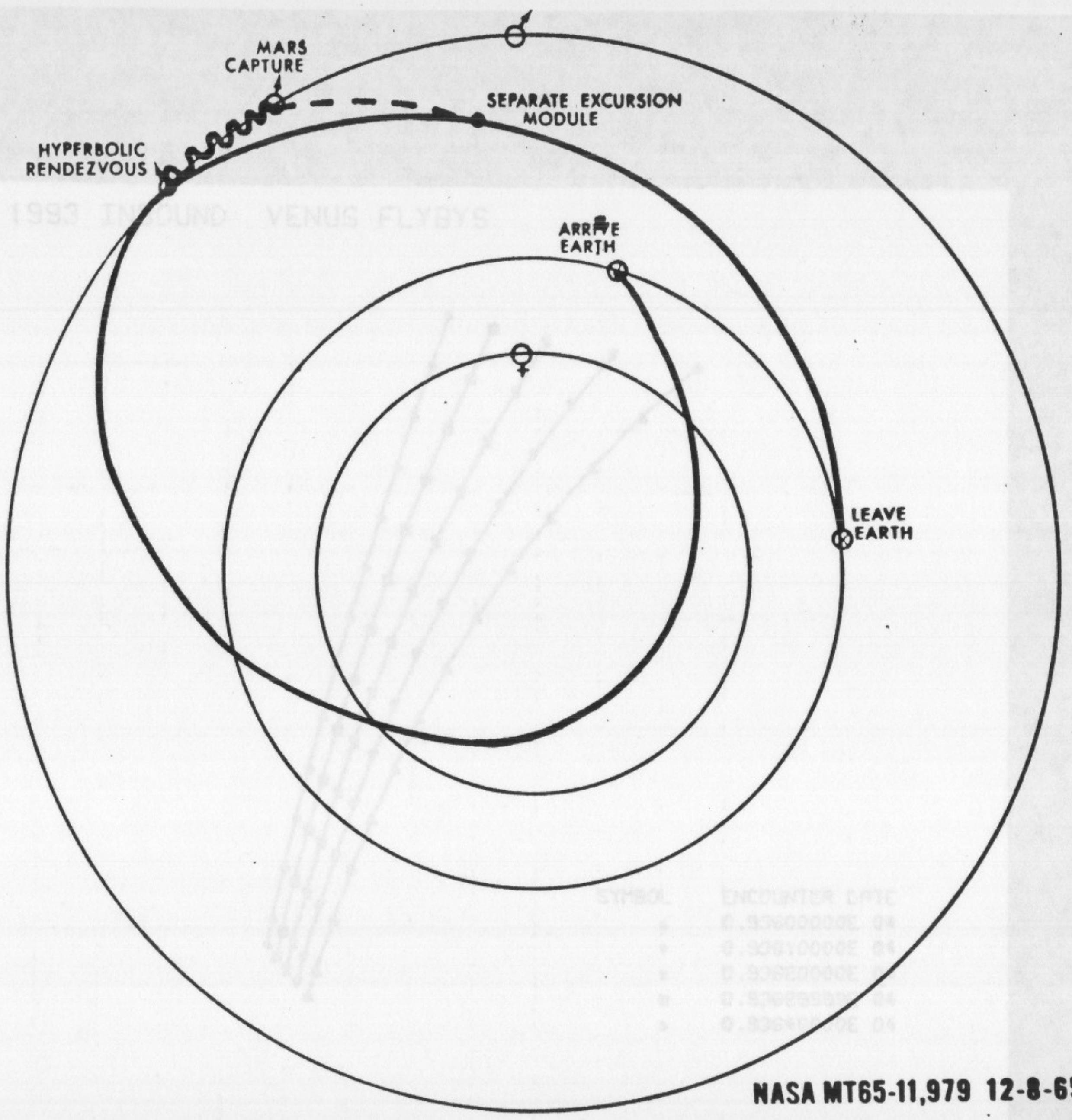


FIG. 12

NASA MT65-11,979 12-8-65

DESIGN CONCEPT OF MISSION ANALYSIS COMPUTER PROGRAM

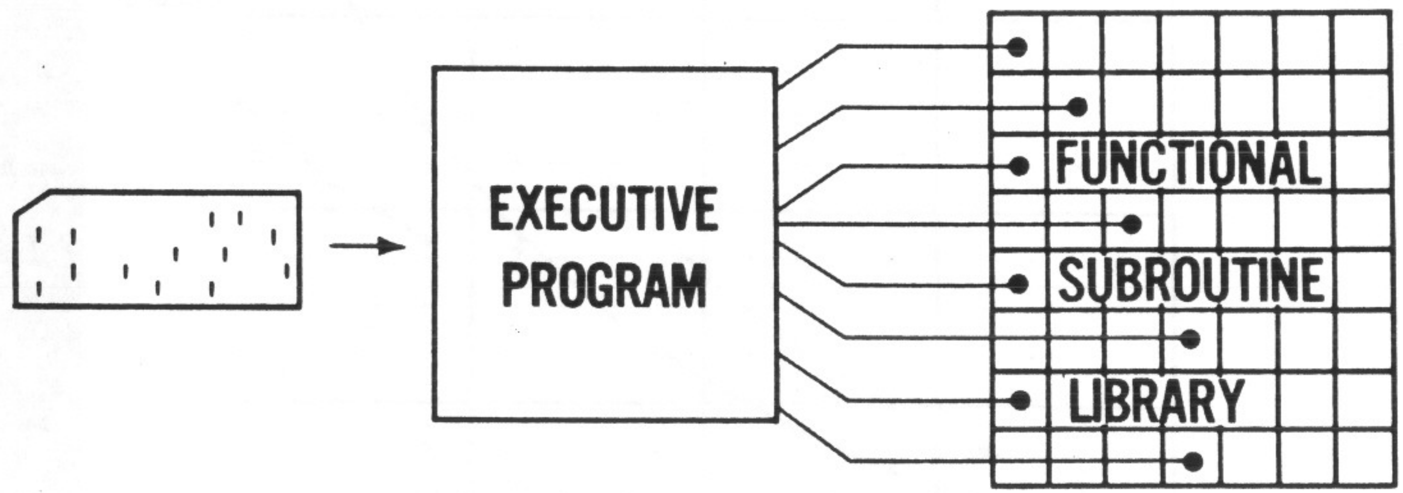


Fig. 14

NASA MT65-11,992
12-8-65