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DEPARTMENT OF
AEROSPACE AND MECHANICAL SCIENCES

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Office of Space Science and Applications
Launch Vehicle and Propulsion Programs Division
Contract NSR 31-001-078

SOLAR ELECTRIC SPACE MISSION ANALYSIS

Progress Report for the Period

1 June through 31 December 1966

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Assistant Professor

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Research Leader

30 April 1967

Aerospace Systems and Mission Analysis Research (ASMAR) Program
Department of Aerospace and Mechanical Sciences
School of Engineering and Applied Science
PRINCETON UNIVERSITY

SOLAR ELECTRIC SPACE MISSION ANALYSIS

Progress Report for the Period 1 June through 31 December 1966

ABSTRACT

Supplemental to the Basic Program of Aerospace Systems and Mission Analysis Research, studies of solar electric space missions have been undertaken to assist the Jet Propulsion Laboratory in establishing the applicability of solar powered electric rocket propelled spacecraft to solar system exploration. This work was undertaken under separate contract at the request of the Electric Propulsion Section of OART, NASA Headquarters.

Early results have provided a check on some solar powered electric rocket propelled Mars orbiter missions in the 1971-79 time period that resulted from a recent study by Hughes Aircraft Company.

Preliminary results for a solar electric Jupiter flyby in an initial mode of heliocentric transfer have been obtained.

Other prospective solar electric missions are being considered.

CONTENTS

SOLAR ELECTRIC SPACE MISSION ANALYSIS*

Progress Report for the Period 1 June through 31 December 1966

I. INTRODUCTION

A. General

Following meetings and discussions during the first quarter of 1966, research on solar electric space missions was initiated on 1 April as a part of the Basic ASMAR Program and subsequently covered by separate contract on 1 June 1966.

Work will be carried out in direct assistance to the Jet Propulsion Laboratory and the Electric Propulsion Section, Office of Advanced Research and Technology, NASA Headquarters in their efforts to establish the usefulness of solar electric propulsion, especially for solar system exploration(1,2).**

The ASMAR Program will attempt to provide computer programs based on a physical understanding of the heliocentric and planetocentric phases of spaceflight trajectories. The programs will be formulated for realistic missions and systems parameters and written using theoretical and numerical analysis techniques to give a wide flexibility and effectiveness in computer usage. While some mission results will be forthcoming from our work, the primary emphasis will be placed on assuring the usefulness and proving the range of the programs. Results

*This research is being supported by the Launch Vehicles and Propulsion Programs Division, Office of Space Science and Applications, NASA Headquarters. Mr. J. W. Haughey of that Division and Mr. J. P. Mullin of the Electric Propulsion Section, Office of Advanced Research and Technology, NASA Headquarters are Program and Technical Monitors. Mr. J. W. Stearns is our contact at the Jet Propulsion Laboratory.

**Arabic numbers in parentheses indicate references listed in APPENDIX A.

from our initial efforts during the period of this report (1 June through 31 December 1966) are given in the sections that follow.

B. Personnel

The assignment of ASMAR personnel (see APPENDIX B) to the Solar Electric Mission Studies will be limited for the most part to certain faculty and staff members. Both Mr. J. P. Layton and Professor P. M. Lion will be involved as will Dr. C. N. Gordon on subcontract from RCA-AED and Mr. J. H. Campbell, who was assigned to the ASMAR Program near the close of this period by AMA. Other AMA personnel as well as other consultants will be used as necessary.

Mr. G. A. Hazelrigg, Jr., a Ph.D. candidate in the Program who has been carrying out thesis research on optimal planetocentric maneuvers, is visiting the Jet Propulsion Laboratory for a six month period to assist them and provide liaison.

C. Princeton University Computer Center

The Princeton University Computer Center provides essential support to the ASMAR Program in satisfying our needs for rather extensive computations. Charges are covered in the University's indirect expenses. The University has been notified that it will be required to institute direct charging for all computing unless it can demonstrate a clear advantage to the government by retention of the present or some alternative method. Direct charging would have a great effect on the ASMAR Program so these developments are being closely watched.

II. SPACEFLIGHT TRAJECTORY ANALYSIS

The spaceflight trajectory analysis work on the Solar Electric Mission Studies has so far consisted primarily of the development of two programs.

The first of these programs, developed by Dr. Colin N. Gordon, is an optimization program for two-dimensional, heliocentric trajectories. It is capable of operating in the rendezvous or flyby modes. The power law may be either constant, solar electric or other. Analytical partial derivatives are used for the differential corrections. This program is presently running, has checked other programs independently developed, and has yielded initial results. The program's most remarkable feature is the radius of convergence. It has no trouble converging within miss distances of one-half A.U. and in certain cases has converged from a miss distance of over 1 A.U. The trajectory calculations are very rapid, and the program is capable of sweeping various parameters automatically; e.g., jet velocity, power level, etc.

The second program being developed under this contract is the ITEM n-body integration. Personnel working on this program are Mr. Leon Lefton and Mr. John Campbell under subcontract from AMA.

In addition to n-body integrating this program contains several other features such as solar pressure, shadow logic, etc. The principal changes and additions to the program during this period were:

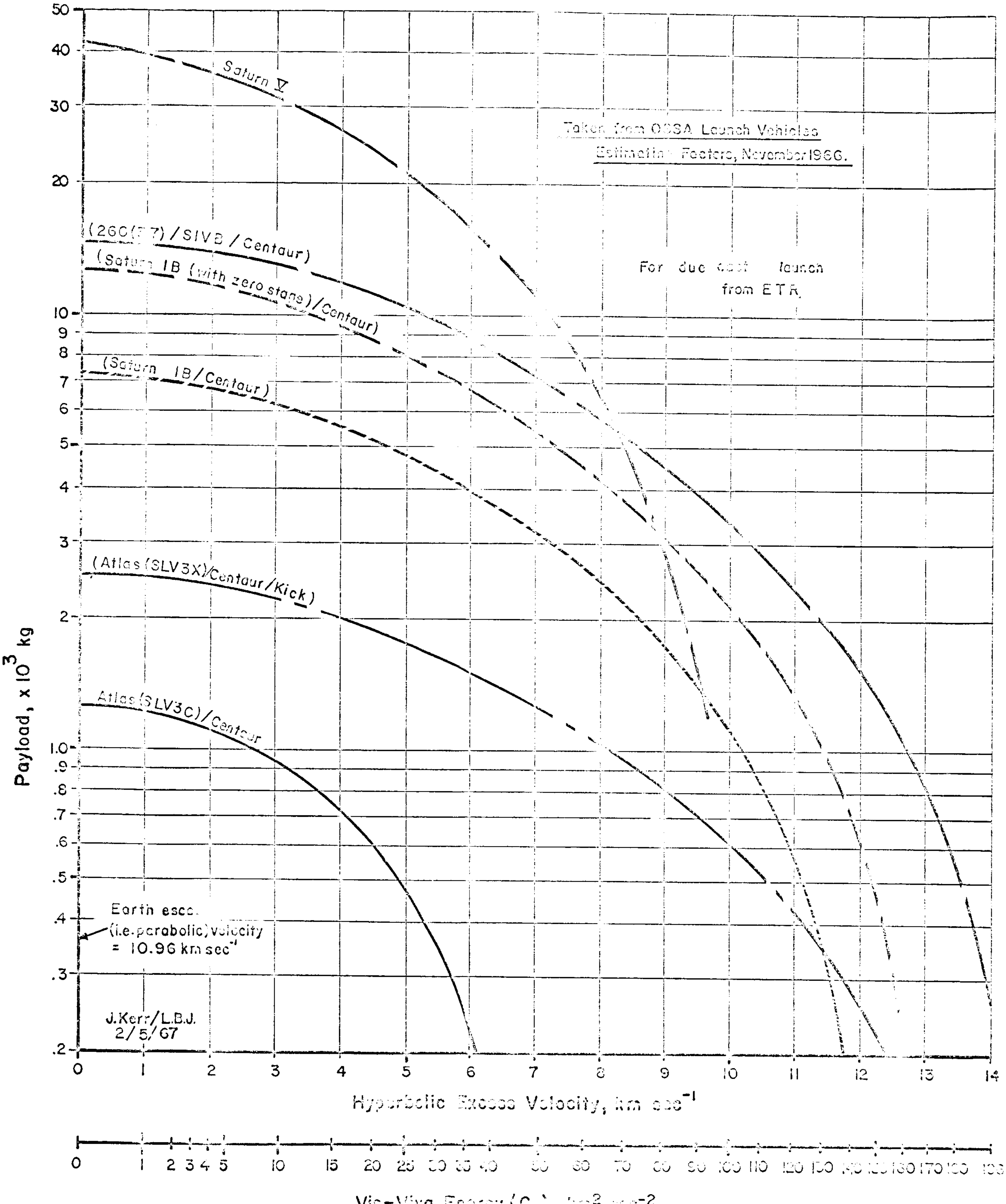
(a) the addition of programmed thrusting capability,

and (b) simplification.

III. LAUNCH VEHICLE CONSIDERATIONS

In the Solar Electric Missions Studies specific launch vehicles will be considered and their spacecraft payload mass/hyperbolic excess velocity capability optimized for the various mission requirements.

Copies of the OSSA Launch Vehicles Estimating Factors, November 1966 have been made available to the ASMAR Program. The curves shown on FIGURE 1 were taken from this source for launch vehicles that may be used in the missions where solar electric propulsion systems are applicable.



Performance Data for Selected Launch Vehicles

FIGURE 1

IV. SOLAR ELECTRIC PROPULSION SYSTEMS

Characteristics of the solar electric propulsion systems that are being used in our mission studies derive from the studies sponsored by the Jet Propulsion Laboratory during 1965 on solar arrays (The Boeing Company), electric propulsion systems (Electro-Optical Systems, Inc.), and solar powered electric propulsion spacecraft (Hughes Aircraft Company) during 1965. The Hughes Program Summary Report (3) provides the primary source of background information for our efforts; however, all solar electric propulsion system parameters are being provided by JPL and approved by Headquarters.

V. SOLAR ELECTRIC MISSION ANALYSIS

During the period of this report some initial work was accomplished while the computer programs based on optimization analysis are being written and brought to usefulness.

A. Mars Orbiter Check

The ITEM program was used to check the Hughes' results (3) for the Mars orbiter with the preliminary results shown on TABLES I through V and FIGURES 2 through 6. These show a substantial check of the Hughes data, but because of incompleteness therein no definitive check will be sought. The cases are believed not to be optimal from a number of standpoints. No further efforts will be made to check these results.

B. Jupiter Flyby Results

The preliminary results of a partially optimizing program applied to the solar-powered electric-propelled Jupiter flyby mission in an initial mode are given below using an Atlas (SLV3C)/Centaur launch vehicle. Electric power from the solar array is taken to vary as $R^{-1.7}$. The Earth departure conditions were specified for the most part and the two dimensional heliocentric trajectory between circular orbits at 1 and 5.2 A.U. was computed to provide an optimum mating of the launch vehicle and solar-electric spacecraft to give maximum net spacecraft mass for the given flight time.

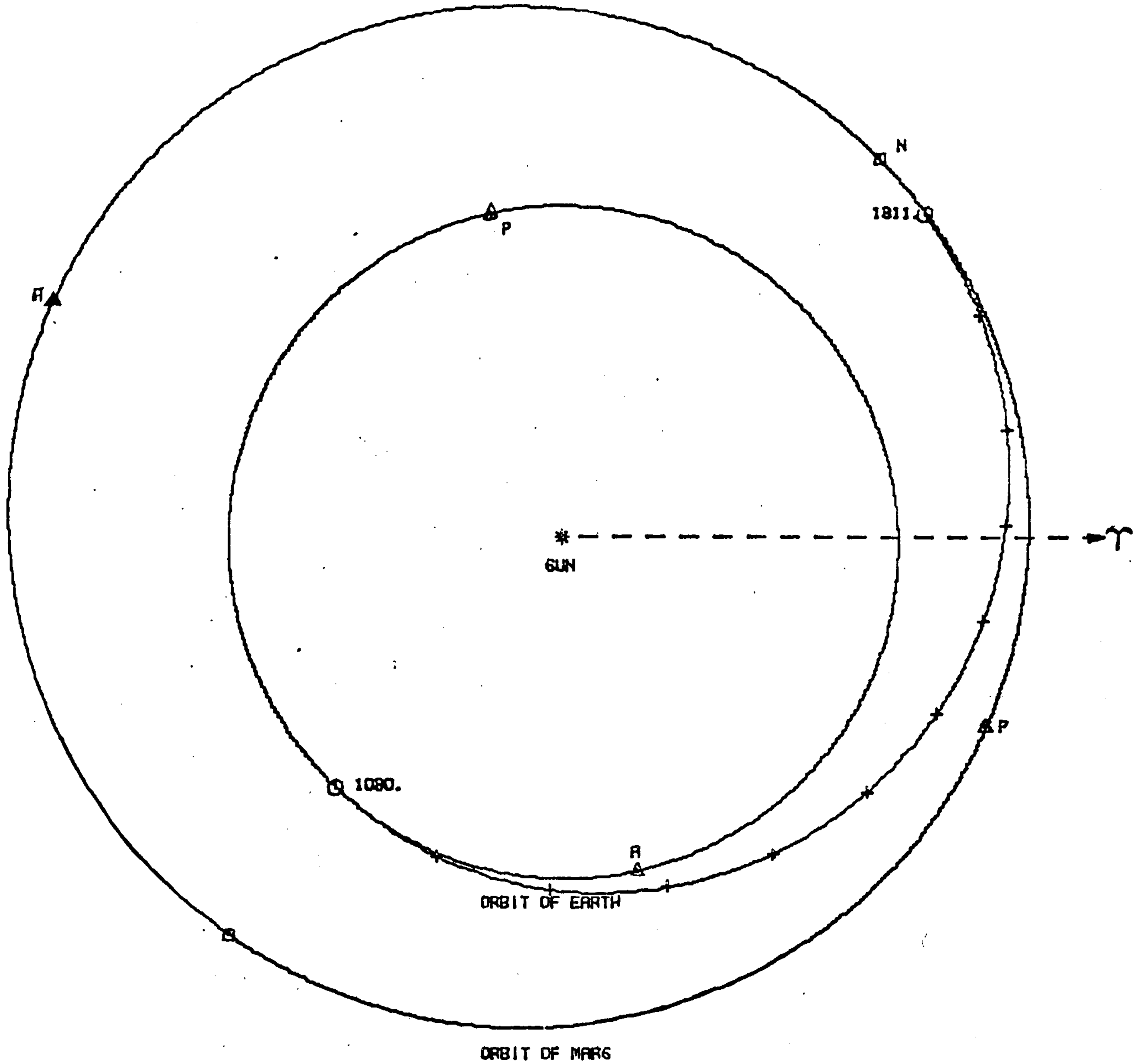
A summary listing of data and results for this initial mode of the solar electric Jupiter flyby is given on page 21.

TABLE I

Solar Electric Mars "Orbiter" 1971

	Calendar Date	Julian Date
Leave Earth sphere of influence, T_o (t = 0 hrs)	May 8, 1971	2441080.438
Vis-Viva Energy, $C_3 = 4.284250\ km^2\ sec^{-2}$		
Arrive near Mars, T_f (t = 230 days + 3 hrs)	Dec 25, 1971	2441310.563
Transfer Angle = 172.888°		

	T_o		T_f			
	Earth Ephemeris	Hughes	Mars Ephemeris	Hughes	Mod. ITEM	Δ(MI-H)
X,AU	-.68351475	-.67969491	1.0972198	1.0966328	1.0834762	-.0131566
Y,AU	-.74280646	-.74666393	.95511574	.95591247	.96126080	+.0053483
Z,AU	.000042125583	-.00278906	-.00658942	.00333529	.00255740	-.0007779
$\dot{X}$,EMOS	.71937913	.76916774	-.50211714	-	-.46638744	-
$\dot{Y}$,EMOS	-.68040780	-.72639255	.68244455	-	.63241905	-
$\dot{Z}$,EMOS	.000041832549	-.03492263	.02666489	-.00174490	-.02570829	-.0239634
S/C Mass, kgm	2514.3			-	2325.7	-
Ratio S/C Mass T_f/T_o				-	.9250	-
Approach Speed to Mars, km/sec				1.961	2.405	+.444



SOLAR ELECTRIC MARS ORBITER 1971

LAUNCH ON MAY 8, 1971

FLIGHT TIME 231 DAYS

FIGURE 2

PRELIMINARY

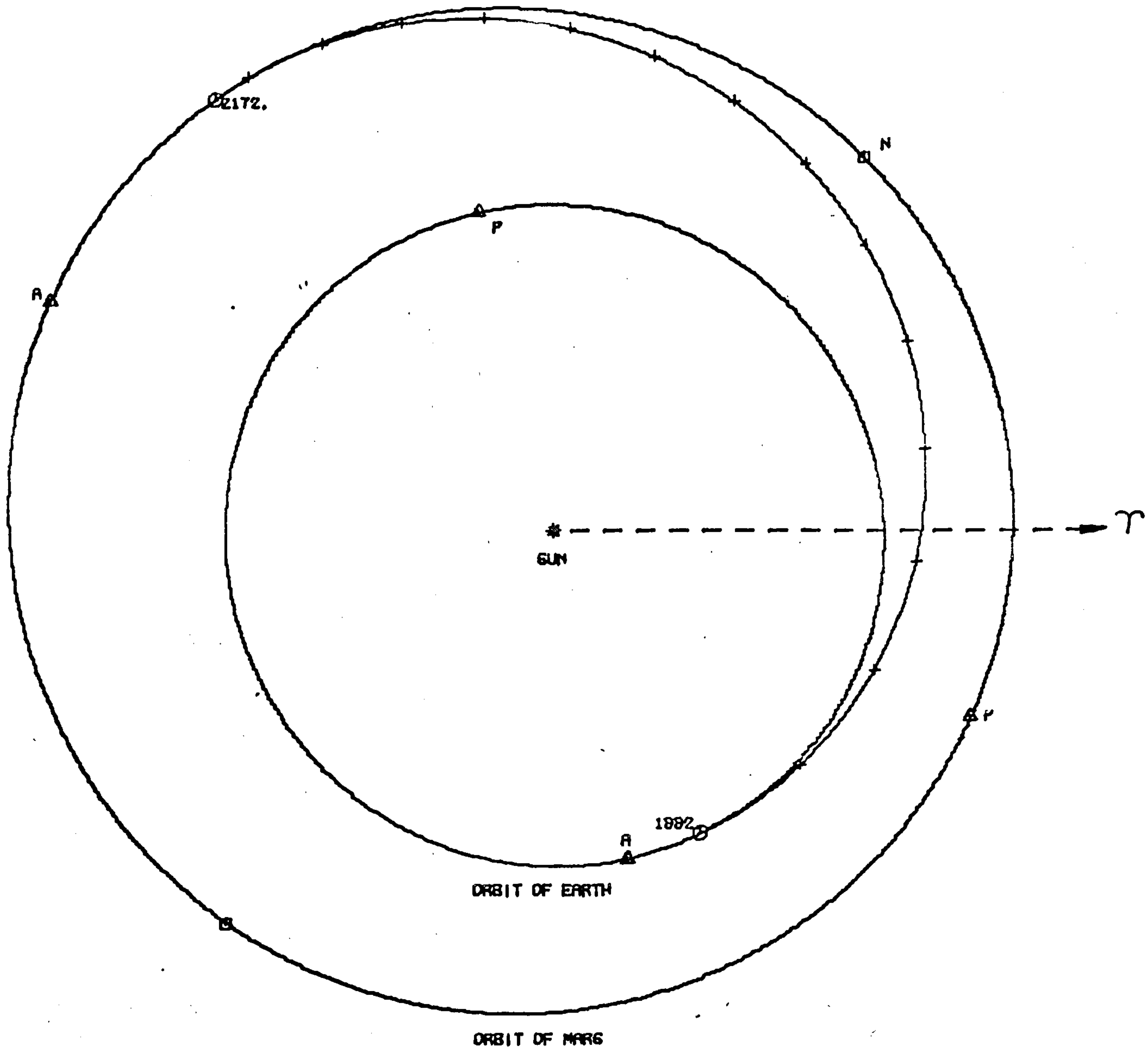
1 November 1966

TABLE II

Solar Electric Mars "Orbiter" 1973

		Calendar Date	Julian Date
Leave Earth sphere of influence, T_o ($t = 0$ hrs)		Jul 18, 1973	2441881.9180
Vis-Viva Energy, $C_3 = 4.284250\ km^2\ sec^{-2}$			
Arrive near Mars, T_f ($t = 290$ days + 6 hrs)		May 4, 1974	2442172.168
Transfer Angle = 193.647^o			

	T_o		T_f			
	Earth Ephemeris	Hughes	Mars Ephemeris	Hughes	Mod. ITEM	Δ(MI-H)
X,AU	-.43433157	.43990889	-1.0192191	-1.0210939	-1.0198274	+.0020112
Y,AU	-.91875923	-.91634484	1.2932204	1.29279030	1.2975192	+.0047289
Z,AU	.000043574721	.00082652	.05217836	-.04178525	.04995134	+.0917366
$\dot{X}$,EMOS	.88761689	.97181858	-.60714355	-	-.57883632	-
$\dot{Y}$,EMOS	.42359476	.46364744	-.43483581	-	-.40812102	-
$\dot{Z}$,EMOS	-.000047628808	-.01350321	.00561932	.00640918	.01433338	+.00792421
S/C Mass, kgm	2267.6			-	2060.6	-
Ratio S/C Mass T_f/T_o				-	.9087	-
Approach Speed to Mars, km/sec				1.151	1.188	+.037



SOLAR ELECTRIC MARS ORBITER 1973

LAUNCH ON JULY 18, 1973

FLIGHT TIME 290 DAYS

FIGURE 3

PRELIMINARY

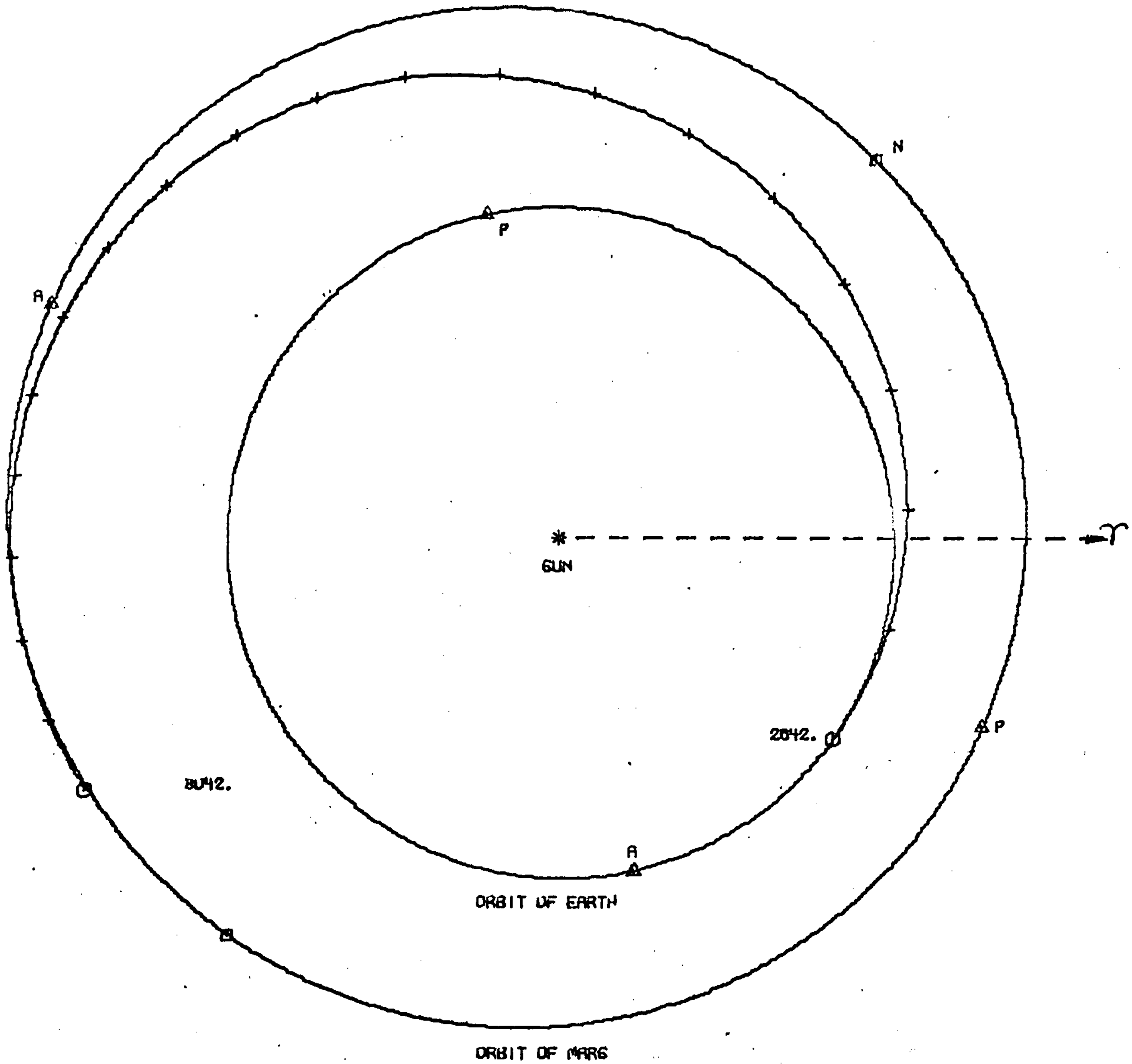
1 November 1966

TABLE III

Solar Electric Mars "Orbiter" 1975

	Calendar Date	Julian Date
Leave Earth sphere of influence, t_o (t = 0 hrs)	Aug 17, 1975	2442641.7036
Vis-Viva Energy, $C_3 = 5.597589\ km^2\ sec^{-2}$		
Arrive near Mars, T_f (t = 400 days + 10.5 hrs)	Sep 20, 1976	2443042.141
Transfer Angle = 246.298^o		

	T_o		T_f			
	Earth Ephemeris	Hughes	Mars Ephemeris	Hughes	Mod. ITEM	Δ(MI-H)
X,AU	.81207179	.81588832	-1.3840137	-1.3835629	-1.4089081	-.0253452
Y,AU	-.60467791	-.59990672	-.79574684	-.79677297	-.78002986	+.0167431
Z,AU	.000027215108	.0025008	.01693795	-.21129974	.02414513	+.2354449
$\dot{X}$,EMOS	.58055977	.63155264	.43701443	-	.41091670	-
$\dot{Y}$,EMOS	.79860931	.86652423	-.63626897	-	-.62467903	-
$\dot{Z}$,EMOS	-.000080109686	-.00291483	-.02409940	.02103958	.00112034	-.0199092
S/C Mass, kgm	2395.2			-	2130.7	-
Ratio S/C Mass T_f/T_o				-	.8896	-
Approach Speed to Mars, km/sec				.908	1.135	+.227



SOLAR ELECTRIC MARS ORBITER 1975

LAUNCH ON AUG 17, 1975

FLIGHT TIME 400 DAYS

FIGURE 4

PRELIMINARY

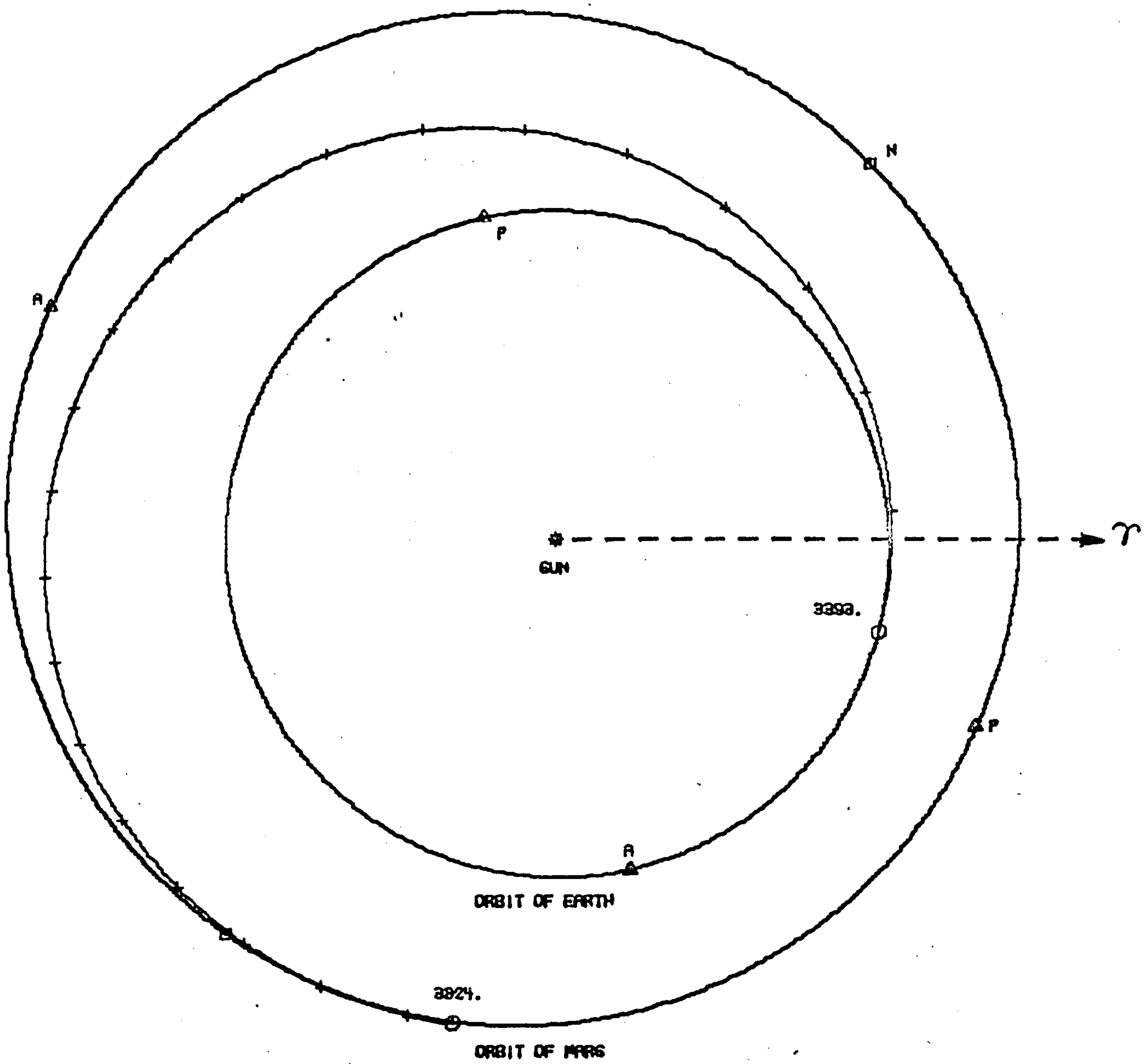
1 November 1966

TABLE IV

Solar Electric Mars "Orbiter" 1977

	Calendar Date	Julian Date
Leave Earth sphere of influence, t_o (t = 0 hrs)	Sep 6, 1977	2443393.2549
Vis-Viva Energy, $C_3 = 4.062134\ km^2\ sec^{-2}$		
Arrive near Mars, T_f (t = 430 days + 6 hrs)	Nov 11, 1978	2443823.505
Transfer Angle = 273.597°		

	T_o		T_f			
	Earth Ephemeris	Hughes	Mars Ephemeris	Hughes	Mod. ITEM	Δ(MI-H)
X,AU	.96696105	.96886610	-.30366671	-.30282720	-.32020429	-.0173771
Y,AU	-.28384636	-.27811922	-1.4476876	-1.4480352	-1.4541280	-.0060928
Z,AU	.000015571713	.00126240	-.02318347	-.1403094	-.02338891	+.1169205
$\dot{X}$,EMOS	.26574941	.28592724	.82800118	-	.79959284	-
$\dot{Y}$,EMOS	.95609573	1.0262130	-.09755981	-	-.10393839	-
$\dot{Z}$,EMOS	-.000051816124	.01510697	-.02224486	.02654276	.00504140	-.02150136
S/C Mass, kgm	2534.5			-	2238.1	-
Ratio S/C Mass T_f/T_o				-	.8831	-
Approach Speed to Mars, km/sec				1.108	1.188	+.080



SOLAR ELECTRIC MARS ORBITER 1977

LAUNCH ON SEP 6, 1977

FLIGHT TIME 431 DAYS

FIGURE 5

PRELIMINARY

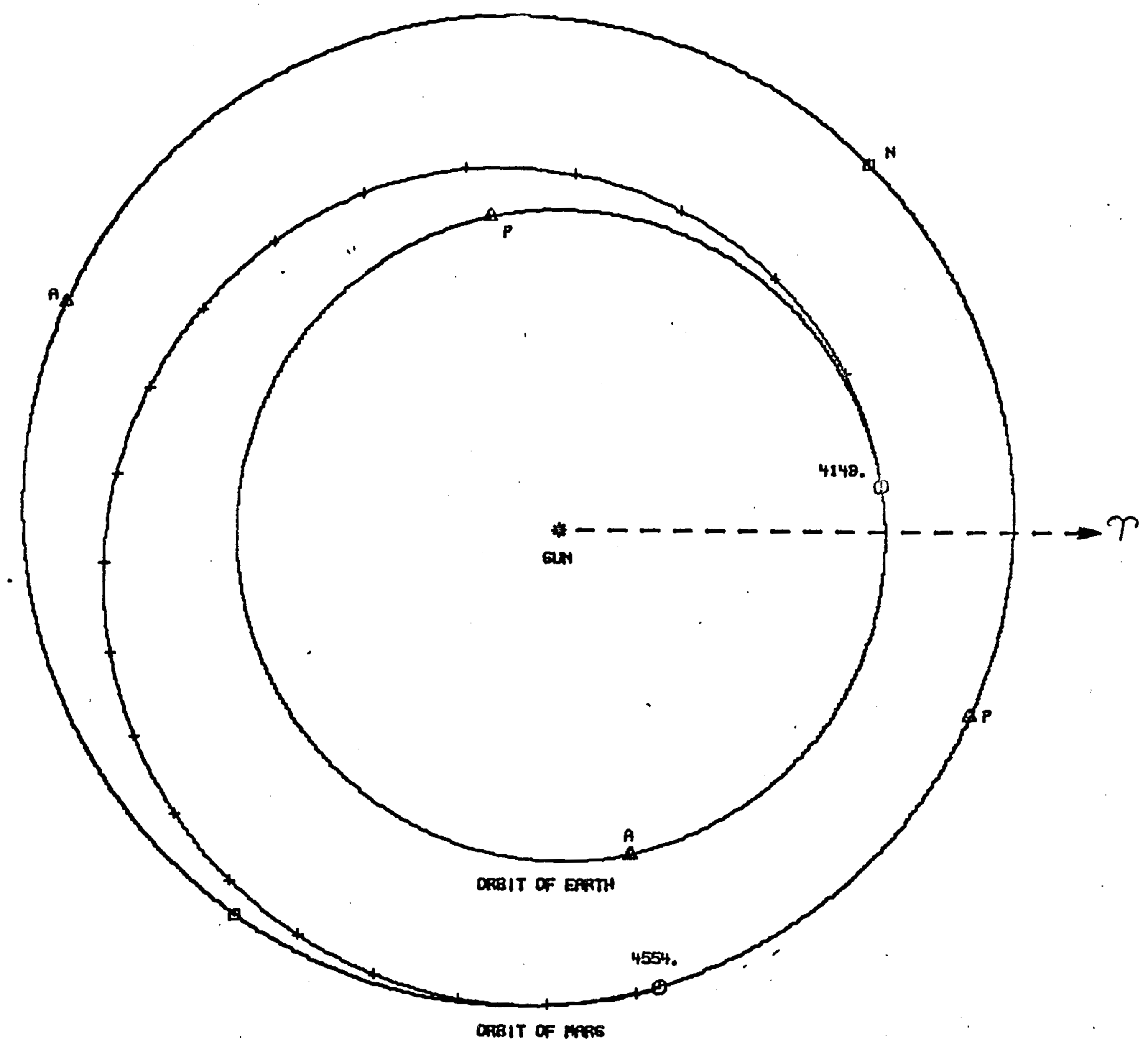
TABLE V

1 November 1966

Solar Electric Mars "Orbiter" 1979

	Calendar Date	Julian Date
Leave Earth sphere of influence, t_o ($t = 0$ hrs)	Oct 1, 1979	2444148.4097
Vis-Viva Energy, $C_3 = 3.094429\ km^2\ sec^{-2}$		
Arrive near Mars, T_f ($t = 405$ days + 9 hrs)	Nov 10, 1980	2444553.785
Transfer Angle = 274.412^o		

	T_o		T_f			
	Earth Ephemeris	Hughes	Mars Ephemeris	Hughes	Mod. ITEM	Δ(MI-H)
X,AU	.99196021	.99148069	.32090550	.32210213	.30967932	-.0124228
Y,AU	.13429613	.13982004	-1.3917614	-1.3919647	-1.4034039	-.0114392
Z,AU	-.000015809666	.00254740	-.03723094	-.08671704	-.03642319	+.0502938
$\dot{X}$,EMOS	.15078670	.1585372	.82438581	-	.78569897	-
$\dot{Y}$,EMOS	.98724151	1.0475929	.25227699	-	.23144750	-
$\dot{Z}$,EMOS	-.000028900089	.02770106	-.01476223	.02134158	.00754481	-.0137968
S/C Mass, kgm	2622.3			-	3232.4	-
Ratio S/C Mass T_f/T_o				-	.8860	-
Approach Speed to Mars, km/sec				1.385	1.467	+.082



SOLAR ELECTRIC MARS ORBITER 1979

LAUNCH ON OCT 1,1979

FLIGHT TIME 406 DAYS

FIGURE 6

Solar Electric Jupiter Flyby - Initial Mode

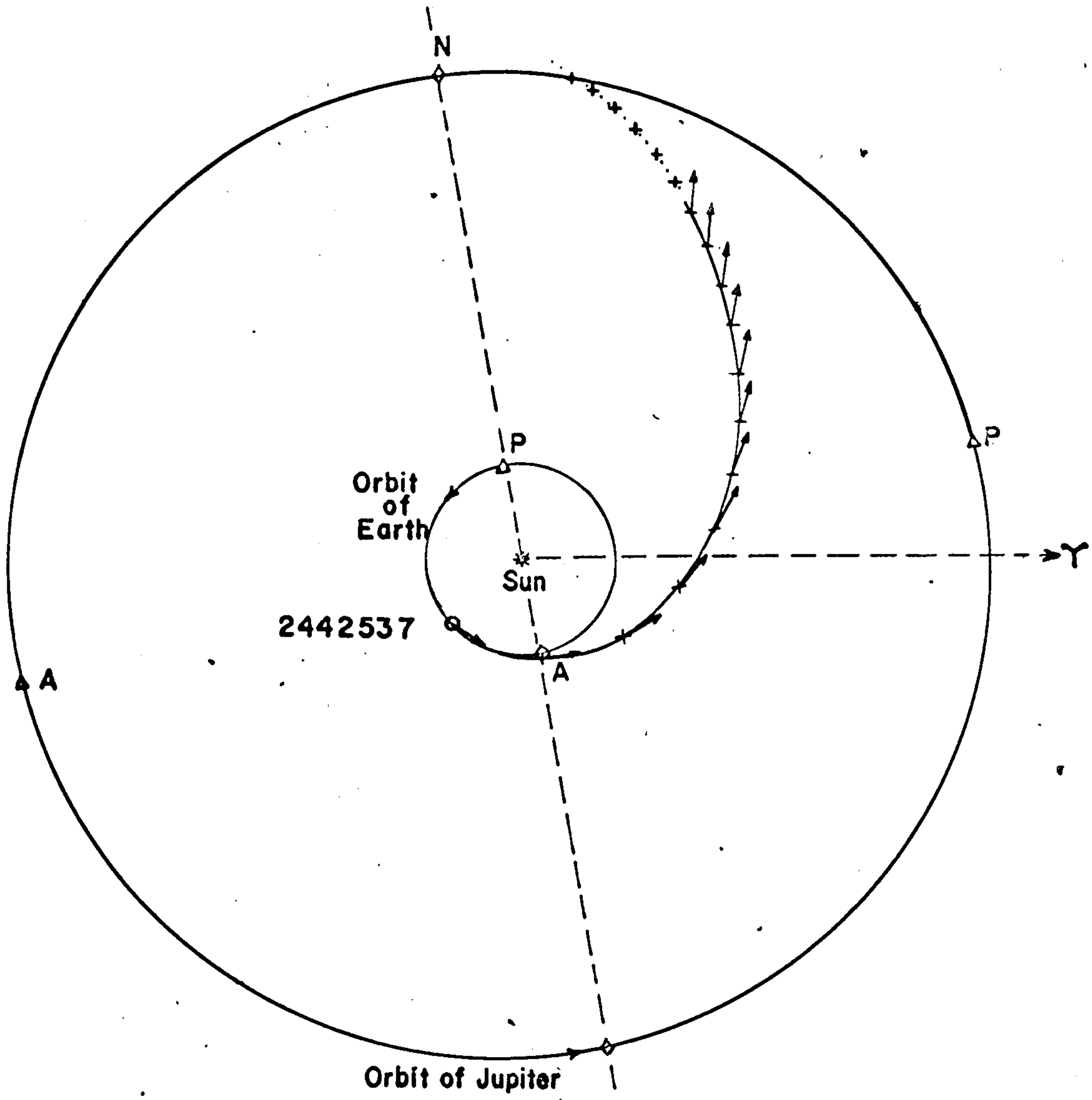
Earth Departure Conditions:	
Initial total spacecraft mass	777 kg
Hyperbolic excess velocity	3.755 km/sec
(Vis-Viva energy	14.1 km^2/sec^2)
Propulsion system specific mass	30.0 kg/kwe
Electric power at 1 AU	10.0 kwe
Propulsion system mass	300 kg
Effective jet velocity	31.8825 km/sec
Efficiency (jet power/electric power)	0.530
Initial acceleration	4.28×10^{-4} m/sec^2
Initial thrust angle	106.5 degrees
Thrust Off Conditions:	
Time	545.4 days
Thrust angle	20.49 degrees
Thrust factor	0.08985
Arrival Conditions (Cross Jupiter's Orbit, 5.2 AU):	
Flight time	900 days
Heliocentric flight angle	3.889 radians
Propellant mass used	165.38 kg
Net spacecraft mass	311.62 kg
Radial velocity relative to Jupiter	3.510 km/sec
Tangential velocity relative to Jupiter	-4.607 km/sec
Hyperbolic excess velocity at Jupiter	5.792 km/sec
Electric power at Jupiter	0.606 kwe

The corresponding departure and arrival dates for the 1974-1978 launch era are:

Depart Earth Orbit	Arrive Jupiter Orbit
Mar 28, 1974	Sep 13, 1976
May 4, 1975	Oct 20, 1977
Jun 7, 1976	Nov 24, 1978
Jul 10, 1977	Dec 27, 1979
Aug 11, 1978	Jan 27, 1981

FIGURE 7 shows a plot of the trajectory and FIGURE 8 gives trajectory profile curves for this mission.

In the next period, although the present program which is in polar coordinates is limited to two-dimensional transfers, we will be able to use "actual" orbits with planetary ephemerides and specify the departure dates for various flight times. The program will optimize the power level, effective jet velocity and other launch vehicles and



Optimum Heliocentric Jupiter Flyby of a Solar Electric Propelled Spacecraft

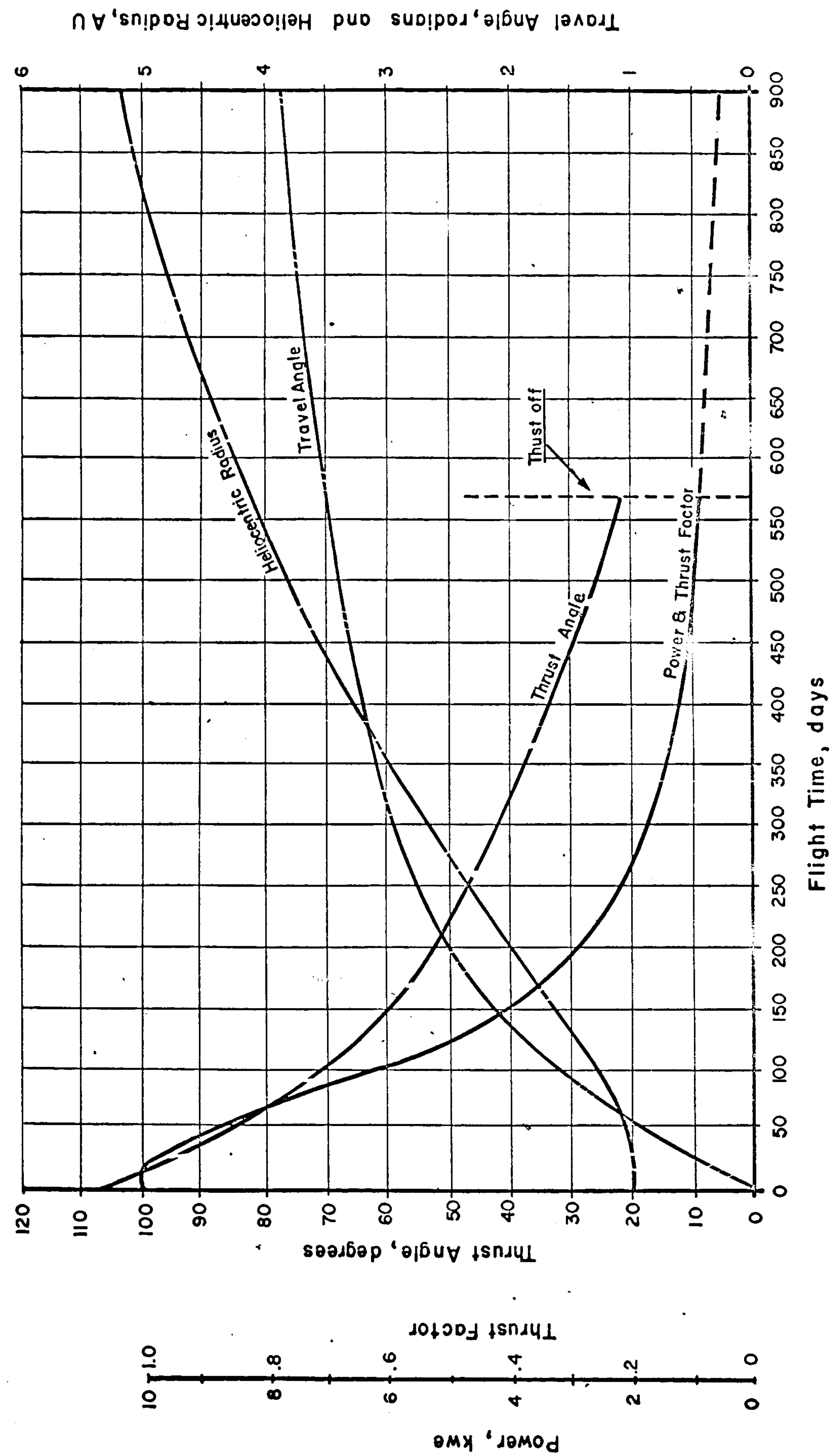
$V_{ej} = 31.8825$ km/sec

$F/m_0 = 0.426 \times 10^{-3}$ m/sec ^{2}

Depart on May 4, 1975

Travel Time 900 days

FIGURE 7



Trajectory Profile for a Solar-Powered Electric Propelled Jupiter Flyby

FIGURE 8

technology will be assumed. Additional details such as spacecraft and other constraints will be included.

C. Other Mission Studies

The characteristics of solar electric propulsion have led to the search for other missions that lend themselves specially to this new technology. Prospective missions will be discussed in the next report as candidates for inclusion in our studies.

APPENDIX A: References

1. Lazar, J. and Mullin, J. P., A Review of the Role of Electric Propulsion, AIAA Paper No. 66-1025 (Presented at AIAA Third Annual Meeting, Boston, Massachusetts, November 29-December 2, 1966).

2. Stearns, J. W. and Kerrisk, D. J., Solar-Powered Electric Propulsion Systems - Engineering and Applications, AIAA Paper No. 66-576. (Presented at AIAA Second Propulsion Joint Specialist Conference, Colorado Springs, Colorado, June 13-17, 1966).

3. Olson, R. N. and Molitor, J. H., Solar Powered Electric Propulsion Program Summary Report, Hughes Report No. SSD 60374R, December 1966.

APPENDIX B:

PRINCETON UNIVERSITY
Department of Aerospace and Mechanical Sciences

As of 1 October 1966

AEROSPACE SYSTEMS AND MISSION ANALYSIS RESEARCH (ASMAR) PROGRAM

Personnel List

Administrative	J. P. Layton, Research Leader	pt
	F. Allison, Senior Project Secretary	ft
	(, Project Secretary	ft)
Spaceflight Trajectory Analysis Research	P. M. Lion, Asst. Prof. (Asst. Res. Ldr.)	1/2t
	A. E. Miller, Programmer	ft
	G. A. Hazelrigg, Grad Student (PhD Cand)	(on leave)
	S. M. Rocklin, Grad Student (MSE Cand)	1/2t
	J. P. Peltier, Grad Student (MSE Cand)	1/2t
	M. Minkoff, Grad Fellow (MSE Cand)	1/2t,nc
	R. A. Philips, Undergraduate Student '67	pt
Aerospace Systems Analysis Research	J. P. Layton, Senior Research Engineer	1/4t
	R. Vichnevetsky, Visiting Research Scientist	1/5t
	P. M. Williams, Research Staff Member	pt
	M. J. Flynn, Undergraduate Student '67	pt
Planetary-Interplanetary Mission Analysis Research	J. P. Layton, Senior Research Engineer	1/4t
	A. B. Shulzycki, Programmer	ft
	J. S. Wood, Grad Fellow (MSE Cand)	1/2t,nc
	J. E. Kerr, Undergraduate Student '67	pt
	E. J. Sarton, Undergraduate Student '68	pt

Consultants:

L. Crocco, Professor	pt,nc
D. Graham, Professor	1/6t
J. Grey, Associate Professor	pt,nc
R. G. Jahn, Associate Professor	pt,nc
R. A. Phinney, Associate Professor	pt,nc
M. Handelsman, Professor (Drexel)	1/5t
A. E. Bryson, Professor (Harvard/MIT)	pt
G. Leitmann, Professor (U.of Cal.,Berkeley)	pt

Subcontracts:

AMA - S. Pines, H. Kelley, et al.	pt
RCA - C. Gordon	1/2t

APPENDIX C: Princeton University Computer Center Capability and Planning, As of 1 April 1966

Professor Edward J. McCluskey, who is the director of the Computer Center, will be replaced by Mr. Roald Buhler, currently an assistant director, as of 1 July 1966. Mr. Hale F. Trotter is the associate director and programming manager; Mr. Theodore A. Dolotta is an assistant director; Mr. Edward G. Aubin, Jr., assistant to the director; Messrs. R. Baumberg, A. M. Jones, Jr. and L. Young are programming staff members; and Mr. A. B. Adams is operations manager.

The Princeton University Computer Center comprises all of the stored-program computer installations on campus. The major installation, which is located in the Engineering Quadrangle, includes an IBM 1410 computer, an IBM 7094 computer with an associated cathode ray tube display system, and an IBM 7044-1401 computer system. At the Forrestal Research Campus there is an IBM 1410 computer system at the Plasma Physics Laboratory, and IBM 360 model 40 computer at the Princeton-Pennsylvania Accelerator, and an IBM 1620 computer in the Guggenheim Laboratories for the Aerospace Propulsion Sciences. In addition, the Computer Center administers twenty hours per week of University use of a CDC 1604 computer owned by the Institute for Defense Analyses and housed in von Neumann Hall adjoining the campus.

An IBM system 360/50 will be installed on main campus in the latter half of 1966. This 360/50 will be replaced by an IBM 360/67 twin processor system in the summer of 1967 at which time the Computer Center will occupy a new building.

All of the computers are available only to University students and staff. No charges are ever made for computer time. There are opportunities for any student or staff member to operate each of the computers himself, and special operators are normally provided only at the Engineering Quadrangle installation. The Computer Center staff provides training seminars on the use of specific programming languages and a daily clinic is conducted by a staff member to provide individual help for specific problems. It is the responsibility of the problem originator to carry out the detailed preparation of his program.