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TRAJECTORIES FOR THE 1976-1980 GRAND TOUR OPPORTUNITIES
Volume I: Graphic and Summary Trajectory Data

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Volume II, NASA CR-61305, contains tabulated trajectory data.

16. ABSTRACT

A close encounter with a planet on a flyby (swingby) trajectory has the effect of a propulsive maneuver on the heliocentric trajectory, thereby resulting in an increase of energy, decrease of energy or a plane change and energy change. Graphic and summary tabular data are presented for swingby missions that collectively encounter all five outer planets. Three mission types

- Jupiter-Saturn-Uranus-Neptune
- Jupiter-Uranus-Neptune
- Jupiter-Saturn-Pluto

are considered. Data for powered maneuvers in the vicinity of Jupiter and Saturn that change the pericenter radius are presented. The earth launch opportunities are for the time period 1976-1980.

17. KEY WORDS

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FOREWORD

This document presents the results of work performed by Lockheed's Huntsville Research & Engineering Center while under subcontract to Northrop Space Laboratories (NSL PO 5-09287) in support of the Aero-Astrodynamics Laboratory of Marshall Space Flight Center (MSFC), Mission Support Contract NAS8-20082. This task was conducted in response to the requirement of Appendix F, Schedule Order No. 44, Technical Directive No. 1.

The NASA technical coordinator for this study was Mr. Bobby Ellison, PD-DO-P, Marshall Space Flight Center, Alabama.

ACKNOWLEDGEMENT

Grateful acknowledgement is extended to Mr. Richard Gold for his contributions to the preparation of this report. His assistance in computing communication and orientation angles and in interpreting the results has added significantly to this Volume's contents.

CONTENTS

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Section 1
INTRODUCTION

The five outer planets, Jupiter, Saturn, Uranus, Neptune, and Pluto, are promising sources of scientific information. Space missions to these planets could produce much data concerning their atmospheric composition, interior properties, magnetic fields, and radiation patterns. However, direct ballistic missions to some of these planets require prohibitively large launch energies or extremely long flight times. Previous studies (Refs. 1 and 2) have shown that significant heliocentric energy changes can be obtained in passing an intermediate planet on a multi-planet mission. By proper selection of swingby planet encounter date and passage trajectory, it is possible to gain energy and thereby to reach portions of the solar system that are unattainable with the original launch energy. During the period from 1976 to 1980, an excellent opportunity for swingby missions to the outer planets occurs. It is possible during this time period to encounter as many as four of the five outer planets on a single mission. Such an opportunity does not occur again for approximately 179 years.

The purpose of this report is to present trajectory data for multi-planet swingby missions to the outer planets during the period from 1976 to 1980. A multitude of data is required to describe the swingby trajectories of interest. Volume II, which is available from the technical coordinator of this study on request, contains tabulated trajectory data. For an overall view of the feasible trajectories, the present volume which contains trajectory data in graphic and in summary tabular forms is much more useful. The data presented were generated with the LMSC SWISTO computer program, which is a medium-accuracy, patched-conic trajectory program (Ref. 3).

Mission Types

Three types of missions are considered in this volume. The planets which are encountered define the mission type.

The first mission type is the Jupiter-Saturn-Uranus-Neptune mission. This mission is referred to as a "Grand-Tour" by many authors. Five Earth launch opportunities occur for this mission from 1976 to 1980. For this mission type both powered and unpowered swingby trajectories are considered. The powered trajectory is a corrected pericenter maneuver, which is explained more fully in Section 4. This maneuver is used to increase the radius of closest approach if necessary or to avoid passing through the rings of Saturn.

An alternate method to avoid possible contact with the rings of Saturn is not to encounter that planet. The resulting mission type is a Jupiter-Uranus-Neptune mission. Three Earth launch opportunities occur for this mission in 1978, 1979, and 1980.

The third mission type is a Jupiter-Saturn-Pluto mission. Due to the relative positioning of Uranus, Neptune, and Pluto during this time period (Pluto is behind Uranus and Neptune), it is not feasible to encounter all five outer planets on one mission; however, a mission to Jupiter, Saturn, and Pluto is possible. Four Earth launch opportunities for this mission occur between 1976 and 1979.

Summary of Sections

In Section 2 three representative missions are presented. Important trajectory parameters are given in a table and the trajectories are depicted on a mission profile chart.

Section 3 contains contours plotted on graphs of Earth departure date versus Jupiter passage date. Contours of constant Earth departure energy, of constant departure asymptote declination, and of constant hyperbolic excess velocity at Jupiter are plotted.

In Section 4, quad- and triad-graphs are presented and explained. These charts depict the trip time and radius of closest approach at each planet for the three mission types.

Section 5 contains tables of representative Grand Tour Missions of short, medium and long duration. The length of the mission is related to the distance of passage at Saturn.

Section 6 discusses the energy cost of decreasing trip time. Graphs of minimum total trip time as a function of Earth launch energy are presented.

Section 7 contains a list of references and a general bibliography of papers pertaining to outer solar system missions.

Section 2
REPRESENTATIVE MISSIONS

Trajectories that are representative of the three mission types have been chosen. For convenience, the Jupiter-Saturn-Uranus-Neptune, Jupiter-Uranus-Neptune, and Jupiter-Saturn-Pluto missions are called missions A, B, and C, respectively.

Important parameters of these three trajectories are presented in Table 2-1. The first section of the table describes the Earth departure. The departure date (the Adjusted Julian Date is the Julian Date -2440000.), the launch energy C_3, and the declination δ and the right ascension α of the departure asymptote are given. The subsequent sections of the table describe planet passage trajectories. The encounter date, the hyperbolic excess velocity V_∞, the periplanet radius r_p, the periplanet velocity V_p, the inclination of the passage hyperbola to the planet equator I_h, the bend angle κ, and the lighting angle η are given. The bend angle is the angle between the incoming and the escape asymptotes; the lighting angle is the angle between the direction of periplanet and the planet-Sun line.

Figure 2-1 is a graphic mission profile of the three representative trajectories. This figure represents to scale the position of the planets at the time that they are encountered on each mission. The remaining figures of this Section depict distances and orientation angles for the representative missions. There are six figures for mission A and five figures for each of the other missions. The first figure for each mission is a graph of the Earth-probe distance and the Sun-probe distance. The second is a graph of the clock and cone angles of Earth from the probe. For each planet encountered on a mission, there is also a graph of the clock and cone angle of the planet as viewed from the probe. Missions A, B, and C are representative of the mission types but are not necessarily practical. For example, from Fig. 2-2 it is evident that Saturn is encountered when it is on the opposite side of the Sun from Earth. Thus, Earth-probe communication would be difficult during Saturn encounter on Mission A.

In Fig. 2-1 the approximate relative positioning of the planets necessary for a multiplanet swingby mission is shown. On each leg of the trajectory from one planet to a second, the first planet must be encountered when it is overtaking the second. If the transfer angle between the two planets is too small, the first planet cannot supply a sufficient increase in the heliocentric energy; if it is too large the trip time is prohibitively large.

The Earth launch opportunity for the Jupiter-Uranus-Nepune mission opens in 1978 and closes in 1980. At 1978 plus a reasonable trip time to Jupiter, Jupiter is coming into the proper position relative to Uranus. At 1980 plus a reasonable trip time to Uranus, the transfer angle from Uranus to Neptune is becoming too small.

The Earth launch opportunity for the Jupiter-Saturn-Pluto mission opens in 1976 and closes in 1979. At 1976 plus a reasonable trip time to Jupiter, Jupiter is coming into the proper position relative to Saturn. At 1979 plus a reasonable trip time to Saturn, the transfer angle from Saturn to Pluto is becoming too small.

The period of 179 years between Grand Tour opportunities is a consequence of the synodic periods of the planets (Table 2-2). The synodic period of two planets is the period between a configuration of those planets and the next repetition of that configuration. There is no simple extension for more than two planets; even assuming circular coplanar orbits a configuration of the planets will not repeat exactly in most cases. However a configuration is repeated approximately at any time that is "close to" integer multiples of all the pairwise synodic periods. From the following set of identities,

9 x Synodic period of Jupiter, Saturn = 178.7 yr.
13 x Synodic period of Jupiter, Uranus = 179.6 yr.
14 x Synodic period of Jupiter, Neptune = 179.0 yr.
4 x Synodic period of Saturn, Uranus = 181.5 yr.
5 x Synodic period of Saturn, Neptune = 179.3 yr.
1 x Synodic period of Uranus, Neptune = 171.4 yr

the approximate period between Grand Tour opportunities is seen to be 179 years, since the timing of the slower moving Uranus-Neptune pair is less critical.

Table 2-1

REPRESENTATIVE TRAJECTORIES

Parameters	Mission A	Mission B	Mission C
Earth Departure Date, A. J. D.	3390	3790	3390
Calendar Date	4 Sept 1977	9 Oct 1978	4 Sept 1977
C_3, km^2/sec^2	116.1	100.2	99.3
δ, deg	25.6	32.0	26.8
α, deg	71.4	98.9	65.8
Second Planet	Jupiter	Jupiter	Jupiter
Encounter Date, A. J. D.	3895	4400	3981
V_∞, km/sec	12.4	9.7	9.7
r_p, planet radii	3.60	2.62	6.01
V_p, km/sec	34.1	38.4	26.4
I_h, deg	5.6	2.2	6.01
κ, deg	99.9	123.5	99.2
η, deg	115.1	119.2	106.2
Third Planet	Saturn	Uranus	Saturn
Encounter Date, A. J. D.	4472	6298	4650
V_∞, km/sec	17.1	14.4	13.7
r_p, planet radii	1.10	2.09	14.4
V_p, km/sec	38.6	20.6	16.7
I_h, deg	29.2	82.2	63.0
κ, deg	84.6	40.0	22.6
η, deg	141.9	100.3	91.4
Fourth Planet	Uranus	Neptune	Pluto
Encounter Date, A. J. D.	5688	7645	7113
V_∞, km/sec	21.6	16.5	14.8
r_p, planet radii	1.41		
V_p, km/sec	28.1		
I_h, deg	79.7		
κ, deg	29.7		
η, deg	110.1		
Fifth Planet	Neptune		
Encounter Date, A. J. D.	6680		
V_∞, km/sec	24.1		
TOTAL TRIP TIME, YEARS	9.01	10.55	10.19

Table 2-2

MEAN MUTUAL SYNODIC PERIODS

Years / Days	Mercury	Venus	Earth	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
MERCURY		0.3958	0.3173	0.2762	0.2458	0.2428	0.2415	0.2412	0.2411
VENUS	144.57		1.5987	0.9142	0.6489	0.6283	0.6197	0.6175	0.6167
EARTH	115.88	583.93		2.1354	1.0921	1.0352	1.0121	1.0061	1.0041
MARS	100.89	333.93	779.95		2.2353	2.0092	1.9240	1.9026	1.8953
JUPITER	89.79	237.00	398.89	816.45		19.8593	13.8125	12.7823	12.4589
SATURN	88.70	229.50	378.10	733.85	7253.61		45.3636	35.8696	33.4338
URANUS	88.22	226.36	369.66	702.73	5045.01	16569.07		171.3892	127.1337
NEPTUNE	88.10	225.55	367.49	694.93	4668.75	13101.37	62599.90		492.3534
PLUTO	88.06	225.26	366.75	692.25	4550.60	12211.71	46435.58	179832.06	

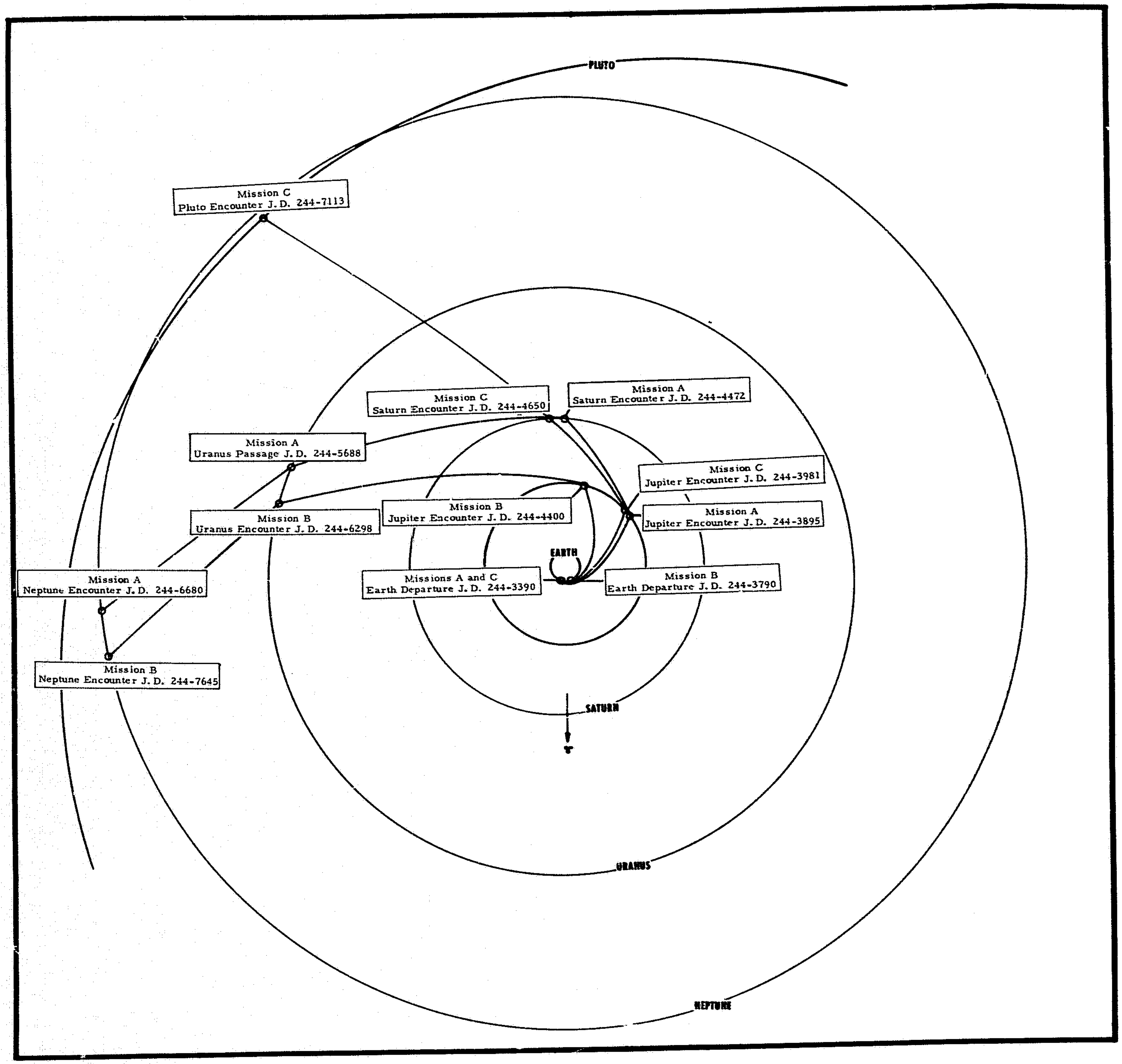
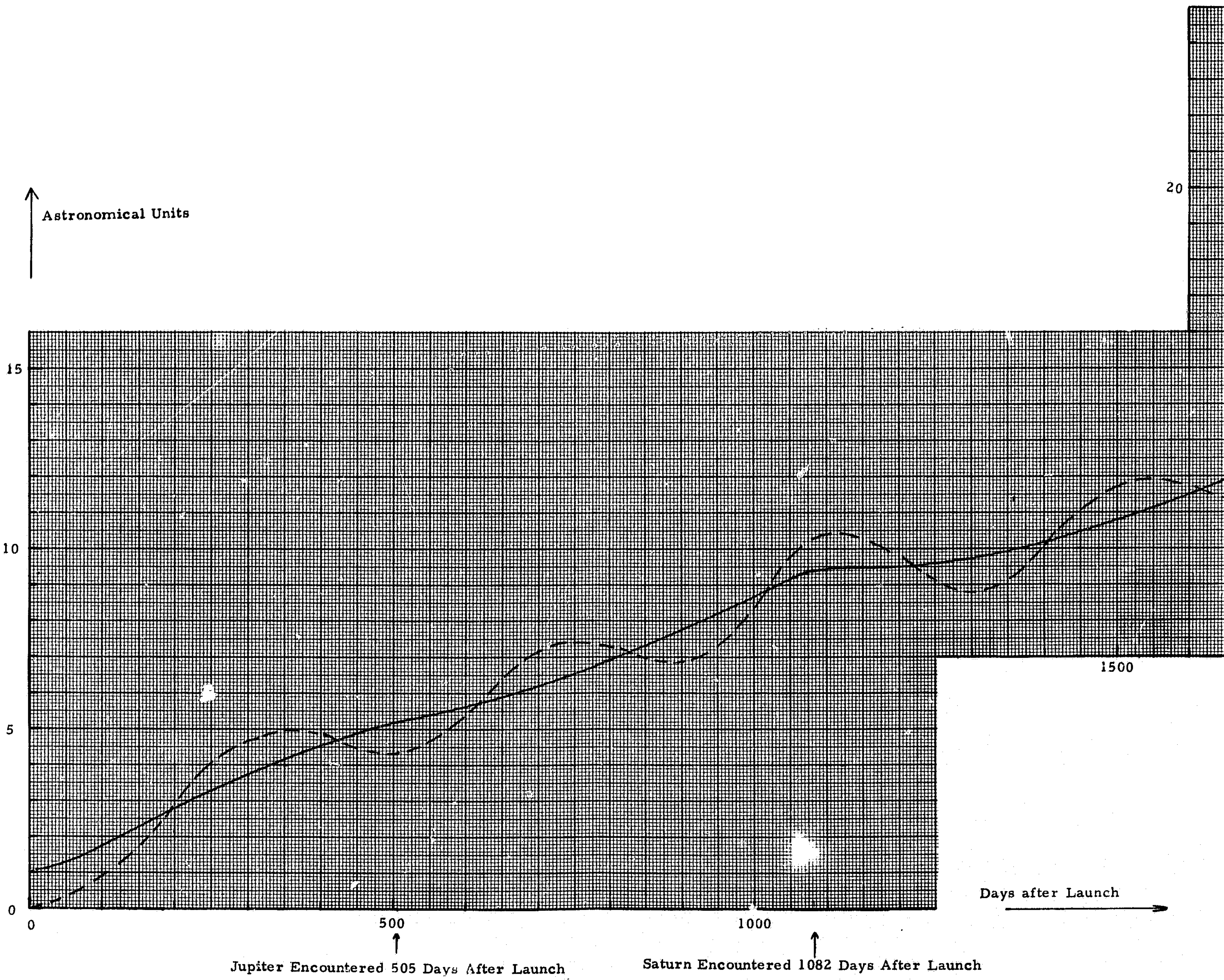


FIGURE 2-1. PROFILES OF THREE MULTIPLANET SWINGBY MISSIONS


Astronomical Units
20
15
10
5
0
0
500
1000
1500
Days after Launch
Jupiter Encountered 505 Days After Launch
Saturn Encountered 1082 Days After Launch

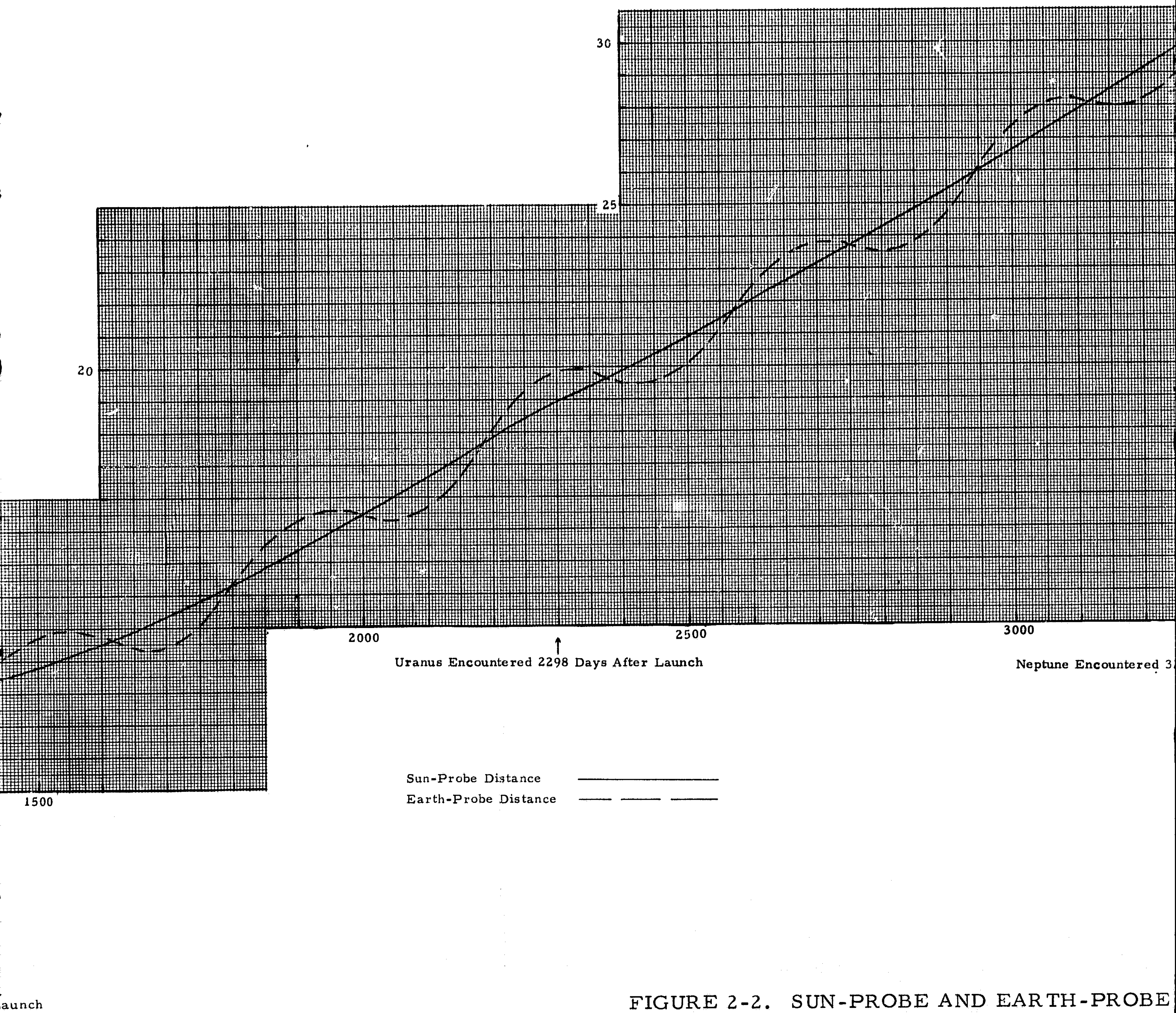


FIGURE 2-2. SUN-PROBE AND EARTH-PROBE
FOR MISSION A

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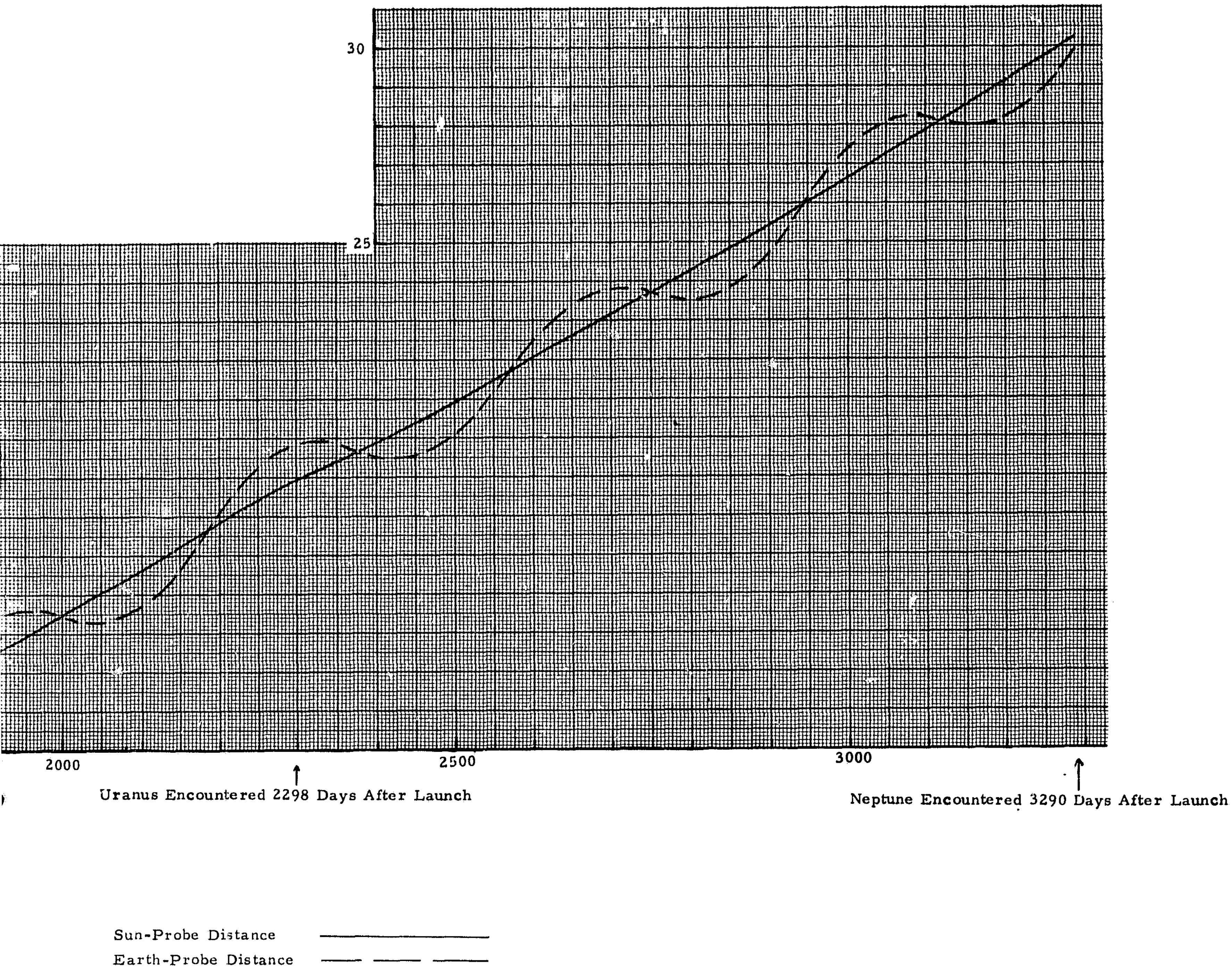

FIGURE 2-2. SUN-PROBE AND EARTH-PROBE DISTANCES FOR MISSION A

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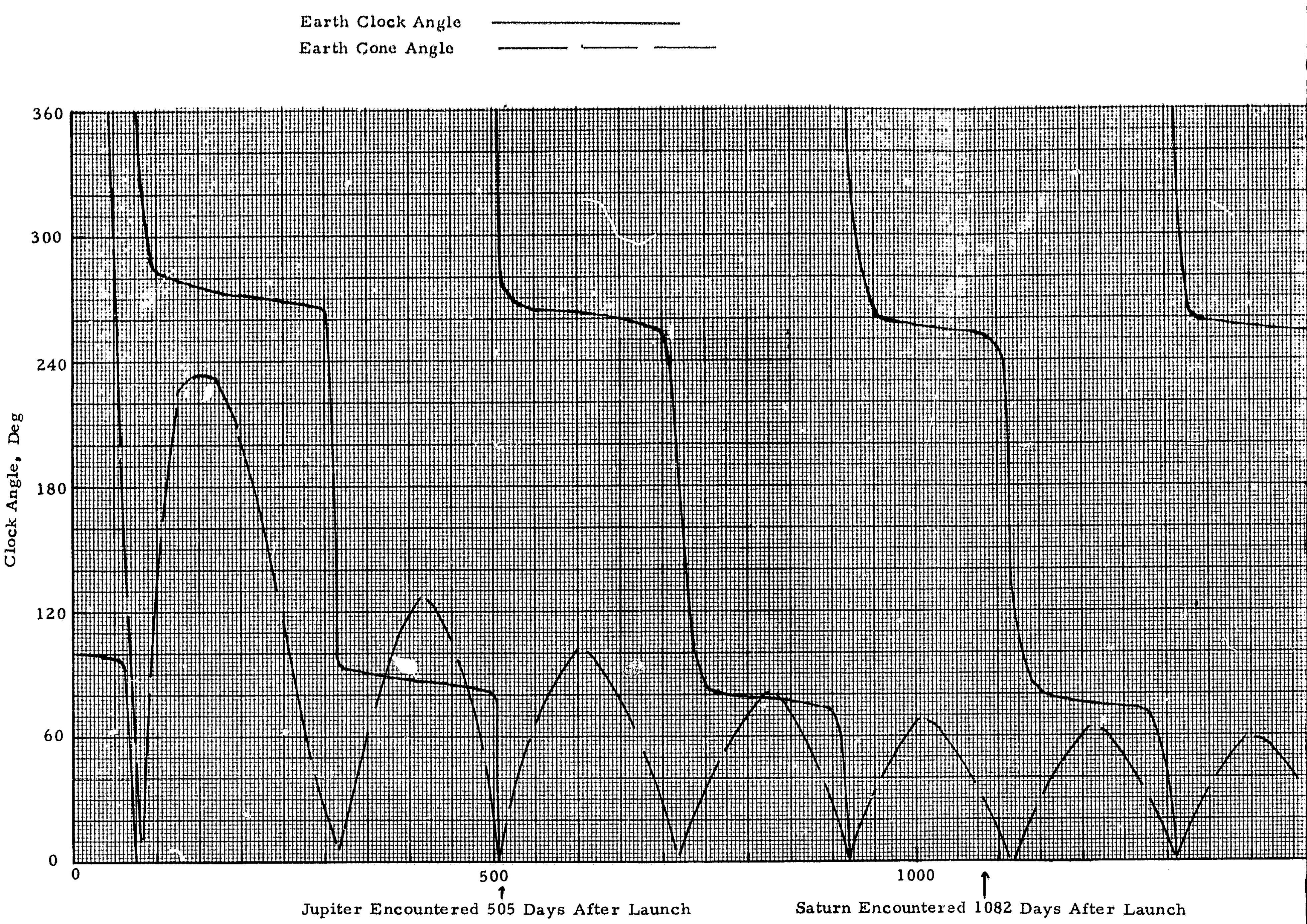

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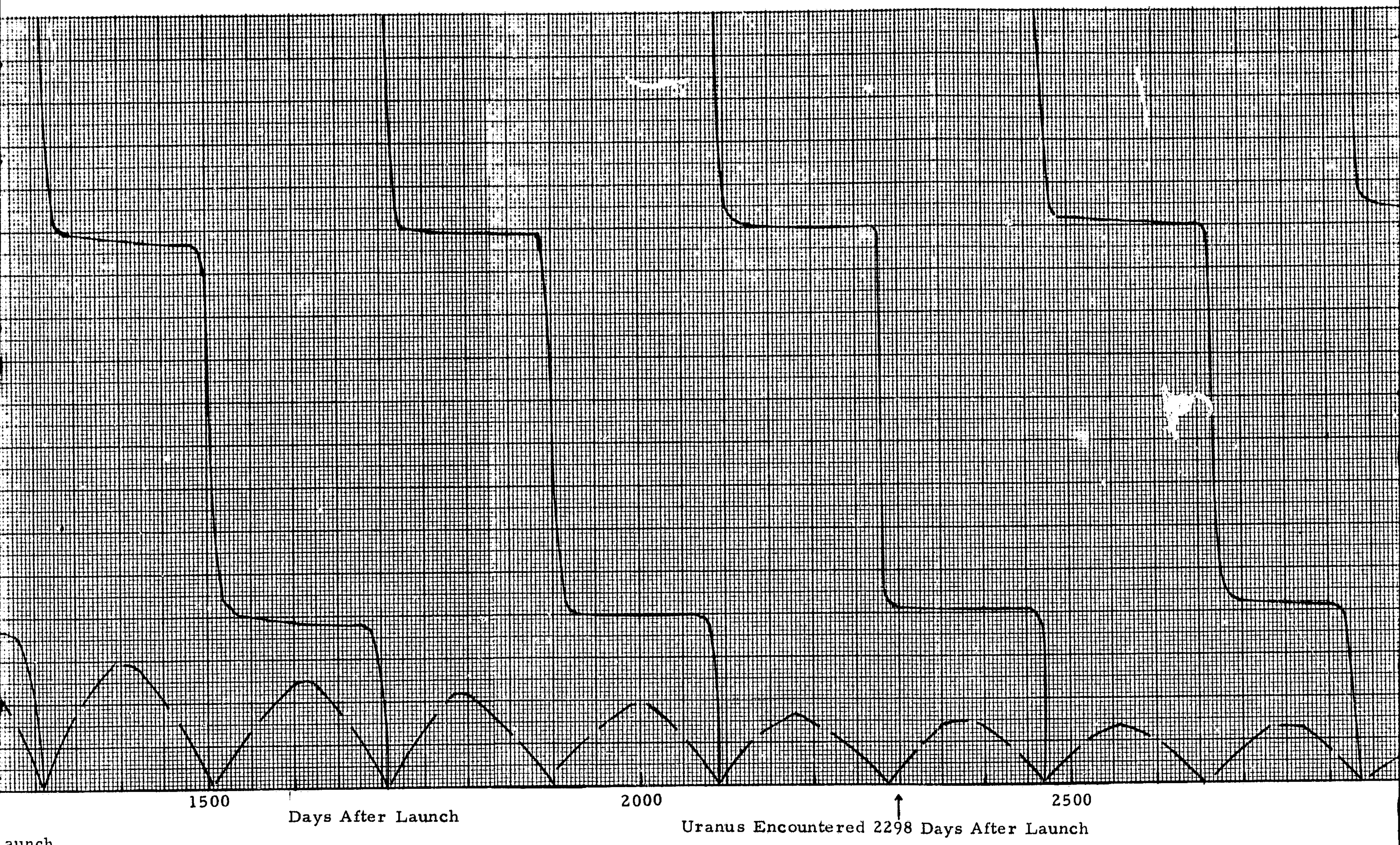

FIGURE 2-3. EARTH CLOCK

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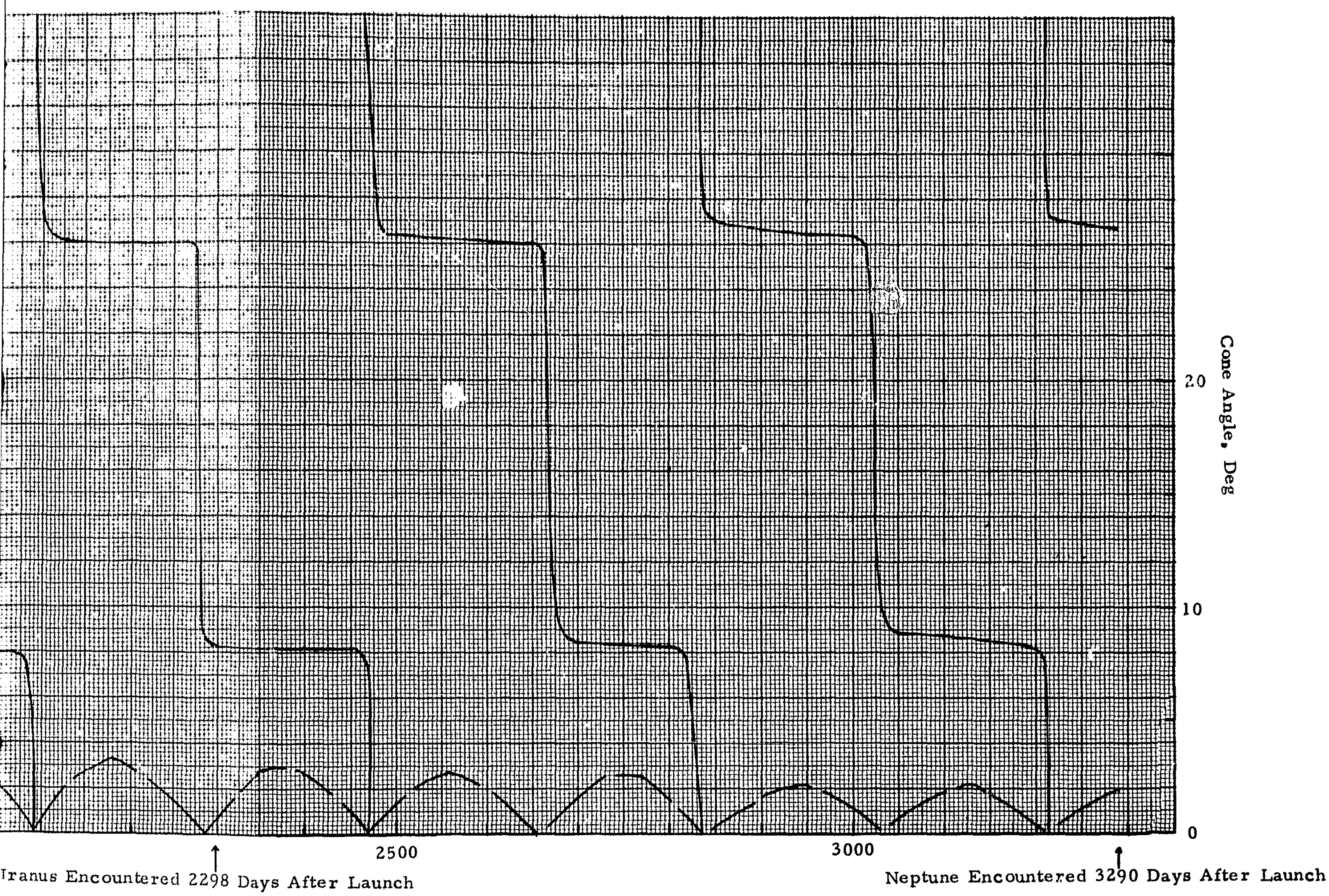

FIGURE 2-3. EARTH CLOCK AND CONE ANGLES FOR MISSION A

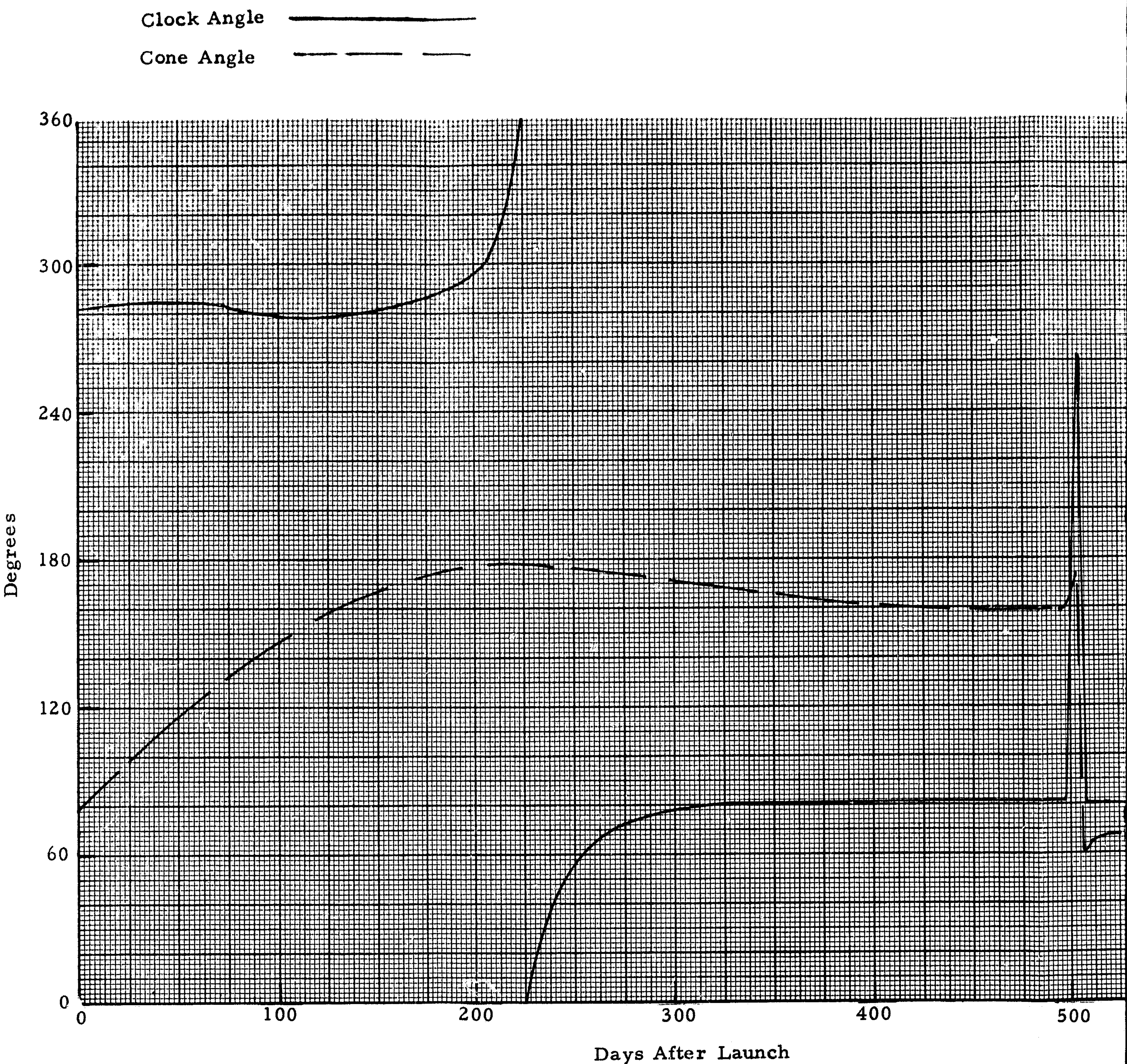

FIGURE 2-4. JUPITER CLOCK AND

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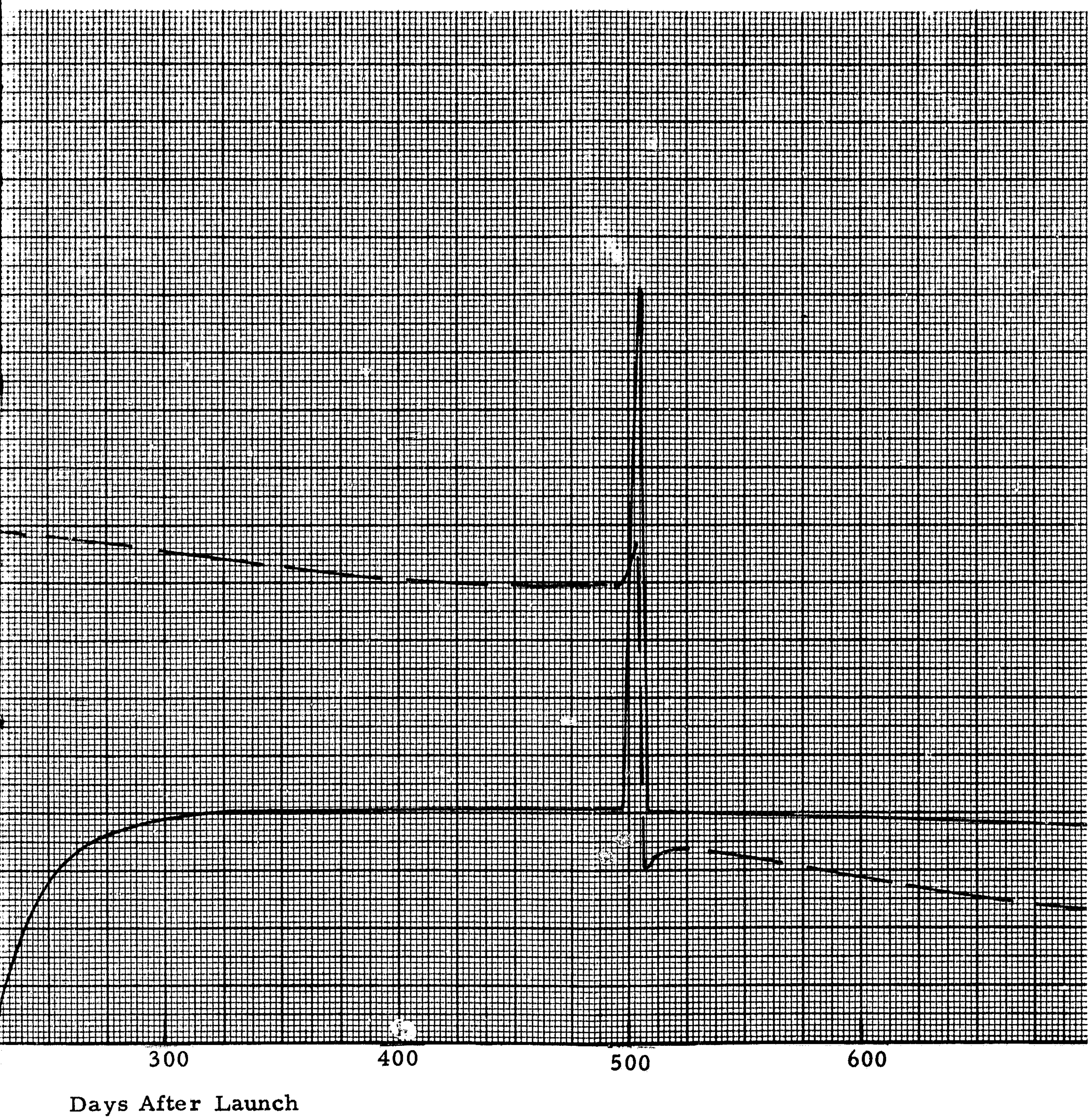

FIGURE 2-4. JUPITER CLOCK AND CONE ANGLES FOR MISSION A

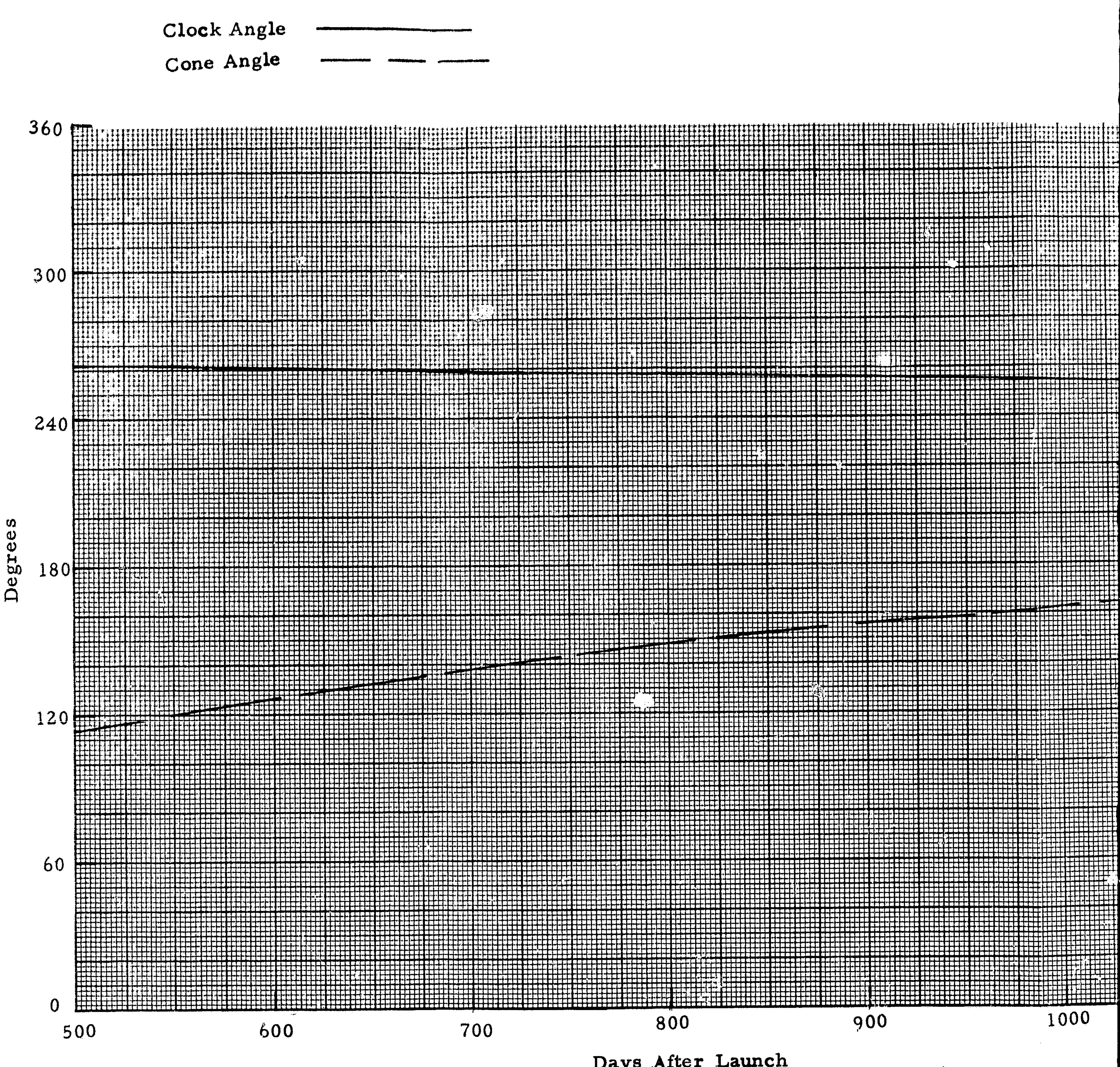

FIGURE 2-5. SATURN CLOCK AND

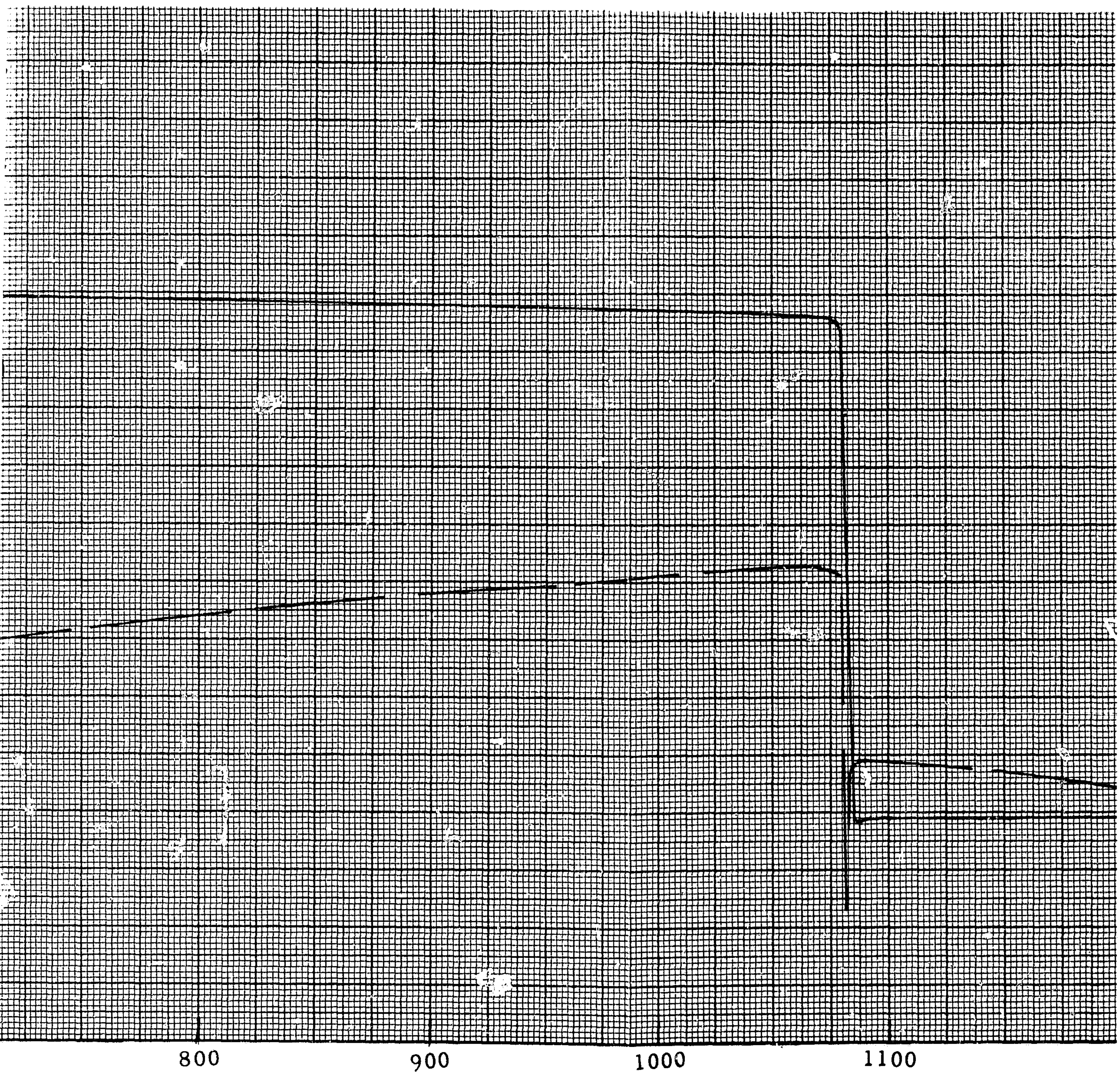

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FIGURE 2-5. SATURN CLOCK AND CONE ANGLES FOR MISSION A

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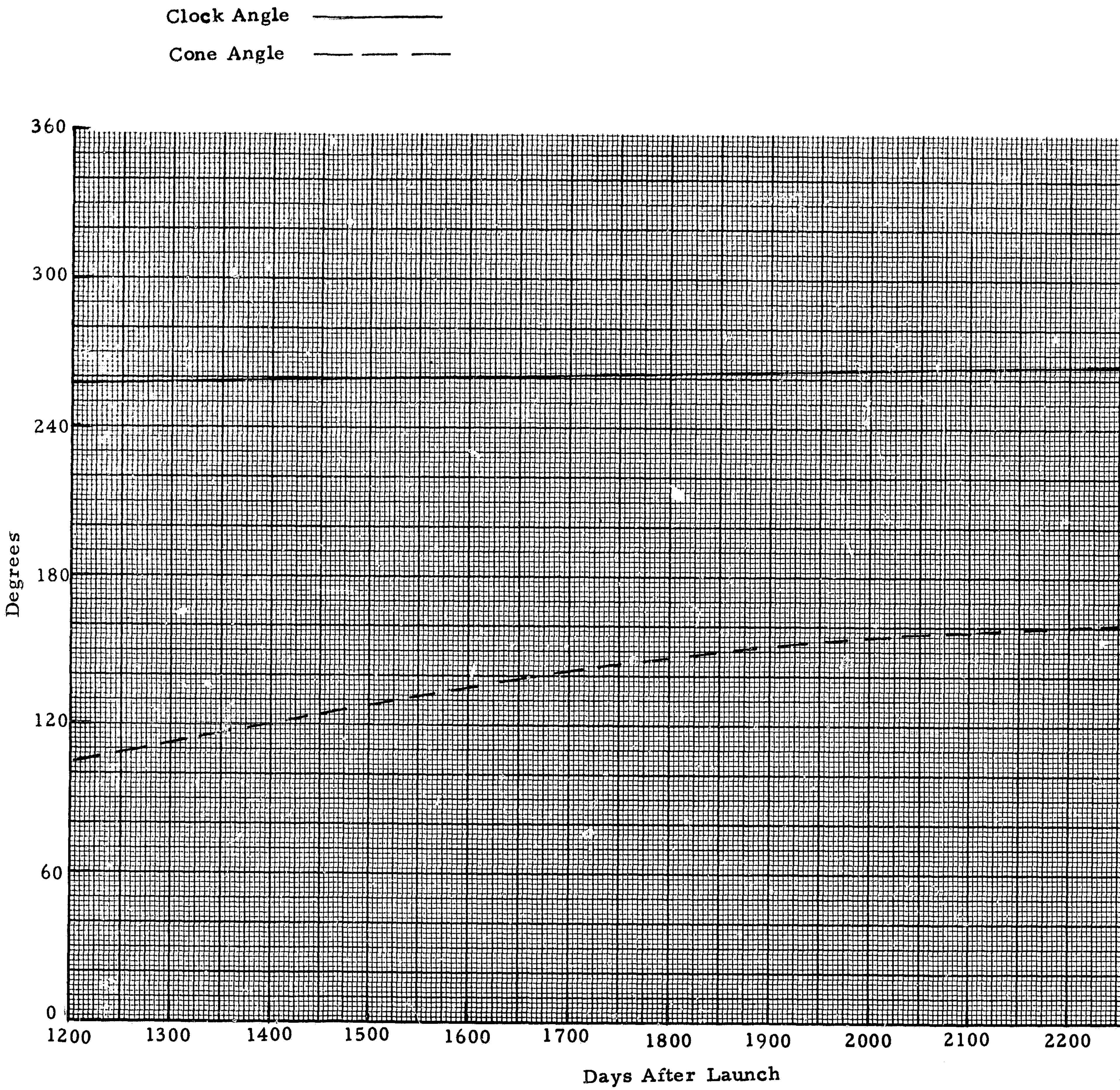

FIGURE 2-6. URANUS CLOCK AND CONE A

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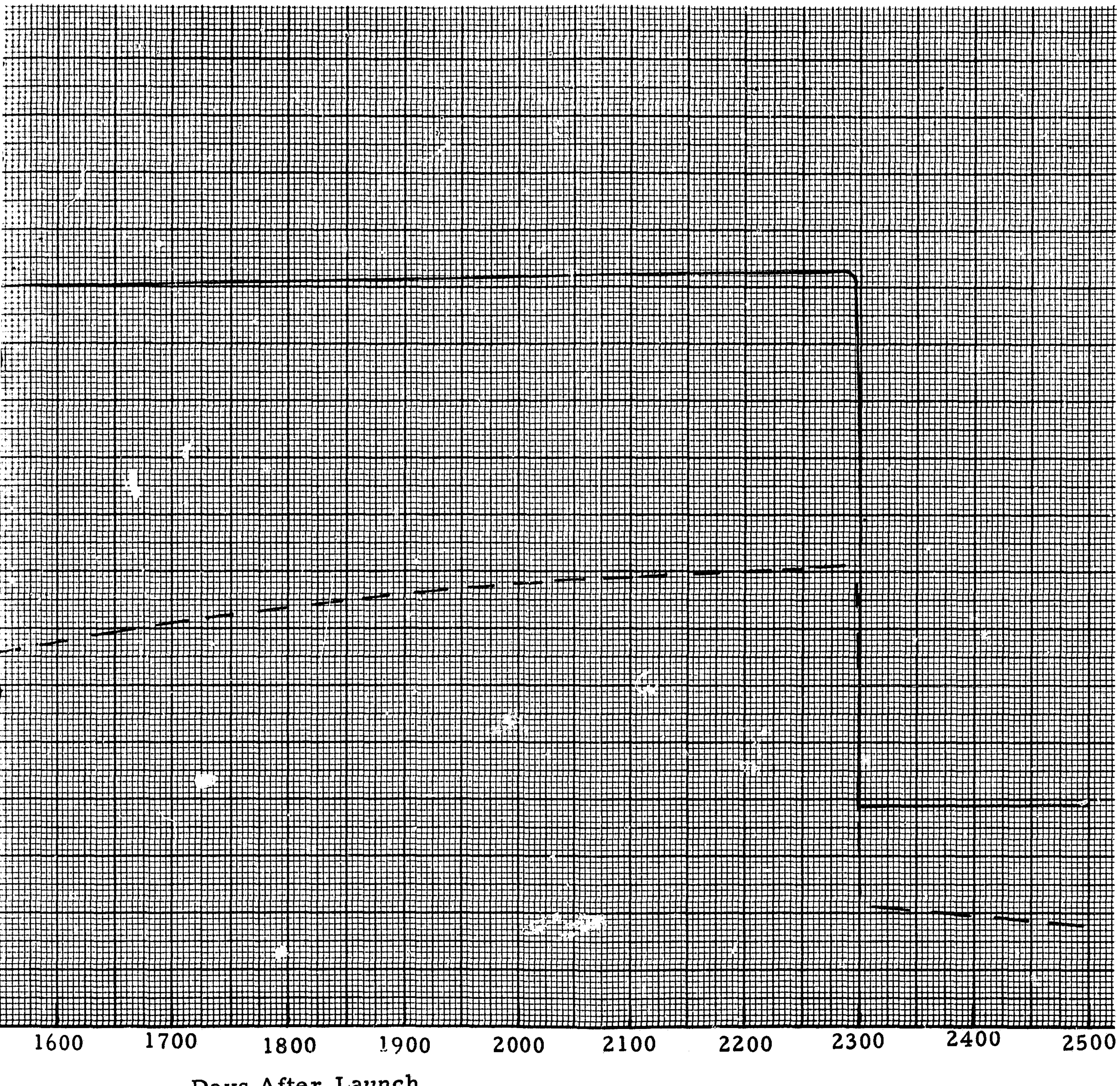
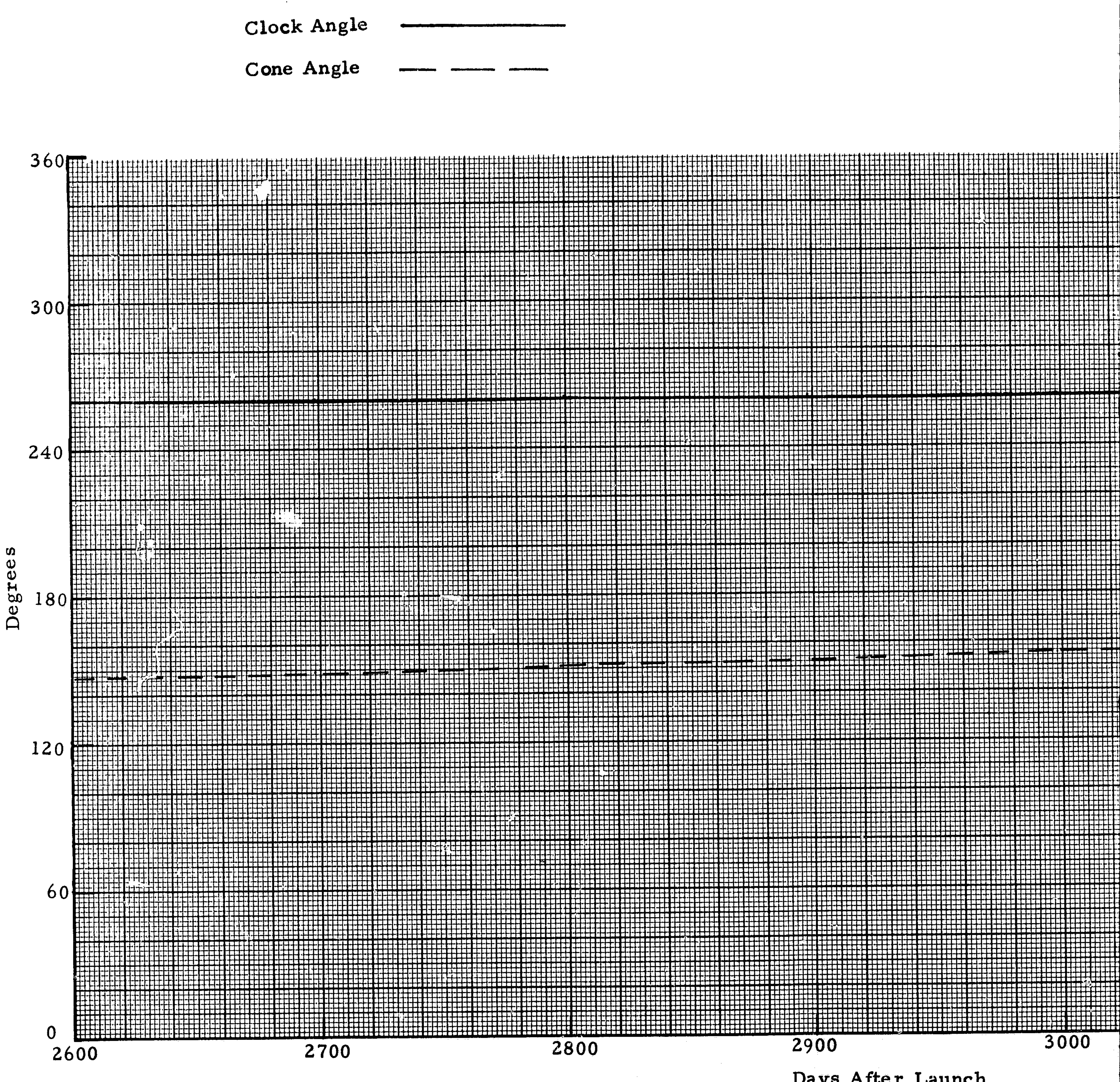


FIGURE 2-6. URANUS CLOCK AND CONE ANGLES FOR MISSION A



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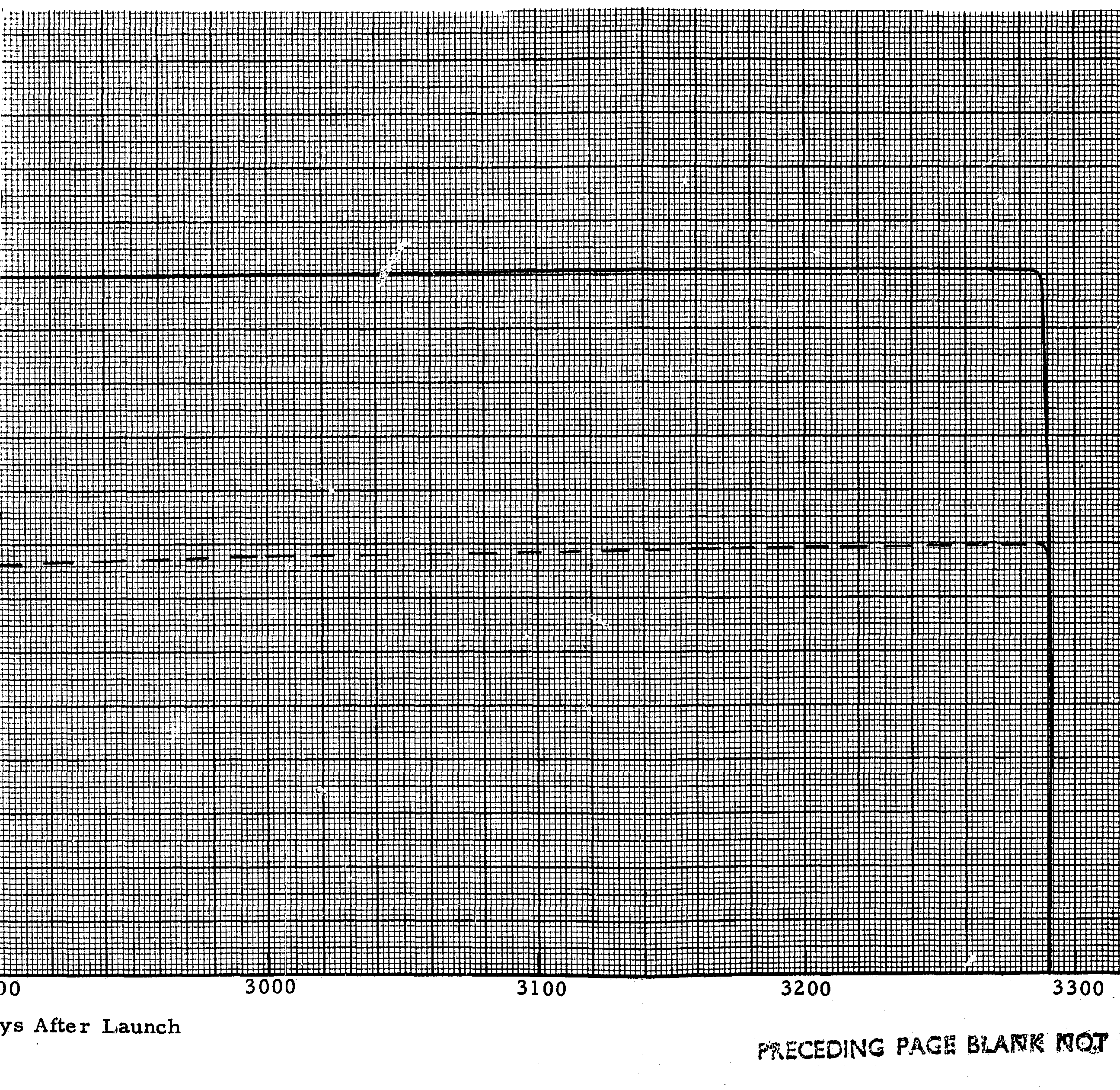

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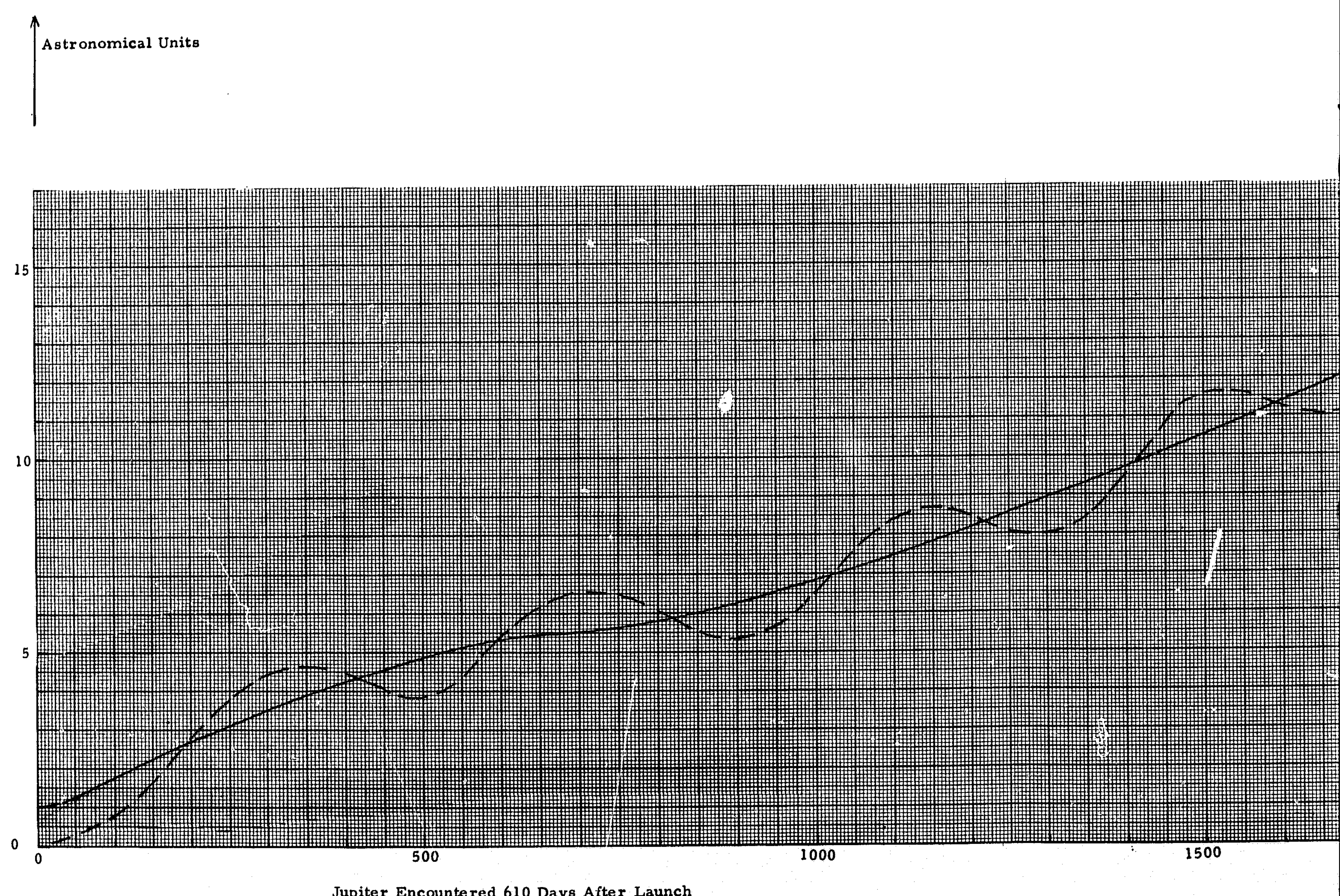
FIGURE 2-7. NEPTUNE CLOCK AND CONE ANGLES FOR MISSION A



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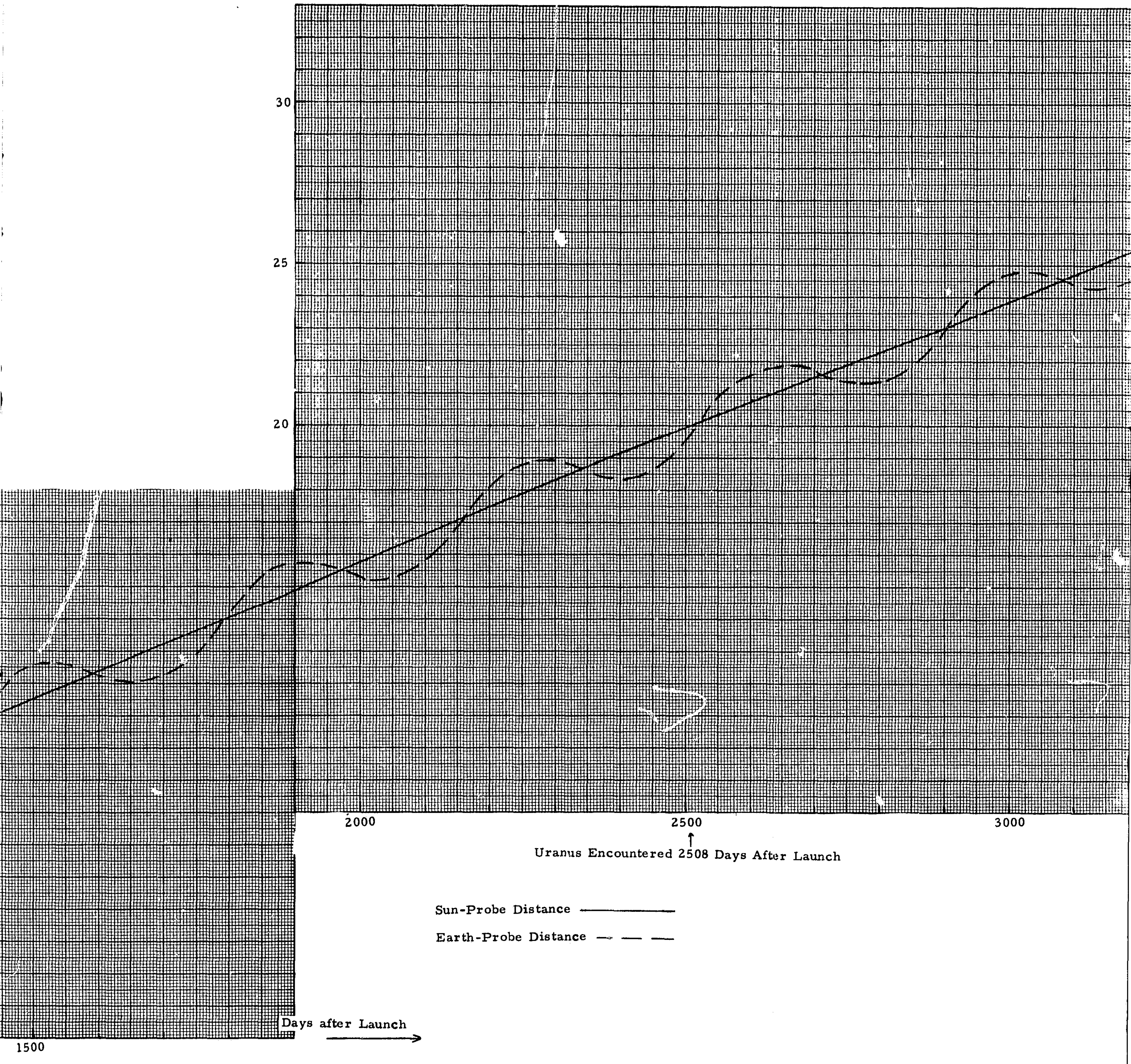

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FIGURE 2-8. SUN-PROBE AND EA

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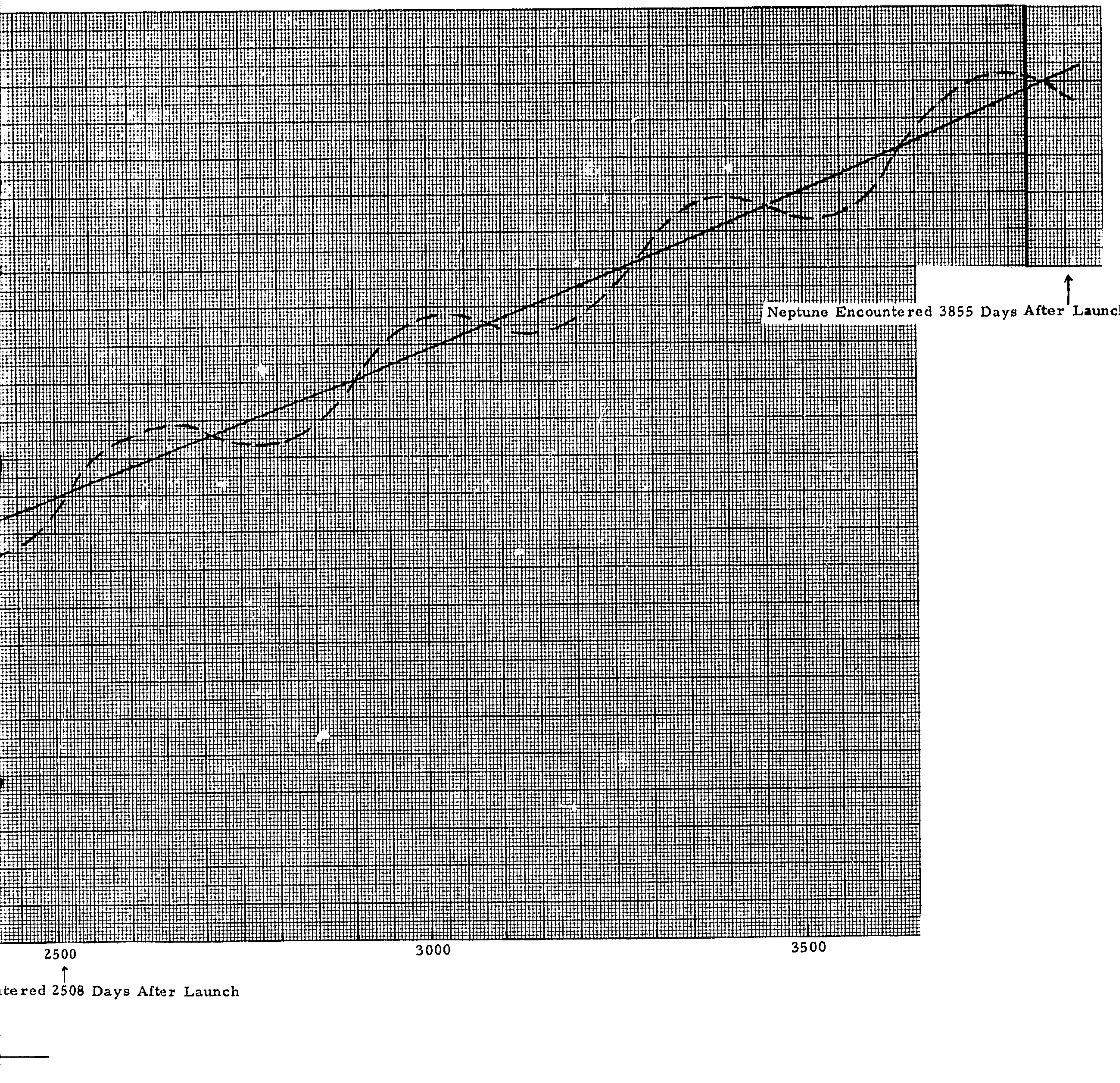

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FIGURE 2-8. SUN-PROBE AND EARTH-PROBE DISTANCES FOR MISSION B

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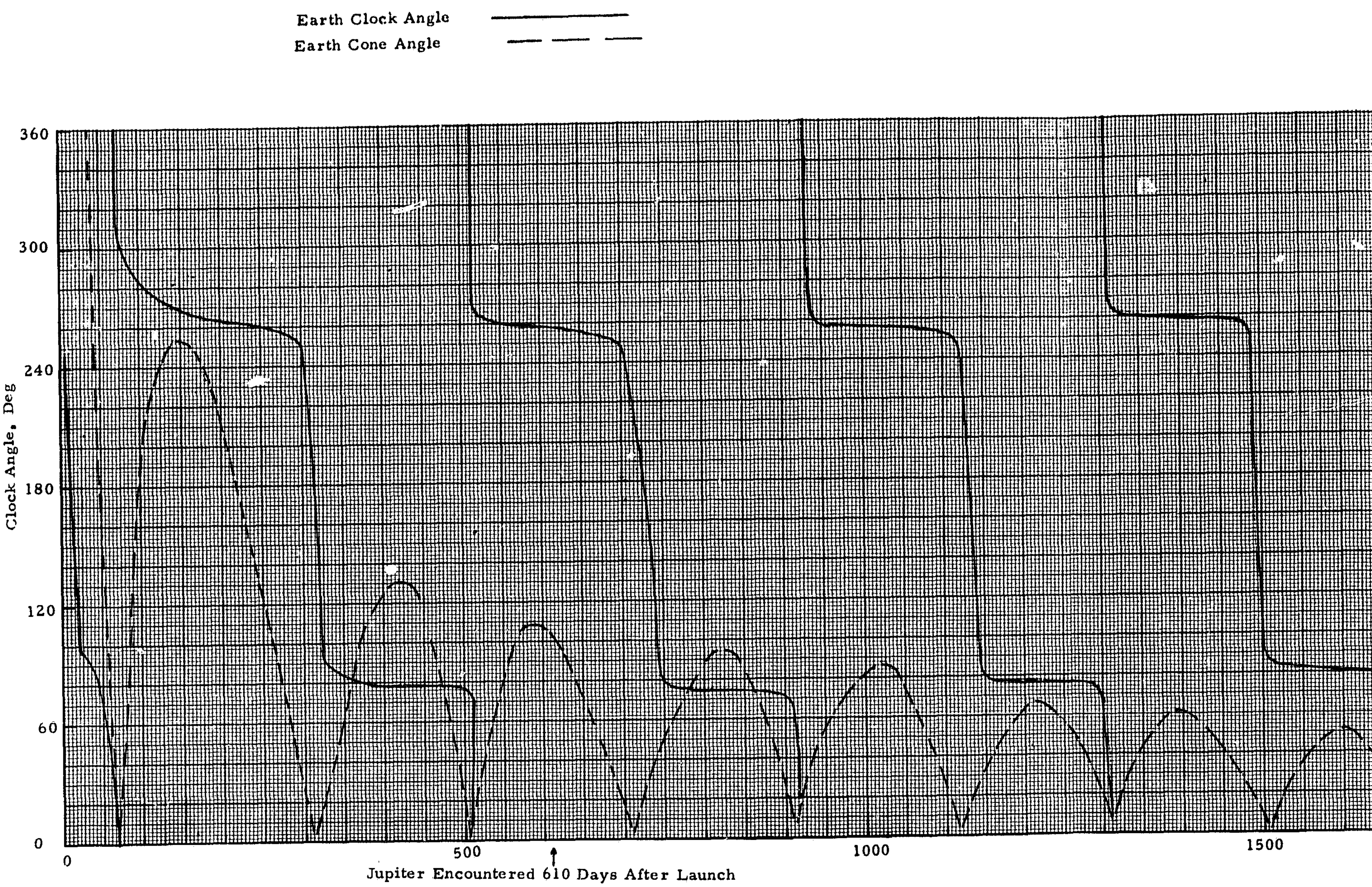

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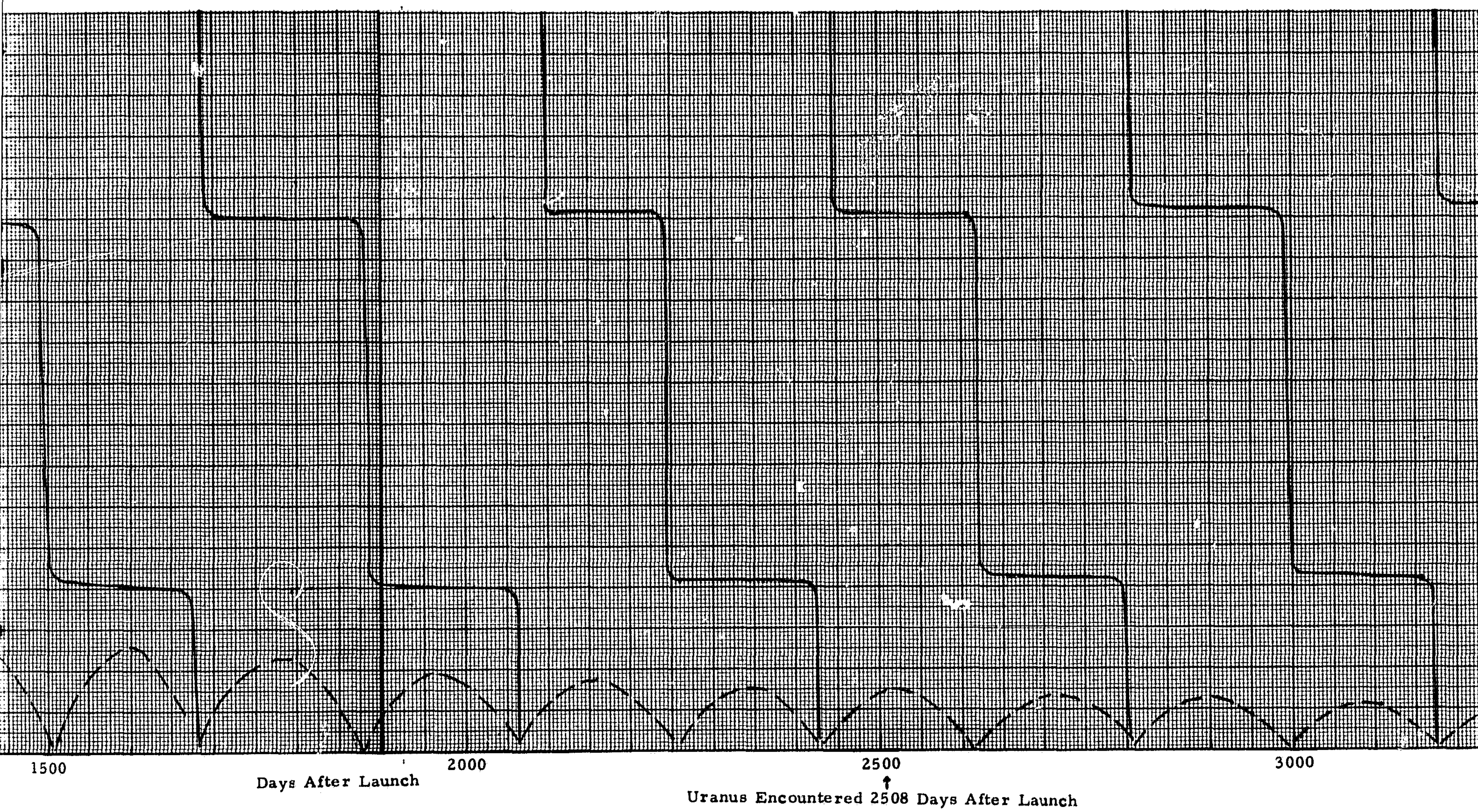

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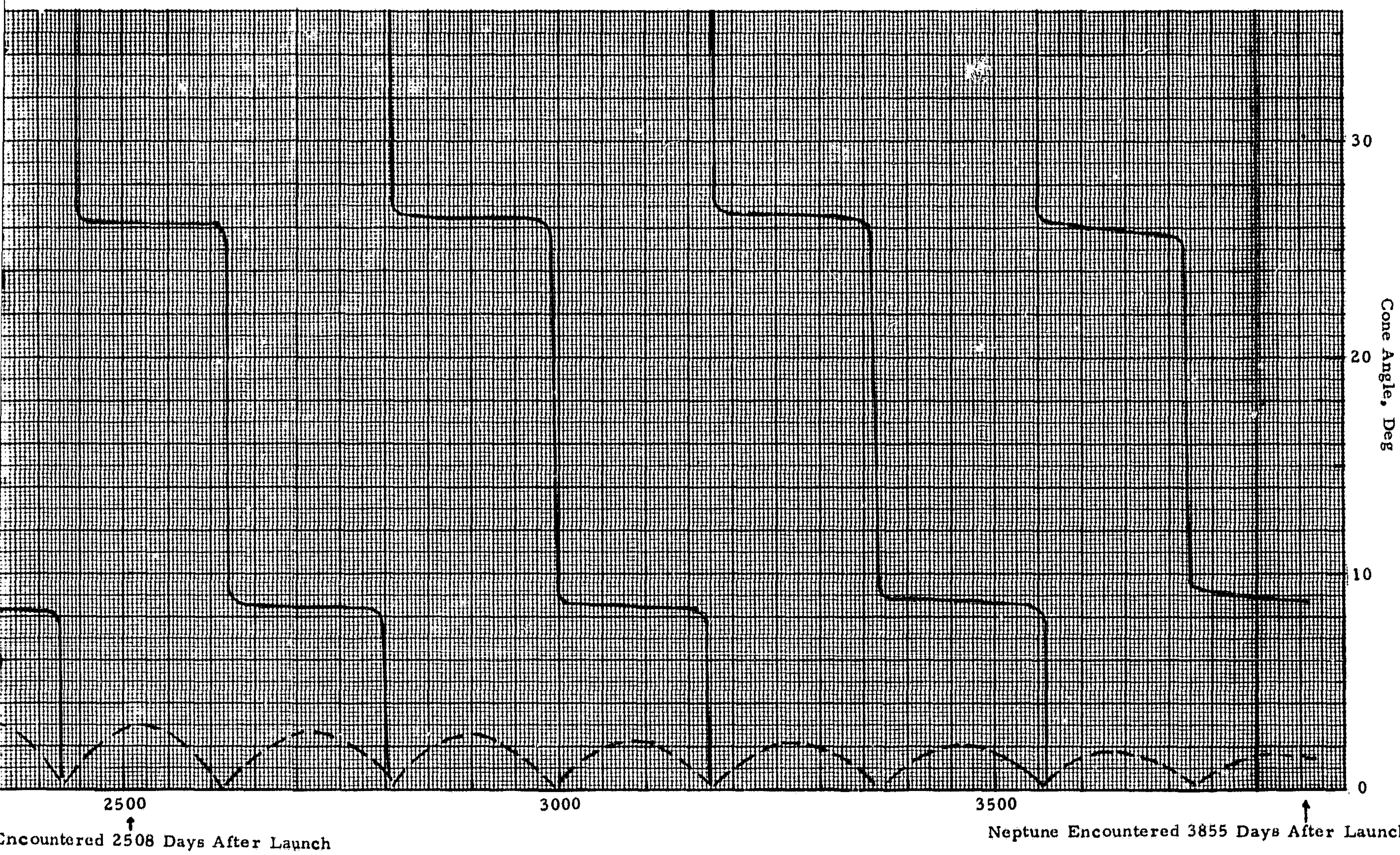
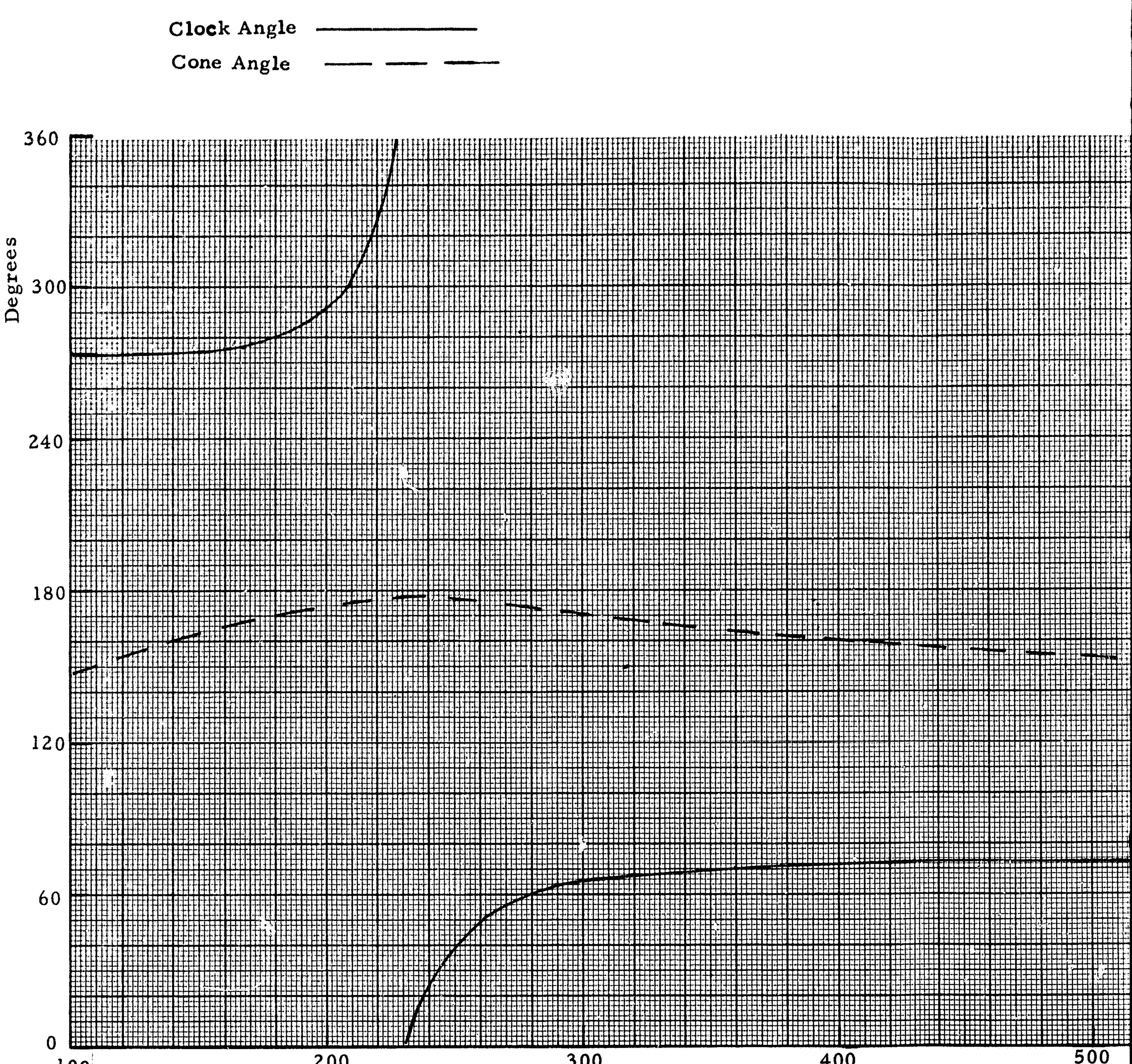


FIGURE 2-9. EARTH CLOCK AND CONE ANGLES FOR MISSION B



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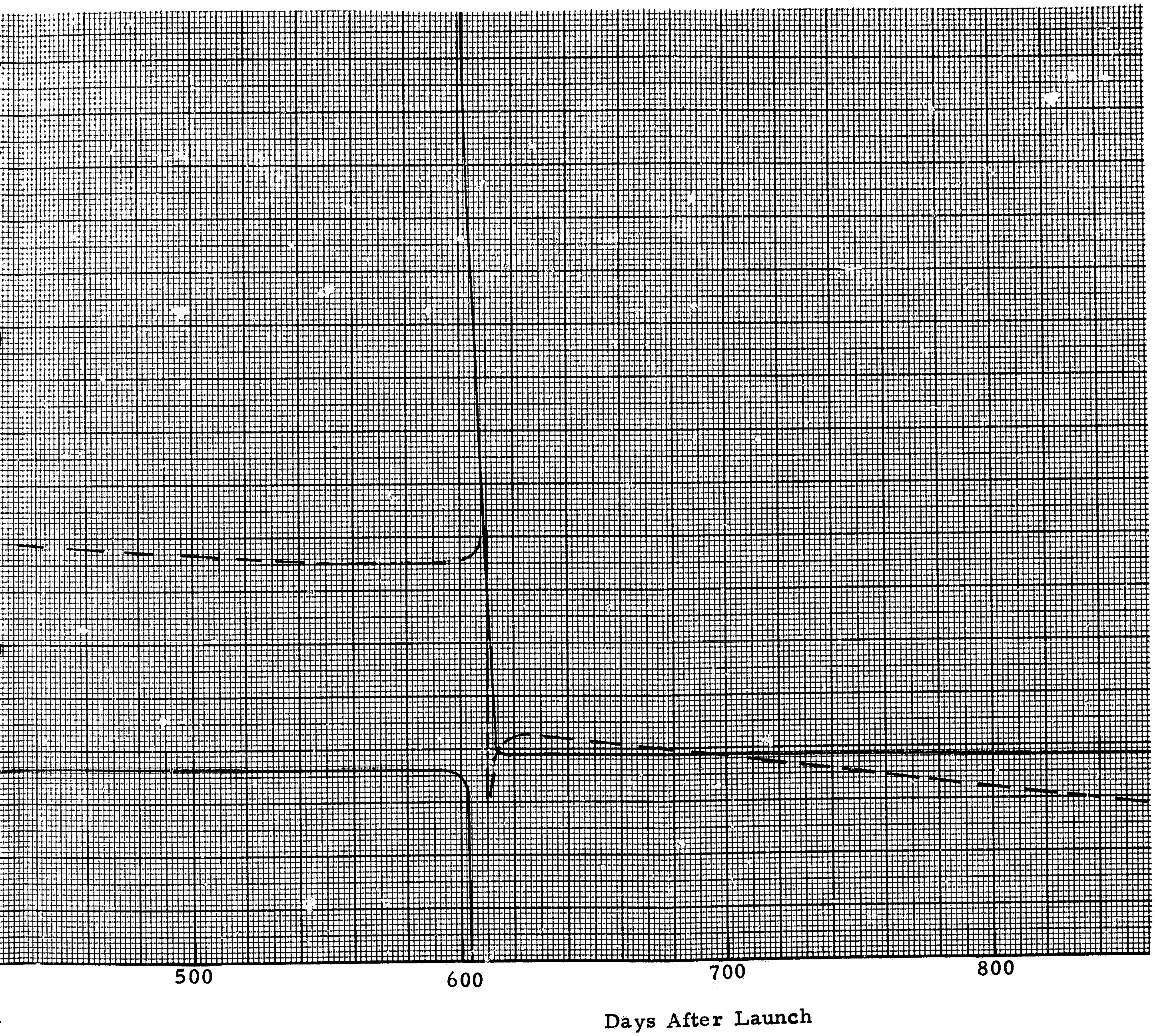
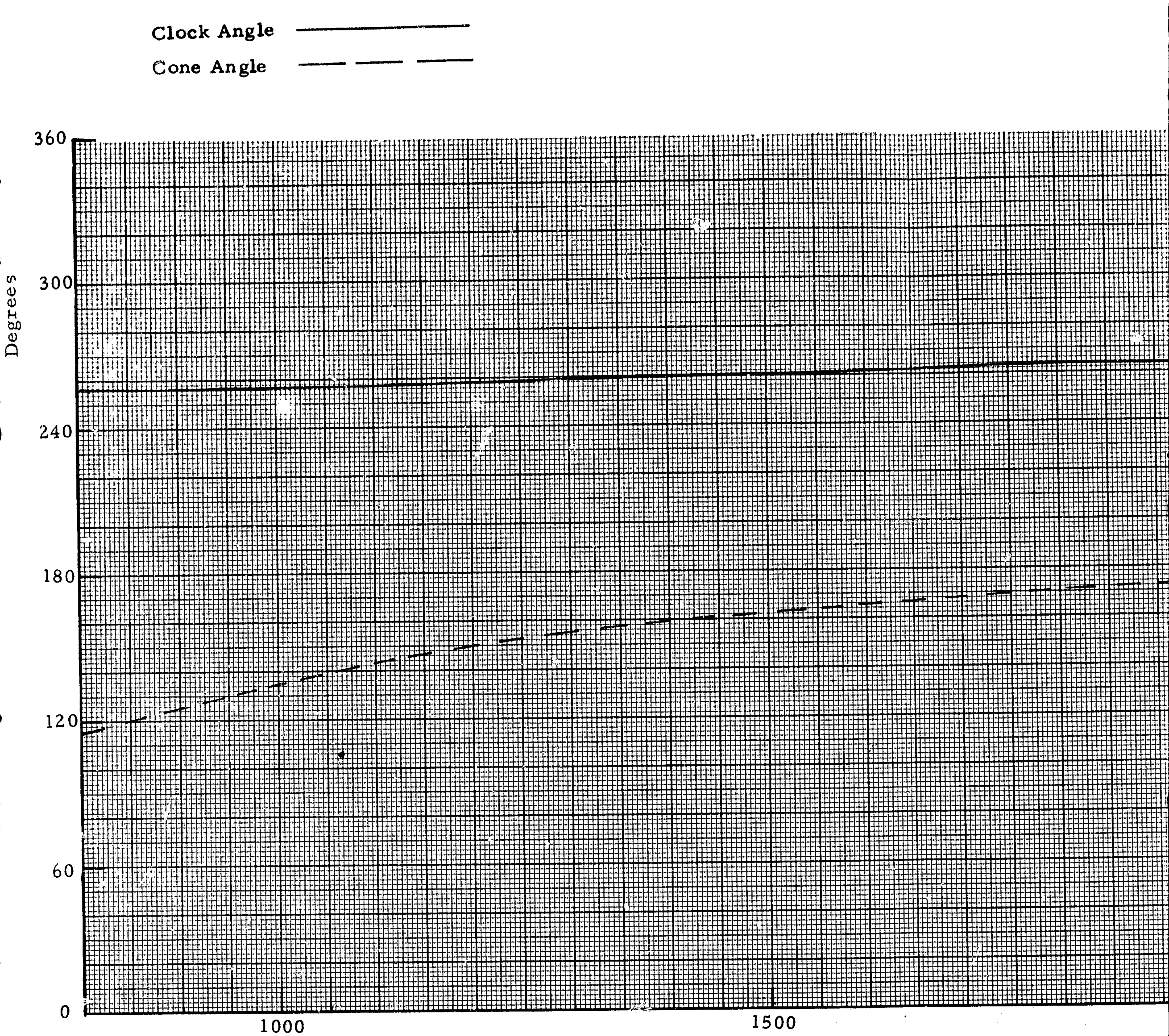


FIGURE 2-10. JUPITER CLOCK AND CONE ANGLES FOR MISSION B



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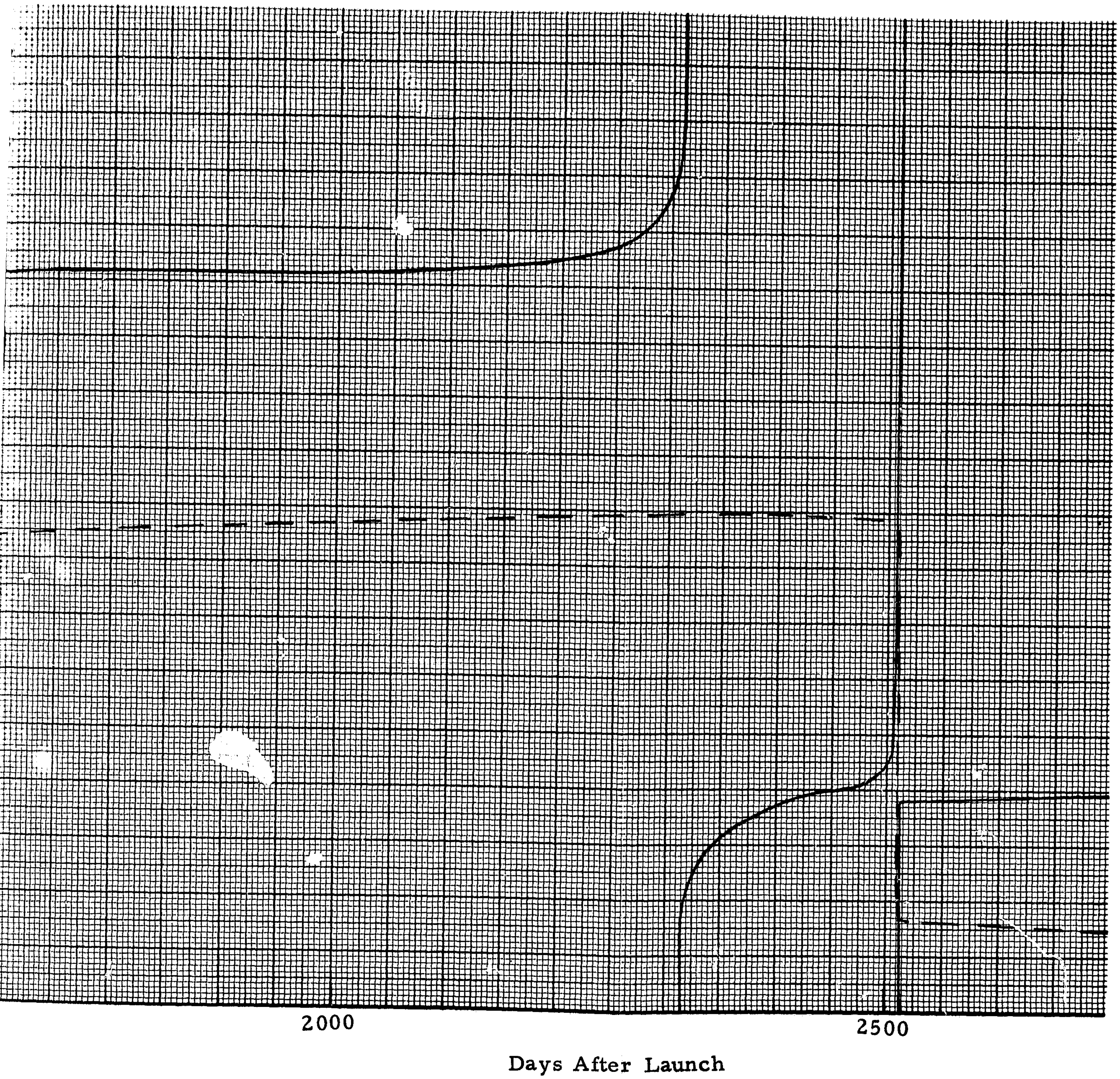

FIGURE 2-11. URANUS CLOCK AND CONE ANGLES FOR MISSION B

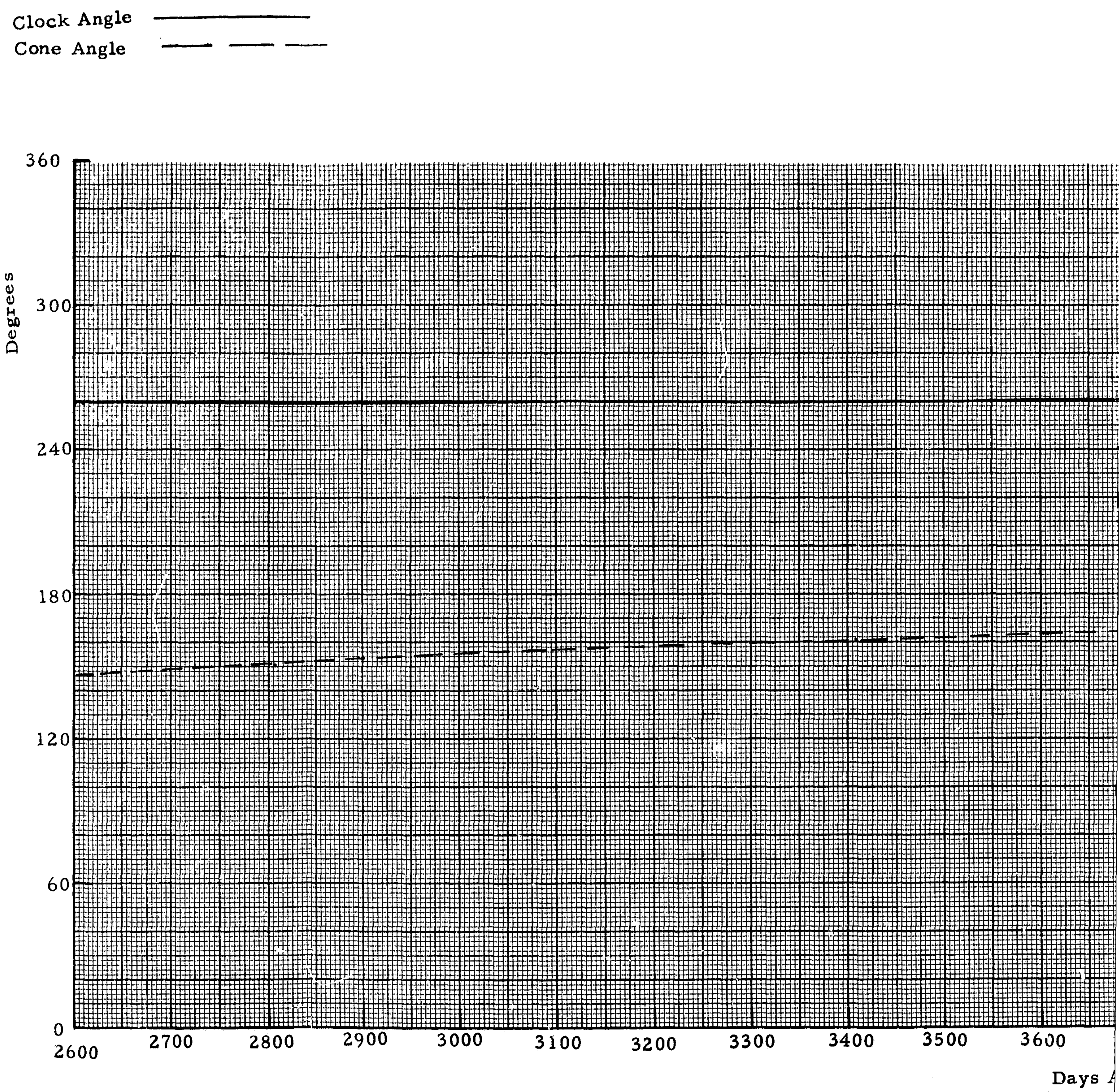

FIGURE 2-12. NEPTUNE CLOCK AND CONE ANGL

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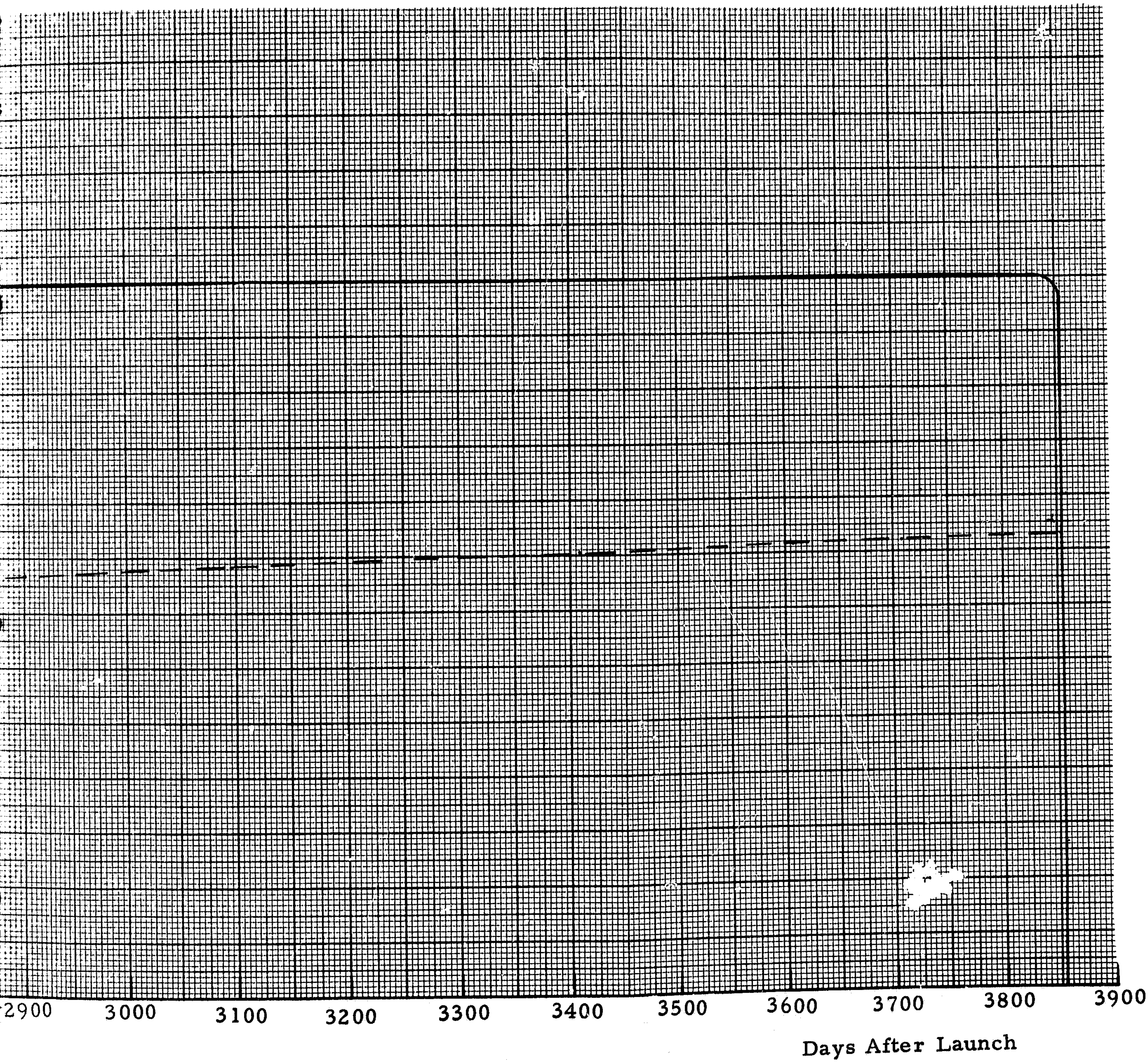

FIGURE 2-12. NEPTUNE CLOCK AND CONE ANGLES FOR MISSION B

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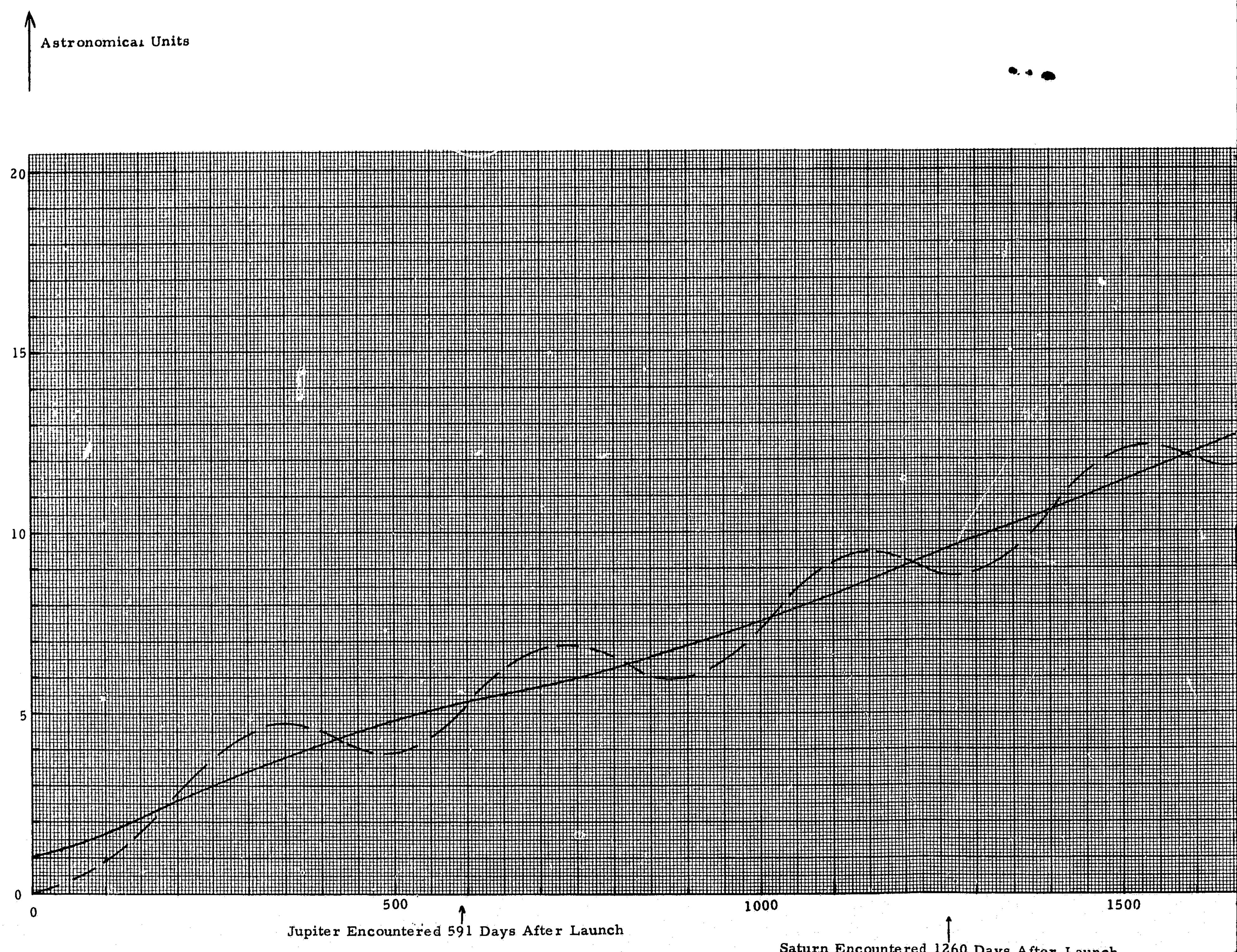

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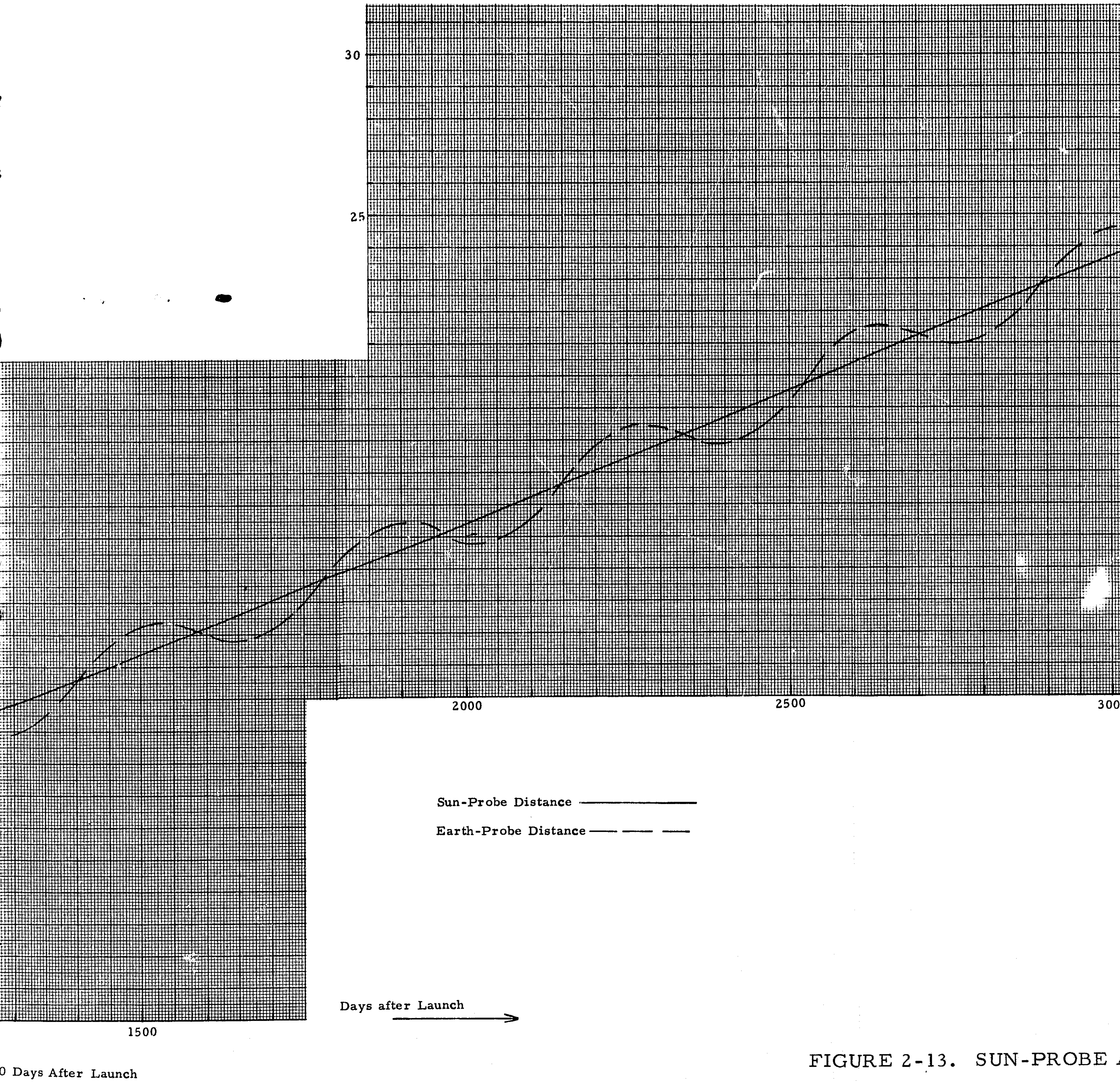

FIGURE 2-13. SUN-PROBE A

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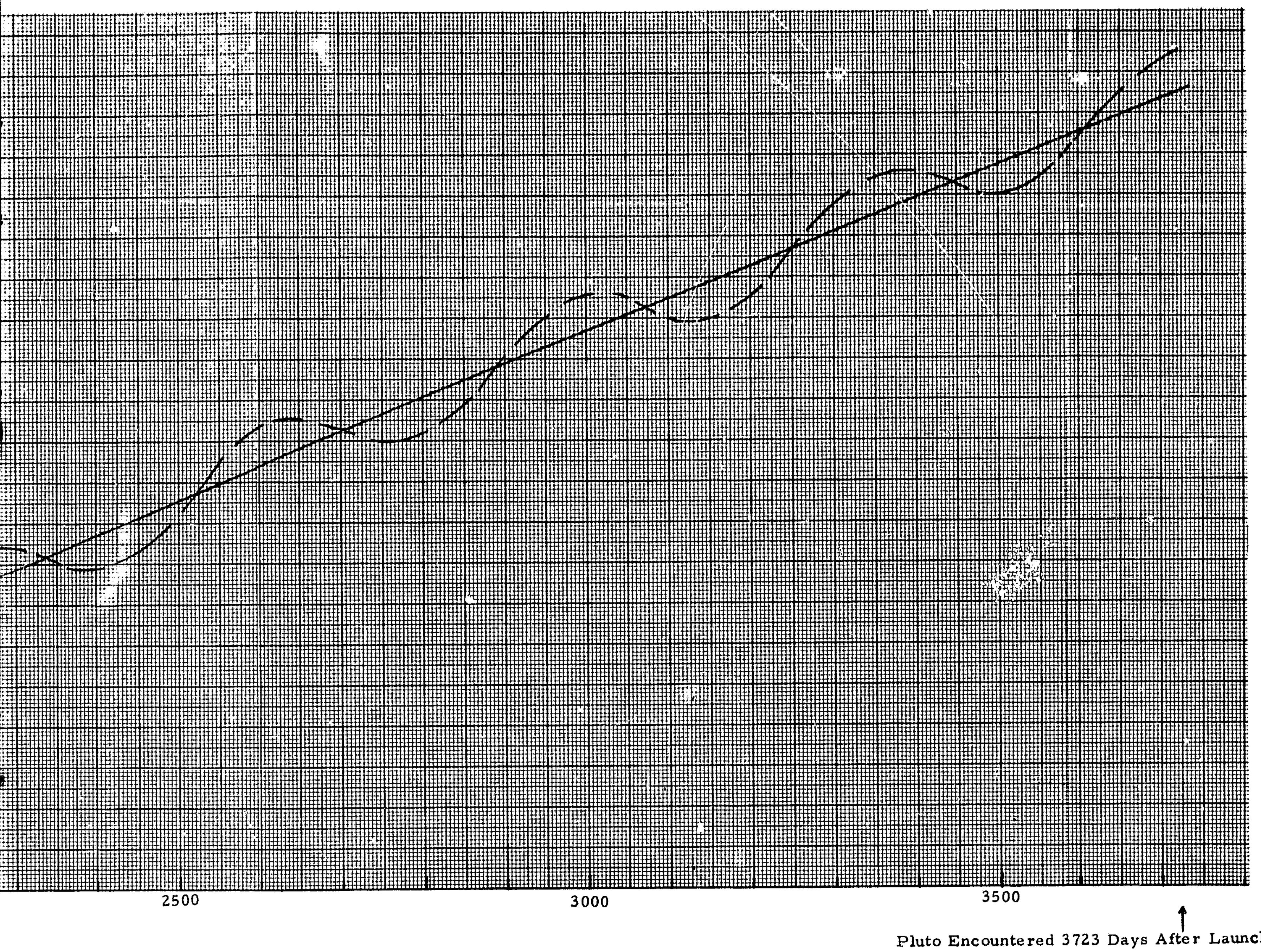
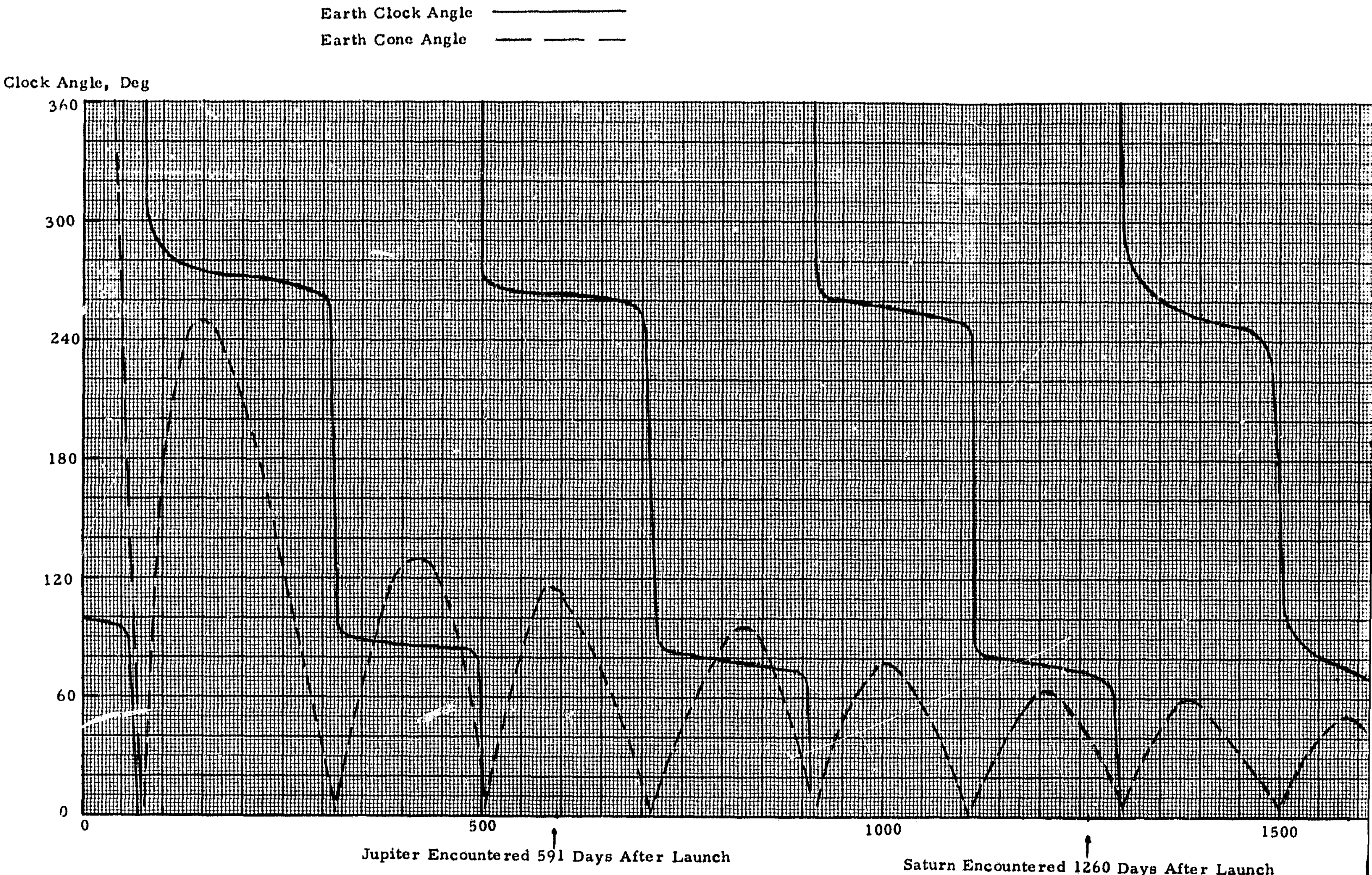


FIGURE 2-13. SUN-PROBE AND EARTH-PROBE DISTANCES FOR MISSION C



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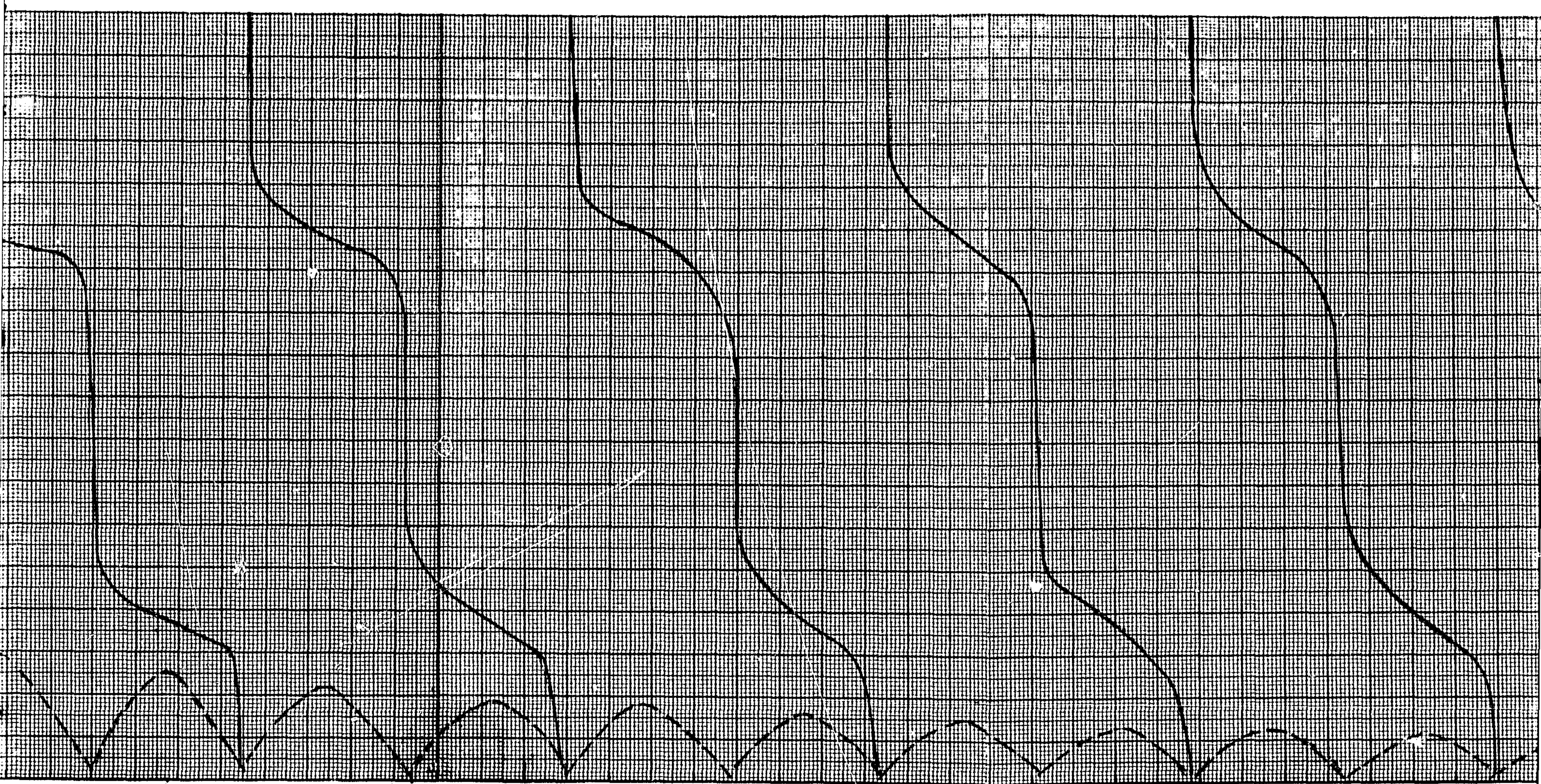

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FIGURE 2-14. EARTH CLOCK ANI

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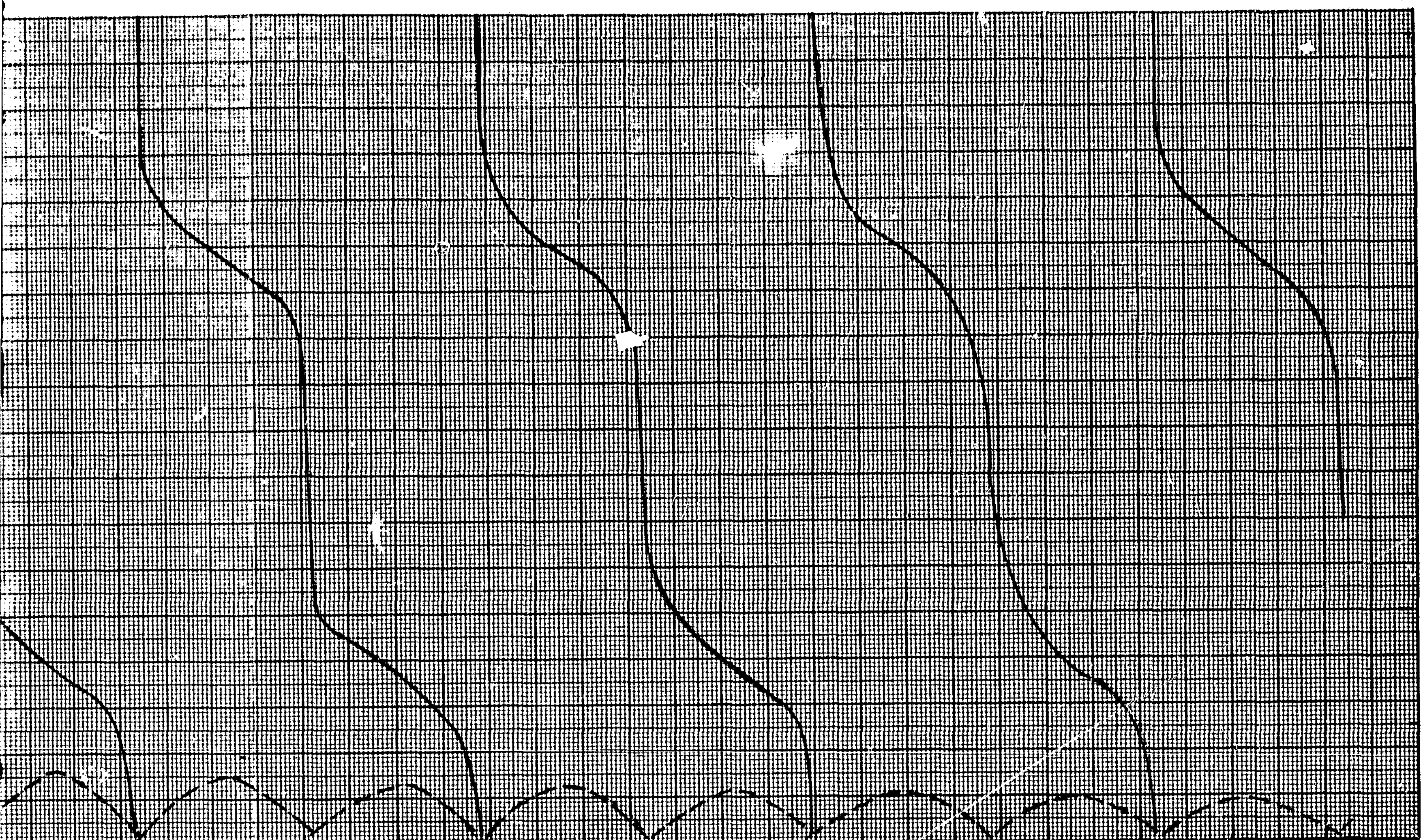
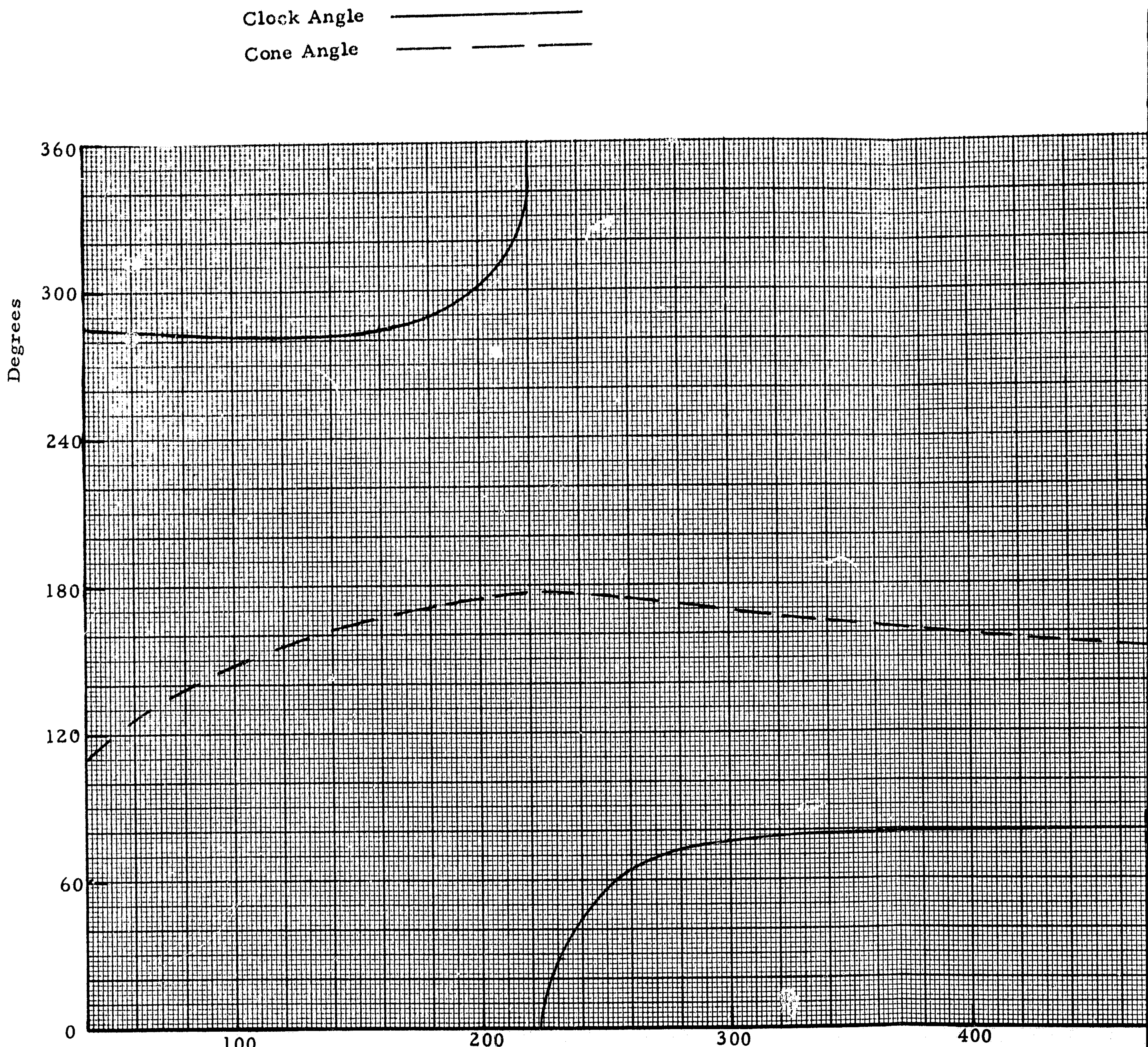


FIGURE 2-14. EARTH CLOCK AND CONE ANGLES FOR MISSION C



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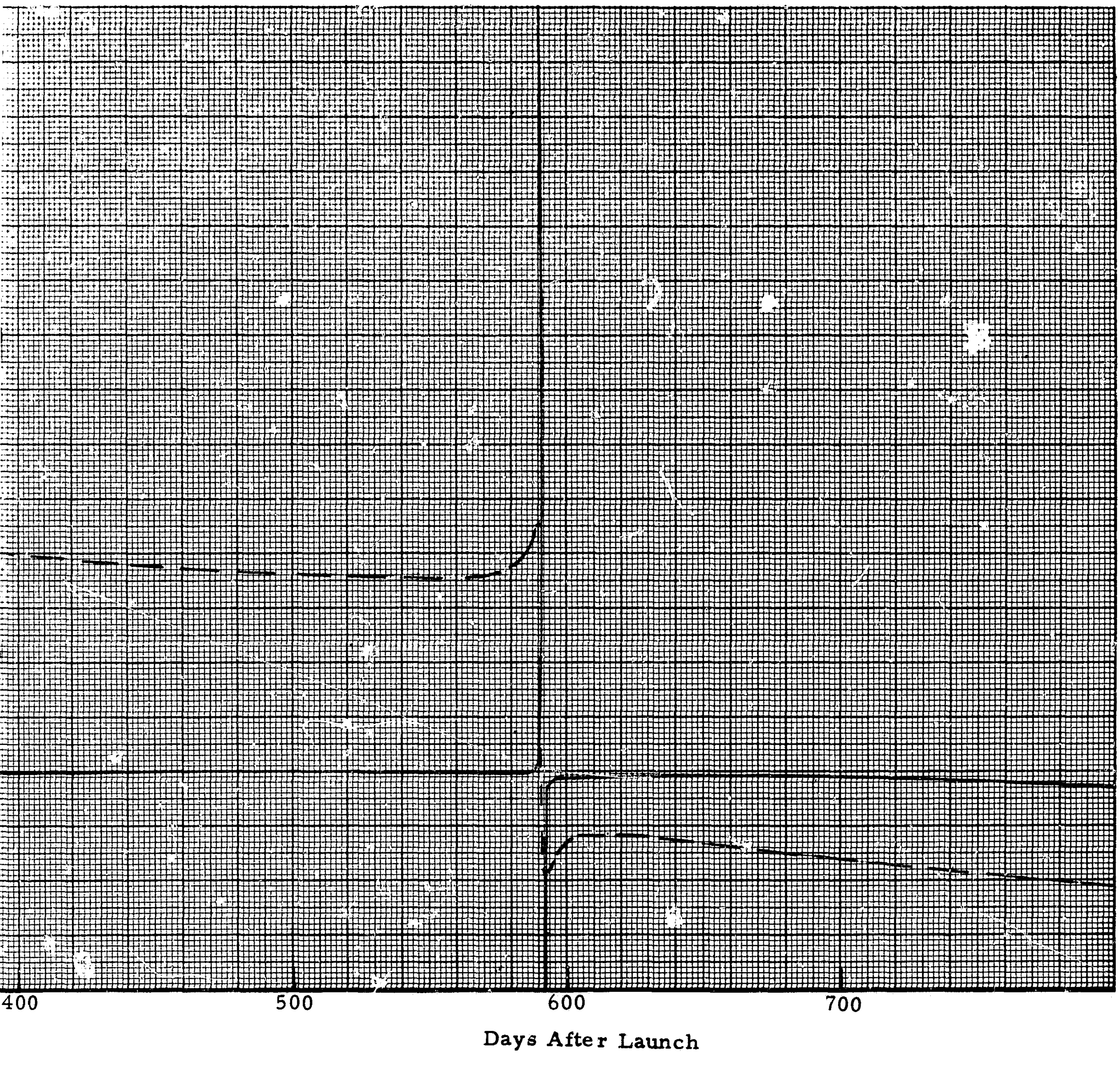
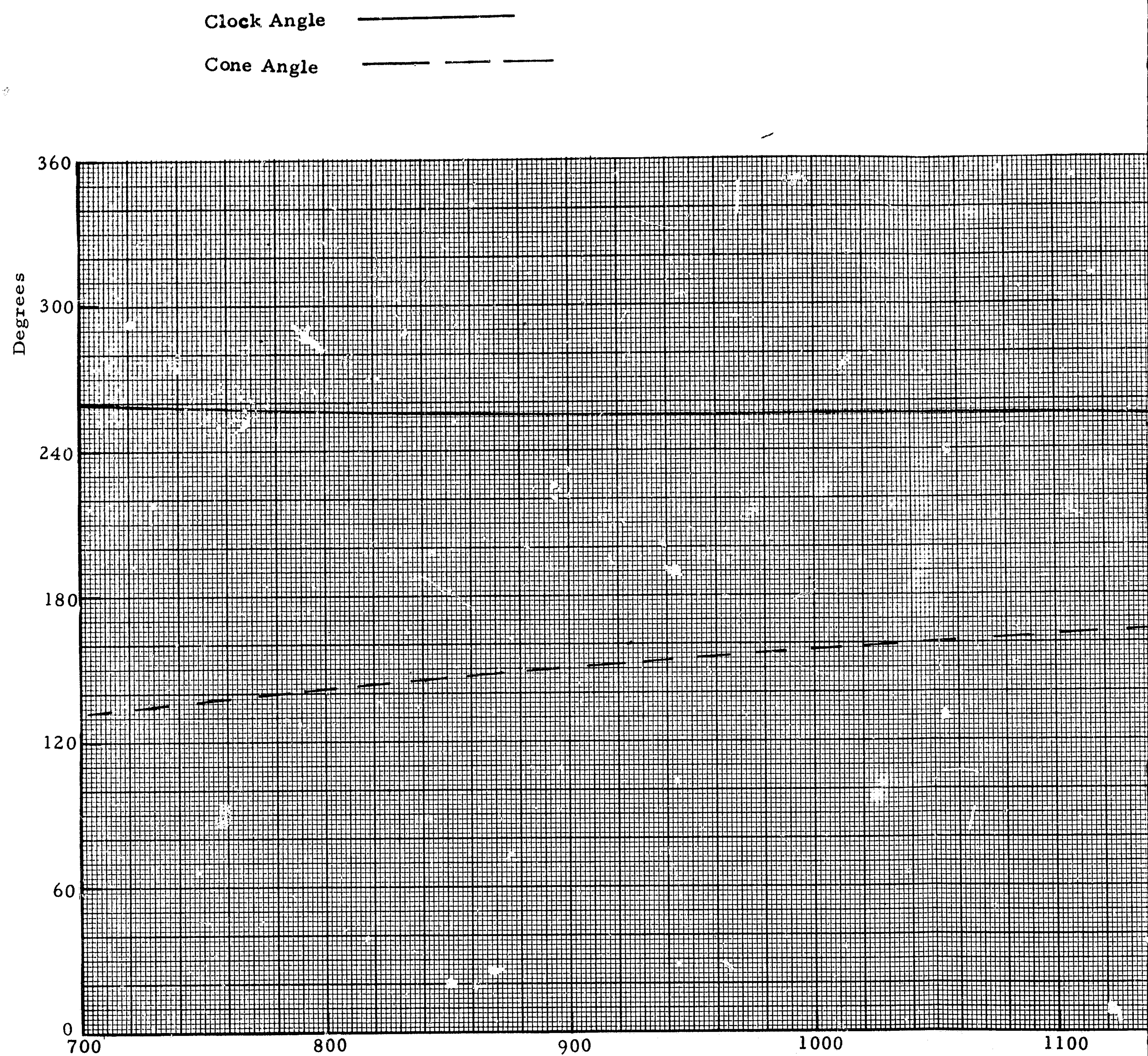


FIGURE 2-15. JUPITER CLOCK AND CONE ANGLES FOR MISSION C



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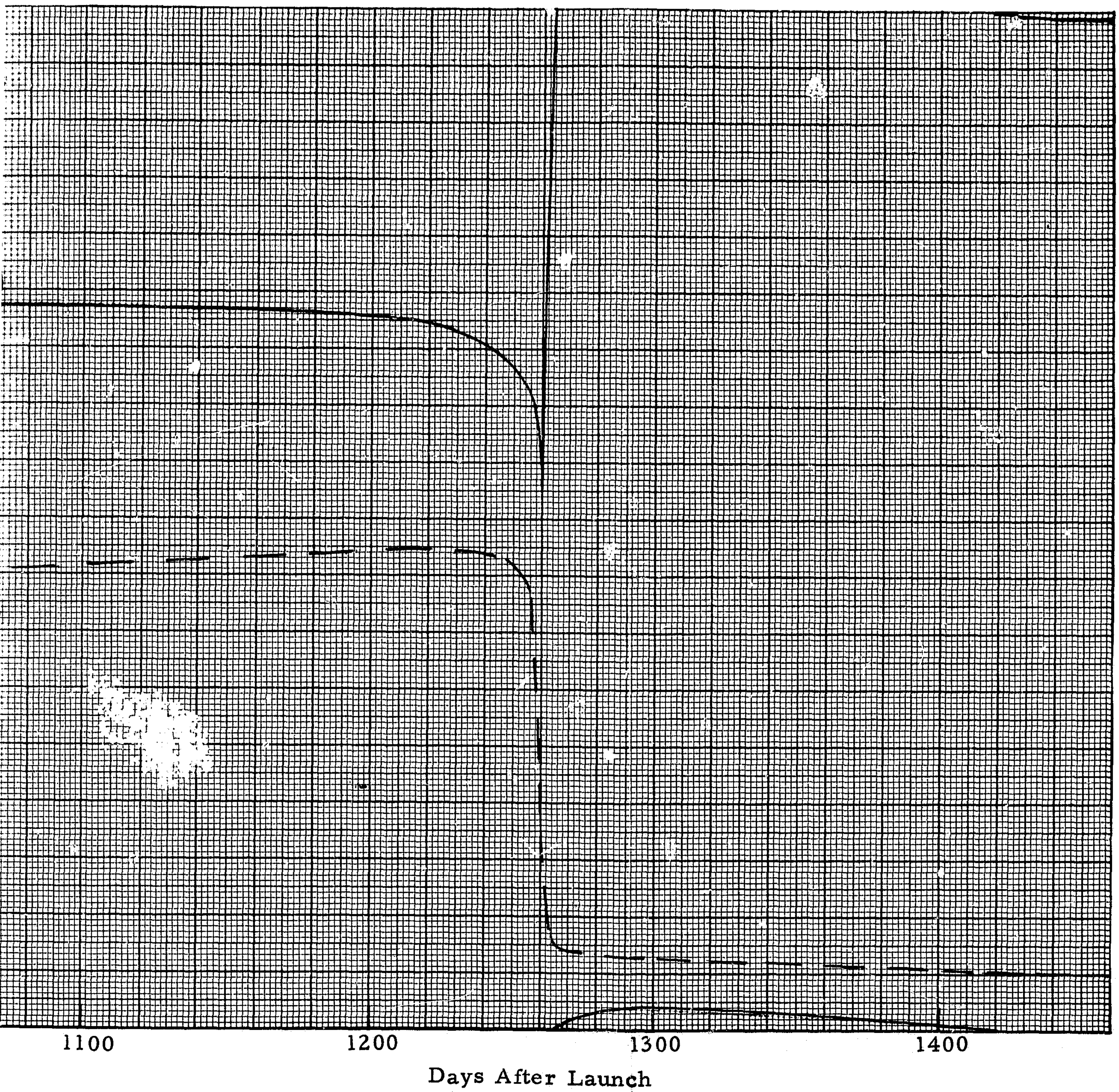
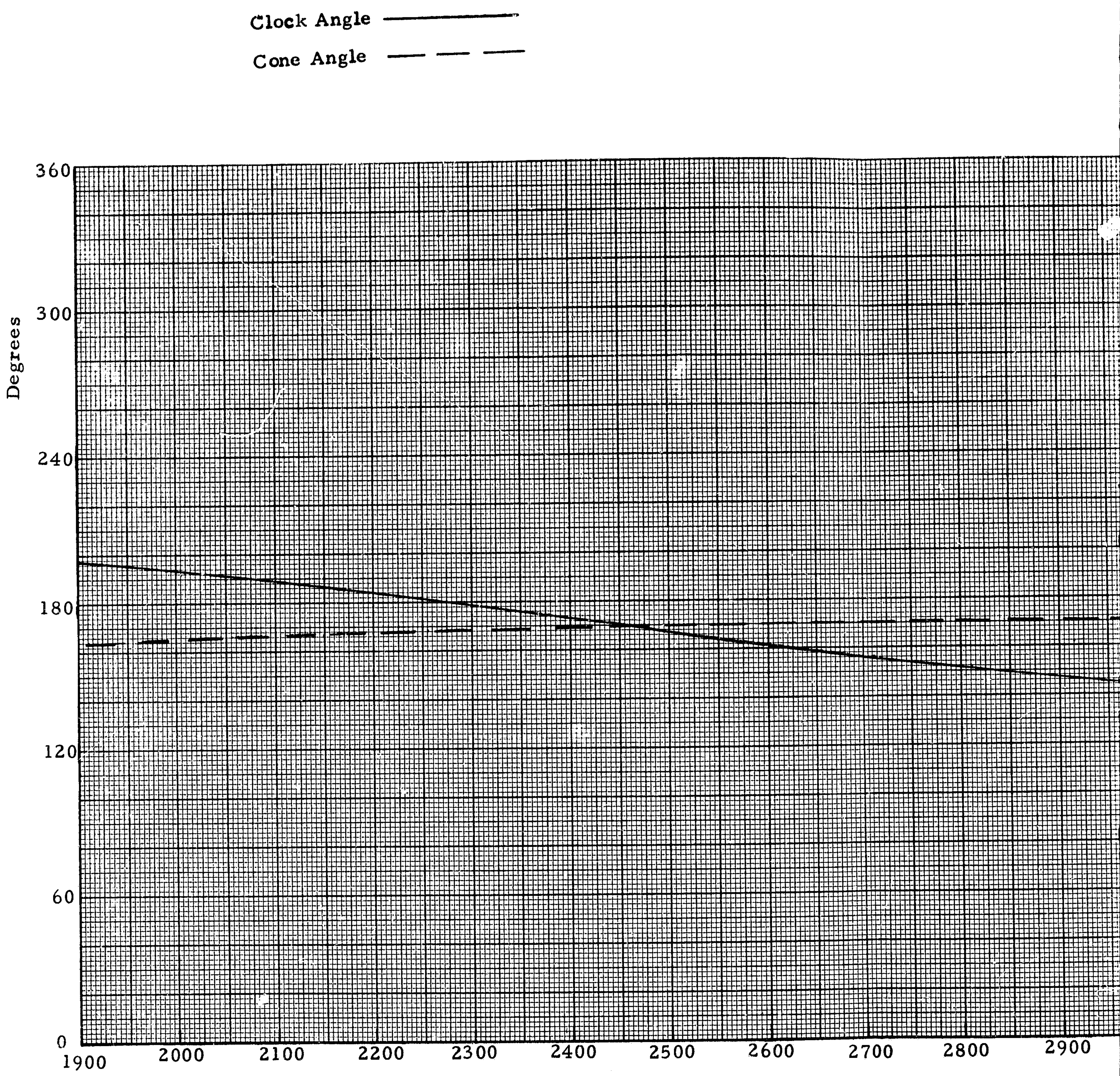


FIGURE 2-16. SATURN CLOCK AND CONE ANGLES FOR MISSION C



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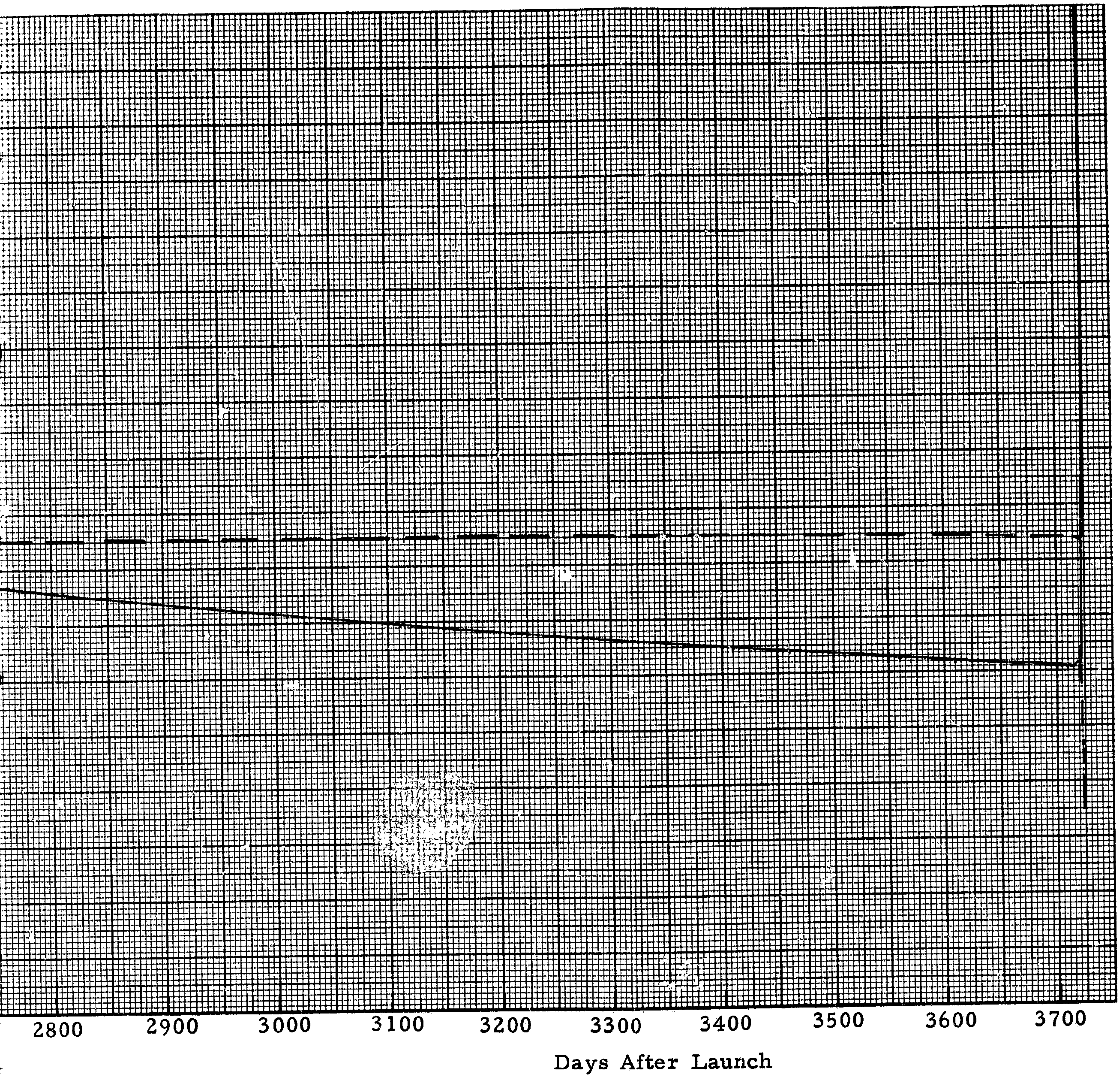


FIGURE 2-17. PLUTO CLOCK AND CONE ANGLES FOR MISSION C

Section 3

EARTH-JUPITER TRAJECTORY DATA

Common to the Grand Tour missions and variations of these missions to the outer planets is the Earth-Jupiter leg of the swingby trajectory. Charts describing this leg of the missions are presented for the years 1976, 1977, 1978, 1979 and 1980.

In Figs. 3-1 through 3-5 contours of constant Earth departure energy C_3 and of constant escape asymptote declination DLA are displayed as a function of Earth departure and Jupiter arrival dates. In Figs. 3-6 through 3-10 contours of constant Earth departure energy C_3 and of constant Jupiter hyperbolic excess velocity VHP are displayed as a function of Earth departure and Jupiter arrival dates. Fig. 3-11 relates C_3 to the magnitude of velocity at perigee of a hyperbolic departure trajectory with a 100 n.mi. perigee altitude.

These parameters depend solely on the Earth departure and Jupiter arrival dates, so these data are applicable to all variations of swingbys employing an Earth-Jupiter leg. On charts in subsequent sections, only C_3 contours are displayed. When considering escape asymptote declination or excess velocity at Jupiter, one must refer to the figures of this section.

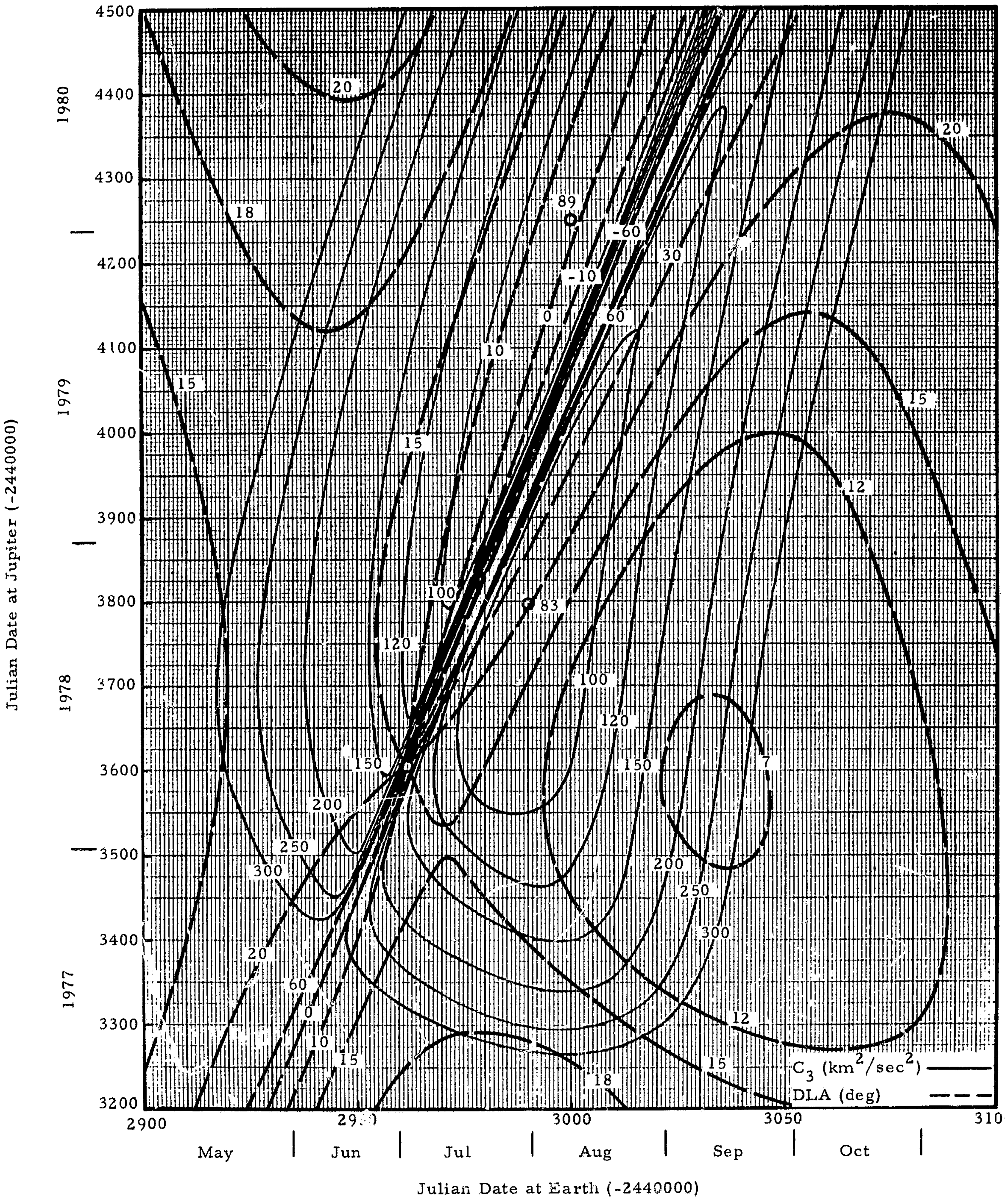


FIGURE 3-1. JUPITER MISSIONS LAUNCHED IN 1976 - LAUNCH ENERGY AND DEPARTURE ASYMPTOTE DECLINATION

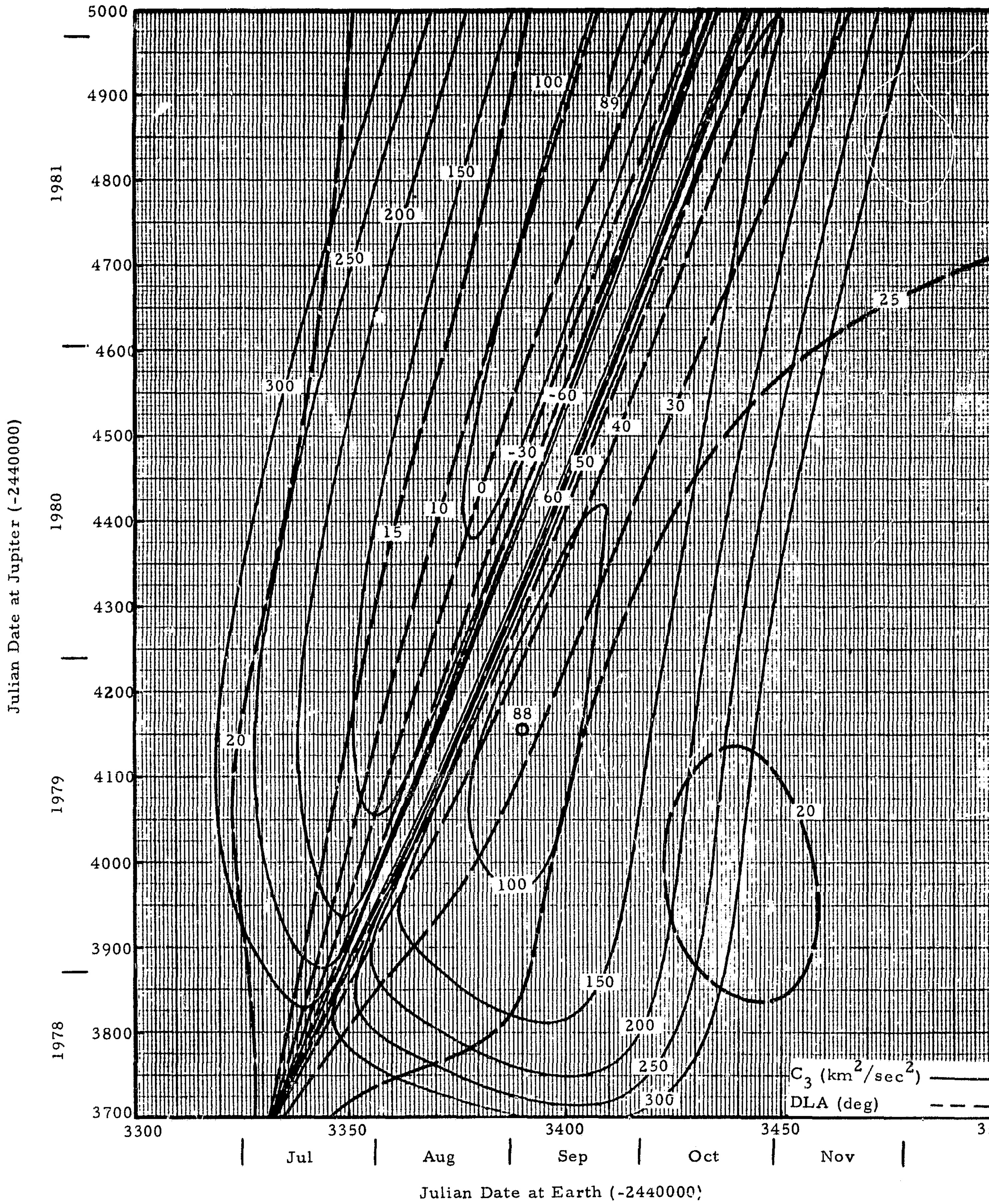


FIGURE 3-2. JUPITER MISSIONS LAUNCHED IN 1977 - LAUNCH ENERGY AND DEPARTURE ASYMPTOTE DECLINATION

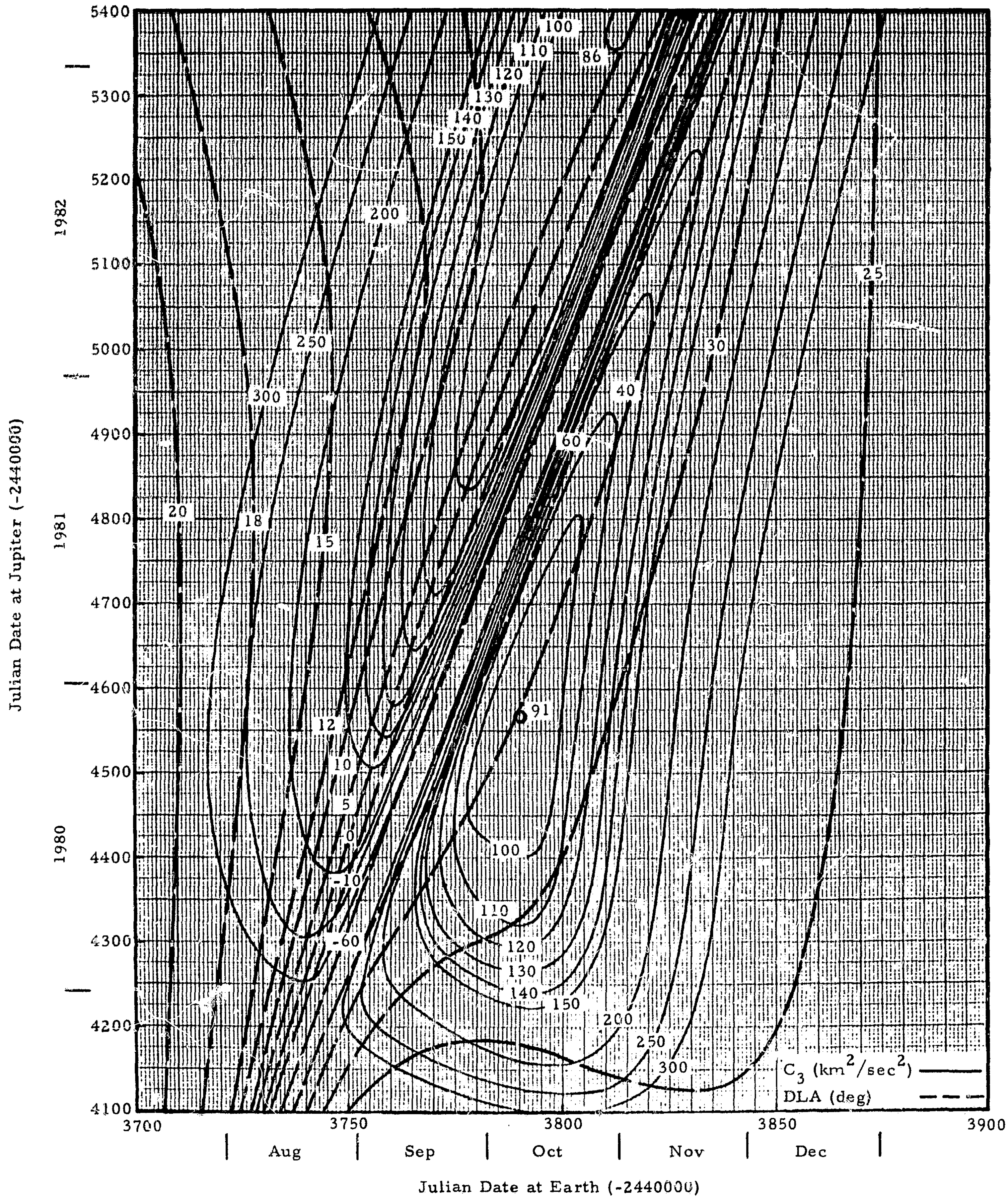


FIGURE 3-3. JUPITER MISSIONS LAUNCHED IN 1978 - LAUNCH ENERGY AND DEPARTURE ASYMPTOTE DECLINATION

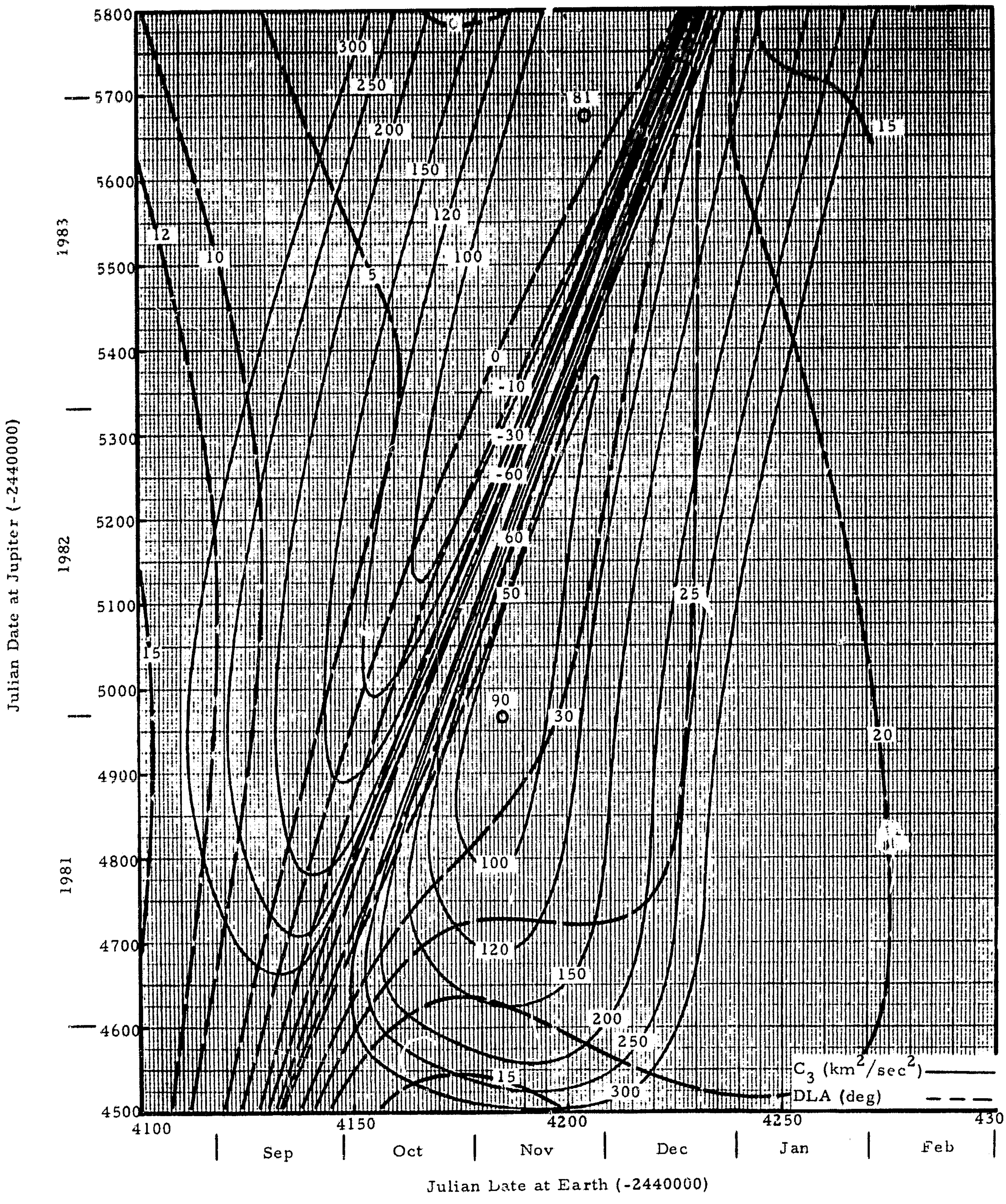


FIGURE 3-4. JUPITER MISSIONS LAUNCHED IN 1979 - LAUNCH ENERGY AND DEPARTURE ASYMPTOTE DECLINATION

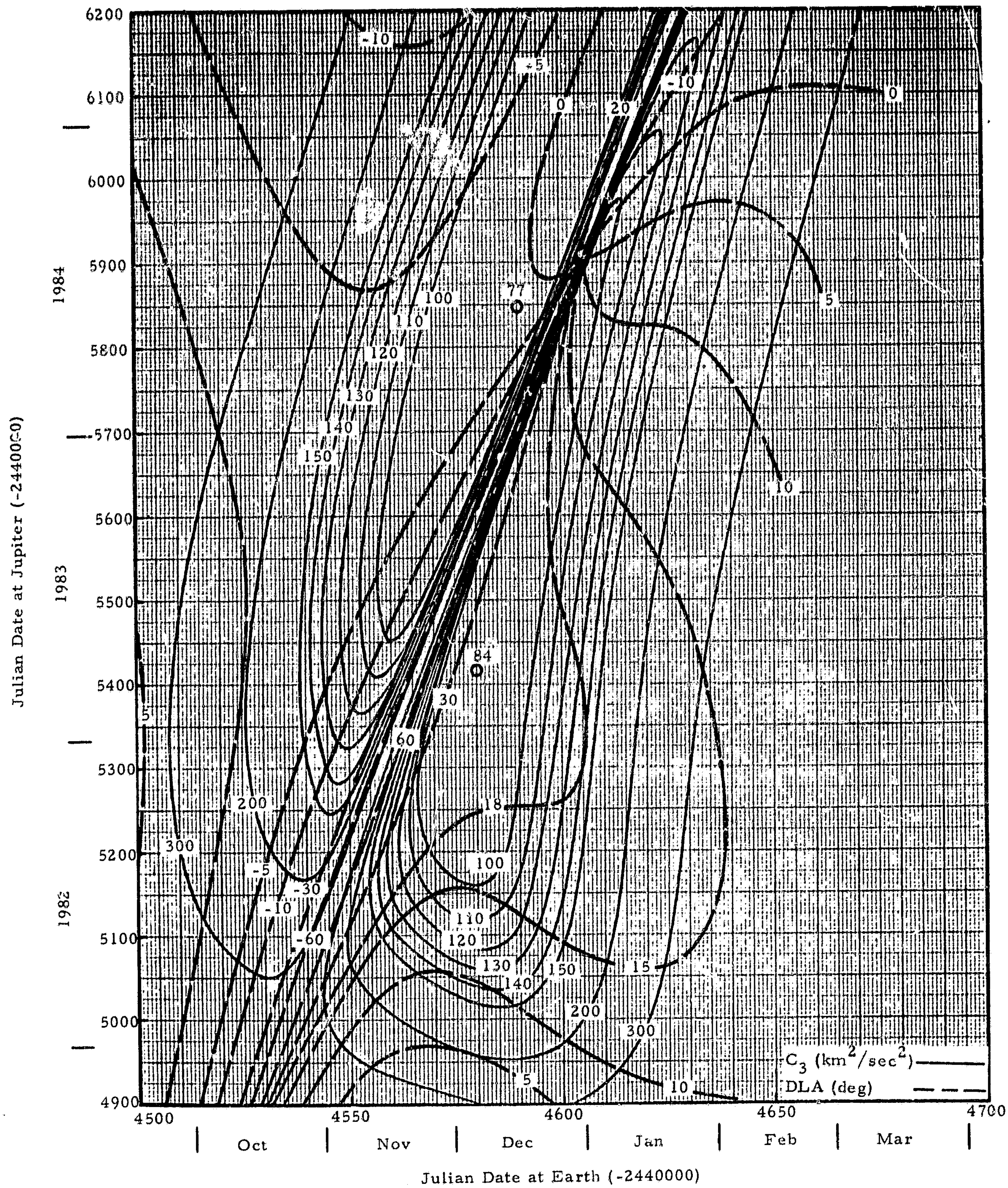


FIGURE 3-5. JUPITER MISSIONS LAUNCHED IN 1980 - LAUNCH ENERGY AND DEPARTURE ASYMPTOTE DECLINATION

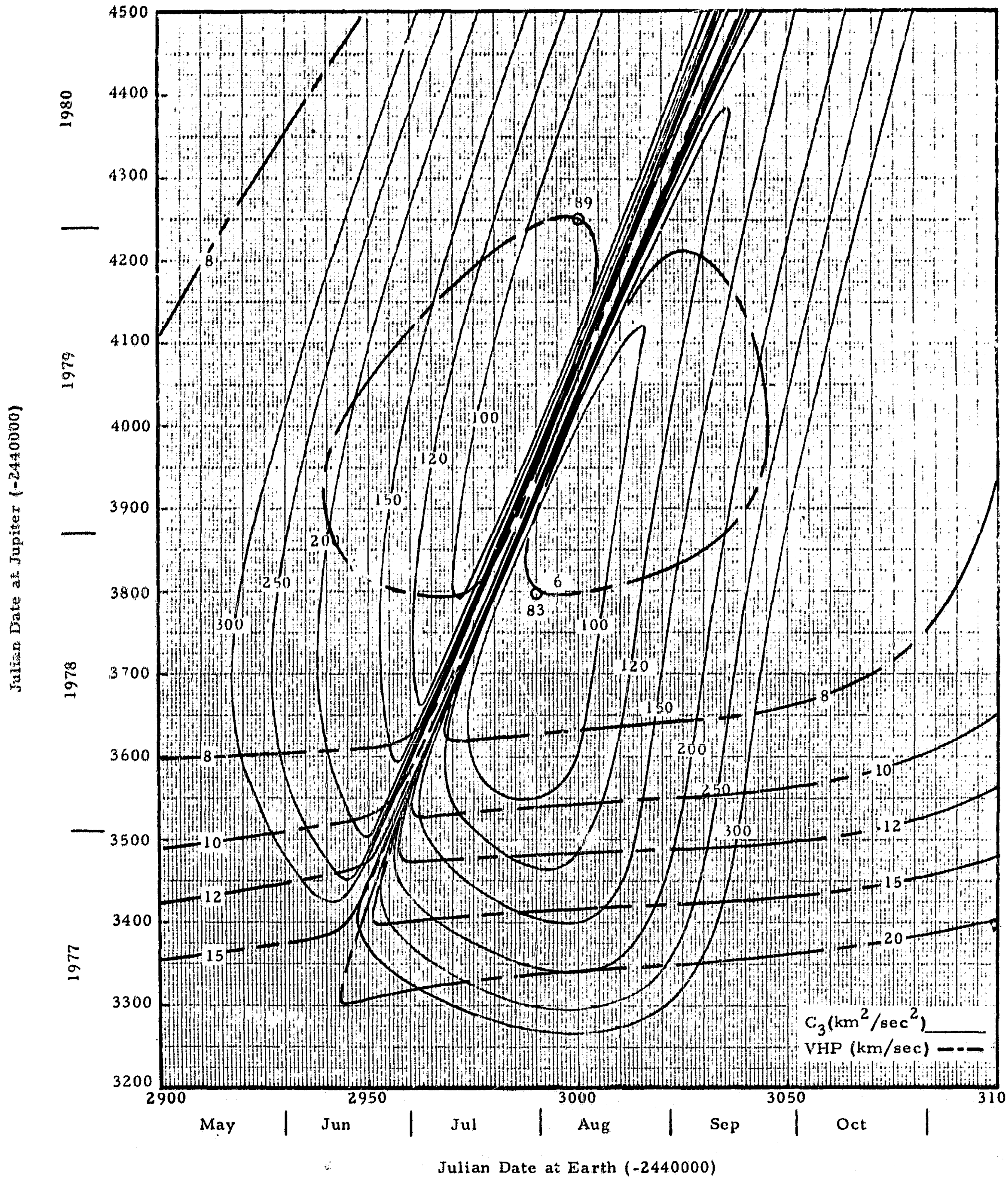


FIGURE 3-6. JUPITER MISSIONS LAUNCHED IN 1976 - LAUNCH ENERGY AND HYPERBOLIC EXCESS SPEED AT JUPITER

1.1 1.8 1.25 1.4 1.6

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS – 1963

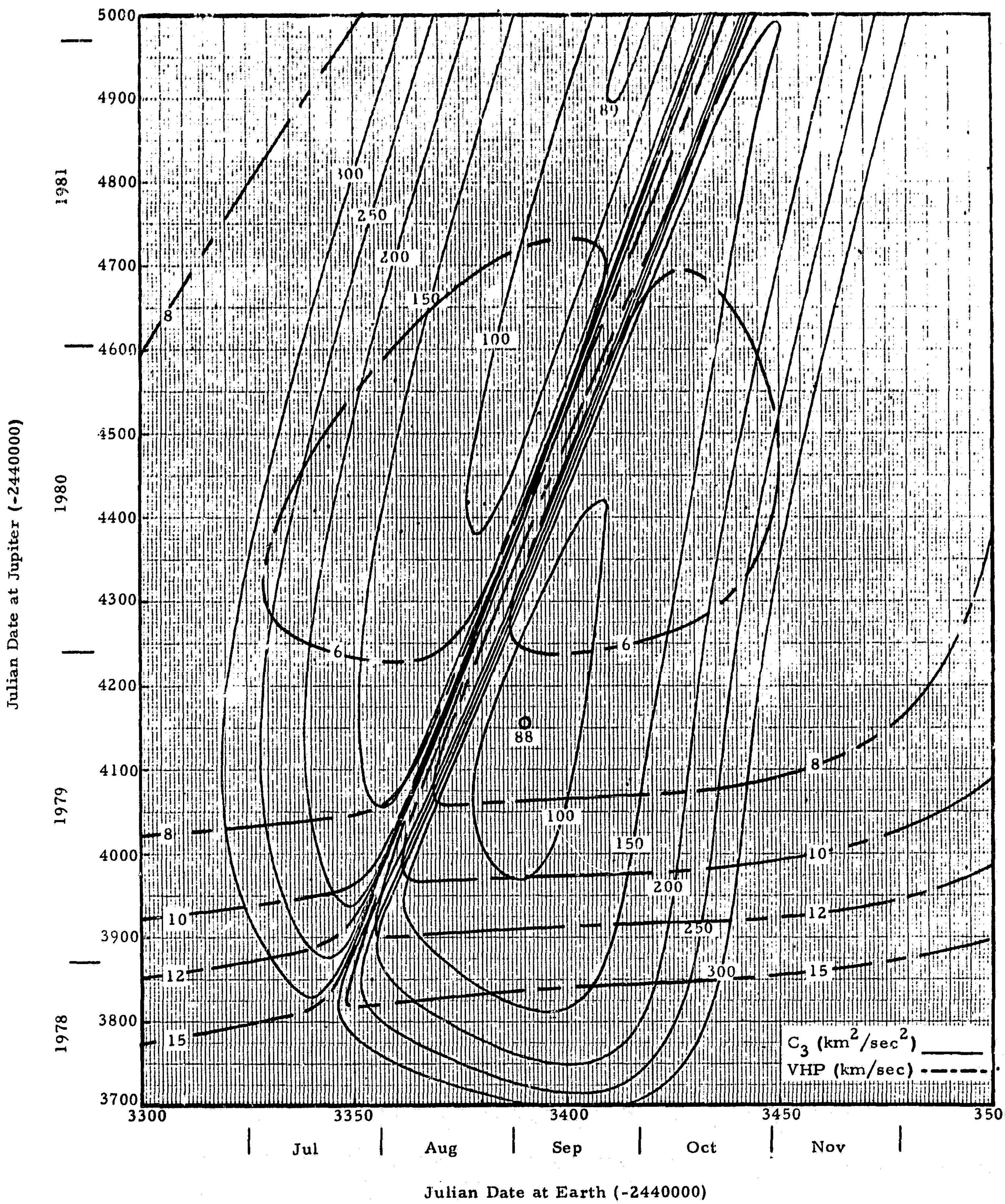


FIGURE 3-7. JUPITER MISSIONS LAUNCHED IN 1977 - LAUNCH ENERGY AND HYPERBOLIC EXCESS SPEED AT JUPITER

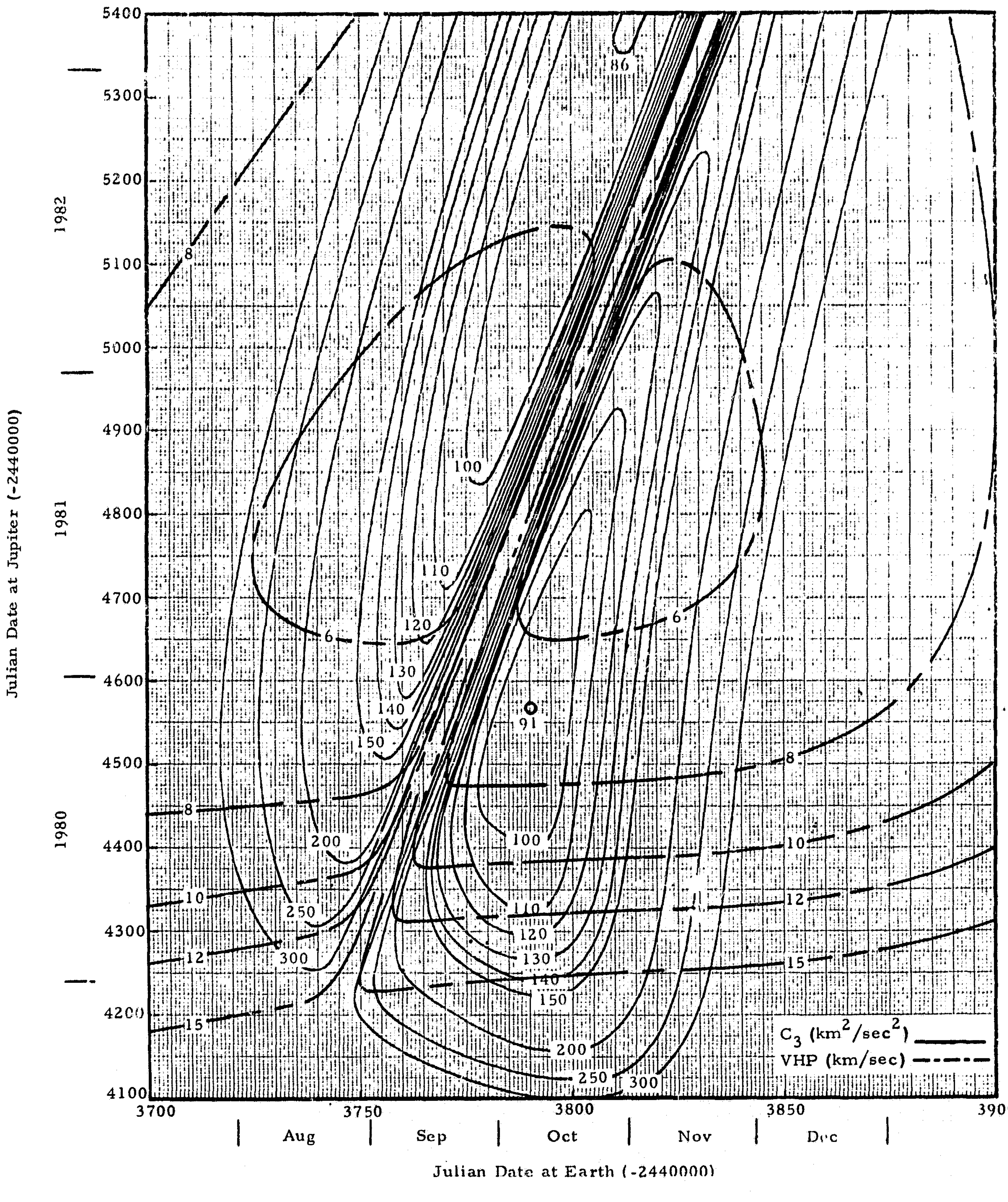


FIGURE 3-8. JUPITER MISSIONS LAUNCHED IN 1978 - LAUNCH ENERGY AND HYPERBOLIC EXCESS SPEED AT JUPITER

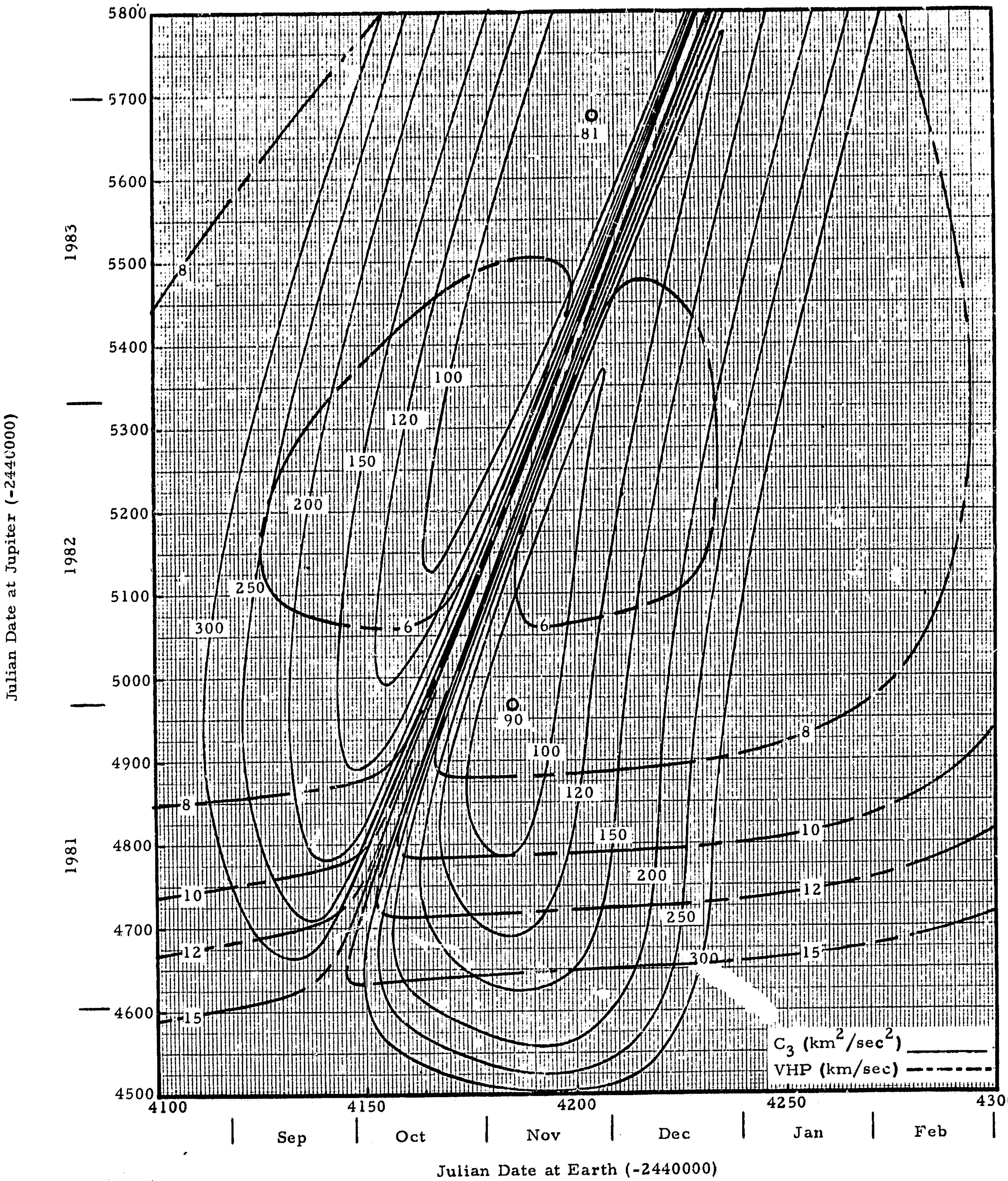


FIGURE 3-9. JUPITER MISSIONS LAUNCHED IN 1979 - LAUNCH ENERGY AND HYPERBOLIC EXCESS SPEED AT JUPITER

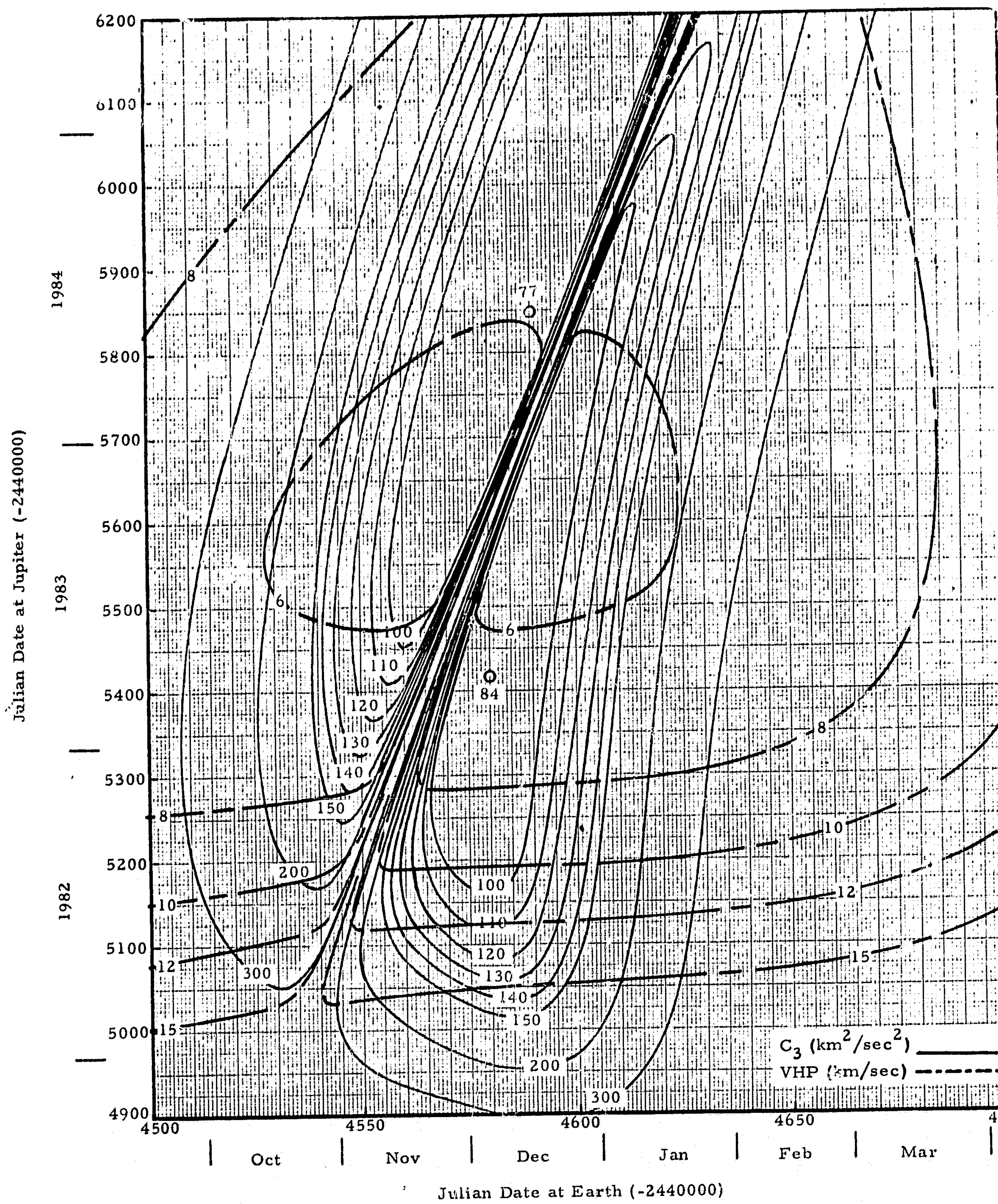


FIGURE 3-10. JUPITER MISSIONS LAUNCHED IN 1980 - LAUNCH ENERGY AND HYPERBOLIC EXCESS SPEED AT JUPITER

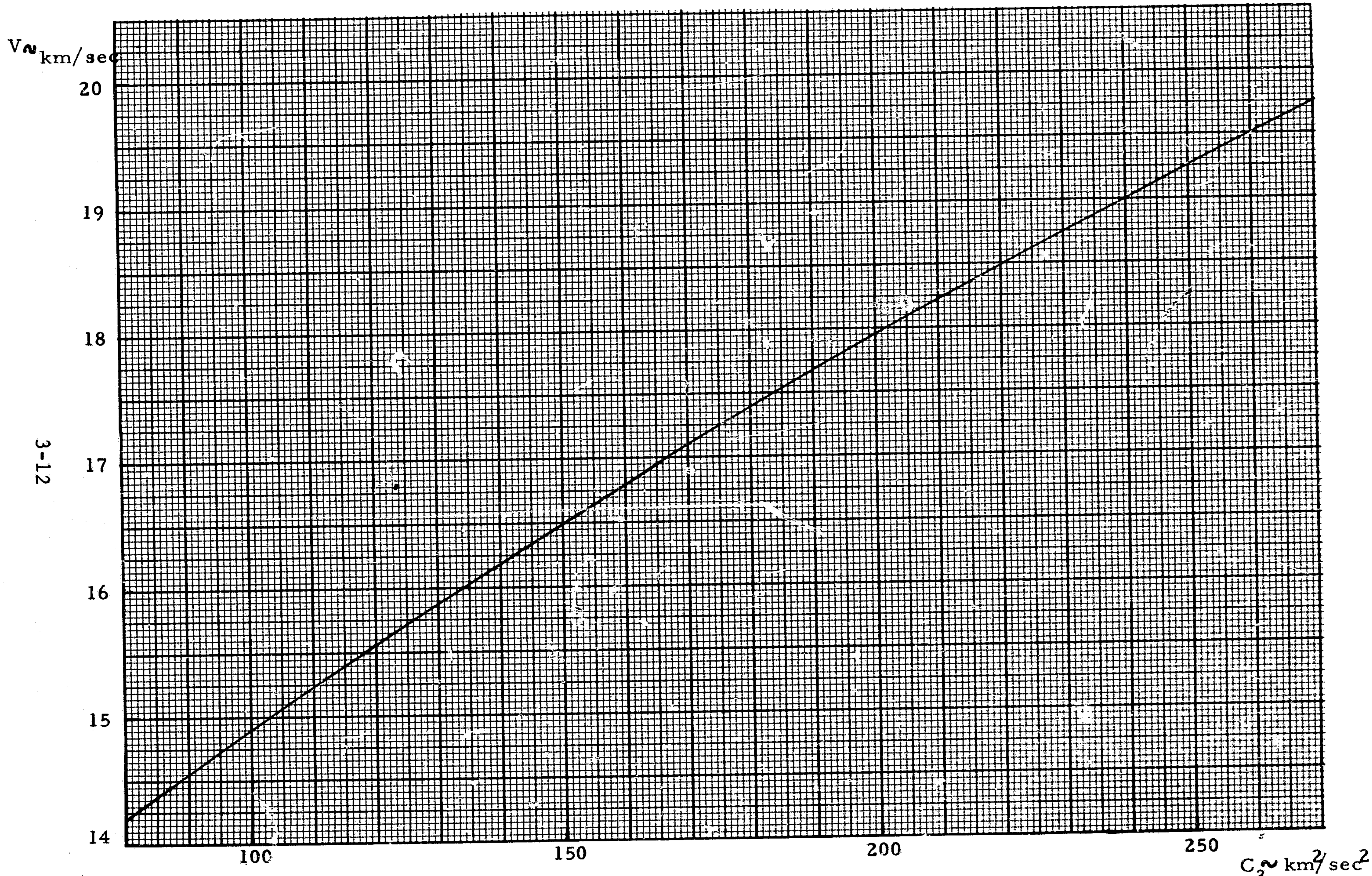


FIGURE 3-11. MAGNITUDE OF VELOCITY AT HYPERBOLIC PERIGEE ALTITUDE OF 100 N. MI.

Section 4
QUAD AND TRIAD GRAPHS

In this section, graphs which describe entire multiplanet swingby missions are presented and explained. This type chart (used by Silver in Ref. 4) displays the date of encounter and the radius of closest approach for each swingby planet. The graphs for the Jupiter-Saturn-Pluto missions and for the Jupiter-Uranus-Neptune missions require three quadrants. The graphs for the Jupiter-Saturn-Uranus-Neptune missions require four quadrants.

Figure 4-1 depicts the conceptual nature of a quad graph for the Earth-launched Jupiter-Saturn-Uranus-Neptune (Grand Tour) mission. Ballistic multiplanet missions in general can be considered as overlapping three-planet missions. The Grand Tour mission is considered as overlapping

Earth-Jupiter-Saturn,
Jupiter-Saturn-Uranus, and
Saturn-Uranus-Neptune

missions. In each quadrant except the first, possible trajectories for a given three-planet set are represented. The axes of the quadrant are the date at the second planet and the date at the third planet. For example, in the second quadrant of Fig. 4-1 the axes are the date at Jupiter and the date at Saturn. Within the quadrant, contours of constant date at the first planet are plotted. A point on one of these contours represents the dates at the first, second and third planet, thereby identifying a three-planet trajectory. Contours of passage distance at the second planet are superimposed over the contours of encounter date at the first planet.

In order to extend a particular trajectory from one three-planet set to the next, it is necessary to match two dates. For example, in order to extend an Earth-Jupiter-Saturn trajectory, it is necessary to find a Jupiter-Saturn-Uranus trajectory with the same dates of encounter at Jupiter and Saturn.

Matching these dates is simplified by the quad graph since the second and third quadrant have a common axis. By dropping straight down on the vertical grid to the third quadrant, the Saturn encounter date is held constant. Interpolation for the Jupiter encounter date on the contours of the third quadrant gives the point in the third quadrant that is the extension of the Earth-Jupiter-Saturn trajectory.

On each axis of the quad and triad graphs there are intervals distinguished by a line drawn parallel to the axis. These intervals extend from 25 days before until 25 days after a conjunction of the Sun with planet whose encounter dates are represented on that axis. During this time, the planet as viewed from the Earth is behind the Sun or at a small angular distance from the Sun. With the present state of the art, communication with a space probe that is encountering the planet during one of these intervals is impossible.

In the first quadrant contours of constant Earth departure energy are plotted. These contours have been provided in the figures of Section 3, and are plotted again here for the convenience of the user.

Jupiter-Saturn-Uranus-Neptune Missions

In Figs. 4-2 through 4-6, quad graphs for ballistic Grand Tour missions launched from Earth between the years 1976 and 1980 are presented. As a general rule, if the launch year is increased, the Earth departure energy and the passage distance at Jupiter are both increased. The ranges of Saturn encounter dates, Uranus encounter dates, and Neptune encounter dates are approximately the same for all years. Therefore, as the Earth launch year is increased, the Earth-Jupiter and Jupiter-Saturn trip times must decrease. Consequently, the Earth departure energy and radius of closest approach at Jupiter tend to increase.

The third quadrants in Figs. 4-2 through 4-6 contain darkened regions, which indicate Jupiter-Saturn-Uranus trajectories with Saturn passage distances between 1.2 and 2.5 Saturn radii. Saturn's rings, designated from the outside inward as A, B, and C, are between 1.18 and 2.3 planet radii from

Saturn (Ref. 5). The rings are composed of many small particles orbiting in Saturn's equitorial plane (Ref. 6) and present a natural barrier for space vehicles with a peri-planet radius between 1.2 and 2.5 planet radii. As stated in Ref. 4,

> ". . . . trips should be restricted to those which pass either inside or outside the Rings. However, the extent of the Rings is not well defined so that it may not be sufficient just to avoid the Rings which are visible at Earth. Ring material which is a few orders of magnitude less dense than the visible Rings could exist outside Ring A and still present a barrier to passage. In fact, some astronomers have reported seeing a faint ring in such a position.
>
> "On the other hand, the region just inside the Crepe or C Ring may be quite free of debris due to the very long-term "sweeping" action of Saturn's upper atmosphere. The trick of passing inside the Rings would be to pass close enough to Saturn to miss any ring material and yet far enough to encounter negligible atmospheric drag. Such a possibility appears to exist for Grand Tours launched in years 1976 through 1980."

The possibility of passing inside the rings is discussed more thoroughly in Section 5.

A mission that would otherwise pass through the rings or encounter the atmosphere of Saturn may be feasible if a powered maneuver is employed in the vicinity of Saturn. Another hazard for a vehicle that passes within 5 planet radii of Jupiter is the strong radiation belt about that planet (Ref. 7). A powered maneuver may also be used advantageously to avoid such a passage of Jupiter. The powered maneuver to be considered changes the pericenter radius of the passage hyperbola but does not change the hyperbolic excess speed. The maneuver consists of a single impulsive velocity increment applied when the vehicle is leaving the sphere of influence of the planet.

Let V_∞ be the hyperbolic excess speed and let $\overline{U}_1$ and $\overline{U}_2$ be unit vectors in the direction of the approach and exit excess velocities for an unpowered swingby hyperbola. The net result of passing through the planet's sphere of influence is to rotate the planetocentric velocity through the desired bend angle κ where

$$\cos(\kappa) = \overline{U}_1 \circ \overline{U}_2 .$$

The required pericenter radius for the unpowered swingby is given by the equation

$$r_p = \frac{\mu}{V_\infty^2} \left[\csc(\tfrac{\kappa}{2}) - 1 \right],$$

where μ is the planet's gravitational constants.

For a corrected pericenter maneuver, the pericenter radius is specified to be r_p^*. The bend angle that is attained subject to the specified pericenter radius is κ^* where

$$\csc\left(\frac{\kappa^*}{2}\right) = \left(\frac{r_p^* \, V_\infty^2}{\mu}\right) + 1 .$$

As shown in Fig. 4-7, the set of all exit direction unit vectors that can be attained with the bend angle κ^* form a cone.

The vector which differs least from $\overline{U}_2$ is chosen as the departure asymptotic direction $\overline{U}_2^*$ ($\overline{U}_2^*$ is in the plane defined by $\overline{U}_1$ and $\overline{U}_2$ and $\overline{U}_2^* \circ \overline{U}_2 = \cos(\kappa - \kappa^*)$). The hyperbolic passage trajectory is targeted so that $\overline{U}_1$ and $\overline{U}_2^*$ are the approach and departure directions (Fig. 4-8). When the vehicle leaves the planet's sphere of influence, an impulse is supplied to change the planetocentric velocity from $V_\infty \overline{U}_2^*$ to $V_\infty \overline{U}_2$. The magnitude of the impulse is

$$\left| V_\infty \overline{U}_2^* - V_\infty \overline{U}_2 \right| = \frac{V_\infty \left| \sin \left(\frac{\kappa - \kappa^*}{2} \right) \right|}{2} .$$

Figs. 4-9 through 4-13, present the magnitude of corrected pericenter maneuvers that:

- Increase the pericenter radius at Jupiter to 5 planet radii,
- Decrease the pericenter radius at Saturn to 1.2 planet radii, or
- Increase the periplanet radius at Saturn to 1.1 planet radii.

Jupiter-Uranus-Neptune Missions

An alternate method to avoid the rings of Saturn is not to encounter that planet. The resulting mission type is a Jupiter-Uranus-Neptune mission. Triad graphs that represent these missions launched from Earth in 1978, 1979, and 1980 are presented in Figs. 4-14 through 4-16. For some trajectories the passage distance at Jupiter is less than 5 planet radii, and radiation would be hazardous to vehicles on these trajectories. At present, however, magnitudes of corrected pericenter maneuvers for these trajectories are not available.

Jupiter-Saturn-Pluto Missions

One ballistic mission that encounters all five outer planets is not possible in the considered time period. However, a trajectory to Pluto that encounters Jupiter and Saturn is possible. Such trajectories are represented in Figs. 4-17 through 4-20 for the Earth launch years 1976 through 1979.

For these missions, the pericenter radius at Saturn is generally outside the outer limit of Saturn's rings, and therefore the rings usually are not hazardous to a mission. However, radiation at Jupiter is a hazard that must be considered. For a given year, the Earth-Jupiter-Saturn trajectories are the same for Grand Tour missions and for Jupiter-Saturn-Pluto missions (the second quardrants of Fig. 4-2 through 4-5 are the same as those of Fig. 4-17 through 4-20, respectively). Thus, the corrected pericenter maneuvers represented in Fig. 4-9 through 4-12 may be used with Jupiter-Saturn-Pluto missions to avoid close passage of Jupiter. The user may refer to those figures for information about a corrected pericenter maneuver at Jupiter.

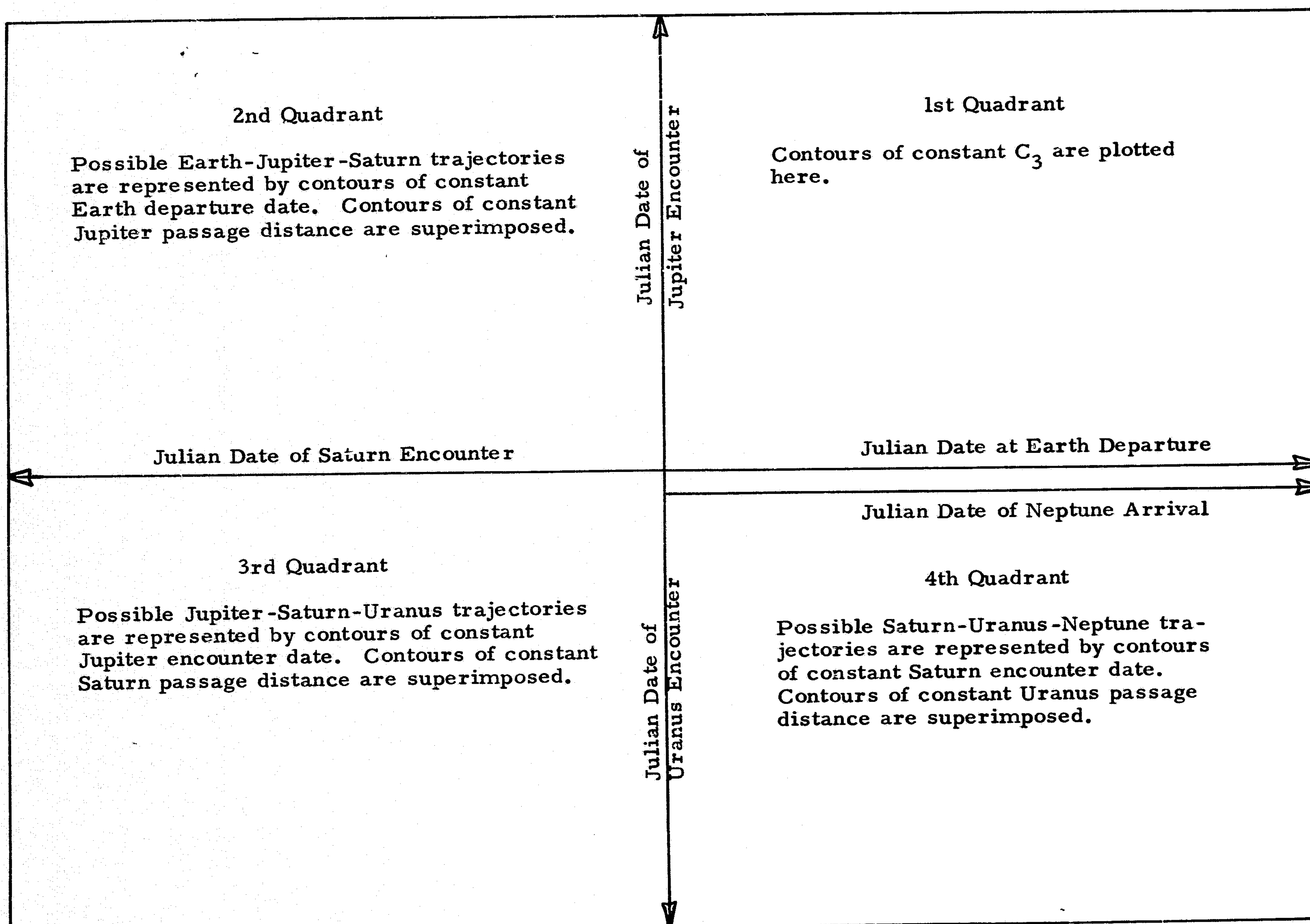
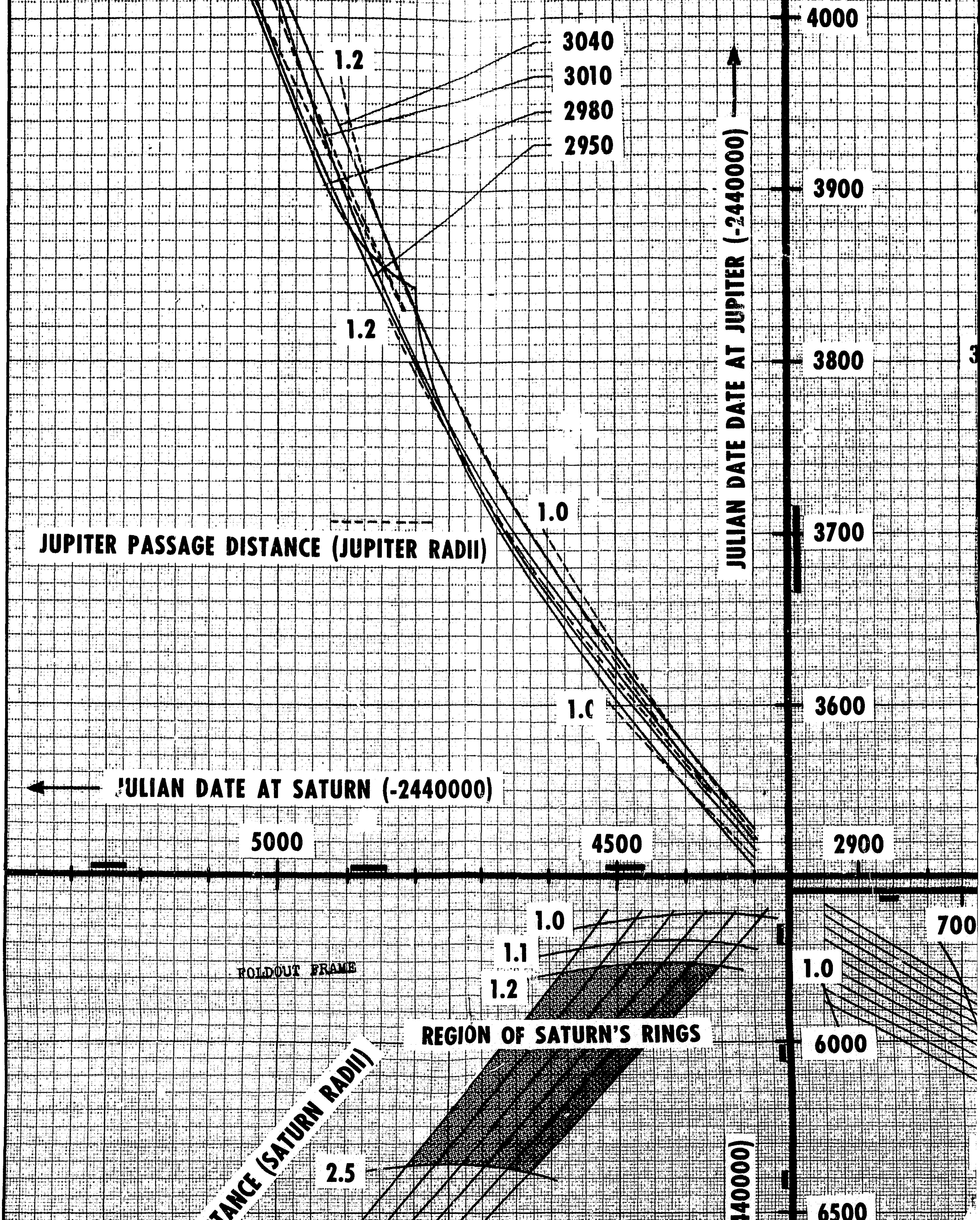
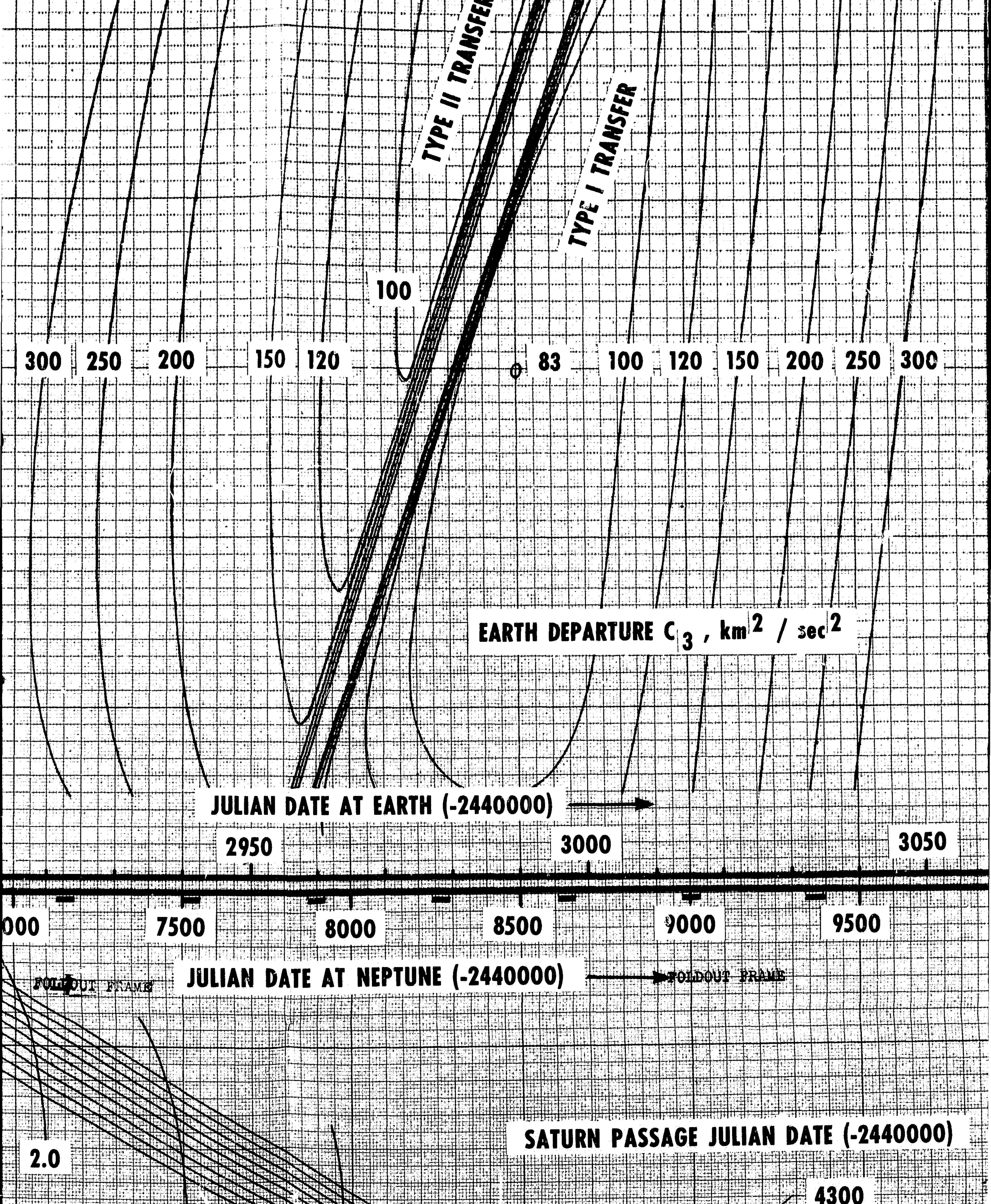


FIGURE 4-1. CONCEPTUAL NATURE OF QUAD GRAPH.



3040
3010
2980
2950
1.2
1.2
1.0
1.0
JUPITER PASSAGE DISTANCE (JUPITER RADII)
JULIAN DATE AT JUPITER (-2440000)
4000
3900
3800
3700
3600
2900
JULIAN DATE AT SATURN (-2440000)
5000
4500
1.0
1.1
1.2
REGION OF SATURN'S RINGS
2.5
1.0
6000
6500
700
FOLDOUT FRAME



TYPE II TRANSFER
TYPE I TRANSFER
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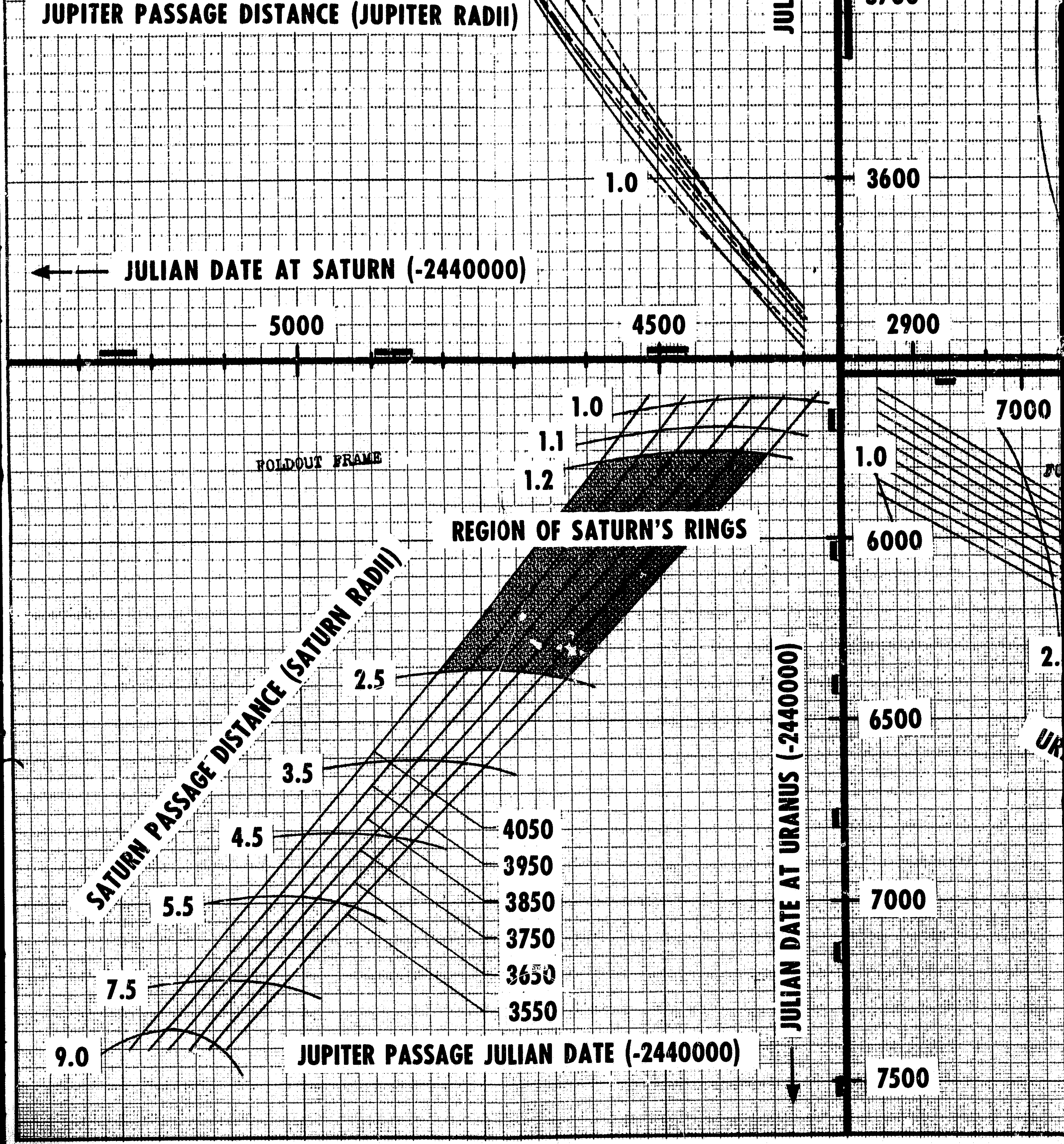
300
250
200
150
120
83
100
120
150
200
250
300
EARTH DEPARTURE C_3, km^2 / sec^2
JULIAN DATE AT EARTH (-2440000)
2950
3000
3050
7500
8000
8500
9000
9500
JULIAN DATE AT NEPTUNE (-2440000)
FOLDOUT FRAME
FOLDOUT FRAME
SATURN PASSAGE JULIAN DATE (-2440000)
2.0
4300


JUPITER PASSAGE DISTANCE (JUPITER RADII)
1.0
3600
JULIAN DATE AT SATURN (-2440000)
5000
4500
2900
1.0
1.1
1.2
7000
1.0
FOLDOUT FRAME
REGION OF SATURN'S RINGS
6000
SATURN PASSAGE DISTANCE (SATURN RADII)
2.5
6500
3.5
4050
4.5
3950
5.5
3850
7000
3750
7.5
3650
3550
9.0
JUPITER PASSAGE JULIAN DATE (-2440000)
JULIAN DATE AT URANUS (-2440000)
7500

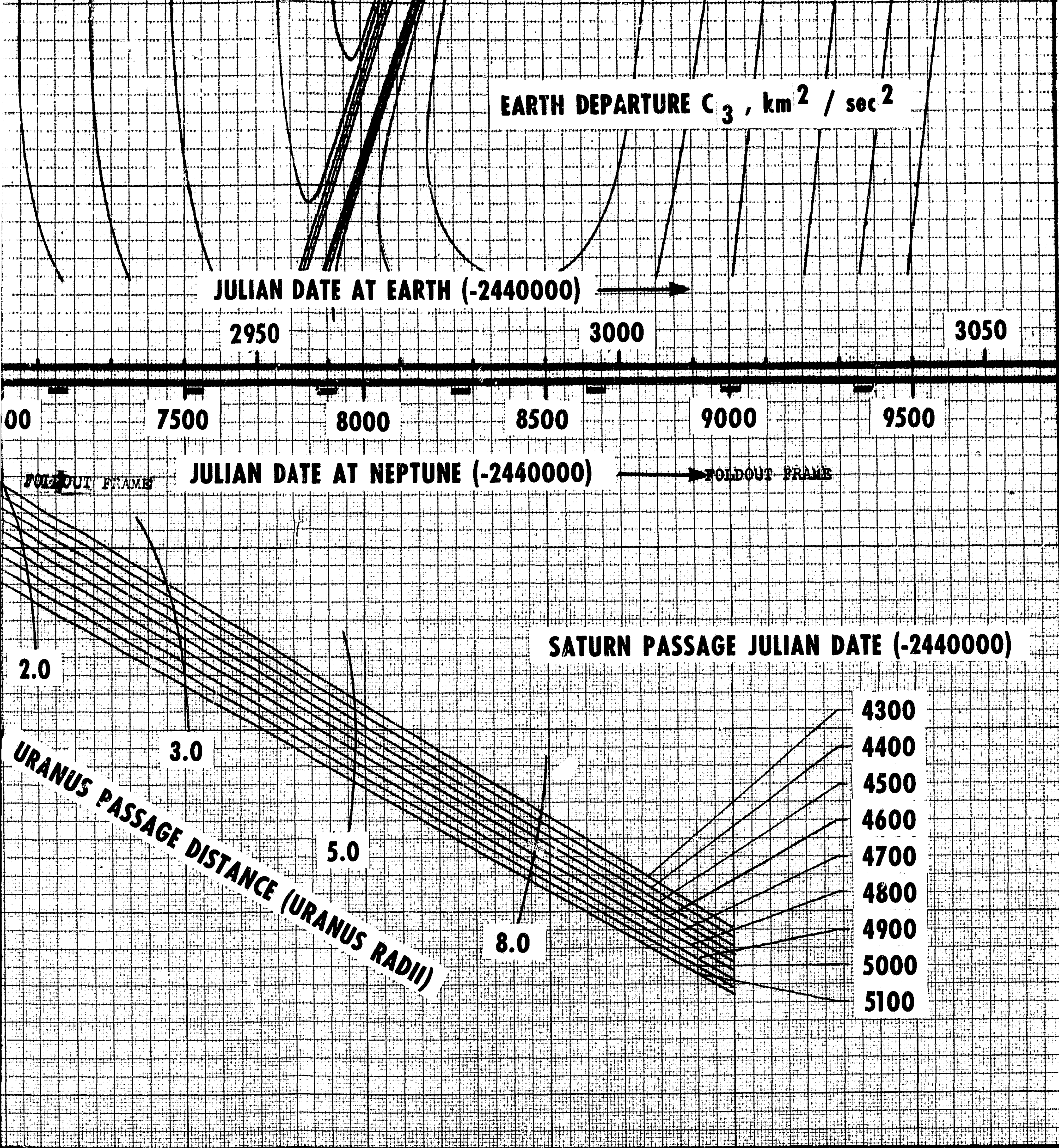
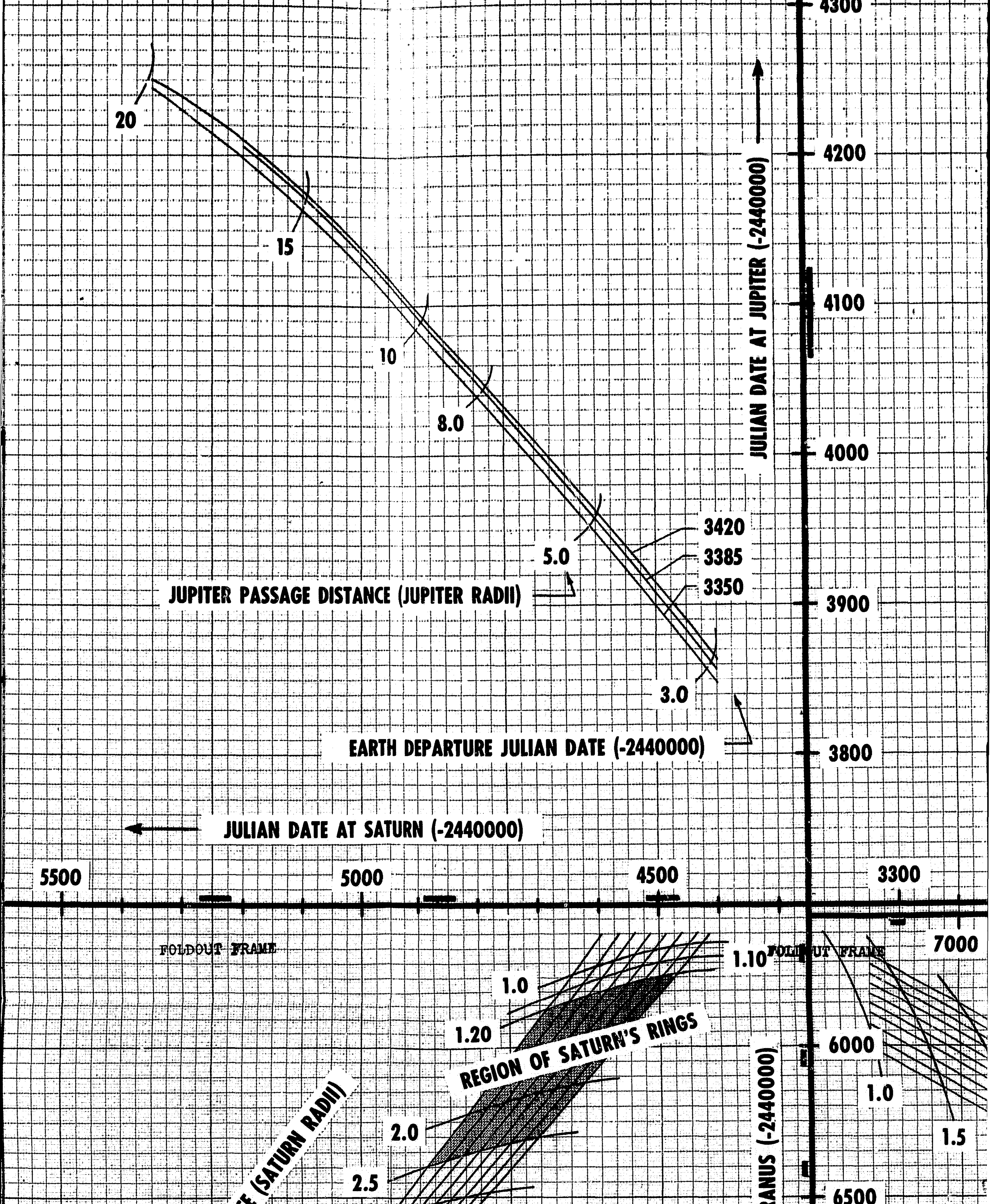
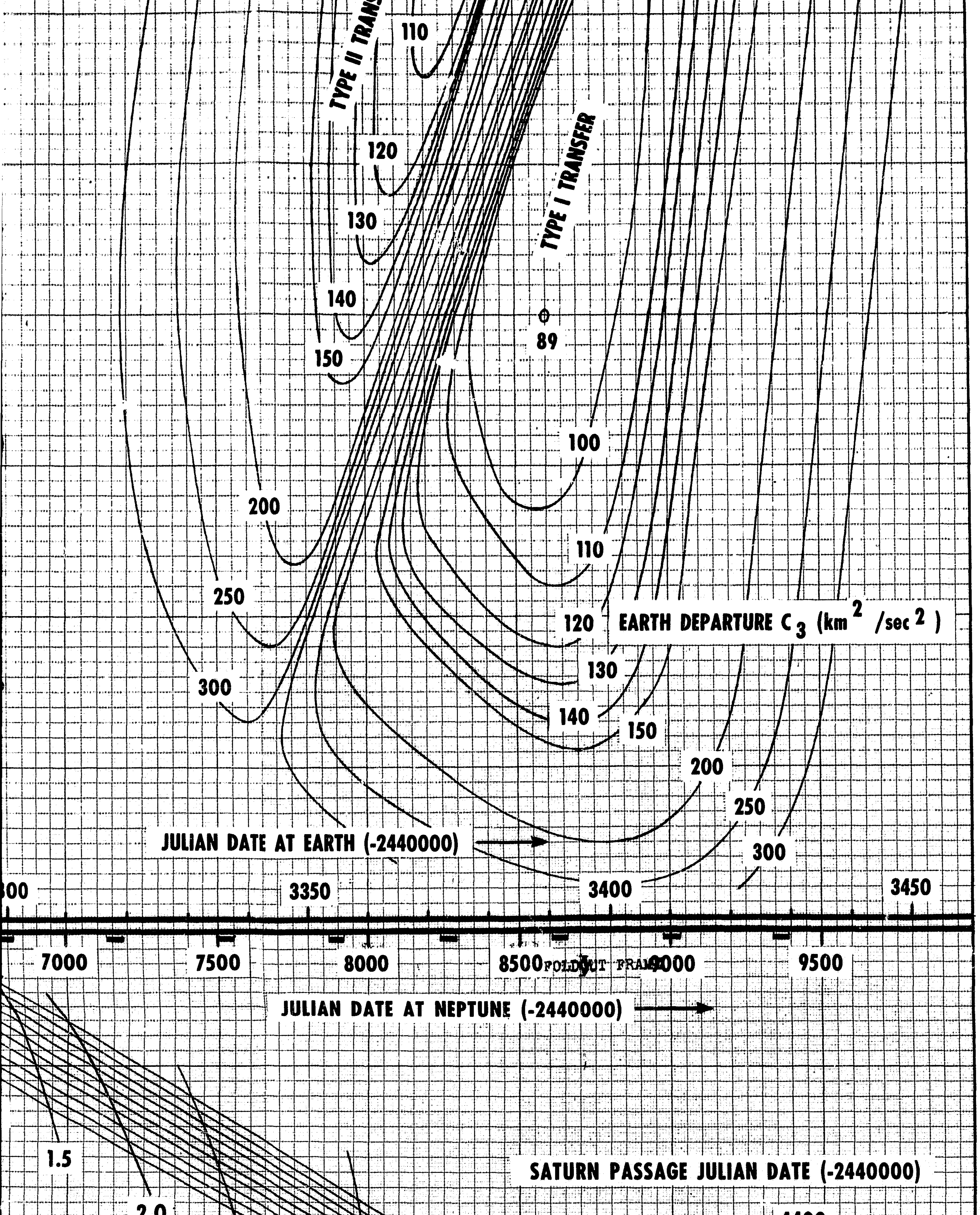


FIGURE 4-2. QUAD GRAPH FOR 1976 GRAND TOUR OF THE JOVIAN PLANTS

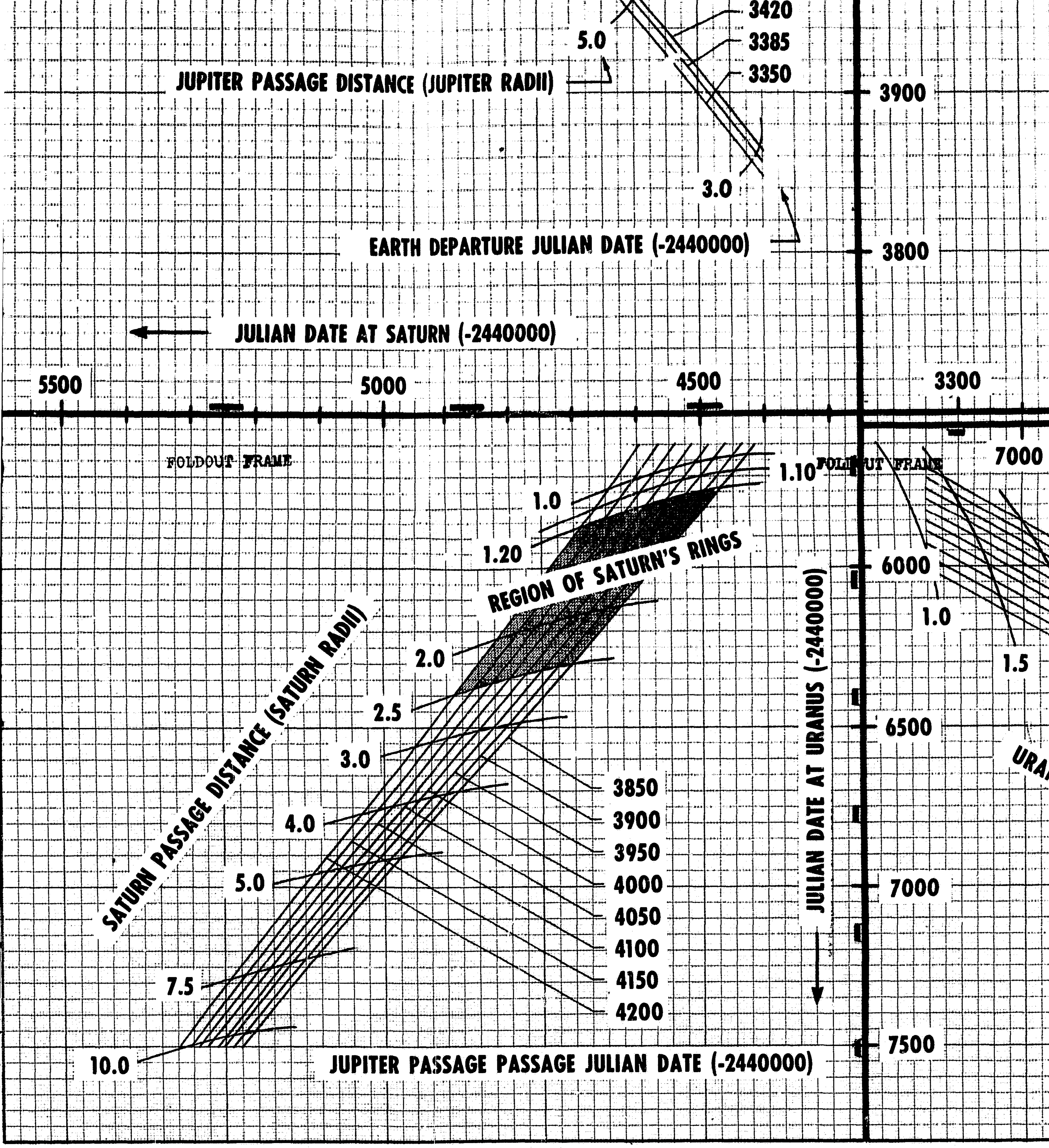
OLDOUT FRAME



JULIAN DATE AT JUPITER (-2440000)
4300
4200
4100
4000
3900
3800
20
15
10
8.0
5.0
3.0
3420
3385
3350
JUPITER PASSAGE DISTANCE (JUPITER RADII)
EARTH DEPARTURE JULIAN DATE (-2440000)
JULIAN DATE AT SATURN (-2440000)
5500
5000
4500
3300
FOLDOUT FRAME
FOLDOUT FRAME
7000
1.10
1.0
1.20
REGION OF SATURN'S RINGS
6000
1.0
1.5
2.0
2.5
(SATURN RADII)
6500



TYPE II TRANS
TYPE I TRANSFER
110
120
130
140
150
89
100
200
250
300
EARTH DEPARTURE C_3 (km^2/sec^2)
JULIAN DATE AT EARTH (-2440000)
3350
3400
3450
7000
7500
8000
8500
9000
9500
JULIAN DATE AT NEPTUNE (-2440000)
1.5
SATURN PASSAGE JULIAN DATE (-2440000)
FOLDOUT FRAME


3420
3385
3350
5.0
JUPITER PASSAGE DISTANCE (JUPITER RADII)
3900
3.0
EARTH DEPARTURE JULIAN DATE (-2440000)
3800
JULIAN DATE AT SATURN (-2440000)
5500
5000
4500
3300
7000
1.10
1.0
1.20
REGION OF SATURN'S RINGS
6000
1.0
1.5
2.0
2.5
3.0
6500
URAN
SATURN PASSAGE DISTANCE (SATURN RADII)
JULIAN DATE AT URANUS (-2440000)
3850
3900
3950
4.0
4000
5.0
4050
4100
7.5
4150
4200
7000
10.0
JUPITER PASSAGE PASSAGE JULIAN DATE (-2440000)
7500

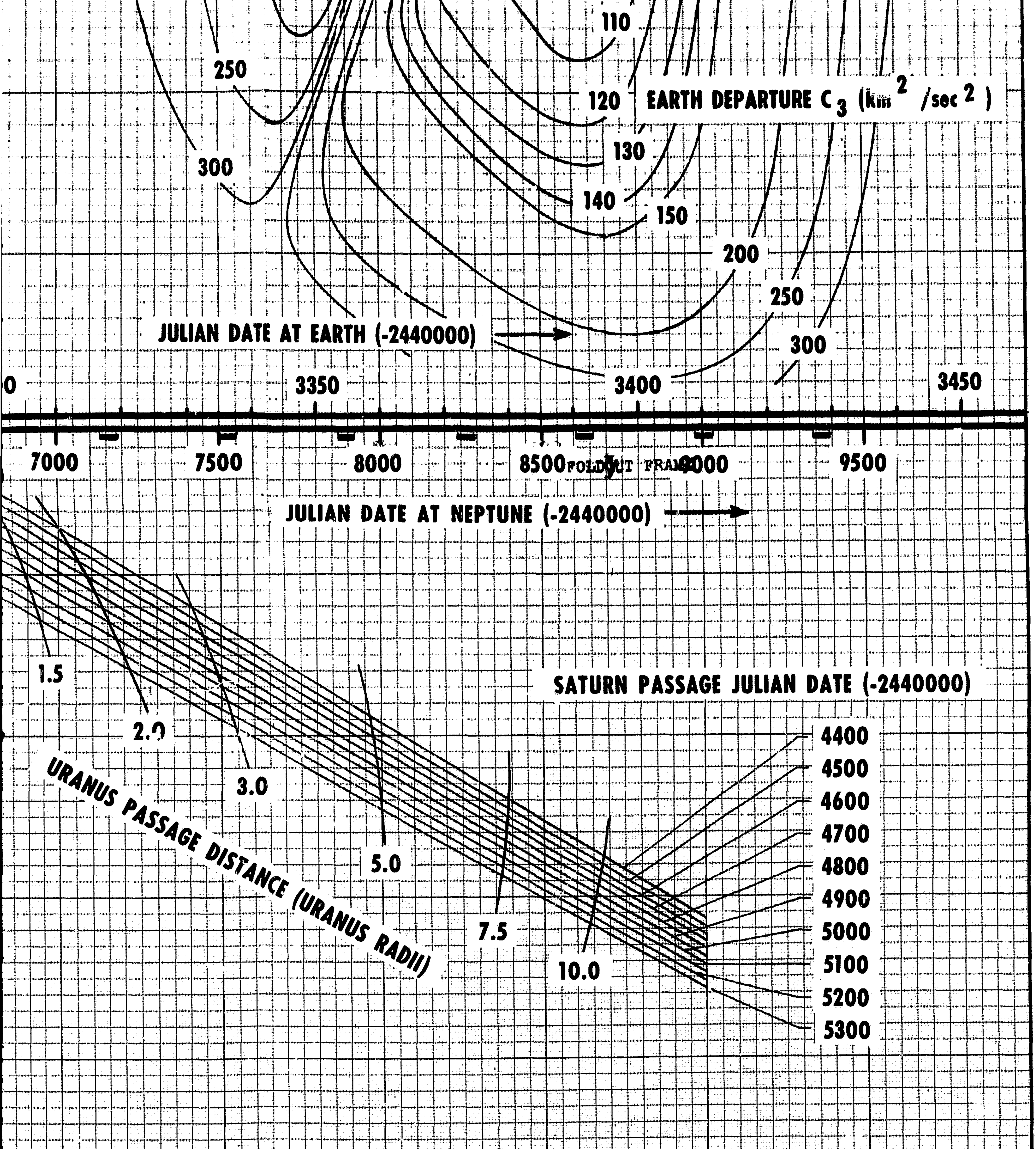
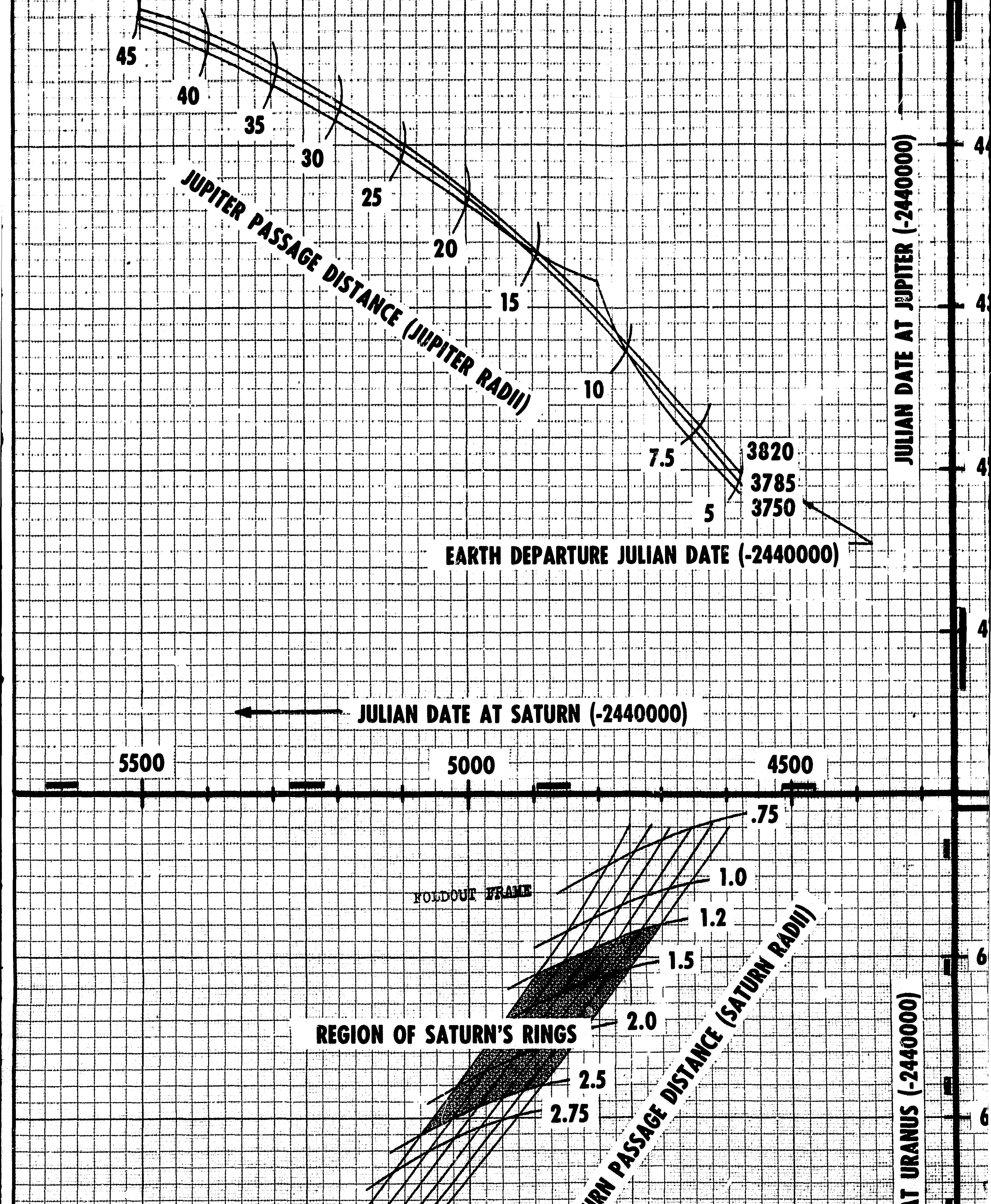
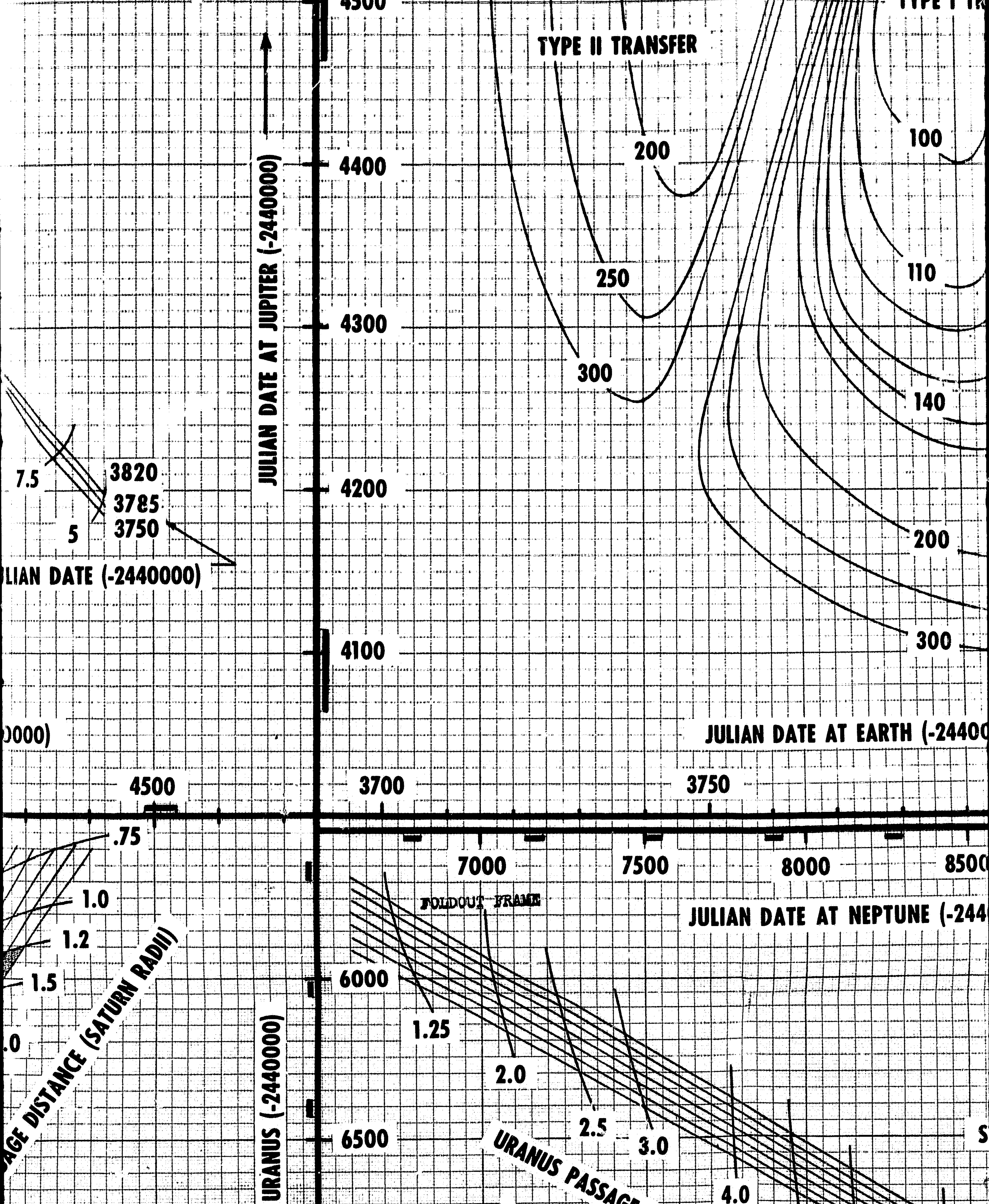


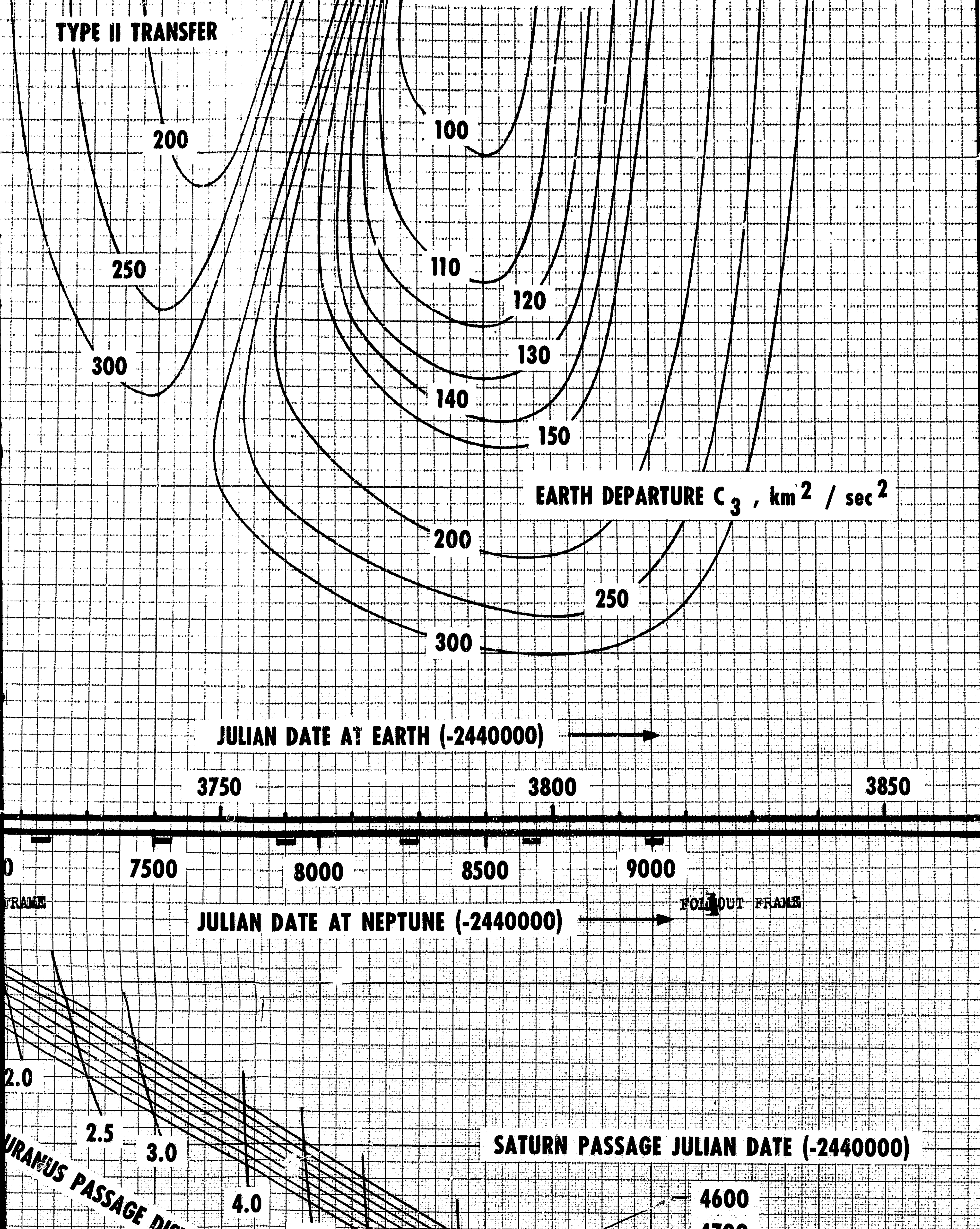
FIGURE 4-3. QUAD GRAPH FOR 1977 GRAND TOUR OF THE JOVIAN PLANETS

FOLDOUT FRAME

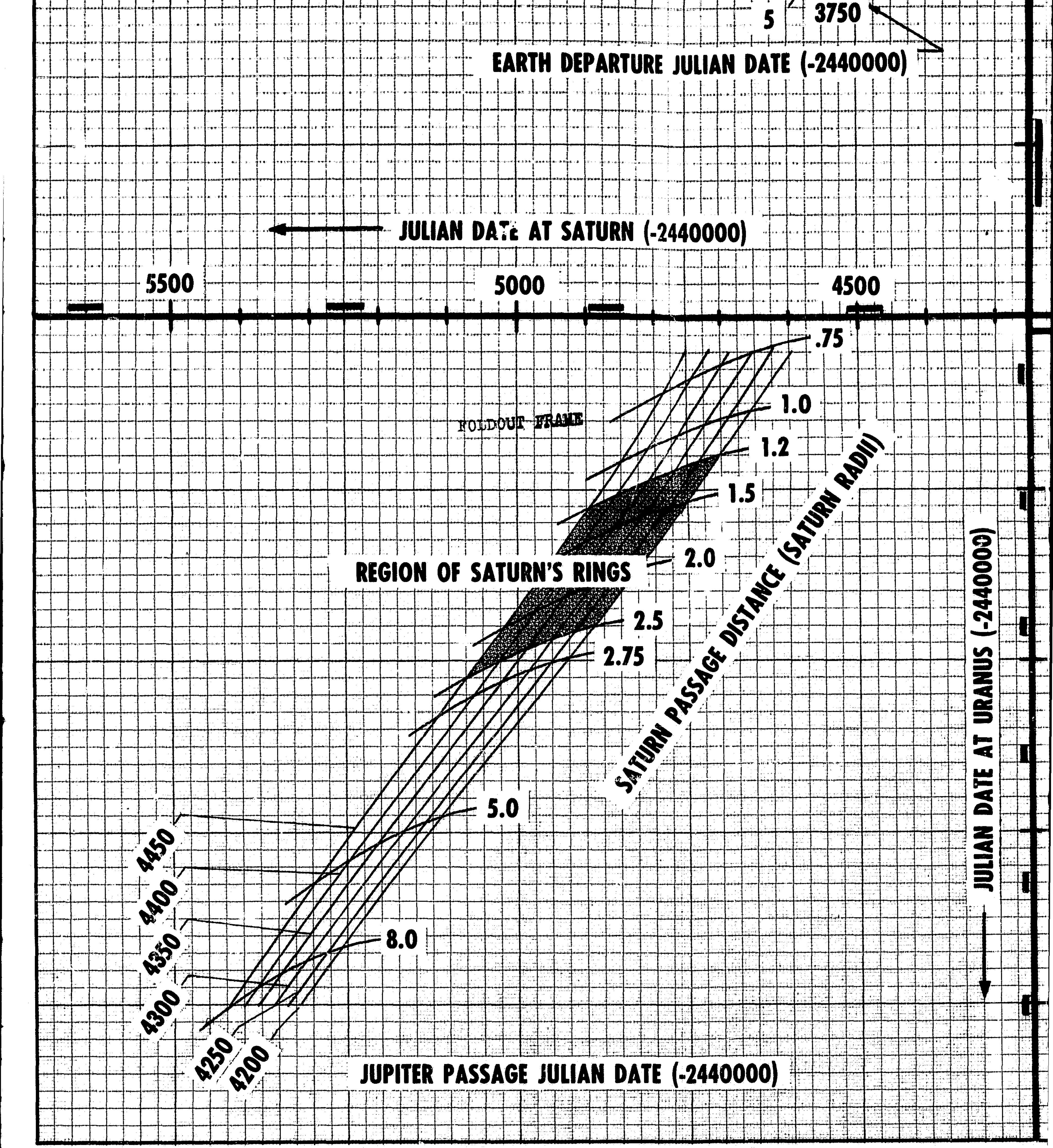


JUPITER PASSAGE DISTANCE (JUPITER RADII)
45
40
35
30
25
20
15
10
7.5
5
3820
3785
3750
EARTH DEPARTURE JULIAN DATE (-2440000)
JULIAN DATE AT JUPITER (-2440000)
JULIAN DATE AT SATURN (-2440000)
5500
5000
4500
.75
1.0
1.2
1.5
2.0
2.5
2.75
REGION OF SATURN'S RINGS
FOLDOUT FRAME


4500
TYPE II TRANSFER
200
100
4400
110
250
4300
300
140
7.5
3820
3785
4200
5
3750
200
JULIAN DATE (-2440000)
300
4100
JULIAN DATE AT JUPITER (-2440000)
JULIAN DATE AT EARTH (-24400
4500
3700
3750
.75
7000
7500
8000
8500
1.0
FOLDOUT FRAME
JULIAN DATE AT NEPTUNE (-244
1.2
1.5
6000
1.25
2.0
2.5
3.0
6500
4.0
URANUS (-2440000)
URANUS PASSAGE
AGE DISTANCE (SATURN RADII)



FOLDOUT FRAME



FOLDOUT FRAME

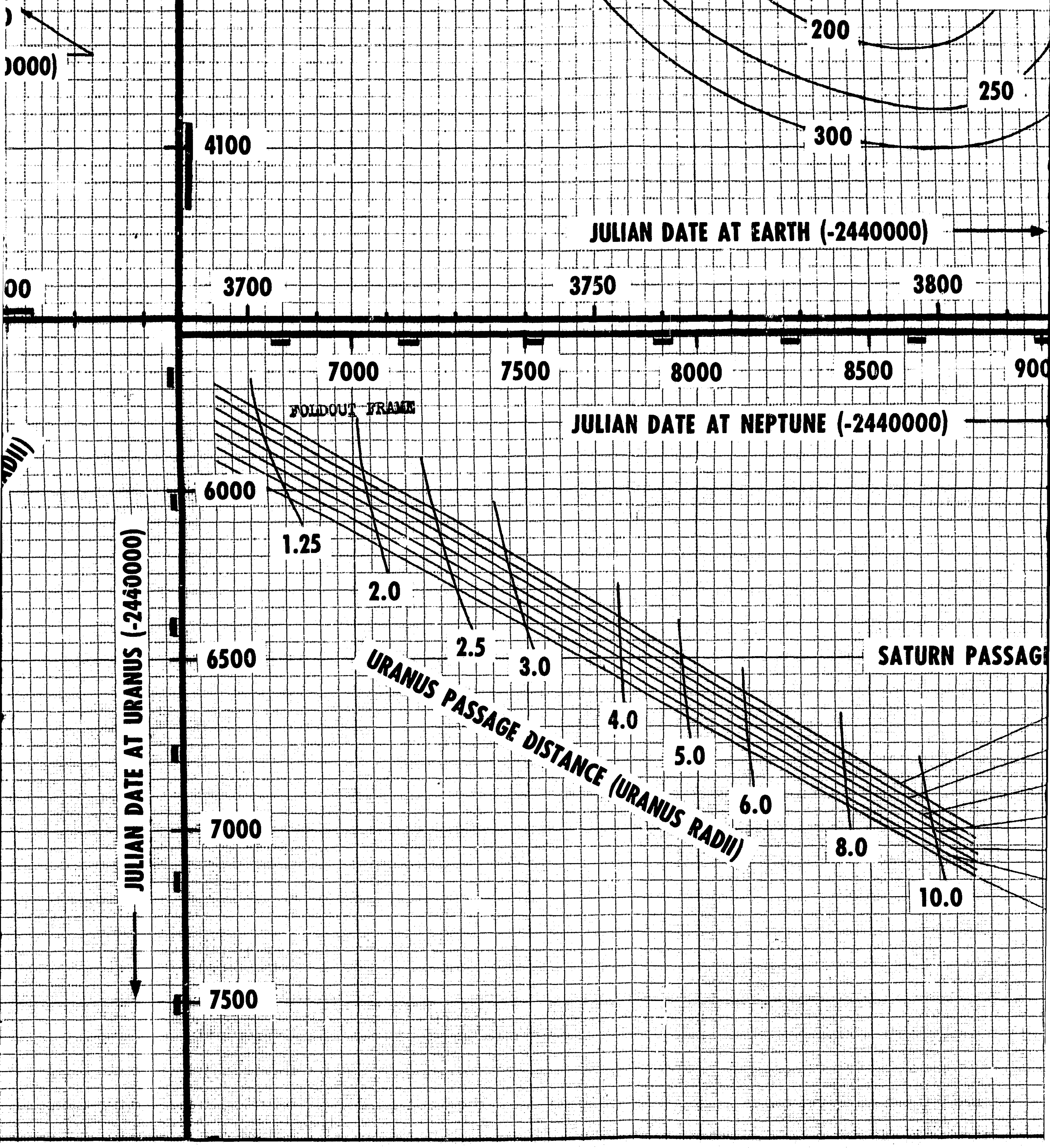


FIGURE 4-4. QUAD GRAPH FOR 1978 GRAND

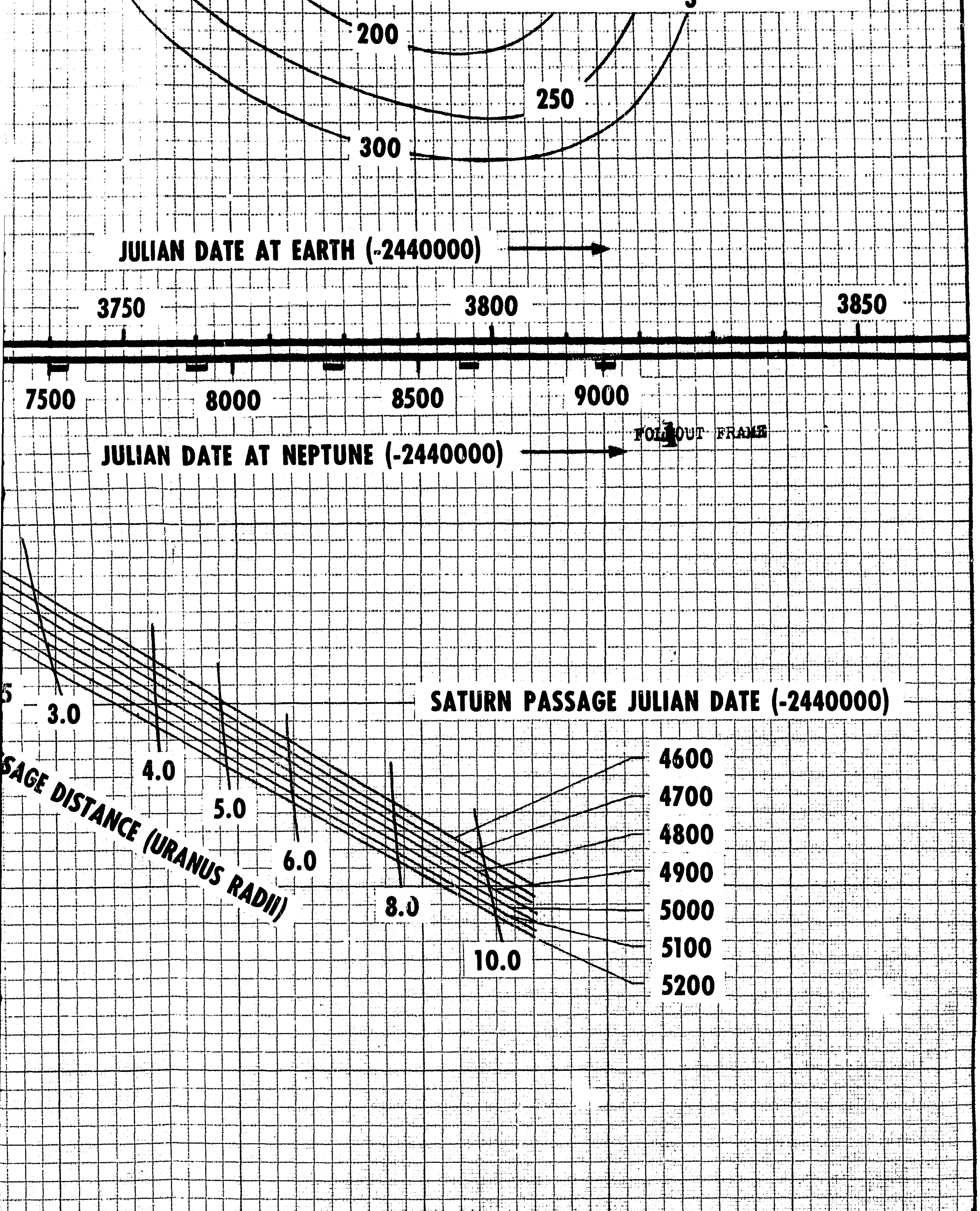
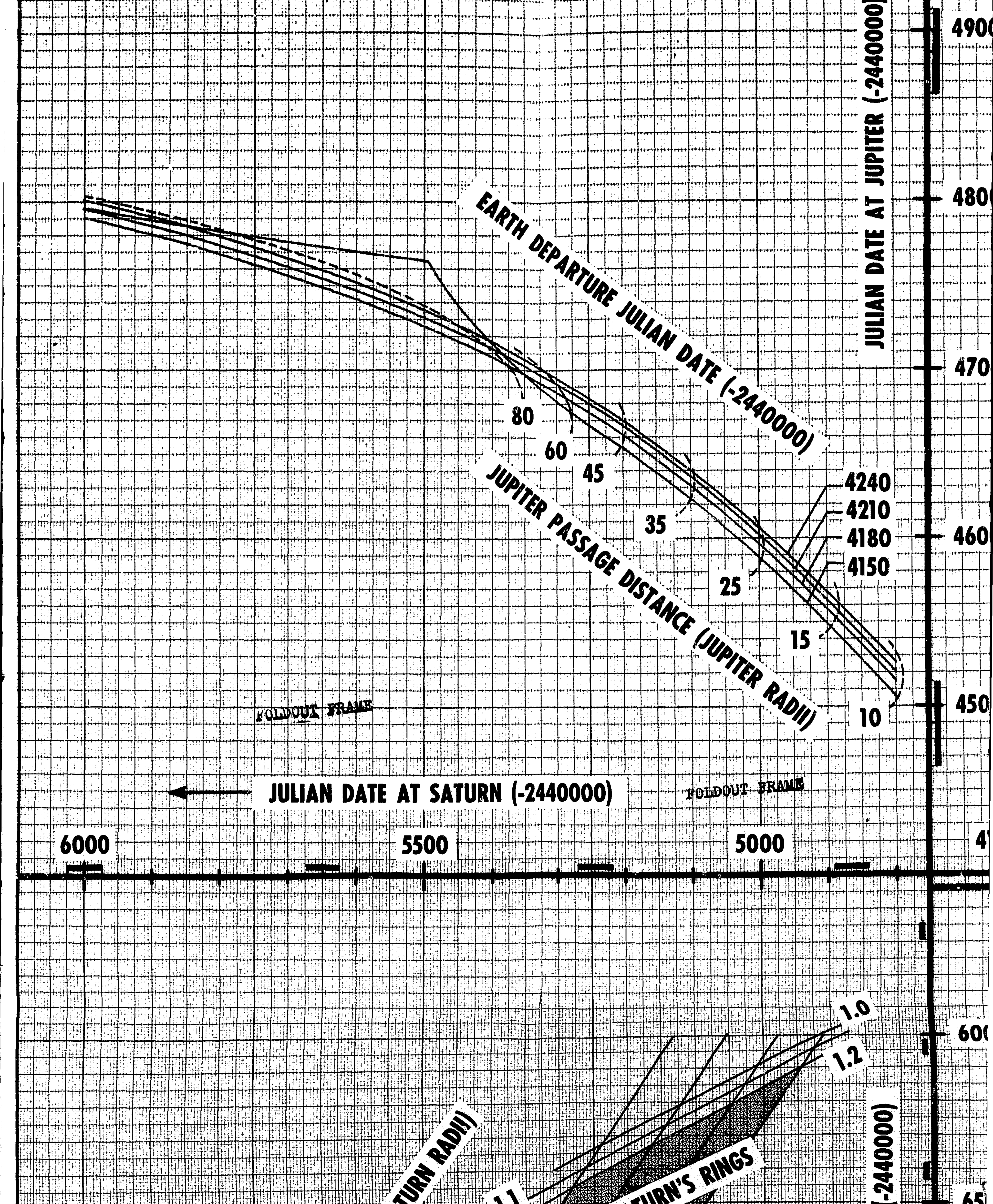
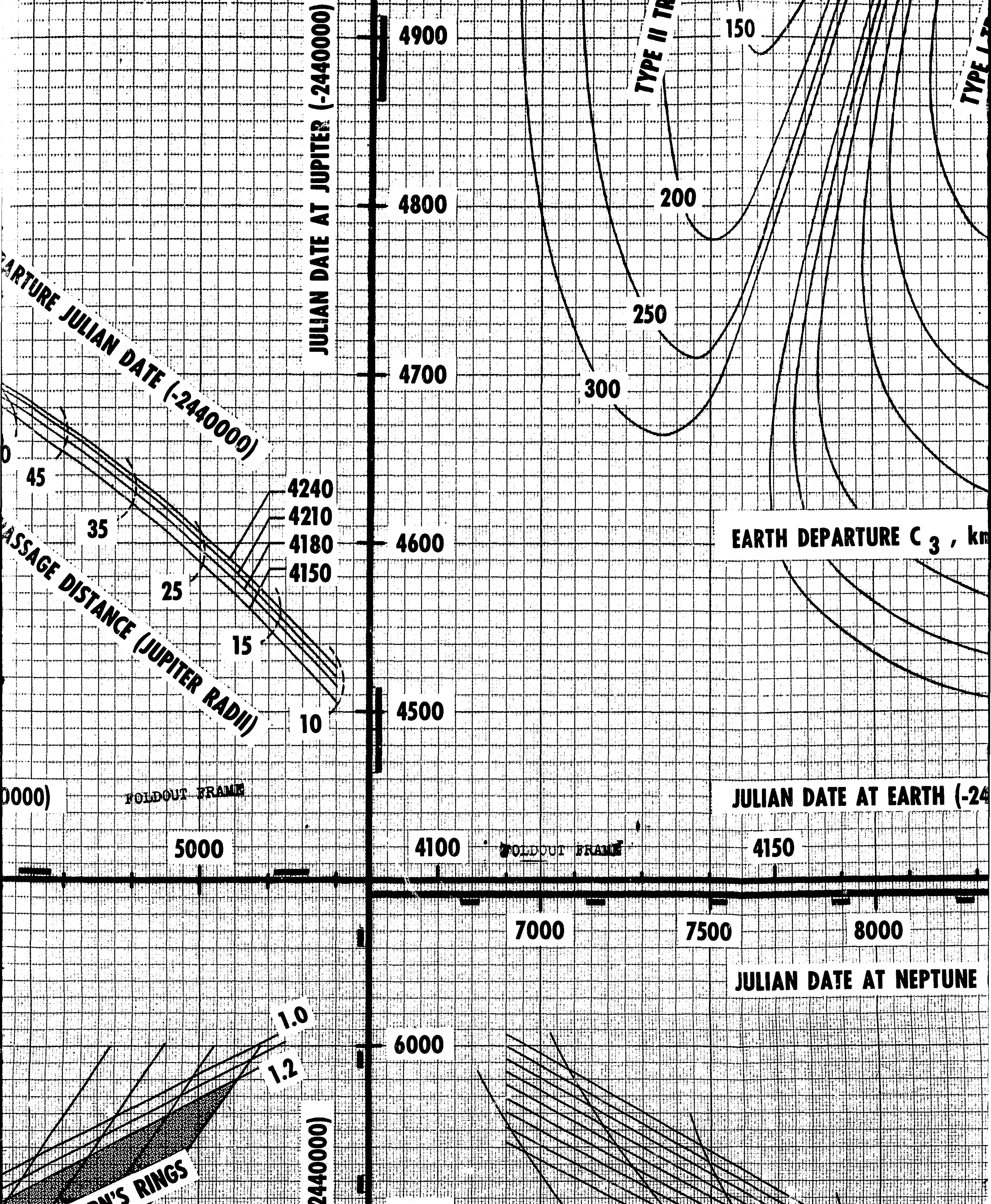
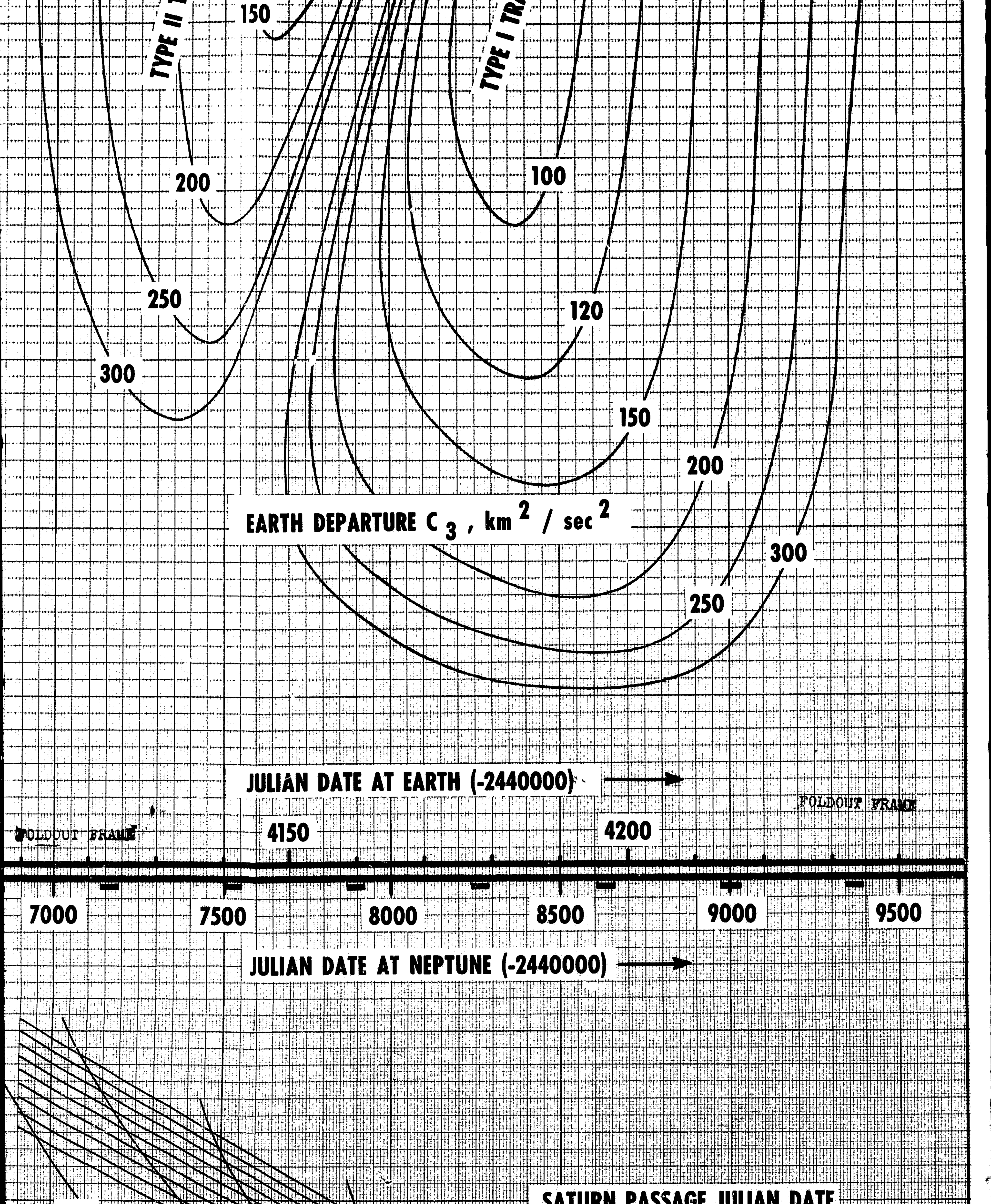


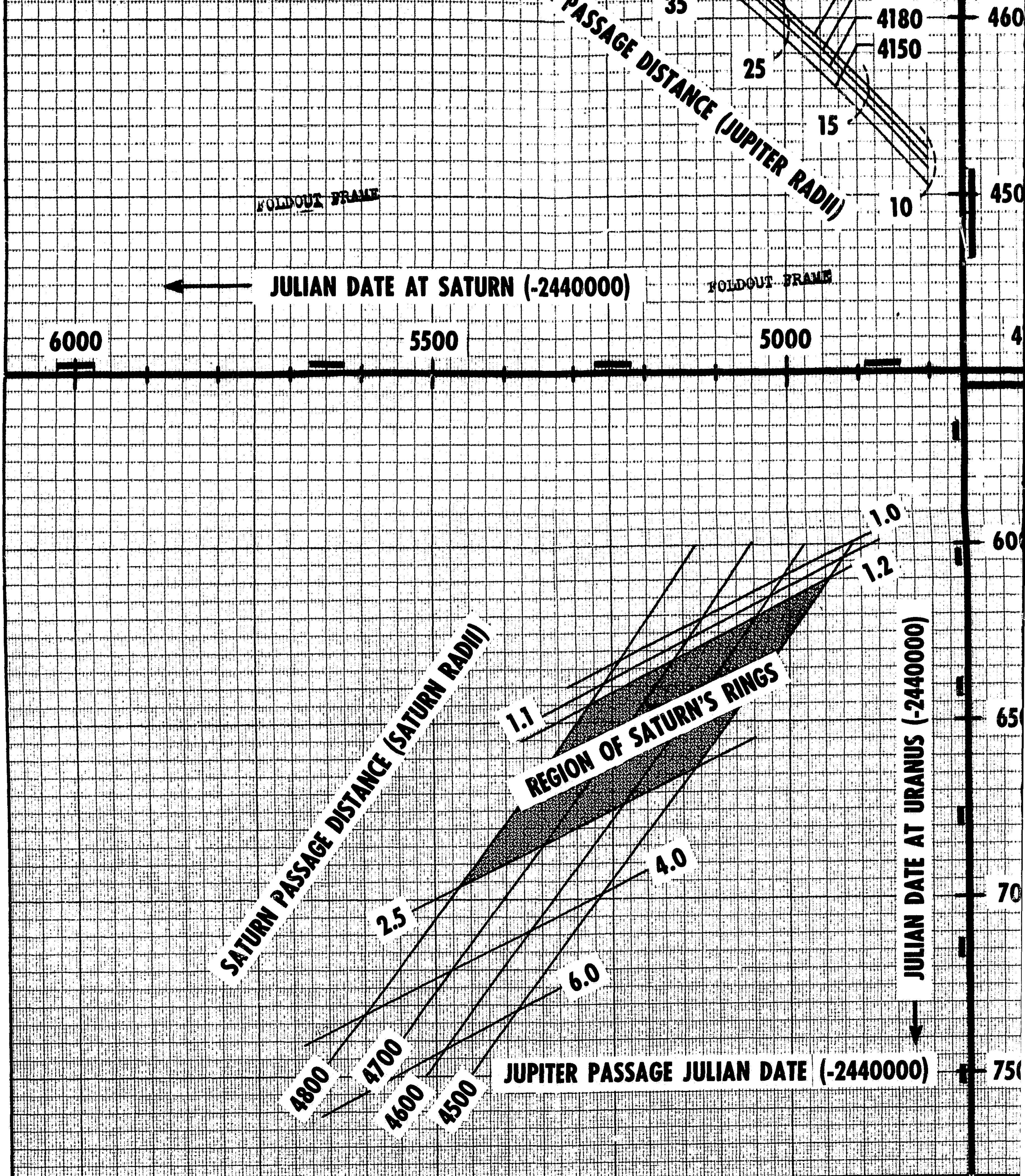
FIGURE 4-4. QUAD GRAPH FOR 1978 GRAND TOUR OF THE JOVIAN PLANETS



EARTH DEPARTURE JULIAN DATE (-2440000)
JULIAN DATE AT JUPITER (-2440000)
4900
4800
4700
4600
4500
80
60
45
35
25
15
10
JUPITER PASSAGE DISTANCE (JUPITER RADII)
4240
4210
4180
4150
FOLDOUT FRAME
JULIAN DATE AT SATURN (-2440000)
FOLDOUT FRAME
6000
5500
5000
1.0
1.2
1.1
600
-2440000)

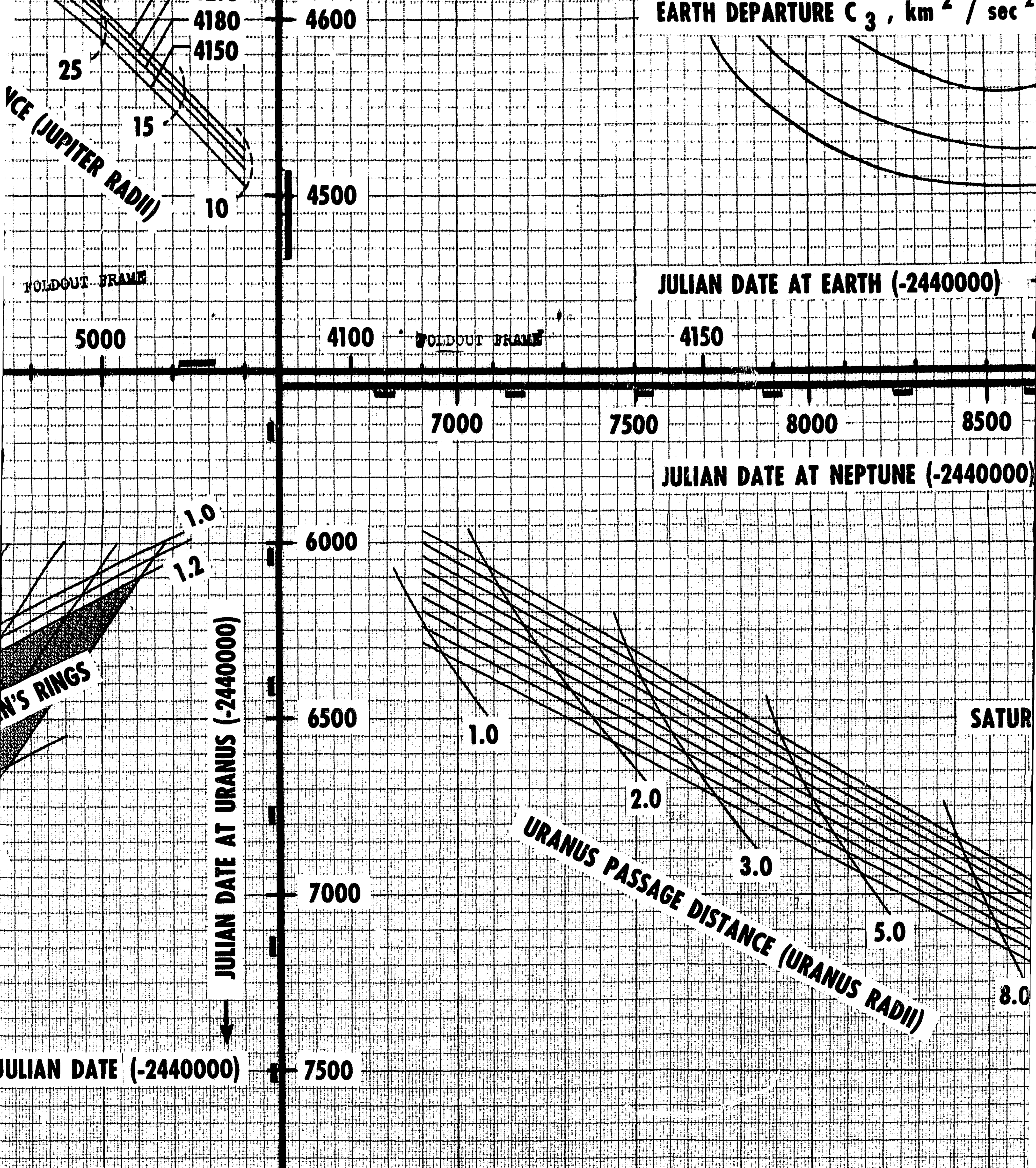

JULIAN DATE AT JUPITER (-2440000)
4900
4800
4700
4600
4500
TYPE II TR
TYPE I
150
200
250
300
EARTH DEPARTURE C 3 , km
ARTURE JULIAN DATE (-2440000)
45
35
25
15
10
4240
4210
4180
4150
ASSAGE DISTANCE (JUPITER RADII)
0000)
FOLDOUT FRAME
JULIAN DATE AT EARTH (-24
5000
4100
FOLDOUT FRAME
4150
7000
7500
8000
JULIAN DATE AT NEPTUNE
1.0
1.2
6000
N'S RINGS
2440000)


150
200
250
300
100
120
150
200
300
250
EARTH DEPARTURE C 3 , km 2 / sec 2
JULIAN DATE AT EARTH (-2440000)
FOLDOUT FRAME
FOLDOUT FRAME
4150
4200
7000
7500
8000
8500
9000
9500
JULIAN DATE AT NEPTUNE (-2440000)
SATURN PASSAGE JULIAN DATE



FOLDOUT FRAME

FOLDOUT FRAME



FICURE 4-5. QUAD GRAPH FOR 1979 GRAND TOU

FOLDOUT FRAME

FOLDOUT FRAME

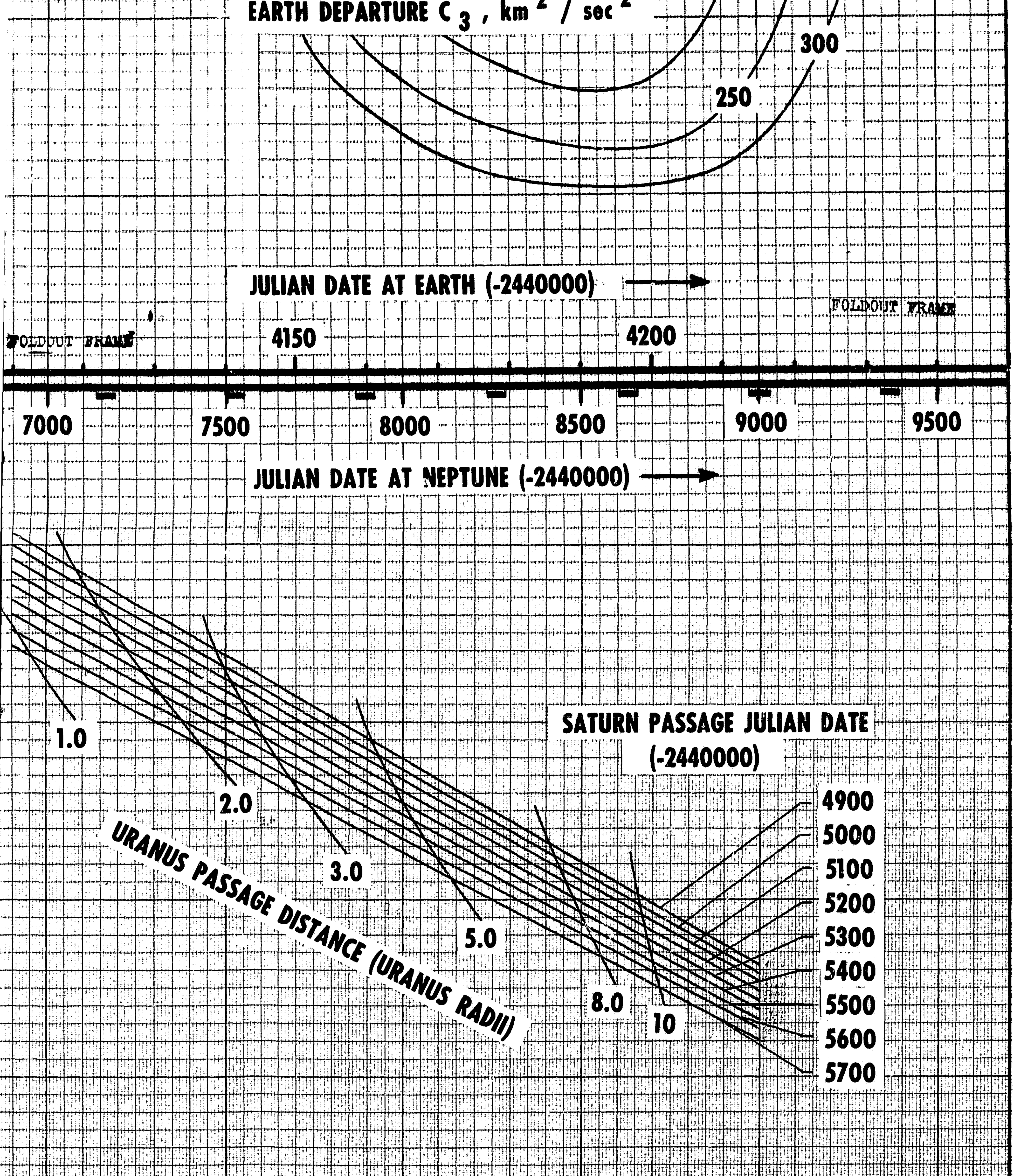
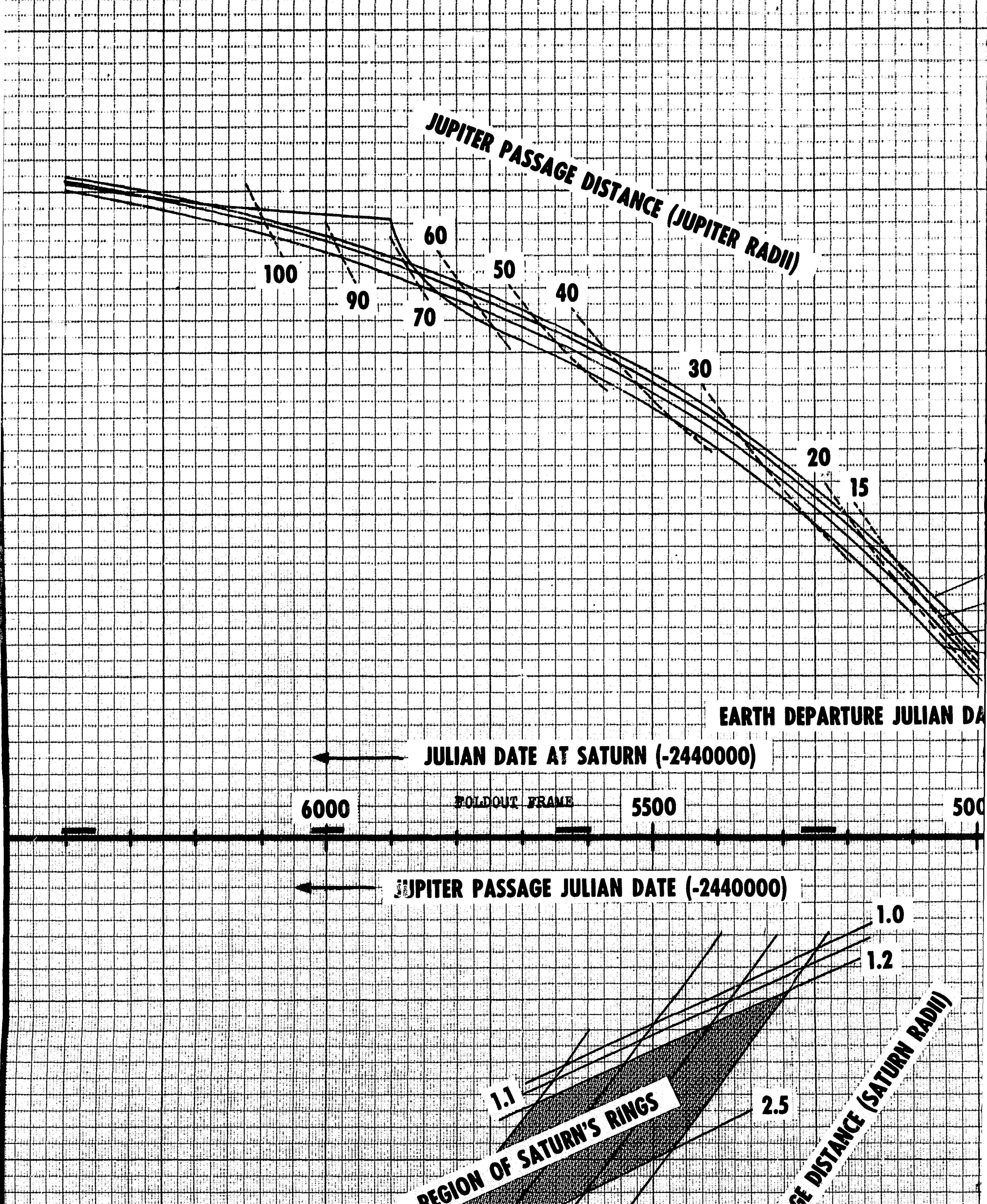
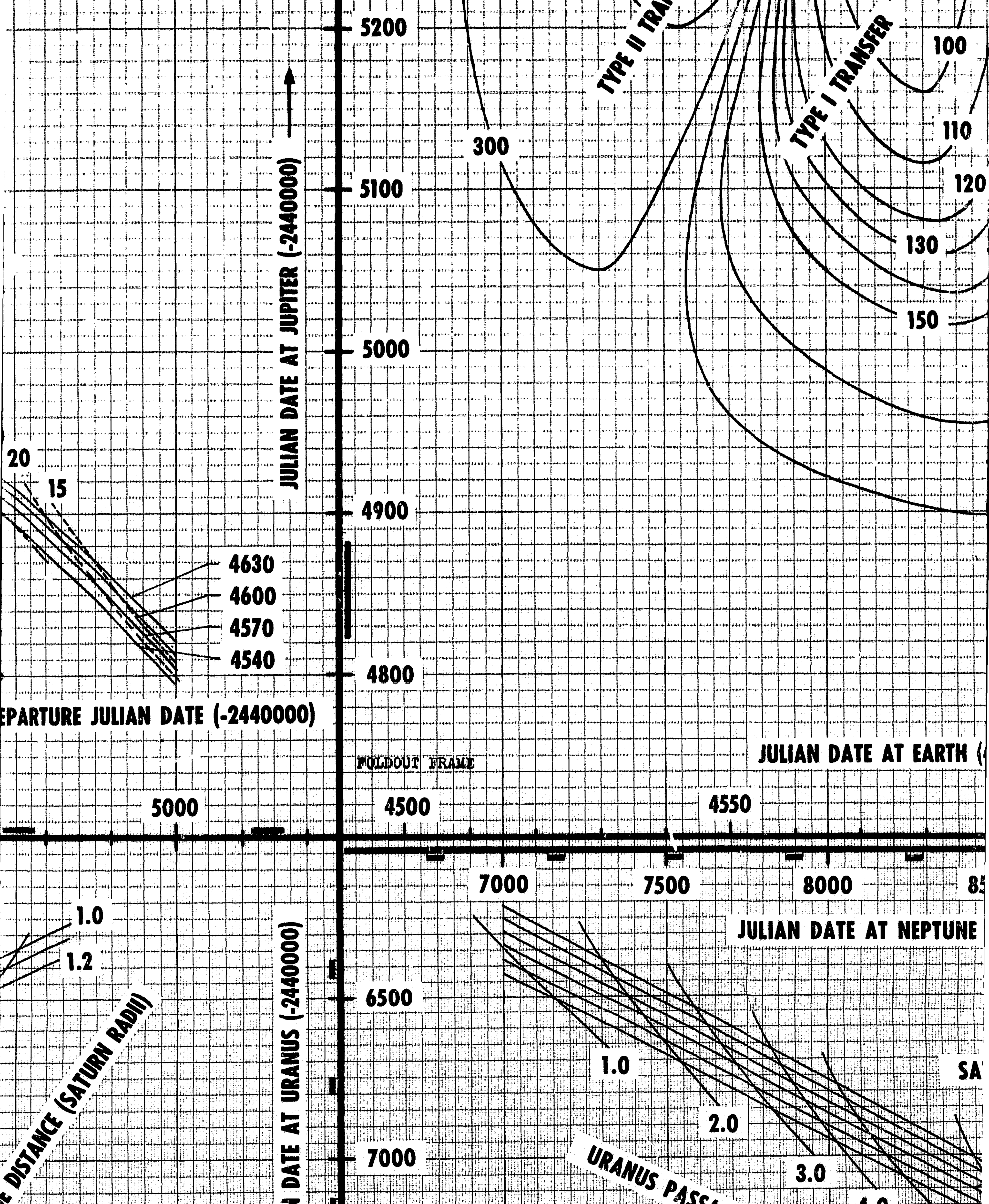
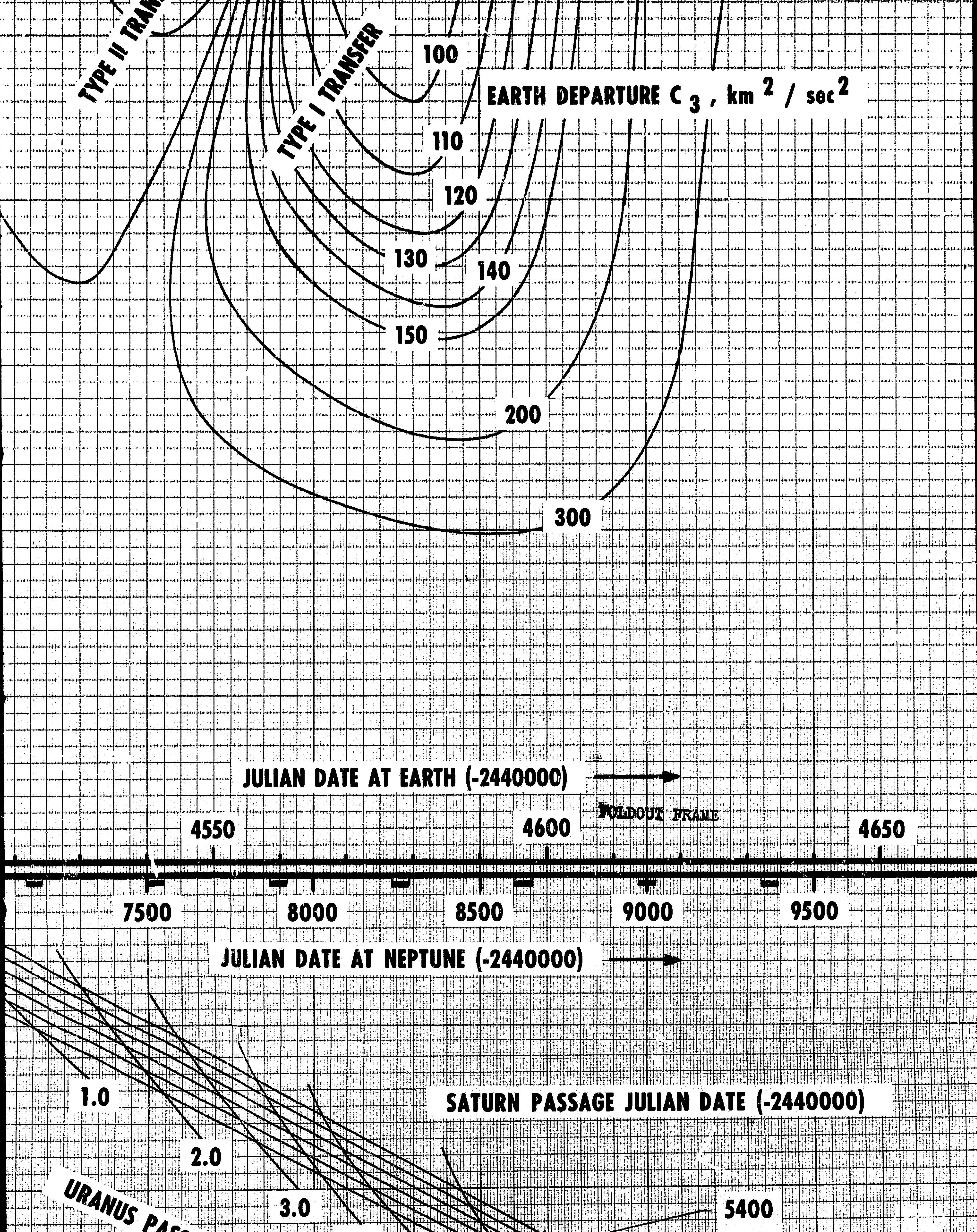


FIGURE 4-5. QUAD GRAPH FOR 1979 GRAND TOUR OF THE JOVIAN PLANETS

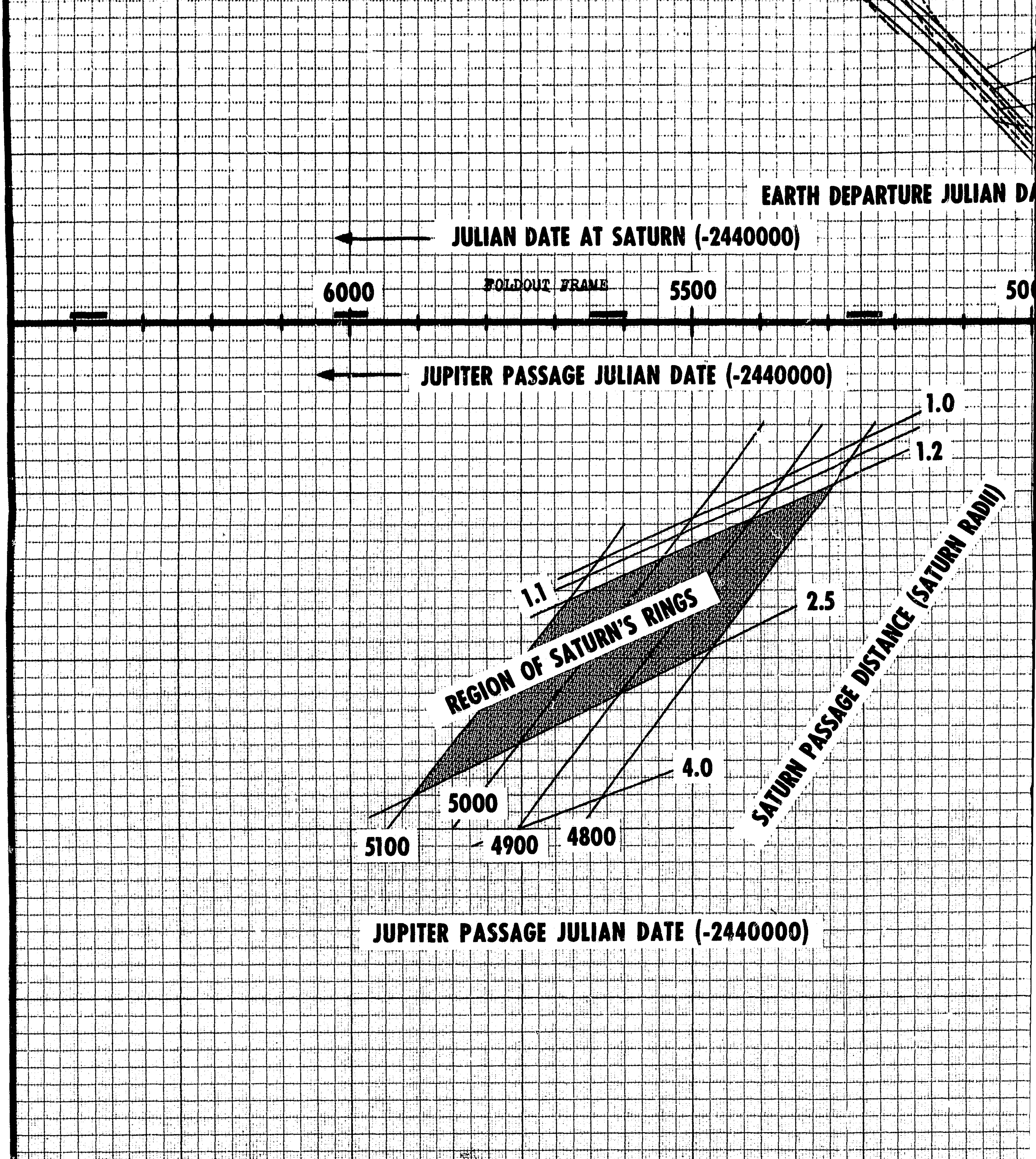


JUPITER PASSAGE DISTANCE (JUPITER RADII)
100
90
70
60
50
40
30
20
15
EARTH DEPARTURE JULIAN DA
JULIAN DATE AT SATURN (-2440000)
FOLDOUT FRAME
6000
5500
500
JUPITER PASSAGE JULIAN DATE (-2440000)
1.0
1.2
1.1
2.5
REGION OF SATURN'S RINGS
SE DISTANCE (SATURN RADII)


TYPE II TRA
TYPE I TRANSFER
5200
5100
5000
4900
4800
100
110
120
130
150
300
JULIAN DATE AT JUPITER (-2440000)
20
15
4630
4600
4570
4540
EPARTURE JULIAN DATE (-2440000)
FOLDOUT FRAME
JULIAN DATE AT EARTH (
5000
4500
4550
7000
7500
8000
JULIAN DATE AT NEPTUNE
1.0
1.2
DISTANCE (SATURN RADII)
N DATE AT URANUS (-2440000)
6500
7000
1.0
2.0
3.0
URANUS PASSA
SA



TYPE II TRANS
TYPE I TRANSFER
100
EARTH DEPARTURE C_3, km^2/sec^2
110
120
130
140
150
200
300
JULIAN DATE AT EARTH (-2440000)
FOLDOUT FRAME
4550
4600
4650
7500
8000
8500
9000
9500
JULIAN DATE AT NEPTUNE (-2440000)
1.0
2.0
3.0
SATURN PASSAGE JULIAN DATE (-2440000)
5400
URANUS PASS



FOLDOUT FRAME

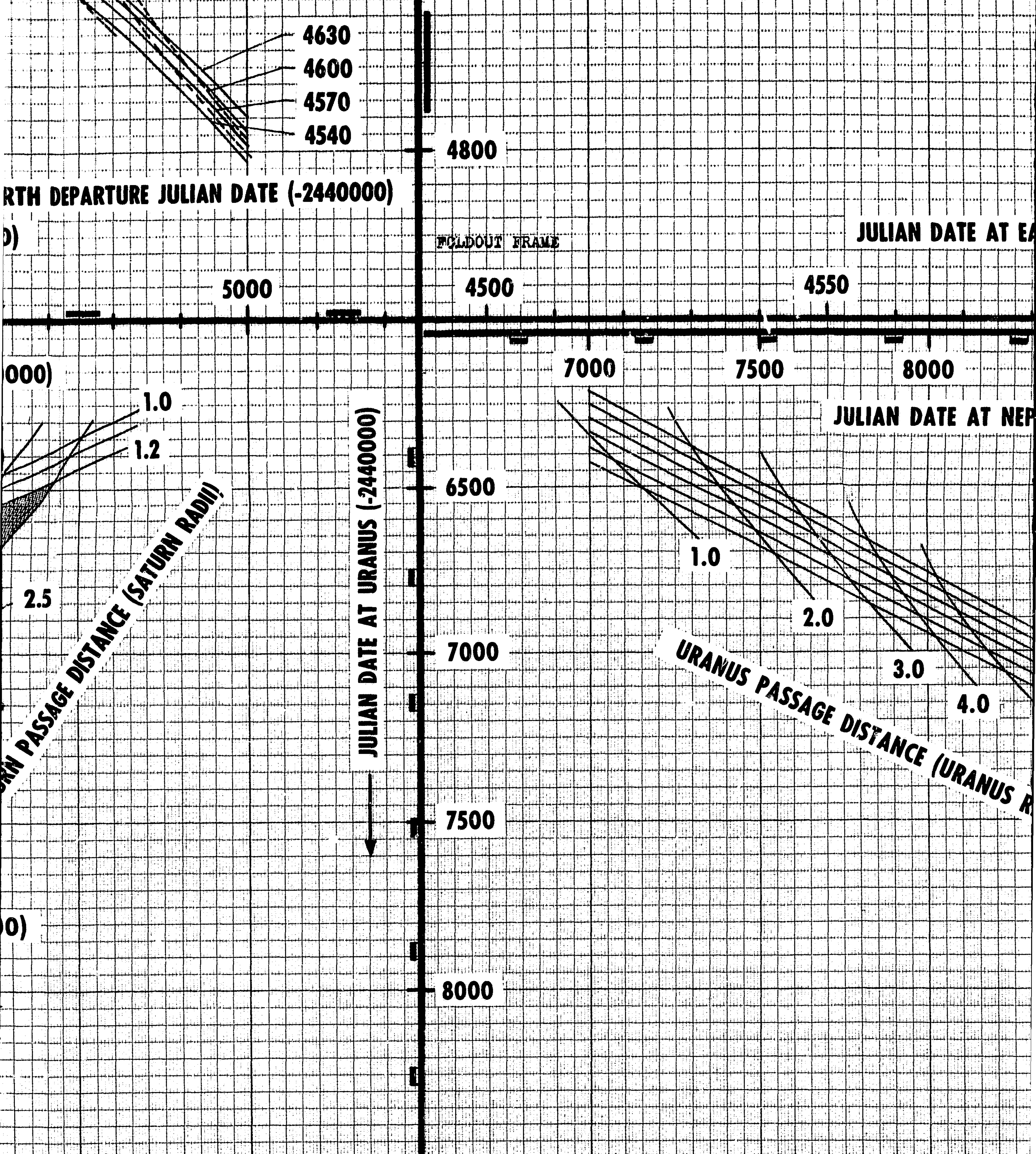


FIGURE 4-6. QUAD C

FOLDOUT FRAME

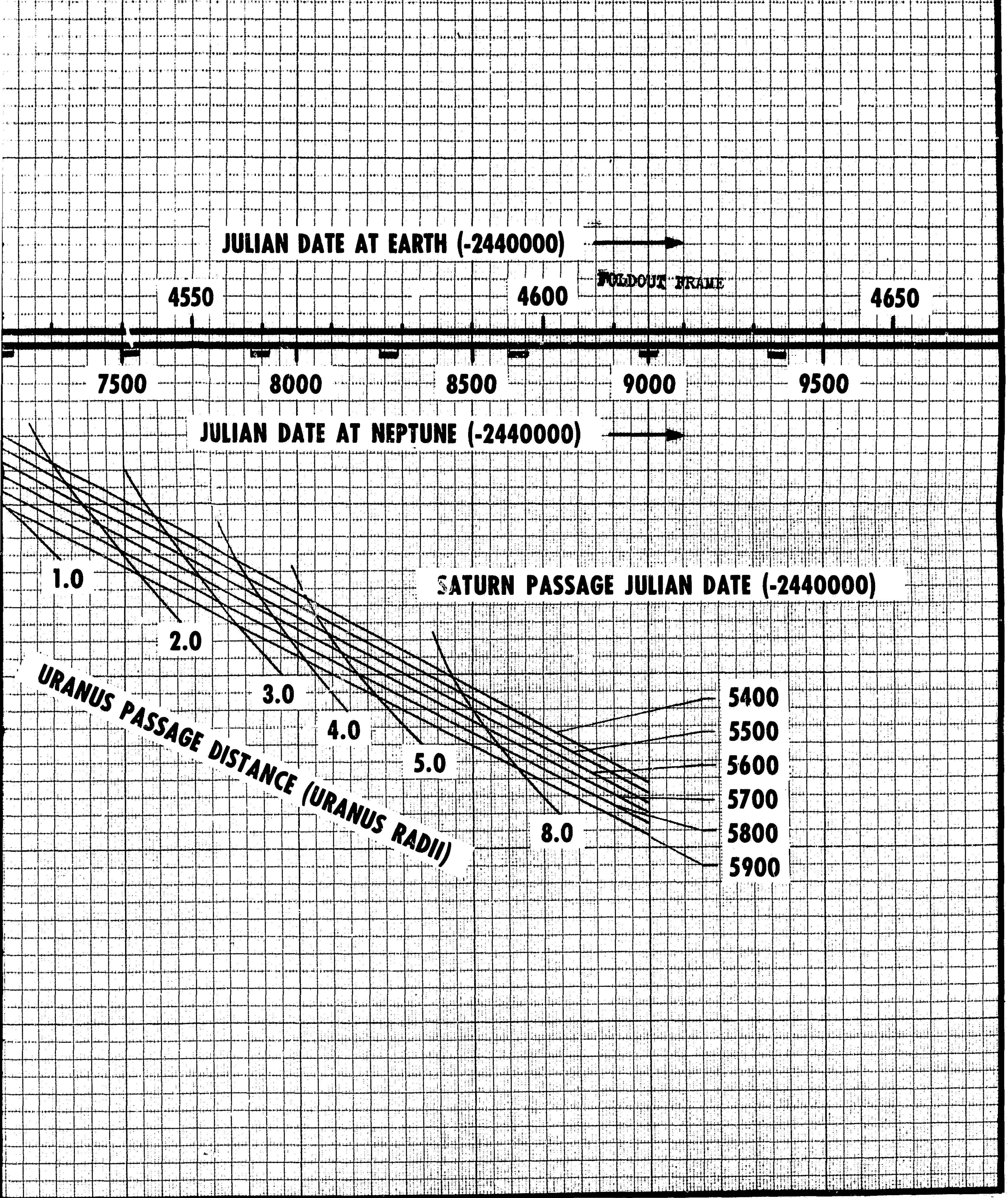


FIGURE 4-6. QUAD GRAPH FOR 1980 GRAND TOUR OF THE JOVIAN PLANETS

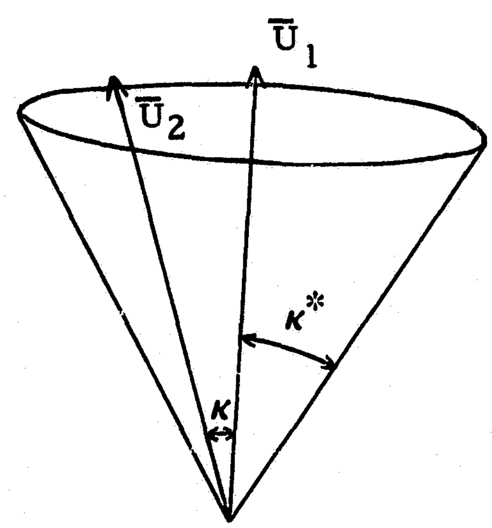


FIGURE 4-7. SET OF HYPERBOLIC EXIT DIRECTIONS THAT PRODUCE A BEND ANGLE OF κ^*

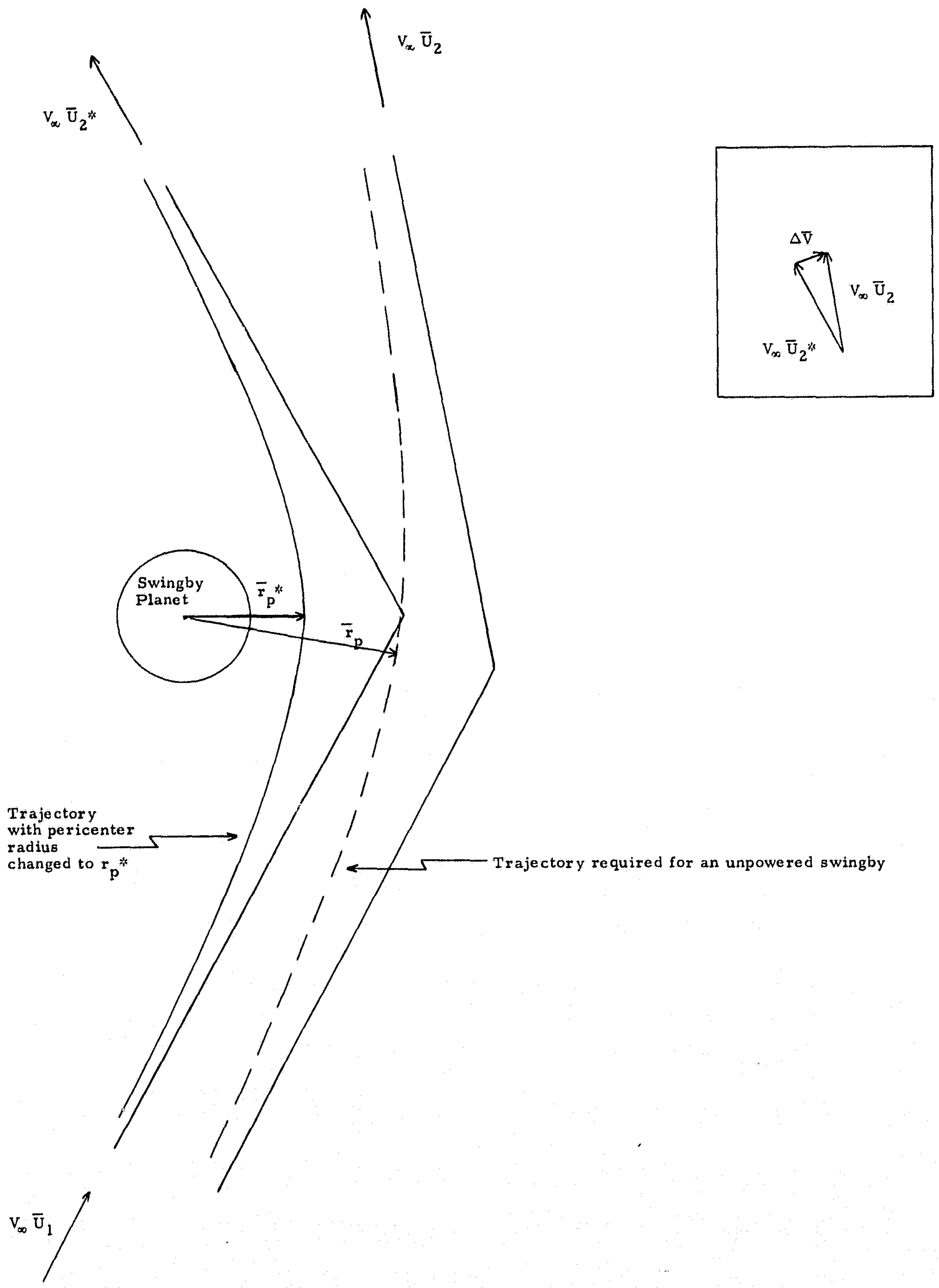
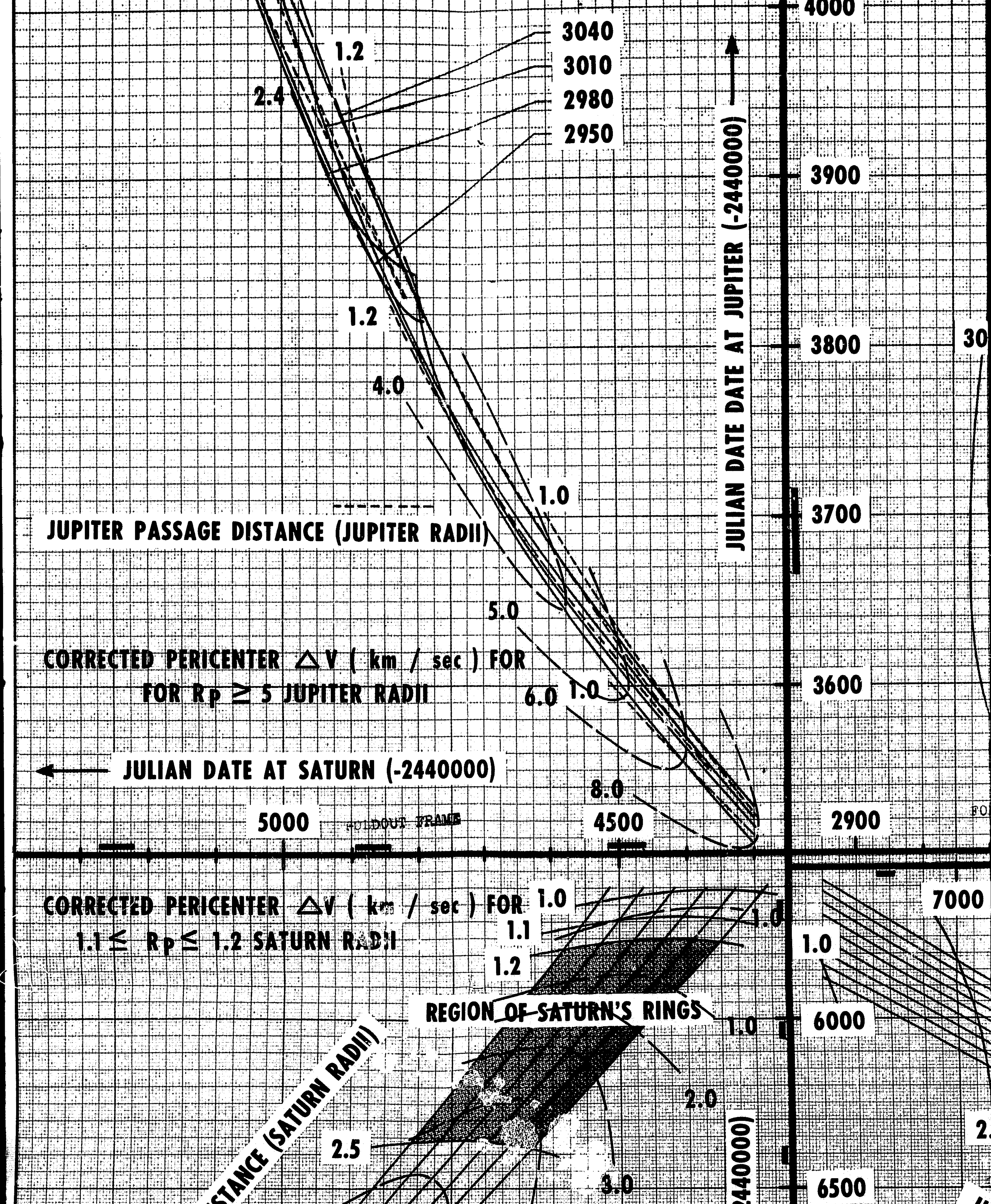
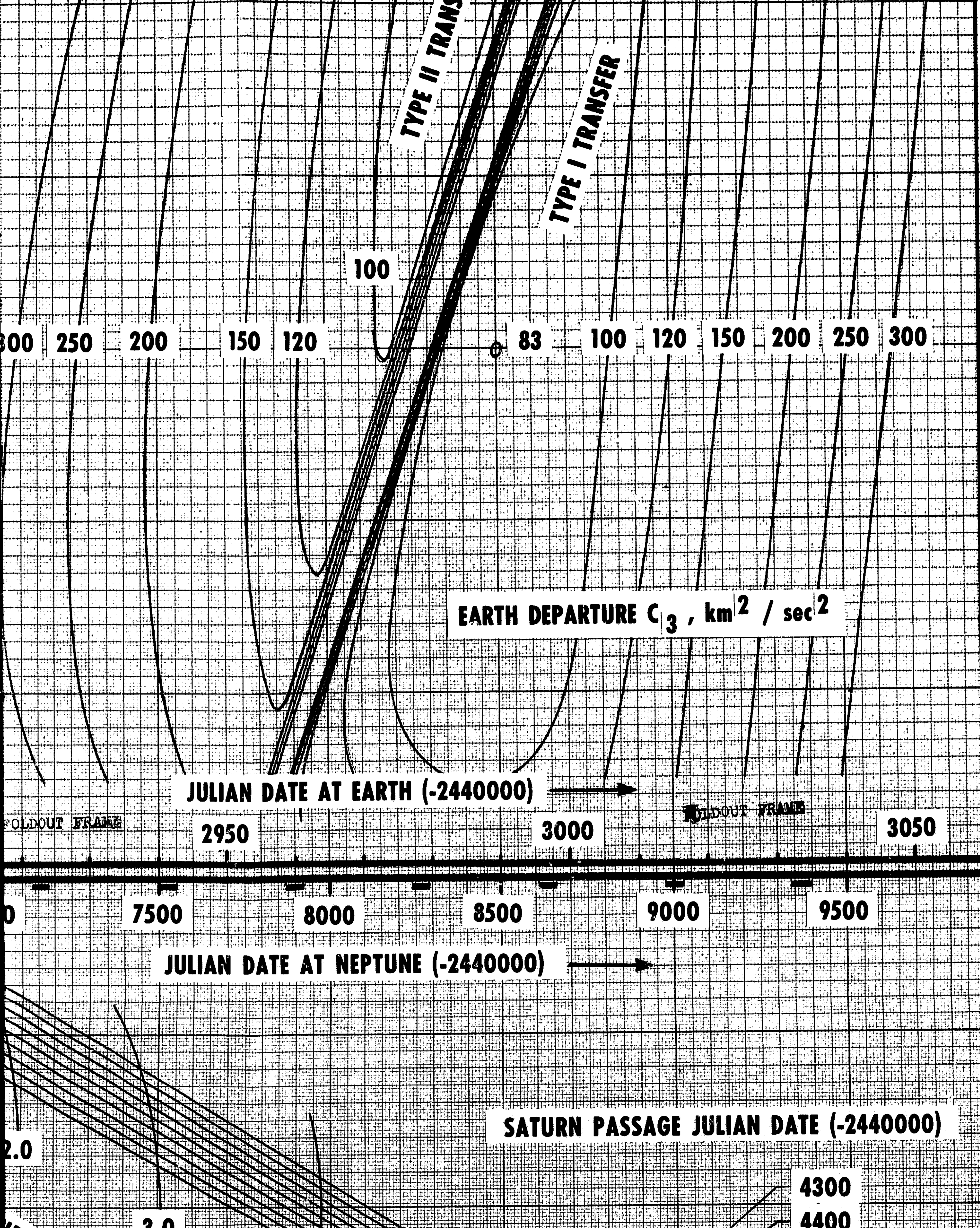
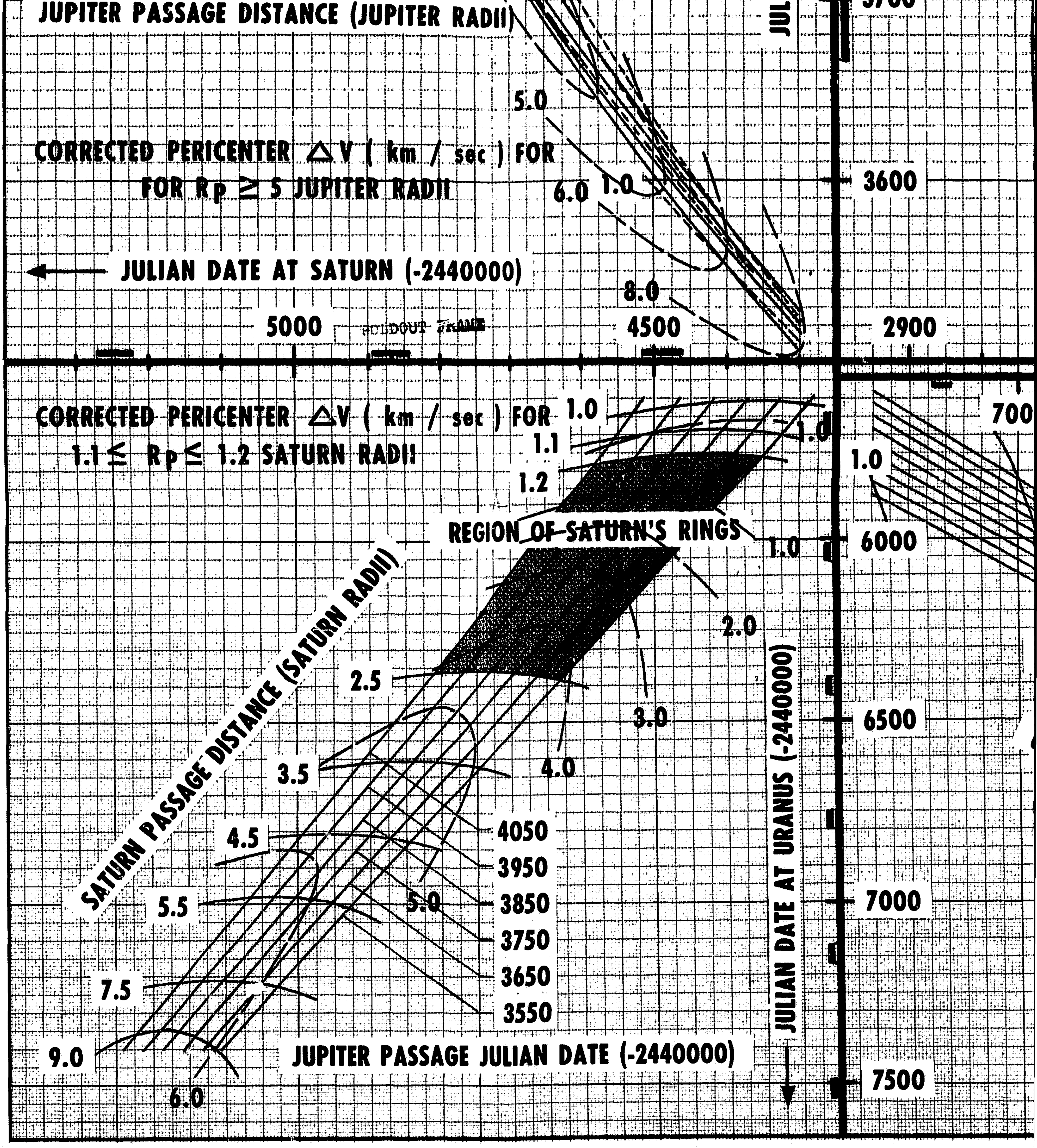


FIGURE 4-8. SWINGBY TRAJECTORY FOR A CORRECTED PERICENTER MANEUVER


4000
3040
3010
2980
2950
1.2
2.4
3900
3800
3700
3600
1.2
4.0
1.0
JULIAN DATE DATE AT JUPITER (-2440000)
JUPITER PASSAGE DISTANCE (JUPITER RADII)
5.0
CORRECTED PERICENTER △V (km / sec) FOR
FOR Rp ≥ 5 JUPITER RADII
6.0
1.0
JULIAN DATE AT SATURN (-2440000)
8.0
5000
FOLDOUT FRAME
4500
2900
CORRECTED PERICENTER △V (km / sec) FOR
1.1 ≤ Rp ≤ 1.2 SATURN RADII
1.0
1.1
1.2
1.0
7000
1.0
REGION OF SATURN'S RINGS
1.0
6000
2.0
2.5
3.0
6500


TYPE II TRANS
TYPE I TRANSFER
100
300
250
200
150
120
83
100
120
150
200
250
300
EARTH DEPARTURE C_3, km^2 / sec^2
JULIAN DATE AT EARTH (-2440000)
FOLDOUT FRAME
FOLDOUT FRAME
2950
3000
3050
7500
8000
8500
9000
9500
JULIAN DATE AT NEPTUNE (-2440000)
SATURN PASSAGE JULIAN DATE (-2440000)
2.0
3.0
4300
4400



FOLDOUT FRAME

FOLDOUT FRAME

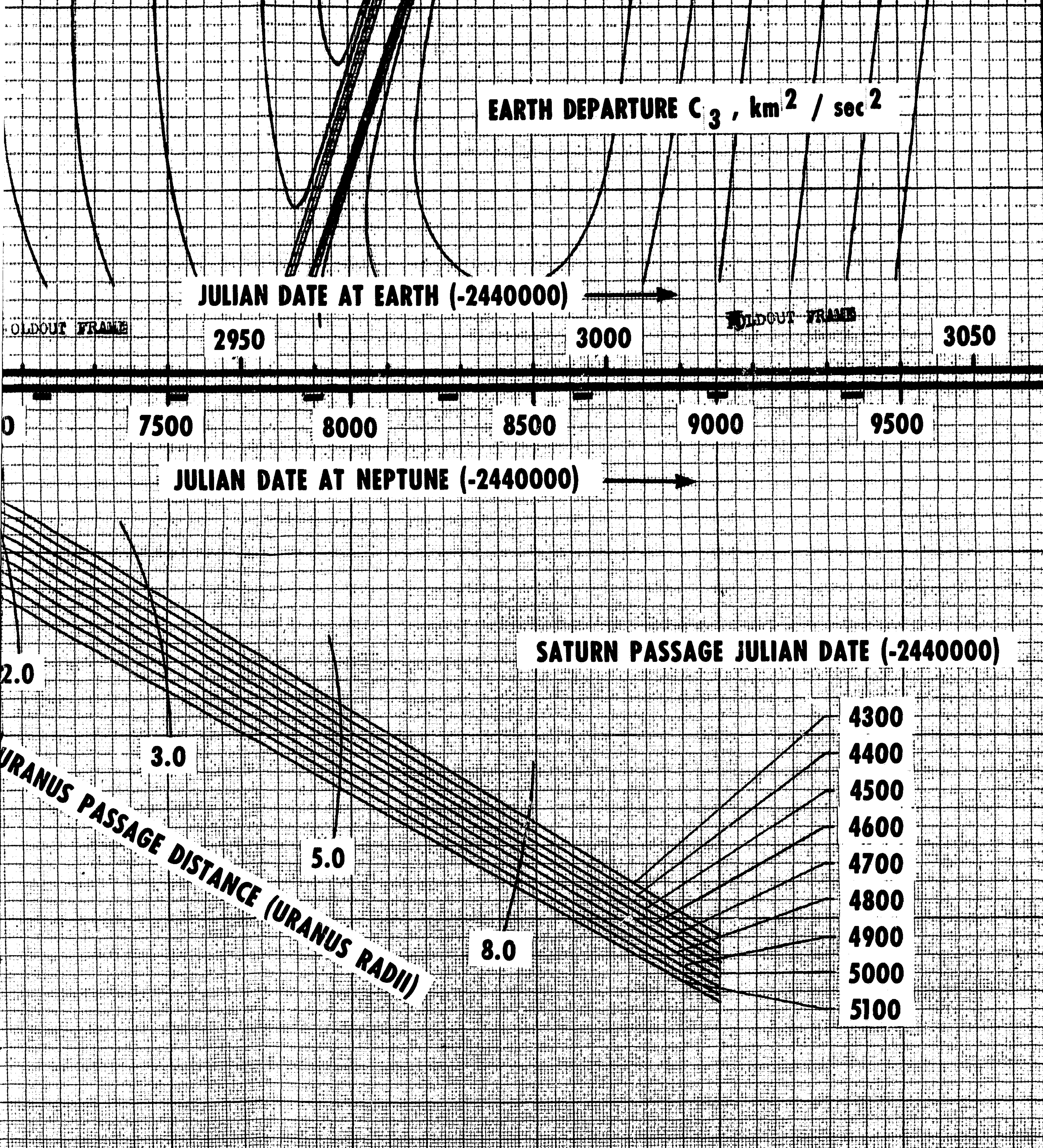
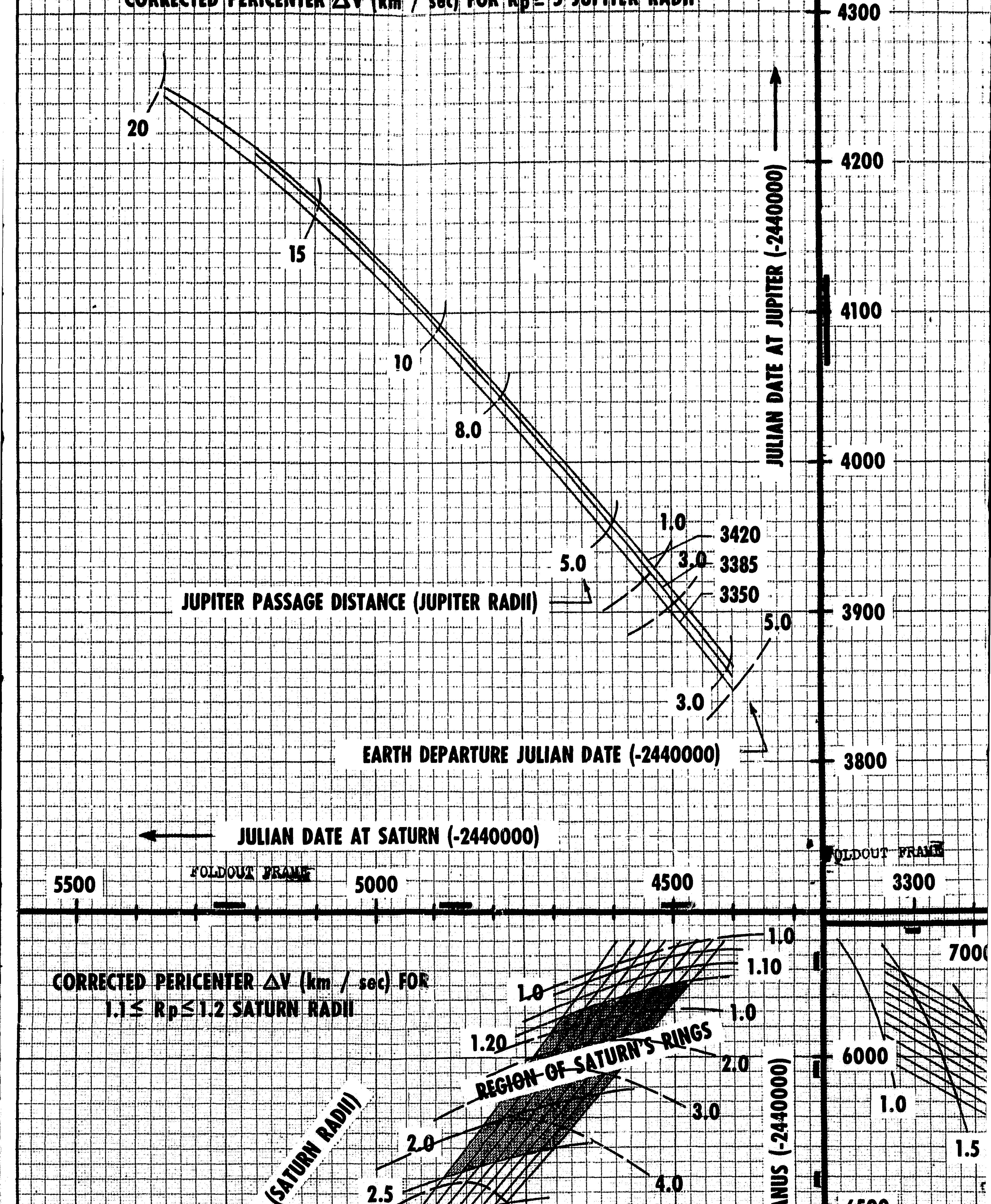
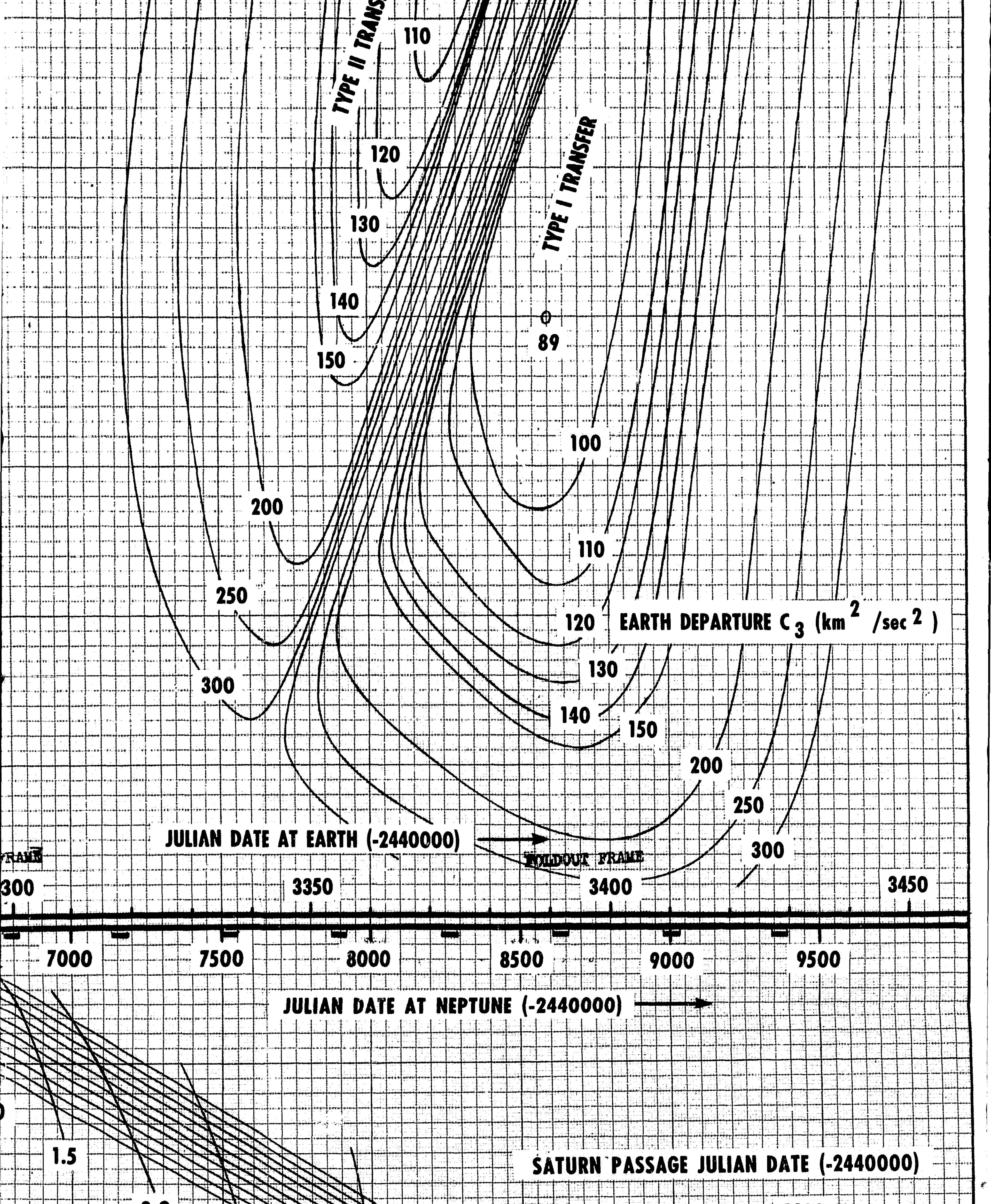


FIGURE 4-9. QUAD GRAPH FOR 1976 GRAND TOUR OF THE JOVIAN PLANETS (WITH CORRECTED PERICENTER MANEUVER)

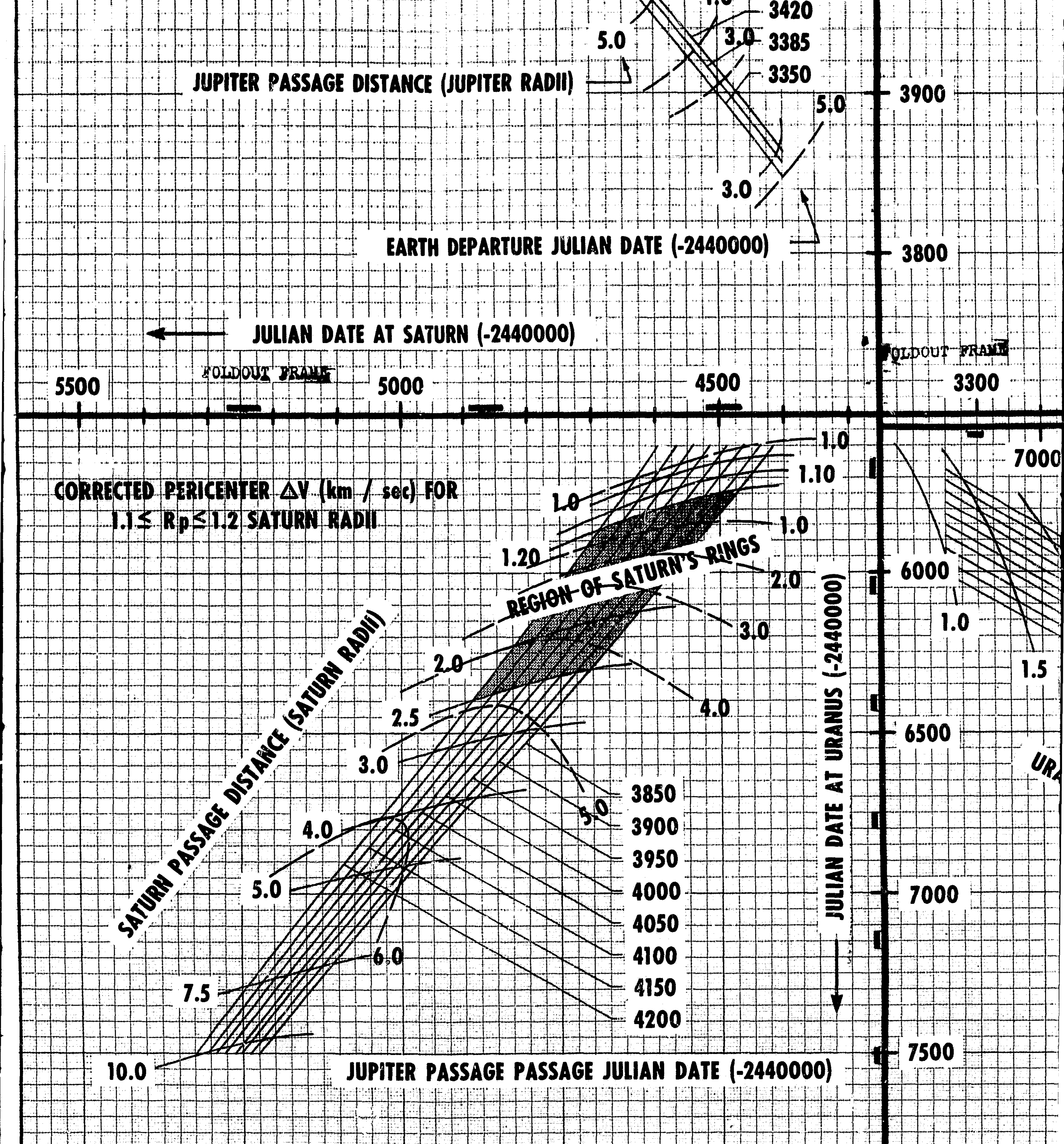
FRAME FOLDOUT FRAME



CORRECTED PERICENTER ΔV (km / sec) FOR Rp = 5 JUPITER RADII
20
15
10
8.0
5.0
1.0
3.0
5.0
3.0
3420
3385
3350
JUPITER PASSAGE DISTANCE (JUPITER RADII)
EARTH DEPARTURE JULIAN DATE (-2440000)
JULIAN DATE AT JUPITER (-2440000)
4300
4200
4100
4000
3900
3800
JULIAN DATE AT SATURN (-2440000)
FOLDOUT FRAME
FOLDOUT FRAME
5500
5000
4500
3300
CORRECTED PERICENTER ΔV (km / sec) FOR
1.1 ≤ Rp ≤ 1.2 SATURN RADII
1.0
1.10
1.0
1.20
1.0
REGION OF SATURN'S RINGS
2.0
3.0
2.0
2.5
4.0
(SATURN RADII)
7000
6000
1.0
1.5



TYPE II TRANS
110
120
130
140
150
TYPE I TRANSFER
89
100
200
110
250
120
EARTH DEPARTURE C 3 (km 2 /sec 2)
130
300
140
150
200
250
JULIAN DATE AT EARTH (-2440000)
FOLDOUT FRAME
300
300
3350
3400
3450
7000
7500
8000
8500
9000
9500
JULIAN DATE AT NEPTUNE (-2440000)
1.5
SATURN PASSAGE JULIAN DATE (-2440000)



FOLDOUT FRAME

FOLDOUT FRAME

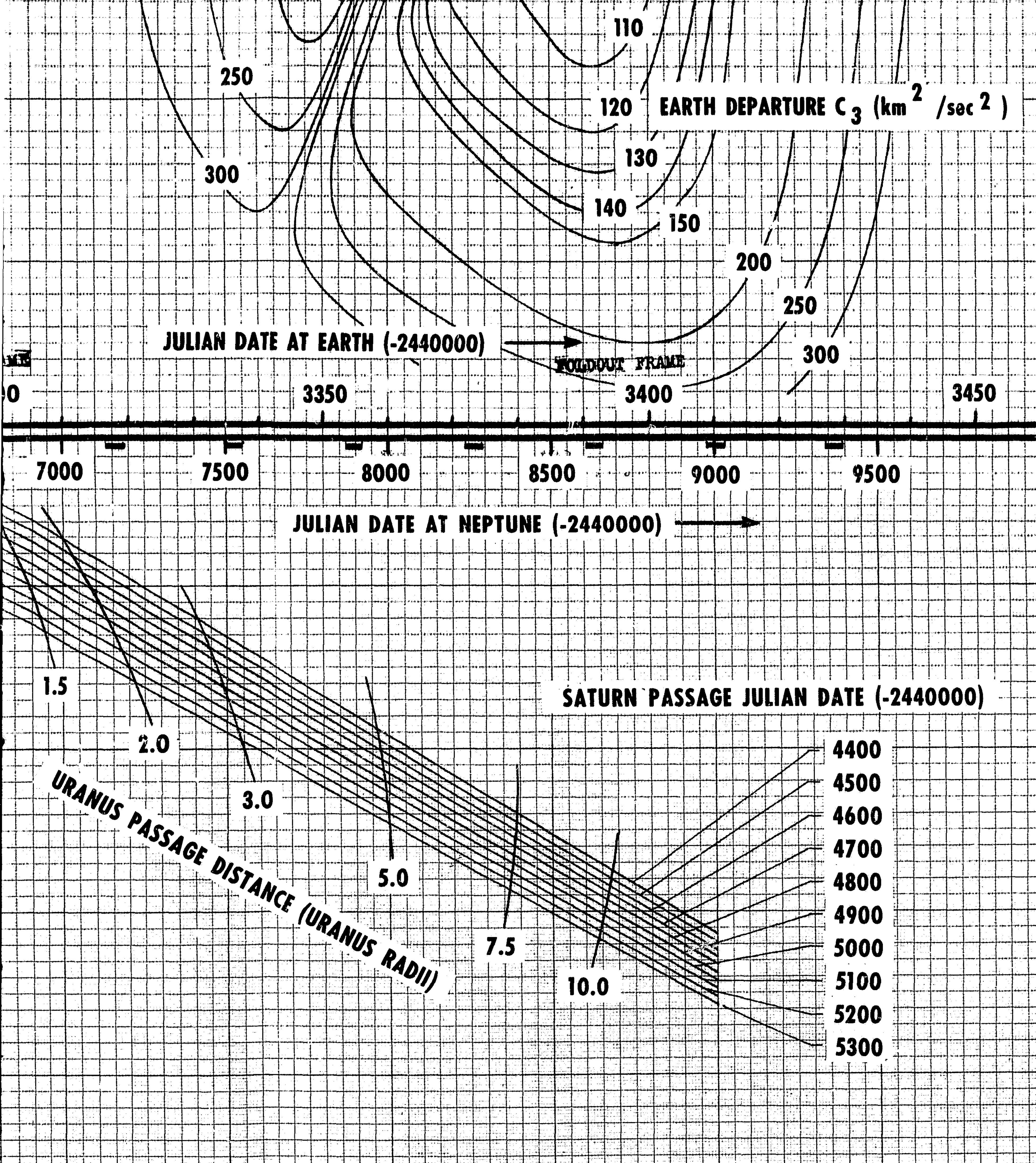
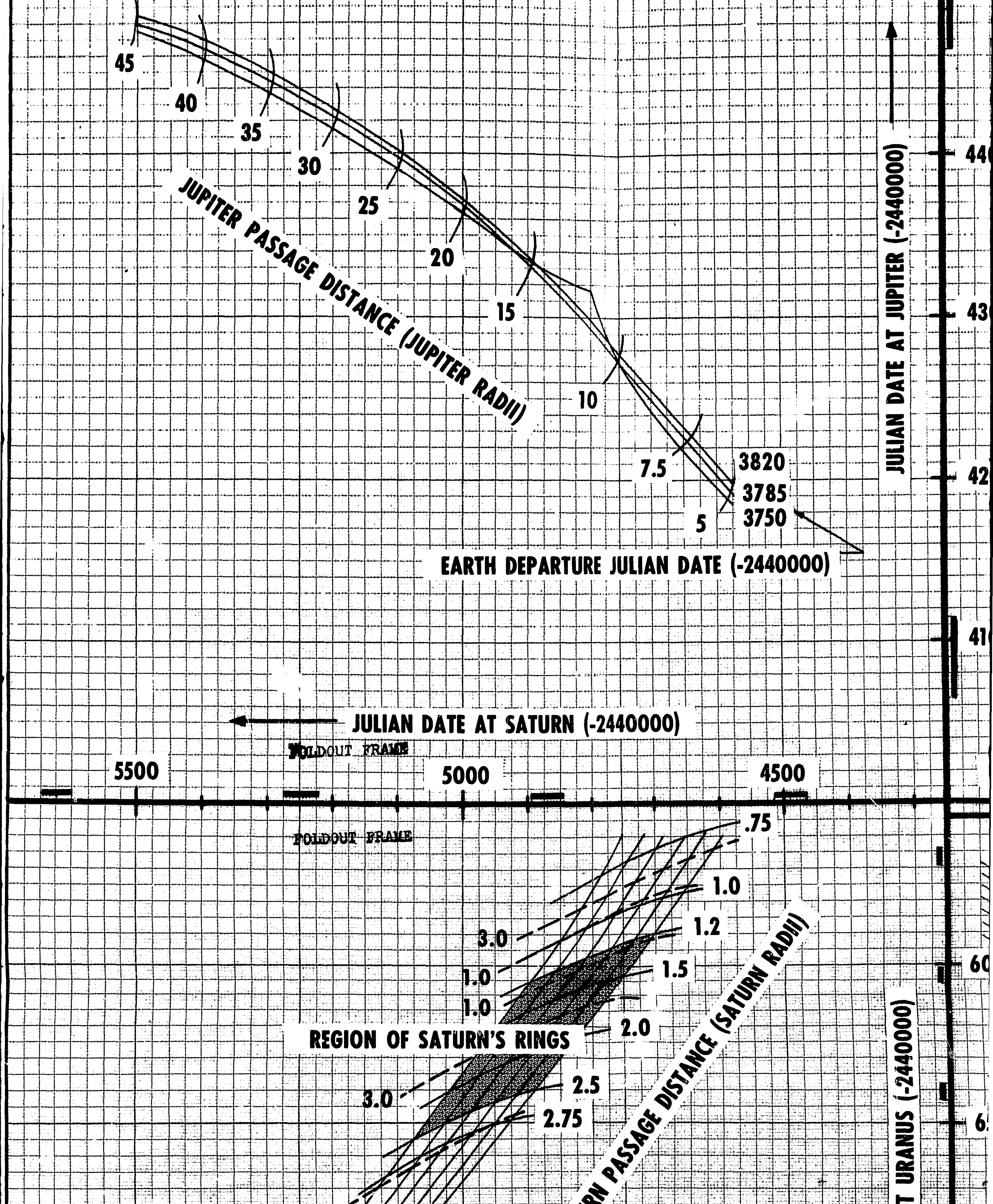
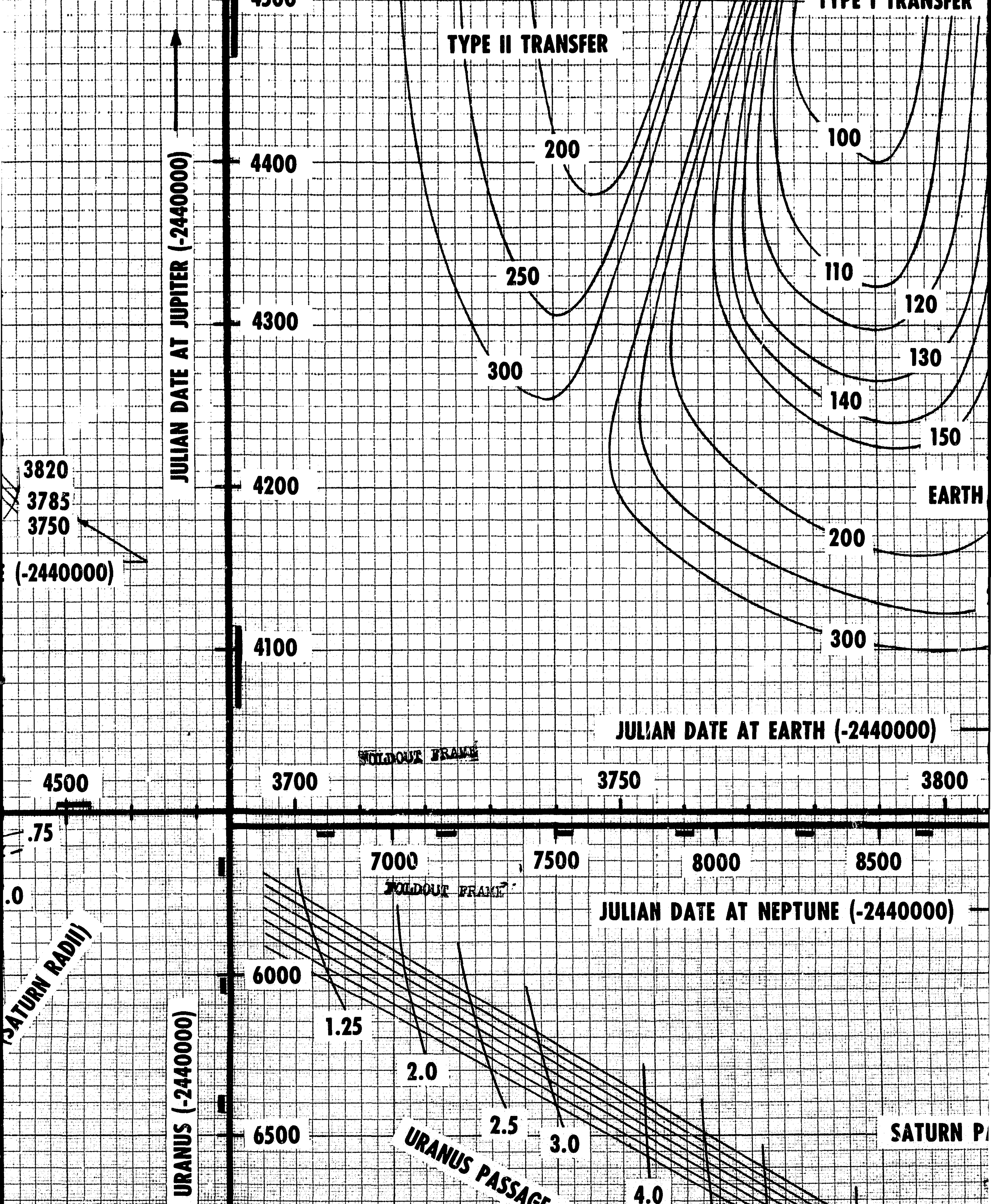
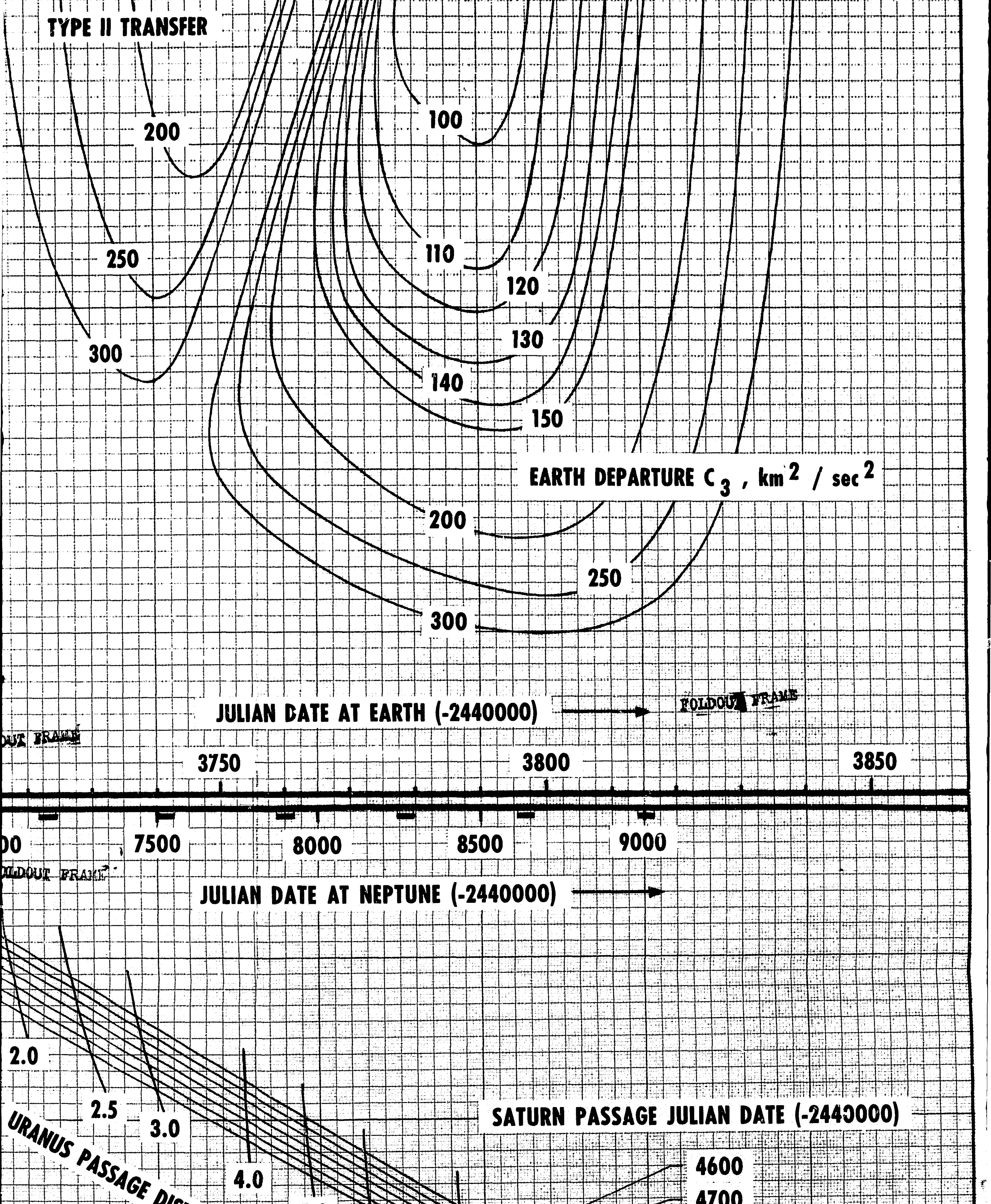


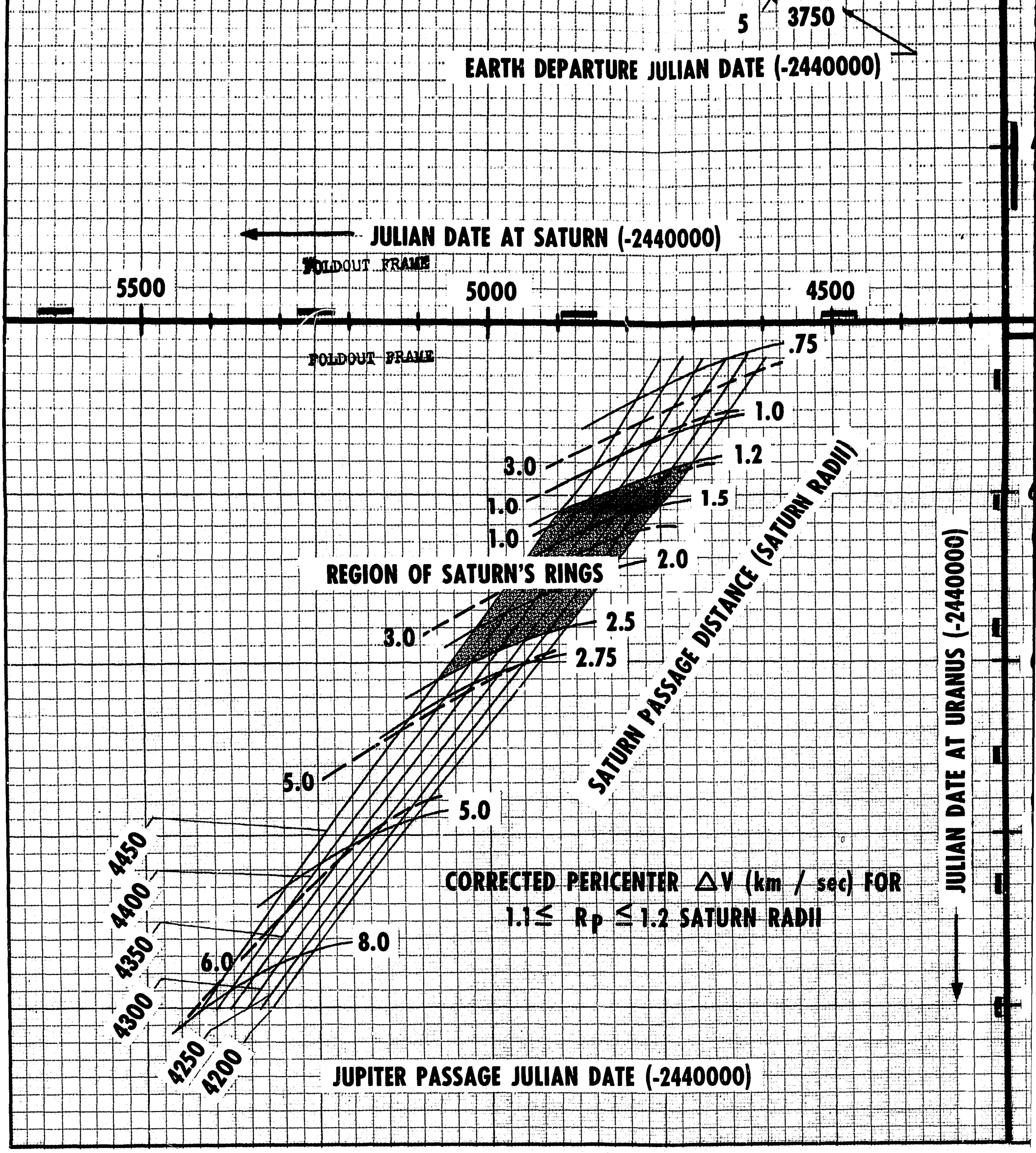
FIGURE 4-10. QUAD GRAPH FOR 1977 GRAND TOUR OF THE JOVIAN PLANETS (WITH CORRECTED PERICENTER MANEUVER)


45
40
35
30
25
20
15
10
7.5
5
3820
3785
3750
JUPITER PASSAGE DISTANCE (JUPITER RADII)
EARTH DEPARTURE JULIAN DATE (-2440000)
JULIAN DATE AT JUPITER (-2440000)
JULIAN DATE AT SATURN (-2440000)
FOLDOUT FRAME
5500
5000
4500
FOLDOUT FRAME
.75
1.0
1.2
1.5
2.0
2.5
2.75
3.0
1.0
1.0
3.0
REGION OF SATURN'S RINGS
RN PASSAGE DISTANCE (SATURN RADII)
T URANUS (-2440000)


TYPE II TRANSFER
200
250
300
100
110
120
130
140
150
200
300
EARTH
4400
4300
4200
4100
JULIAN DATE AT JUPITER (-2440000)
3820
3785
3750
(-2440000)
JULIAN DATE AT EARTH (-2440000)
FOLDOUT FRAME
4500
3700
3750
3800
.75
7000
7500
8000
8500
FOLDOUT FRAME
JULIAN DATE AT NEPTUNE (-2440000)
6000
6500
URANUS (-2440000)
1.25
2.0
2.5
3.0
4.0
URANUS PASSAGE



TYPE II TRANSFER
100
110
120
130
140
150
200
250
300
EARTH DEPARTURE C_3, km^2 / sec^2
JULIAN DATE AT EARTH (-2440000)
FOLDOUT FRAME
3750
3800
3850
7500
8000
8500
9000
JULIAN DATE AT NEPTUNE (-2440000)
2.0
2.5
3.0
4.0
SATURN PASSAGE JULIAN DATE (-2440000)
4600
4700
URANUS PASSAGE



FOLDOUT FRAME

FOLDOUT FRAME

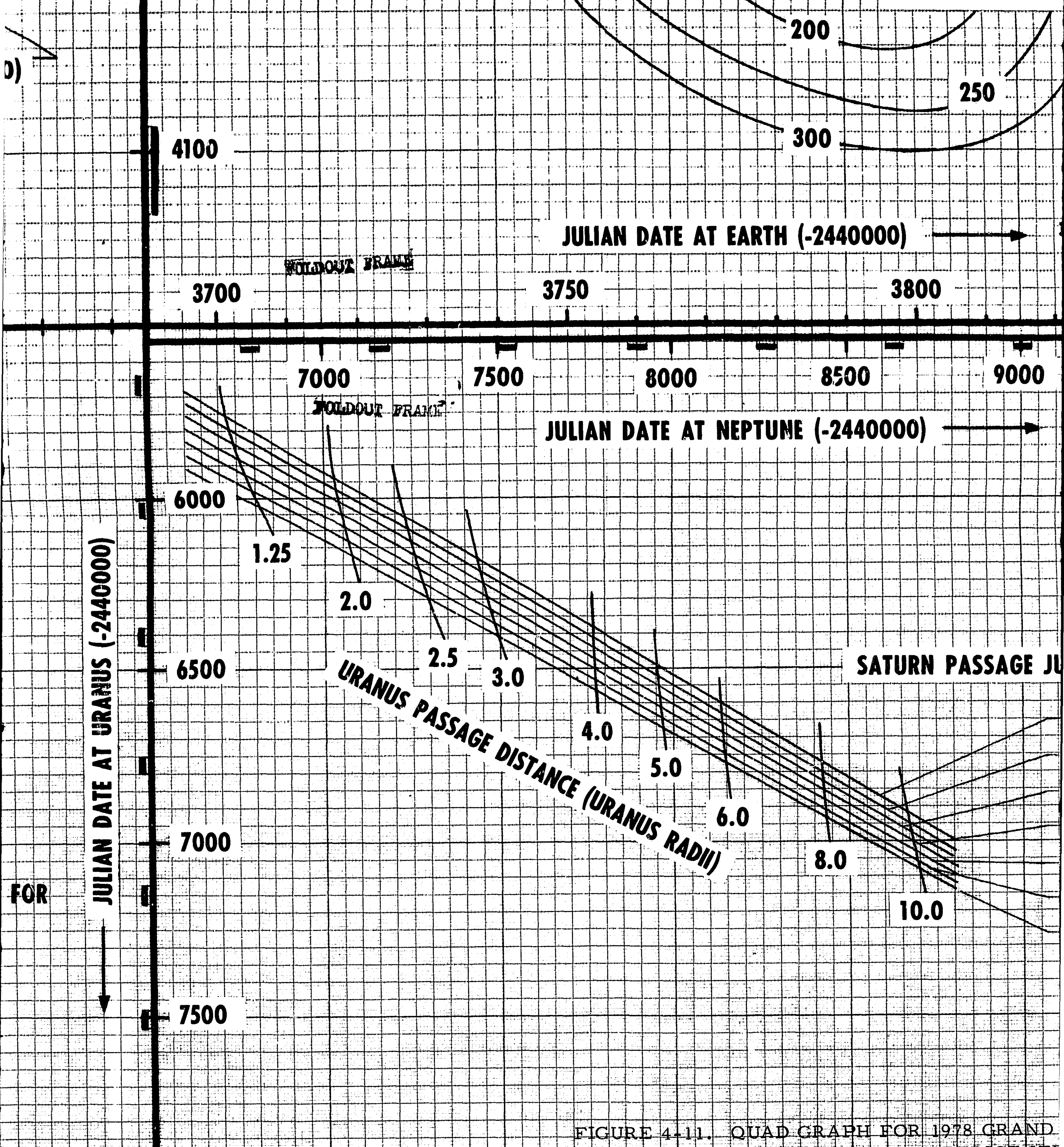


FIGURE 4-11. QUAD GRAPH FOR 1978 GRAND
(WITH CORRECTED PERICENTH

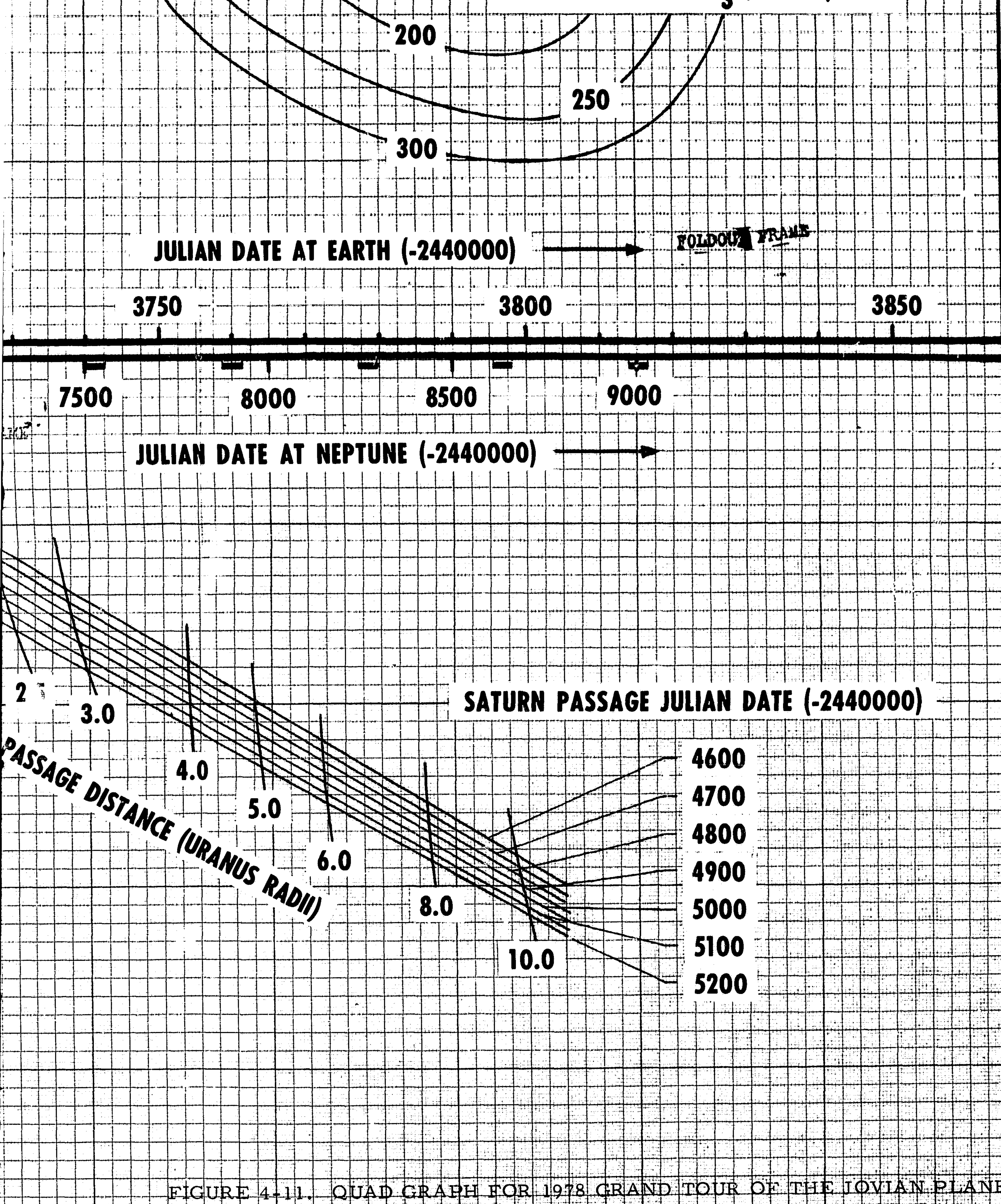
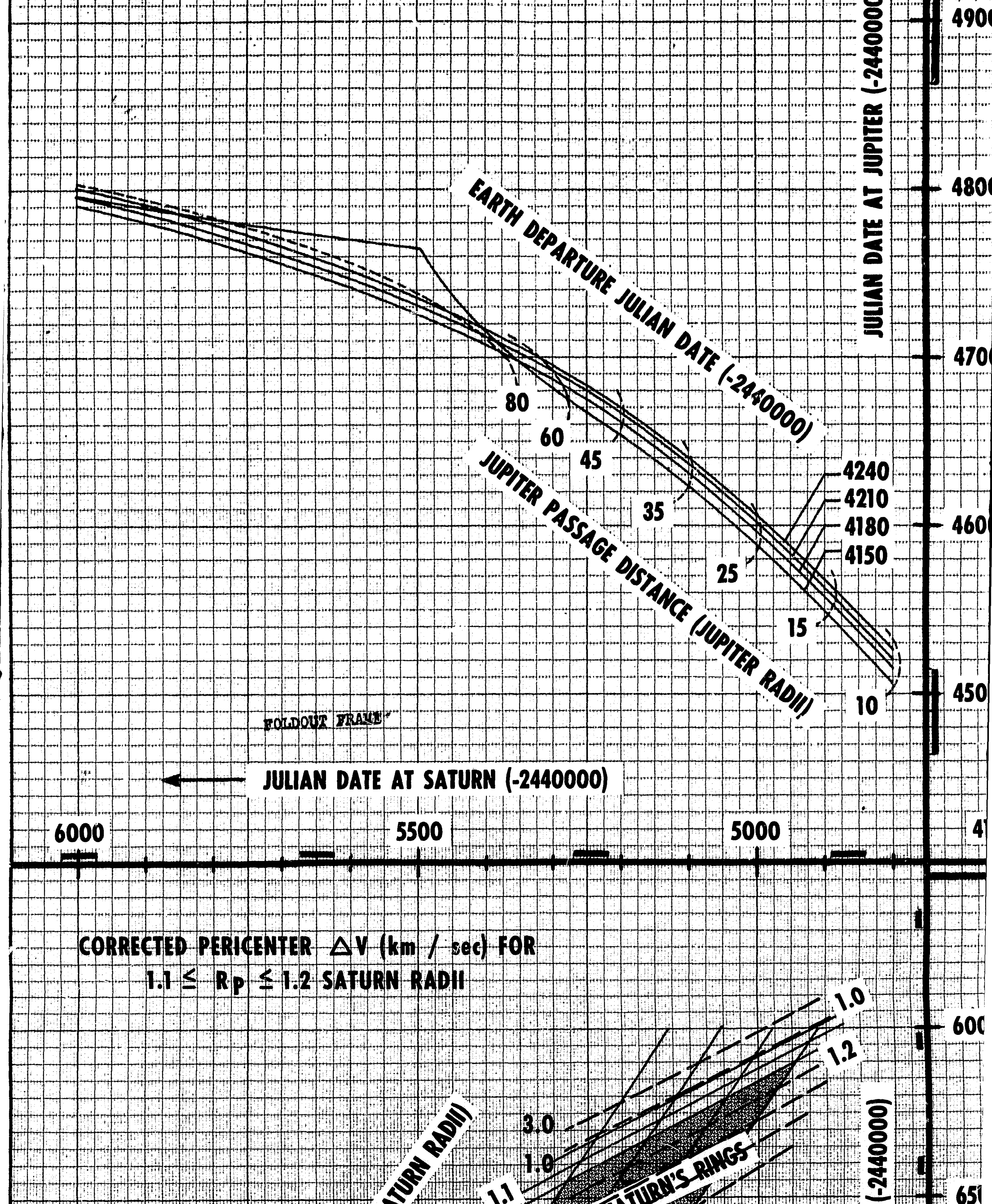
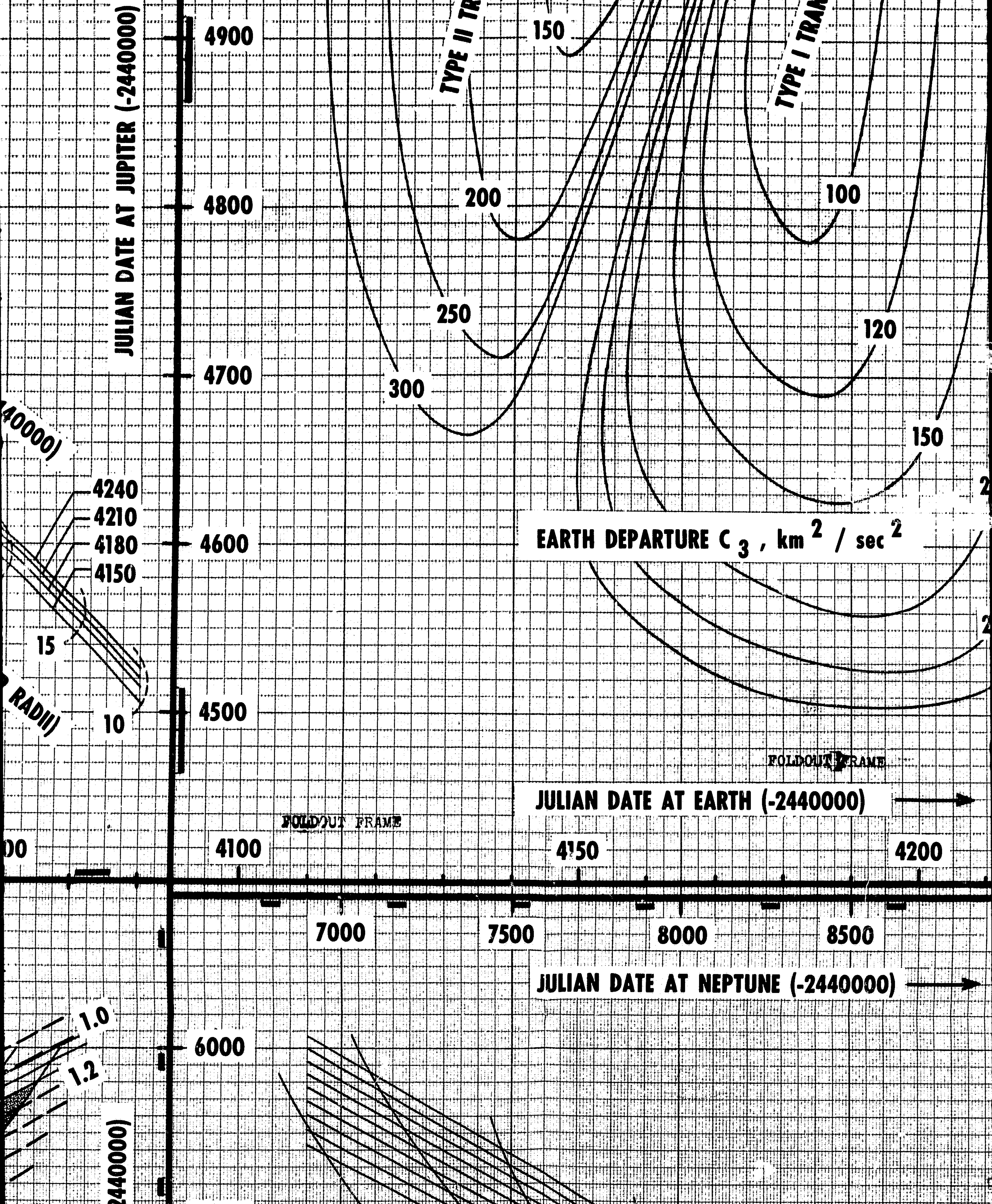
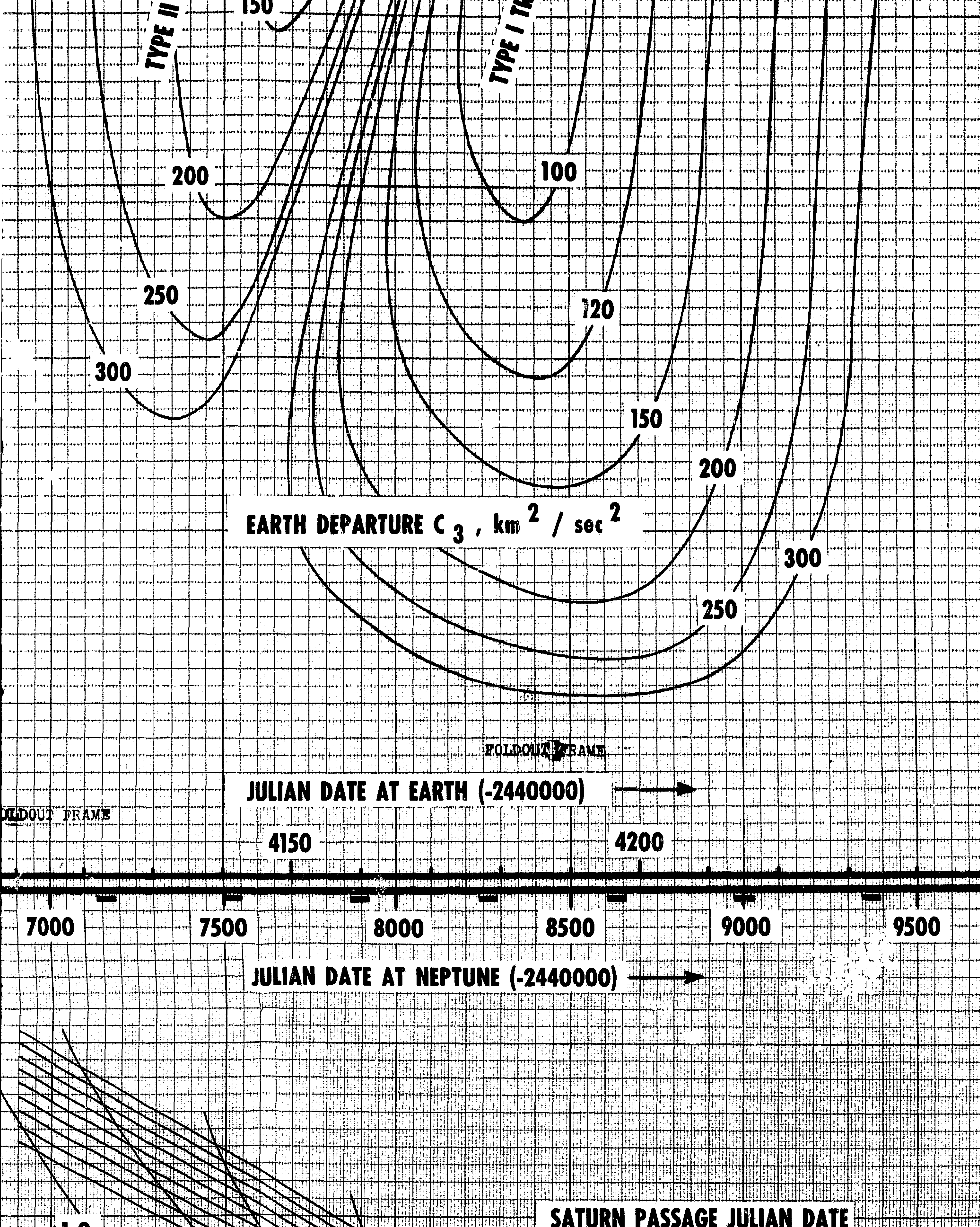


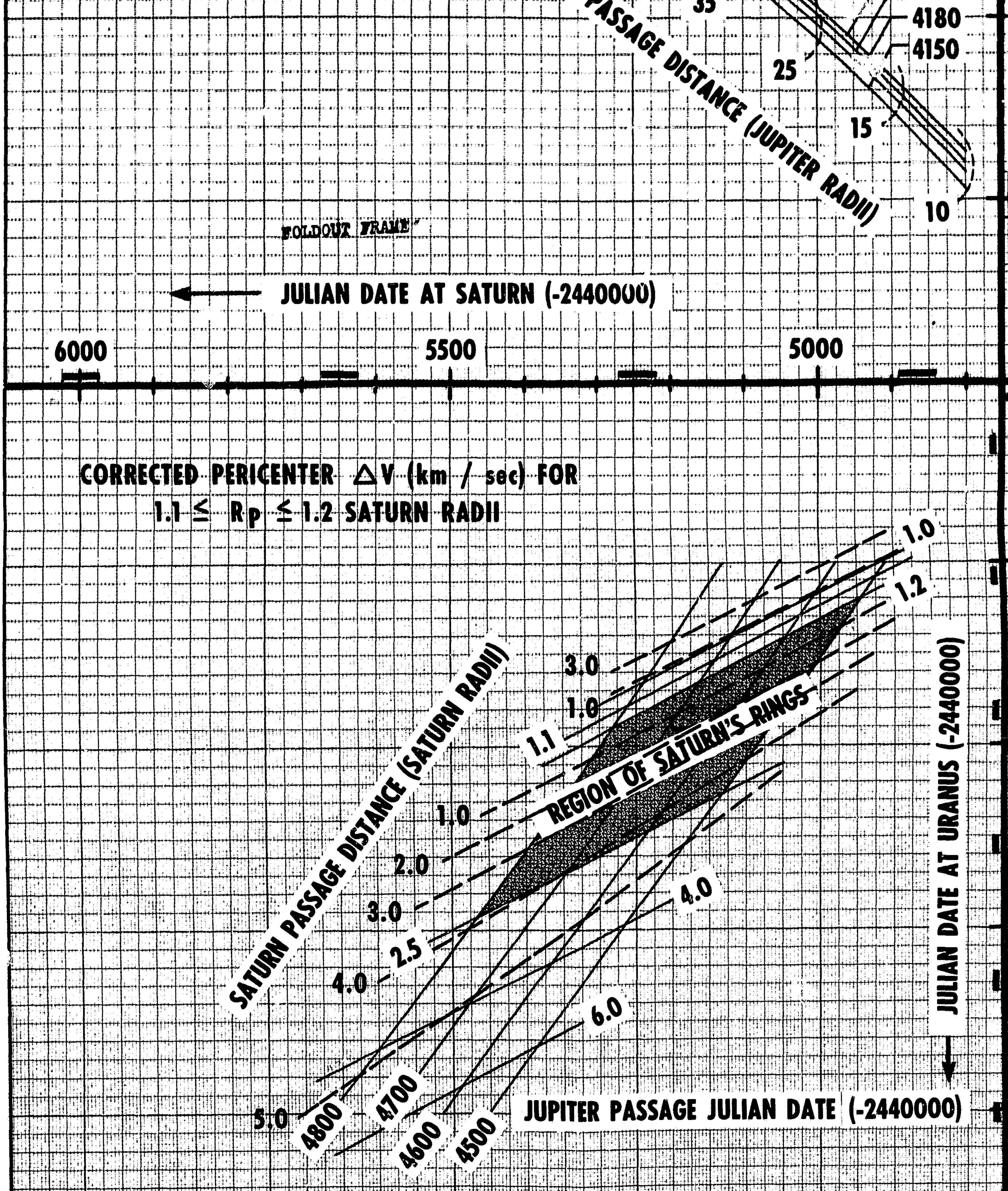
FIGURE 4-11. QUAD GRAPH FOR 1978 GRAND TOUR OF THE JOVIAN PLANETS (WITH CORRECTED PERICENTER MANEUVER)


EARTH DEPARTURE JULIAN DATE (-2440000)
JUPITER PASSAGE DISTANCE (JUPITER RADII)
80
60
45
35
25
15
10
4240
4210
4180
4150
JULIAN DATE AT JUPITER (-244000
4900
4800
4700
4600
450
FOLDOUT FRAME
JULIAN DATE AT SATURN (-2440000)
6000
5500
5000
CORRECTED PERICENTER ΔV (km / sec) FOR
1.1 ≤ Rp ≤ 1.2 SATURN RADII
1.0
1.2
3.0
1.0
1.1
SATURN'S RINGS
(-2440000)
600
65

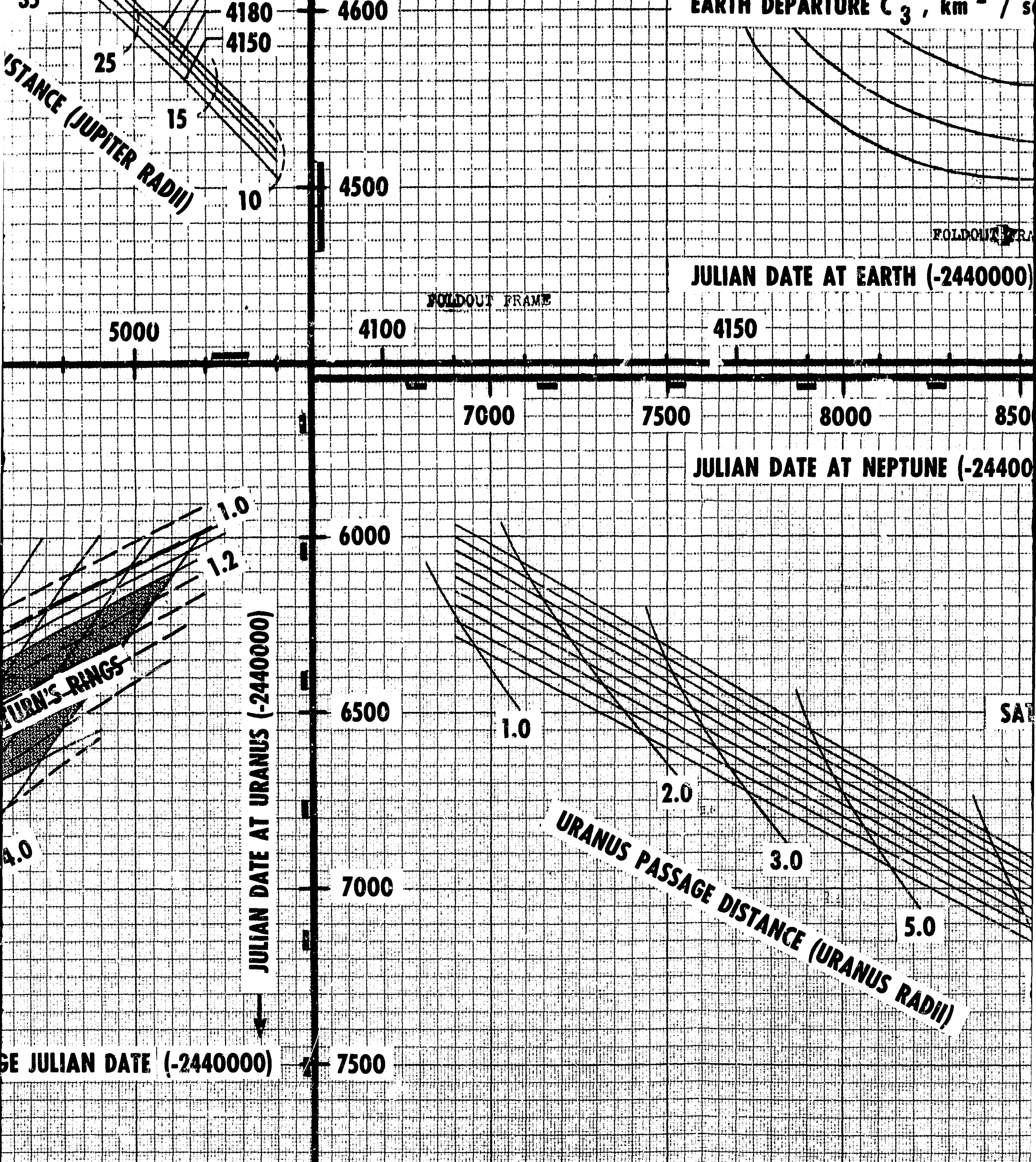


JULIAN DATE AT JUPITER (-2440000)
4900
4800
4700
4600
4500
TYPE II TR
TYPE I TRAN
150
200
250
300
100
120
150
EARTH DEPARTURE C_3, km^2/sec^2
4240
4210
4180
4150
15
10
RADII)
40000)
JULIAN DATE AT EARTH (-2440000)
4100
4150
4200
FOLDOUT FRAME
FOLDOUT FRAME
7000
7500
8000
8500
JULIAN DATE AT NEPTUNE (-2440000)
6000
1.0
1.2
2440000)


TYPE II
150
200
250
300
100
120
150
200
300
250
EARTH DEPARTURE C_3 , km^2 / sec^2
FOLDOUT FRAME
JULIAN DATE AT EARTH (-2440000)
FOLDOUT FRAME
4150
4200
7000
7500
8000
8500
9000
9500
JULIAN DATE AT NEPTUNE (-2440000)
SATURN PASSAGE JULIAN DATE



FOLDOUT FRAME



FOLDOUT FRAME

FIGURE 4-12. QUAD GRAPH FOR 1979 GRAND T...
(WITH CORRECTED PERICENTER...

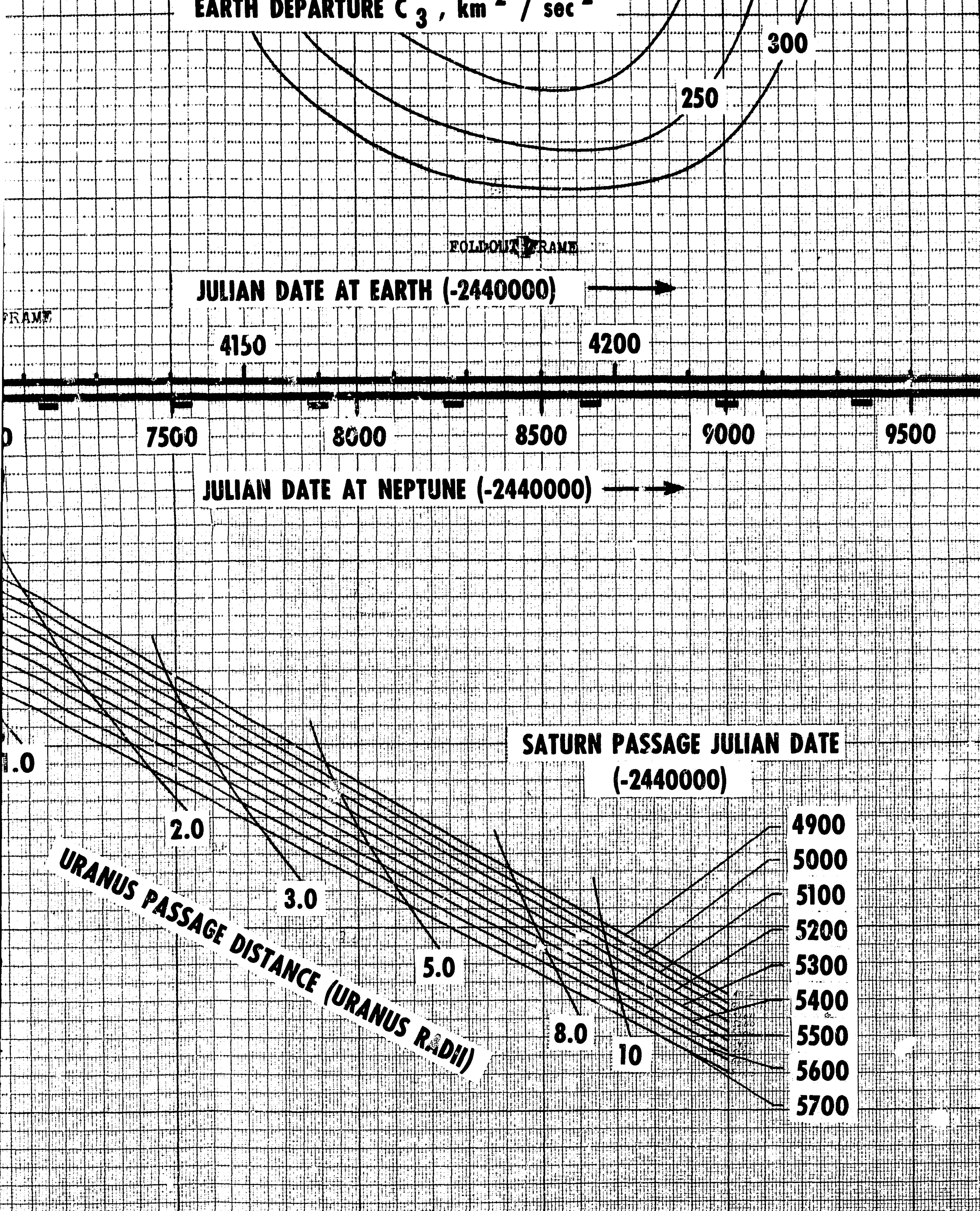
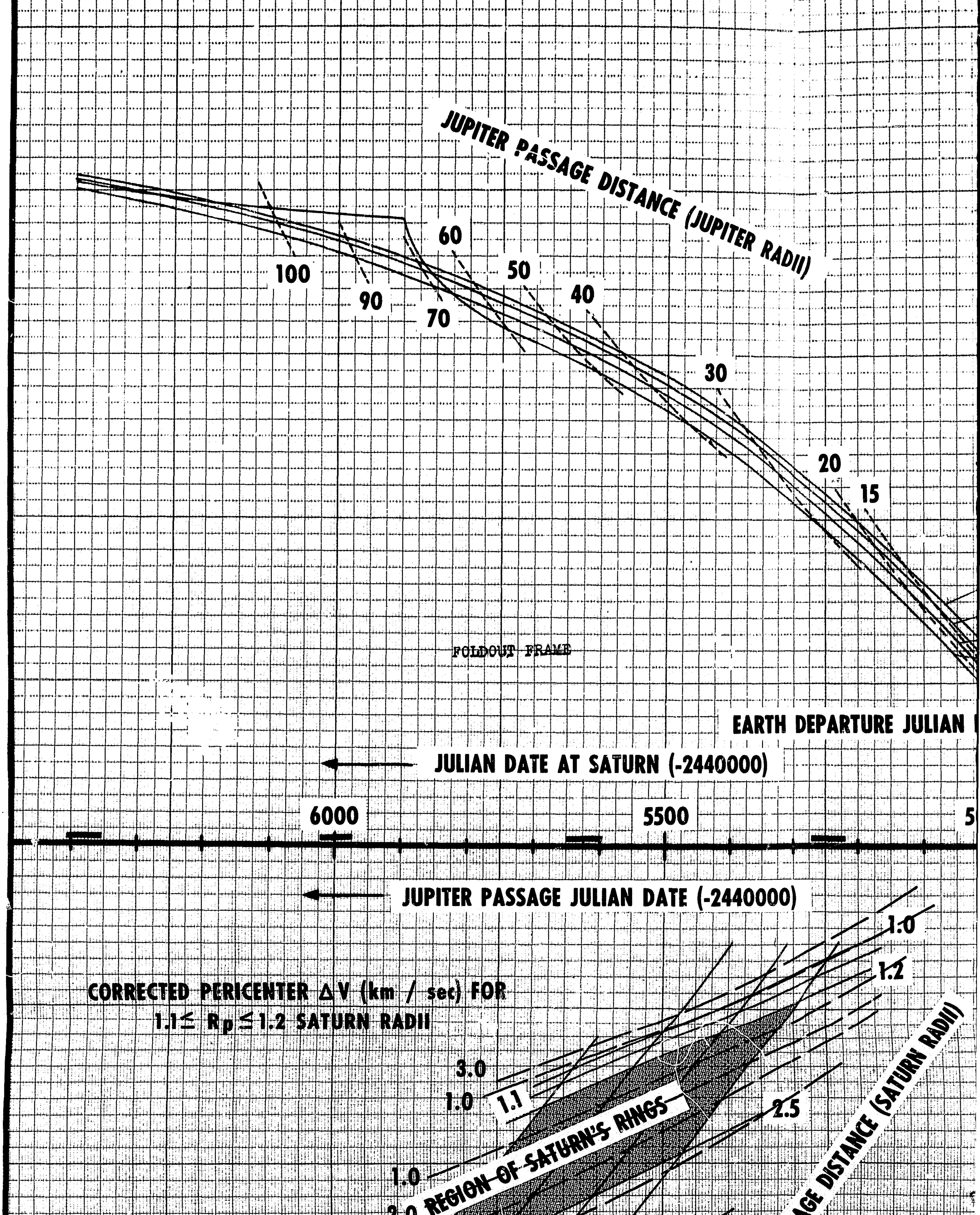
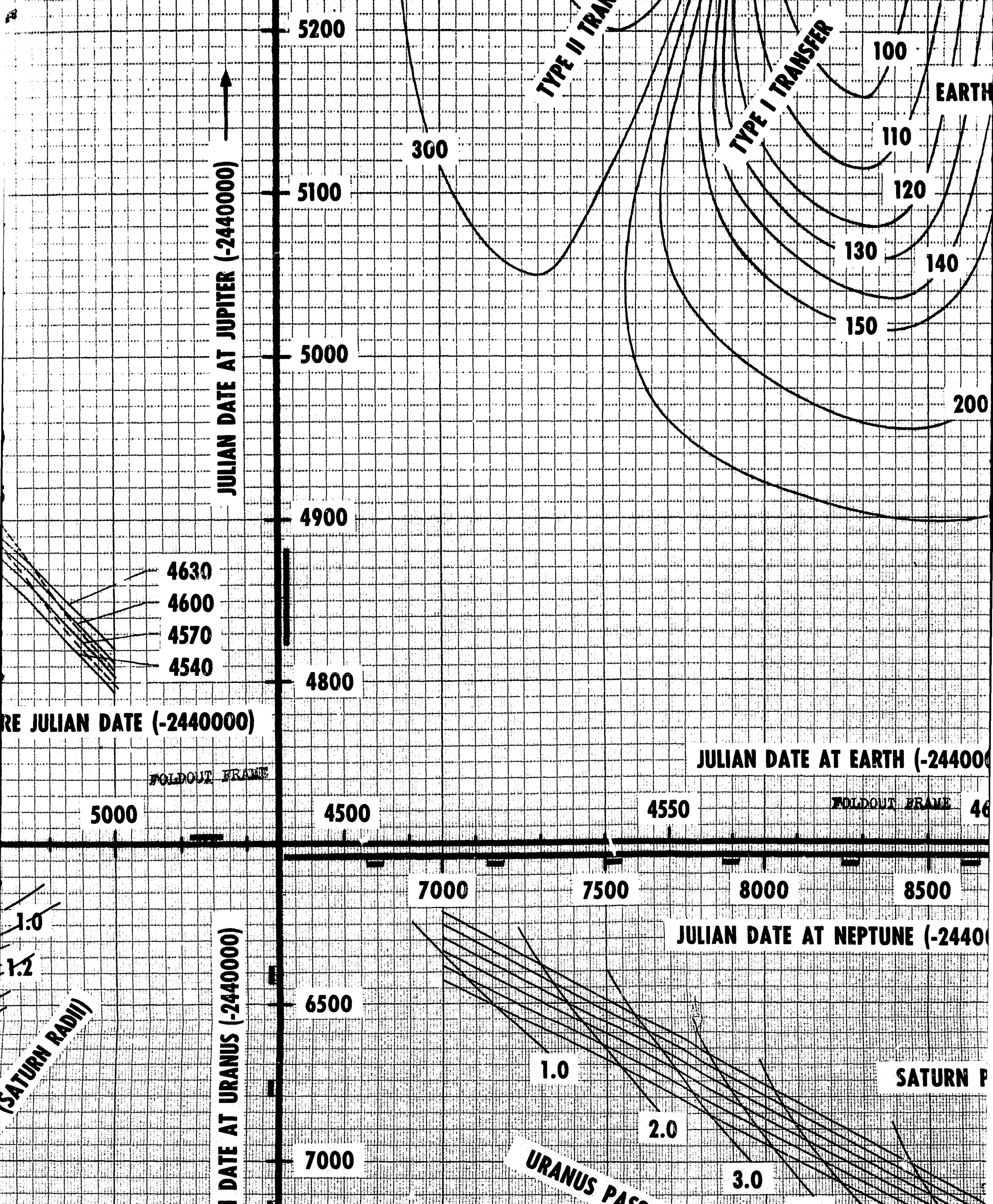
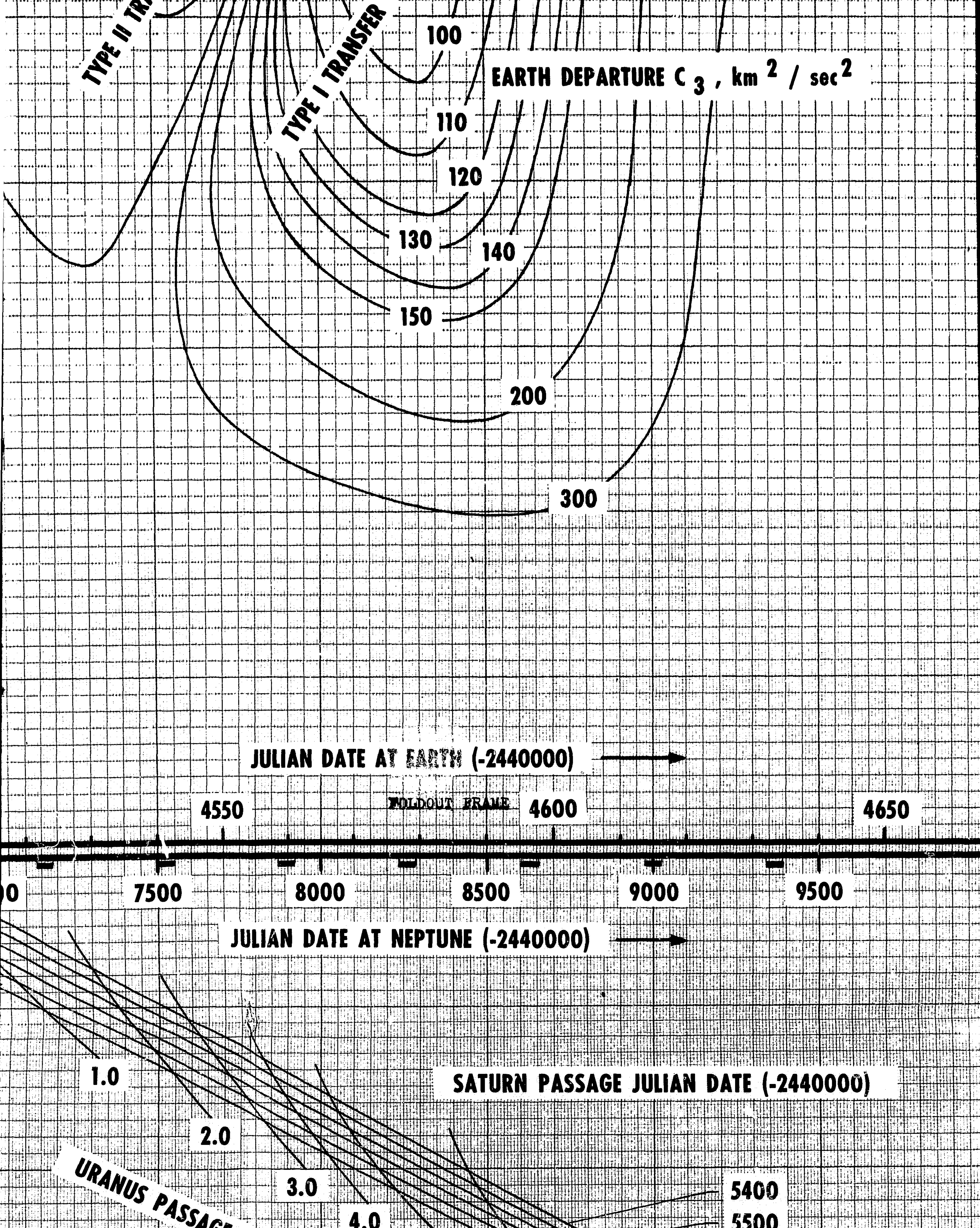


FIGURE 4-12. QUAD GRAPH FOR 1979 GRAND TOUR OF THE JOVIAN PLANETS (WITH CORRECTED PERICENTER MANEUVER)

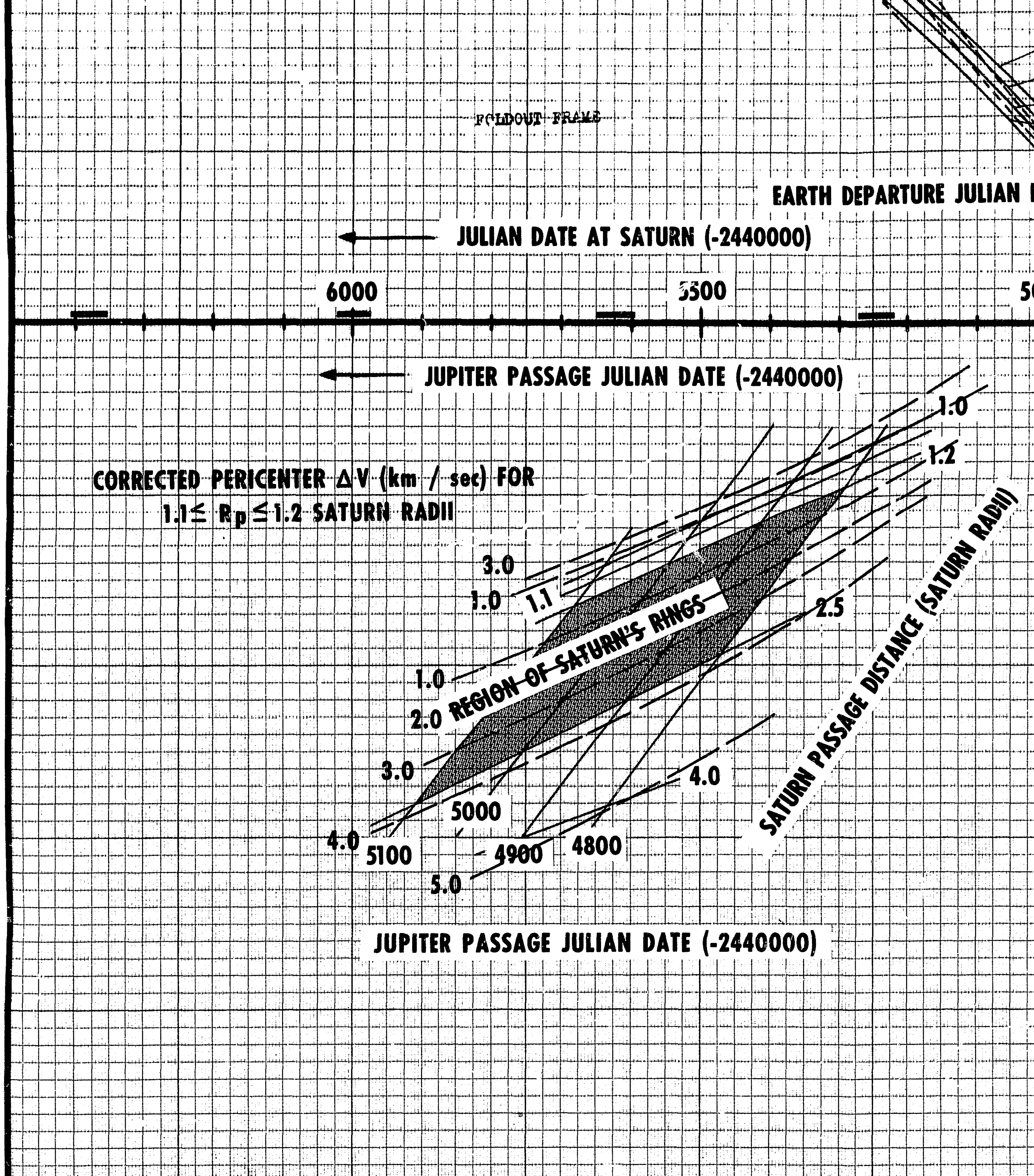
FOLDOUT FRAME


JUPITER PASSAGE DISTANCE (JUPITER RADII)
100
90
70
60
50
40
30
20
15
FOLDOUT FRAME
EARTH DEPARTURE JULIAN
JULIAN DATE AT SATURN (-2440000)
6000
5500
JUPITER PASSAGE JULIAN DATE (-2440000)
CORRECTED PERICENTER ΔV (km / sec) FOR
1.1≤ Rp ≤1.2 SATURN RADII
3.0
1.0
1.1
1.0
1.2
2.5
1.0
REGION OF SATURN'S RINGS
AGE DISTANCE (SATURN RADII)


TYPE II TRANSFER
TYPE I TRANSFER
EARTH
100
110
120
130
140
150
200
300
5200
5100
5000
4900
4800
JULIAN DATE AT JUPITER (-2440000)
4630
4600
4570
4540
JULIAN DATE (-2440000)
FOLDOUT FRAME
5000
4500
4550
JULIAN DATE AT EARTH
FOLDOUT FRAME
7000
7500
8000
8500
JULIAN DATE AT NEPTUNE
1.0
1.2
(SATURN RADII)
DATE AT URANUS (-2440000)
6500
7000
1.0
2.0
3.0
SATURN
URANUS



TYPE II TRANSFER
TYPE I TRANSFER
100
EARTH DEPARTURE C_3, km^2 / sec^2
110
120
130
140
150
200
300
JULIAN DATE AT EARTH (-2440000)
FOLDOUT FRAME
4550
4600
4650
7500
8000
8500
9000
9500
JULIAN DATE AT NEPTUNE (-2440000)
1.0
2.0
3.0
4.0
SATURN PASSAGE JULIAN DATE (-2440000)
5400
5500


FOLDOUT FRAME
EARTH DEPARTURE JULIAN D
JULIAN DATE AT SATURN (-2440000)
6000
5500
JUPITER PASSAGE JULIAN DATE (-2440000)
CORRECTED PERICENTER ΔV (km / sec) FOR
1.1≤ Rp ≤1.2 SATURN RADII
1.0
1.2
3.0
1.0
1.1
REGION OF SATURN'S RINGS
2.5
1.0
2.0
3.0
4.0
4.0
5000
5100
4900
4800
5.0
SATURN PASSAGE DISTANCE (SATURN RADII)
JUPITER PASSAGE JULIAN DATE (-2440000)

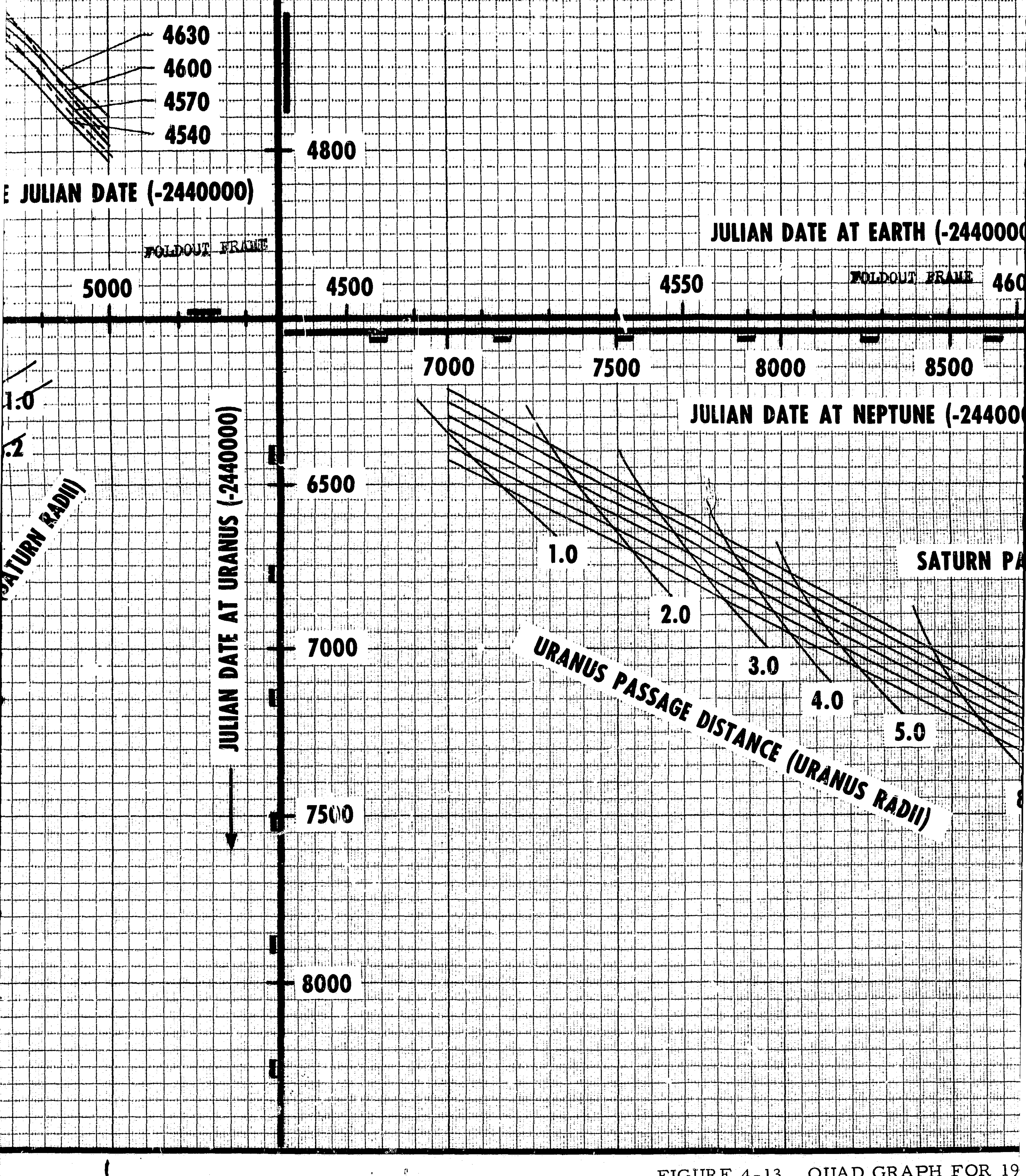


FIGURE 4-13. QUAD GRAPH FOR 19
(WITH CORRECTED F

FOLDOUT FRAME

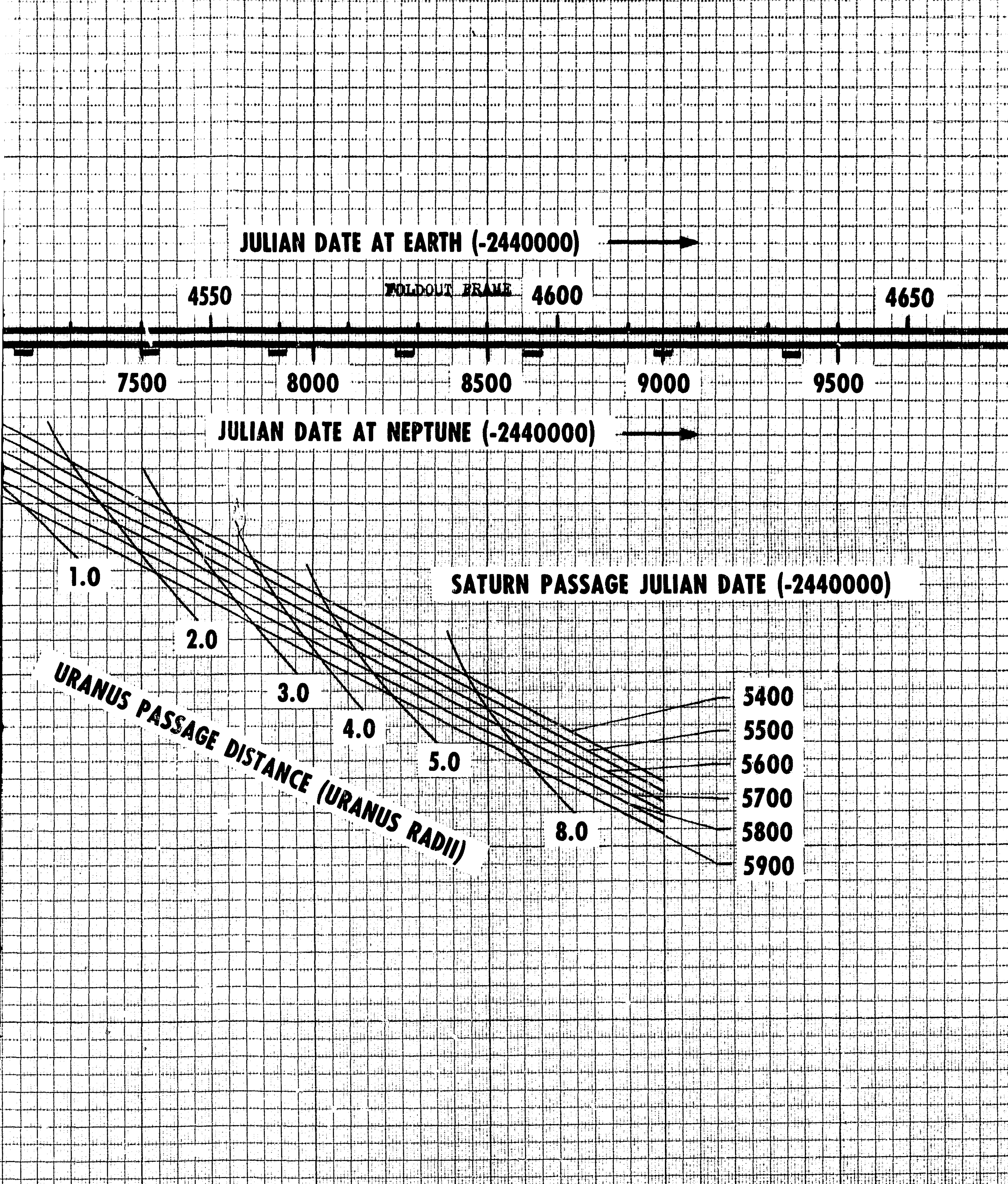
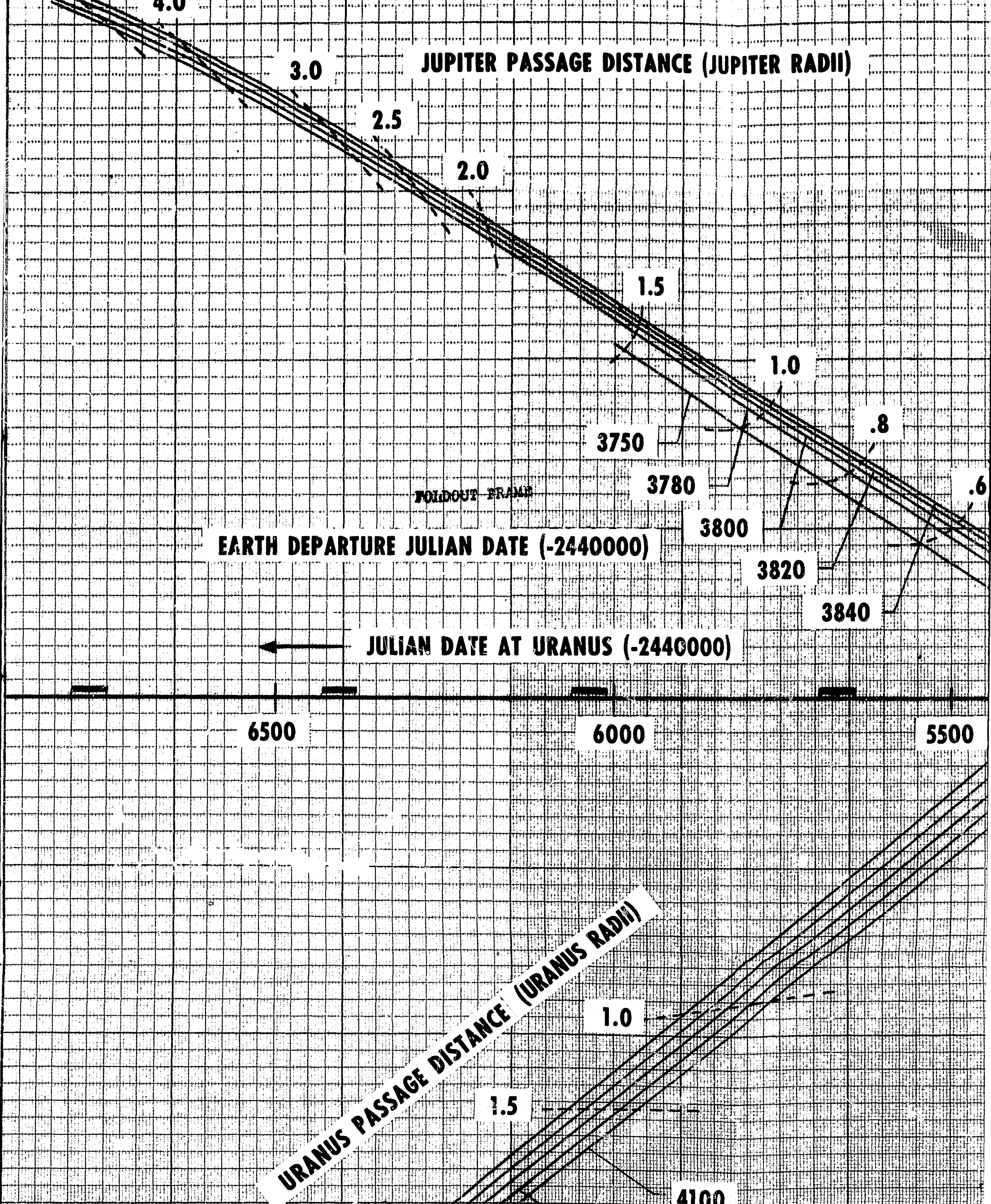
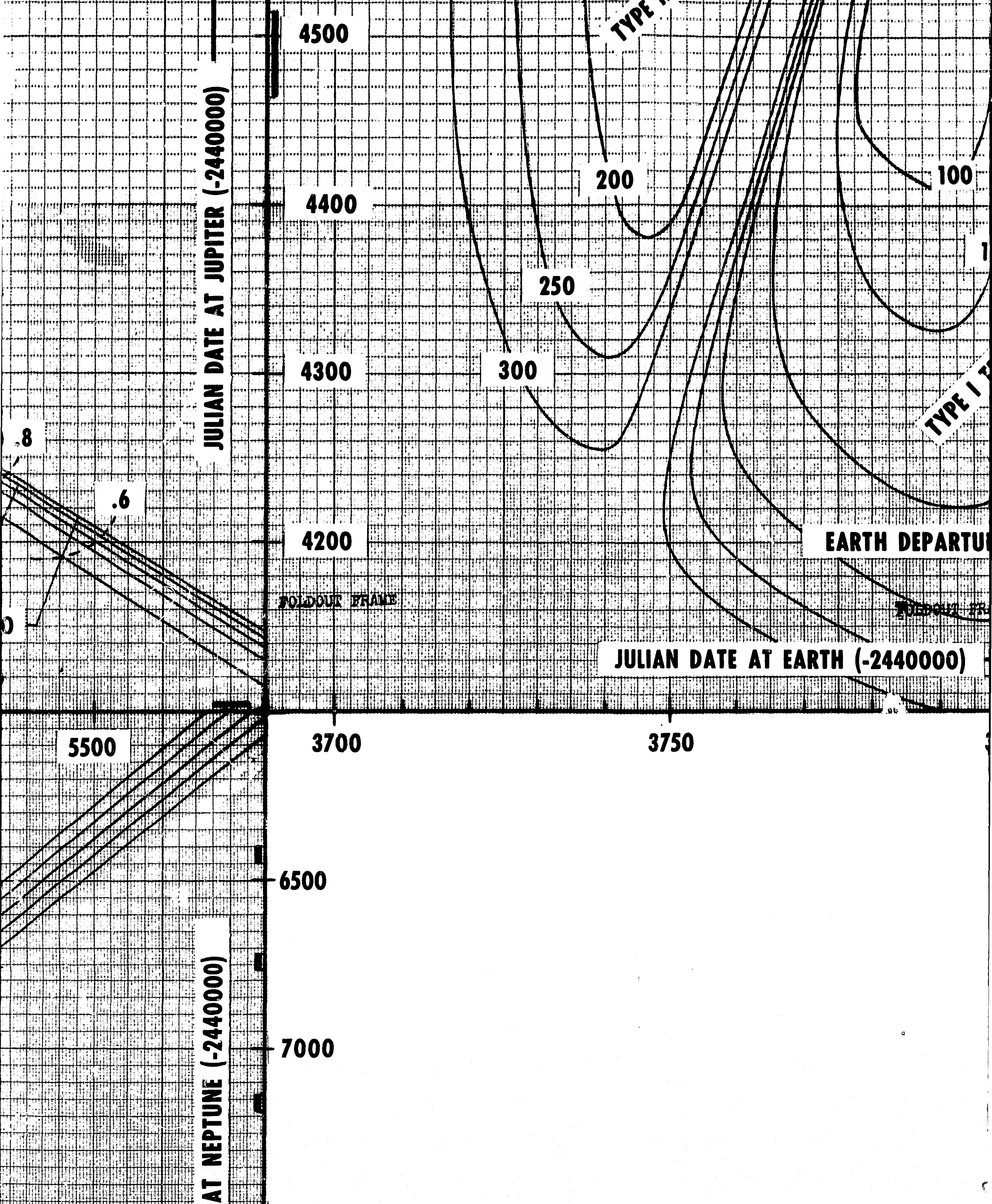
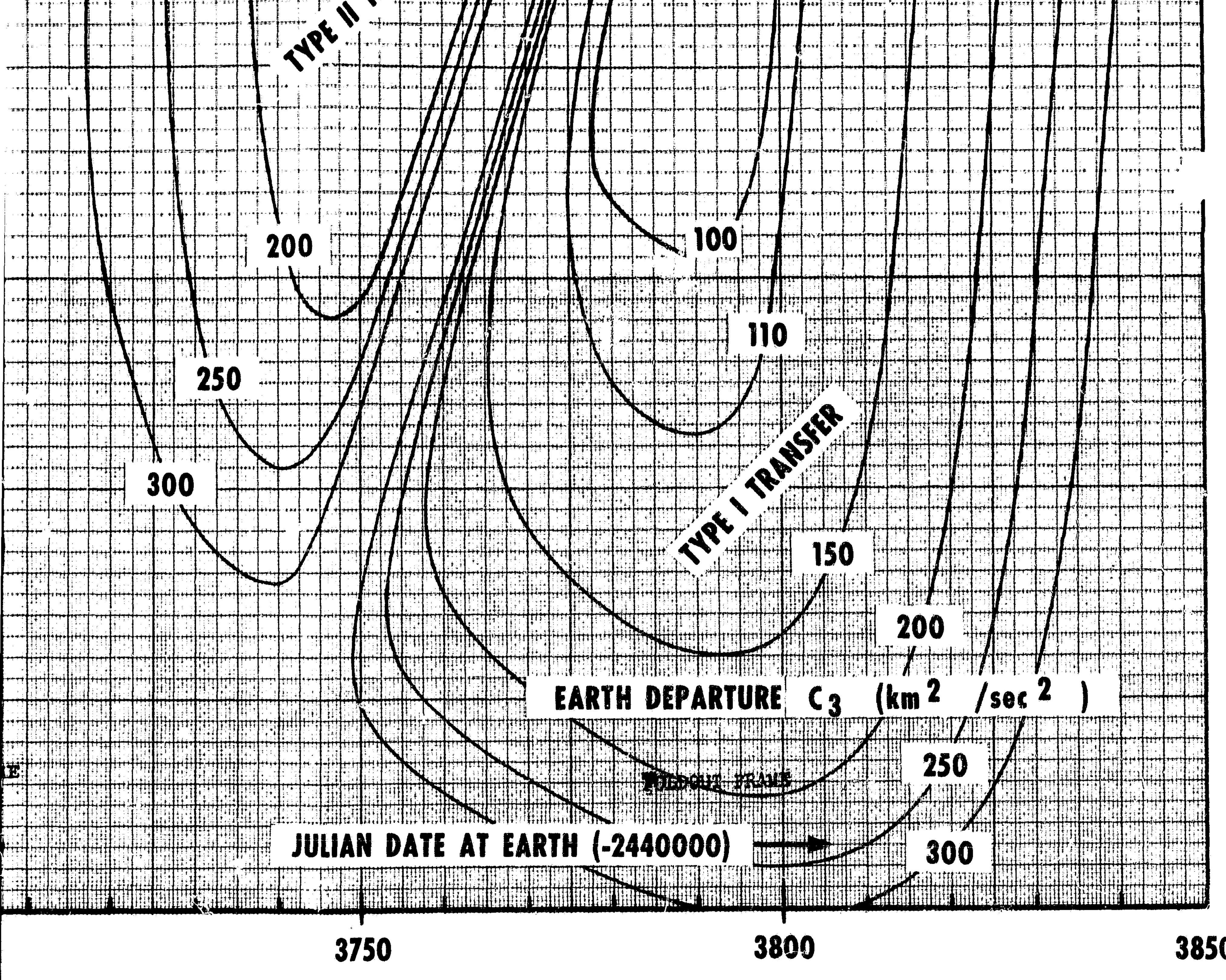


FIGURE 4-13. QUAD GRAPH FOR 1980 GRAND TOUR OF THE JOVIAN PLANETS (WITH CORRECTED PERICENTER MANEUVER)

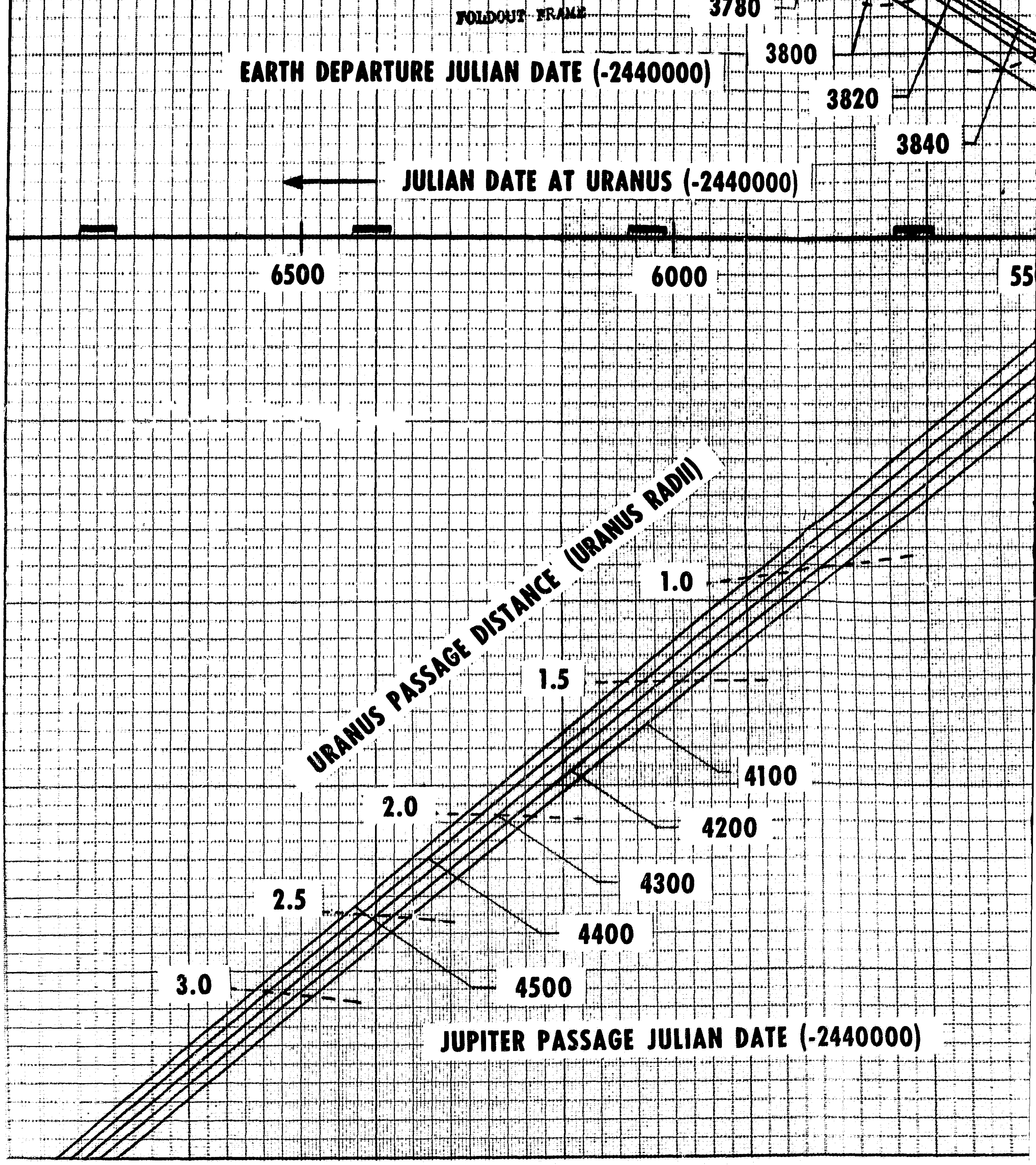

4.0
3.0
JUPITER PASSAGE DISTANCE (JUPITER RADII)
2.5
2.0
1.5
1.0
3750
.8
3780
FOLDOUT FRAME
.6
3800
EARTH DEPARTURE JULIAN DATE (-2440000)
3820
3840
JULIAN DATE AT URANUS (-2440000)
6500
6000
5500
URANUS PASSAGE DISTANCE (URANUS RADII)
1.0
1.5
4100



4500
4400
4300
4200
JULIAN DATE AT JUPITER (-2440000)
TYPE I
TYPE I
200
100
250
300
.8
.6
EARTH DEPARTU
FOLDOUT FRAME
JULIAN DATE AT EARTH (-2440000)
5500
3700
3750
6500
7000
AT NEPTUNE (-2440000)



TYPE II
200
100
110
250
TYPE I TRANSFER
300
150
200
EARTH DEPARTURE C_3 (km^2/sec^2)
250
JULIAN DATE AT EARTH (-2440000)
300
3750
3800
3850


3780
3800
3820
3840
EARTH DEPARTURE JULIAN DATE (-2440000)
JULIAN DATE AT URANUS (-2440000)
6500
6000
55
URANUS PASSAGE DISTANCE (URANUS RADII)
1.0
1.5
2.0
2.5
3.0
4100
4200
4300
4400
4500
JUPITER PASSAGE JULIAN DATE (-2440000)

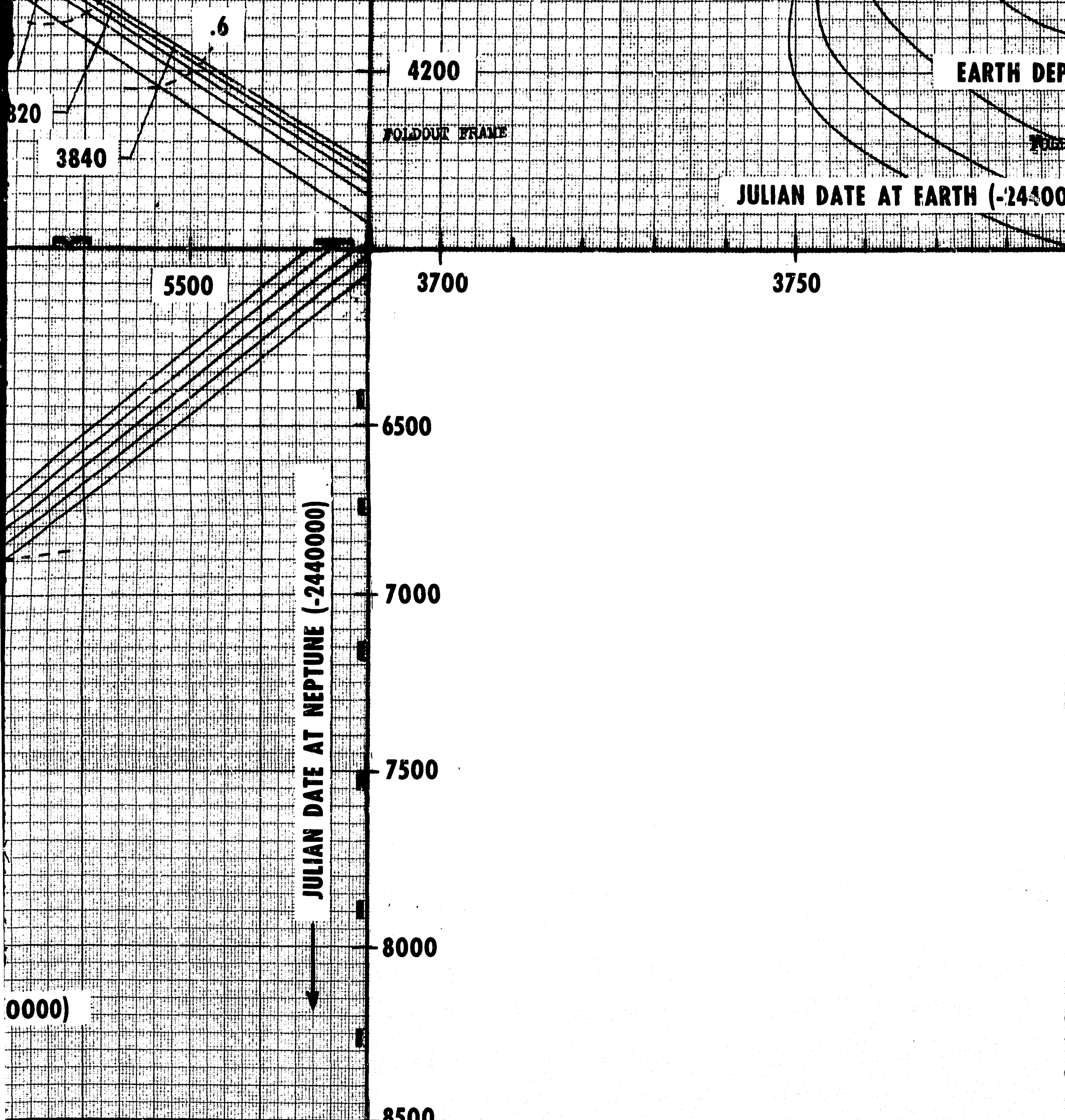


FIGURE 4-14. TRIAD GR

FOLDOUT FRAME

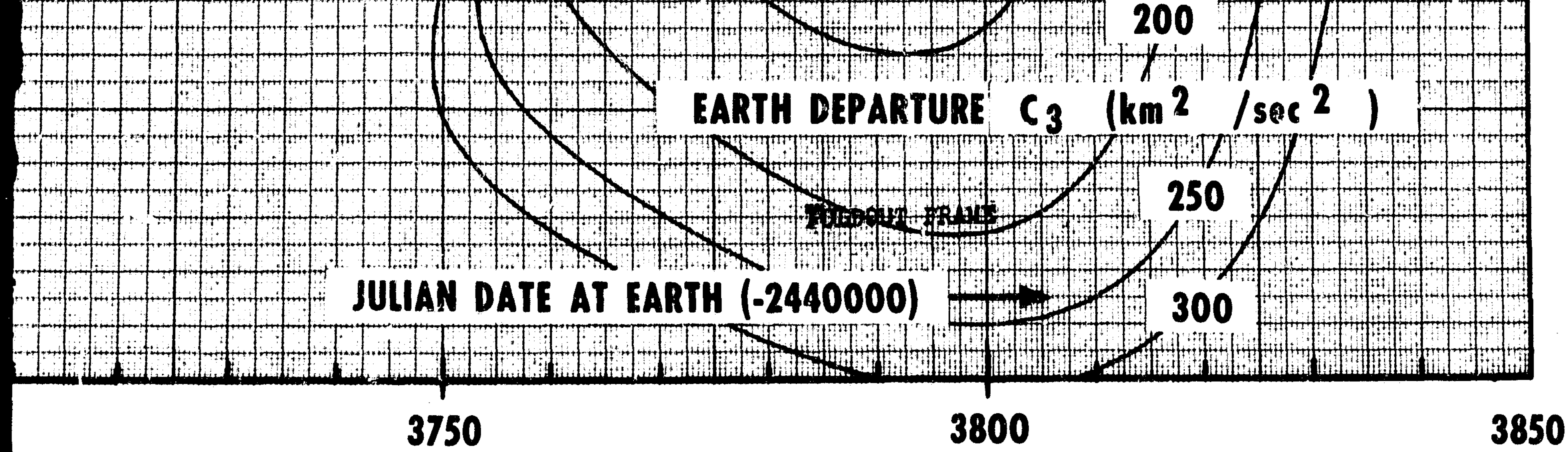
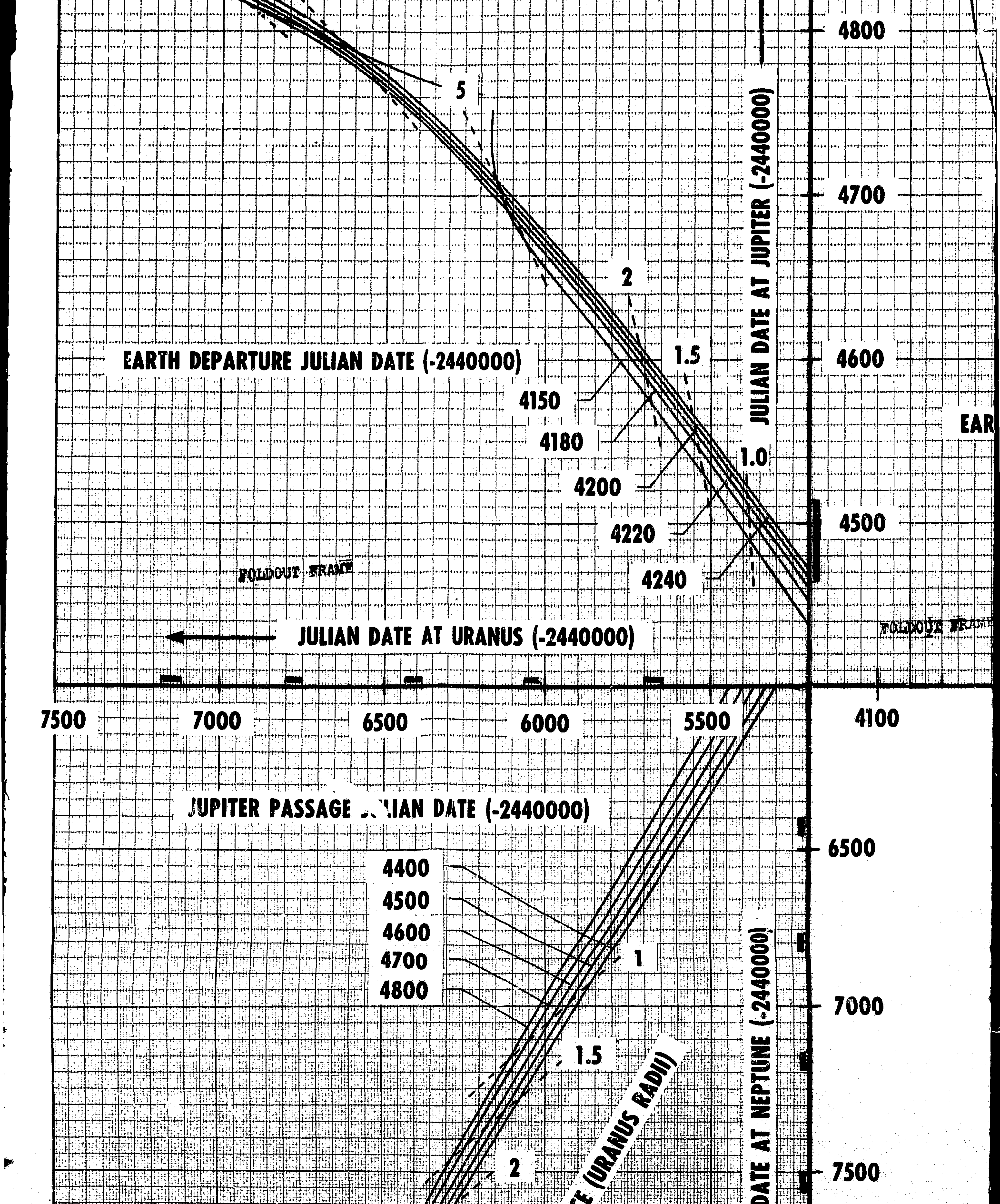
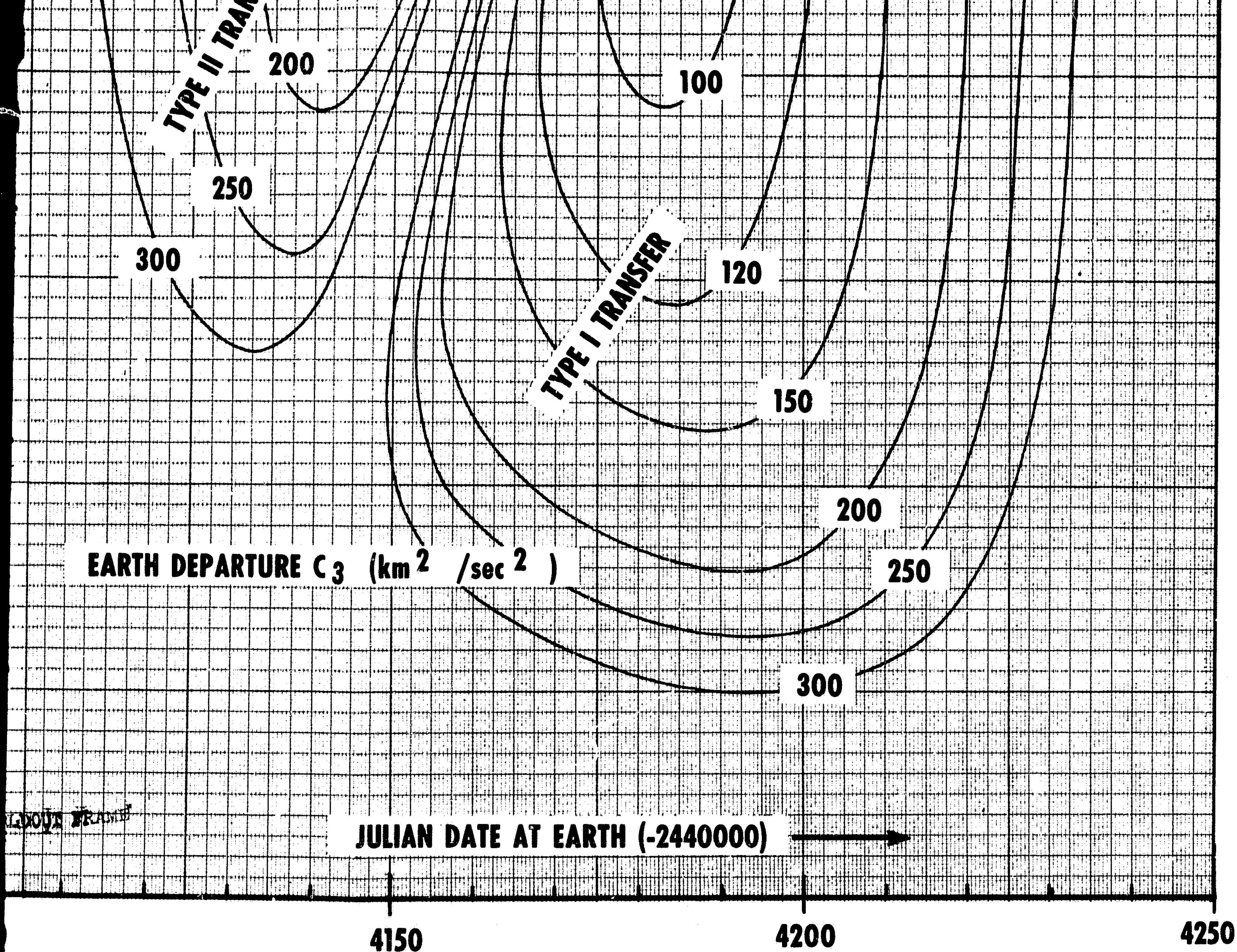


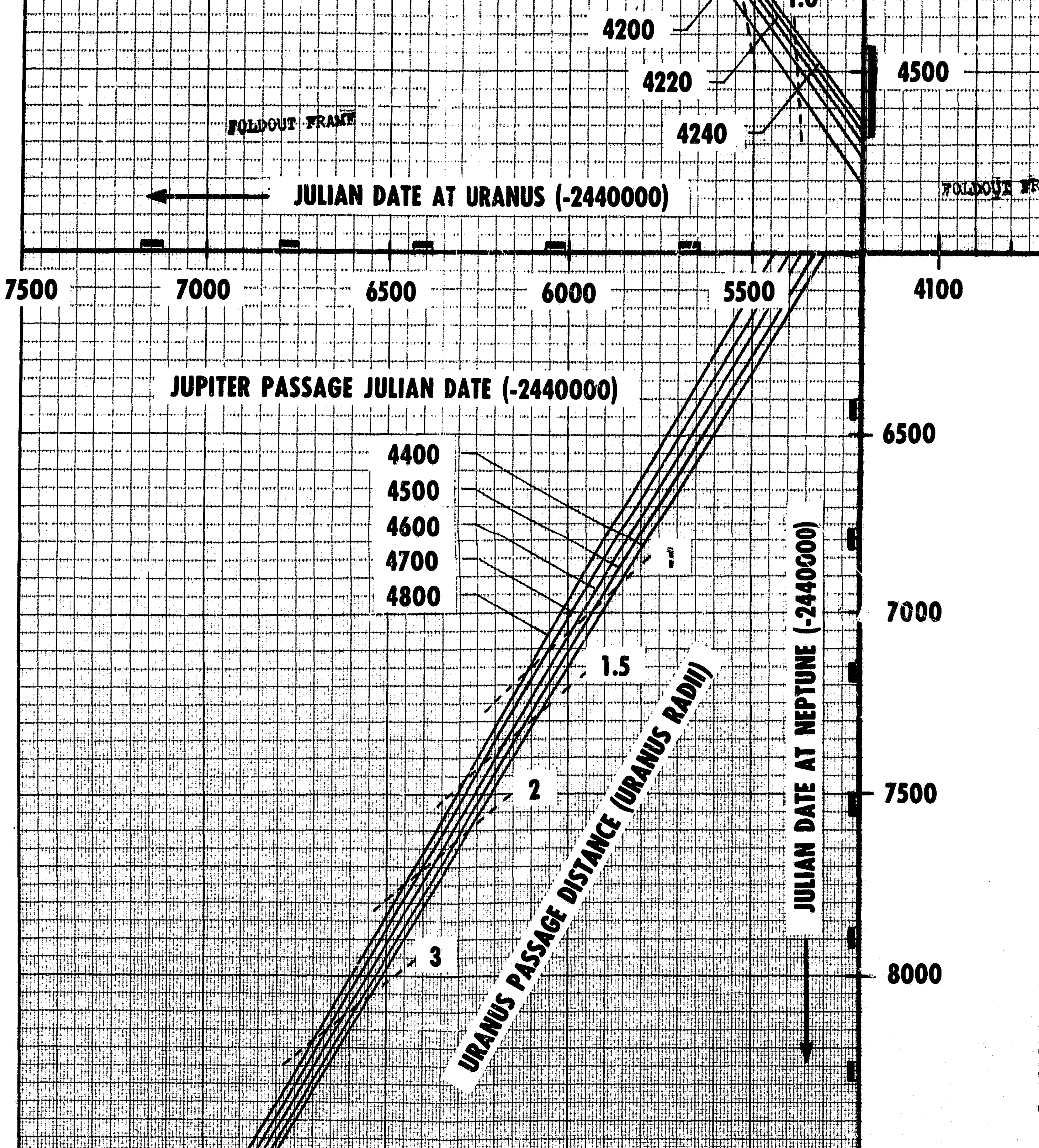
FIGURE 4-14. TRIAD GRAPH FOR 1978 ALTERNATE GRAND TOUR

FOLDOUT FRAME



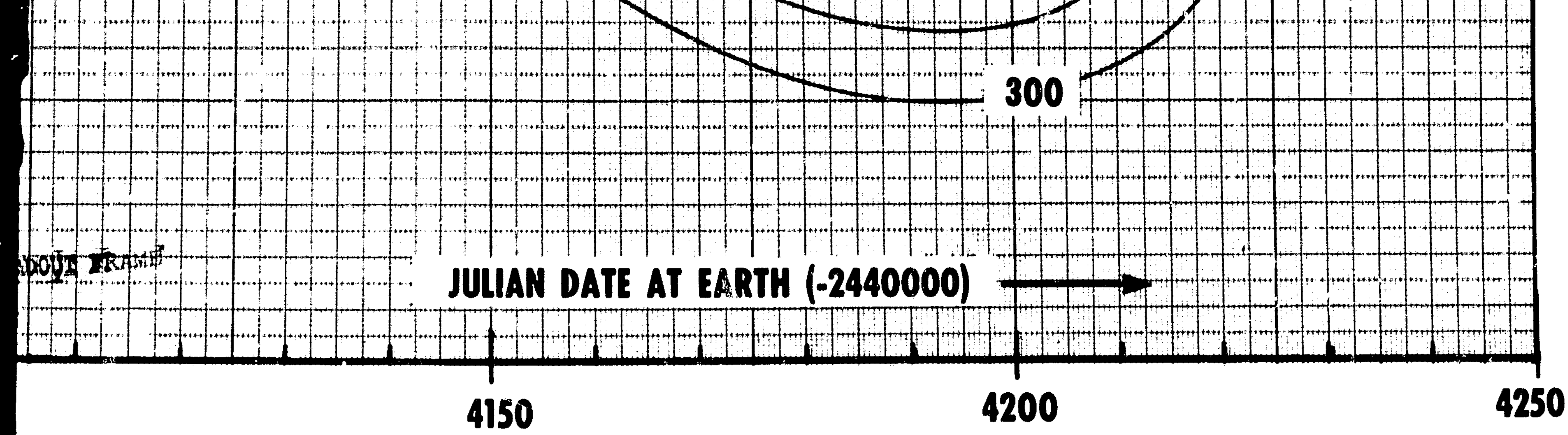
EARTH DEPARTURE JULIAN DATE (-2440000)
4150
4180
4200
4220
4240
5
2
1.5
1.0
JULIAN DATE AT JUPITER (-2440000)
4800
4700
4600
4500
EAR
FOLDOUT FRAME
FOLDOUT FRAME
JULIAN DATE AT URANUS (-2440000)
7500
7000
6500
6000
5500
4100
JUPITER PASSAGE JULIAN DATE (-2440000)
4400
4500
4600
4700
4800
1
1.5
2
6500
7000
7500
(URANUS RADII)
DATE AT NEPTUNE (-2440000)


TYPE II TRANS
200
250
300
100
120
TYPE I TRANSFER
150
200
250
300
EARTH DEPARTURE C_3 (km^2/sec^2)
JULIAN DATE AT EARTH (-2440000)
4150
4200
4250



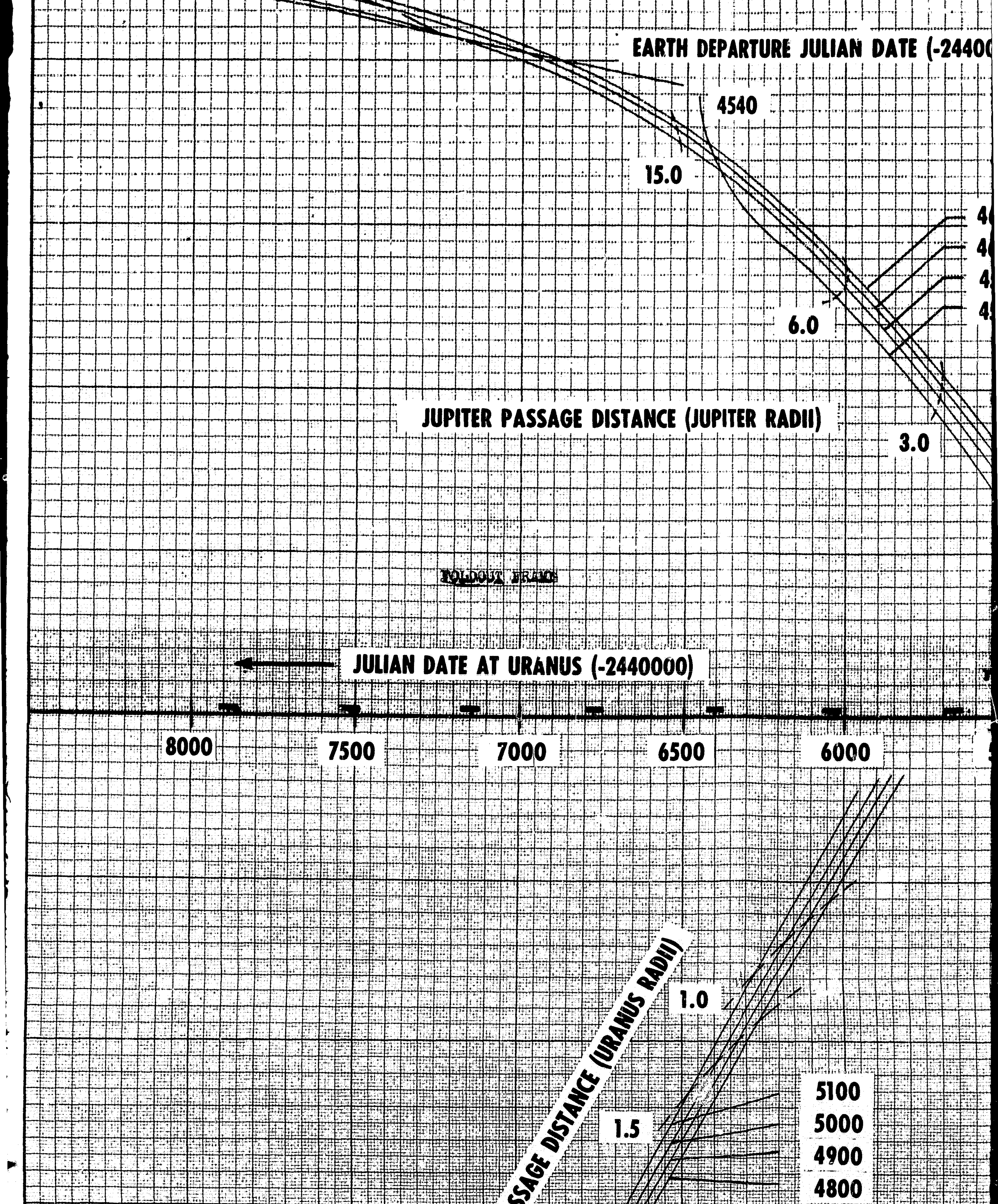
FOLDOUT FRAME

FOLDOUT FRAME

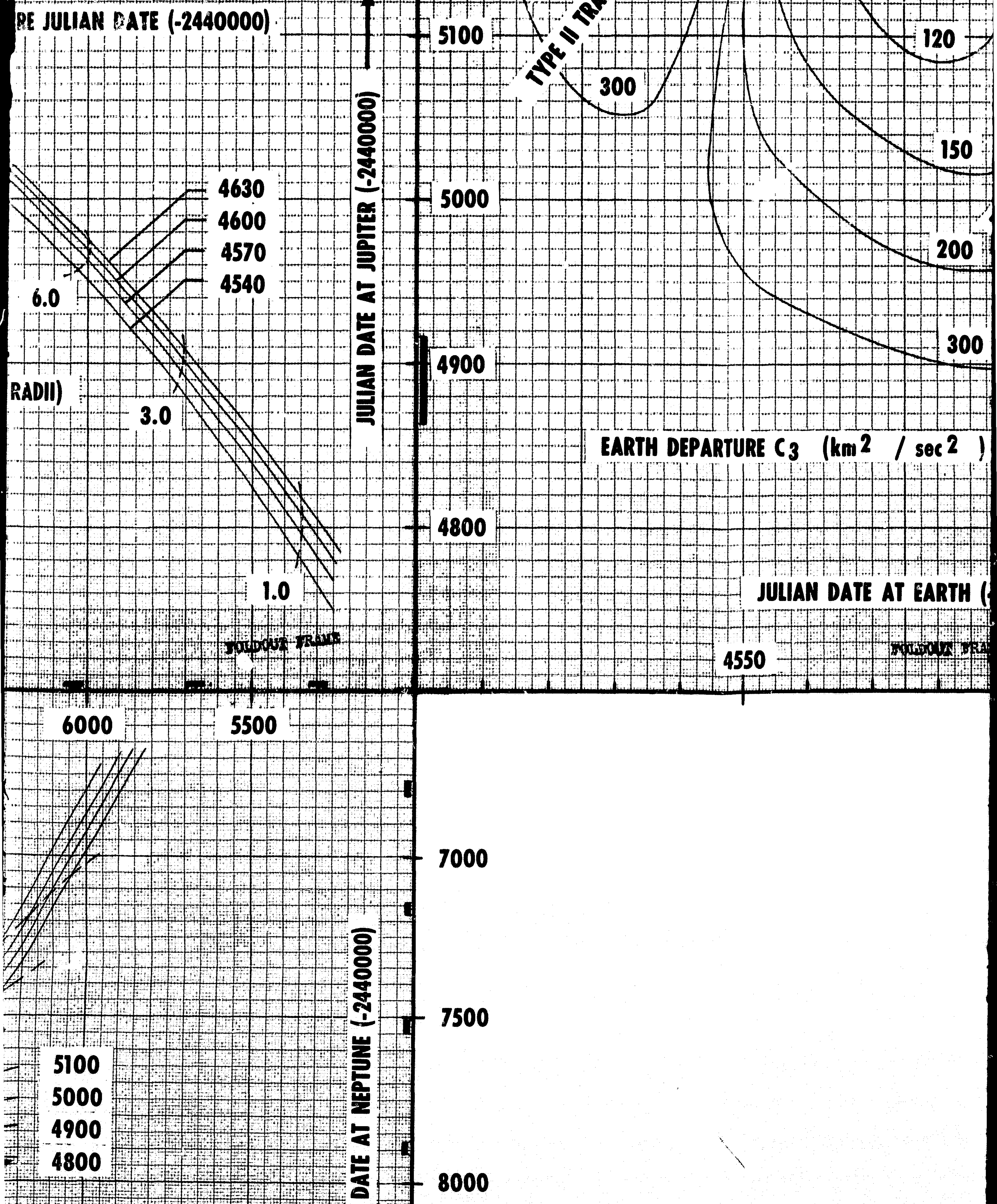


FOLDOUT FRAME

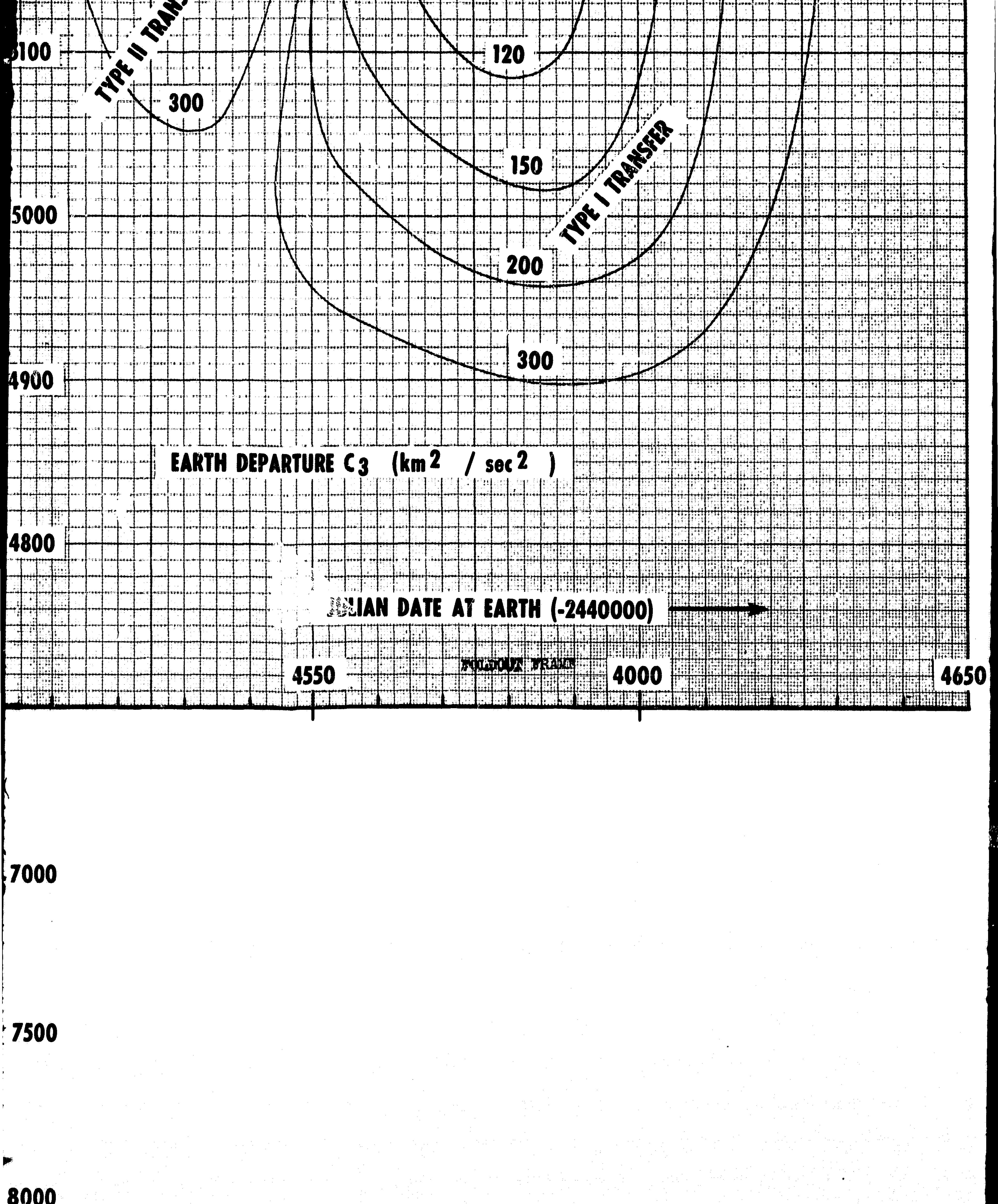
FIGURE 4-15. TRIAD GRAPH FOR 1979 ALTERNATE GRAND TOUR



EARTH DEPARTURE JULIAN DATE (-24400
4540
15.0
6.0
JUPITER PASSAGE DISTANCE (JUPITER RADII)
3.0
FOLDOUT FRAME
JULIAN DATE AT URANUS (-2440000)
8000
7500
7000
6500
6000
1.0
1.5
5100
5000
4900
4800

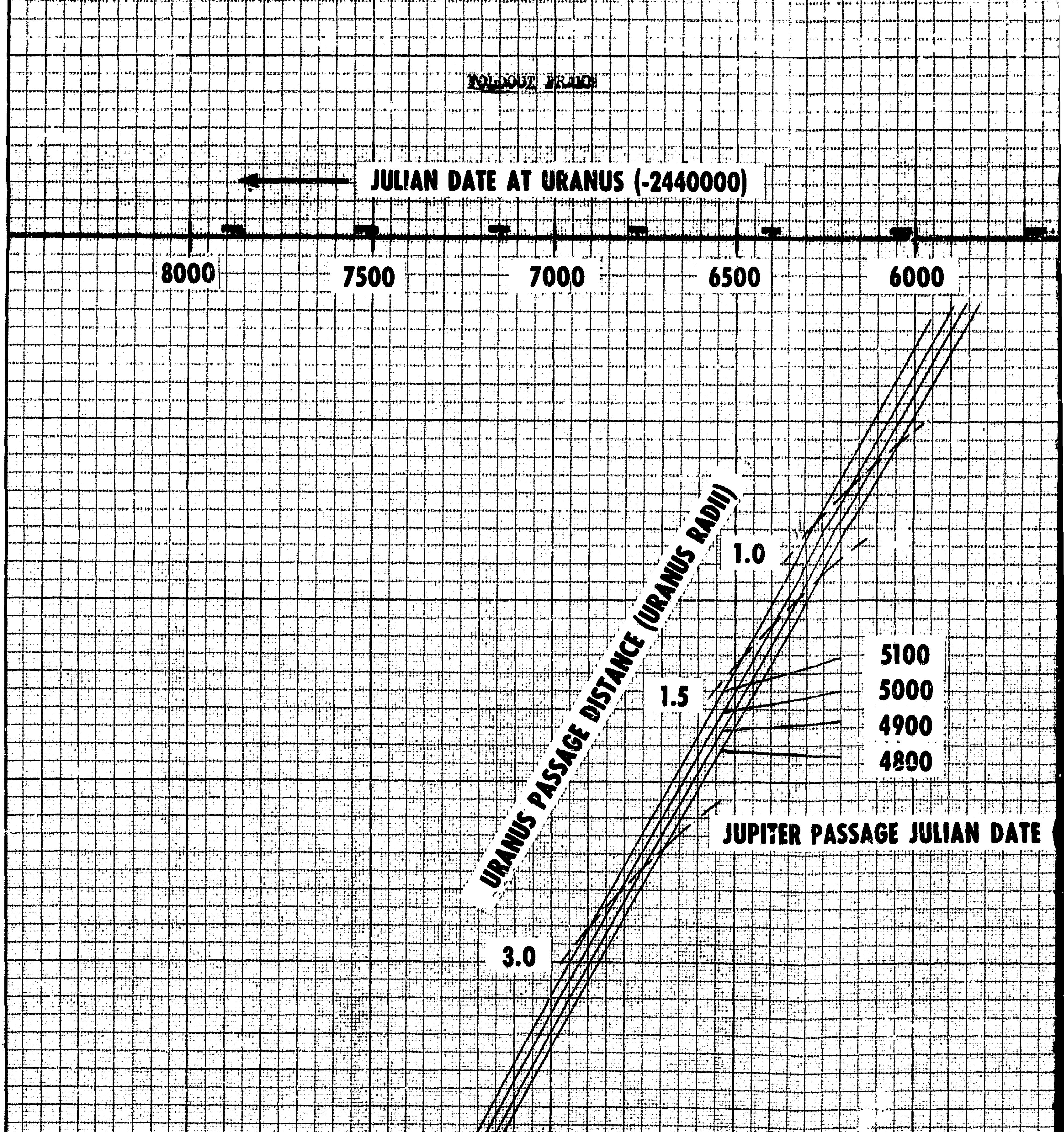


RE JULIAN DATE (-2440000)
TYPE II TRA
5100
5000
4900
4800
JULIAN DATE AT JUPITER (-2440000)
300
120
150
200
300
4630
4600
4570
4540
6.0
RADII)
3.0
1.0
EARTH DEPARTURE C_3 (km^2 / sec^2)
JULIAN DATE AT EARTH (
FOLDOUT FRAME
4550
6000
5500
7000
7500
8000
DATE AT NEPTUNE (-2440000)
5100
5000
4900
4800



FOLDOUT FRAME

FOLDOUT FRAME



FOLDOUT FRAME

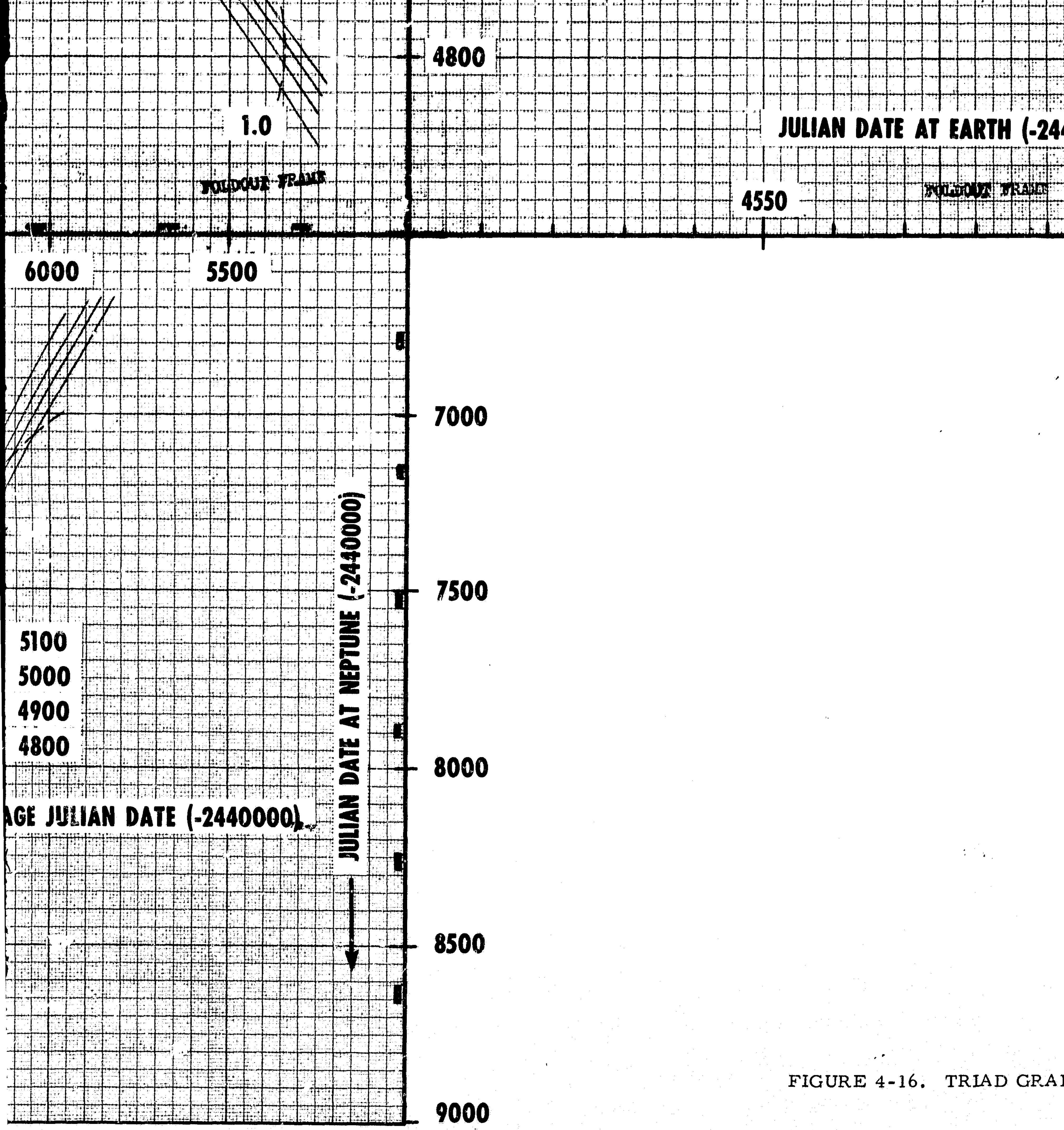


FIGURE 4-16. TRIAD GRAP

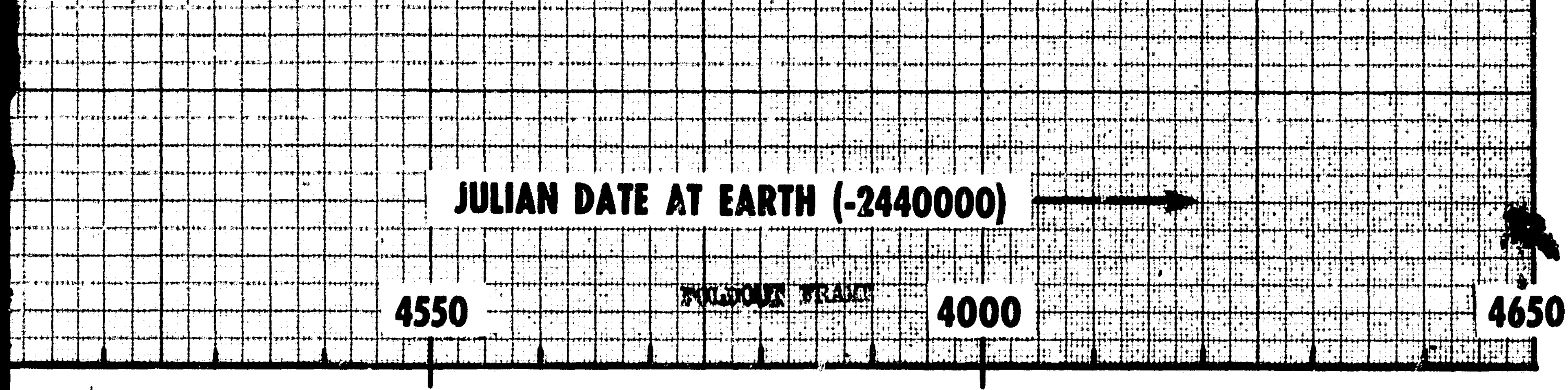
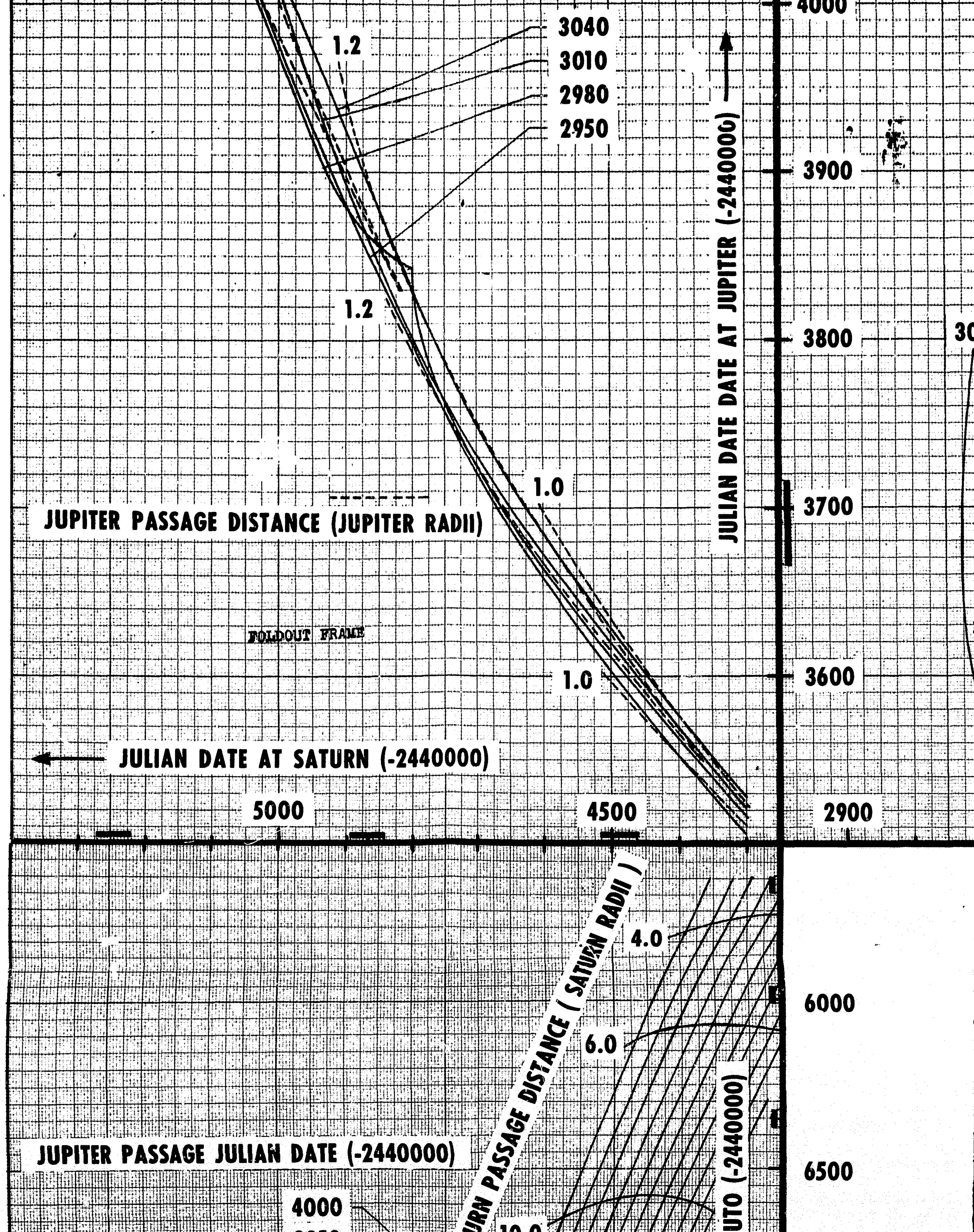
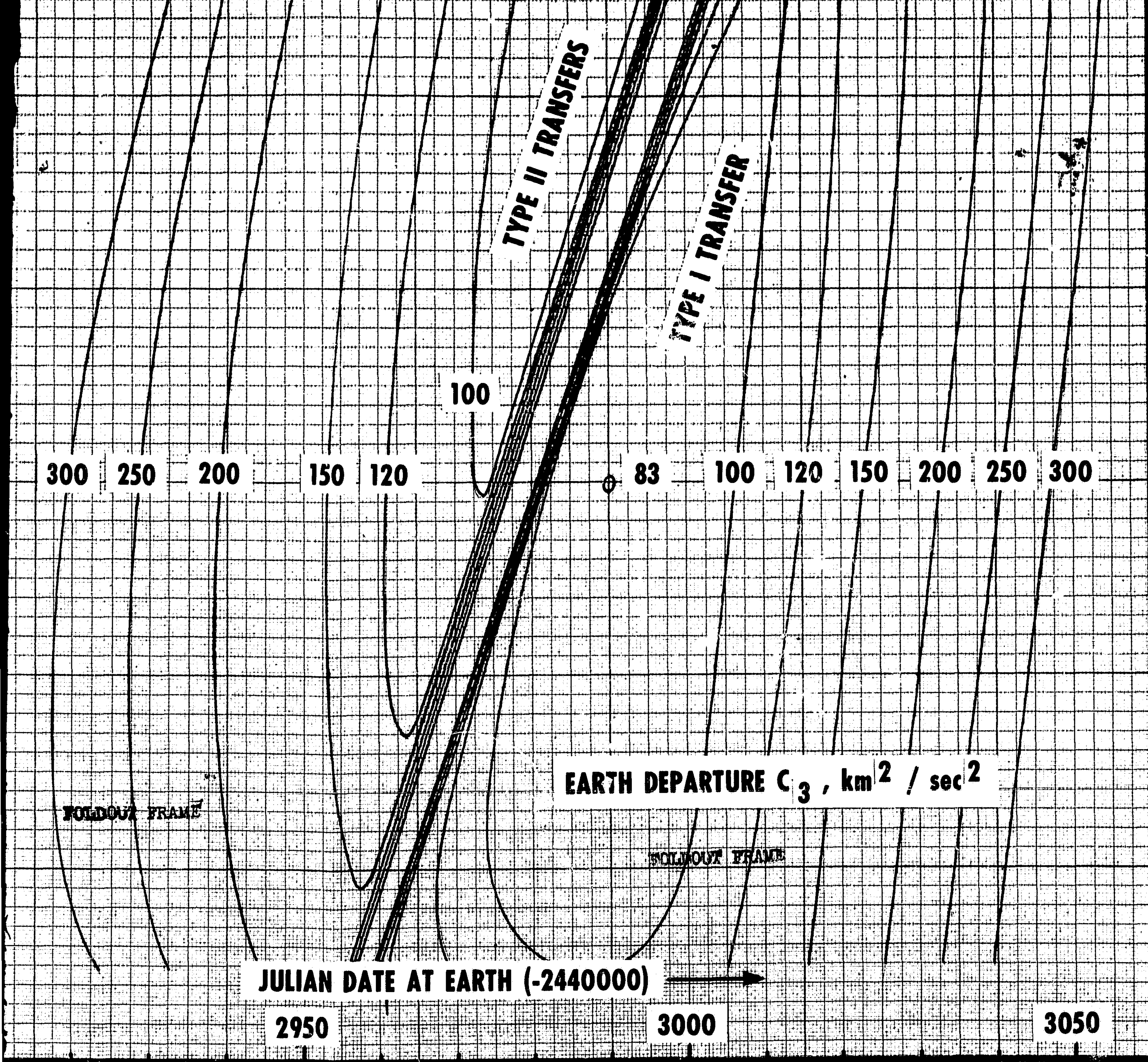
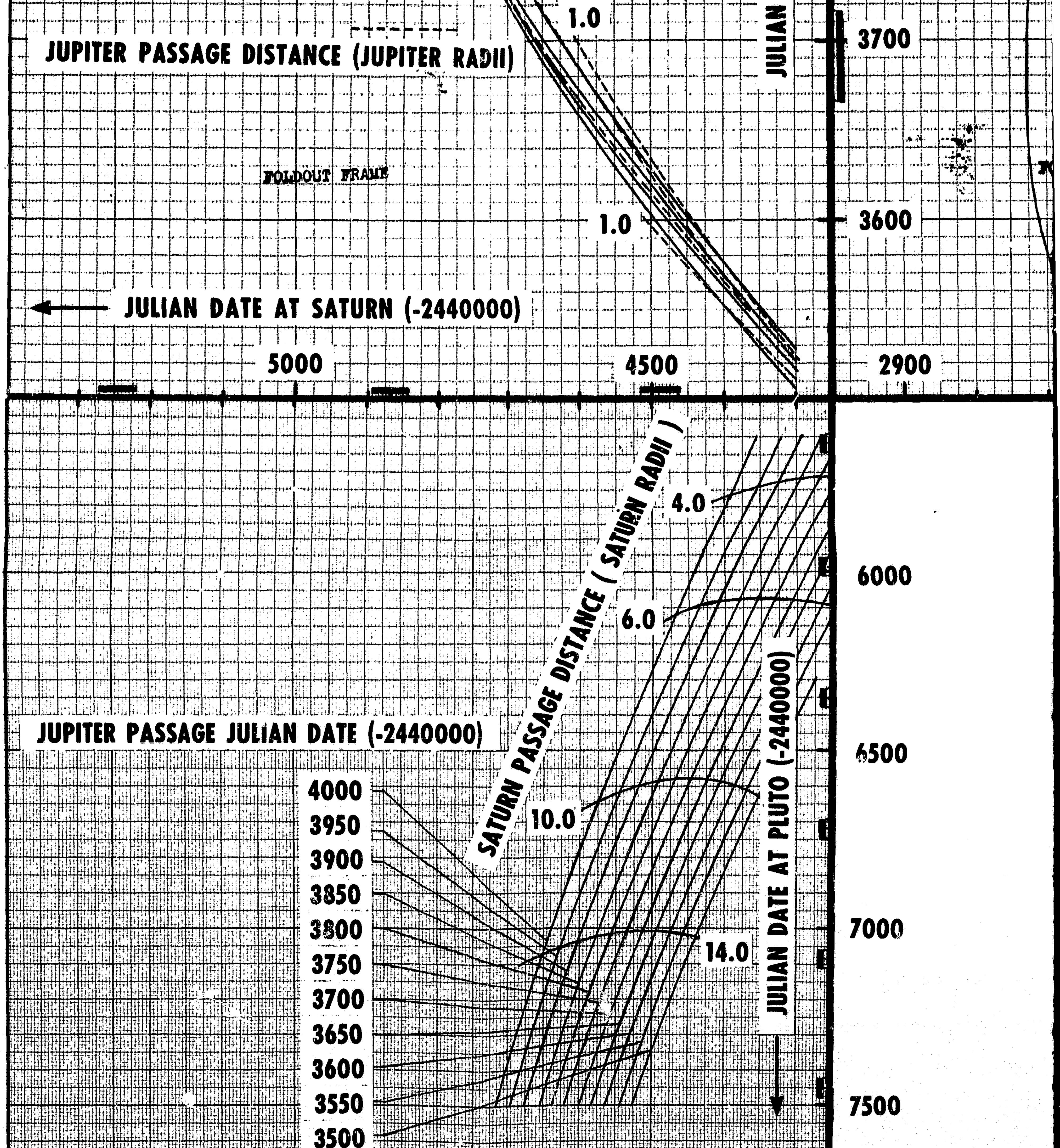
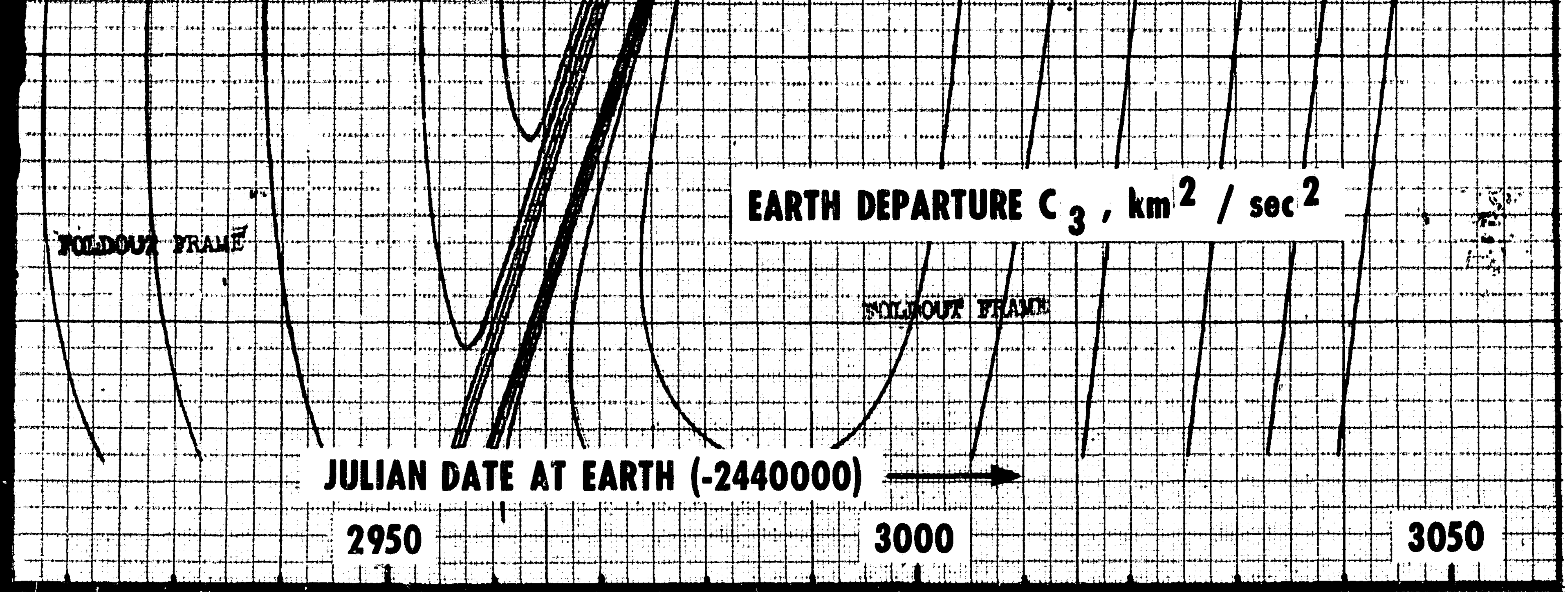


FIGURE 4-16. TRIAD GRAPH FOR 1980 ALTERNATE GRAND TOUR


4000
3040
3010
2980
2950
1.2
1.2
3900
3800
30
1.0
3700
JUPITER PASSAGE DISTANCE (JUPITER RADII)
JULIAN DATE DATE AT JUPITER (-2440000)
FOLDOUT FRAME
1.0
3600
JULIAN DATE AT SATURN (-2440000)
5000
4500
2900
SATURN PASSAGE DISTANCE (SATURN RADII)
4.0
6000
6.0
JUPITER PASSAGE JULIAN DATE (-2440000)
6500
4000
(-2440000)

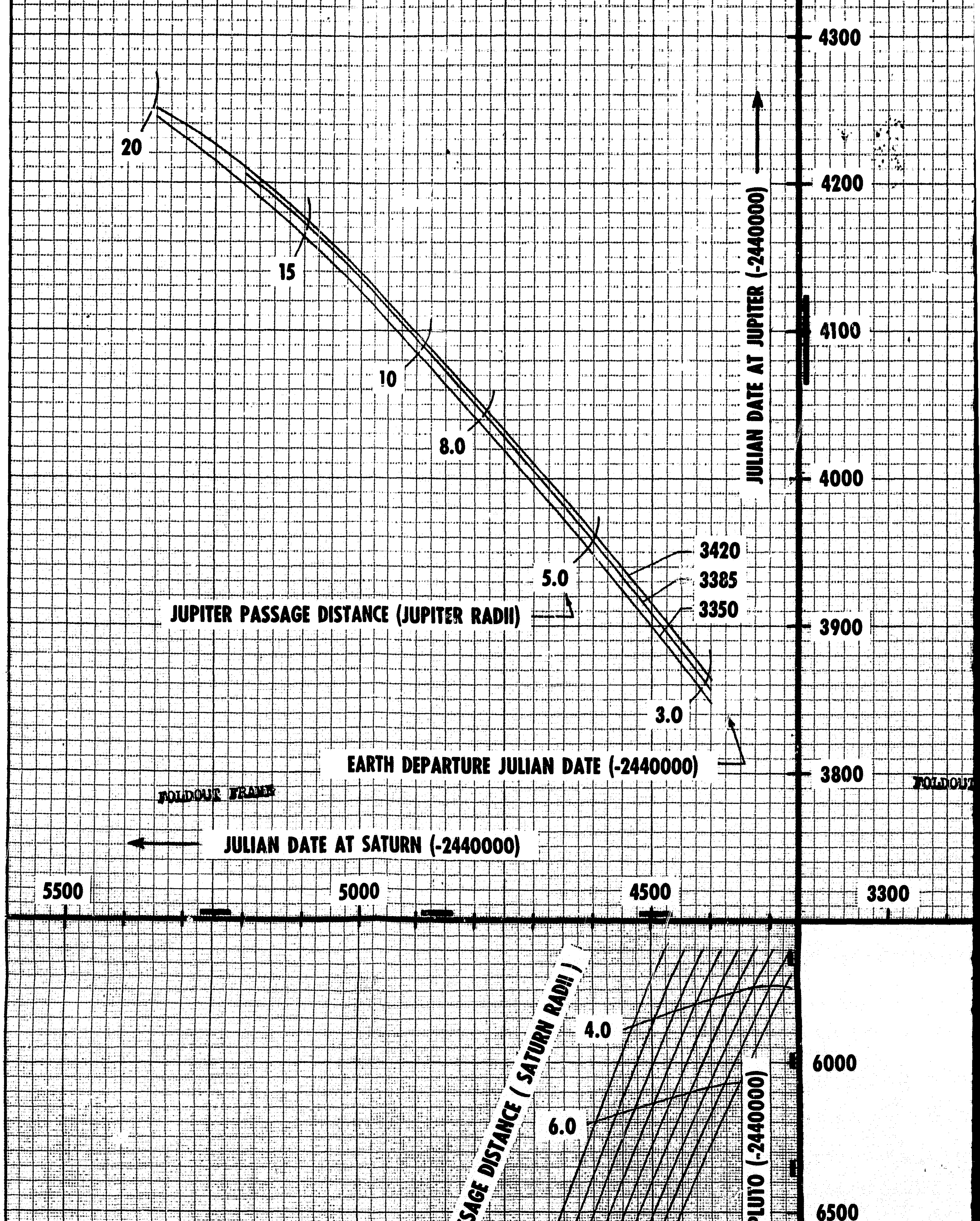

TYPE II TRANSFERS
TYPE I TRANSFER
100
300
250
200
150
120
100
83
100
120
150
200
250
300
EARTH DEPARTURE C_3, km^2 / sec^2
FOLDOUT FRAME
FOLDOUT FRAME
JULIAN DATE AT EARTH (-2440000)
2950
3000
3050


JULIAN
3700
1.0
JUPITER PASSAGE DISTANCE (JUPITER RADII)
1.0
3600
JULIAN DATE AT SATURN (-2440000)
5000
4500
2900
SATURN PASSAGE DISTANCE (SATURN RADII)
4.0
6.0
10.0
14.0
6000
6500
7000
7500
JUPITER PASSAGE JULIAN DATE (-2440000)
4000
3950
3900
3850
3800
3750
3700
3650
3600
3550
3500
JULIAN DATE AT PLUTO (-2440000)

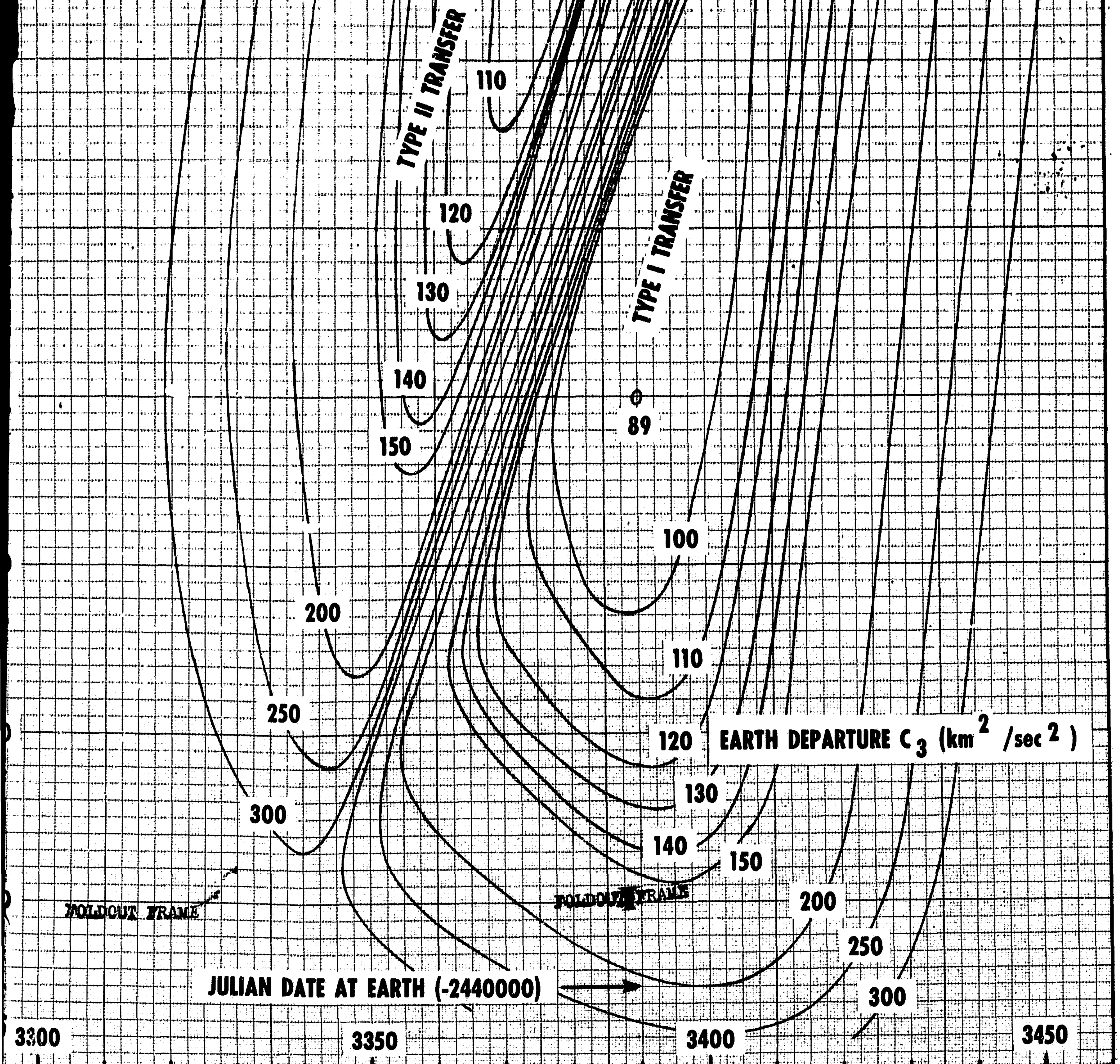


FOLDOUT FRAME

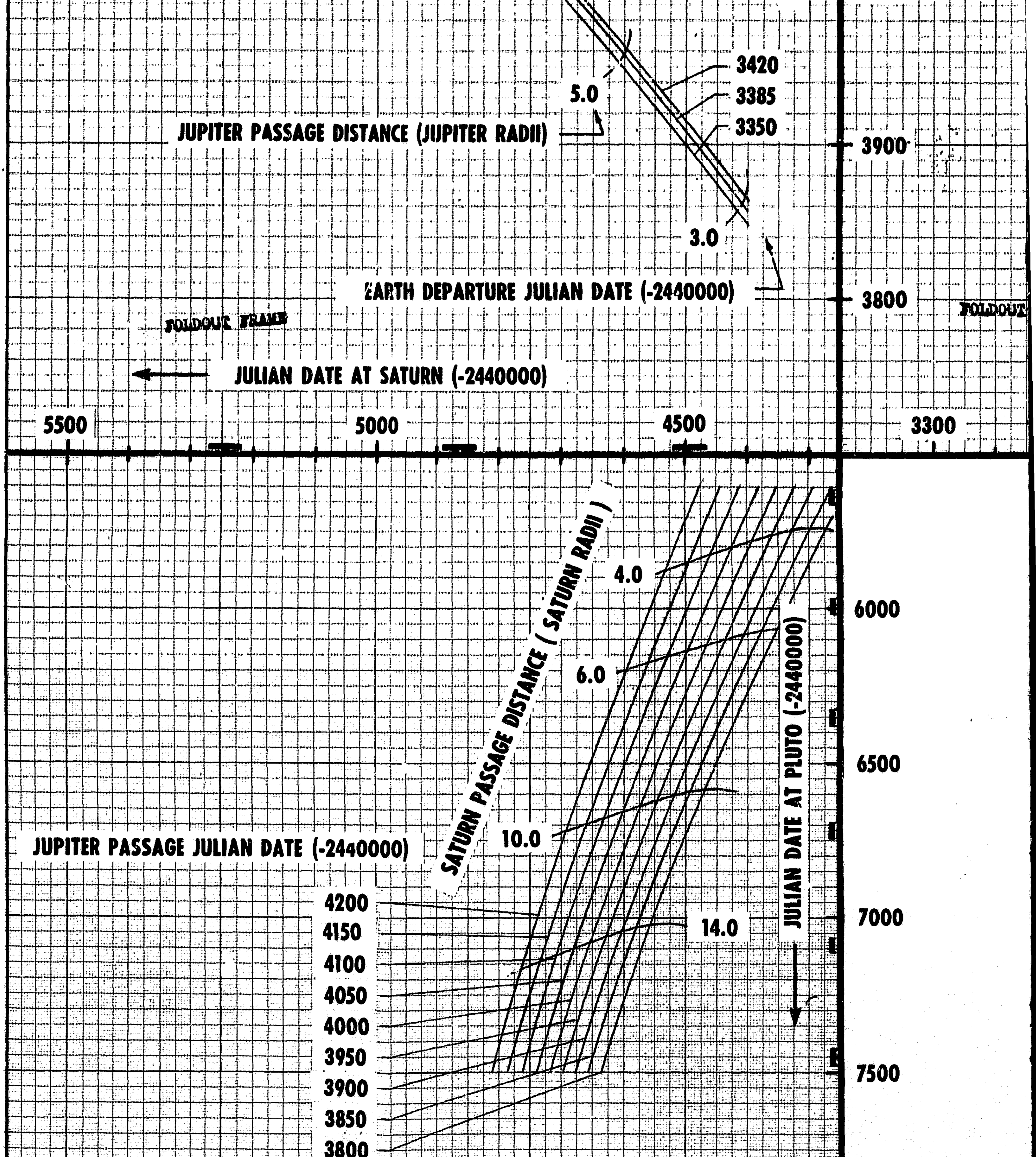
FIGURE 4-17. TRIAD GRAPH FOR 1976 ALTERNATE GRAND TOUR TO PLUTO



20
15
10
8.0
5.0
3.0
3420
3385
3350
JUPITER PASSAGE DISTANCE (JUPITER RADII)
EARTH DEPARTURE JULIAN DATE (-2440000)
JULIAN DATE AT JUPITER (-2440000)
4300
4200
4100
4000
3900
3800
3300
FOLDOUT FRAME
JULIAN DATE AT SATURN (-2440000)
5500
5000
4500
4.0
6.0
SAGE DISTANCE (SATURN RADII)
PLUTO (-2440000)
6000
6500



TYPE II TRANSFER
TYPE I TRANSFER
110
120
130
140
150
89
100
110
120
130
140
150
200
250
300
200
250
300
EARTH DEPARTURE C_3 (km^2/sec^2)
FOLDOUT FRAME
FOLDOUT FRAME
JULIAN DATE AT EARTH (-2440000)
3300
3350
3400
3450

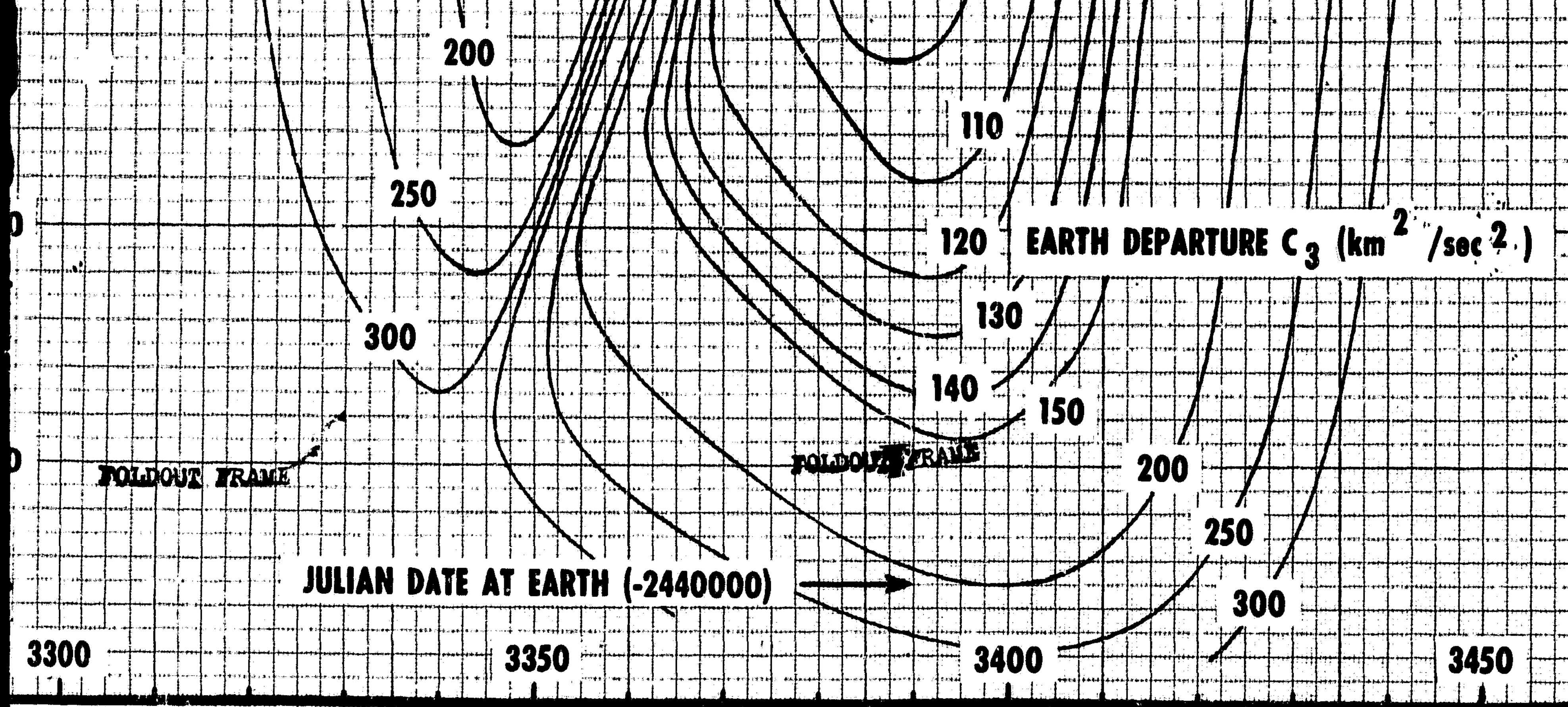


FOLDOUT FRAME

FOLDOUT FRAME

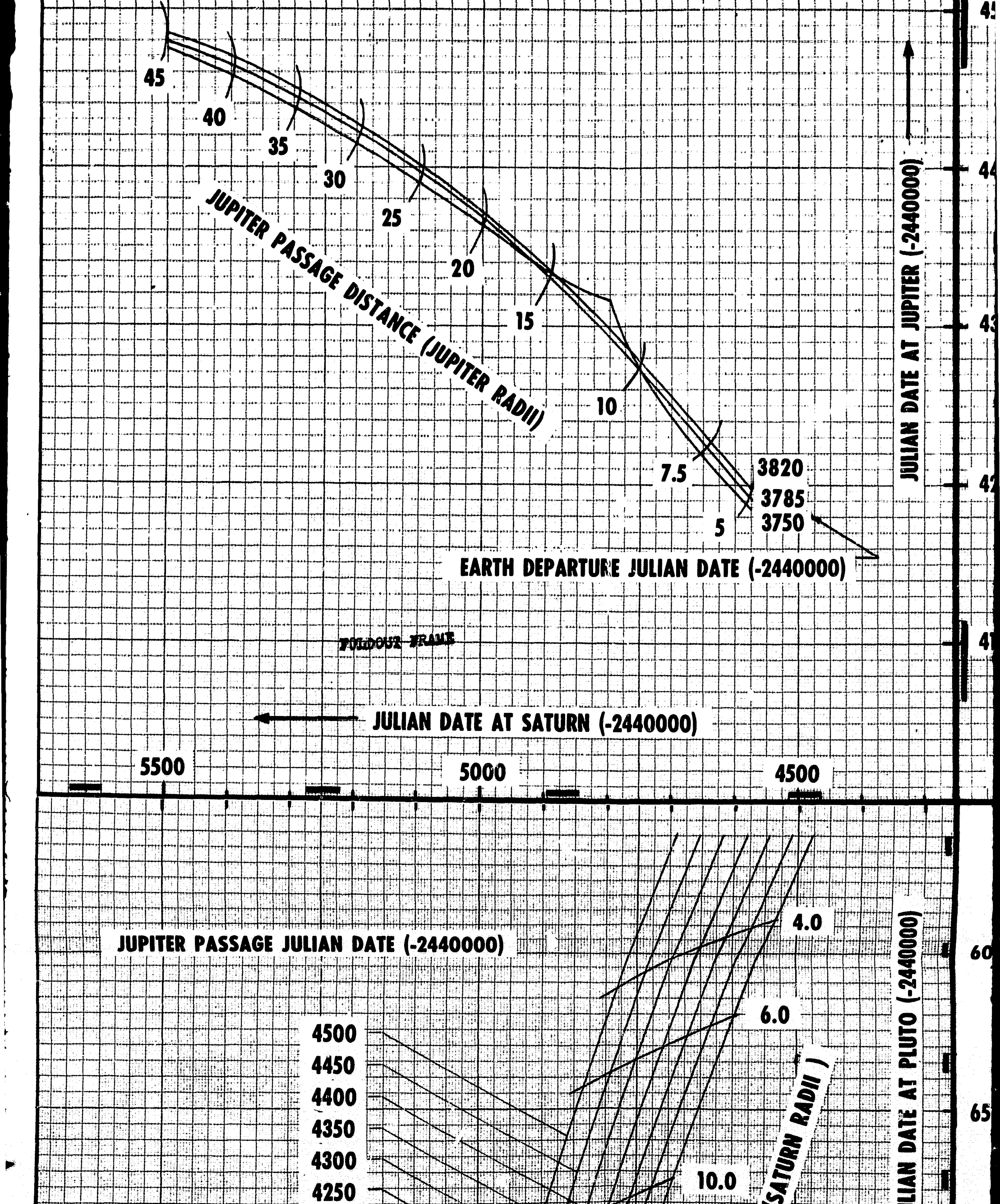
FOLDOUT FRAME

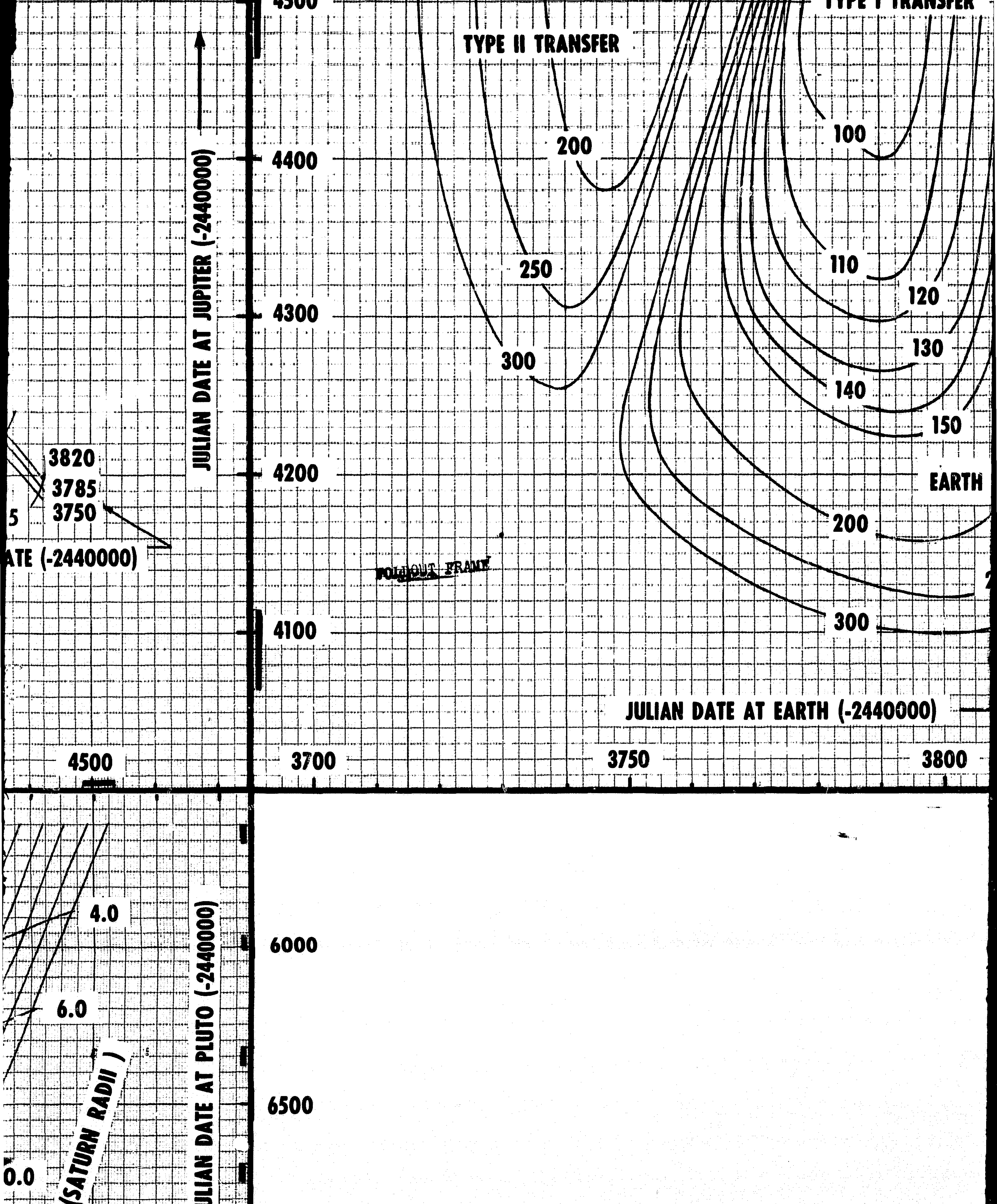
FOLDOUT



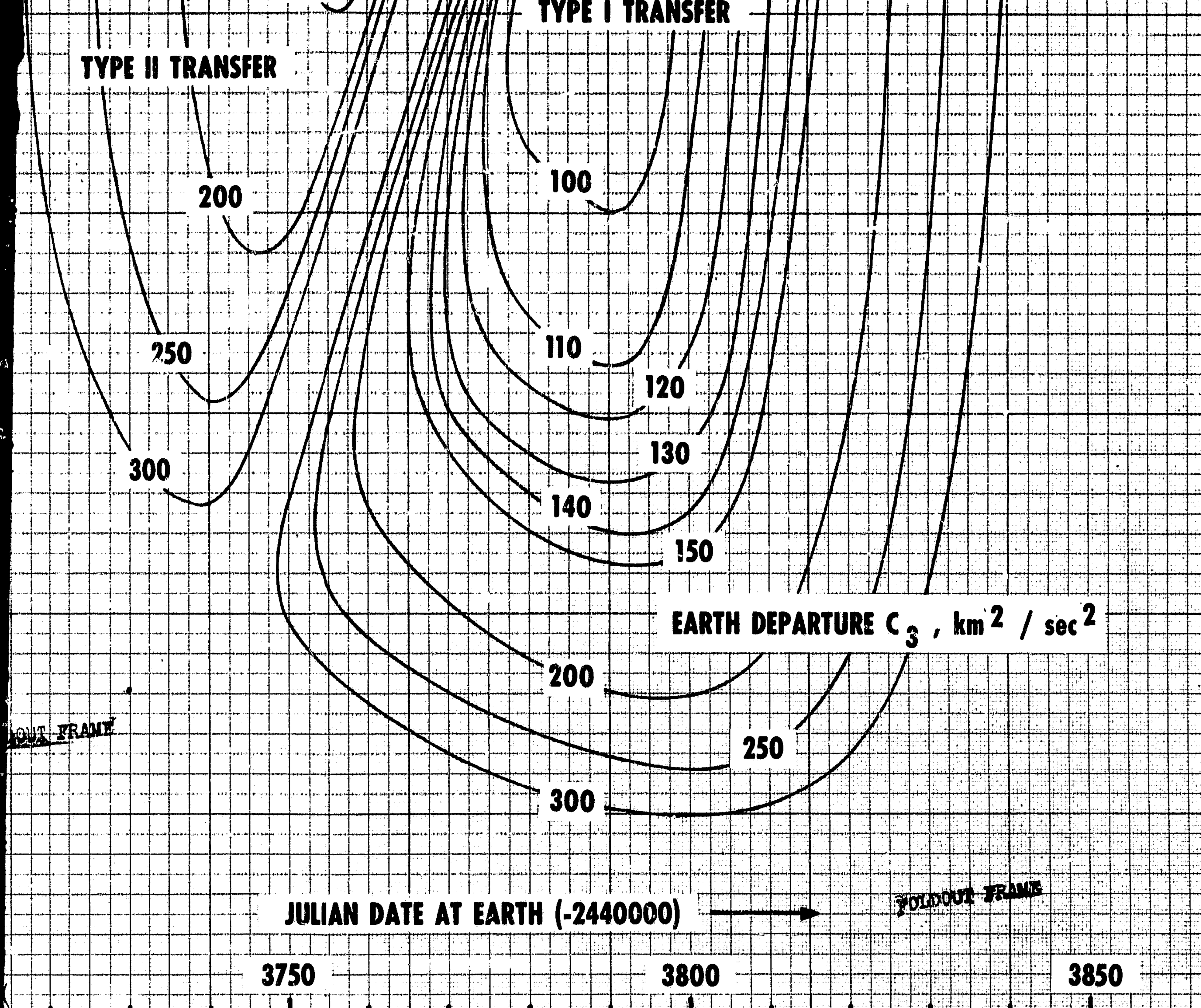
FOLDOUT FRAME

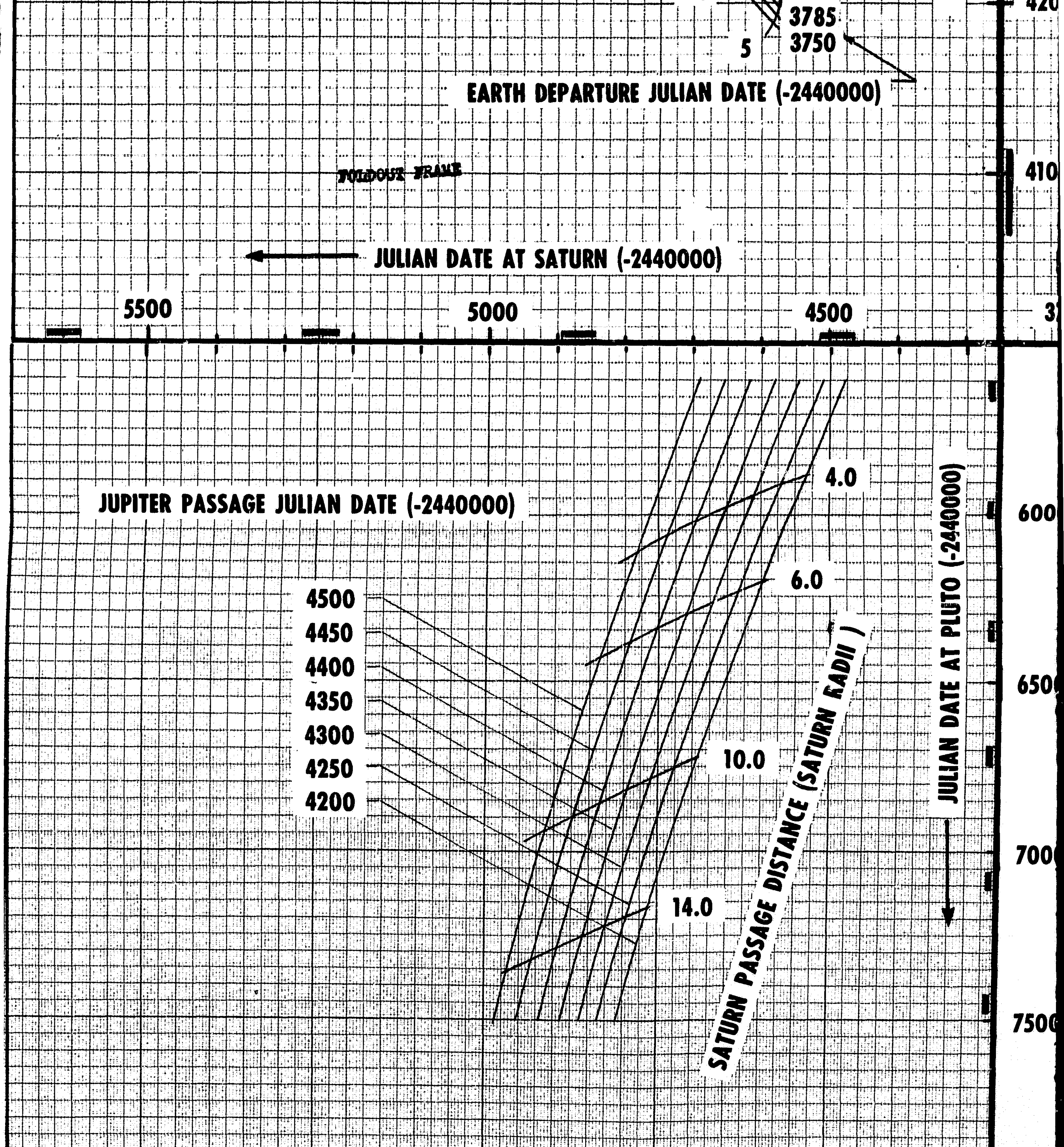
FIGURE 4-18. TRIAD GRAPH FOR 1977 ALTERNATE GRAND TOUR TO PLUTO


45
40
35
30
25
20
15
10
7.5
5
JUPITER PASSAGE DISTANCE (JUPITER RADII)
3820
3785
3750
EARTH DEPARTURE JULIAN DATE (-2440000)
JULIAN DATE AT JUPITER (-2440000)
FOLDOUT FRAME
JULIAN DATE AT SATURN (-2440000)
5500
5000
4500
JUPITER PASSAGE JULIAN DATE (-2440000)
4.0
6.0
4500
4450
4400
4350
4300
4250
10.0
SATURN RADII)
LIAN DATE AT PLUTO (-2440000)



TYPE II TRANSFER
TYPE I TRANSFER
JULIAN DATE AT JUPITER (-2440000)
4400
4300
4200
4100
200
250
300
100
110
120
130
140
150
EARTH
200
300
3820
3785
3750
ATE (-2440000)
FOLDOUT FRAME
JULIAN DATE AT EARTH (-2440000)
4500
3700
3750
3800
4.0
6.0
0.0
(SATURN RADII)
JULIAN DATE AT PLUTO (-2440000)
6000
6500


TYPE I TRANSFER
TYPE II TRANSFER
100
110
120
130
140
150
200
250
300
200
250
300
EARTH DEPARTURE C_3, km^2 / sec^2
JULIAN DATE AT EARTH (-2440000)
3750
3800
3850


3785
3750
5
EARTH DEPARTURE JULIAN DATE (-2440000)
JULIAN DATE AT SATURN (-2440000)
5500
5000
4500
JUPITER PASSAGE JULIAN DATE (-2440000)
4500
4450
4400
4350
4300
4250
4200
4.0
6.0
10.0
14.0
SATURN PASSAGE DISTANCE (SATURN RADII)
JULIAN DATE AT PLUTO (-2440000)
600
650
700
750
410
420

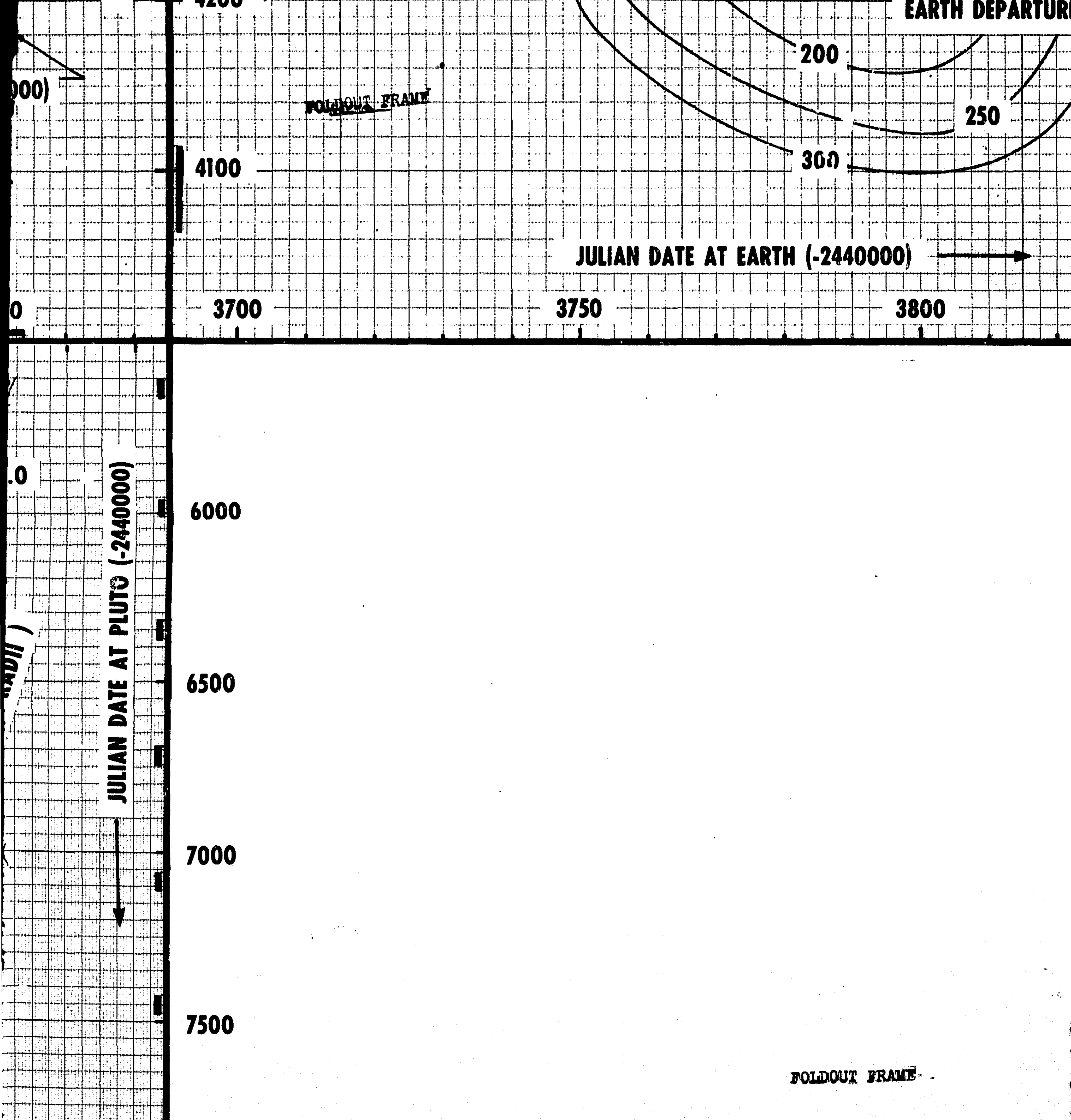
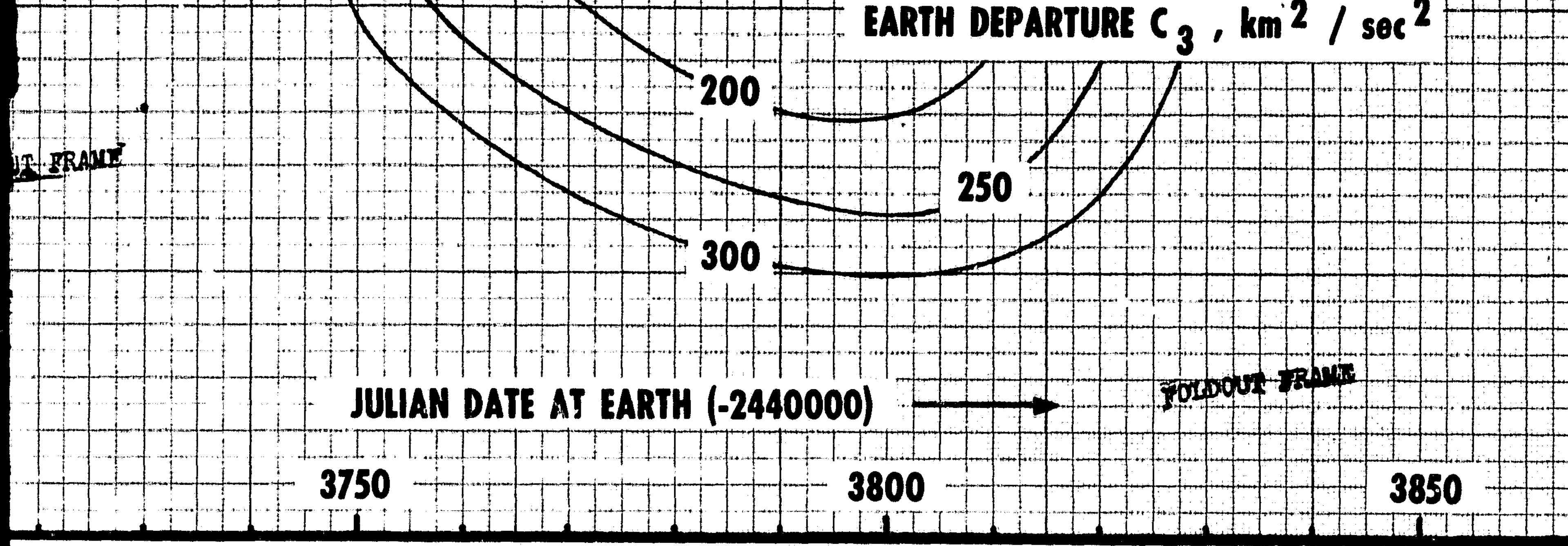
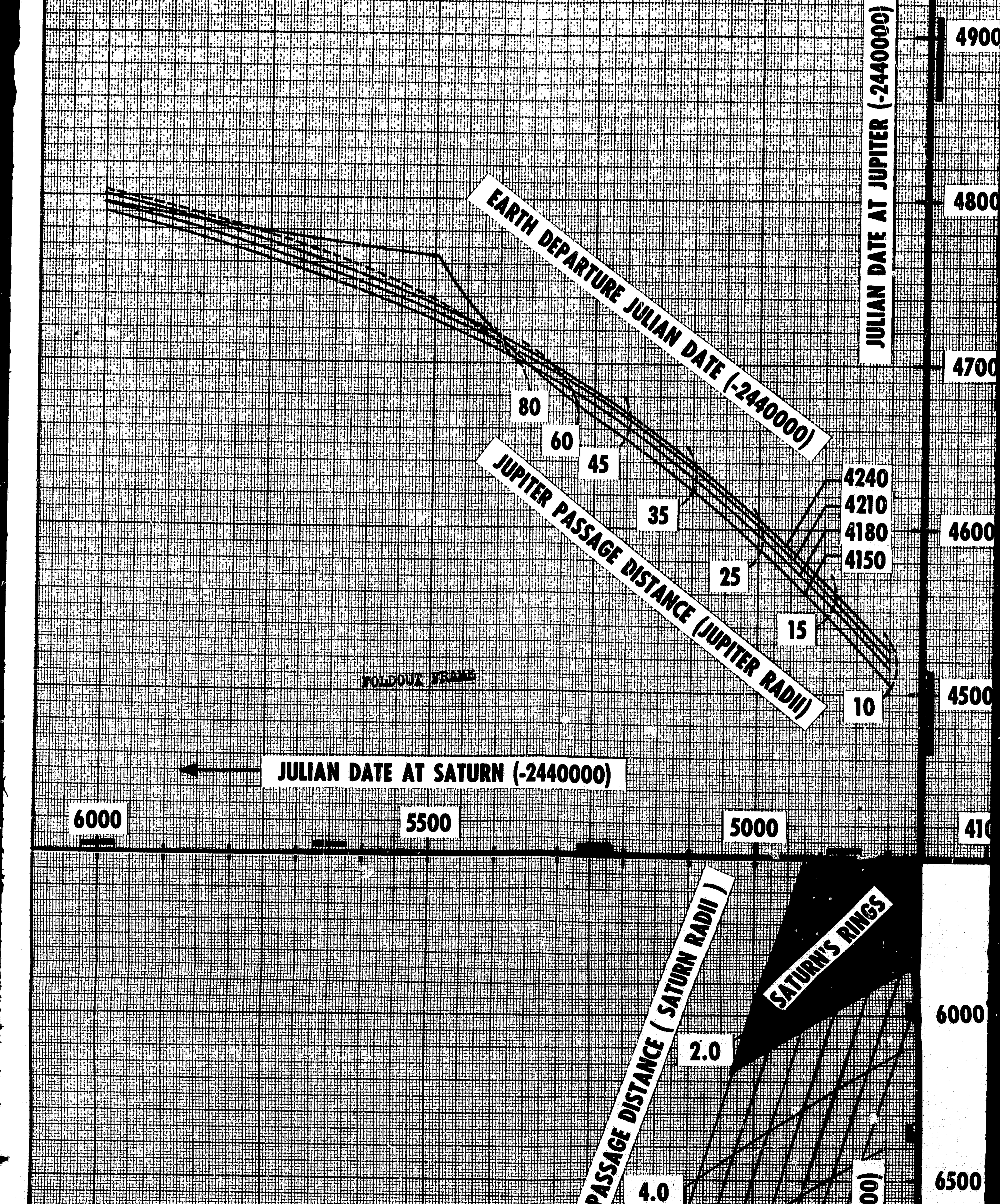


FIGURE 4-19. TRIAD GRAPH FOR 1978 ALTERNA

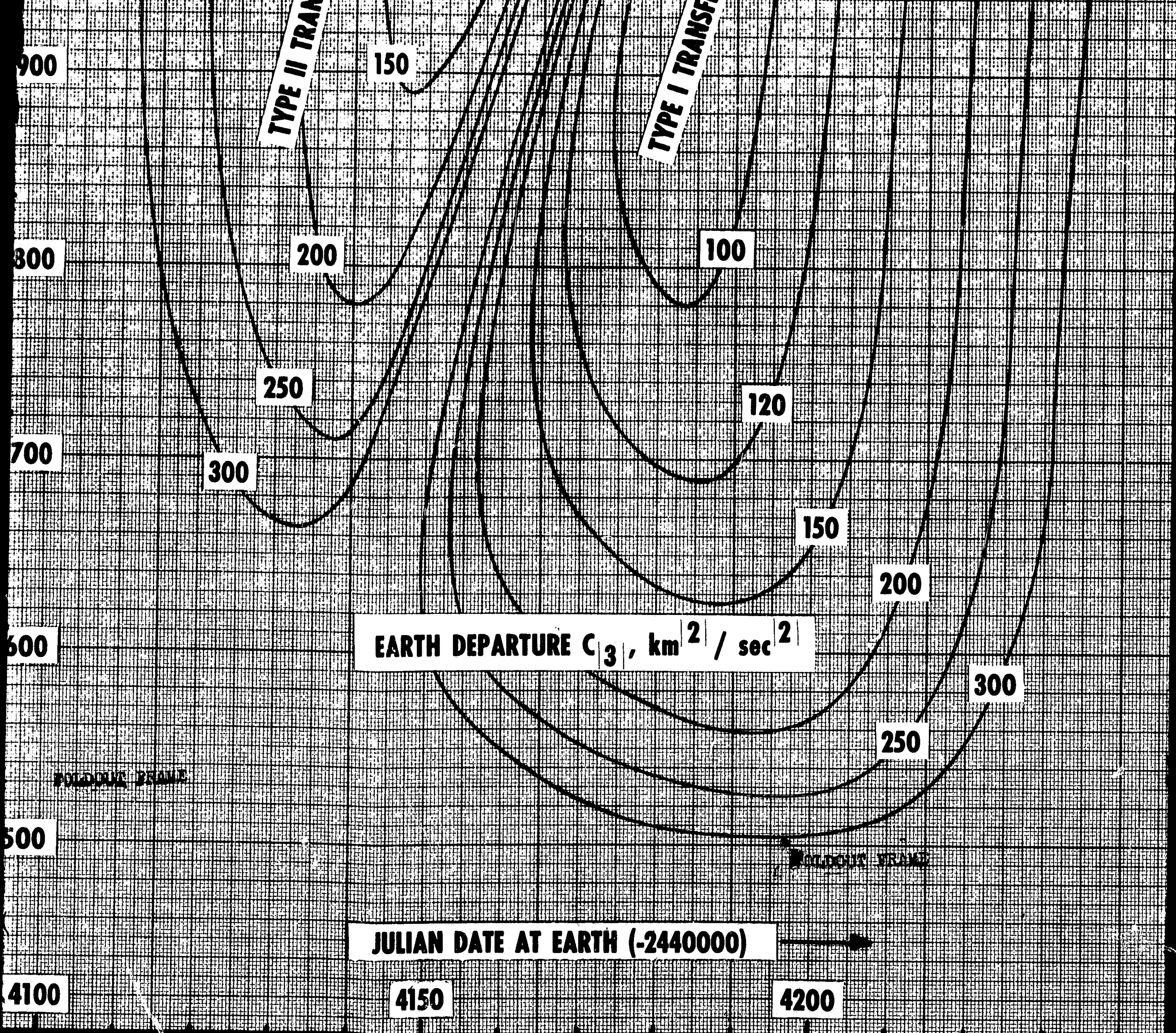


FOLDOUT FRAME

FIGURE 4-19. TRIAD GRAPH FOR 1978 ALTERNATE GRAND TOUR TO PLUTO

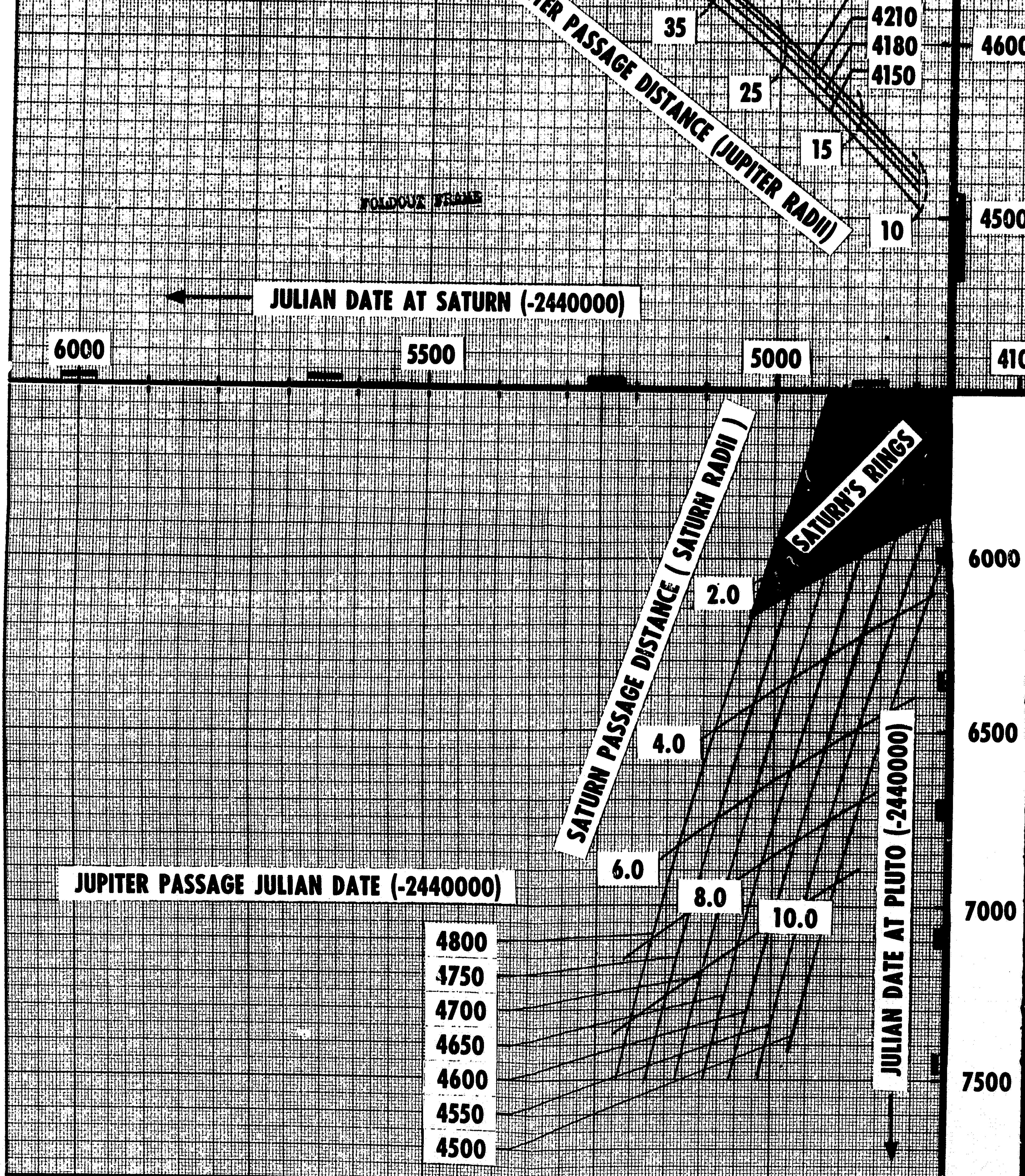


EARTH DEPARTURE JULIAN DATE (-2440000)
JULIAN DATE AT JUPITER (-2440000)
4900
4800
4700
4600
4500
80
60
45
35
25
15
10
4240
4210
4180
4150
JUPITER PASSAGE DISTANCE (JUPITER RADII)
JULIAN DATE AT SATURN (-2440000)
6000
5500
5000
SATURN'S RINGS
PASSAGE DISTANCE (SATURN RADII)
2.0
4.0
6000
6500


TYPE II TRAN
TYPE I TRANSF
150
200
250
300
100
120
150
200
250
300
900
800
700
600
500
EARTH DEPARTURE C3, km2 / sec2
FOLDOUT FRAME
FOLDOUT FRAME
JULIAN DATE AT EARTH (-2440000)
4100
4150
4200

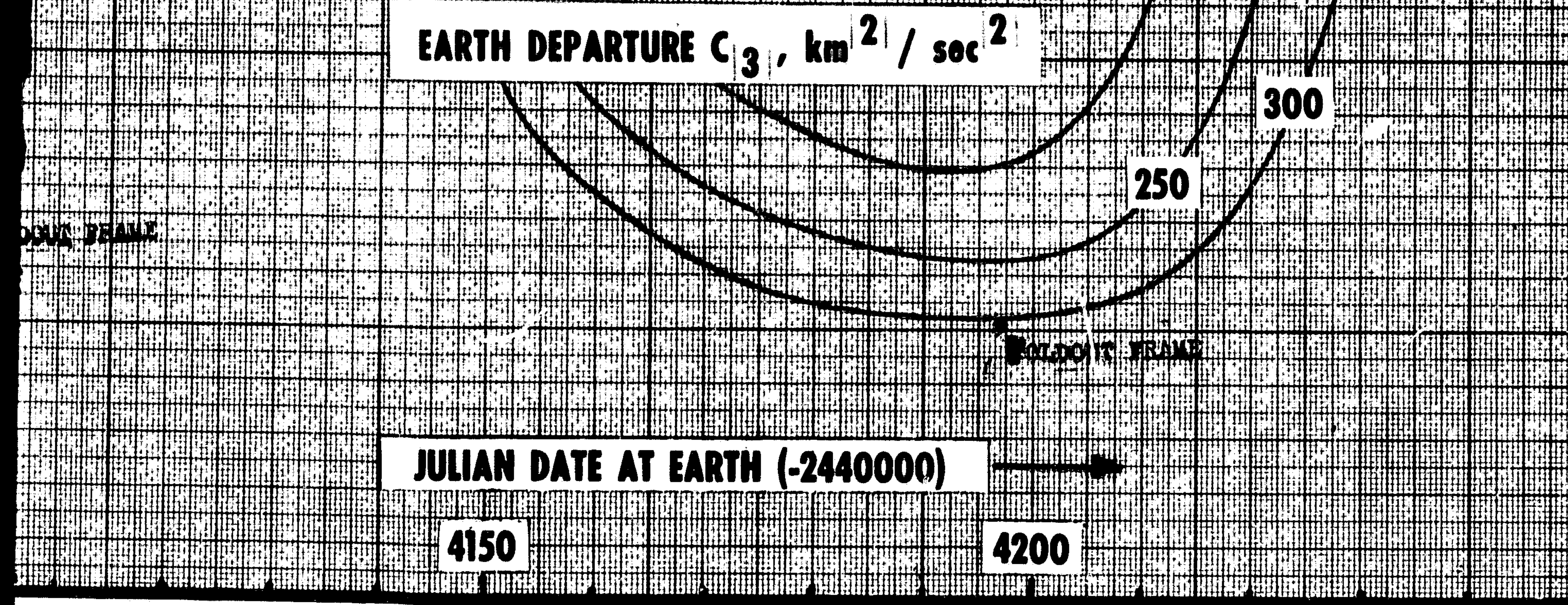
00

00



FOLDOUT FRAME

FOLDOUT FRAME



FOLDOUT FRAME

FIGURE 4-20. TRIAD GRAPH FOR 1979 ALTERNATE GRAND TOUR TO PLUTO

Section 5

GRAND TOUR MISSIONS OF SHORT, MEDIUM, AND LONG DURATION

In Tables 5-1, 5-2, and 5-3, trajectory parameters of several representative Grand Tour Missions are presented. The trajectories of Table 5-1 have relatively short total trip times and pass very close to Saturn The trajectories of Table 5-2 are of medium duration and pass close to the outside of Saturn's rings. Trajectories of Table 5-3 pass far from the rings of Saturn and are of long duration.

The parameters in Tables 5-1, 5-2, and 5-3 are the same as those in Table 2-1. The first section of each table contains launch parameters: the date of launch, the launch energy, the declination, δ, and the right ascension α, of the escape asymptote. The subsequent sections of the tables contain parameters describing the passage of swingby planets. The parameters are the hyperbolic excess speed V_∞, the pericenter radius, r_p, the speed at pericenter, V_p, the inclination of the passage hyperbola to the planet's equator, I_h, the bend angle κ, and the lighting angle η. The bend angle is the angle between approach and exit asymptotes. The lighting angle is the angle between the vector to pericenter and the planet-Sun vector.

The distance of the probe from Saturn when it passes through the plane of the rings (Saturn's equatorial plane) is critical to the missions represented in Table 5-1. A trajectory passing inside the rings must have a pericenter distance that is large enough to avoid the atmosphere but must be within 1.18 planet radii when it passes through the equatorial plane.

Table 5-4 contains additional parameters that describe the hyperbolic swingby of Saturn for the trajectories represented in Tables 5-1. They are the hyperbolic semimajor axis a_h, the hyperbolic eccentricity, e_h, the declination of pericenter δ_p, and the radius of passage through the plane of the rings r_{SR}.

The radius of passage through the plane of the rings is found from the inclination of the hyperbola I_h in Table 5-1 and the other quantities in Table 5-4. In the spherical triangle of Fig. 5-1, the true anomaly of passage through the rings θ_{SR} is obtained from the equation

$$\sin(\theta_{SR}) = \frac{\sin(\delta_p)}{\sin(I_h)} \quad .$$

Then it follows that

$$r_{SR} = \frac{a_h(e_h^2 + 1)}{1 + e_h \cos(\theta_{SR})}$$

Only the short representative trajectories launched from Earth in 1977 and 1978 pass through the plane of the rings at less than 1.18 Saturn Radii (the inner boundary of the rings). It should not be inferred from this fact that passage inside the rings is possible only for spacecraft launch in 1977 and 1978. Trajectories that depart Earth in other years and pass through the plane of the rings at less than 1.18 Saturn Radii can be chosen from the tabulated data of Volume II. However, the calculation of passage distances to three significant figures from patched conic trajectory data is questionable. Even a slight alteration of Saturn's gravitational constant in the SWISTO computer program would change these distances. Recall that the purpose of this report is to present an overall view of Grand Tour and Alternate Grand Tour Missions. More refined trajectory data over smaller ranges of dates are required for a final mission selection. Trajectories for which the pericenter radius has been computed to be 1.2 Saturn radii or less should not be disregarded in a preliminary analysis.

Table 5-1

GRAND TOUR MISSIONS OF SHORT DURATION

	1976	1977	1978	1979	1980
Earth Departure Date, A.J.D.	2990	3392	3791	4189	4584
Calendar Date	31 July	6 Sept.	10 Oct.	12 Nov.	11 Dec.
C_3, km^2/sec^2	103.3	117.6	135.7	151.6	180.3
δ, deg	12.8	25.2	27.5	20.5	6.8
α, deg	34.9	70.4	109.5	144.3	177.3
Jupiter Encounter Date, A.J.D.	3530	3890	4250	4620	4975
V_∞, km/sec	10.7	12.6	14.9	16.9	19.7
r_p, Jupiter Radii	1.06	3.48	8.53	35.59	33.83
V_p, km/sec	59.4	34.8	25.4	19.7	22.2
I_h, deg	4.8	5.5	7.0	14.0	171.3
κ, deg	139.3	99.8	58.4	17.4	13.9
η, deg	129.3	115.8	99.9	82.5	69.8
Saturn Encounter Date, A.J.D.	4325	4461	4696	5059	5485
V_∞, km/sec	15.0	17.3	17.9	15.7	14.5
r_p, Saturn Radii	1.12	1.07	1.07	1.14	1.09
V_p, km/sec	37.5	39.1	39.4	37.4	37.7
I_h, deg	29.4	29.2	29.1	29.1	29.3
κ, deg	92.9	84.5	82.4	88.7	95.8
η, deg	147.8	146.6	104.1	125.7	106.9
Uranus Encounter Date, A.J.D.	5720	5665	5808	6198	6608
V_∞, km/sec	19.3	21.9	22.5	20.2	18.4
r_p, Uranus Radii	1.68	1.37	1.44	2.20	3.22
V_p, km/sec	25.4	28.8	28.7	24.8	21.9
I_h, deg	100.0	100.2	100.9	102.3	103.8
κ, deg	30.9	29.9	27.4	23.4	19.8
η, deg	59.3	58.1	58.8	62.2	66.4
Neptune Encounter Date, A.J.D.	6813	6647	6752	7206	7666
V_∞, km/sec	21.8	24.4	25.0	22.5	20.4
Total Trip Time, yrs	10.47	8.91	8.11	8.26	8.44

Table 5-2

GRAND TOUR MISSIONS OF MEDIUM DURATION

	1976	1977	1978	1979	1980
Earth Departure Date, A.J.D.	2988	3388	3786	4185	4584
Calendar Date	29 July	2 Sept.	5 Oct.	8 Nov.	11 Dec.
C_3, km^2/sec^2	84.1	91.6	102.0	116.9	138.0
δ, deg	17.3	30.0	32.2	24.1	10.3
α, deg	31.8	64.4	103.3	139.4	117.0
Jupiter Encounter Date, A.J.D.	3741	4060	4380	4704	5036
V_∞, km/sec	6.6	8.0	10.2	12.9	16.0
r_p, Jupiter Radii	1.64	9.35	23.32	79.86	60.53
V_p, km/sec	47.4	21.2	16.1	14.6	17.8
I_h, deg	6.2	7.2	9.0	17.8	170.9
κ, deg	148.5	97.7	50.8	13.7	12.0
η, deg	106.8	96.5	84.6	74.5	113.4
Saturn Encounter Date, A.J.D.	4725	4825	5040	5375	5800
V_∞, km/sec	10.2	11.1	10.9	9.9	9.8
r_p, Saturn Radii	2.79	2.63	2.68	2.72	2.47
V_p, km/sec	24.0	25.0	24.7	24.1	25.1
I_h, deg	29.6	29.3	29.3	29.3	29.4
κ, deg	87.9	84.0	85.1	90.7	94.5
η, deg	140.0	137.9	129.5	113.5	93.5
Uranus Encounter Date, A.J.D.	6433	6390	6565	6915	7280
V_∞, kn/sec	14.2	15.2	14.8	13.5	12.7
r_p, Uranus Radii	4.36	3.83	4.53	6.78	9.29
V_p, km/sec	17.5	18.7	17.9	15.8	14.5
I_h, deg	101.8	101.9	100.6	104.4	106.0
κ, deg	23.8	23.5	21.3	17.8	15.0
η, deg	66.2	65.3	66.8	70.7	75.2
Neptune Encounter Date, A.J.D.	7790	7667	7854	8287	8708
V_∞, km/sec	14.4	17.3	16.8	15.2	14.1
Total Trip Time, yrs	13.15	11.72	11.14	11.23	11.29

Table 5-3

GRAND TOUR MISSIONS OF LONG DURATION

	1976	1977	1978	1979
Earth Departure Date, A.J.D.	3005	3395	3786	4183
Calendar Date	15 Aug.	9 Sept.	31 Aug.	6 Nov.
C_3, km^2/sec^2	92.1	89.7	94.8	107.62
δ, deg	29.6	32.0	35.2	25.9
α, deg	26.2	58.6	100.7	138.3
Jupiter Encounter Date, A.J.D.	4006	4178	4450	4744
V_∞, km/sec	5.6	6.4	8.5	11.5
r_p, Jupiter Radii	2.04	16.21	37.68	103.14
V_p, km/sec	42.5	16.3	13.0	12.9
I_h, deg	11.1	8.4	10.4	18.47
κ, deg	150.2	93.9	46.9	13.4
η, deg	71.8	79.3	75.2	71.0
Saturn Encounter Date, A.J.D.	5030	5125	5325	5600
V_∞, km/sec	8.1	7.9	7.6	7.6
r_p, Saturn Radii	5.20	5.49	5.72	4.87
V_p, km/sec	17.8	17.4	0.5693	0.6076
I_h, deg	29.5	29.4	29.4	29.4
κ, deg	82.5	81.8	83.9	89.2
η, deg	131.7	128.1	118.4	103.2
Uranus Encounter Date, A.J.D.	6928	7014	7224	7444
V_∞, km/sec	11.7	11.5	10.9	10.5
r_p, Uranus Radii	8.68	9.5	12.64	15.85
V_p, km/sec	13.8	13.5	12.4	11.8
I_h, deg	103.7	104.2	105.5	106.8
κ, deg	18.4	17.4	15.1	13.2
η, deg	71.6	72.6	75.1	77.8
Neptune Encounter Date, A.J.D.	8490	8597	8878	9143
V_∞, km/sec	13.3	13.0	12.2	11.6
Total Trip Time, yrs	15.02	14.24	13.94	13.58

Table 5-4

ADDITIONAL SATURN PASSAGE PARAMETERS

	1976	1977	1978	1979	1980
a_h, Saturn Radii	2.93	2.20	2.06	2.66	3.13
e_h	1.38	1.49	1.52	1.43	1.35
δ_p, deg	15.15	14.25	14.24	15.71	17.75
r_{SR}, Saturn Radii	1.22	1.17	1.17	1.27	1.25

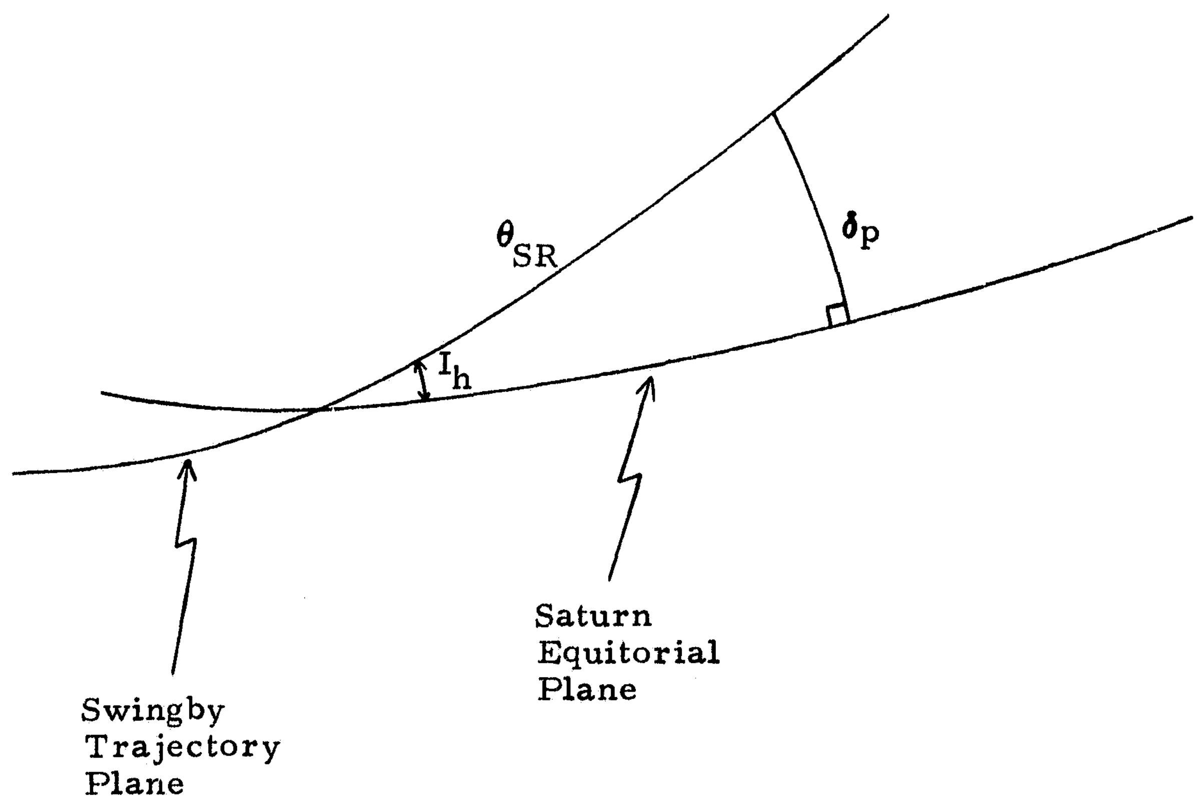


FIGURE 5-1. RELATION OF TRUE ANOMALY OF PASSAGE THROUGH SATURN'S RINGS TO THE HYPERBOLIC INCLINATION AND DECLINATION OF PERICENTER

Section 6
ENERGY COST OF DECREASING TRIP TIME

A critical factor that must be considered in planning for missions to the outer planets is trip time. For a reasonable probability of mission success, the total trip time must be less than the expected lifetime of the spacecraft's components. The upper bound on trip time will depend on the spacecraft configuration that is chosen, but it is anticipated to be approximately nine years. Any decrease of trip time increases the probability of mission success.

For a given launch energy, the trajectory that minimizes total trip time may be chosen. To obtain any shorter trip time requires an increase in launch energy. Thus, a tradeoff must be made between Earth launch energy and trip time. For an analysis of this tradeoff, consider the minimum trip time T_m as a function of Earth launch energy C_3.

An approximate $T_m(C_3)$ curve can be obtained from the Quad and Triad graphs in Section 4. In the first quadrant of these graphs, each contour represents a set of Earth-Jupiter trajectories with a specified launch energy. Note that

1. the arrival date at the final planet has a much larger range than the Earth launch date, and
2. for a fixed-Earth launch date, the arrival time at the final planet increases as the Jupiter encounter date increases.

Thus, for a specified launch energy, the minimum total trip time is approximately the total trip time of trajectory which has the earliest Jupiter encounter date. By taking the Earth-Jupiter trajectory with the earliest Jupiter encounter date (represented by the bottom point of a C_3 contour in the first quadrant) and extending it to the final planet, one obtains an approximation for $T_m(C_3)$.

Figures 6-1 and 6-2 are $T_m(C_3)$ curves for Jupiter-Uranus-Neptune and Jupiter-Saturn-Pluto missions respectively. It is evident from these figures that the rate of decrease of total trip time decreases as launch energy increases. Once the nearly horizontal portion of these curves is attained, a further increase in launch energy does not significantly reduce total trip time.

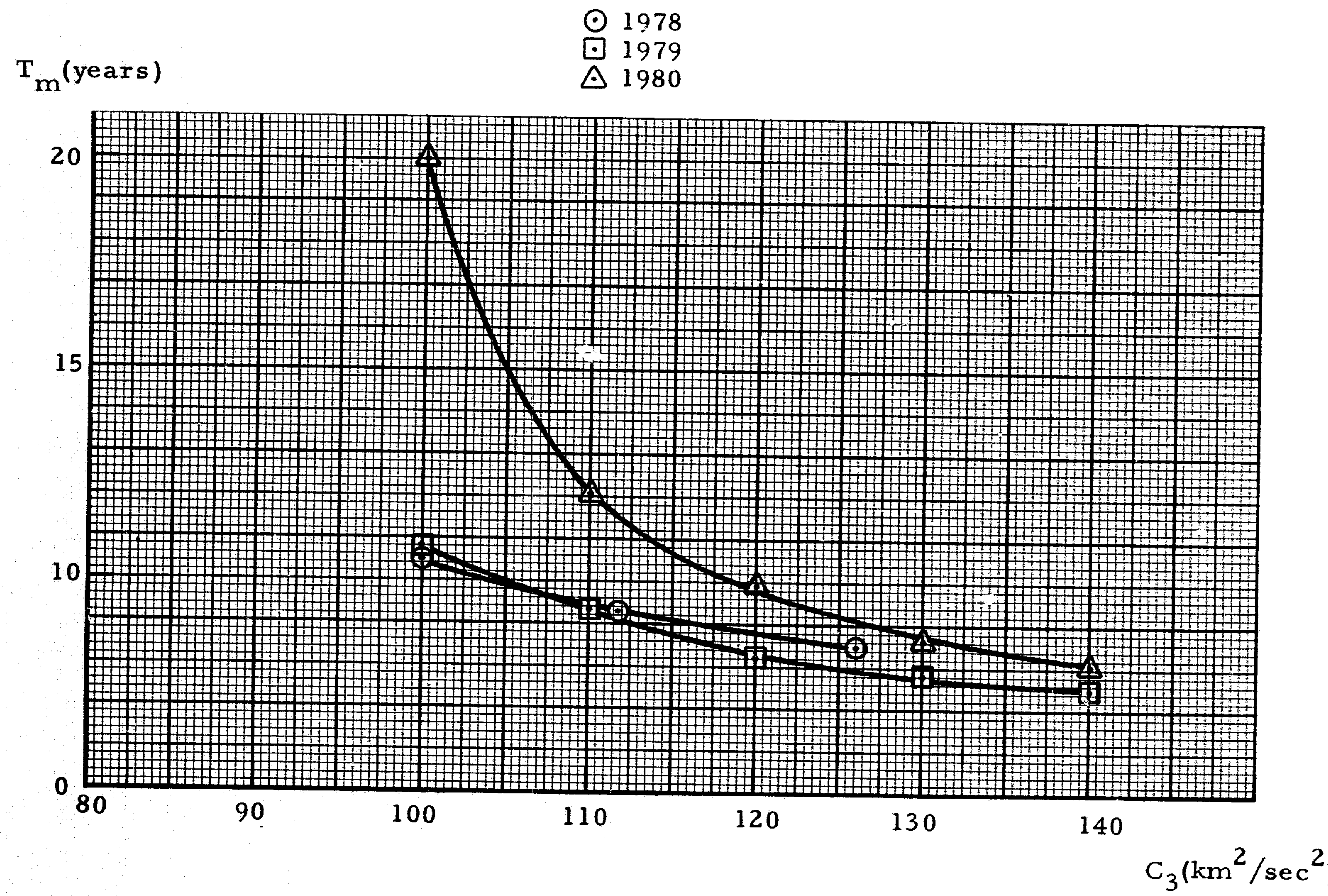


FIGURE 6-1. JUPITER-URANUS-NEPTUNE MISSIONS — MINIMUM TRIP TIME AS A FUNCTION OF C_3

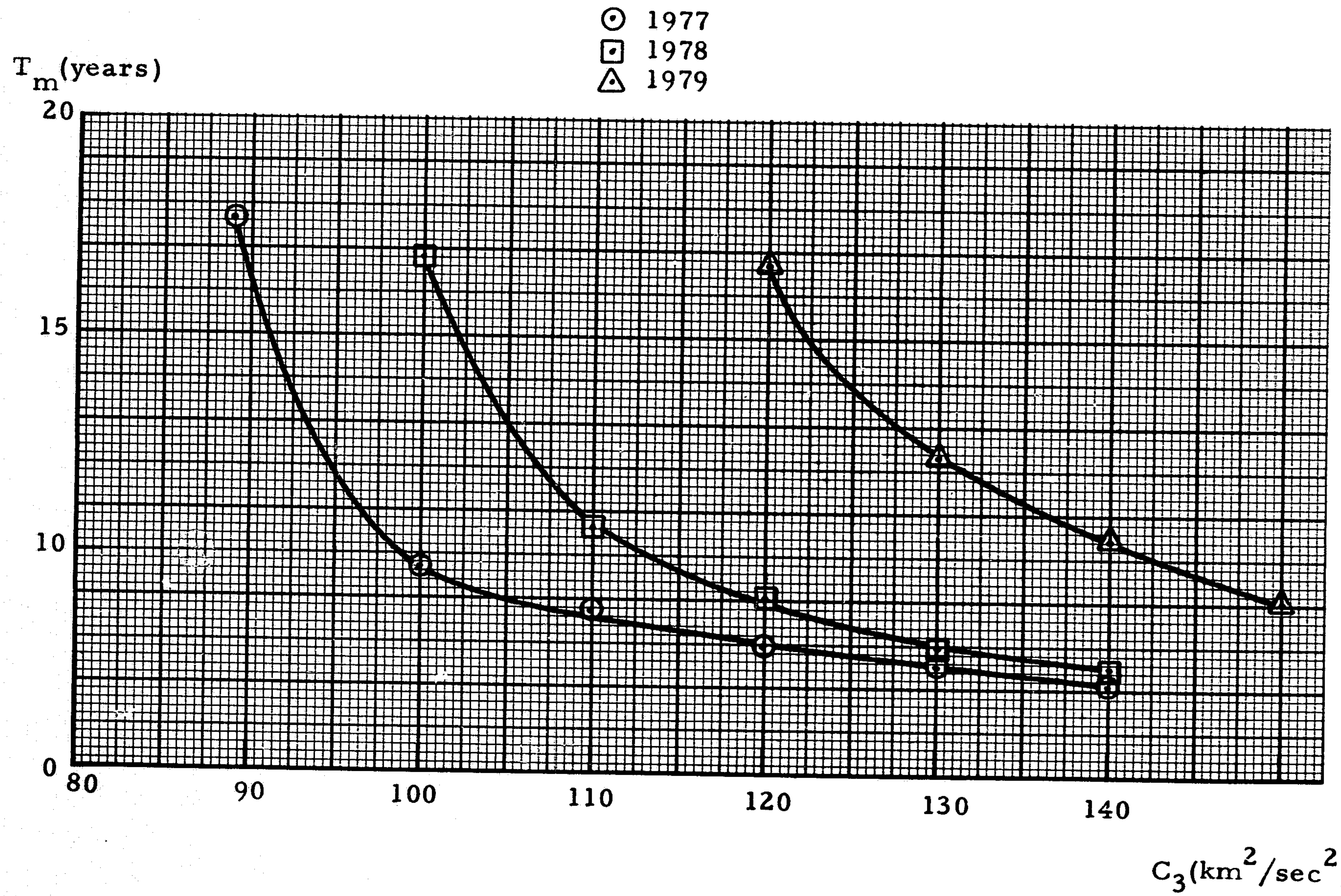


FIGURE 6-2. JUPITER-SATURN-PLUTO MISSIONS — MINIMUM TRIP TIME AS A FUNCTION OF C_3

Section 7

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