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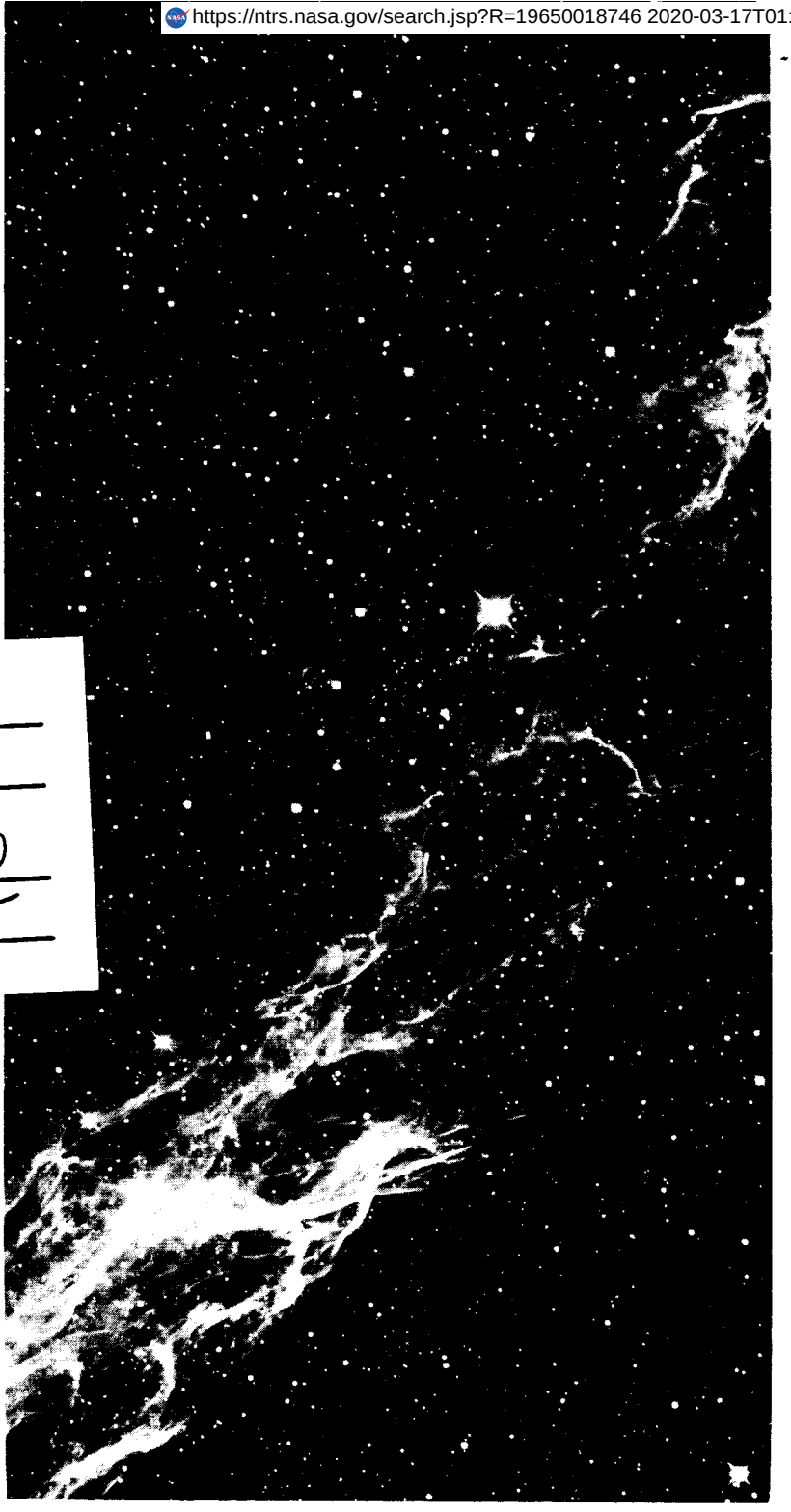

Report No. T-11

SIGHTING AND TRAJECTORY ANALYSIS FOR PERIODIC COMETS: 1975-1986

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SIGHTING AND TRAJECTORY ANALYSIS FOR PERIODIC COMETS: 1975-1986

by

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Contract No. NASr-65(06)

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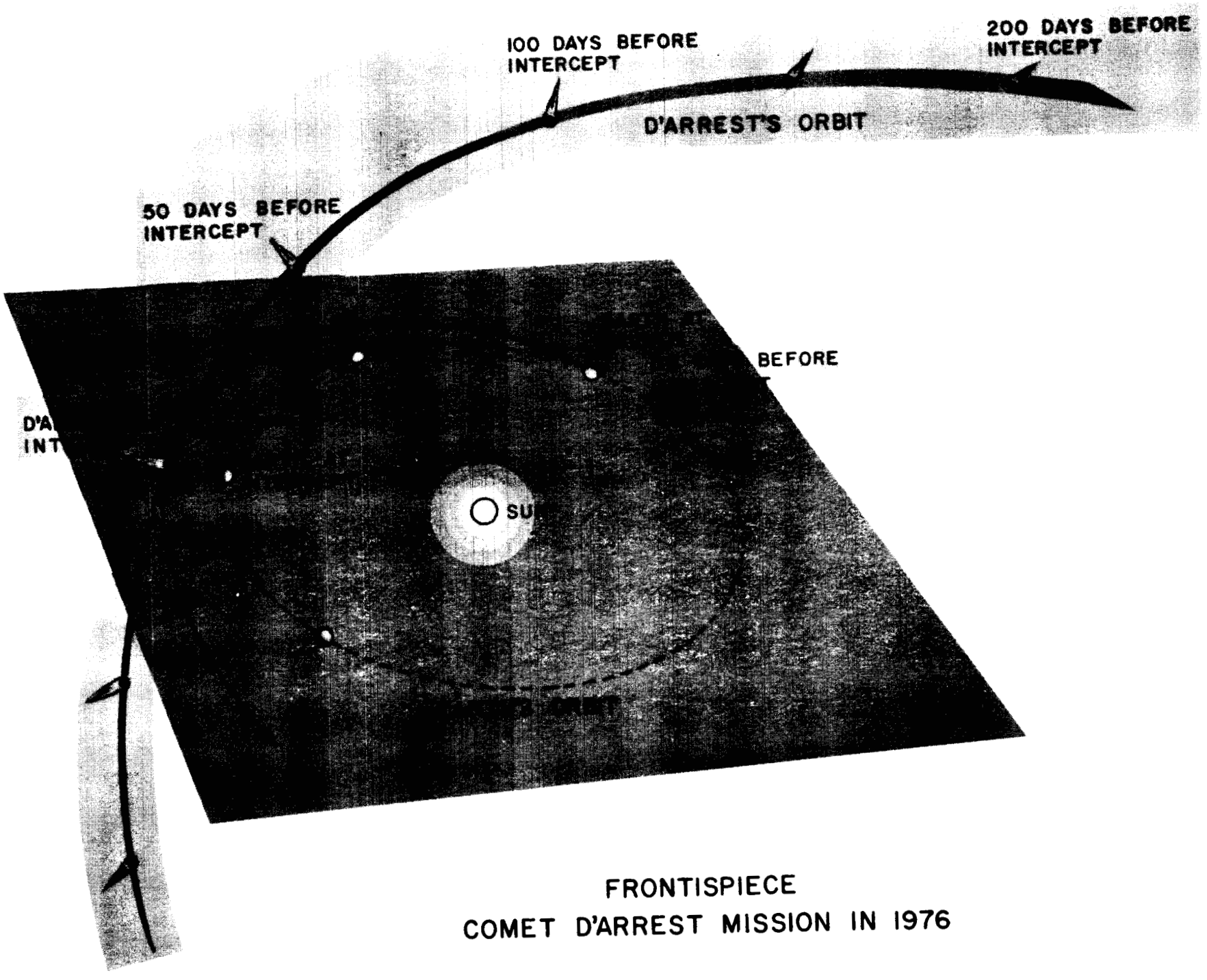
March 15, 1965

COMET D'ARREST MISSION IN 1976

Ideal Velocity	-	41,200 ft/sec
Closing Velocity	-	13 km/sec
Launch Date	-	4/21/76
Intercept Date	-	8/14/76
Perihelion Date	-	8/14/76
Communications Distance	-	0.17 AU
Spacecraft Weight	-	500 lbs.
Launch Vehicle	-	Atlas Agena



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COMET D'ARREST MISSION IN 1976

ABSTRACT

SIGHTING AND TRAJECTORY ANALYSIS
FOR PERIODIC COMETS: 1975-1986

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Possible intercept missions to 55 apparitions of 36 well known short period comets have been analyzed to delineate those of potential interest in long range planning. Detailed perturbation calculations, ballistic trajectory calculations and sighting calculations were performed for each apparition of each comet. A mission to comet D'Arrest in 1976 is, by far, our "best" mission between 1965 and 1986. The D'Arrest mission would launch 4/76 with ΔV = 41,200 ft/sec for a four month flight arriving at perihelion when the comet is 7th magnitude. Closing velocity is 13 km/sec. Up to six months tracking are available before launch. A 1970 D'Arrest apparition is available for preliminary observation, and a 1982 apparition for a follow-on flight. A mission to Halley's comet could launch in 1985 with ΔV = 43,000 ft/sec for a 7 to 10 month flight arriving, when the comet is 4th or 5th magnitude, with a closing velocity of 70 km/sec. Halley's is the bright, outstanding periodic comet.

Author

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Report No. T-11

SIGHTING AND TRAJECTORY ANALYSIS FOR PERIODIC COMETS: 1975-1986

1. SUMMARY

Possible intercept missions to 55 apparitions of 36 well known short period comets have been analyzed, to delineate those of potential interest in long range planning. This work is a direct extension of a previous ASC/IITRI Report, No. T-7 (Narin, Pierce 1964). Detailed perturbation calculations have been performed to determine the positions and 55 perihelion dates of the 36 comets moving under the influence of gravitational fields of the Sun and planets. Ballistic trajectories to the comets were then calculated to determine ideal velocity, time of flight, closing velocity and communications distance as a function of launch date. Sighting calculations (which are very approximate due to uncertainties in comet brightness) were performed to determine the expected brightness of the comets and the number of hours the comet might be visible in the night sky. The 55 apparitions were then divided into three classes:

Class I : Missions of Primary Interest (3 apparitions)

Class II : Missions of Secondary Interest (7 apparitions)

Class III: Missions of Low Interest
(45 apparitions)

In order to be considered as either Class I or II a comet had to

1) be visible and at least as bright as magnitude 12 at intercept (magnitude 12 is an approximate lower limit for spectroscopic measurements from Earth).

2) be recoverable two months before launch, that is, of brightness at least magnitude 20 and visible at least one hour per day from some latitude of Earth. (Magnitude 20 is an approximate lower limit for comet detection with current techniques.)

The most important factor in eliminating missions from Class I or II is the brightness calculation, since most periodic comets are fainter than magnitude 12. The division of the 10 Class I and II comets into 3 best and 7 secondary is clearly somewhat subjective, but is based on trajectory and sighting data and on brief considerations of the scientific data available for each specific comet. With this last comment in mind, we may list the following 3 "best" opportunities in chronological order. The ΔV values are ideal velocities for 30 day launch windows.

D'Arrest (1976) — The "best" mission between 1965 and 1986. Launch 4/76 with ΔV = 41,200 ft/sec for a four month flight arriving at perihelion when the comet is 7th magnitude. Closing velocity is 13 km/sec. Up to 6 months tracking is available before launch. There is a 1970 apparition for preliminary observation, and a 1982 apparition for a follow-on flight.

Kopff (1983)	Launch 3/83 with ΔV = 43,000 ft/sec for a 6 month flight arriving two weeks after perihelion, when the comet is 12th magnitude. Closing velocity is 8-9 km/sec; this low closing velocity is the main reason for Kopff being Class I rather than Class II, since it is possible to consider a rendezvous mission. Four or five months tracking available before launch.
Halley (1986)	Launch 7/85 with ΔV = 42,500 ft/sec for a 7 month flight arriving 6 weeks after perihelion, when the comet is 5th magnitude. Closing velocity is 70 km/sec. Up to 9 months tracking available before launch. Halley is the bright, outstanding periodic comet; the high closing velocity might complicate the mission somewhat.

2. GENERAL DISCUSSION

For long range planning purposes, it is of interest to know which comets are accessible and attractive for exploratory missions in the next twenty years. This report is the fourth in a series of seven Astro Sciences Center reports on the comets; the first two were a discussion of the scientific objectives of missions to the comets (Roberts 1964a) and a compendium of data on periodic comets (Roberts 1964b); the third (Narin and Pierce 1964) discussed perturbations, sighting and trajectories for 1965-1975 comets; the fifth report will survey comet missions (Roberts 1965); the sixth will discuss missions to new comets, and the seventh will summarize the ASC work on the comets.

Since the comets are brightest and most active near perihelion, this study considered all short period comets which have well known orbits and which have perihelion between January 1975 and May 1986 (Halley's perihelion). Table 3, page 16, shows the 36 comets considered and their 55 perihelion dates.

Because of (1) inaccuracies in the comet orbital elements, (2) inexactness in calculating the perturbing effects of the planets on comet orbits, and (3) secular (non-gravitational) accelerations of the comets, the orbits of the comets are not well enough known to consider launching to a comet without optically recovering and tracking the comet before launch. In order to predict the future positions of the comets as accurately as possible, detailed perturbation calculations must be carried out for each comet. The latest published data in the British Astronomical Association Handbooks (BAAH) or in Porter's Catalogue (Porter 1961) were used as initial data for perturbation calculations. The Lewis Research Center NBODY code for the IBM 7094 computer was used to carry out the perturbation calculation; this code calculated the positions of the comets moving under the influence of the gravitational fields of the Sun and the planets Mercury through Uranus. The reader is referred to ASC/IITRI Report T-7 for details of the perturbation calculation and for osculating orbital elements for all the comets considered. A few perturbation calculations performed subsequent to Report T-7 are included in this report as Section 7.

Once the comet's orbital elements were determined by means of the perturbation calculation, the ASC/IITRI Conic Section Trajectory system for the IBM 7094 (Pierce, Narin 1964) was used to calculate ballistic trajectories from Earth to each comet. The calculations yield ideal velocity ΔV, communications distance RC, time of flight TF, closing velocity VHP and launch and arrival dates. Flight times of up to 400 days were considered. In order to be considered interesting, a flight had to arrive at the comet within a few months of perihelion, when the comet was magnitude 12 or brighter. All of the interesting comets have ΔV requirements of less than 50,000 ft/sec. Report T-7 describes the trajectory calculations in more detail. The results are contained in Tables 1 to 3 and Figures 1 to 55.

The last major stage in the computation was sighting calculations. Since most of the short period comets are relatively dim, the problems of detecting them are often formidable. Furthermore the brightness of most comets is poorly known. The ground rules used in the study were that the comet should be visible two months before launch, at launch, and at intercept. By visible it is meant that the comet is above the horizon in the night sky for at least one hour from some latitude on Earth and at least as bright as magnitude 20. These computations were performed on the IBM 7094 using a specially written code SIGHT. Since the available data on comet brightness are very approximate some judgment was used in interpreting the calculating sighting data. The data used in the brightness calculation is shown in

Table 4.

The most important effects of the sighting calculation are to severely limit the interest in a mission if the comet is fainter than 12th magnitude (an approximate limit for spectroscopic measurement from Earth) and to raise the ΔV necessary to intercept a comet (because launch must occur after recovery of the comet). The magnitude 12 limit is placed on the comet brightness so that the data taken at the comet can be compared with simultaneous spectroscopic measurements from Earth.

As a last step an attempt was made to choose from the trajectory data, the sighting data, and ASC/IITRI studies of the scientific interest of the comets (Roberts 1964a, 1964b) which comets are most attractive for exploratory missions. Fortunately, the scientifically interesting comets are the relatively bright and active comets which tend to be easy comets to intercept. However the final synthesis of trajectory, sighting and scientific data into an ordering of comet missions is a somewhat subjective procedure.

Before interpreting the data presented in the tables a number of points should be kept in mind; these points are discussed further in the other ASC/IITRI comet reports.

1) A most critical factor in intercepting a comet is the accuracy with which the comet orbital elements are known. A miss distance of 10,000 km from the nucleus would probably occur if the comet probe does not carry on-board comet acquisition and terminal guidance capability. Since comet nucleus

diameters are typically 1-10 km, and coma diameters 20,000-2,000,000 km (Roberts 1964a) a probe without terminal acquisition and guidance will probably traverse the coma but be limited in its examination of the nucleus.

2) It would be highly desirable to make spectroscopic measurements from Earth as the spacecraft intersects the comet. This implies the comet must be of magnitude less than approximately 12 at intercept.

3) The brightness of the comets is not well known, and changes from apparition to apparition; the brightness formulas are often in error by a few magnitudes. Thus all magnitude figures given are very approximate. The typical, small diminution of comet absolute brightness from apparition to apparition, typically less than a magnitude per apparition, has been ignored.

3. RESULTS

3.1 Missions of Primary Interest (Chronological Summary Table)

Table 1 is a chronological summary table of the missions of primary interest. ΔV in the second column is the ideal velocity sufficient for launch any time within a 30 day launch window, and TF is the time of flight range for the window. Note that the launch window is determined by sighting, as well as trajectory considerations. Normally the first flight takes the longest time; thus the launch of 4/21/76 for D'Arrest has a flight time of 115 days, and arrives at perihelion. The

arrival date of a flight launched at the beginning of the launch window is given in the third column, the spacecraft to comet closing velocity VHP is also given as is the Earth to comet communications distance RC at time of intercept.

The magnitude data given in the sighting data summary, columns 4 and 5, are approximate and must be used as an indication of the brightness rather than as an exact figure. Column 4 gives the expected comet magnitude 60 days before launch, and the number of hours the comet would be above the horizon in the night sky for an observer at Earth latitudes + 25° and - 25°. Column 5 gives the corresponding data for the comet at intercept. The last column gives some general comments on the particular mission. The data used for the magnitude calculation is included as Table 4.

Of the 3 Class I opportunities in 1975-1986 the first, to D'Arrest, is very attractive since D'Arrest is a bright comet of reasonable scientific interest, for which the recovery and sighting are excellent. It would probably be possible to recover D'Arrest by 12/1/75, five months before launch; the extra three months of tracking, over the chosen minimum of two months, could greatly contribute to probable mission success. Kopff is somewhat faint; however, the low closing velocity is an asset. Halley's, of course, is the bright, outstanding periodic comet; it is well known and scientifically interesting.

3.2 Missions of Secondary Interest (Chronological Summary Table)

Table 2 is a chronological summary table of missions of secondary interest; its form is identical to that of Table 1.

3.3 All Missions (Alphabetical Summary Table)

Table 3 is a listing of all perihelia; if the comet does not attain magnitude 12 or brighter it is described as of low interest in this table; if it is magnitude 12 or brighter it is described in more detail in Tables 1 and 2.

4. CONCLUSIONS

The first conclusion is that D'Arrest in 1976, is an outstanding, attractive opportunity. It appears to be the best mission between 1965 and 1986. Halley's comet in 1986 is also of great interest, although the mission might be complicated by the high closing velocity. A mission to Kopff in 1983 is interesting because the relatively low closing velocity of 8 to 9 km/sec allows a rendezvous mission to be considered.

A second conclusion is that, to interpret the trajectory and sighting data, careful consideration must be given to each apparition of each comet on an individual basis; furthermore the possible scientific value of the missions can and should be a strong influence on the final assessment of any particular mission priority.

There are two possible extensions of this study:

1) Inclusion of other periodic comets.
2) Inclusion of new comets.

The inclusion of other periodic comets is difficult, since this study attempted to include all the well known comets; the uncertainties in orbital elements and brightness for other periodic comets are usually so great as to preclude detailed perturbation, sighting and trajectory calculations.

The possible inclusion of new comets is a somewhat different study. The new comets are particularly interesting in that they are often bright and active; however, since they cannot be predicted in advance any mission to a new comet implies a pre-built spacecraft and vehicle, on the shelf, waiting for discovery of the comet. We are now surveying the last few decades to ascertain if there would have been any feasible missions to new comets.

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6. NOMENCLATURE

a	Semi-major axis of comet orbit
e	Eccentricity of comet orbit
i	Inclination of comet orbit
q	Perihelion distance of comet orbit
RC	The communications distance, or distance between the Earth and the target at time of arrival of the spacecraft at the target.
T	Period of comet orbit
TF	Time of flight for a mission
T_p	Perihelion date of comet
VHL	Launch hyperbolic excess speed: the difference between the spacecraft's velocity in heliocentric coordinates after Earth escape and the Earth's velocity in its orbit at the same time.
VHP	Closing velocity (hyperbolic excess speed at the target): spacecraft to target velocity difference at arrival time.
ΔV	Ideal velocity: the total velocity increment which must be given to a spacecraft leaving Earth: $$\Delta V = \sqrt{(36,178)^2 + (VHL)^2} + 4000 \text{ ft/sec}$$ Here 36,178 ft/sec is the characteristic velocity for Earth escape, launching from Cape Kennedy, and 4000 ft/sec is a correction for gravitational and frictional losses during launch.
w	Argument of perihelion of comet orbit
Ω	Longitude of the ascending node of comet orbit

7. OSCULATING ORBITAL ELEMENTS

The orbital elements given in Tables 5, 6 and 7 are recalculations of those in ASC/IITRI Report No. T-7 for D'Arrest, Harrington-Abell and Tuttle using more recent starting data (Marsden 1965); the changes in orbital elements are not large enough to affect any of the results reported in Report No. T-7.

8. FIGURES

Six parameter plots are included, as Figures 1 to 55, for each apparition considered. The six parameters ΔV, VHP, Comet Brightness, RC, TF and Arrival Time are all plotted against the launch date. For example on Figure 1, for Comet Arend, the minimum energy launch on 4/11/82 would have

ΔV = 43,000 ft/sec

VHP = 14 km/sec

Brightness = 23rd magnitude

RC = 3 AU

TF = 300 days

Arrival Time = 105 days before perihelion.

Since perihelion occurs on 5/26/83, from the magnitude plot it can be seen that the comet would be about 19th magnitude at intercept. The dashed line is used for brightness when the comet is not visible for one hour in the night sky; thus at intercept (100 days before perihelion) the comet would not be easily visible. (The divisions on the abscissa are 100 days apart.)

Table 1

CHRONOLOGICAL SUMMARY TABLE OF OPPORTUNITIES OF PRIMARY INTEREST

Comet Name Perihelion Date	Trajectory Data Summary: Launch 1st date, ΔV (30 day window), TF	Trajectory Data Summary: Intercept 1st date, VHP, RC	Sighting Data Summary: Launch - 60 days Magnitude, visible hrs at ± 25° latitude	Sighting Data Summary: Intercept Magnitude, visible hrs at ± 25° latitude	Scientific Data and General Comments
D'Arrest 8/14/76	4/21/76; ΔV = 41,200 ft/sec; TF = 85-115	0 days after perihelion; VHP = 13.0 km/sec; RC = 0.18	Mag 18; visible 4.8 hrs at +25°; 4.4 hrs at -25°	Mag 7; visible at 7.5 hrs at 25°; 9.8 hrs at -25°	A very excellent mission; probably the best, between 1965 and 1986, in almost every respect.
Kopff 8/18/83	2/26/83; ΔV = 43,000 ft/sec; TF = 175-190	15 days; VHP = 8.0-9.0; RC = 1.0	Mag 17; visible 3.54 hrs at +25°; 2.36 hrs at -25°	Mag 12; visible 4.56 hrs at +25°; 6.55 hrs at -25°	Very good recovery is an asset; greater brightness is desirable.
Halley 1/8/86	1/85; ΔV = 43,000 ft/sec; TF = 300; of 7/85; ΔV = 42,500 ft/sec; TF = 210	50 days before; VHP = 65; RC = 0.5 50 days after; VHP = 69; RC = 1.25	Mag 19; visible 8 hrs at +25°; 6 hrs at -25° Mag 16; poor vis.	Mag 4; visible 6 hrs at +25°; 4 hrs at -25° Mag 5; visible 2 hrs at +25°; 3 hrs at -25°	The bright, outstanding comet; however, the extremely high VHP imposes problems for a mission.

Table 2

CHRONOLOGICAL SUMMARY TABLE OF OPPORTUNITIES OF SECONDARY INTEREST

Comet Name Perihelion Date	Trajectory Data Summary: Launch 1st date, ΔV (30 day window), TF	Trajectory Data Summary: Intercept 1st date, VHP, RC	Sighting Data Summary: Launch - 60 days magnitude, visible hrs at ± 25° latitude	Sighting Data Summary: Intercept magnitude, visible hrs at ± 25° latitude	Scientific Data and General Comments
Grigg-Skjellerup 4/9/77	1/2/77; ΔV = 46,000 ft/sec; TF = 70-100	0 days; VHP = 15.0; RC = 0.22	Mag 20; visible 5.04 hrs at +25°; 4.26 hrs at -25°	Mag 11; visible 3.00 hrs at +25°; 5.15 hrs at -25°	A good mission although greater brightness is desirable.
Encke 12/6/80	8/19/80; ΔV = 53,000 ft/sec; TF = 60-80 days	30 days before perihelion; VHP = 21-23; RC = 4-8	Mag 20; visible 2.50 hrs at +25°; 3.09 hrs at -25°	Mag 7; visible 2.88 hrs at +25°; 0 hrs at -25°	High energy, high closing velocity & marginal recovery place this bright comet in Class II.
Tuttle 12/13/80	5/21/80; ΔV = 45,700 ft/sec; TF = 160-190	20 days before; VHP = 34; RC = 0.54	Mag 20; visible 0 hrs at +25°; 2.04 hrs at -25°	Mag 9; visible 2.28 hrs at +25°; 4.92 hrs at -25°	The high VHP is a problem.
Grigg-Skjellerup 5/13/82	1/17/82; ΔV = 45,500 ft/sec; TF = 105-130	10 days; VHP = 18.0; RC = 0.33	Mag 20; visible 6.66 hrs at +25°; 5.63 hrs at -25°	Mag 11; visible 7.3 hrs at +25°; 6.34 hrs at -25°	A good mission, although greater brightness is desirable.
D'Arrest 10/13/82	2/17/82; ΔV = 44,000 ft/sec; TF = 210-240	5 days after; VHP = 12.0-15.0; RC = 1.25	Mag 20; visible 2.95 Hrs at +25°; 1.20 hrs at -25°	Mag 12; visible 3.05 hrs at +25°; 4.00 hrs at -25°	This apparition of D'Arrest could provide data subsequent to the 1976 mission.

Table 2 (Cont'd)

Comet Name Perihelion Date	Trajectory Data Summary: Launch 1st date, ΔV (30 day window), TF	Trajectory Data Summary: Intercept 1st date, VHP, RC	Sighting Data Summary: Launch - 60 days magnitude, visible hrs at ± 25° latitude	Sighting Data Summary: Intercept magnitude, visible hrs at ± 25° latitude	Scientific Data and General Comments
Encke 3/27/84	10/22/83; ΔV = 52,000 ft/sec; TF = 185-200	38 days after; VHP = 27.0; RC = .85	Mag 20; visible 7.87 hrs at +25°; 7.74 hrs at -25°	Mag 11; visible 1.17 hrs at +25°; 3.48 hrs at -25°	This apparition of Encke is not quite as good as the 1980 apparition.
Giacobini-Zinner 9/4/85	4/24/85; ΔV = 48,500 ft/sec; TF = 155-170	8 days after; VHP = 21.0; RC = 0.50	Mag 20; visible 3.28 hrs at +25°; 2.60 hrs at -25°	Mag 12; visible 5.16 hrs at +25°; 5.87 hrs at -25°	A reasonably good opportunity.

Table 3

ALPHABETICAL SUMMARY TABLE OF ALL COMET PERIHELIA

Comet Name Perihelion Date	Mission Interest	Comments
Arend 5/26/83	Low	Faint (Mag $\sim$19), poor recovery, $\Delta V \sim$ 43,000 ft/sec
Arend-Rigaux 1/26/78	Low	Somewhat faint (Mag $\sim$14), late recovery, possible ΔV = 42,000 ft/sec flight
11/22/84	Low	Somewhat faint (Mag $\sim$14), late recovery, $\Delta V \sim$ 55,000 ft/sec
Ashbrook-Jackson 8/18/78	Low	Faint (Mag $\sim$16), short launch window, $\Delta V \sim$ 53,000 ft/sec
1/22/86	Low	Faint (Mag $\sim$16), short launch window, $\Delta V \sim$ 45,000 ft/sec
Borrelly 2/18/81	Low	Somewhat faint (Mag $\sim$13), otherwise a reasonably attractive apparition
Brooks 2 11/26/80	Low	Somewhat faint (Mag $\sim$14), fair recovery for ΔV = 45,000 ft/sec launch window
Comas Sola 9/26/78	Low	Somewhat faint (Mag $\sim$14), poor recovery for launch window, $\Delta V \sim$ 60,000 ft/sec after recovery

Table 3 (Cont'd)

Comet Name Perihelion Date	Mission Interest	Comments
Daniel		
7/7/78	Low	Faint (Mag ~17), $\Delta V \sim 70{,}000$ ft/sec after recovery
8/2/85	Low	Faint (Mag ~16), $\Delta V \sim 70{,}000$ ft/sec after recovery
D'Arrest		
8/18/76	Primary	A very attractive opportunity; see Table 1
10/13/82	Secondary	See Table 2
Encke		
8/16/77	Low	Very poor sighting
12/6/80	Secondary	See Table 2
3/27/84	Secondary	See Table 2
Faye		
2/27/77	Low	Faint (Mag ~15), $\Delta V \sim 50{,}000$ ft/sec after recovery
7/9/84	Low	Faint (Mag ~15), poor recovery, poor sighting, $\Delta V \sim 60{,}000$ ft/sec after recovery
Finlay		
6/26/81	Low	Somewhat faint (Mag ~13), late recovery, $\Delta V \sim 55{,}000$ ft/sec after recovery and rapidly increasing
Forbes		
9/24/80	Low	Faint (Mag ~15), late recovery, $\Delta V \sim 45{,}000$ ft/sec

Table 3 (Cont'd)

Comet Name Perihelion Date	Mission Interest	Comments
Giacobini-Zinner 2/11/79	Low	Somewhat faint (Mag $\sim$14), $\Delta V \sim$ 60,000 ft/sec after recovery and rapidly increasing
9/4/85	Secondary	See Table 2
Grigg-Skjellerup 4/9/77	Secondary	See Table 2
5/13/82	Secondary	See Table 2
Halley 1/8/86	Primary	See Table 1
Harrington 12/24/80	Low	Faint (Mag $\sim$16), poor recovery, $\Delta V \sim$ 50,000 ft/sec with late arrival
Harrington-Abell 4/18/76	Low	Very faint (Mag $\sim$20), very high energy shots, poor arrival time
1/1/86	Low	Very faint (Mag $\sim$18), poor arrival time for low energy shots
Honda-Mrkos-Pajdusakova 4/15/80	Low	Very faint (Mag $\sim$20), or not visible in night sky
5/24/85	Low	Very faint (Mag $\sim$20), or not visible in night sky
Johnson 1/1/77	Low	Faint (Mag $\sim$15), late arrival, $\Delta V \sim$ 45,000 ft/sec
11/26/83	Low	Faint (Mag $\sim$15), late arrival, $\Delta V \sim$ 48,000 ft/sec

Table 3 (Cont'd)

Comet Name Perihelion Date	Mission Interest	Comments
Kopff 3/14/77	Low	Somewhat faint (Mag$\sim$13) at intercept, long flights with difficult recovery and short launch window
8/18/83	Primary	See Table 1
Neujmin 1 10/8/84	Low	Somewhat faint (Mag$\sim$14), at perihelion, but recoverable with $\Delta V \sim$ 42,000 ft/sec
Neujmin 3 12/8/82	Low	Faint (Mag$\sim$17), poor recovery, short launch window after recovery
Perrine-Mrkos 5/16/82	Low	Late recovery gives short launch window; Mag$\sim$16 when visible in night sky
Pons-Winnecke 11/24/76	Low	$\Delta V \sim$ 70,000 ft/sec after recovery; Mag$\sim$18 when visible
4/2/83	Low	Somewhat faint (Mag$\sim$14); late recovery forces ΔV 60-70,000 ft/sec
Reinmuth 1 10/28/80	Low	Faint (Mag$\sim$16) with late recovery forces, $\Delta V \sim$ 70,000 ft/sec
Reinmuth 2 1/29/81	Low	Faint (Mag$\sim$15) and in conjunction at perihelion, fair recovery with $\Delta V \sim$ 50,000 ft/sec after recovery

Table 3 (Cont'd)

Comet Name Perihelion Date	Mission Interest	Comments
Schaumasse		
9/3/76	Low	Somewhat faint (Mag ~13) and in conjunction, $\Delta V \sim 60{,}000$ ft/sec
12/4/84	Low	Reasonably bright (Mag ~12) at intercept; late recovery produces short launch window, with ΔV 58,000 ft/sec
Schwassmann-Wachmann 2		
3/14/81	Low	Somewhat faint (Mag ~14), recovery o.k., comet, $\Delta V \sim$ 45,000 ft/sec
Tempel 2		
2/19/78	Low	Somewhat faint (Mag ~14) and in conjunction with the Sun. $\Delta V \sim$ 60,000 ft/sec, after recovery
5/30/83	Low	Somewhat faint (Mag ~13), but $\Delta V \sim$ 60,000 ft/sec with short launch window after recovery
Tuttle		
12/13/80	Secondary	See Table 2
Tuttle-Giacobini-Kresak		
1/15/79	Low	$\Delta V \sim$ 65,000 ft/sec after recovery, Mag ~13
8/31/84	Low	$\Delta V \sim$ 55,000 ft/sec after recovery and rapidly rising; poor timing gives late arrival; Mag ~17 when in night sky
Vaisala		
8/1/82	Low	Very faint (Mag ~18) and in conjunction at perihelion; possible fair recovery

Table 3 (Cont'd)

Comet Name Perihelion Date	Mission Interest	Comments
Whipple 3/28/78	Low	Faint (Mag$\sim$16), ΔV = 46,000 ft/sec, good recovery
Wirtanen 5/26/80	Low	Faint (Mag$\sim$17) and in conjunction at perihelion
Wolf-Harrington 3/14/78	Low	Faint (Mag$\sim$15), $\Delta V \sim$ 42,000 ft/sec, marginal recovery forces ΔV up
9/21/84	Low	Faint (Mag$\sim$15), $\Delta V \sim$ 70,000 ft/sec after recovery
Wolf 1/25/76	Low	Very faint (Mag$\sim$18) and in conjunction at perihelion
5/31/84	Low	Very faint (Mag$\sim$18), and in conjunction at perihelion

Table 4

PARAMETERS USED IN THE MAGNITUDE EQUATION

$$M = M_o + A \log_{10} r + 5 \log_{10} \Delta$$

M = Magnitude
M_o = Absolute magnitude of comet
r = Comet-Sun distance AU
Δ = Earth-comet distance AU
A,5 = Empirical coefficients
A = 15 unless noted otherwise

Comet	M_o	Comet	M_o	Comet	M_o
Arend	11.5	Finlay	11.5	Perrine-Mrkos	9.0
Arend-Rigaux	12	Forbes	11.3	Pons-Winnecke	12.5
Ashbrook-Jackson*	11.5	Giacobini-Zinner	11.5	Reinmuth 1	10.6
Borrelly	10	Grigg-Skjellerup	13.4	Schaumasse	10
Brooks 2	10	Harrington-Abell	12	Schwassmann-Wachmann 2	8.0
Comas Sola	8.5	Halley	4.6	Tempel 2	10.5
Daniel	11.5	Honda-Mrkos-Pajdusakova	14.1	Tuttle	9.0
D'Arrest	9.5	Johnson	8.5	Tuttle-Giacobini Kresak	11.7
Encke	11.5	Kopff	8.5	Whipple *	10.5
Faye*	11.1	Neujmin 3	10	Wolf-Harrington	10.8

* A in these cases equals 10.

Table 5

OSCULATING ORBITAL ELEMENTS FOR COMET D'ARREST

Calendar	Julian	a (AU)	e	i (deg)	Ω (deg)	w (deg)	T_p (Next Perihelion)
10/18/63	2,438,320.5	3.544212	0.613599	18.0790	143.6059	174.5130	10/22/63
12/7/63	38,370.5	3.544684	0.613650	18.0787	143.6056	174.5145	6/25/70
12/26/65	39,120.5	3.537471	0.614365	18.1122	143.4777	174.4333	6/18/70
3/21/67	39,570.5	3.528678	0.617589	18.2389	143.3907	174.3400	6/10/70
8/18/67	39,720.5	3.520392	0.621721	18.3597	143.3878	174.3104	6/4/70
11/26/67	39,820.5	3.506065	0.628811	18.4737	143.4188	174.3912	5/28/70
3/5/68	39,920.5	3.463869	0.645872	18.2828	143.2957	175.2839	5/16/70
4/24/68	39,970.5	3.435021	0.653942	17.8128	142.9228	176.3351	5/13/70
8/2/68	40,070.5	3.407926	0.656966	17.1011	142.1604	177.7766	5/15/70
5/14/70	40,720.5	3.388418	0.654839	16.7439	141.4849	178.7666	5/18.4445/70
7/3/70	40,770.5	3.388658	0.654864	16.7438	141.4847	178.7672	8/12/76
6/2/72	41,470.5	3.388685	0.655270	16.7532	141.4566	178.7738	8/13/76
5/3/74	42,170.5	3.388018	0.655622	16.7634	141.4514	178.8074	8/13/76
7/11/76	42,970.5	3.385981	0.655347	16.7574	141.4297	178.8556	8/13.8250/76
8/30/76	43,020.5	3.386185	0.655370	16.7578	141.4287	178.8656	11/6/82
10/4/77	43,420.5	3.387681	0.656131	16.7871	141.2802	178.9701	11/8/82
12/28/78	43,870.5	3.367824	0.663351	17.3669	140.5491	179.1883	10/23/82
5/27/79	44,020.5	3.339819	0.673267	18.9501	139.8360	179.1077	9/23/82
9/4/79	44,120.5	3.365045	0.658585	20.7025	139.5285	177.8645	8/31/82
6/30/80	44,420.5	3.437620	0.627257	19.8596	139.2930	176.8240	9/15/82
8/4/81	44,820.5	3.447686	0.623069	19.6125	138.9825	176.8475	9/17/82
9/8/82	45,220.5	3.445350	0.622499	19.5922	138.8917	176.9296	9/17.7594/82
10/28/82	45,270.5	3.445504	0.622516	19.5921	138.8916	176.9309	2/8/89
9/27/84	45,970.5	3.446861	0.622845	19.5998	138.8662	176.9647	2/10/89
8/28/86	46,670.5	3.447107	0.622850	19.6033	138.8615	177.0094	2/11/89
12/25/88	47,520.5	3.446585	0.622337	19.5909	138.8334	177.0286	2/11.8674/89
2/13/89	47,570.5	3.446358	0.622312	19.5911	138.8331	177.0293	7/7/95

Table 6

OSCULATING ORBITAL ELEMENTS FOR COMET HARRINGTON-ABELL

Epoch		a	e	i	Ω	w	T_p
Calendar	Julian	(AU)		(deg)	(deg)	(deg)	(Next Perihelion)
2/25/62	2,437,720.5	3.736060	0.522337	16.8151	145.9633	338.2217	5/16/69
8/13/64	38,620.5	3.732644	0.522732	16.8193	145.9364	338.1462	5/12/69
1/30/67	39,520.5	3.730361	0.523480	16.8377	145.9082	338.2109	5/12/69
4/9/69	40,320.5	3.726973	0.523282	16.8373	145.9037	338.2909	5/12.5931/69
5/29/69	40,370.5	3.727075	0.523295	16.8373	145.9037	338.2922	7/22/76
7/22/72	41,520.5	3.715467	0.526131	16.9060	145.5703	338.2036	7/10/76
8/26/73	41,920.5	3.699910	0.533258	17.2011	145.2887	338.3019	6/28/76
1/23/74	42,070.5	3.672090	0.550153	17.9094	145.1639	338.5126	6/7/76
3/14/74	42,120.5	3.628190	0.583244	18.9347	145.2593	338.8823	5/3/76
3/24/74	42,130.5	3.604668	0.603453	19.2856	145.3169	339.1814	4/14/76
4/3/74	42,140.5	3.563406	0.642849	19.2946	145.3163	339.9949	3/8/76
4/13/74	42,150.5	3.497676	0.721230	14.9030	144.0374	343.2659	1/2/76
4/19/74	42,156.5	3.492349	0.748623	4.9419	132.0926	355.7183	12/10/75
4/22/74	42,159.5	3.512002	0.737800	1.5500	47.2185	79.9189	12/17/75
4/23/74	42,161.0	3.524153	0.728733	2.7037	3.9602	122.7256	12/23/75
4/28/74	42,165.5	3.558805	0.699293	5.9039	344.8554	140.5308	1/14/76
5/3/74	42,170.5	3.587248	0.672712	7.4559	341.7702	142.5765	2/3/76
4/2/76	42,870.5	3.641293	0.577582	8.0363	340.4094	141.2156	4/17.9517/76
5/22/76	42,920.5	3.641435	0.577598	8.0363	340.4095	141.2169	3/31/83
2/16/79	43,920.5	3.645239	0.577881	8.0375	340.3496	141.3445	4/4/83
11/12/81	44,920.5	3.646618	0.577096	8.0347	340.3494	141.3646	4/5/83
3/27/83	45,420.5	3.646134	0.576872	8.0326	340.3391	141.3607	4/6.0067/83
5/16/83	45,470.5	3.645858	0.576840	8.0326	340.3388	141.3622	3/22/90
4/15/85	46,170.5	3.657442	0.575255	8.0380	340.0340	141.9734	4/3/90

Table 7

OSCULATING ORBITAL ELEMENTS FOR COMET TUTTLE

Epoch		a	e	i	Ω	w	T_p
Calendar	Julian	(AU)		(deg)	(deg)	(deg)	(Next Perihelion)
11/13/39	2,429,580.5	5.699676	0.820593	54.6509	269.8432	206.9578	6/19/53
6/20/42	30,530.5	5.706749	0.820915	54.6851	269.8291	206.9804	6/29/53
3/16/45	31,530.5	5.711928	0.820809	54.5808	269.7949	207.0472	7/7/53
12/11/47	32,530.5	5.714854	0.820043	54.4509	269.7186	207.0703	7/7/53
9/6/50	33,530.5	5.723700	0.820063	54.4493	269.7202	206.9793	7/4/53
6/2/53	34,530.5	5.735794	0.820558	54.4682	269.7506	206.9285	7/3.9747/53
7/22/53	34,580.5	5.734886	0.820529	54.4684	269.7506	206.9277	3/29/67
2/27/56	35,530.5	5.745268	0.820652	54.4447	269.7509	206.9839	4/12/67
11/23/58	36,530.5	5.745029	0.820457	54.3503	269.7253	206.9948	4/10/67
8/19/61	37,530.5	5.744122	0.820756	54.2876	269.6887	206.9252	4/2/67
5/15/64	38,530.5	5.746662	0.821376	54.3588	269.7664	206.8534	3/30/67
2/9/67	39,531.0	5.743164	0.821883	54.3762	269.7921	206.9140	3/30.4969/67
3/31/67	39,581.0	5.743525	0.821894	54.3759	269.7921	206.9138	1/3/81
12/25/69	40,581.0	5.741709	0.821568	54.3257	269.7996	206.9348	12/31/80
9/20/72	41,581.0	5.735789	0.821199	54.2996	269.7954	206.8755	12/20/80
6/17/75	42,581.0	5.734117	0.821490	54.4029	269.8653	206.7741	12/14/80
3/2/78	43,570.1	5.727934	0.822452	54.4842	269.9406	206.8010	12/13/80
11/26/80	44,570.1	5.720489	0.822565	54.4639	269.8862	206.8946	12/13.4853/80
1/15/81	44,620.1	5.720065	0.822552	54.4639	269.8861	206.8955	8/19/94
12/16/82	45,320.1	5.707767	0.822278	54.5056	269.8721	206.8542	8/3/94
12/1/83	45,670.1	5.696485	0.822225	54.5661	269.8747	206.7721	7/18/94
11/15/84	46,020.1	5.687826	0.822093	54.5643	269.8738	206.7003	7/5/94
3/15/87	46,870.1	5.682241	0.822345	54.6647	269.9208	206.6012	6/26/94

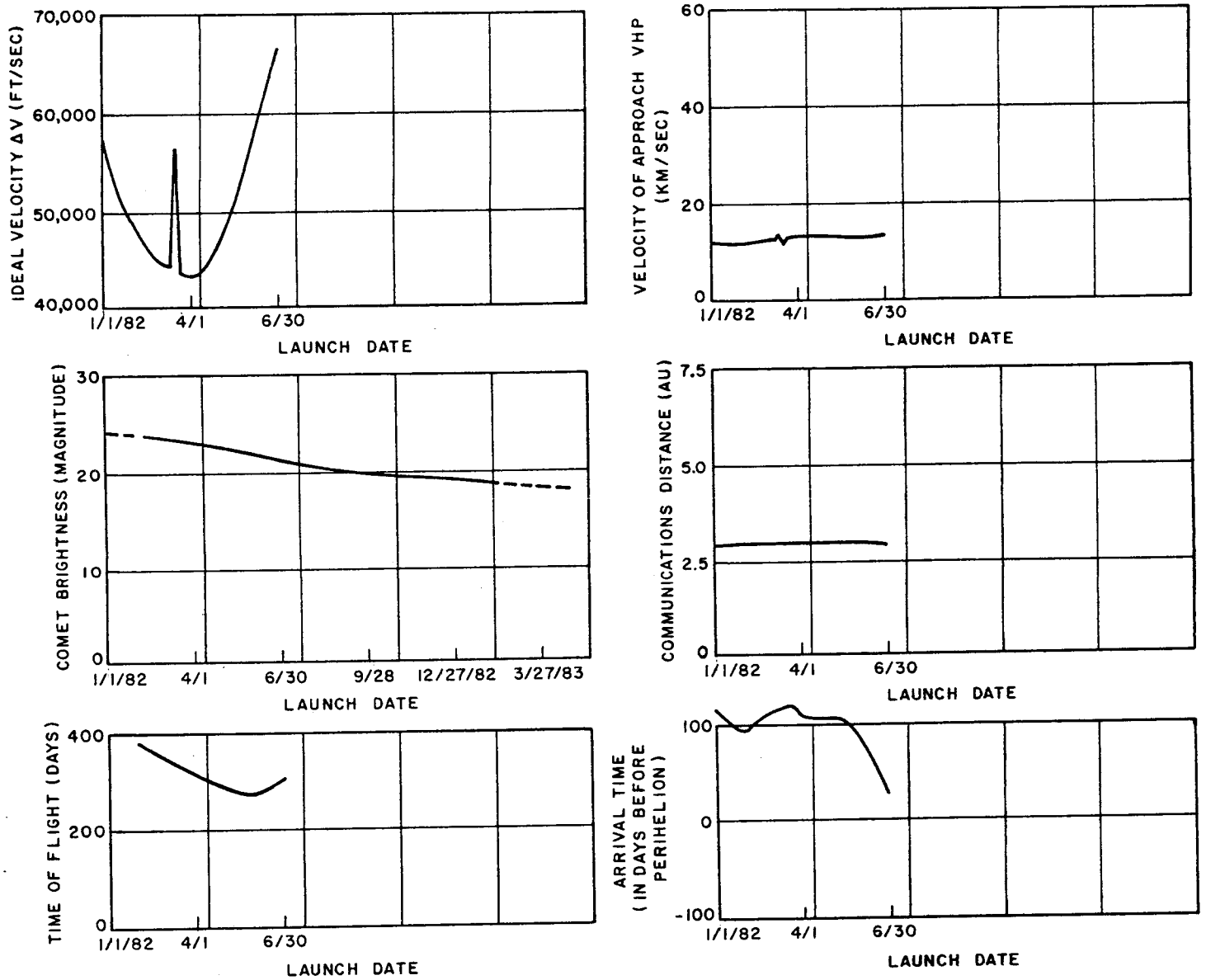

Figure 1 SIX PARAMETER PLOT FOR COMET AREND, PERIHELION DATE: 5/26/83

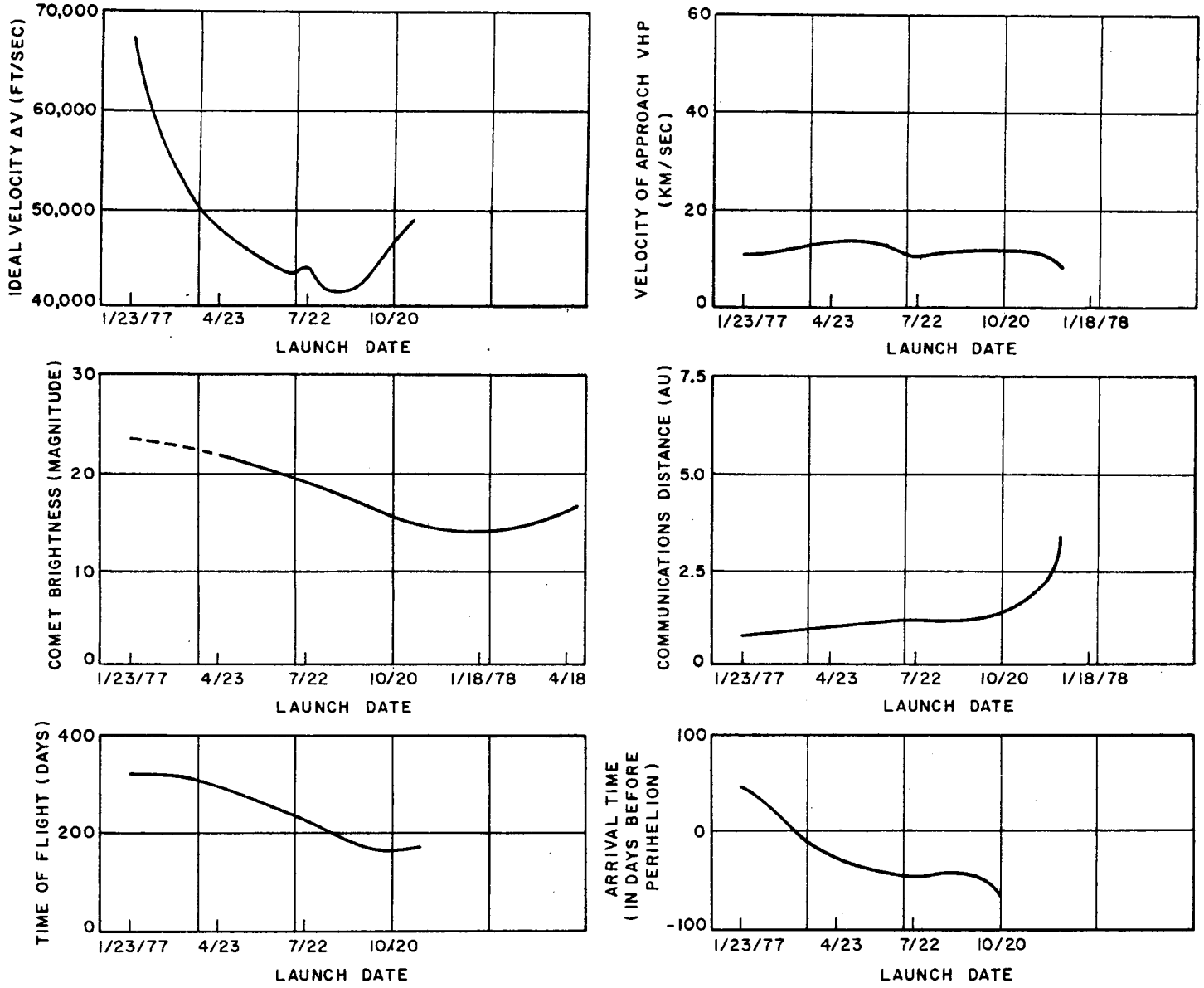

Figure 2 SIX PARAMETER PLOT FOR COMET AREND-RIGAUX, PERIHELION DATE: 1/26/78

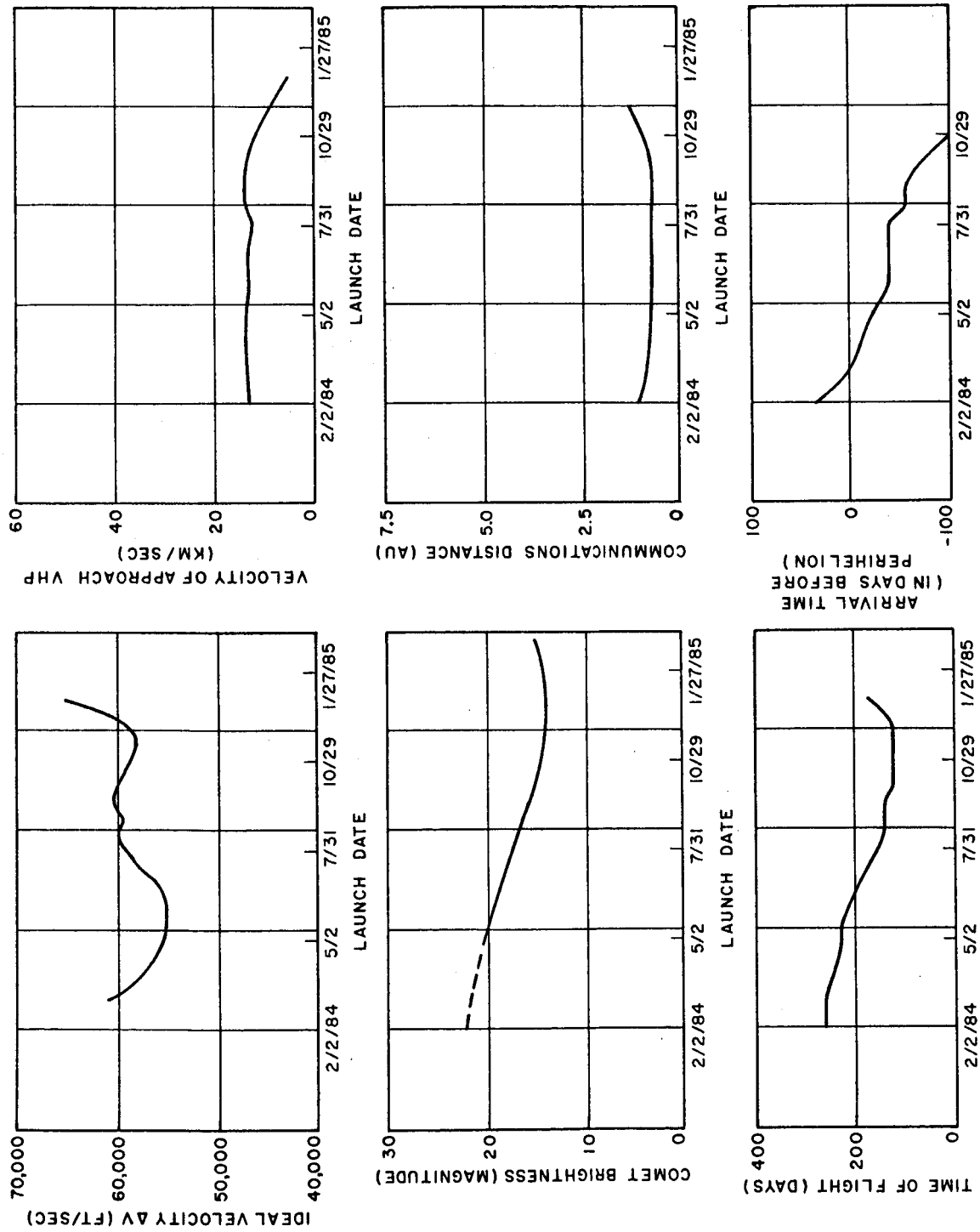

Figure 3 SIX PARAMETER PLOT FOR COMET AREND-RIGAUX, PERIHELION DATE: 11/22/84

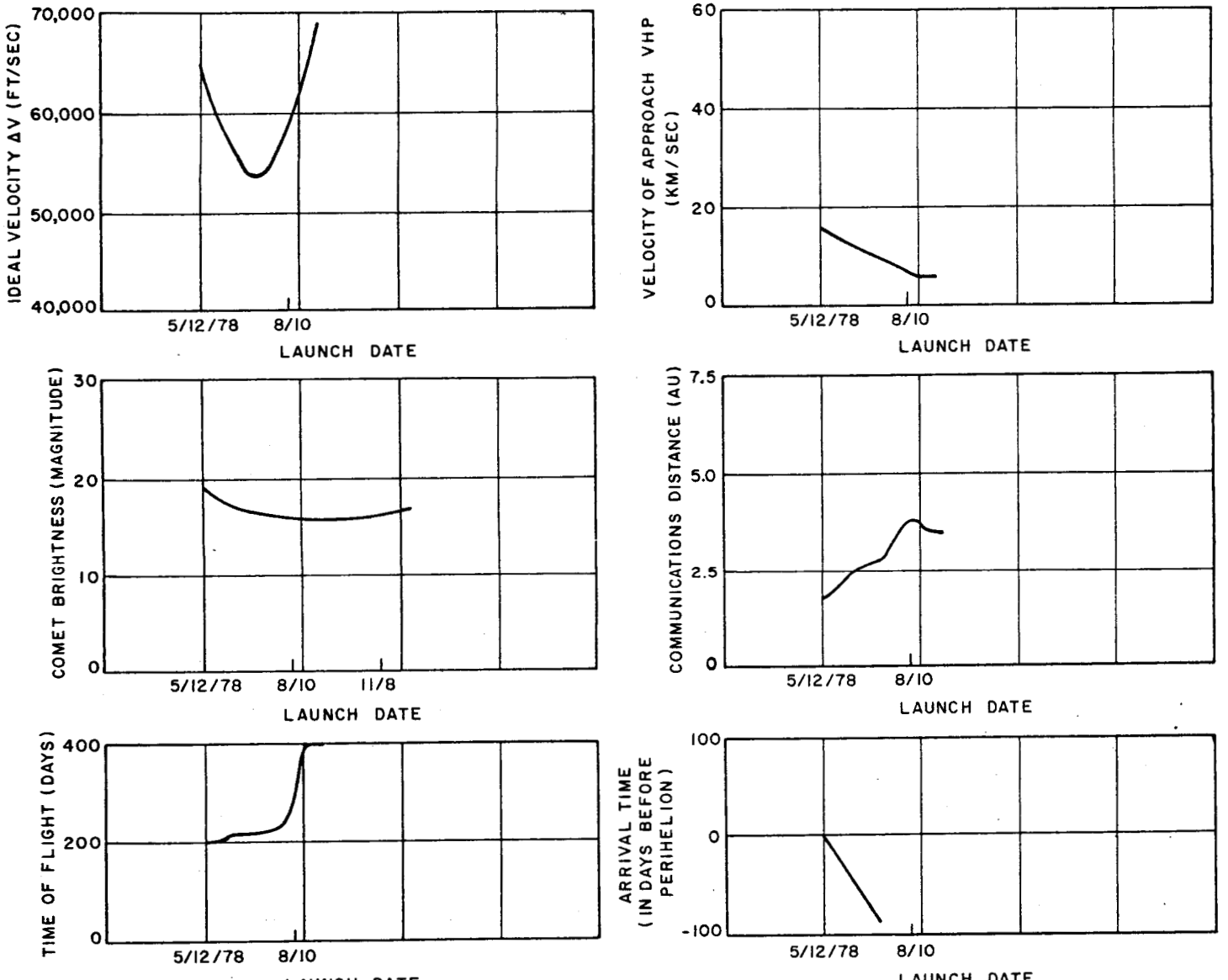

Figure 4 SIX PARAMETER PLOT FOR COMET ASHBROOK-JACKSON, PERIHELION DATE: 8/18/78

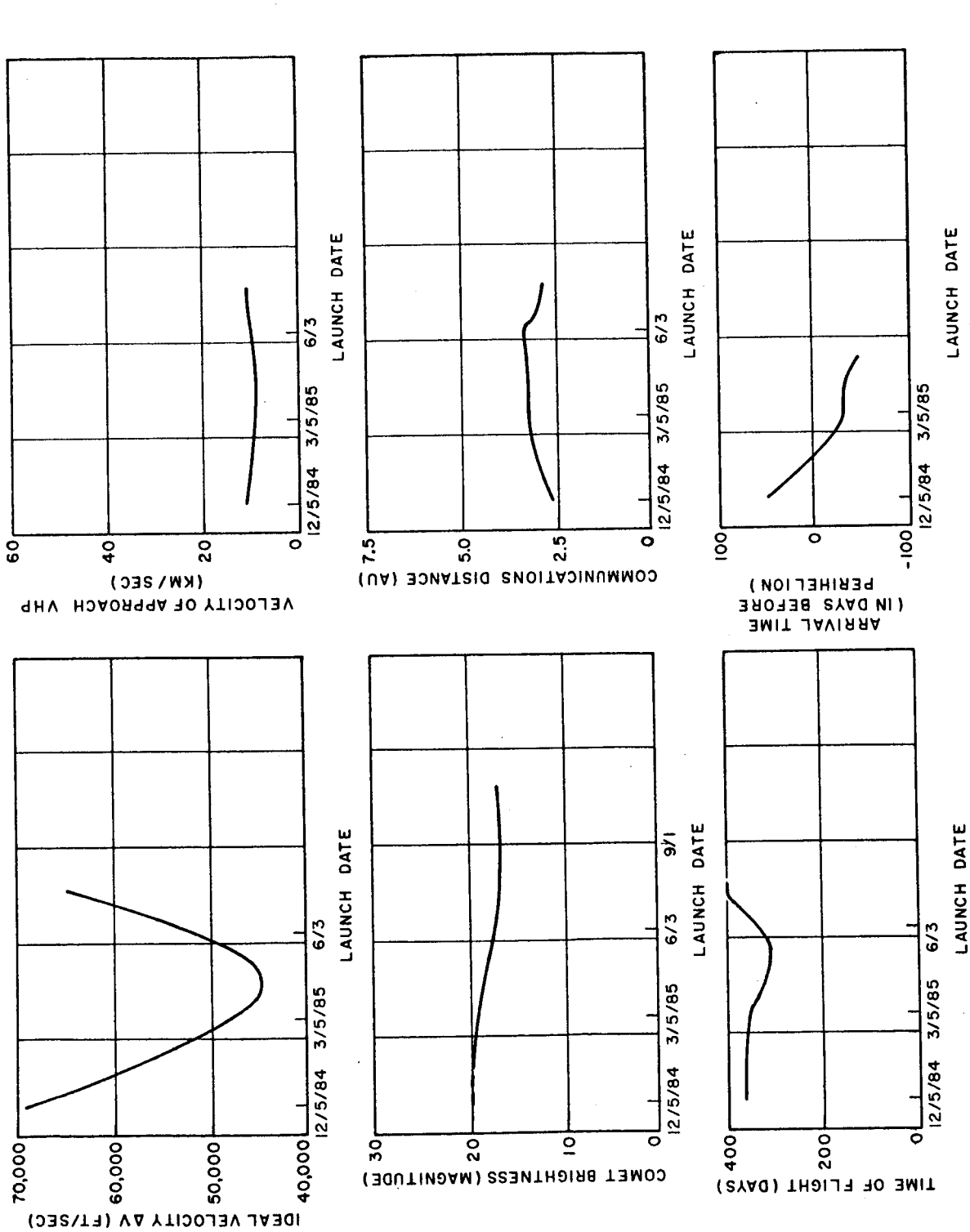

Figure 5 SIX PARAMETER PLOT FOR COMET ASHBROOK-JACKSON, PERIHELION DATE: 1/22/86

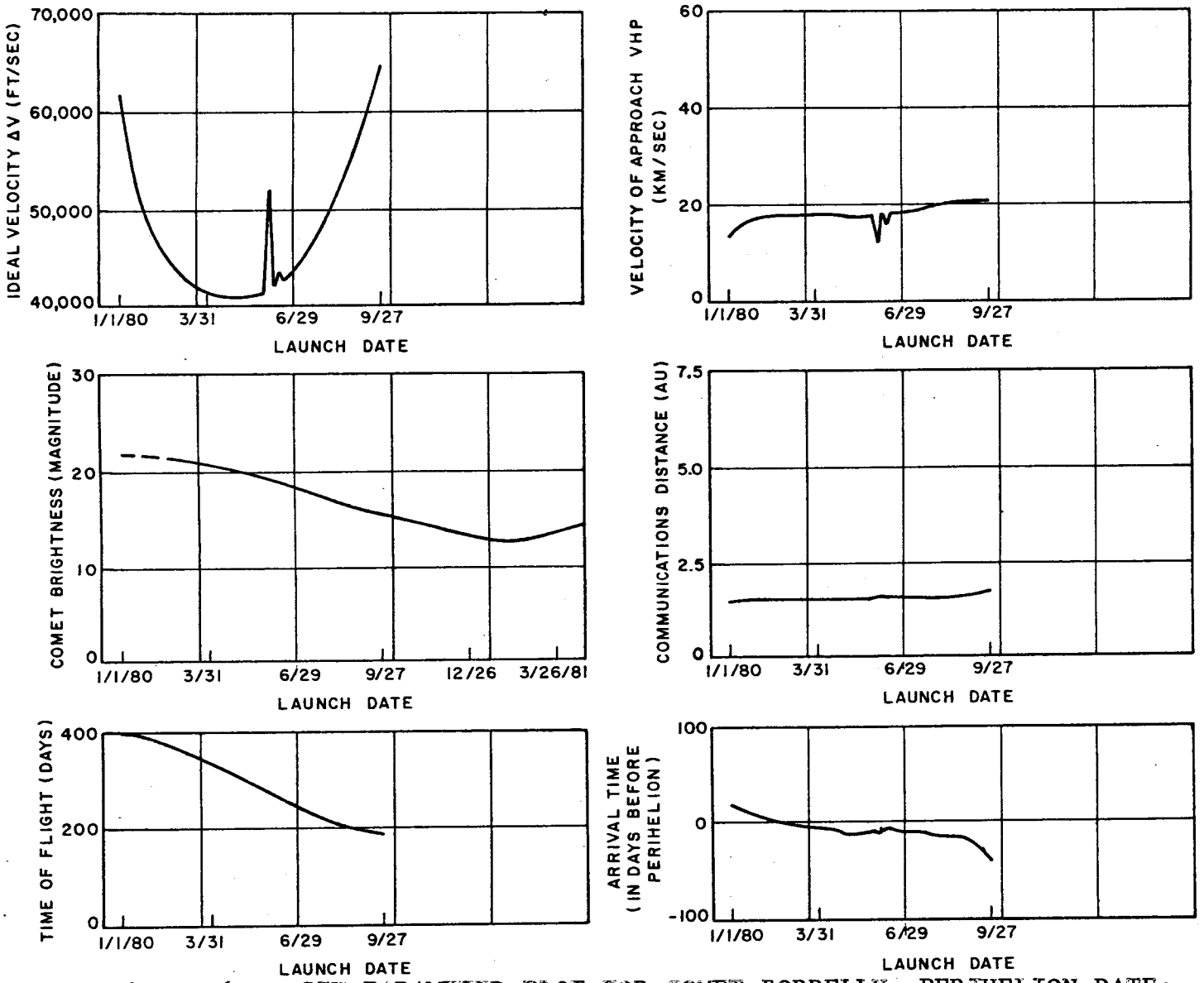

Figure 6 SIX PARAMETER PLOT FOR COMET BORRELLY, PERIHELION DATE: 2/18/81

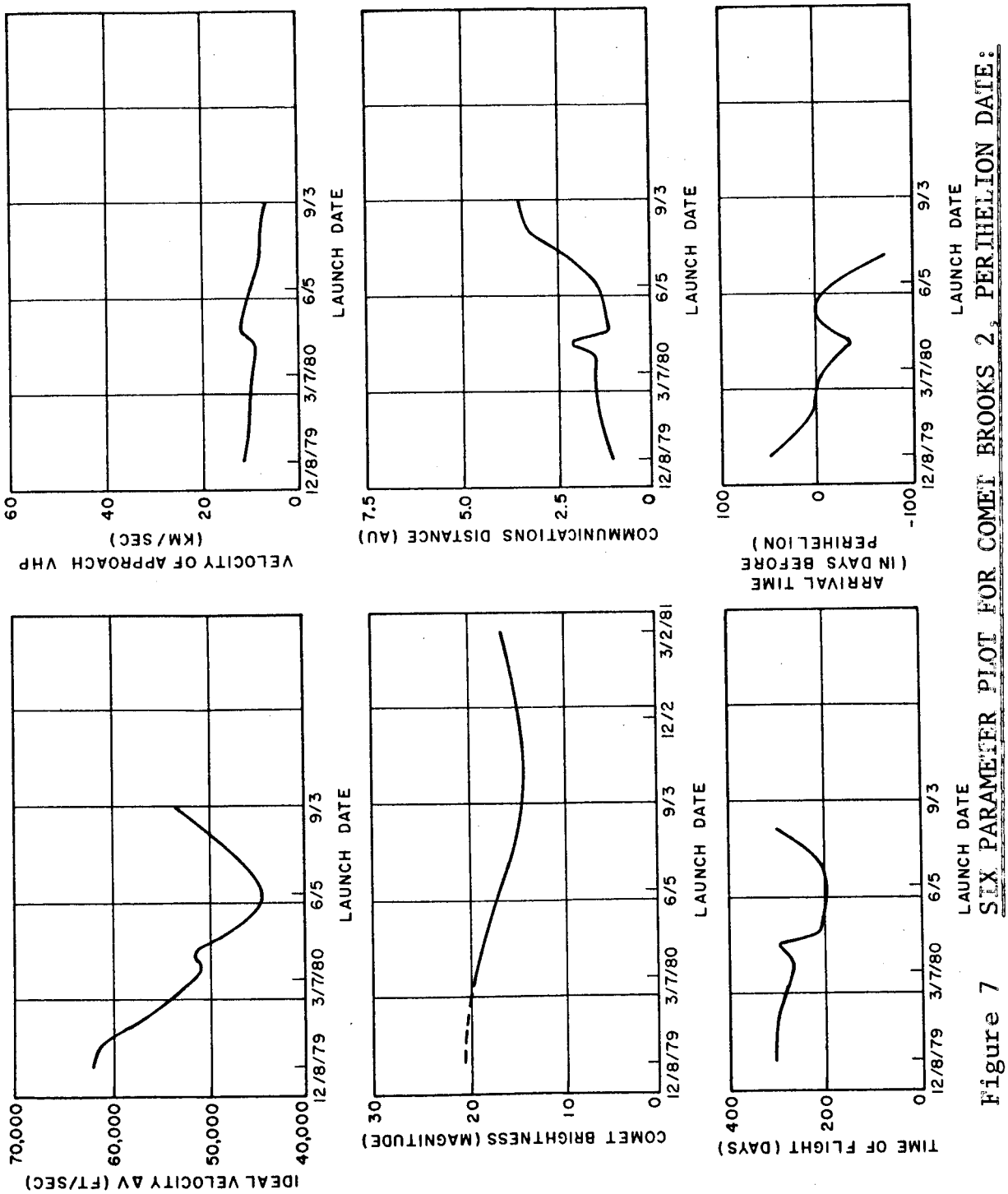

Figure 7 SIX PARAMETER PLOT FOR COMET BROOKS 2, PERIHELION DATE: 11/26/80

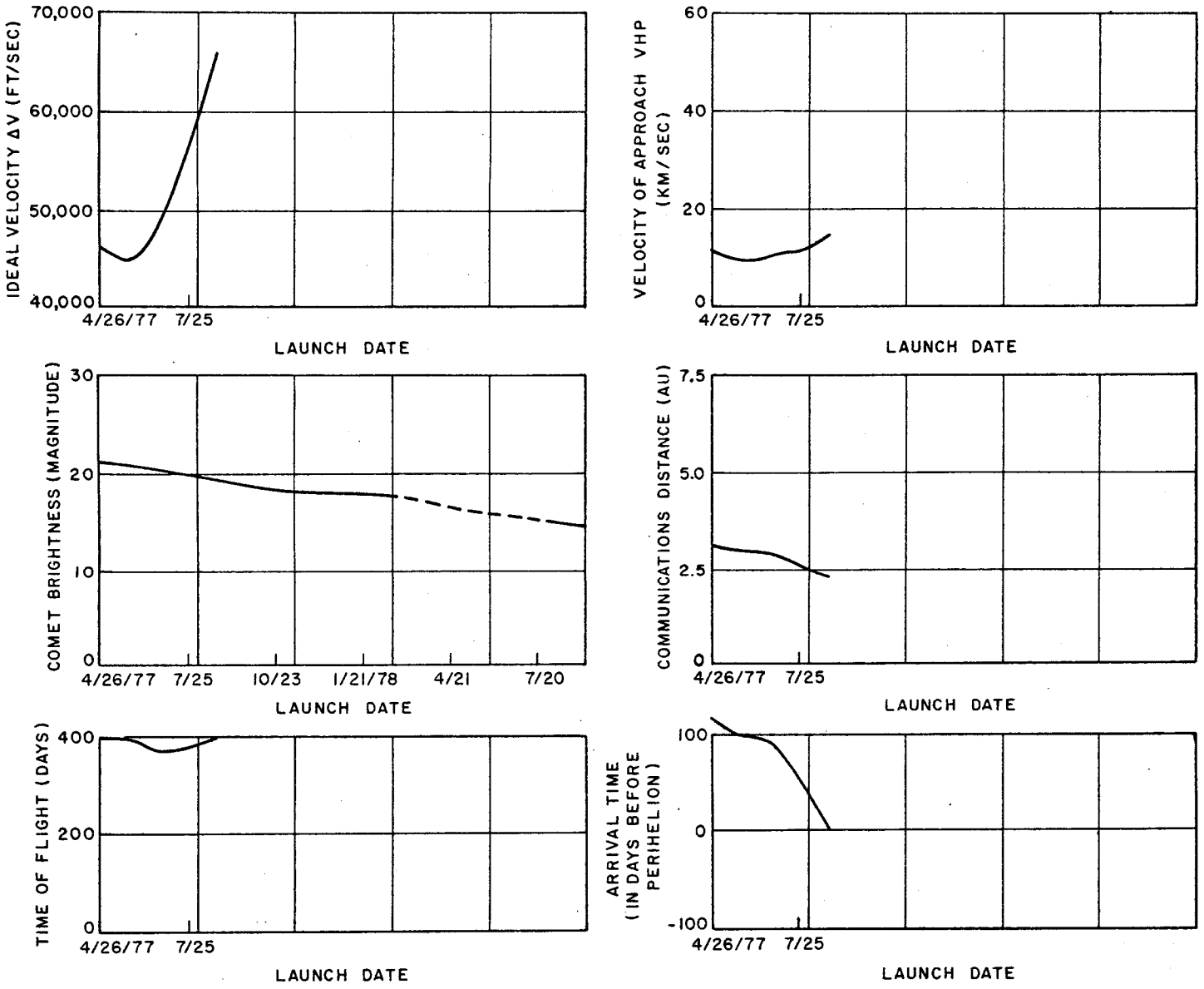

Figure 8 SIX PARAMETER PLOT FOR COMET COMAS SOLA, PERIHELION DATE: 7/26/78

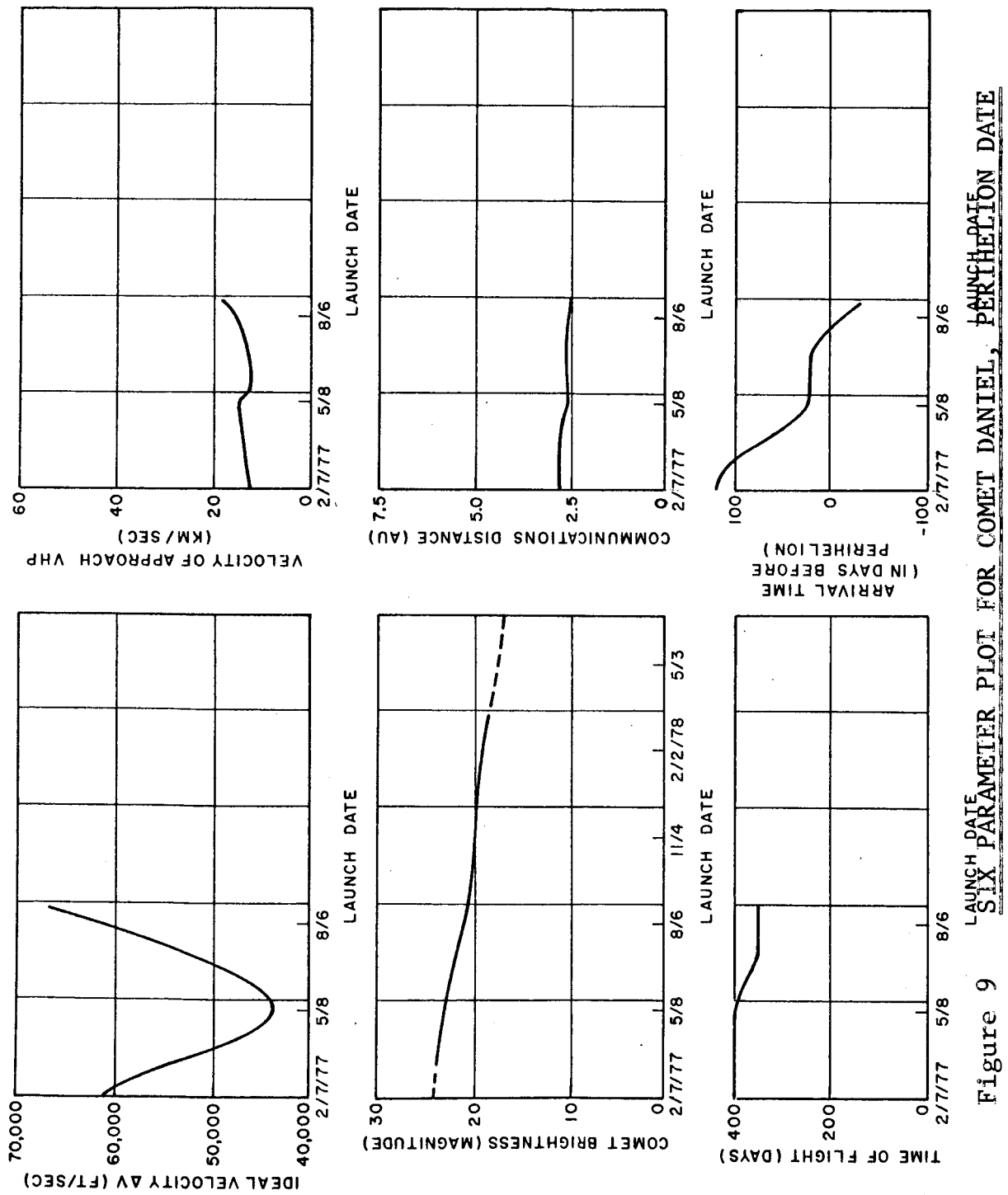

Figure 9 SIX PARAMETER PLOT FOR COMET DANIEL, LAUNCH DATE, PERIHELION DATE 7/7/78

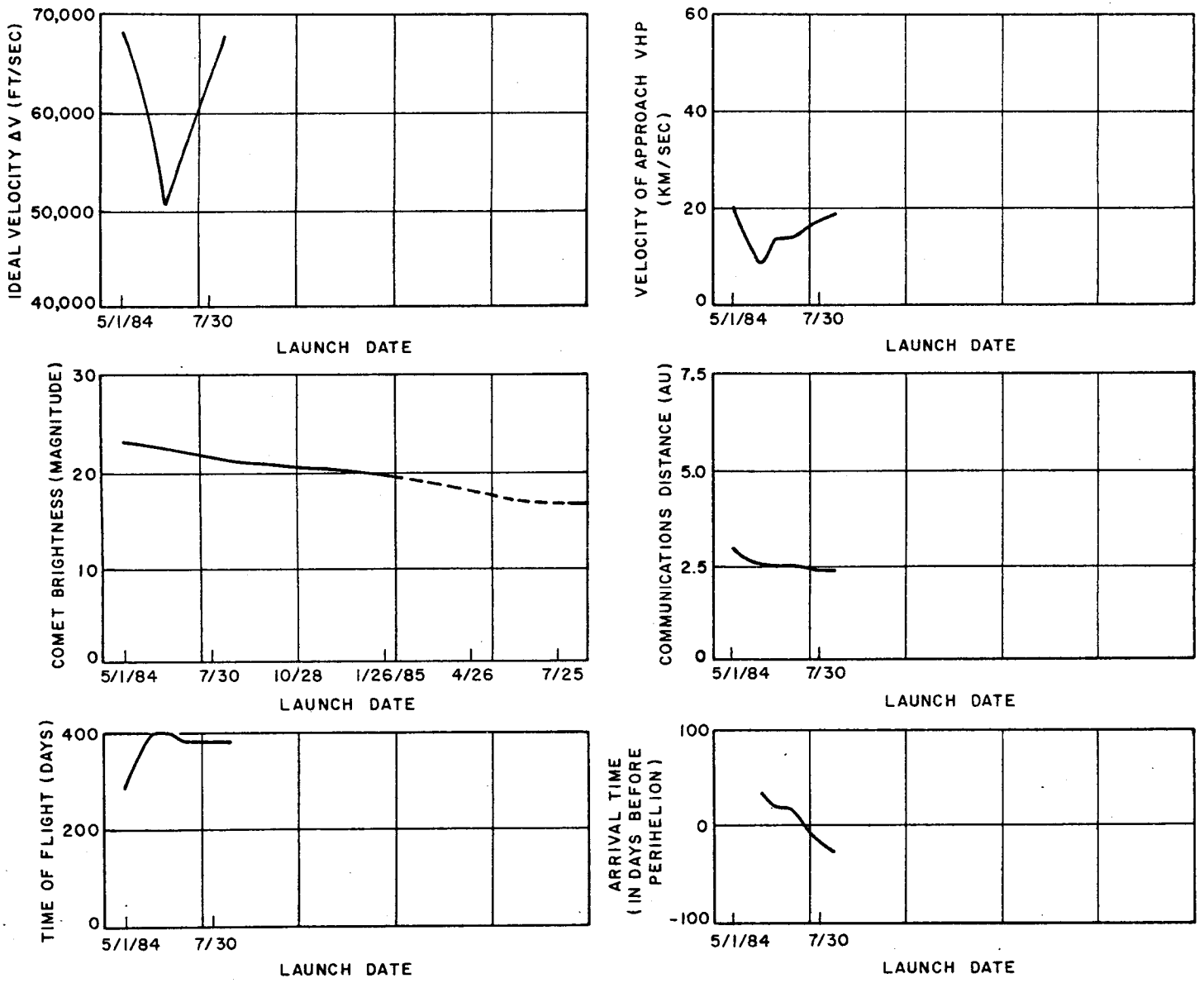

Figure 10 SIX PARAMETER PLOT FOR COMET DANIEL, PERIHELION DATE 8/2/85

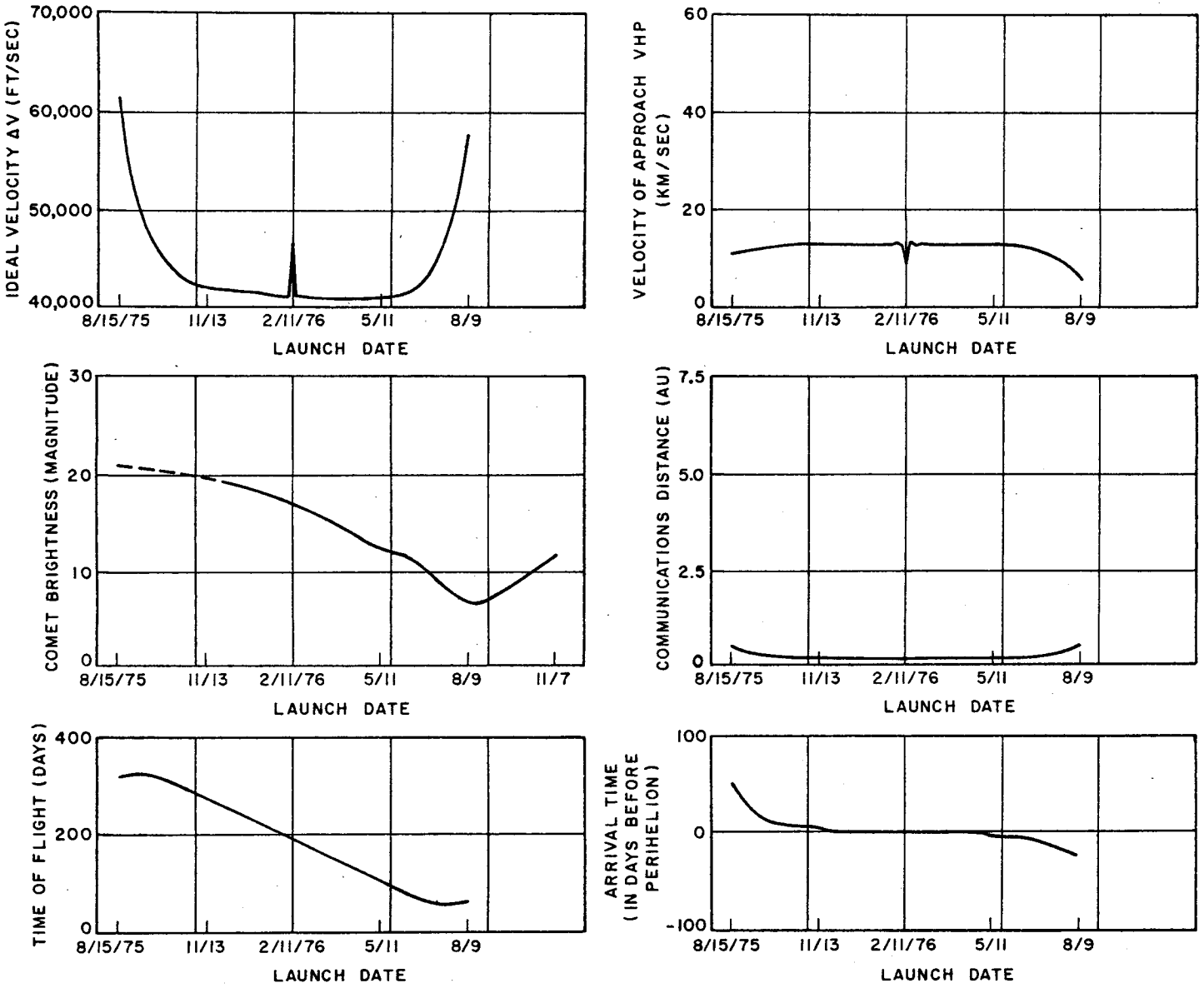

Figure 11 SIX PARAMETER PLOT FOR COMET D'ARREST, PERIHELION DATE 8/18/76

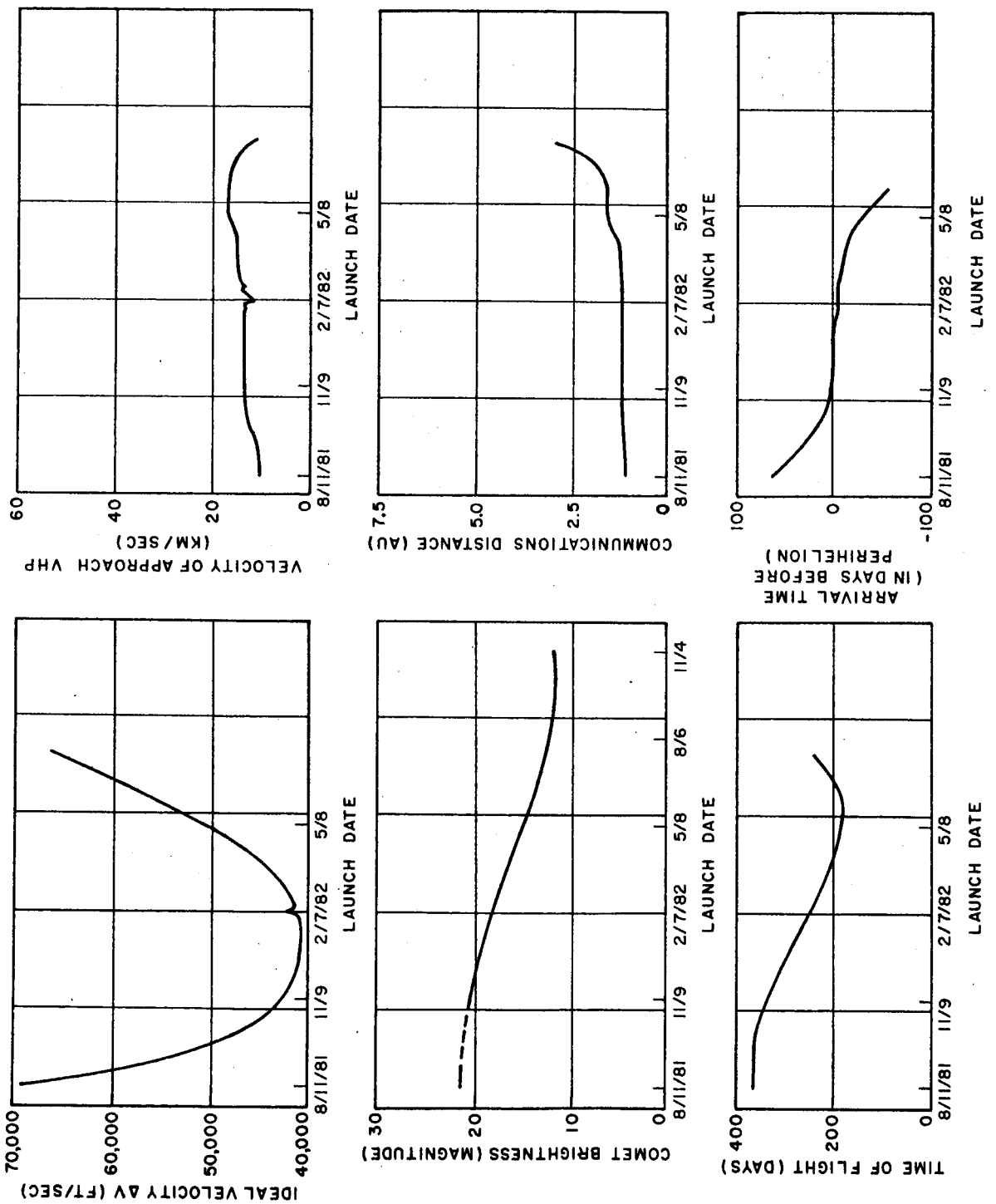

Figure 12 SIX PARAMETER PLOT FOR COMET D'ARREST, PERIHELION DATE 10/13/82

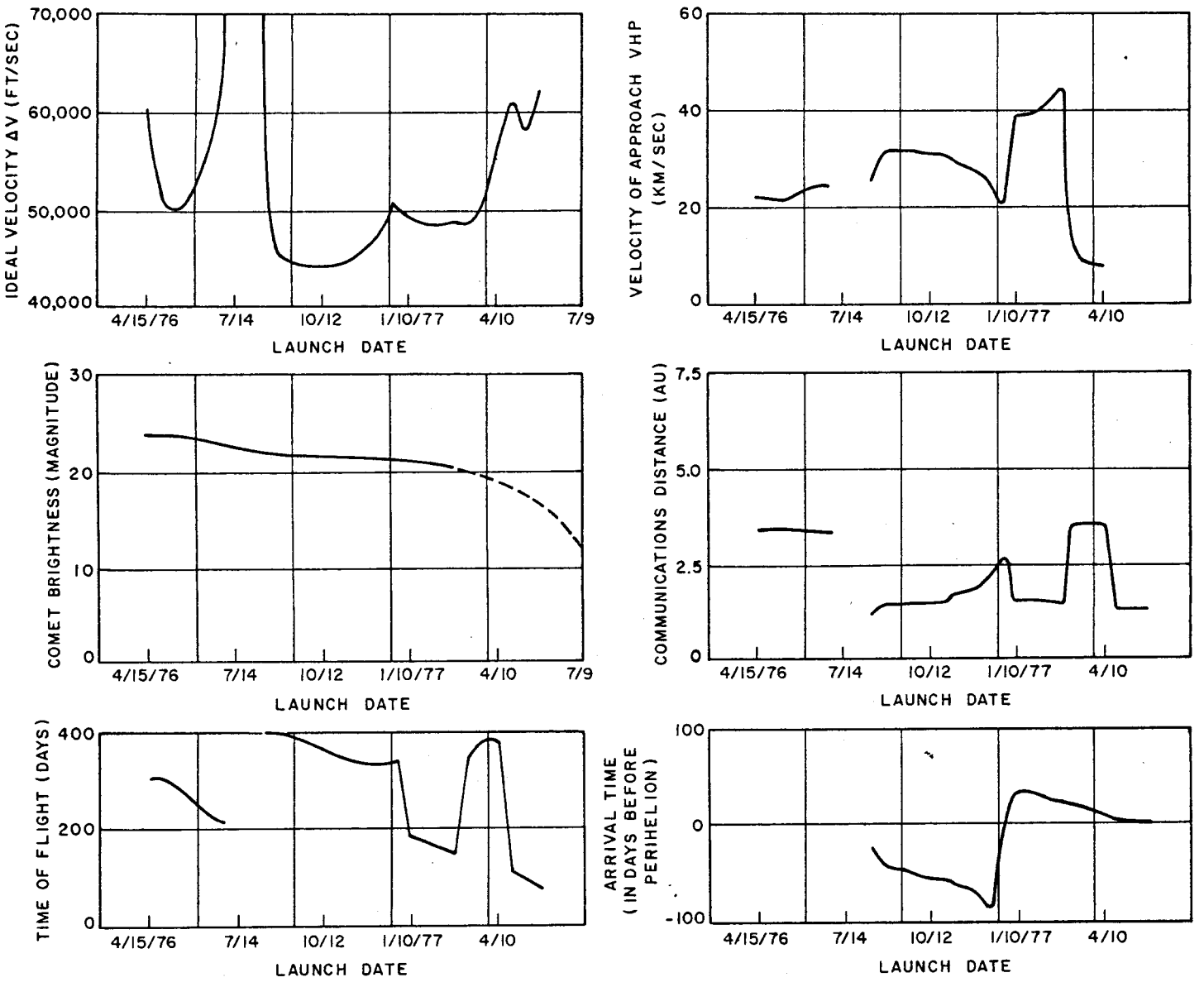

Figure 13 SIX PARAMETER PLOT FOR COMET ENCKE, PERIHELION DATE 8/16/77

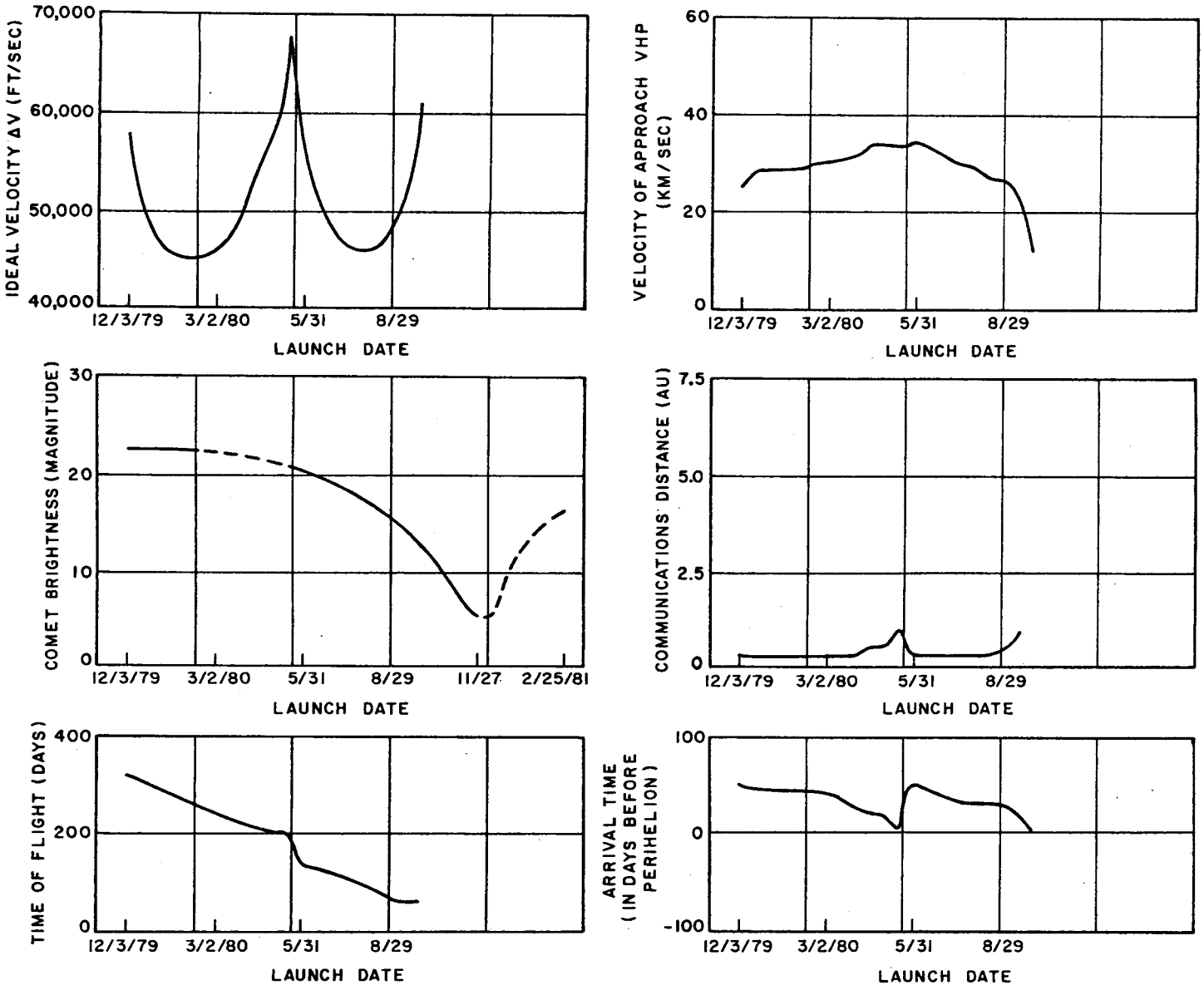

Figure 14 SIX PARAMETER PLOT FOR COMET ENCKE, PERIHELION DATE 12/6/80

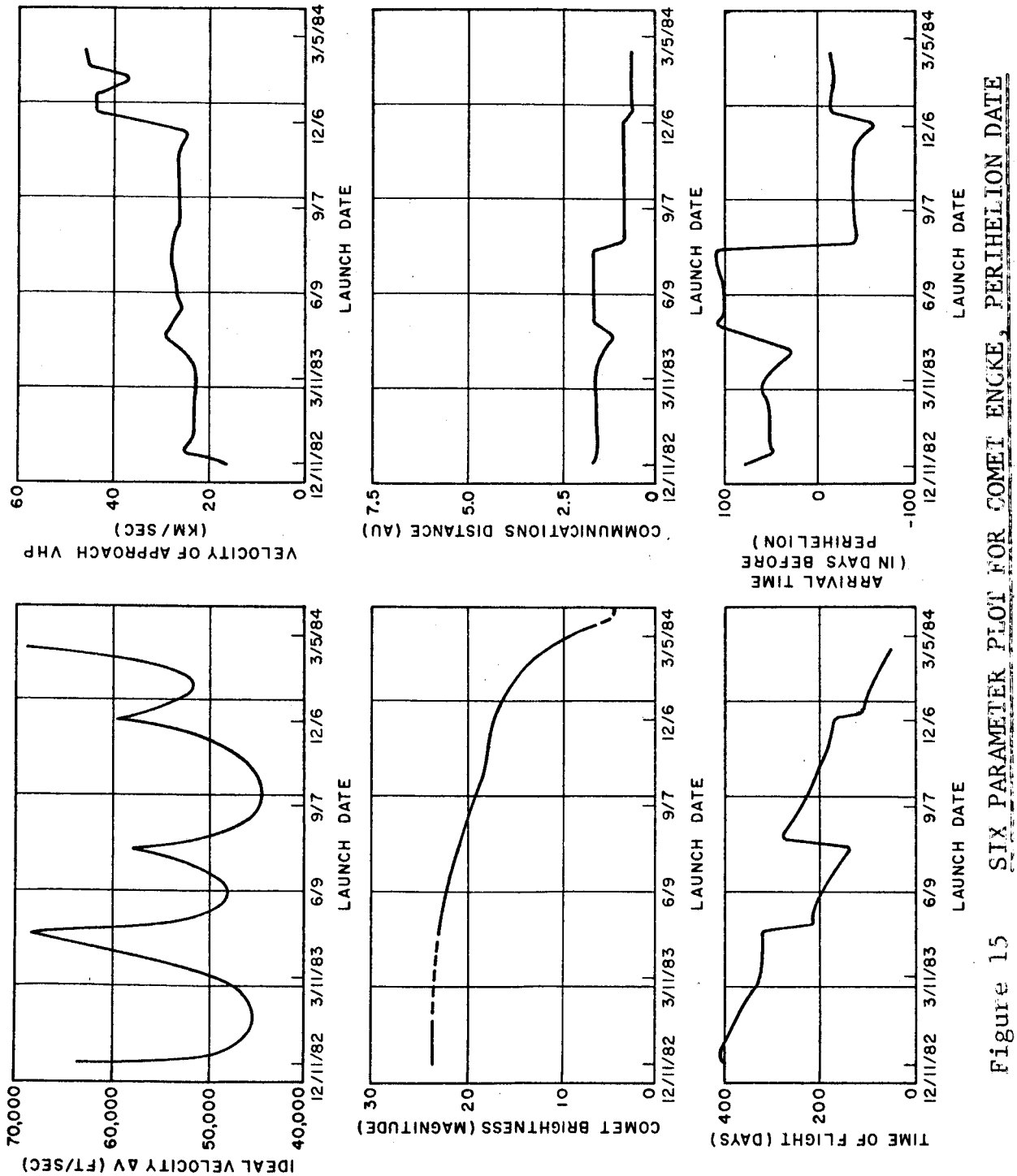

Figure 15 SIX PARAMETER PLOT FOR COMET ENCKE, PERIHELION DATE 3/27/84

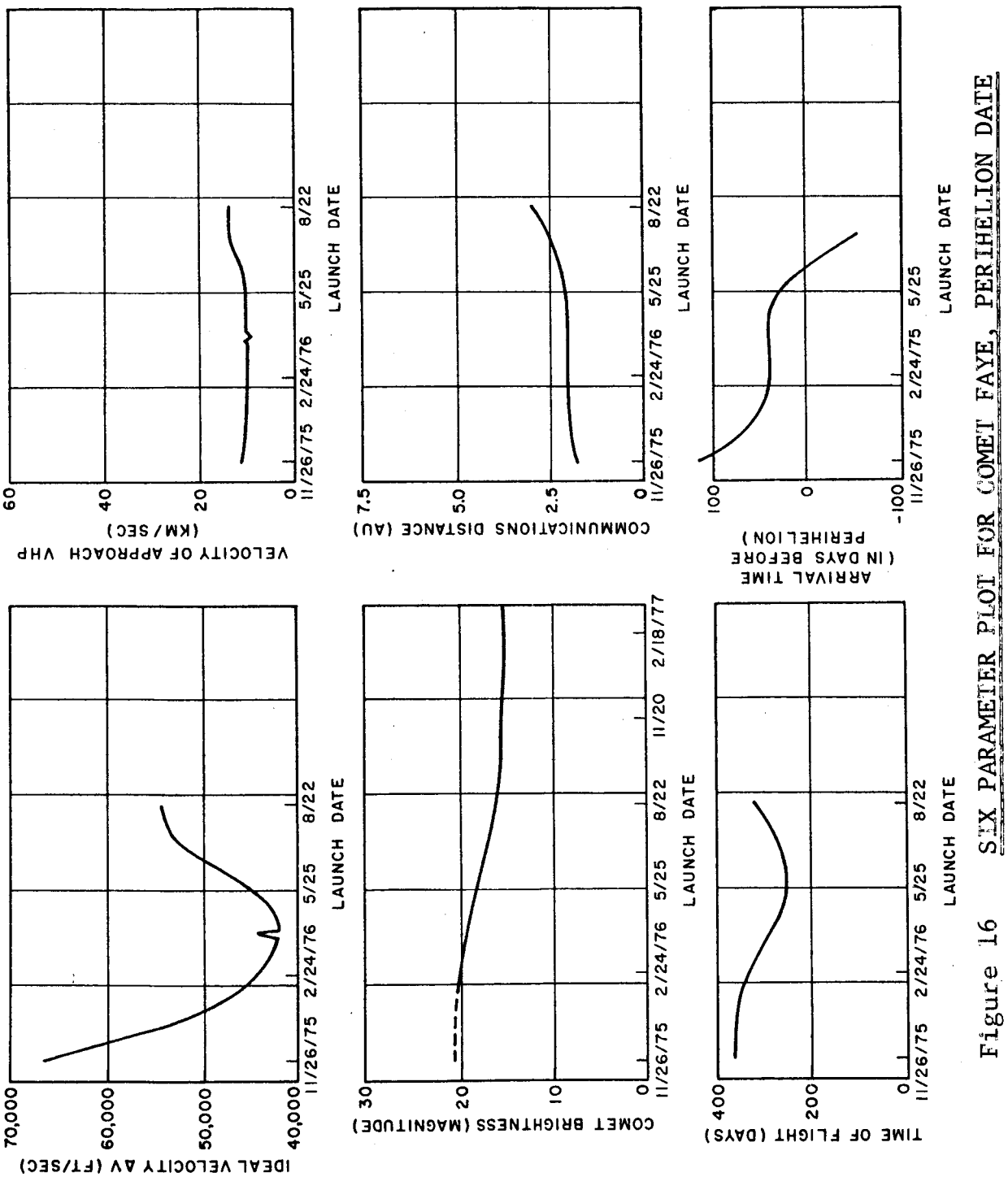

Figure 16 SIX PARAMETER PLOT FOR COMET FAYE, PERIHELION DATE 2/27/77

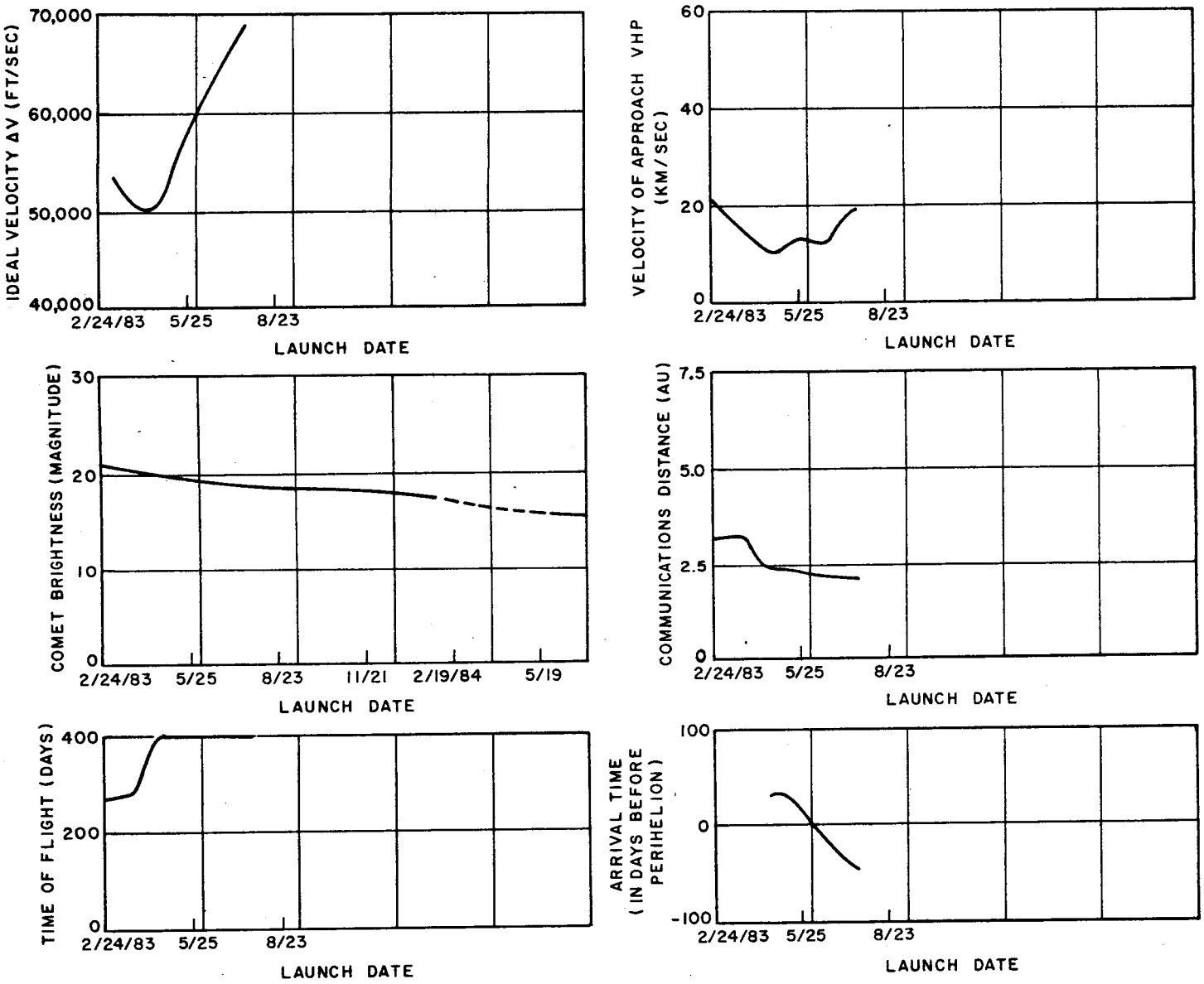

Figure 17 SIX PARAMETER PLOT FOR COMET FAYE, PERIHELION DATE 7/9/84

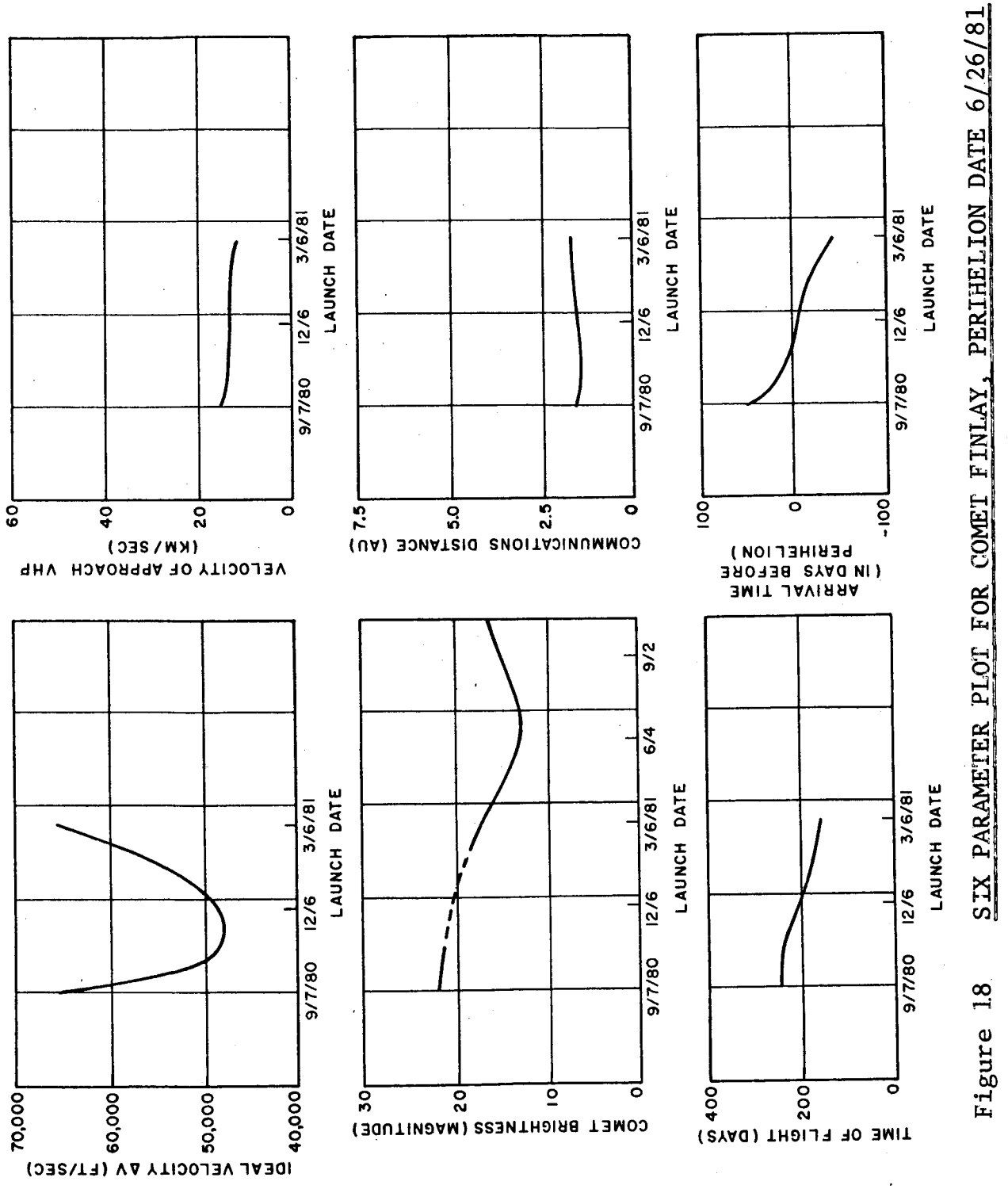

Figure 18 SIX PARAMETER PLOT FOR COMET FINLAY, PERIHELION DATE 6/26/81

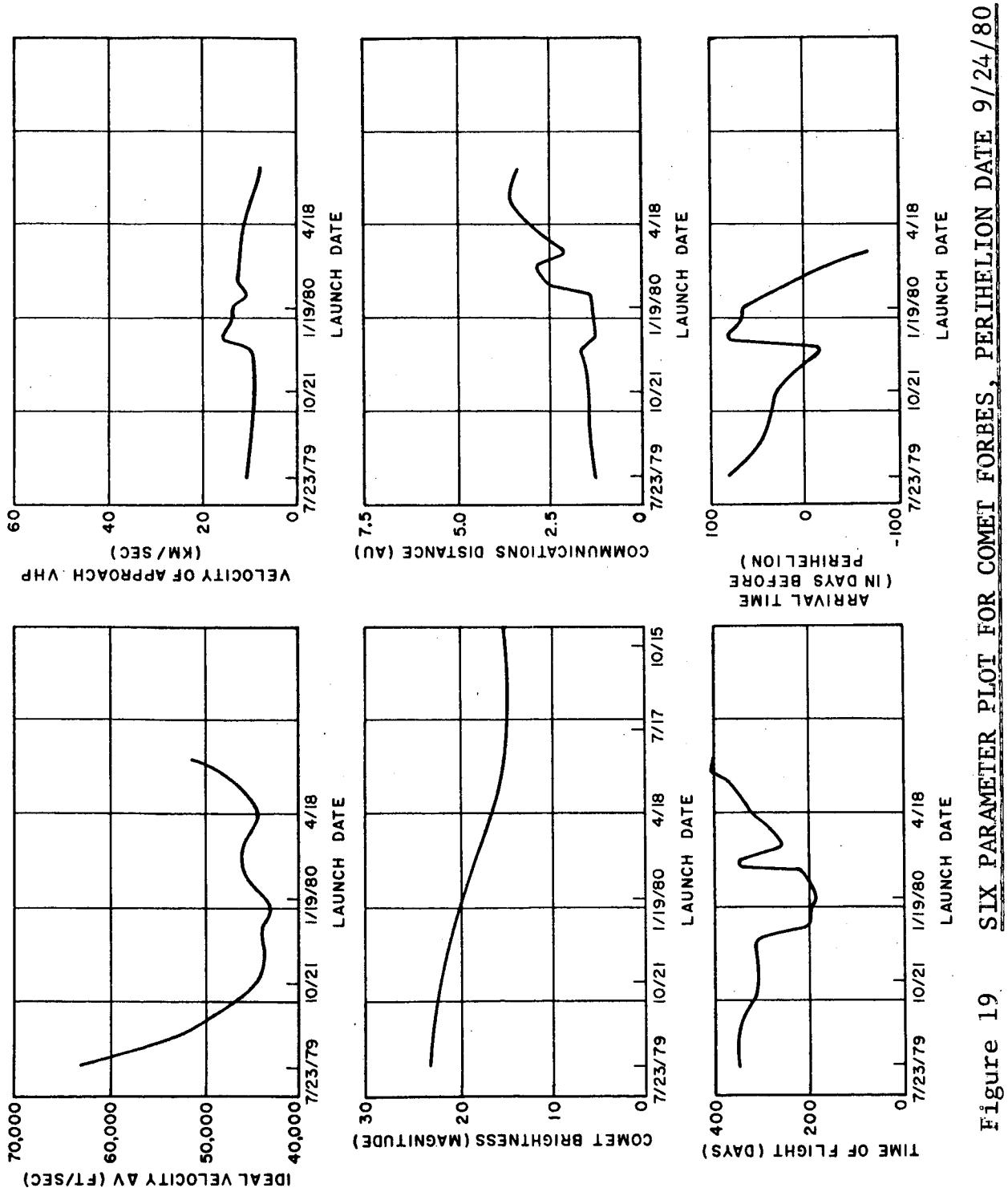

Figure 19 SIX PARAMETER PLOT FOR COMET FORBES, PERIHELION DATE 9/24/80

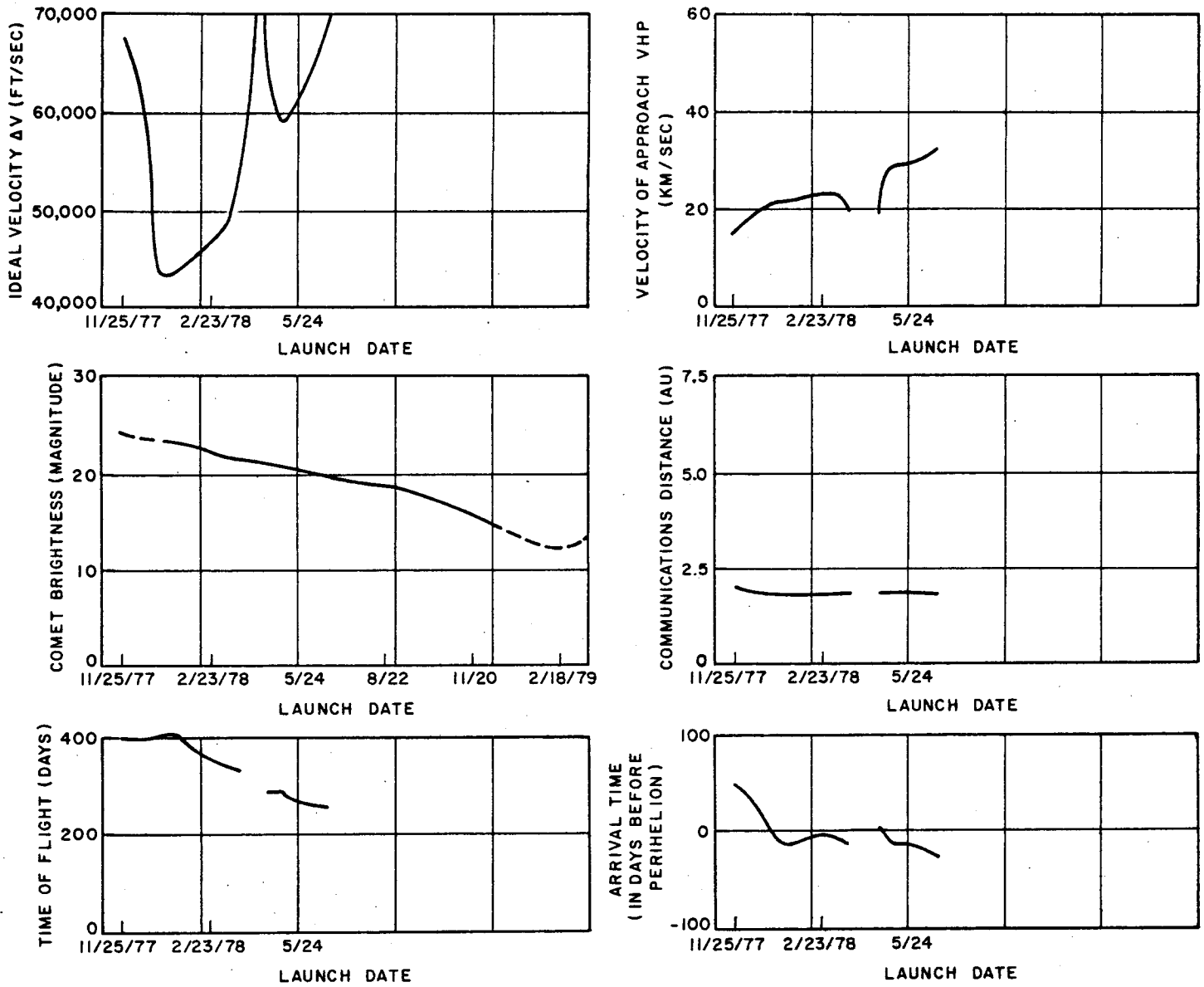

Figure 20 SIX PARAMETER PLOT FOR COMET GIACOBINI-ZINNER, PERIHELION DATE 2/11/79

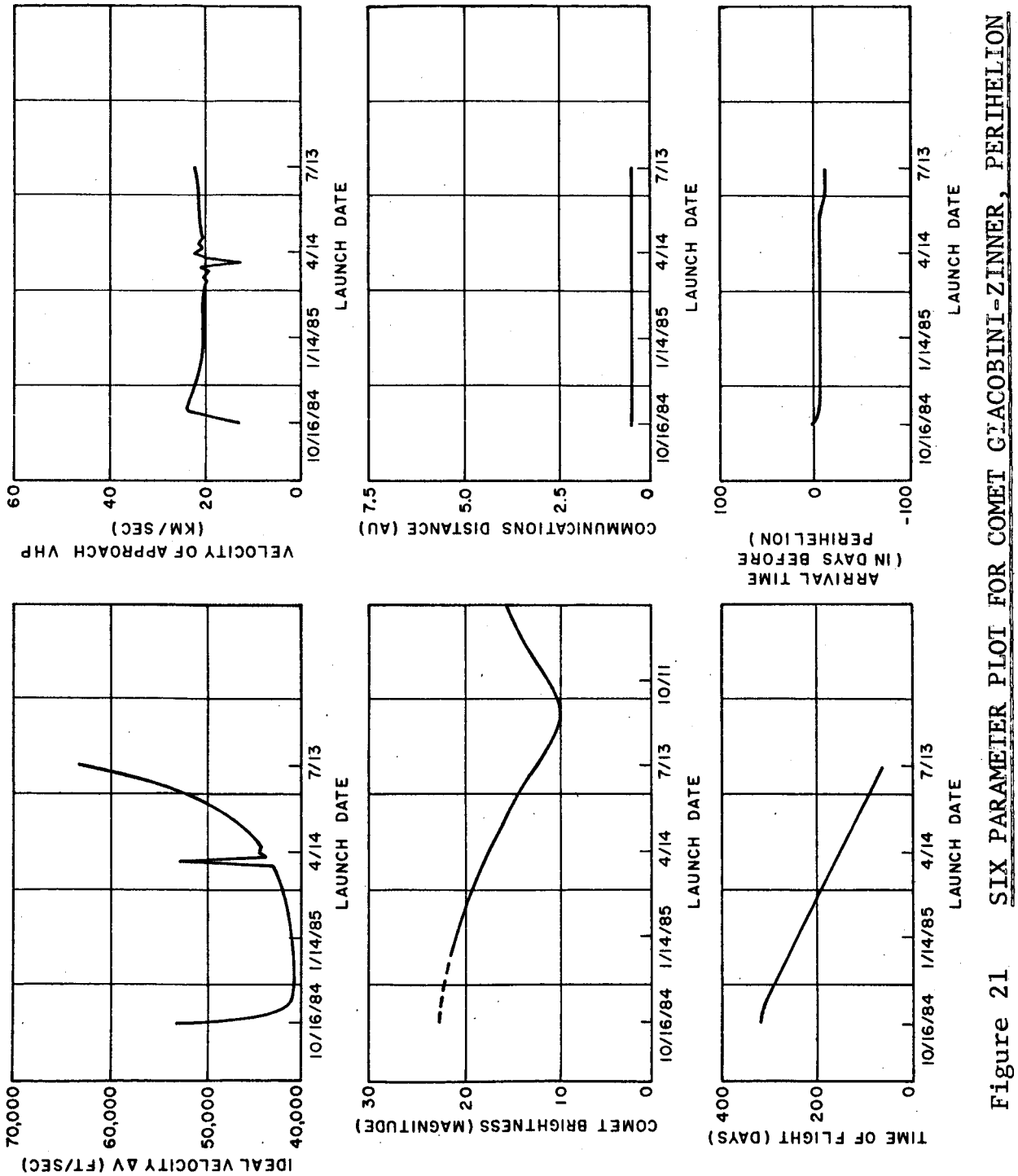

Figure 21 SIX PARAMETER PLOT FOR COMET GIACOBINI-ZINNER, PERIHELION DATE 9/4/85

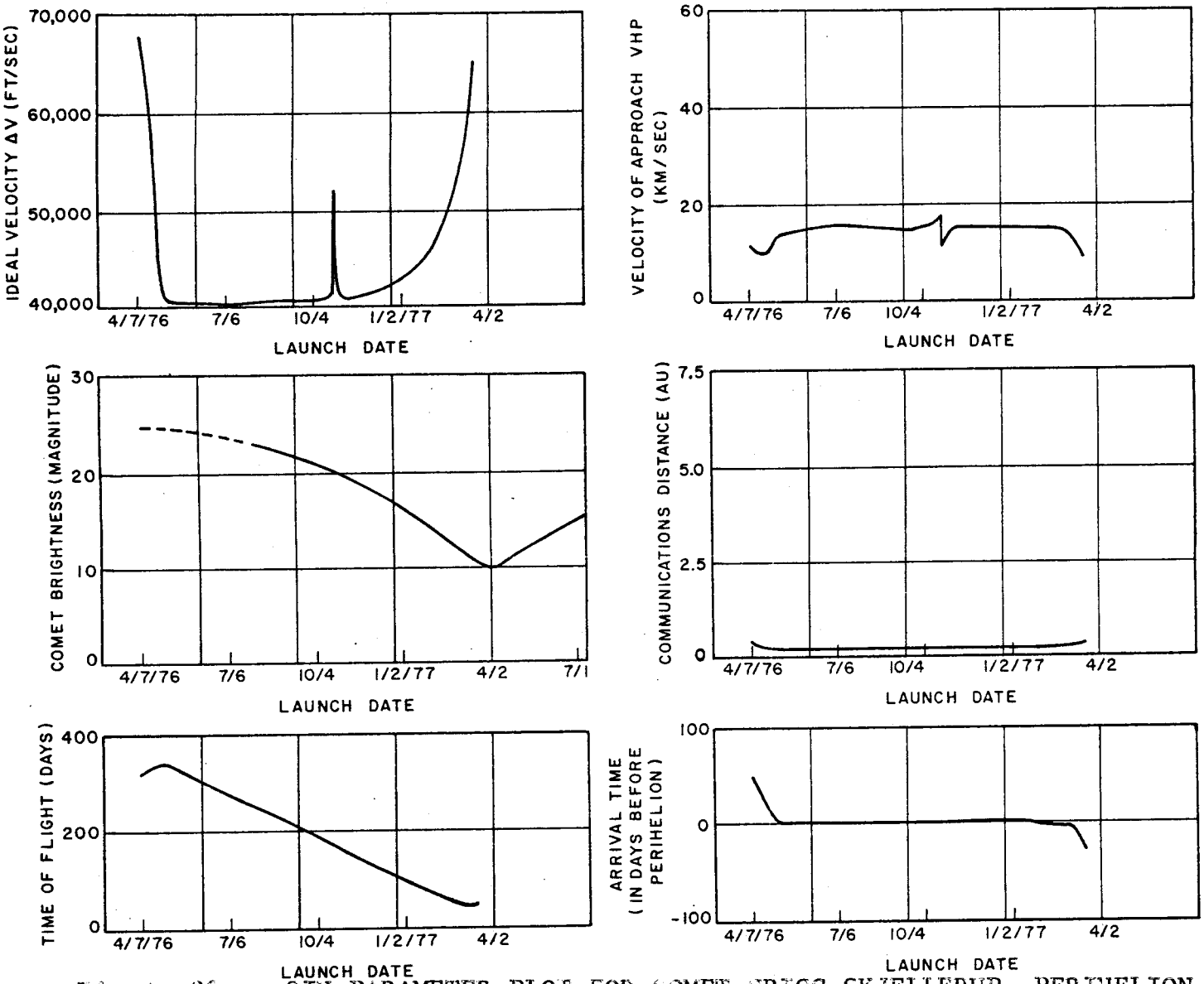

Figure 22 SIX PARAMETER PLOT FOR COMET GRIGG-SKJELLERUP, PERIHELION DATE 4/9/77

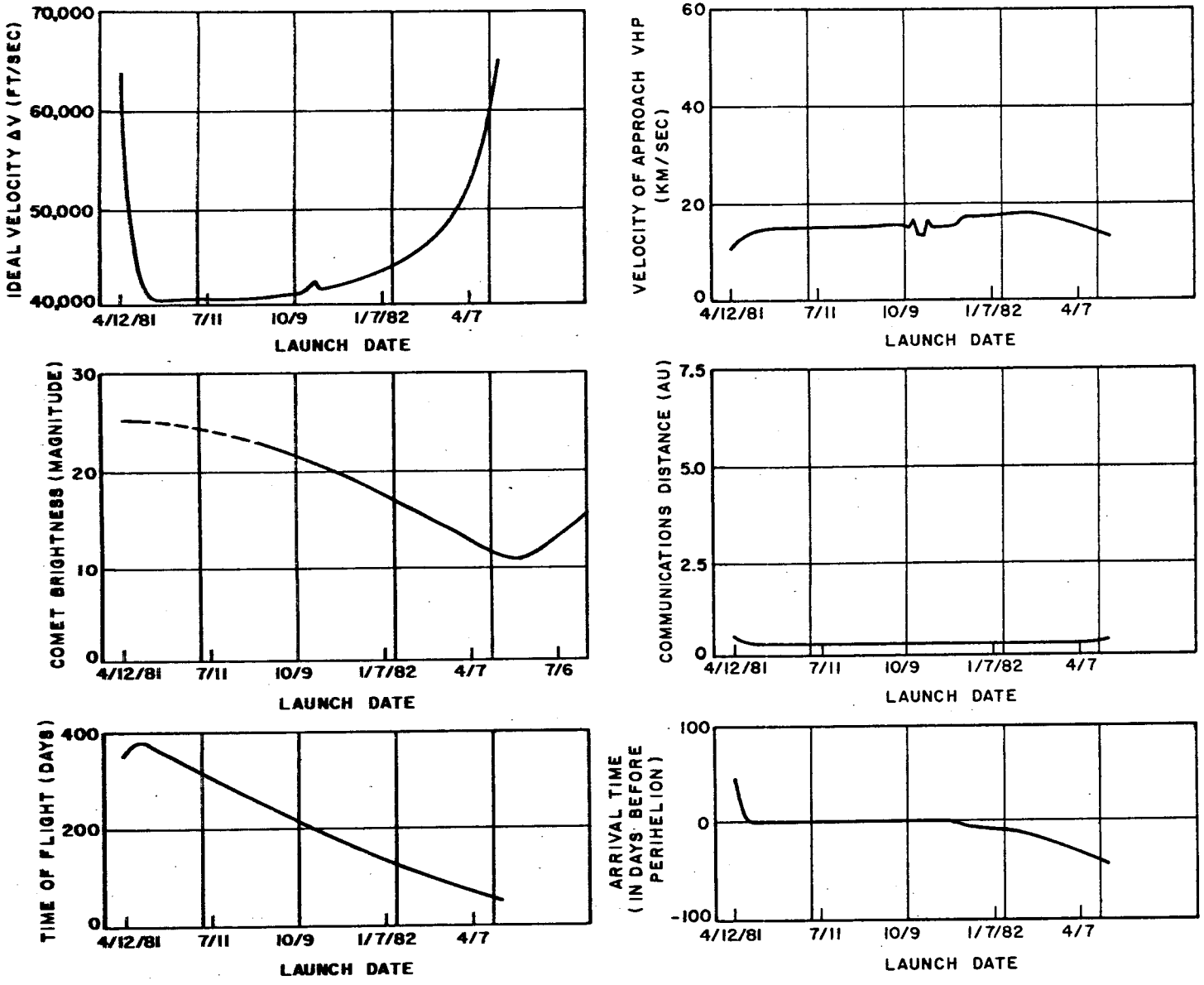

Figure 23 SIX PARAMETER PLOT FOR COMET GRIGG-SKJELLERUP, PERIHELION DATE 5/13/82

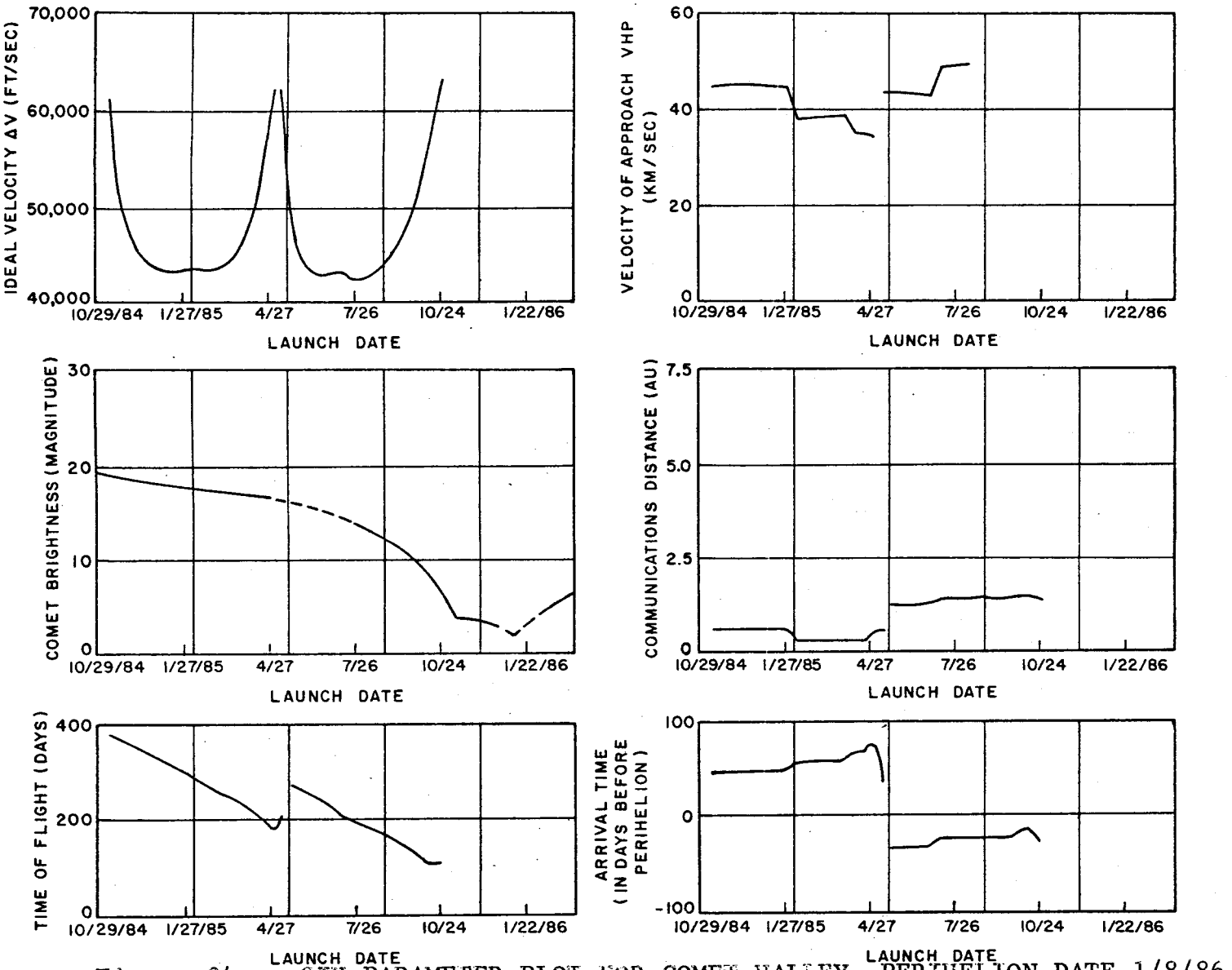

Figure 24 SIX PARAMETER PLOT FOR COMET HALLEY, PERIHELION DATE 1/8/86

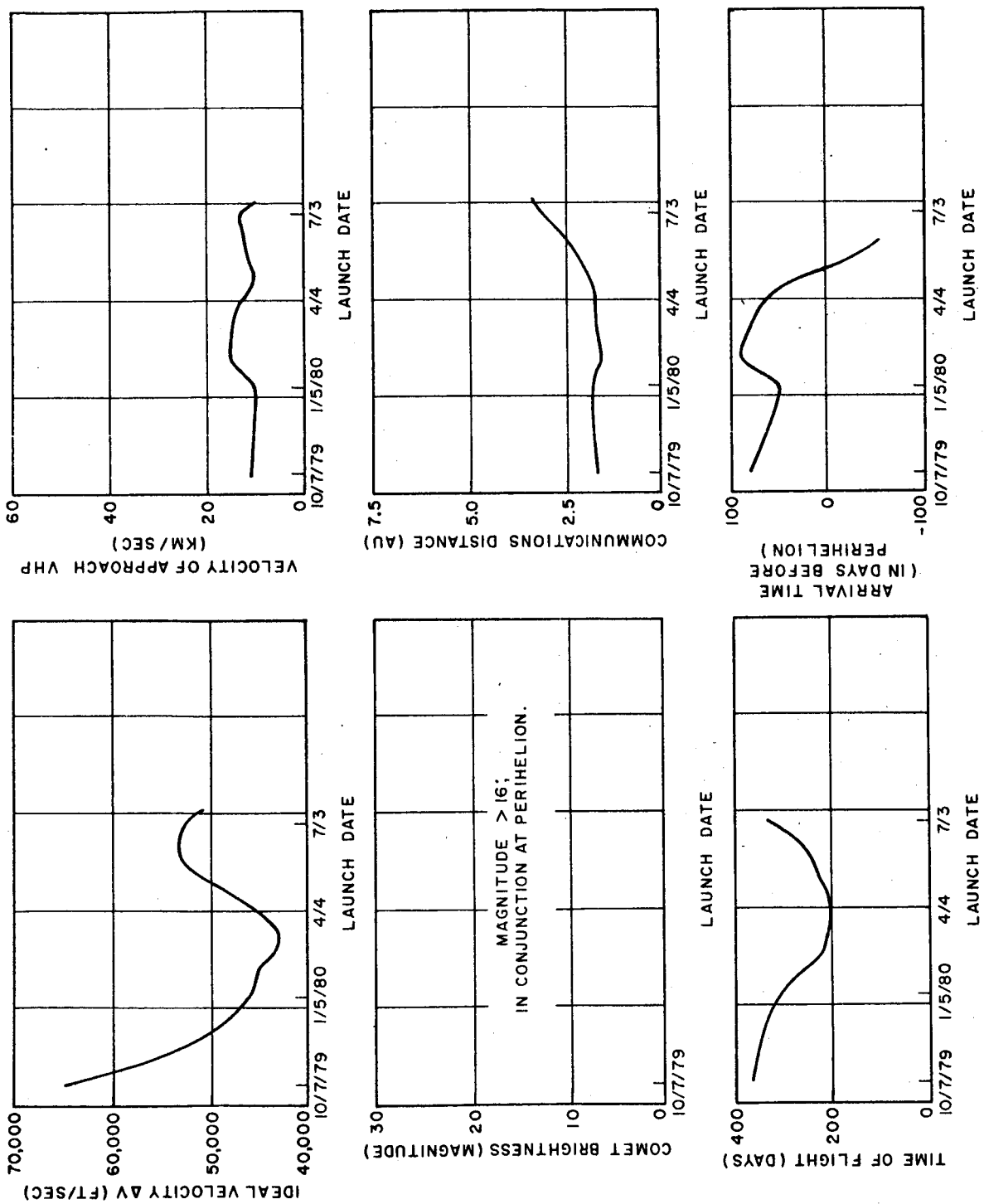

Figure 25 SIX PARAMETER PLOT FOR COMET HARRINGTON, PERIHELION DATE 12/24/80

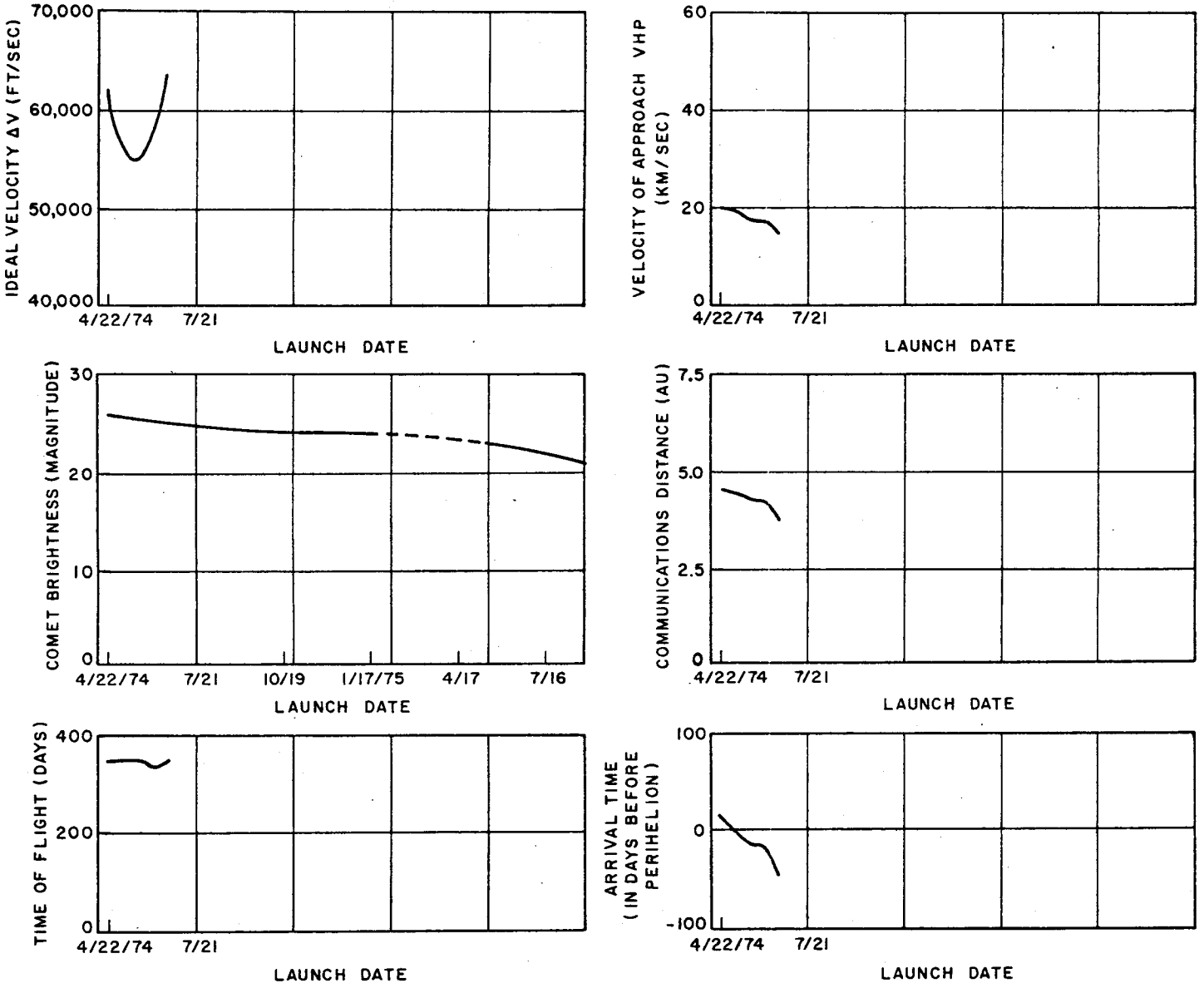

Figure 26 SIX PARAMETER PLOT FOR COMET HARRINGTON-ABELL, PERIHELION DATE 4/18/76

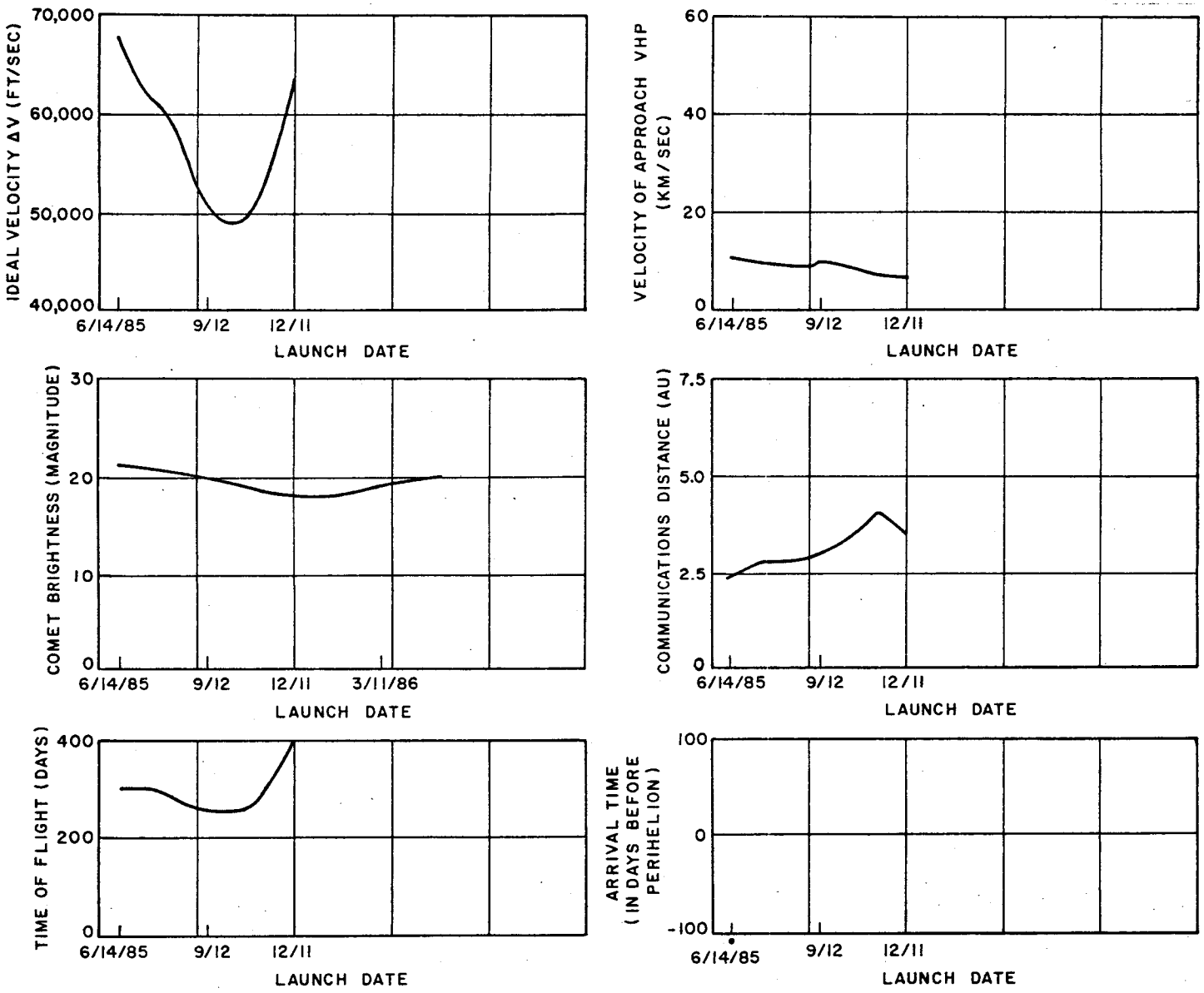

Figure 27 SIX PARAMETER PLOT FOR COMET HARRINGTON-ABELL, PERIHELION DATE 1/1/86

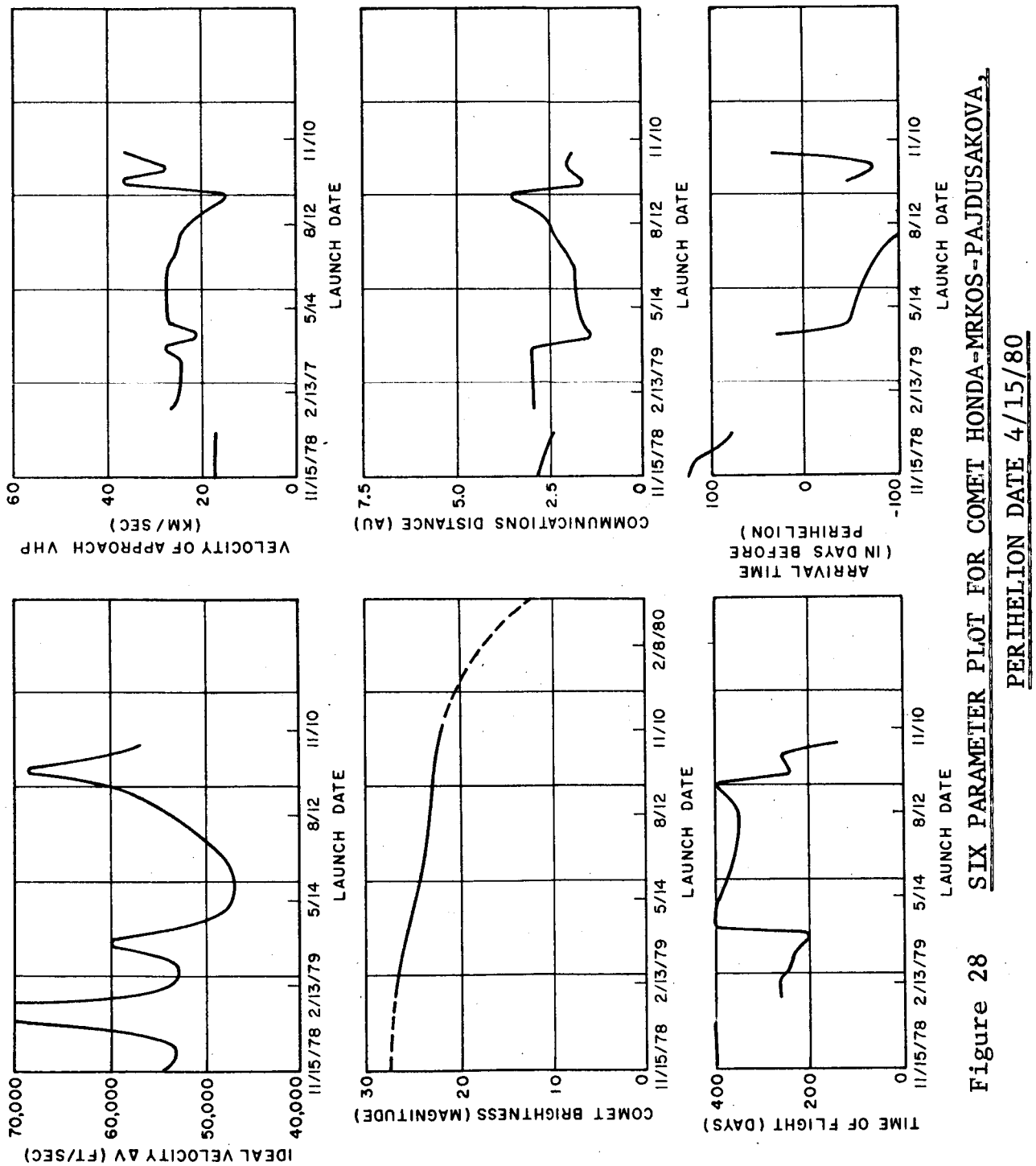

Figure 28 SIX PARAMETER PLOT FOR COMET HONDA-MRKOS-PAJDUSAKOVA, PERIHELION DATE 4/15/80

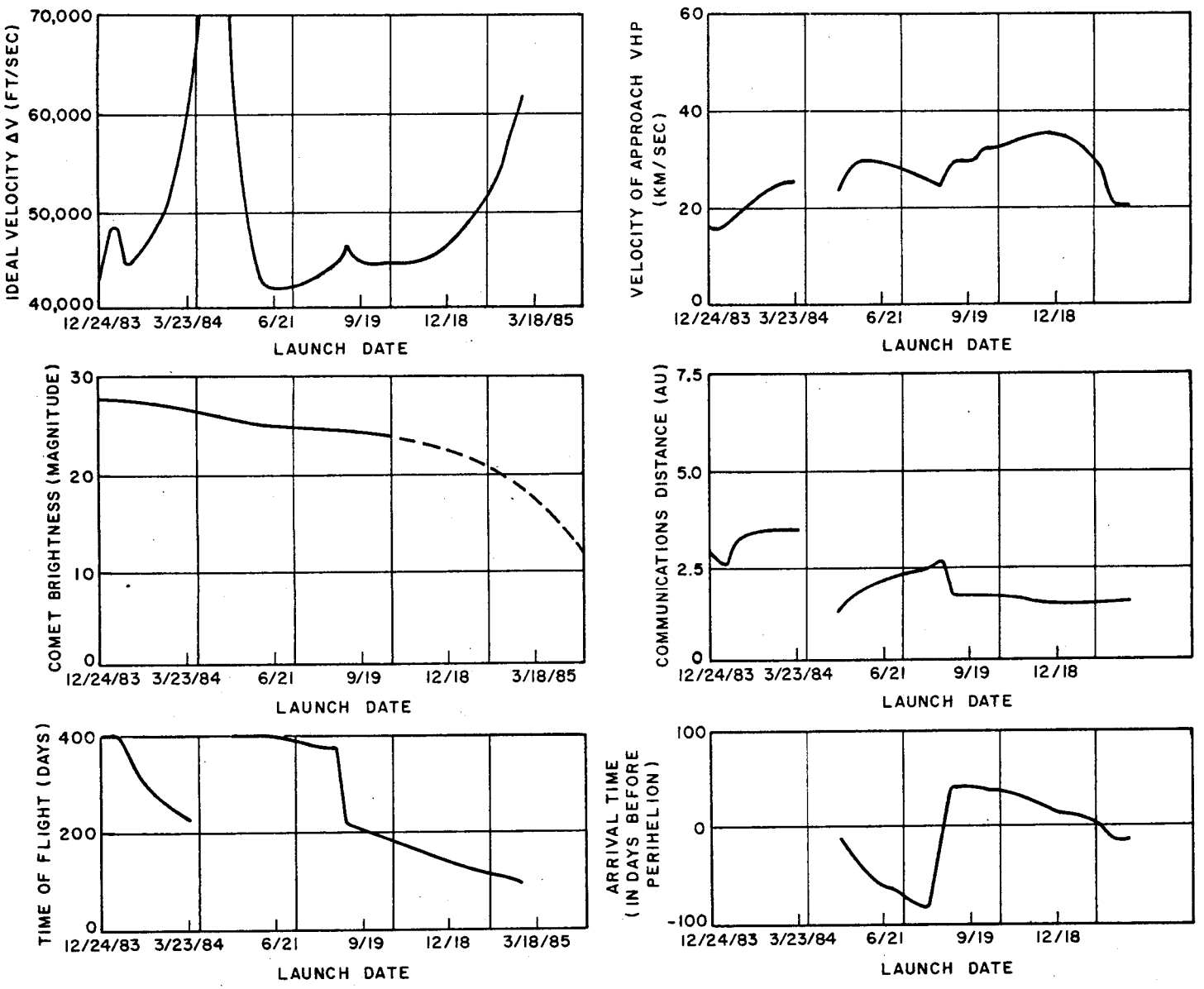

Figure 29 SIX PARAMETER PLOT FOR COMET HONDA-MRKOS-PAJDUSAKOVA, PERIHELION DATE 5/24/85

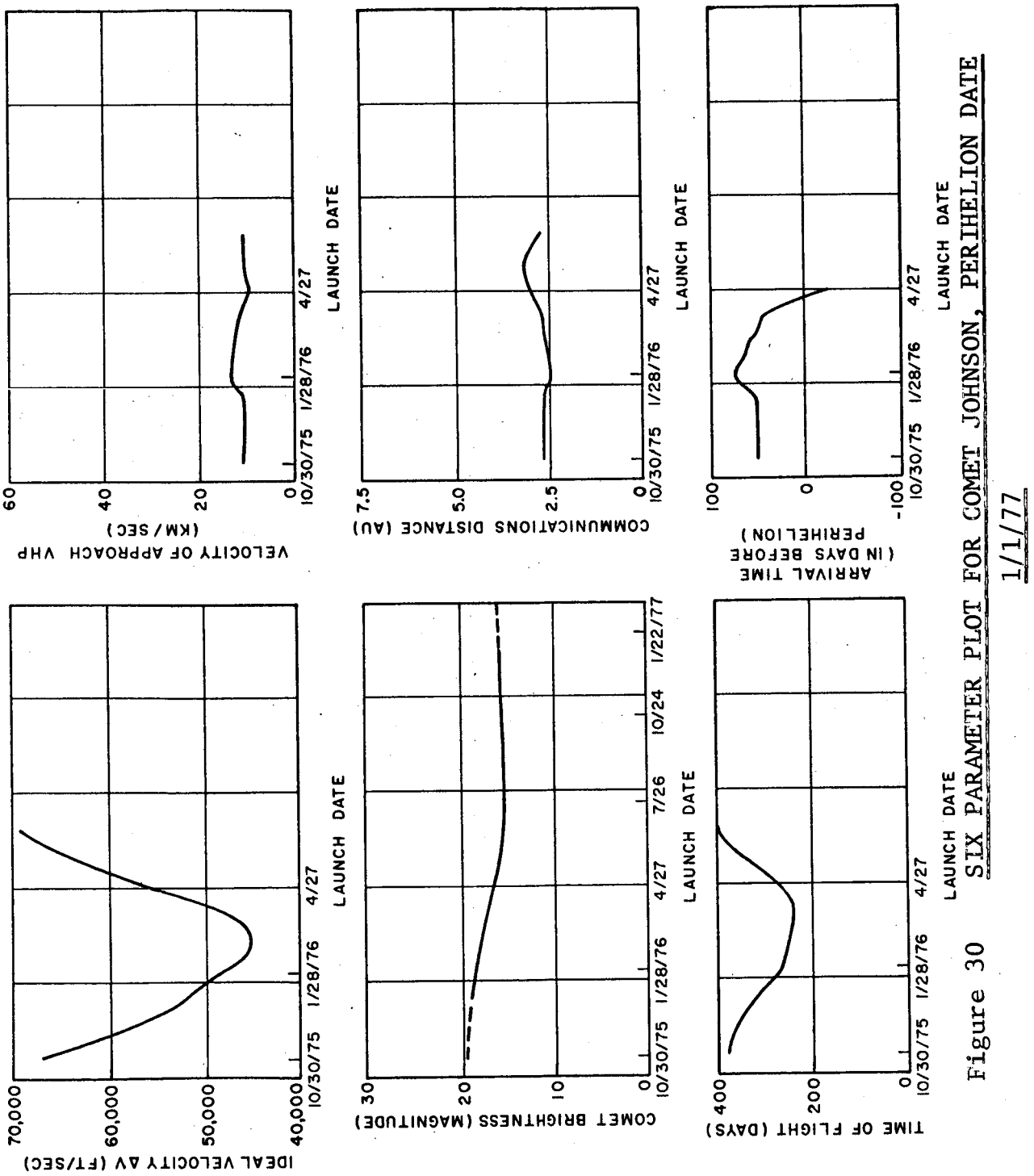

Figure 30 SIX PARAMETER PLOT FOR COMET JOHNSON, PERIHELION DATE 1/1/77

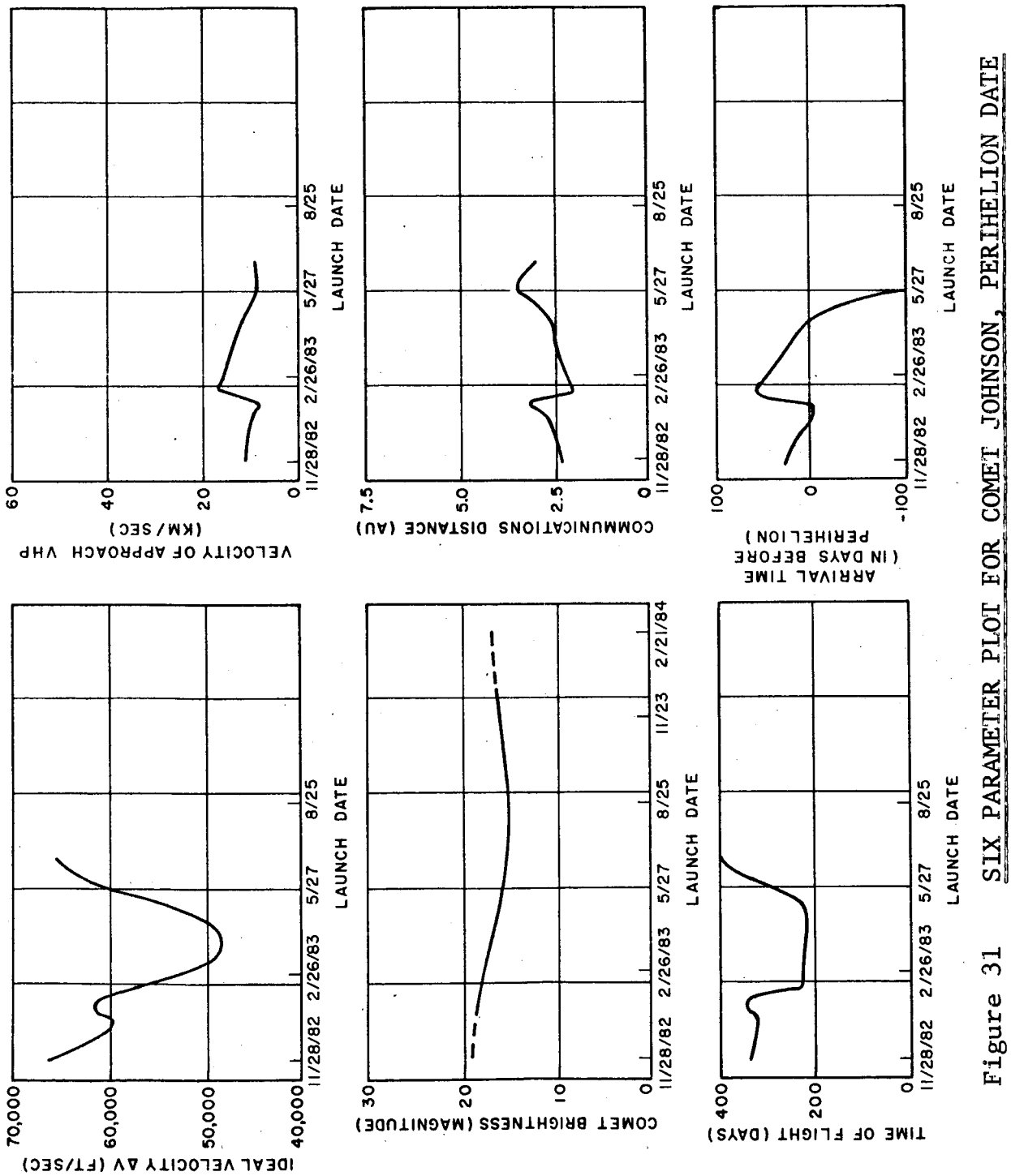

Figure 31 SIX PARAMETER PLOT FOR COMET JOHNSON, PERIHELION DATE 11/26/83

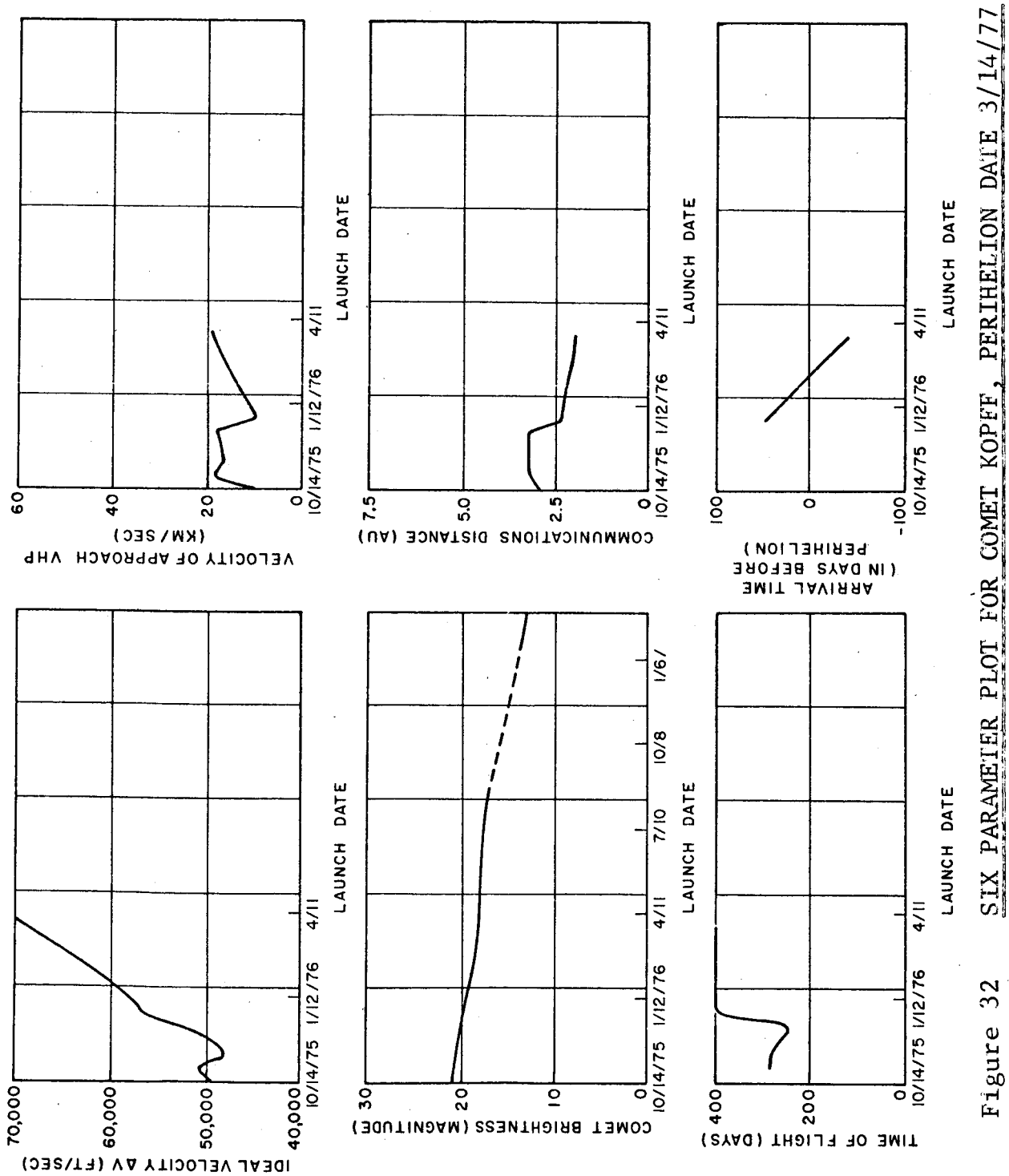

Figure 32 SIX PARAMETER PLOT FOR COMET KOPFF, PERIHELION DATE 3/14/77

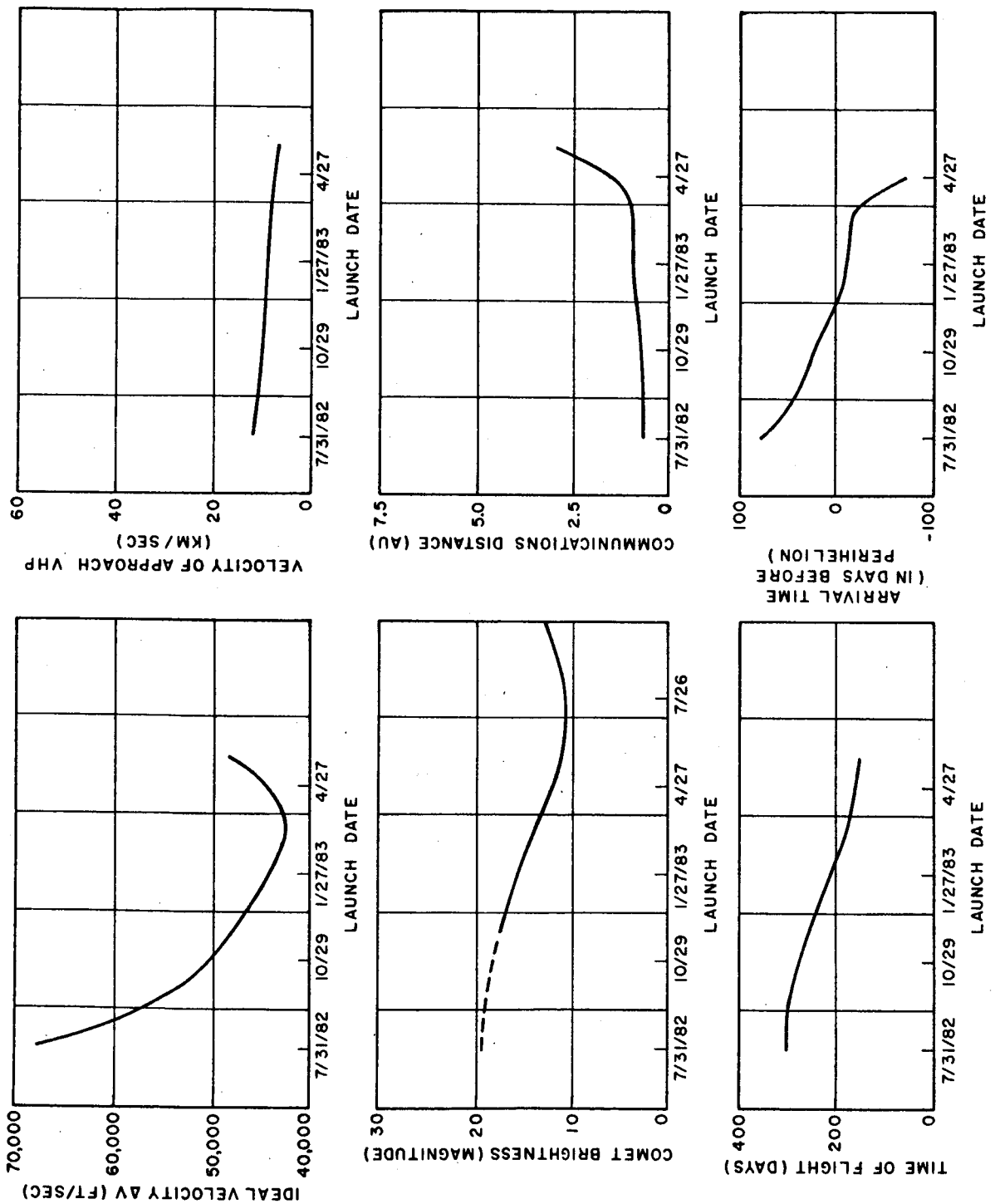

Figure 33 SIX PARAMETER PLOT FOR COMET KOPFF, PERIHELION DATE 8/18/83

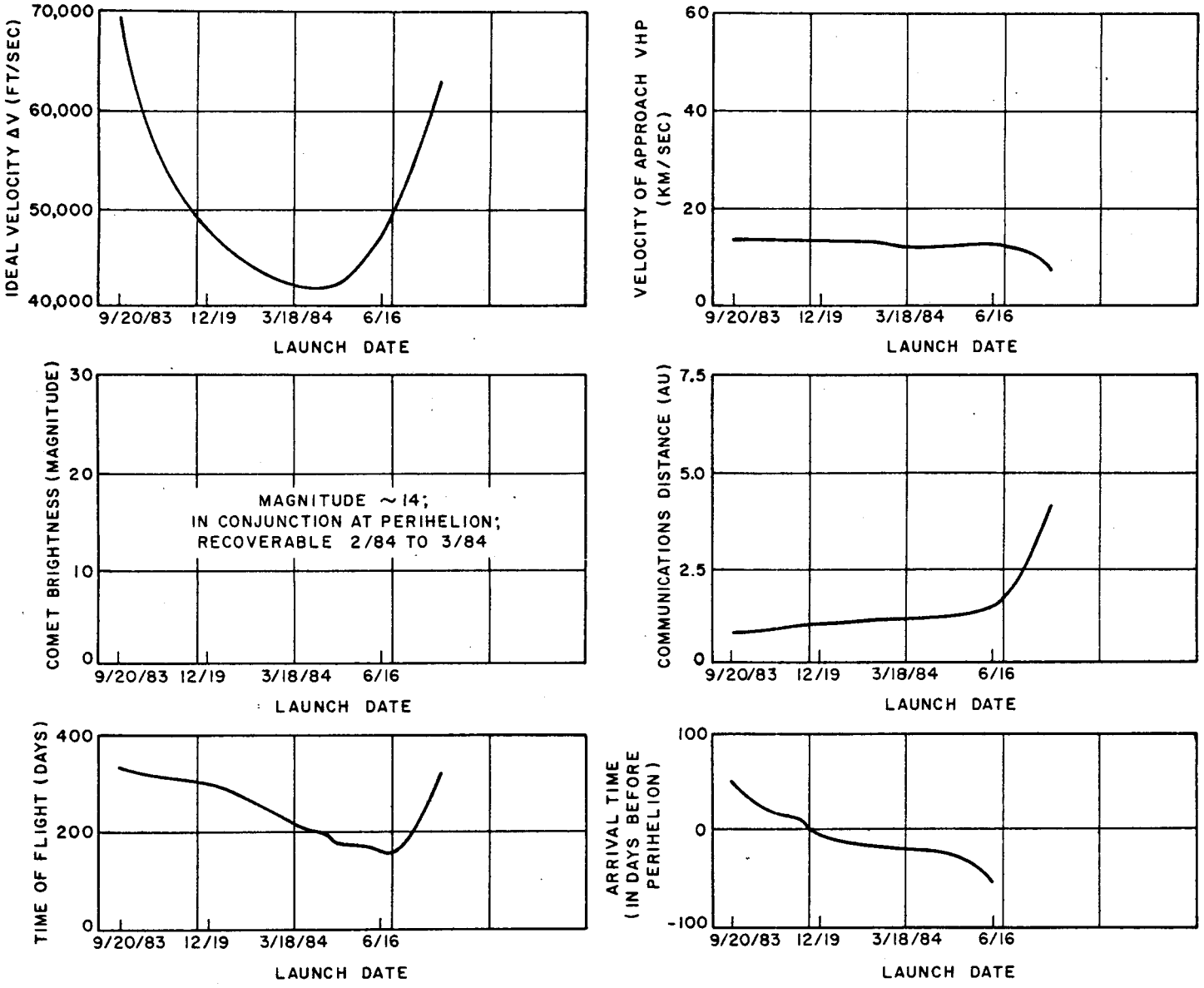

Figure 34 SIX PARAMETER PLOT FOR COMET NEUJMIN 1, PERIHELION DATE 10/8/84

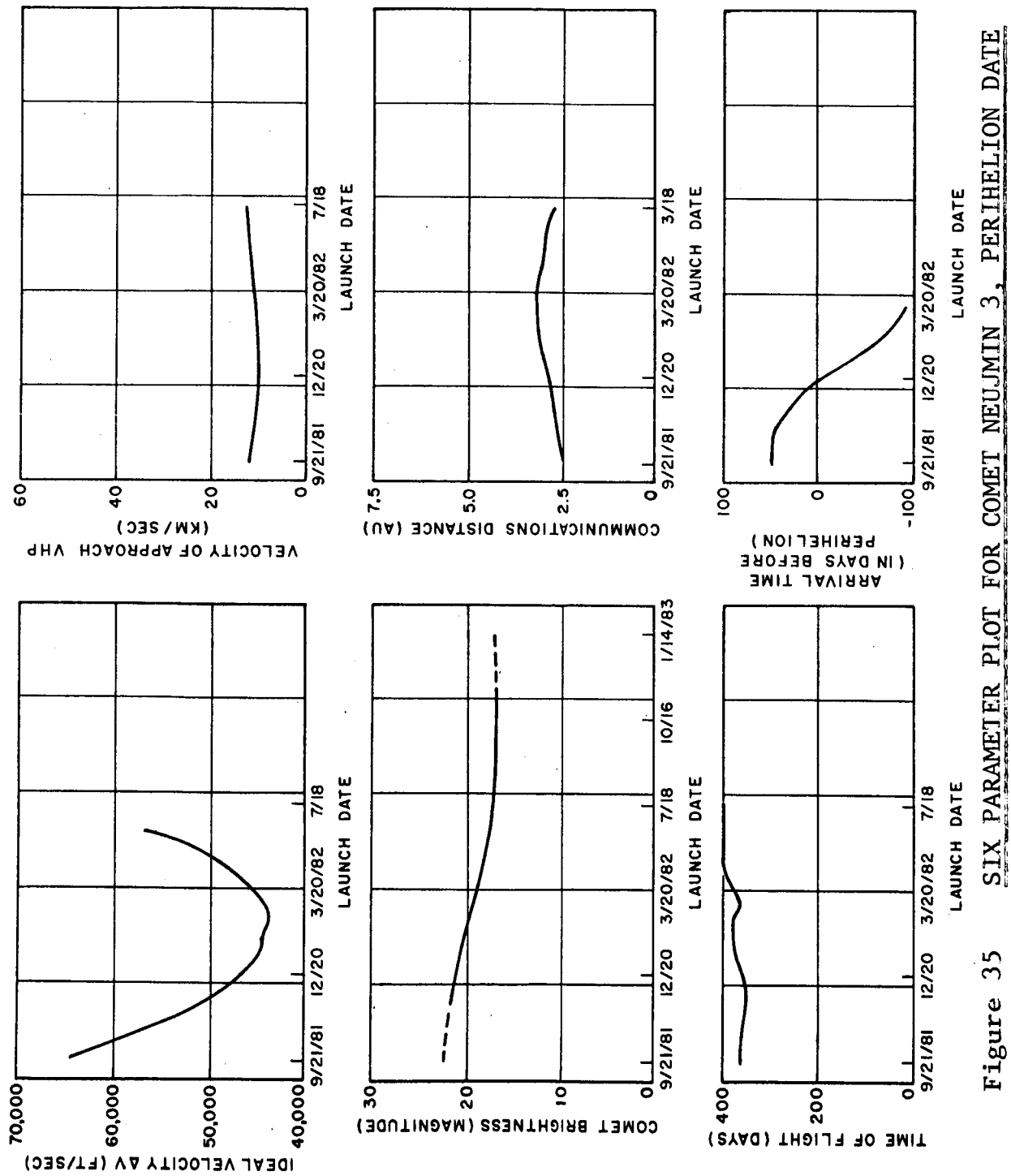

Figure 35 SIX PARAMETER PLOT FOR COMET NEUJMIN 3, PERIHELION DATE 12/8/82

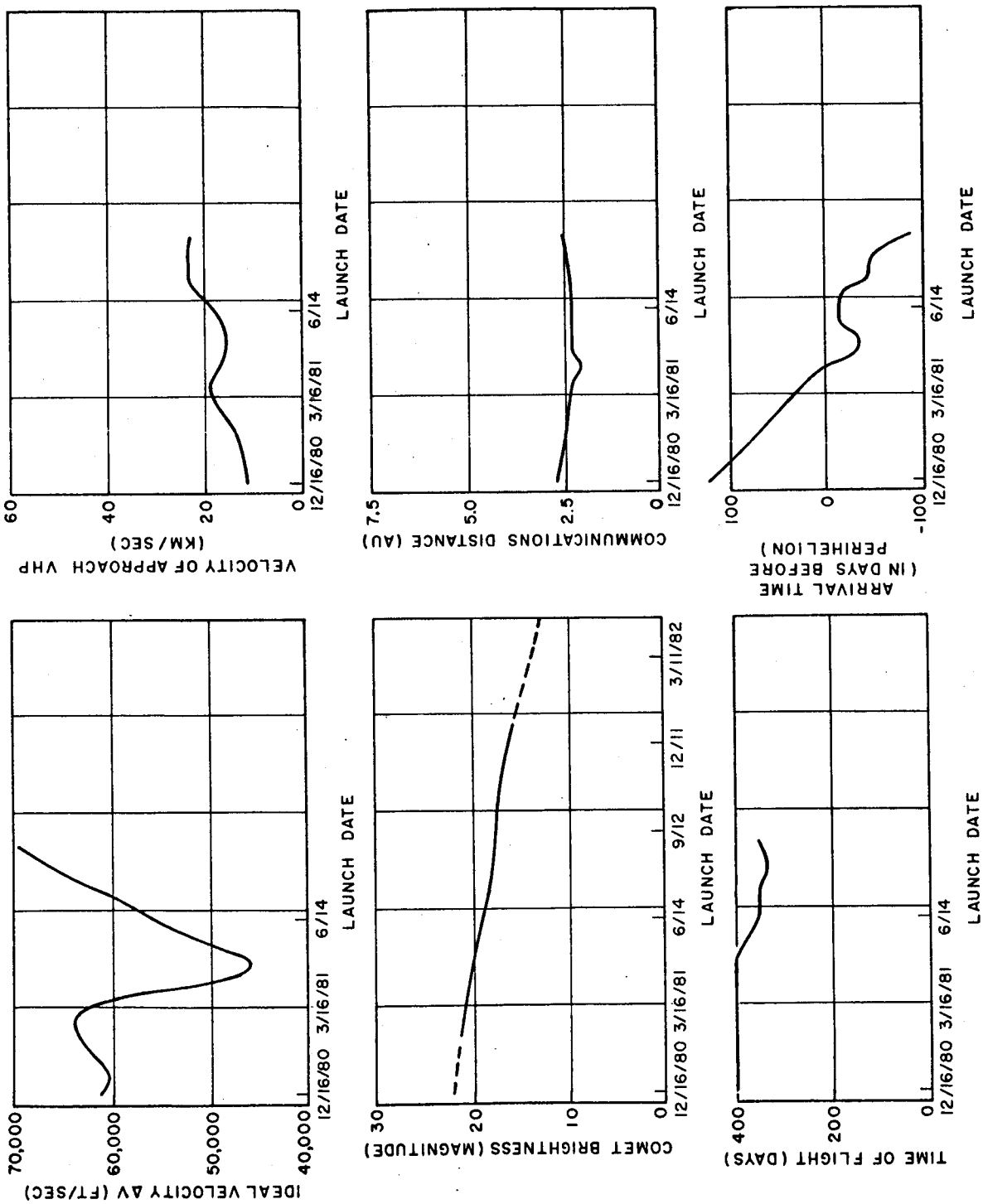

Figure 36 SIX PARAMETER PLOT FOR COMET PERRINE-MRKOS, PERIHELION DATE 5/16/82

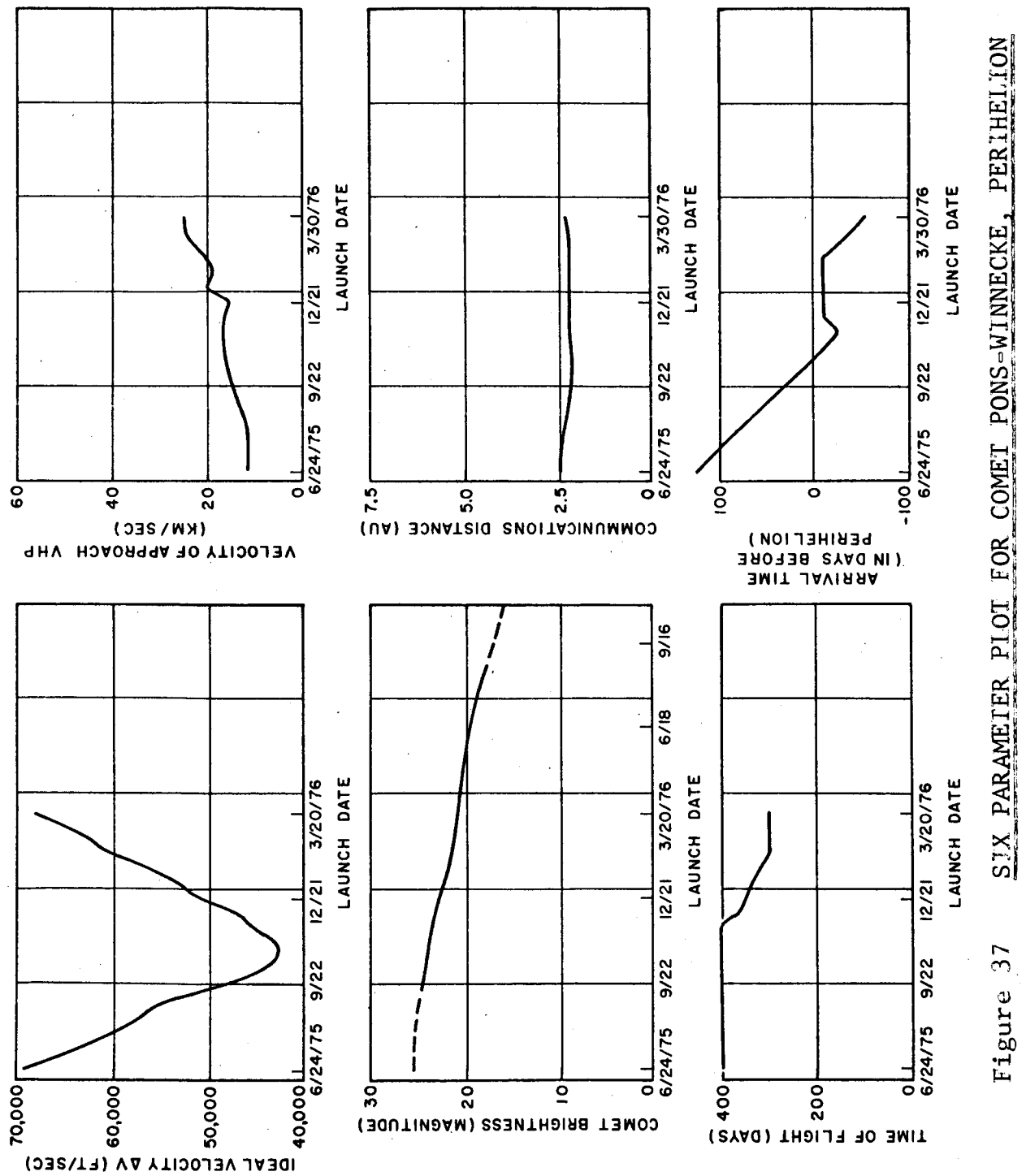

Figure 37 SIX PARAMETER PLOT FOR COMET PONS-WINNECKE, PERIHELION DATE 11/24/76

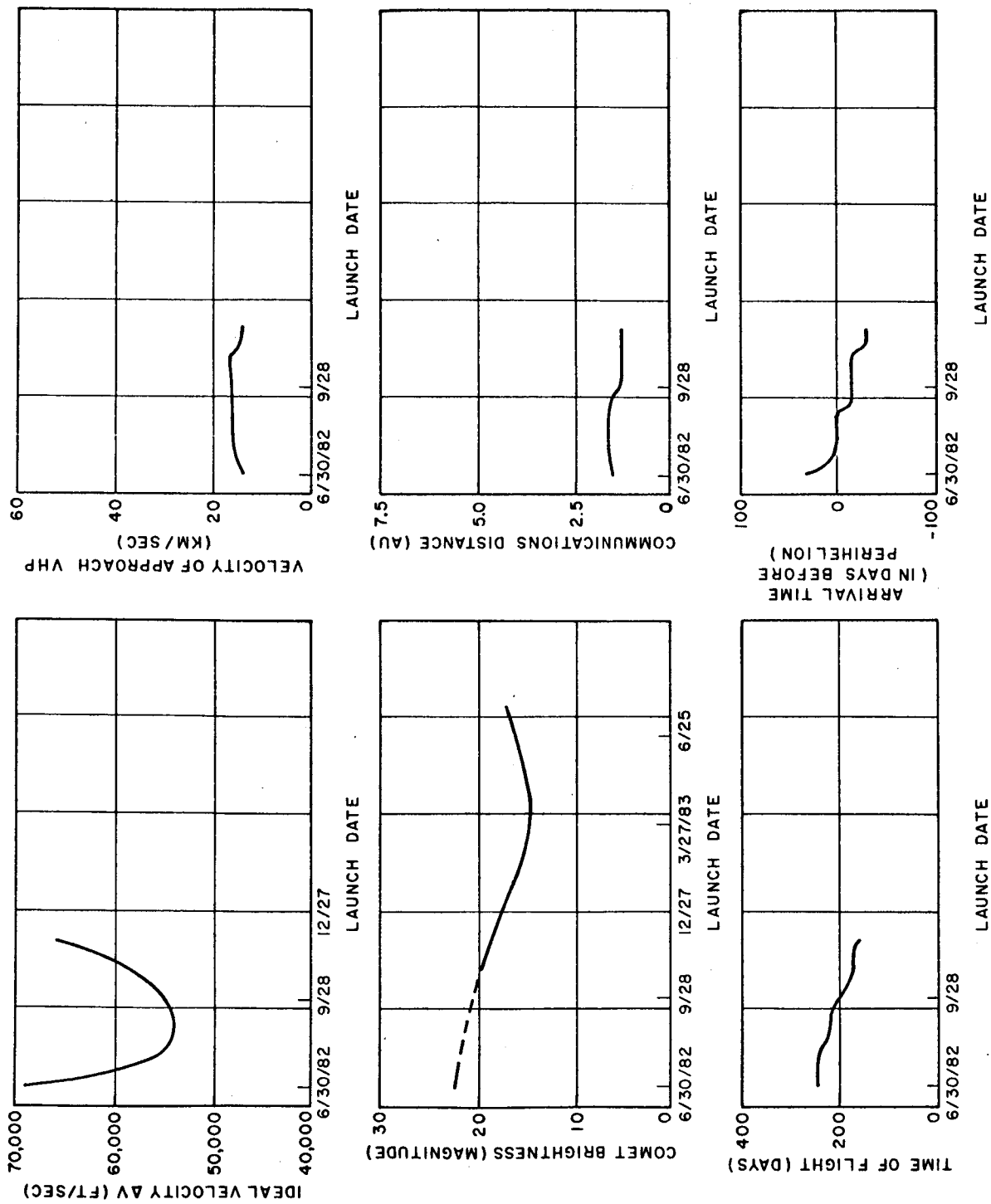

Figure 38 SIX PARAMETER PLOT FOR COMET PONS-WINNECKE, PERIHELION DATE 4/2/83

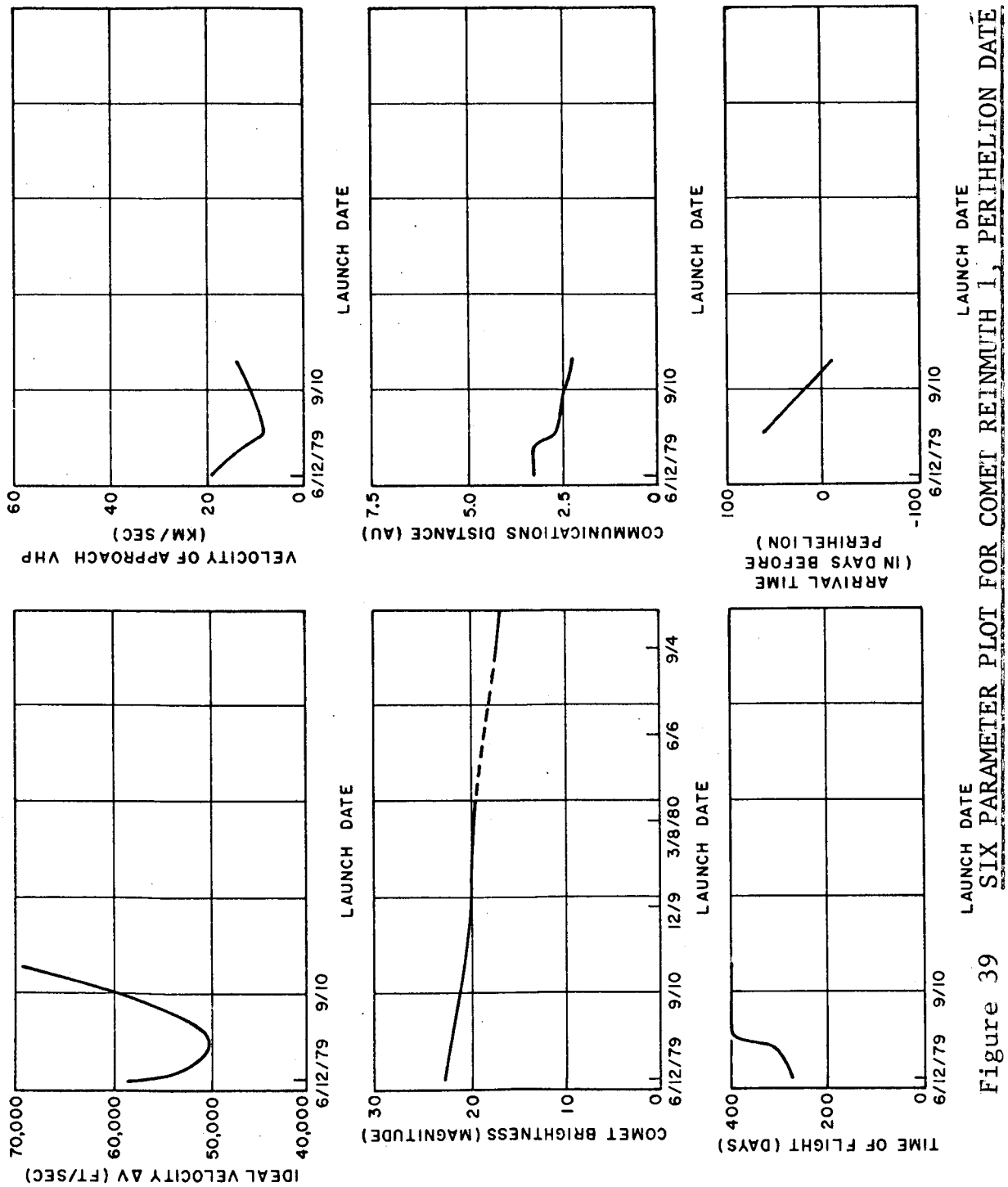

Figure 39 SIX PARAMETER PLOT FOR COMET REINMUTH 1, PERIHELION DATE 10/28/80

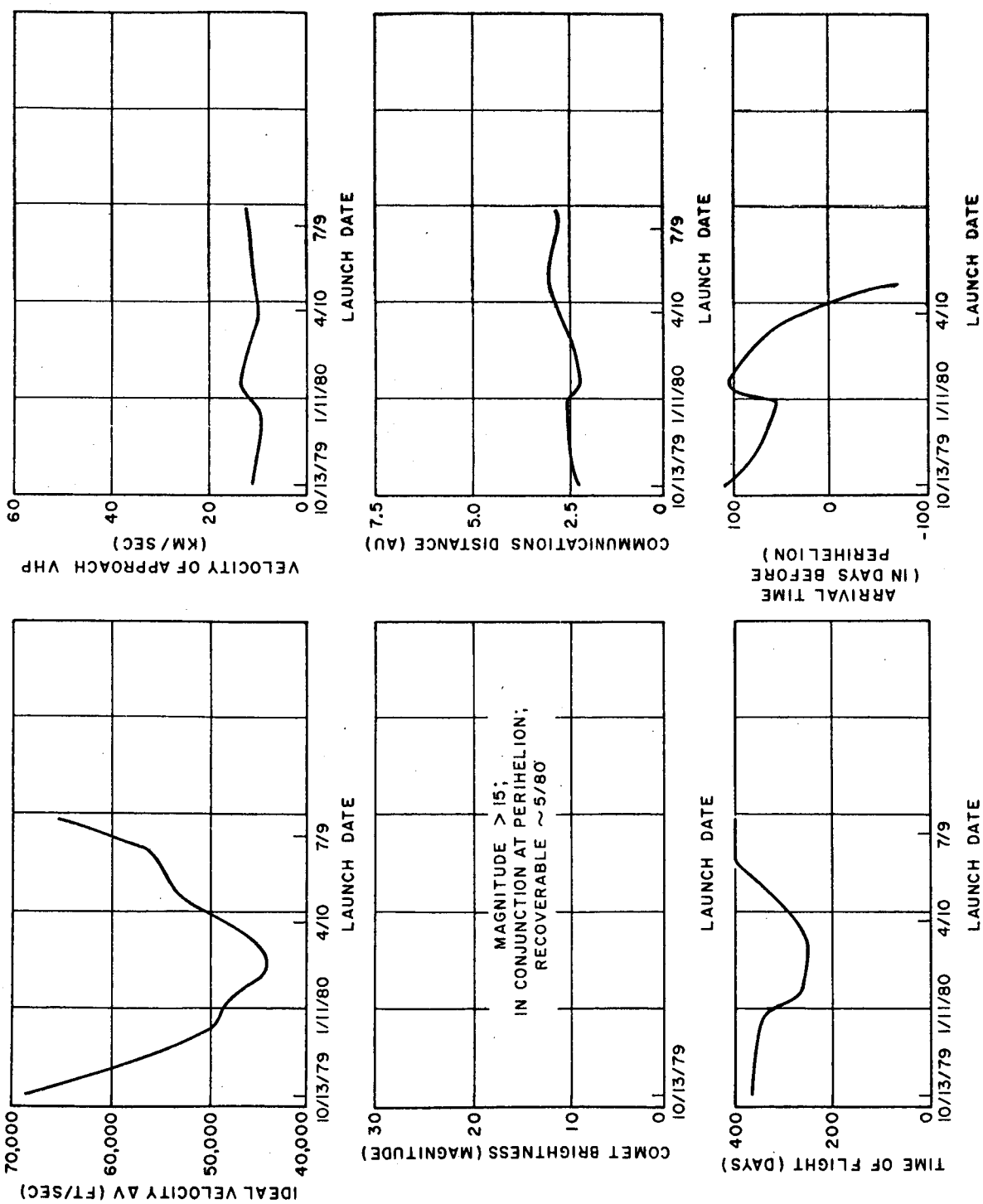

Figure 40 SIX PARAMETER PLOT FOR COMET REINMUTH 2, PERIHELION DATE 1/29/81

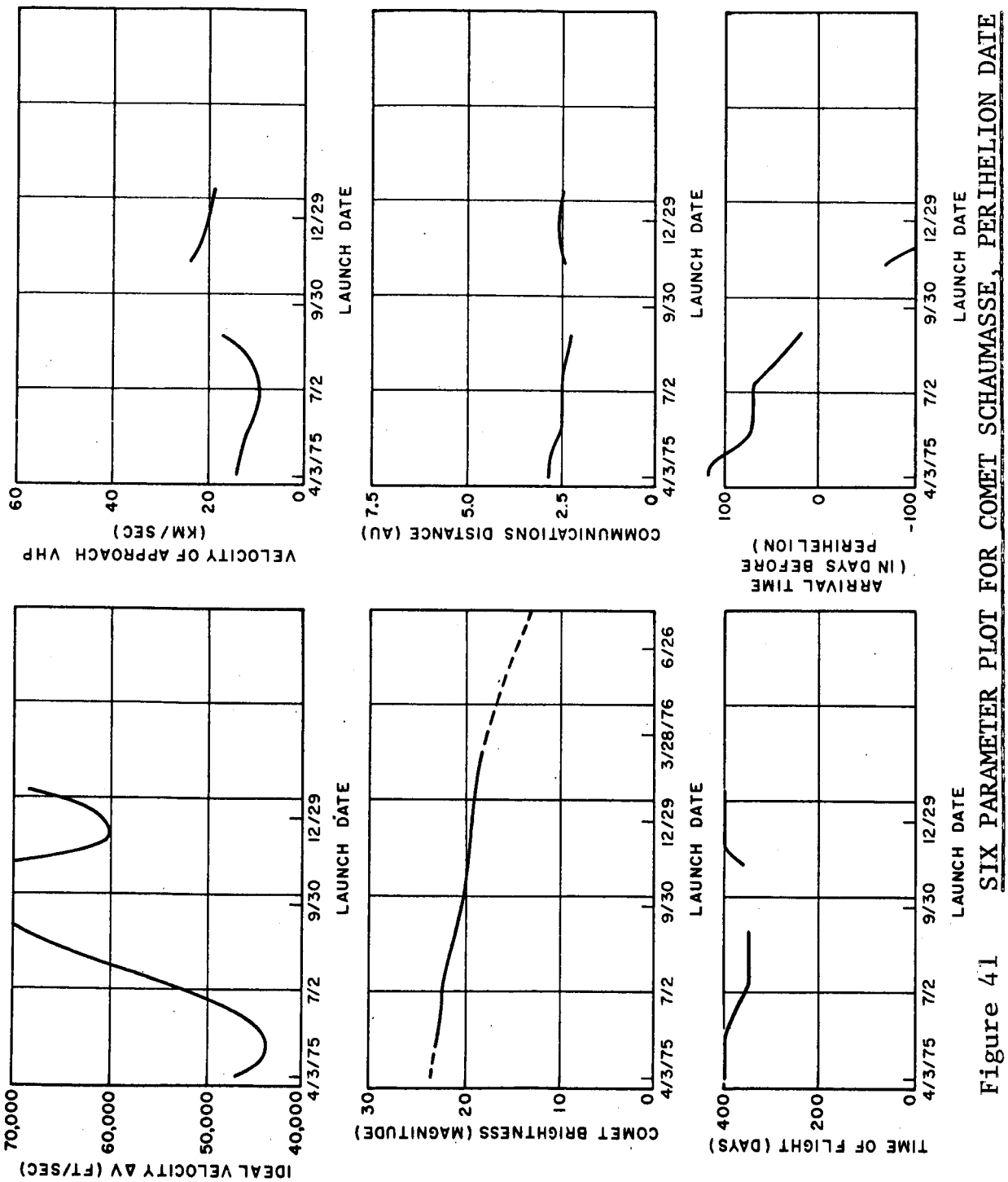

Figure 41 SIX PARAMETER PLOT FOR COMET SCHAUMASSE, PERIHELION DATE 9/3/76

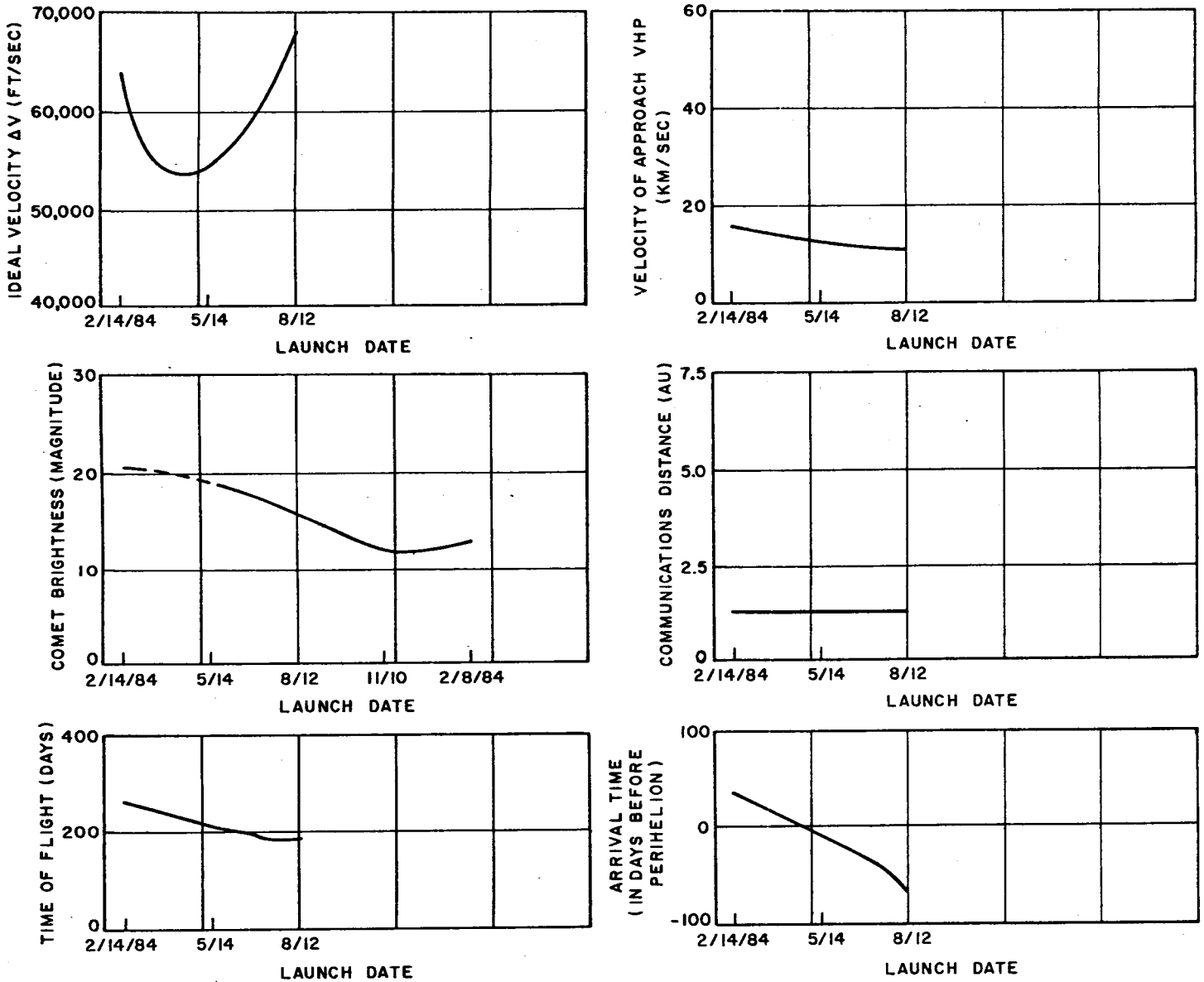

Figure 42 SIX PARAMETER PLOT FOR COMET SCHAUMASSE, PERIHELION DATE 12/4/84

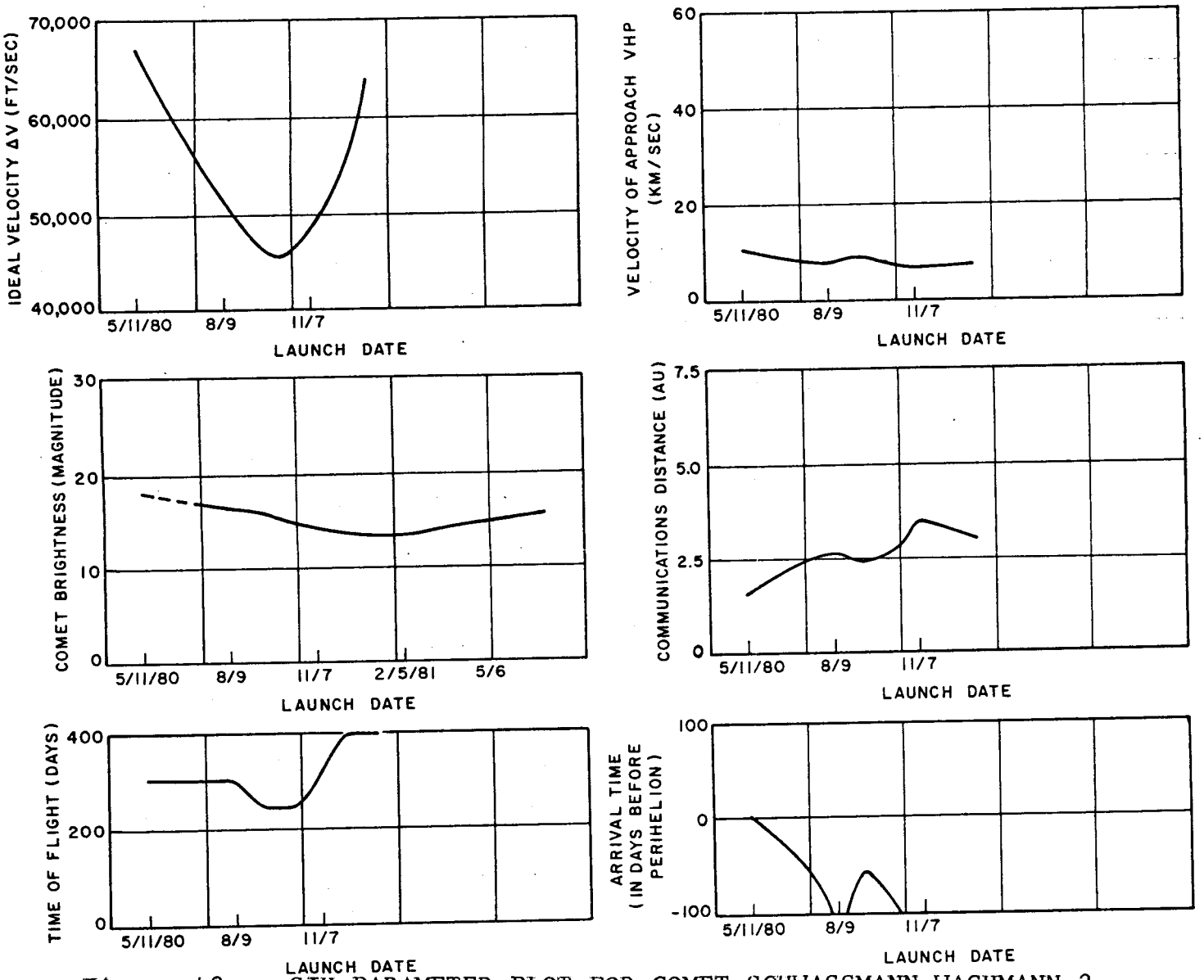

Figure 43 SIX PARAMETER PLOT FOR COMET SCHWASSMANN-WACHMANN 2, PERIHELION DATE 3/14/81

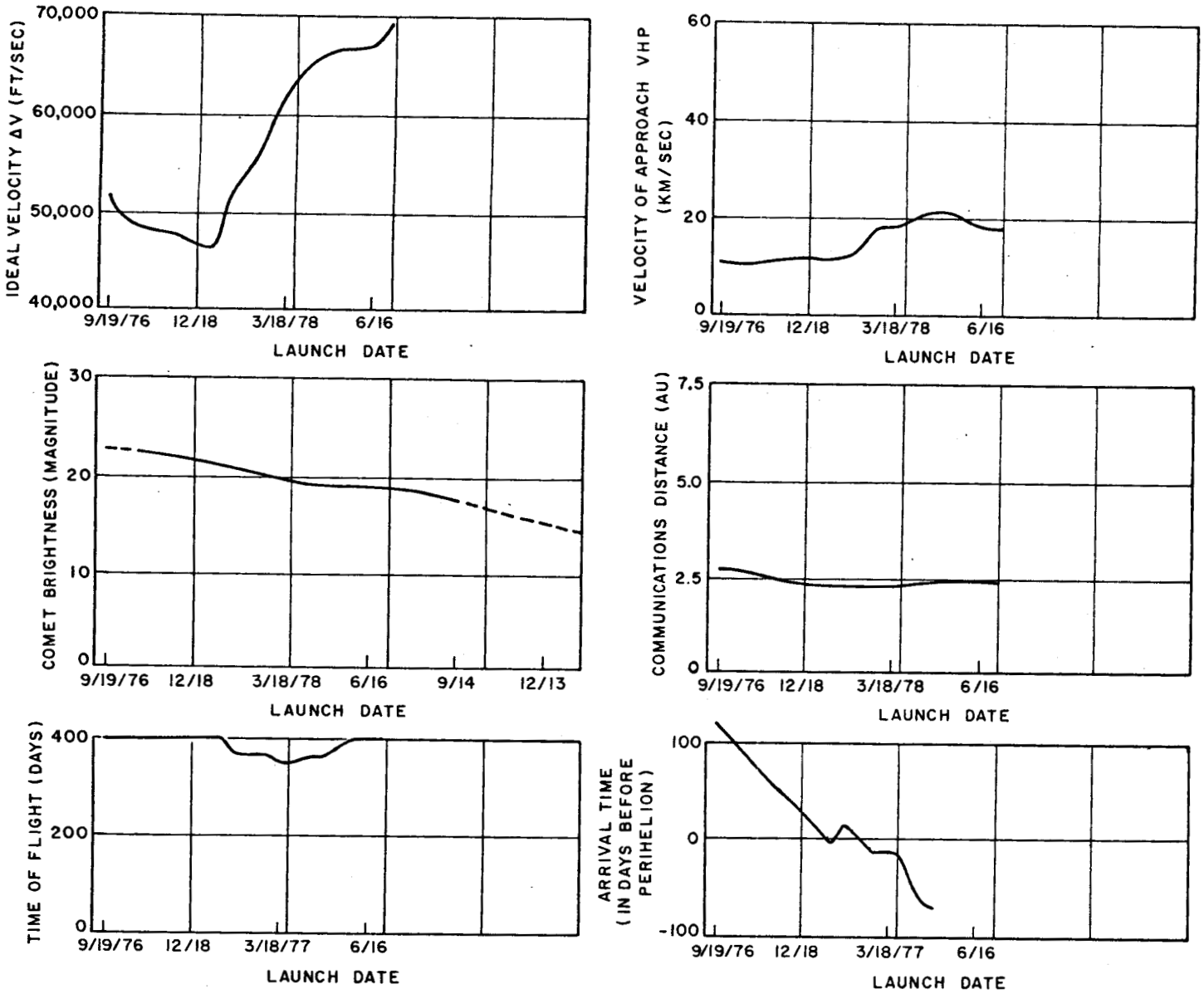

Figure 44 SIX PARAMETER PLOT FOR COMET TEMPEL 2, PERIHELION DATE 2/19/78

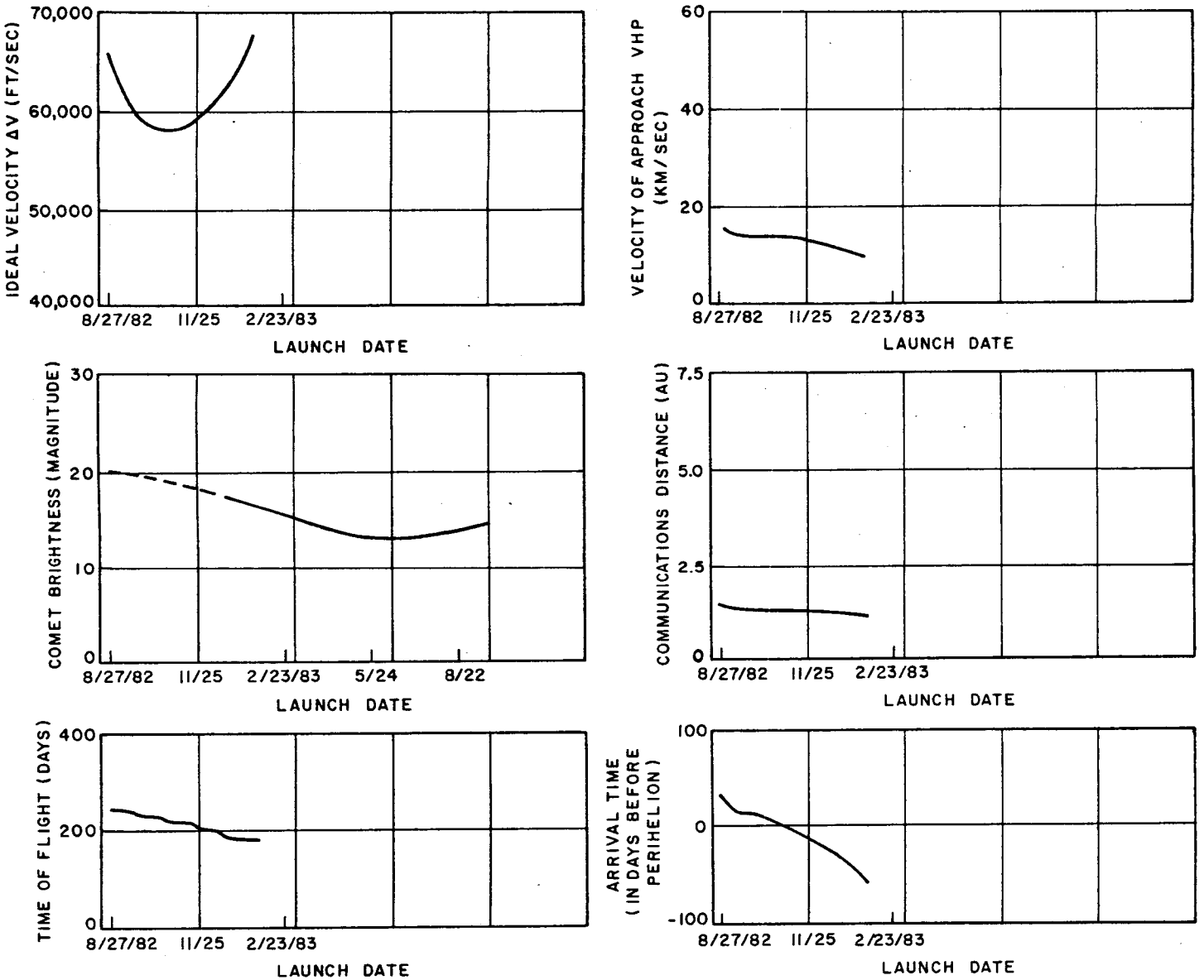

Figure 45 SIX PARAMETER PLOT FOR COMET TEMPEL 2, PERIHELION DATE 5/30/83

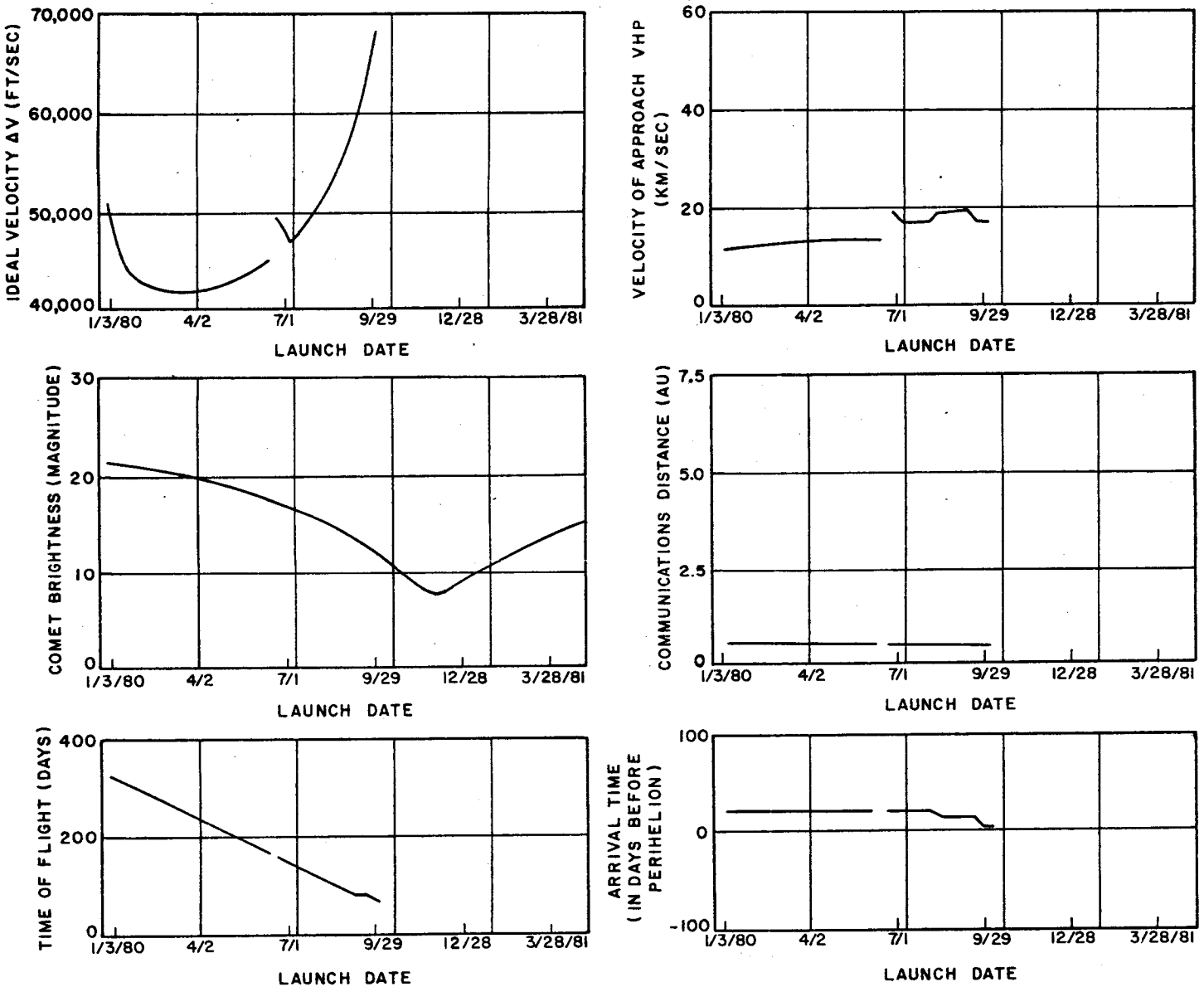

Figure 46 SIX PARAMETER PLOT FOR COMET TUTTLE, PERIHELION DATE 12/13/80

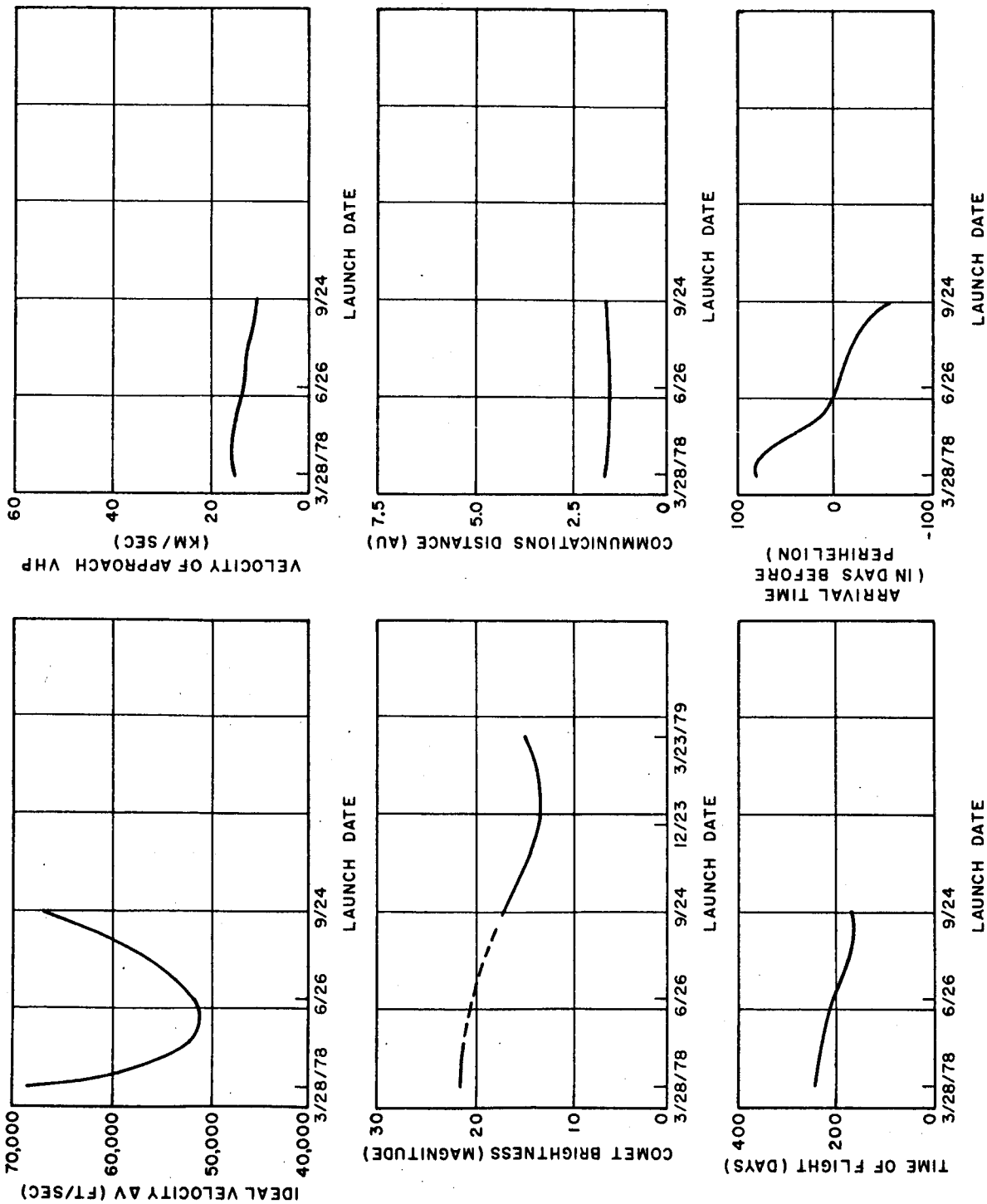

Figure 47 SIX PARAMETER PLOT FOR COMET TUTTLE-GIACOBINI-KRESAK, PERIHELION DATE 1/15/79

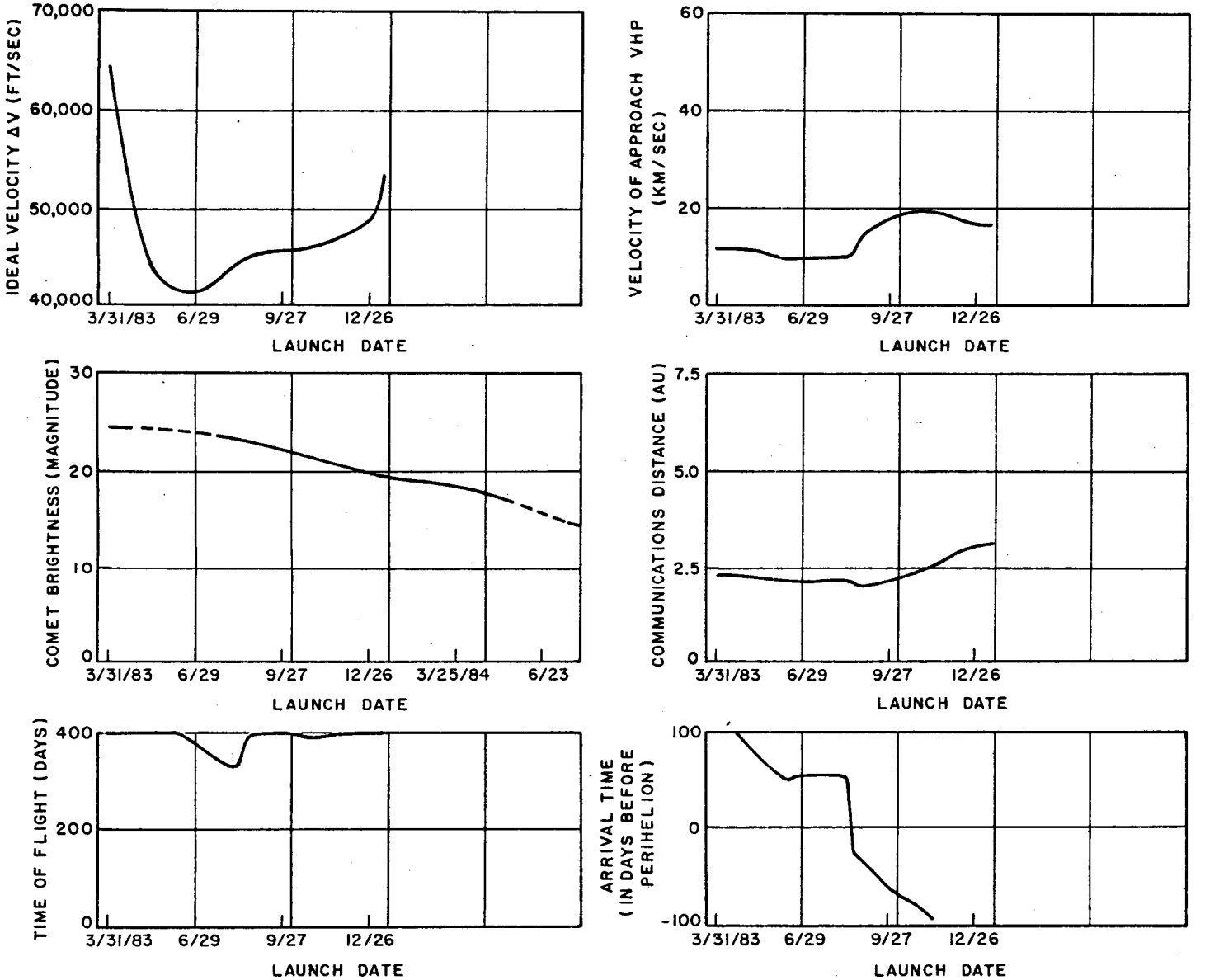

Figure 48 SIX PARAMETER PLOT FOR COMET TUTTLE-GIACOBINI-KRESAK, PERIHELION DATE 8/31/84

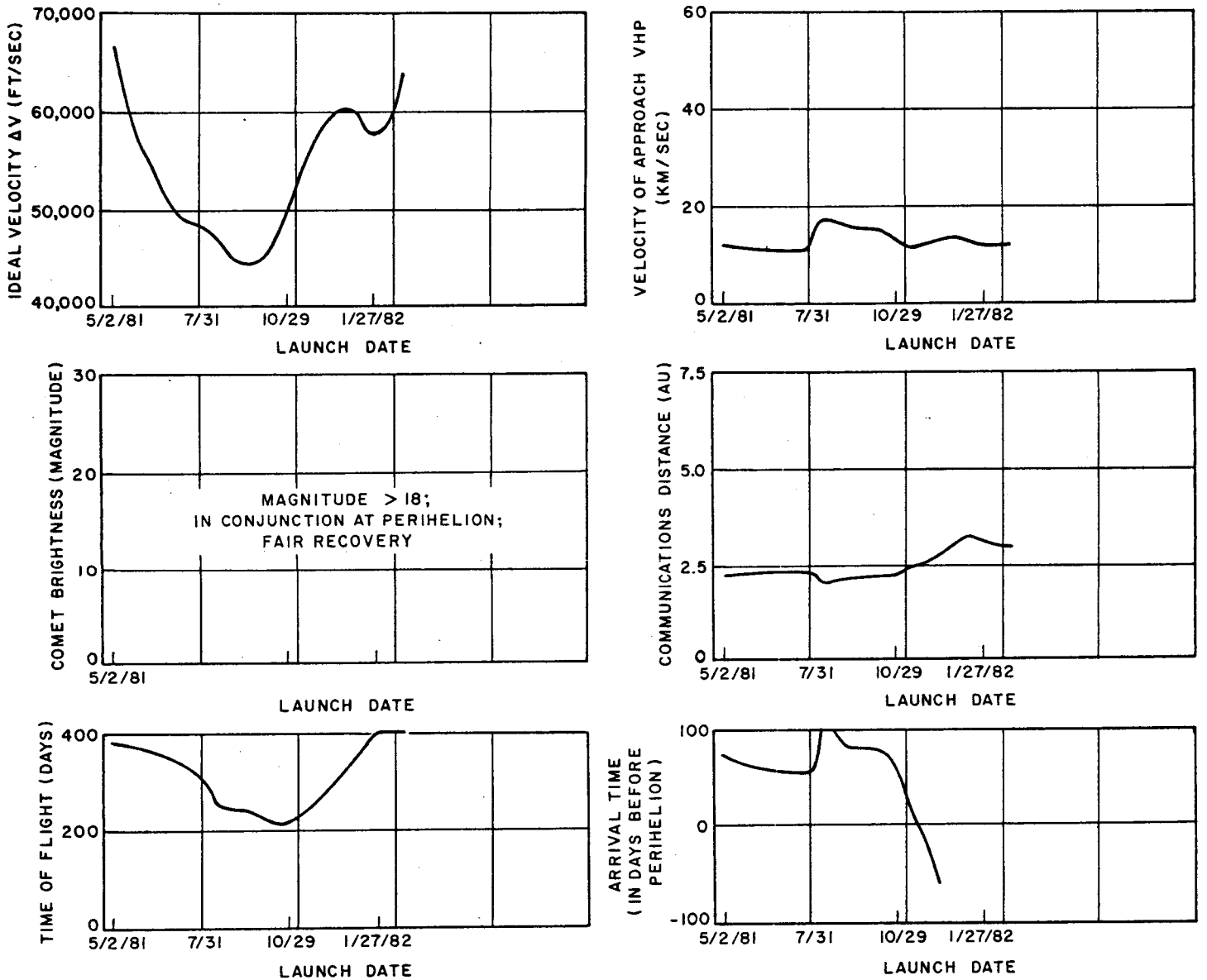

Figure 49 SIX PARAMETER PLOT FOR COMET VAISALA, PERIHELION DATE 8/1/82

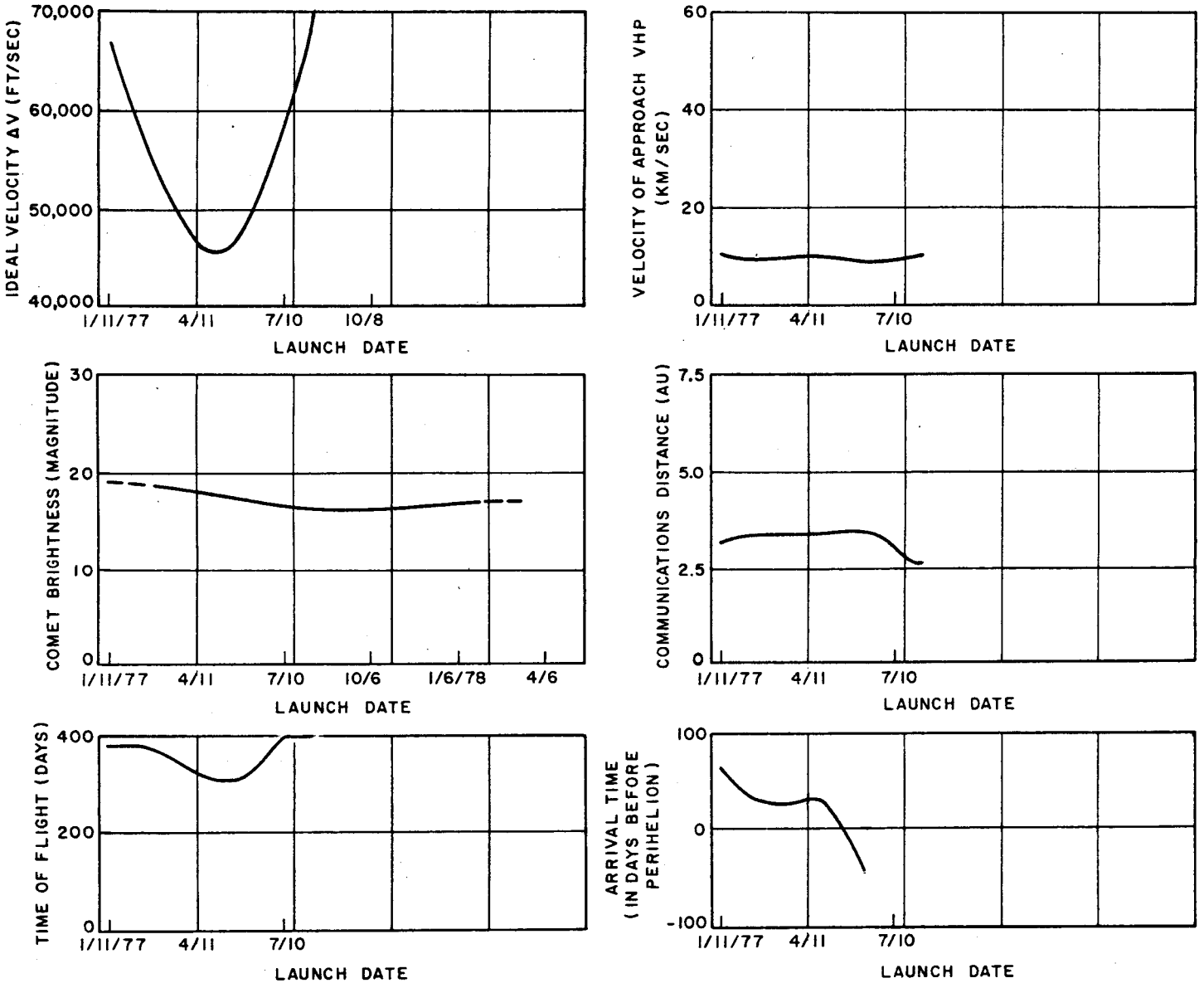

Figure 50 SIX PARAMETER PLOT FOR COMET WHIPPLE, PERIHELION DATE 3/28/78

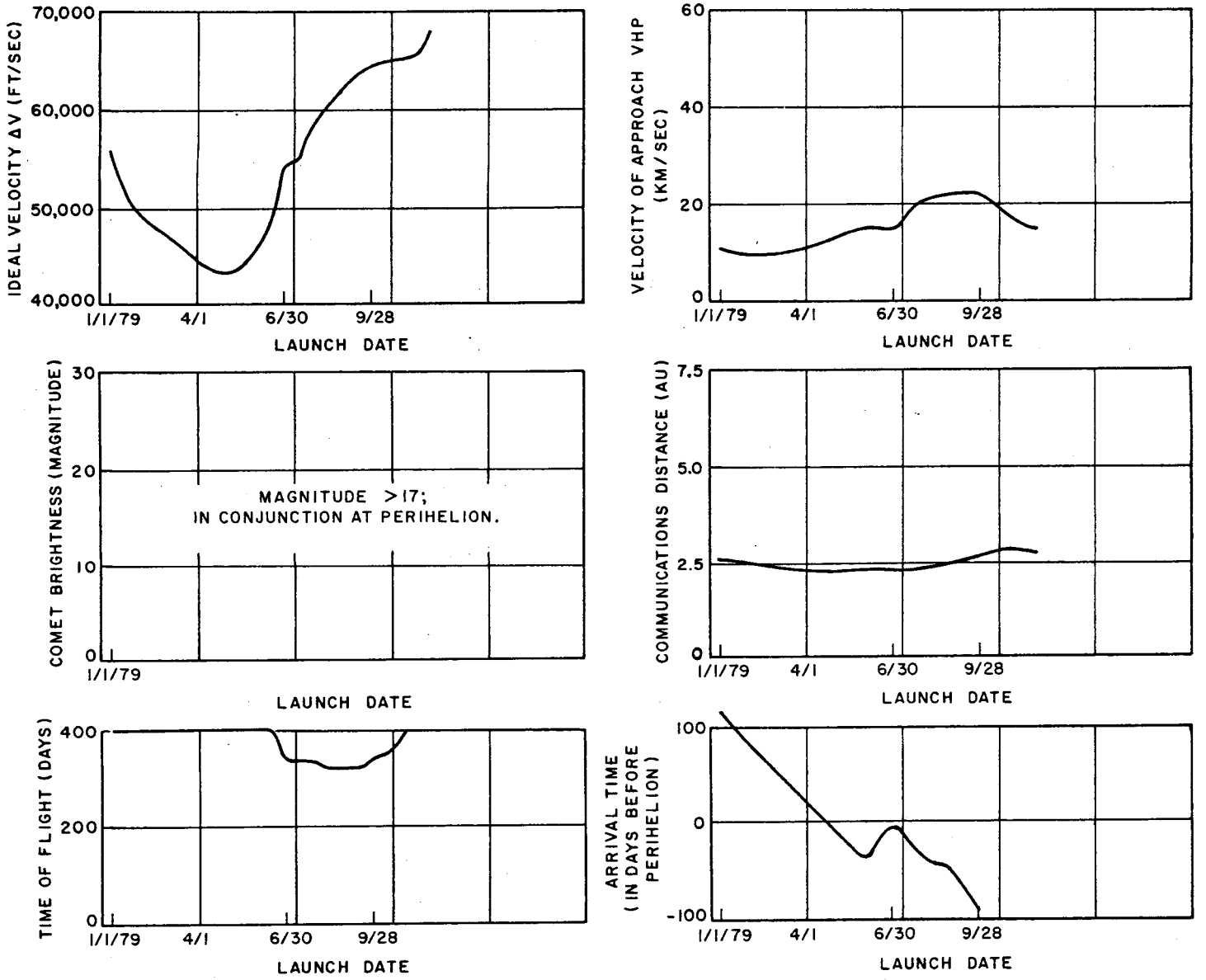

Figure 51 SIX PARAMETER PLOT FOR COMET WIRTANEN, PERIHELION DATE 5/26/80

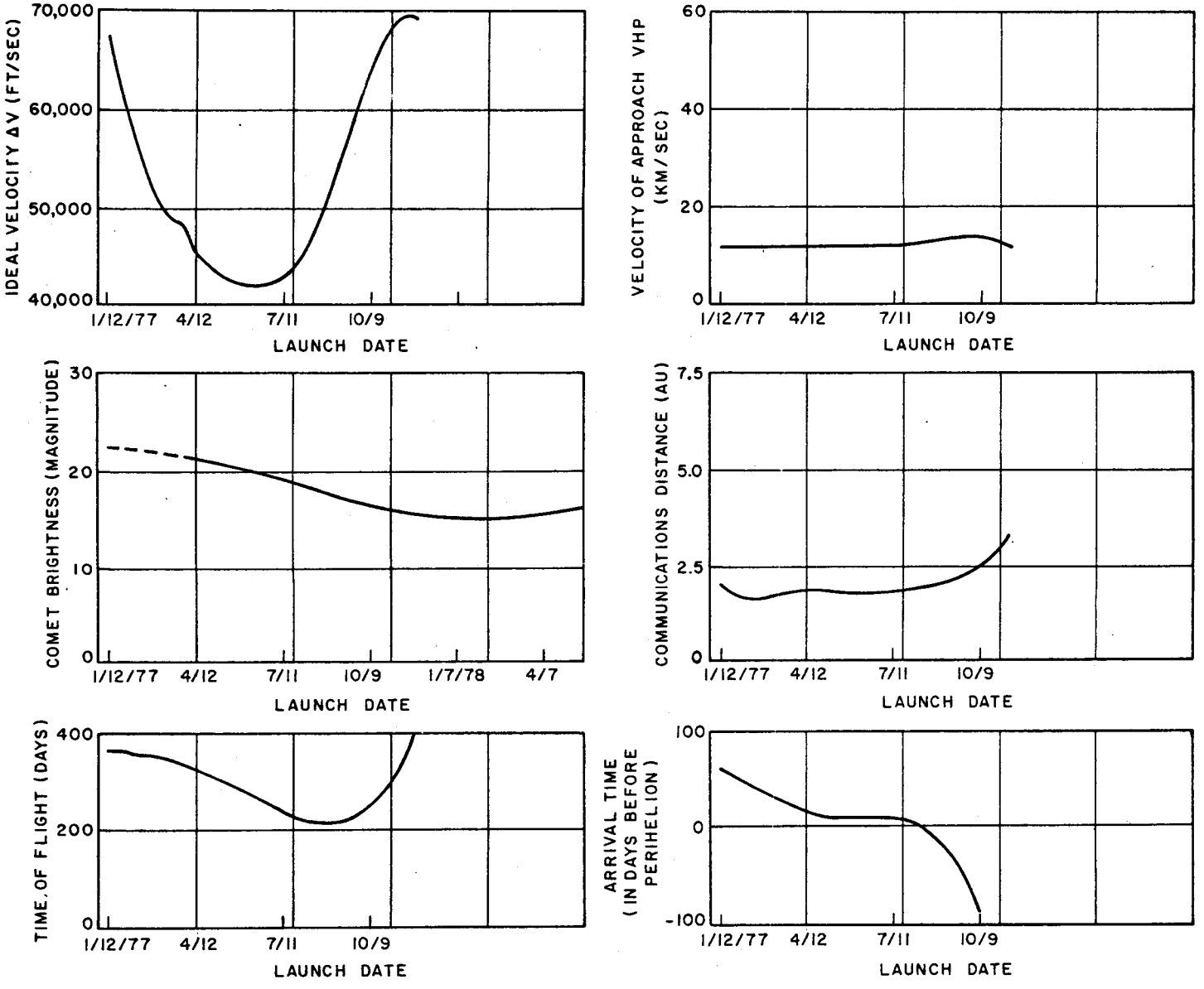

Figure 52 SIX PARAMETER PLOT FOR COMET WOLF-HARRINGTON, PERIHELION DATE 3/14/78

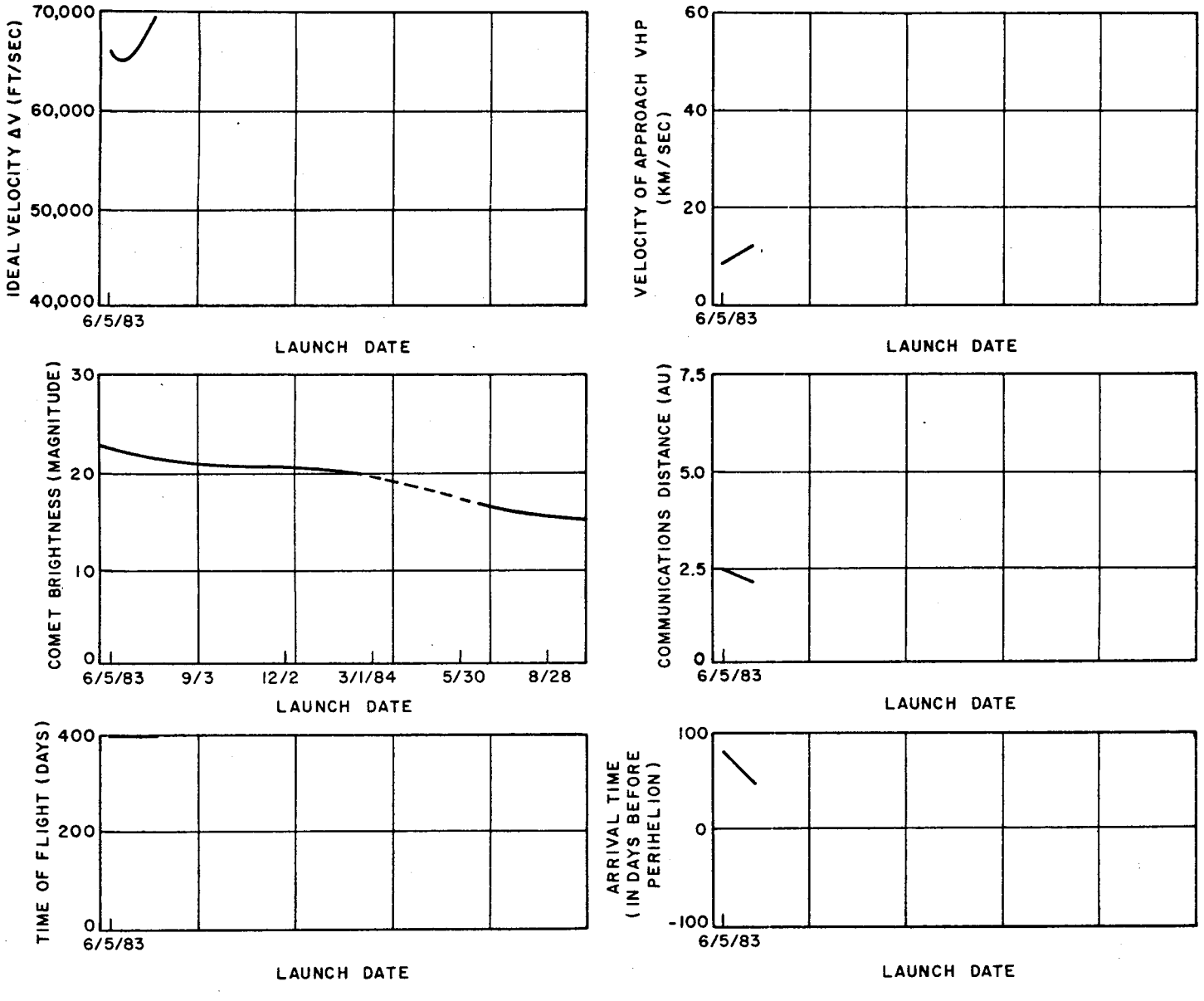

Figure 53 SIX PARAMETER PLOT FOR COMET WOLF-HARRINGTON, PERIHELION DATE 9/21/84

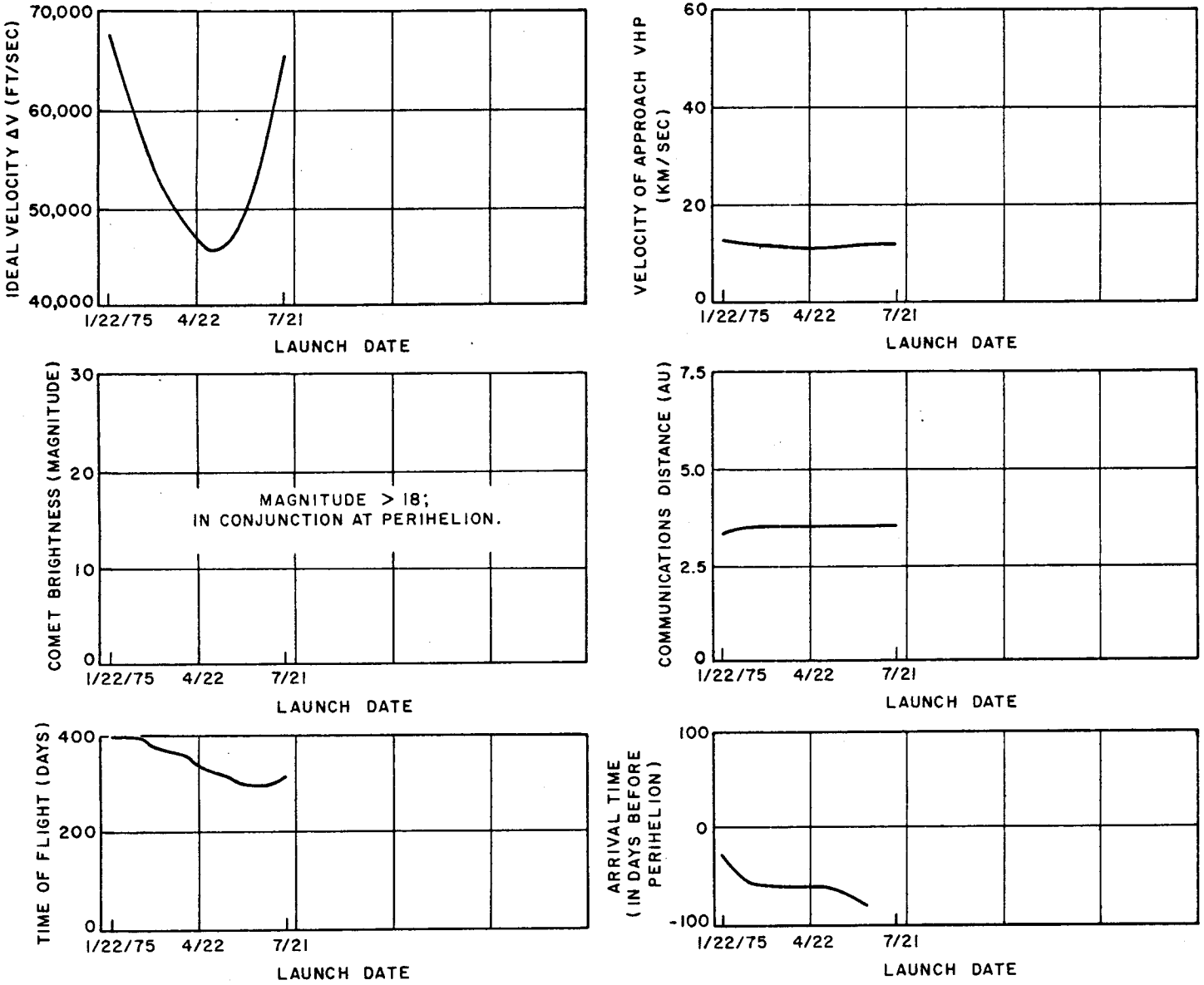

Figure 54 SIX PARAMETER PLOT FOR COMET WOLF, PERIHELION DATE 1/25/76

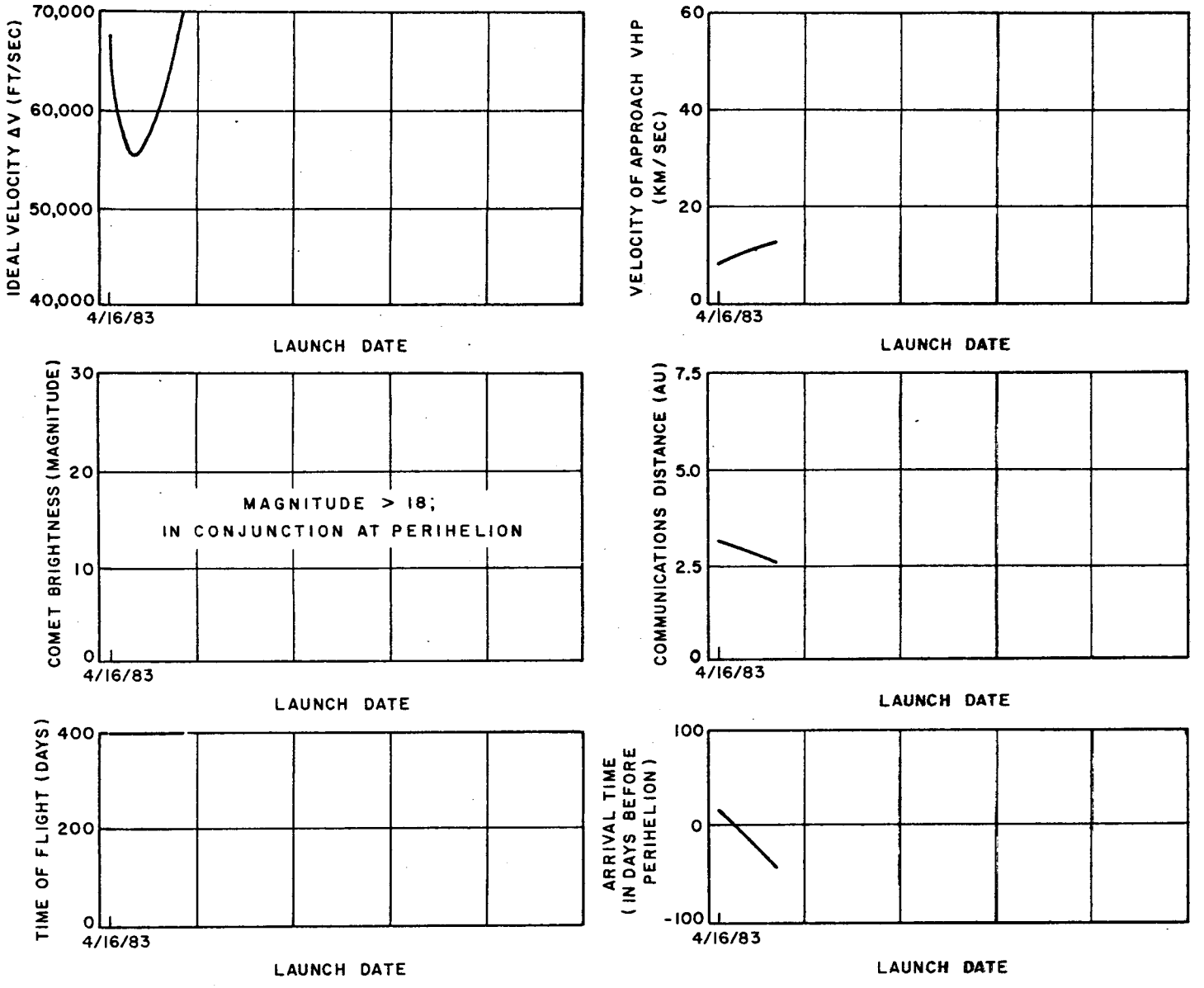

Figure 55 SIX PARAMETER PLOT FOR COMET WOLF, PERIHELION DATE 5/31/84