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by Tim J. Kreiter

Lewis Research Center
Cleveland, Ohio

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SUMMARY

Intercept trajectories to asteroid Eros and comet D'arrest were investigated using a three-dimensional, patched conic, analysis technique. Launch intervals and launch windows are established for trajectories encountering Eros and D'arrest at their perihelia. These trajectories exhibit near-minimum injection energy requirements inasmuch as the perihelia of Eros and D'arrest lie very nearly in the ecliptic plane. Geocentric and heliocentric trajectory parameters are presented graphically, and the payload capabilities of three launch vehicles (SLV-3A/Agena, SLV-3C/Kick, and SLV-3C/Centaur) are given for these opportunities.

INTRODUCTION

One of the principal objectives of the United States space effort is the accumulation of scientific information on a broad front. Emphasizing the investigation of phenomenon within the solar system, current programs are directed toward the Moon, Mars, and Venus as evidenced by the Ranger, Mariner, Surveyor, Apollo, and Voyager projects. Trips to Mercury, Jupiter, Saturn, and other destinations will be forthcoming as adequate spacecraft and booster technology become available.

Many advanced interplanetary missions can be performed, however, using present boosters in conjunction with appropriate upper stages. Examples of these are asteroid and cometary probes.

In this study, the 1974 asteroid Eros and the 1976 comet D'arrest opportunities were investigated. They typify advanced missions of considerable scientific importance which could be attempted in the near future by using, for the most part, present-day technology.

Eros is the largest of the close-approach asteroids. Its unusual shape (supposedly 22 km by 6 km) suggests a fragmentary origin; therefore, it has always been high on the list of astronomical curiosities in our solar system. Its period is about 1.76 years, and the most attractive launch opportunities from launch energy considerations occur in 1974 and 1982.

The comet D'arrest opportunity in 1976 has been described in reference 1 as the best comet mission between 1965 and 1986. Up to 6 months of tracking are available prior to launch, and trajectories may be selected which will encounter the comet at perihelion. Perihelion encounters are desirable because a comet is brightest and most active at perihelion. The magnitude of D'arrest at perihelion is about 6.5, which is sufficient brightness to allow correlation between probe measurements and Earth-based measurements at intercept.

Three candidate booster vehicles were selected in this study for payload comparisons since the spacecraft weights desired for these missions have not been determined and will depend primarily on the complexity of the scientific experiments. The boosters considered were the SLV-3A/Agena, the SLV-3C/Kick, and the SLV-3C/Centaur. The SLV-3A/Agena and SLV-3C/Centaur are advanced versions of the present Atlas/Agena and Atlas/Centaur boosters, respectively. The SLV-3C/Kick vehicle is a proposed launch vehicle that would utilize a new high energy upper stage (kick stage).

ANALYSIS

The SLV-3A/Agena, SLV-3C/Kick, and SLV-3C/Centaur launch vehicles are shown in figure 1. The SLV-3A/Agena and the SLV-3C/Centaur will not be discussed in detail since they are derived from relatively well-known vehicles and are currently being developed for use by NASA . The kick stage, however, is a proposed stage and several configurations are presently under study. The specific configuration assumed herein is a liquid-hydrogen - liquid-oxygen system having a 7000-pound propellant capacity and being powered by one 15 000-pound-thrust engine. The kick-stage jettison weight was assumed to be about 1800 pounds. More details on various kick-stage designs may be found in reference 2.

The SLV-3A/Agena, SLV-3C/Kick, and SLV-3C/Centaur payload capabilities are shown as functions of geocentric vis-viva injection energy in figure 2. (Vis-viva energy is twice the total energy of the planetocentric conic.) The booster data presented in figure 2 were obtained by integrating the equations of motion of the powered flight trajectories on a digital computer. Booster performance parameters and system weights were based on current available data. An indirect ascent flight mode having a 100-nautical-mile parking-orbit altitude was assumed, and a launch azimuth of 115° east of north was used in constructing the figure. Also incorporated into the booster data are 3σ flight performance reserves.

A patched conic, digital computer program was used to establish the vis-viva energy requirements for the asteroid and comet trajectories in this study. The patched conic technique treats the total trajectory in three distinct phases: (1) near-Earth phase wherein the conic is a hyperbola relative to the Earth, (2) heliocentric coast phase wherein the conic is an ellipse relative to the Sun, and (3) near-target phase wherein the motion is a hyperbola relative to the target body.

For a given launch date, the Earth's position in space (Sun-Earth vector at launch) may be computed by consulting an ephermeris or by computation on the basis of known orbital elements (the latter approach was used herein). The Sun-target vector on the arrival date may be found in a similar fashion. References 1 and 4 list the orbital elements of D'arrest and Eros that were used in this study. The orbital elements (see table I) of Earth may be found in references 3 and 5. The elements of comet D'arrest are variable due to the perturbations of the planets; however, those shown are typical of the 1976 apparition.

The Sun-Earth and Sun-target vectors establish the heliocentric conic trajectory geometry as shown in figure 3 which, in turn, dictates geocentric vis-viva injection energy. An iterative procedure on the computer is required to determine the unique conic that has the specified launch and arrival date (i.e., flight time) and that passes through the two vectors in space. Patched conic techniques are well documented, and the details and manipulations involved will not be repeated here. More information on the associated trajectory geometry and Kepler equations may be found in reference 3.

The trajectory profile is as follows. The launch vehicle inserts the upper stage and payload into a 100-nautical-mile circular parking orbit. When the required coasting period has elapsed, the upper stage is reignited and injects the payload into a geocentric hyperbola having a specific vis-viva energy. After several days, the spacecraft has escaped the Earth's gravitational field and its motion is governed solely by the gravitational field of the Sun.

The spacecraft was assumed to encounter the target body without propulsive braking. In other words, if a reduction in approach velocity is desired, it must be performed by a separate propulsion system which is forthright considered to be part of the payload.

RESULTS AND DISCUSSION

The heliocentric trajectory geometry is quite similar for the asteroid Eros and comet D'arrest opportunities inasmuch as their perihelia almost coincide with their descending nodes. The descending node is the point in space where the celestial body pierces the ecliptic plane in a north to south direction. The orbit of Eros is inclined about 11° relative to the ecliptic, and the orbit of D'arrest is inclined about 17°.

An isometric view of a typical comet D'arrest trajectory is presented in figure 4.

The observer is situated north of the ecliptic plane. The geometry would be similar for an asteroid Eros trajectory. The orbit inclination of asteroid Eros, however, would be less than that of comet D'arrest, and the location of the vernal equinox (♈) relative to the line of nodes would be different.

The orbital elements of a comet vary greatly from one apparition to the next due primarily to the perturbations of the outer planets so that it will be necessary to track the comet for at least 2 months prior to launch in order to establish its orbit with sufficient certainty to attempt an intercept (ref. 1). The comet must therefore be bright enough at this time (recovery) from a particular latitude in the night sky to facilitate observation. A minimum magnitude of 20 at recovery has been suggested (ref. 1). A magnitude of 12 has been set as the minimum desirable brightness at intercept. This value is based on Earth-based spectroscopic limitations. By definition, the lower the magnitude, the brighter the object. For comparison, Polaris is magnitude 2, and Sirius is magnitude -1.6. Sixth magnitude stars are barely visible to the unaided eye under the best seeing conditions.

In figure 5, the magnitude of comet D'arrest is shown as a function of date. Comet D'arrest is seen to have a magnitude of about 6.5 at perihelion and is brighter than magnitude 20 for at least 7 or 8 months prior to perihelion.

Heliocentric Conic Trajectory Parameters

The initial phase of the trajectory study involves the selection of a launch interval and the range of trip times to be considered. Heliocentric trajectories may then be computed with departure on particular days and arrival a given number of days later. In this study, the arrival date was specified (perihelion); consequently, a linear relation exists between launch date and trip time over the launch interval. As will be shown later, the launch energy requirements are nearly minimum for perihelion arrival trajectories to Eros and D'arrest.

Heliocentric trajectory parameters, namely, communication distance at encounter, approach velocity (at encounter), declination of the geocentric outward radial (i.e., the asymptote of the Earth-escape hyperbola), geocentric vis-viva injection energy, and flight time, are shown as functions of launch date for the 1974 asteroid Eros opportunity in figure 6(a) and for the 1976 comet D'arrest opportunity in figure 6(b). The solid curves on figure 6 represent near-perihelion arrivals. The dashed curves in figure 6(a) represent trajectories for which the approach velocity at encounter has been minimized. Use of minimum approach velocity trajectories would be desirable to prolong the time spent in the vicinity of the target body.

The Eros launch interval consists of two segments - one representing the type I trajectories, the other representing type II trajectories. (Type I trajectories exhibit heliocentric travel angles less than 180° and type II trajectories exhibit heliocentric travel angles greater than 180°.) The existence of both trajectory types within the Eros launch interval was purely coincidental, and it is a result of the relative geometry between Earth and Eros. Type II trajectories did not appear in the D'arrest launch interval; however, they might have appeared if a wider launch interval had been examined.

It can be observed from figure 6(b) that the approach velocities for the comet D'arrest intercept trajectories are about 13 kilometers per second. This parameter cannot be reduced appreciably by resorting to faster or slower transfer trajectories, as will be demonstrated later. The magnitude of the approach velocity might preclude the inclusion of experiments requiring long stay times in the vicinity of the comet (e.g., a television system). Other comet missions, however, exhibit even higher approach velocities. Approach velocities for an encounter with Halley's comet in 1986 are nearly 70 kilometers per second (ref. 1). Retrorockets could reduce these velocities, but the achievement of zero relative velocity would appear to be almost impossible.

The average approach velocity for the Eros intercept trajectories is seen from figure 6(a) to be about 7 kilometers per second. This could be reduced to the amount shown by the dashed curve with proper trajectory selection. As hyperbolic approach velocity is minimized, however, geocentric injection energy is increased, which, in effect, reduces the injected payload.

For a collision trajectory (zero miss distance), the range near encounter is given by the product of the approach velocity and the time from intercept. Figures 7(a) and (b) present range near encounter as a function of time from closest approach for various miss distances at Eros and D'arrest, respectively. If experiments were to be conducted within a 100 000-kilometer range, the observation periods would be about 7.9 hours for asteroid Eros and about 4.4 hours for comet D'arrest.

The sensitivities of communication distance, approach velocity, declination of the outward radial, and vis-viva energy with arrival date are presented for specific launch dates in figures 8(a) and (b) for Eros and D'arrest, respectively. It is seen that trajectories arriving at perihelion exhibit injection energies and communication distances which are nearly minimum. The approach velocity relative to Eros for the date shown (August 9) could have been minimized by intercepting it about 10 days before perihelion. From figure 6(a), it can be seen that the same trend exists prior to September 18. After September 18 for the Eros launch interval, hyperbolic approach velocity may be reduced by vehicle arrival several days after perihelion. For the D'arrest case, an arrival 7 days after perihelion is seen to minimize the approach velocity, but only a 0.2-kilometer-per-second differential in approach velocity out of a total of about 13 kilometers per second exists between the perihelion arrival trajectory and the minimum approach velocity trajectory, whereas a 1.2 kilometer-per-second differential out of about 7 exists in the case of Eros. The use of nonminimum energy trajectories to reduce the approach velocity at encounter would therefore appear to be more fruitful for the 1974 asteroid Eros opportunity than for the 1976 comet D'arrest opportunity. For the purposes of this study, however, it was assumed that all intercept trajectories would arrive with Eros and D'arrest at their perihelia.

Geocentric Conic Trajectory Parameters

Once heliocentric trajectory parameters have been defined for a given launch date, the geocentric conic may be determined (ref. 3). This geocentric conic essentially remains fixed in inertial space for a given day, and the launch vehicle must be capable of merging into this imaginary three-dimensional path in space. Inasmuch as the Earth and launch site (Cape Kennedy) are rotating, a unique combination of launch azimuth and parking-orbit coast time is required for a given launch time in order to achieve the desired trajectory. These two parameters define the daily launch windows. Figures 9(a) and (b) present launch azimuth and parking-orbit coast time as functions of time of launch for Eros and D'arrest trajectories, respectively. The SLV-3C/Kick vehicle performance data were used in developing figure 9. Azimuth and coast-time requirements for SLV-3A/Agena and SLV-3C/Centaur launches would be similar.

For a given launch azimuth, two times of day exist for which liftoff is permissible. The first is seen to exhibit a higher parking-orbit coast-time requirement than the second. Both solutions are satisfactory and may be utilized. Generally, the shorter coast-time solution is preferred on the premise that the system reliability of the short coast solution would be greater than that of the long coast solution. The exact difference is not known. In this study, the short coast-time solutions have been presented for illustrative purposes, but this is not to preclude use, if necessary, of the longer coast-time solutions. Furthermore, it was assumed that launches would be made at launch azimuths between 90° and 115°, inasmuch as this azimuth sector is typical of range safety requirements. Payload capability was calculated assuming a 115° launch azimuth, since this yields the lowest payload and is therefore most conservative.

Parking-orbit coast time, time of launch, and payload capabilities of the SLV-3A/Agena, SLV-3C/Kick, and SLV-3C/Centaur are presented as functions of launch date for the 1974 asteroid Eros opportunity in figure 10(a) and the 1976 comet D'arrest opportunity in figure 10(b). The parking-orbit coast-time and time-of-launch requirements shown in figure 10 reflect SLV-3C/Kick vehicle performance. However, these parameters would be only slightly different for the SLV-3A/Centaur vehicles.

For the 1974 asteroid Eros opportunity, daily launch windows are generally greater than $3\frac{1}{2}$ hours, assuming a 90° to 115° launch azimuth sector, and parking orbit coast times between 20 and 40 minutes are required for developing these windows. Over a 3-month interval, payload capability is greater than 1000 pounds for the SLV-3A/Agena, greater than 1600 pounds for the SLV-3C/Kick, and greater than 2300 pounds for the SLV-3C/Centaur; the curves are well behaved except for the transition period near the end of July. At this time, the heliocentric trajectory geometry is peculiar inasmuch as types I and II trajectories are merging.

For the 1976 D'arrest opportunity, daily launch windows are always greater than $2\frac{1}{2}$ hours for a 90° to 115° launch azimuth sector, and parking-orbit coast times between 10 and 20 minutes are required. Payload capability is greater than 900 pounds for the SLV-3A/Agena, greater than 1500 pounds for the SLV-3C/Kick, and greater than 2100 pounds for the SLV-3C/Centaur, and is fairly constant over a 3-month launch interval. All parameters are observed to be well behaved without exception for the D'arrest opportunity.

Preferred Launch Intervals

When planning scientific missions, it has been a common practice to quote mission parameters for a 1-month launch interval. The selection of this interval is generally based on spacecraft and mission constraints as well as launch vehicle performance considerations. For the two potential missions described in this study, a specific launch interval selection would be premature at this time inasmuch as mission details have not yet been established.

For the sake of comparison, however, launch intervals of a month were selected. For the 1974 asteroid Eros opportunity, the launch period beginning August 9 and ending September 8 was chosen. Throughout this period, flight times range from 140 to 170 days, a vis-viva energy of about 4.5 kilometers squared per second squared is required, communication distance at encounter is less than 0.13 astronomical unit, and the approach velocity at intercept is about 7.2 kilometers per second. Payload capabilities are 1030, 1625, and 2310 pounds for the SLV-3A/Agena, SLV-3C/Kick, and SLV-3C/Centaur, respectively, and launch windows of about $3\frac{1}{2}$ hours exist for a 90° to 115° launch azimuth sector.

For the 1976 comet D'arrest opportunity, the launch period selected begins on March 22 and ends on April 21. In this period, flight times range from 115 to 145 days, a vis-viva energy of about 6.8 kilometers squared per second squared is required, communication distance at encounter is less than 0.16 astronomical unit, and the hyperbolic approach velocity at intercept is about 12.8 kilometers per second. Payload capabilities of the SLV-3A/Agena, SLV-3C/Kick, and SLV-3C/Centaur are 950, 1540, and 2160 pounds, respectively, and launch windows are about $2\frac{1}{2}$ hours for a 90° to 115° launch azimuth sector.

SUMMARY OF RESULTS

Spacecraft may be launched to asteroid Eros in 1974 and to comet D'arrest in 1976 using intermediate-sized launch vehicles such as the SLV-3A/Agena, SLV-3C/Kick, or SLV-3C/Centaur. If trajectories are selected which encounter Eros and D'arrest at their respective perihelia, the resulting launch energies will be nearly minimum. This is, in part, due to the fact that the perihelion of each almost coincides with its descending node.

According to current performance estimates and a 1-month launch interval, injected payloads of about 1030 (SLV-3A/Agena), 1625 (SLV-3C/Kick), or 2310 pounds (SLV-C/Centaur) appear feasible for the 1974 Eros opportunity; payloads of about 950 (SLV-3A/Agena), 1540 (SLV-3C/Kick), or 2160 pounds (SLV-3C/Centaur) appear feasible for the 1976 D'arrest opportunity.

Daily launch windows of about $2\frac{1}{2}$ and $3\frac{1}{2}$ hours exist for the 1976 D'arrest and 1974 Eros opportunities, respectively, assuming a 90^{0} to 115^{0} launch azimuth sector. For 1-month intervals, flight times are between 140 and 170 days for Eros trajectories and between 115 and 145 days for D'arrest trajectories, unbraked velocities of approach are about 7.2 kilometers per second for Eros and about 12.8 kilometers per second for D'arrest trajectories, and communication distances at encounter are less than 0.13 astronomical unit for Eros and less than 0.16 astronomical unit for D'arrest.

The parameters summarized herein are of course subject to changes contingent on spacecraft and mission design constraints which have yet to be specified.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, July 6, 1966,
180-06-06-02-22.

REFERENCES

1. Narin, F.; and Rejzer, B.: Sighting and Trajectory Analysis for Periodic Comets: 1975-1986. Rep. No. T-11 (NASA CR-63794), IIT Research Inst., Mar. 15, 1965.

2. Anon: An Analysis of Chemical Upper Stages for NASA Scientific Missions. NASA TM X-52127, 1965.

3. Clark, V. C., Jr.; Bollman, W. E.; Roth, R. Y.; and Scholey, W. J.: Design Parameters for Ballistic Interplanetary Trajectories. Part I. One-way Transfers to Mars and Venus. Tech. Rep. 32-77, Calif. Inst. Tech., Jet Propulsion Lab., Jan. 16, 1963.

4. Cole, Dandridge M.: Asteroids Stir Growing Interest. Missiles and Rockets, vol. 12, no. 8, Feb. 25, 1963, pp. 43, 46, 48, 50, 52-54.

5. Strack, William C.; and Huff, Vearl N.: The N-Body Code - A General Fortran Code for the Numerical Solution of Space Mechanics Problems on an IBM 7090 Computer. NASA TN D-1730, 1963.

TABLE I. - ORBITAL ELEMENTS FOR D'ARREST, EARTH, AND EROS

Object	Semimajor axis, a, AU	Eccentricity, e	Orbit inclination, i, deg	Longitude of ascending node, Ω, deg	Argument of perihelion, ω, deg	Epoch, t_o	Mean anomaly at epoch t_o, M_o, deg
D'arrest	3.385981	0.655347	16.7574	141.4297	178.8556	Aug. 13.825, 1976	0.000
Earth	1.000000	[a].016729 - .000042T	0	0	102.078056 + 1.71667T	Jan. 3.6, 1960	.000
Eros	1.4581	.2398	10.831	304.071	177.930	Jan. 18, 1931	.586

[a] T is measured in Julian centuries from 1950.0

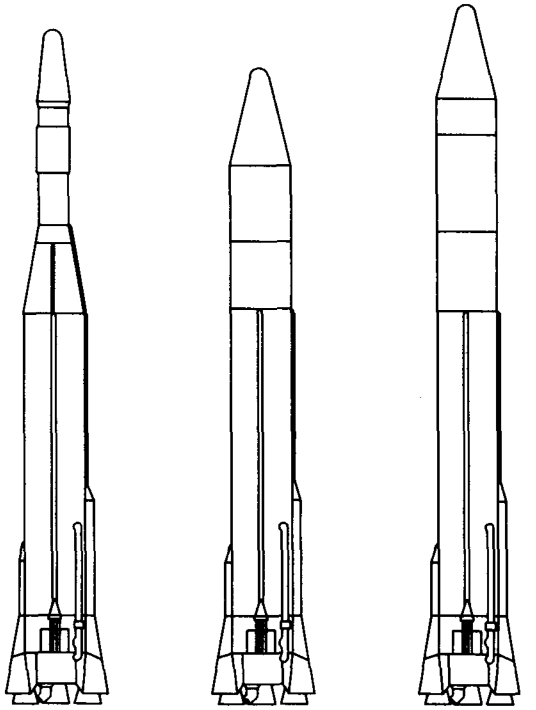

SLV-3A/Agena SLV-3C/Kick SLV-3C/Centaur

Figure 1. - SLV-3A/Agena, SLV-3C/Kick, and SLV-3C/Centaur launch vehicles.

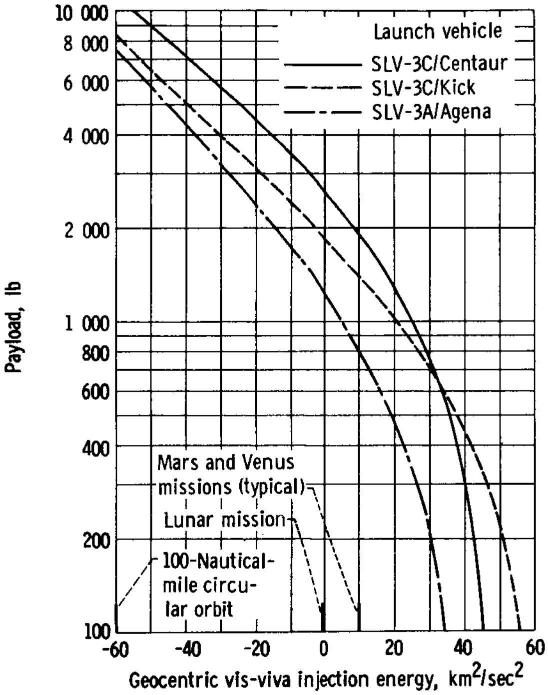


Figure 2. - SLV-3A/Agena, SLV-3C/Kick, and SLV-3C/Centaur payload capabilities as functions of geocentric vis-viva injection energy. Launch azimuth, 115°; parking-orbit altitude, 100 nautical miles; parking-orbit coast time, 20 minutes.

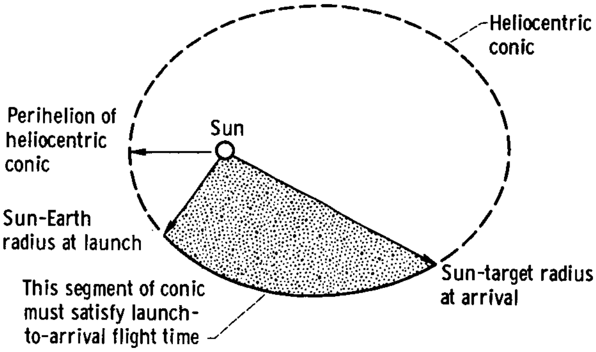


Figure 3. - Selection of heliocentric conic trajectories.

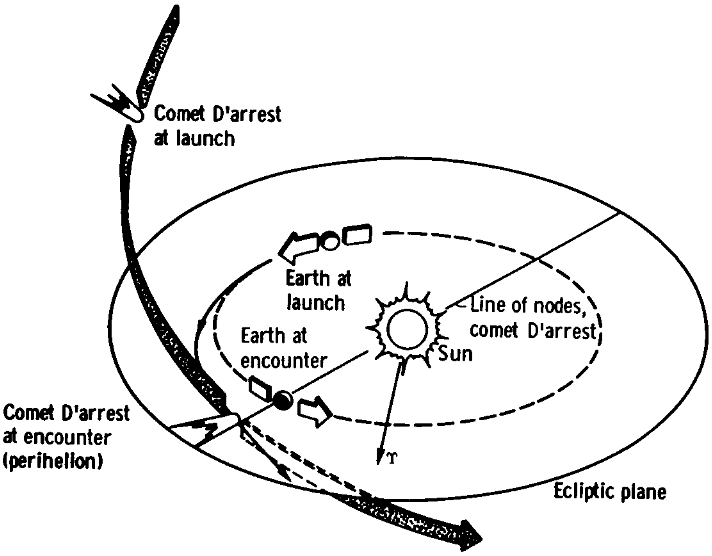


Figure 4. - Typical trajectory geometry for comet D'arrest mission. Launch date, April 21, 1976; flight time, 115 days.

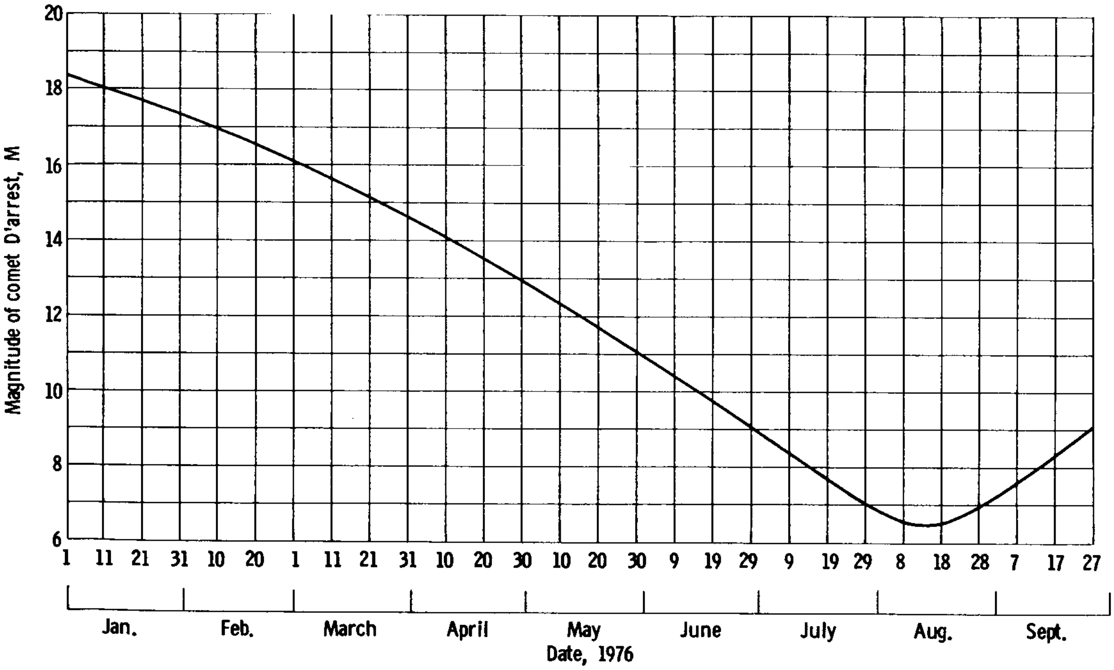
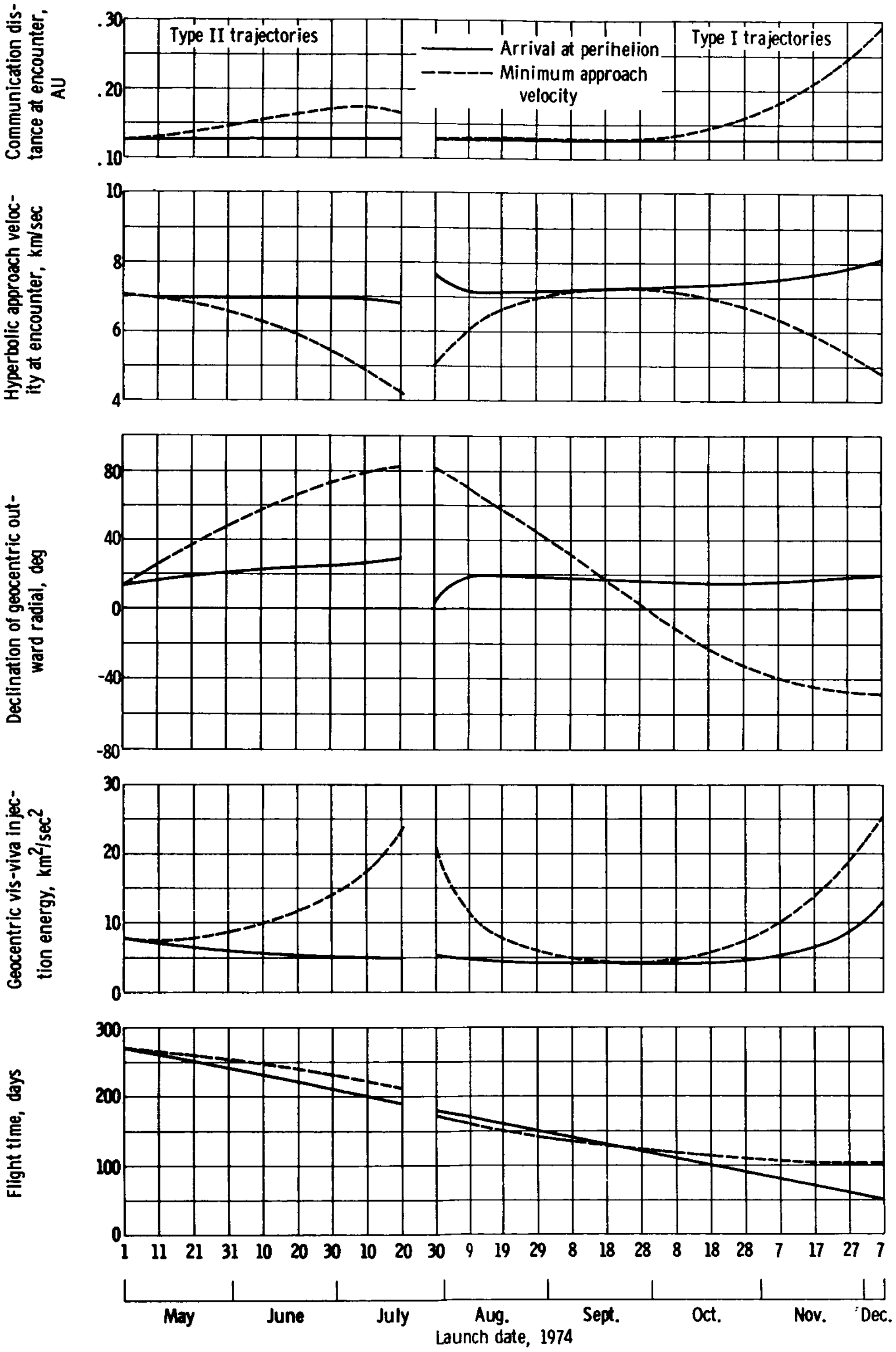
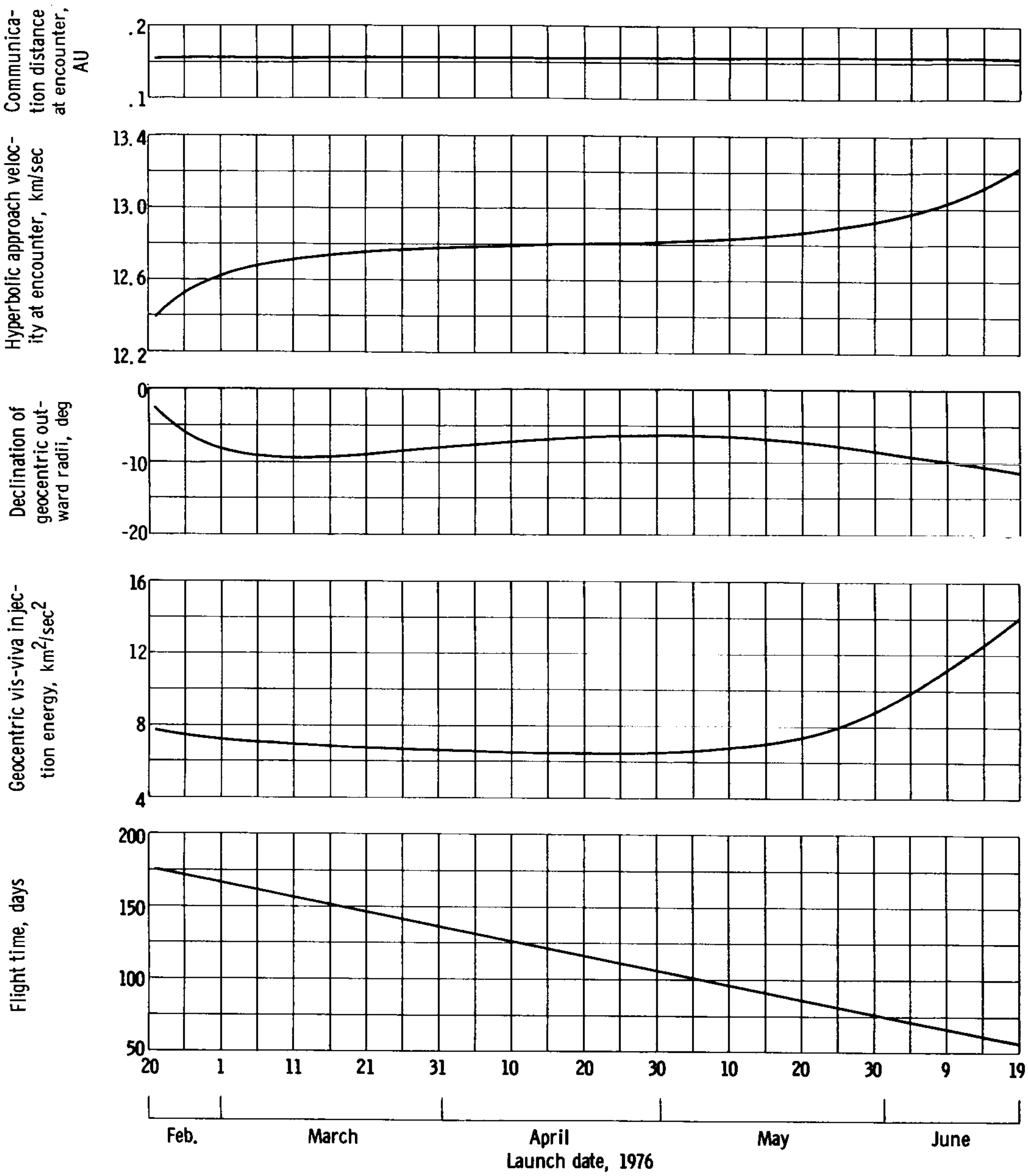


Figure 5. - Magnitude of comet D'arrest as function of date. From reference 1, $M = 9.5 + 15 \log_{10} r + 5 \log_{10} \Delta$, where r is comet-to-Sun distance (AU) and Δ is comet-to-Earth distance (AU).



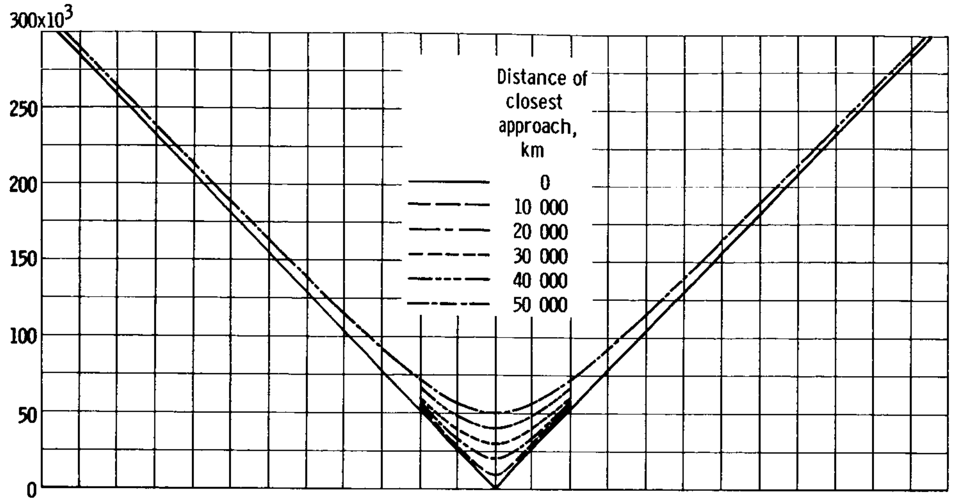
(a) Asteroid Eros.

Figure 6. - Communication distance, approach velocity, declination of outward radial, vis-viva energy, and flight time as functions of launch date for intercept trajectories to asteroid Eros and comet D'arrest.

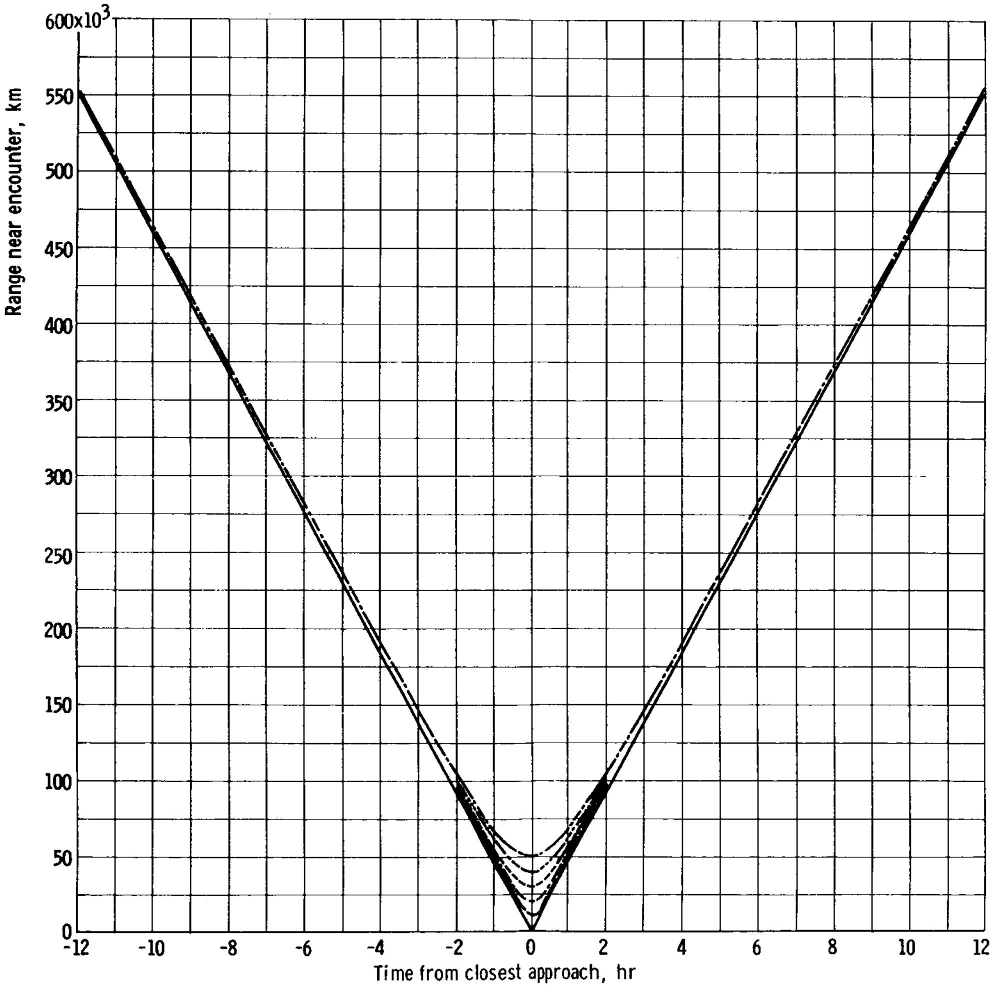


(b) Comet D'arrest.

Figure 6. - Concluded.

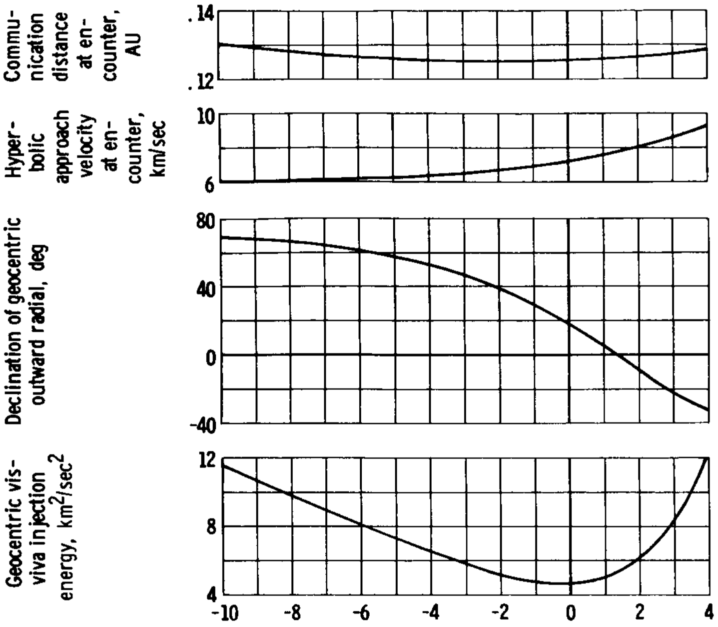


(a) Asteroid Eros. Approach velocity, 7.2 kilometers per second.

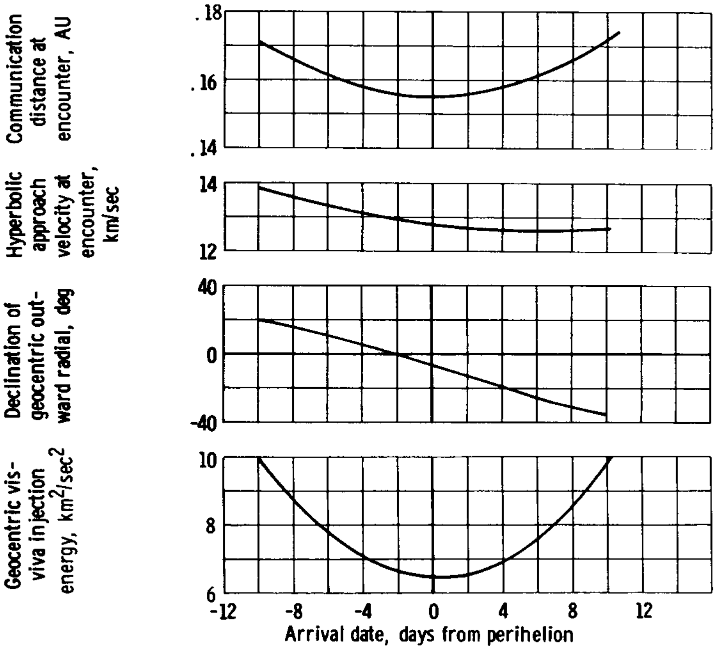


(b) Comet D'arrest. Approach velocity, 12.8 kilometers per second.

Figure 7. - Range as function of time from closest approach for asteroid Eros and comet D'arrest.

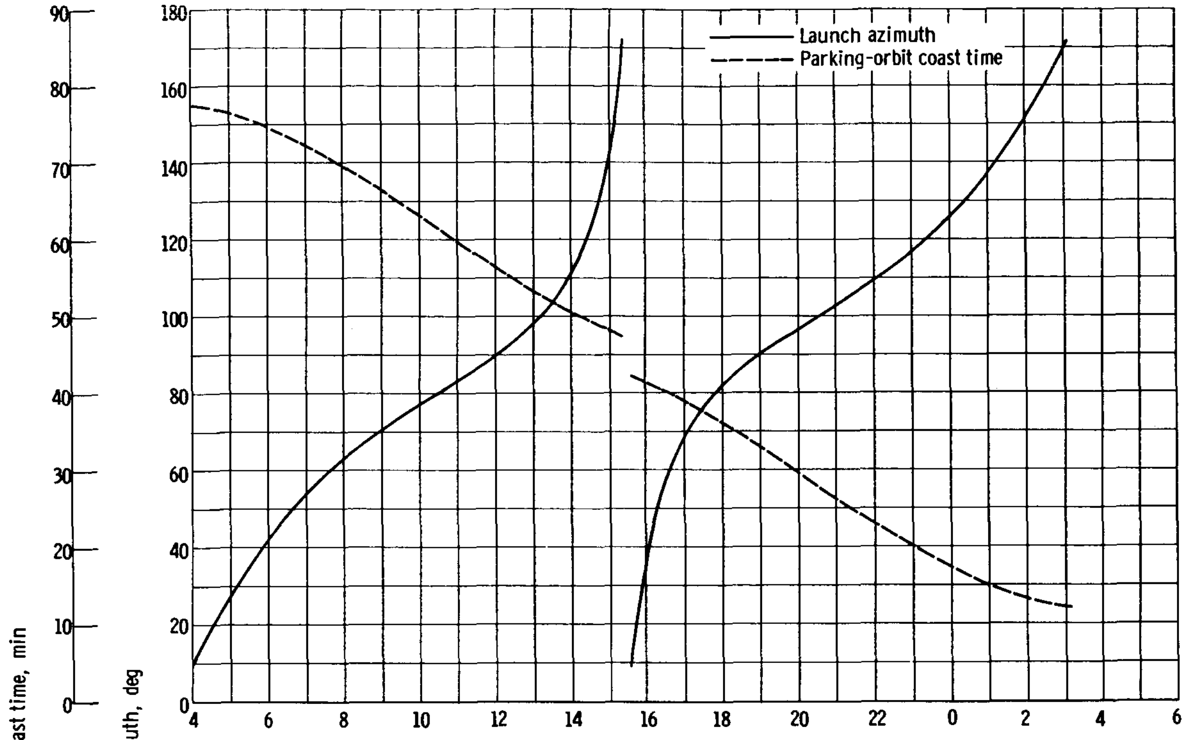


(a) Asteroid Eros. Launch date, August 9, 1974.

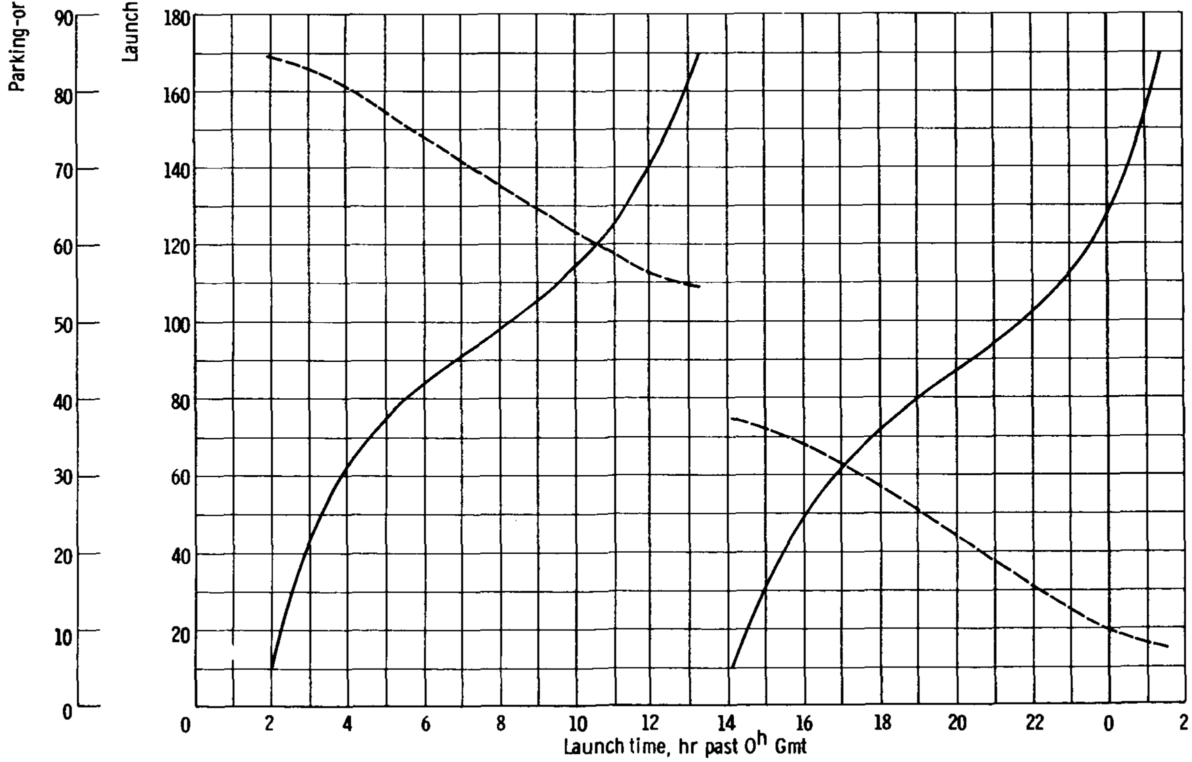


(b) Comet D'arrest. Launch date, April 21, 1976.

Figure 8. - Communication distance at encounter, approach velocity, declination of outward radial, and geocentric vis-viva injection energy as functions of arrival date for asteroid Eros and comet D'arrest trajectories.

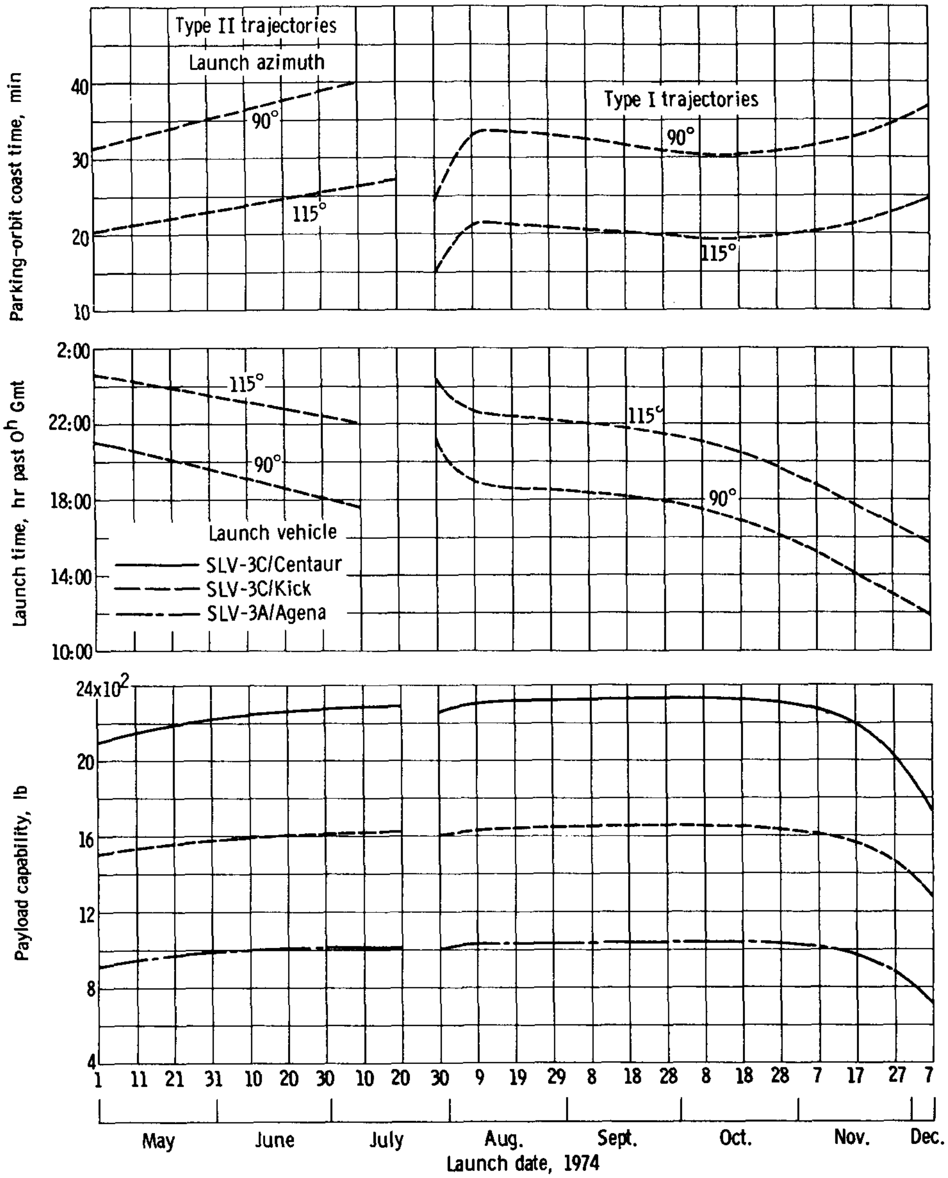


(a) Asteroid Eros. Launch date, August 9, 1974; flight time, 170 days.



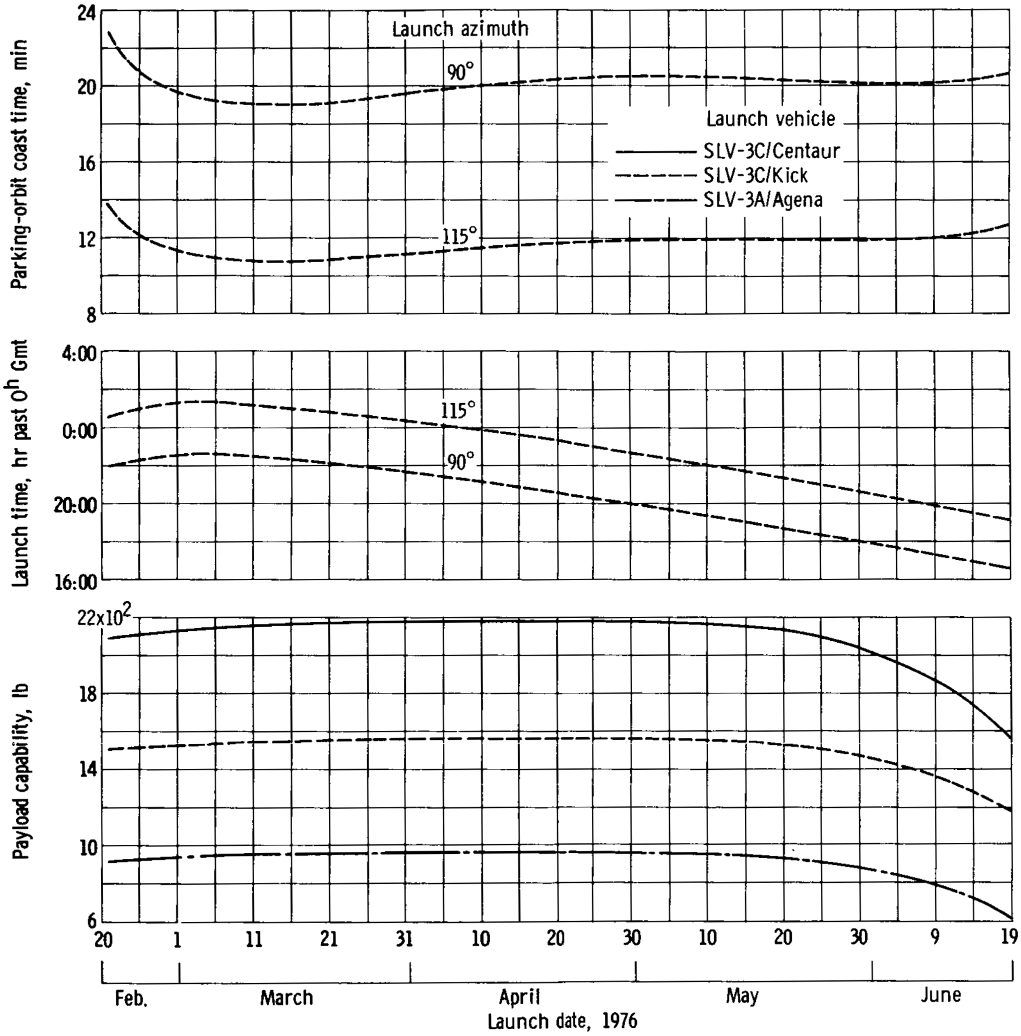
(b) Comet D'arrest. Launch date, April 21, 1976; flight time, 115 days.

Figure 9. - Launch azimuth and parking orbit coast time as functions of launch time for intercept trajectories to asteroid Eros and comet D'arrest.



(a) Asteroid Eros.

Figure 10. - Parking orbit coast time, time of launch, and payload capability as functions of launch date for intercept trajectories to asteroid Eros and comet D'arrest.



(b) Comet D'arrest.

Figure 10. - Concluded.