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PRELIMINARY FEASIBILITY STUDY OF A MULTI-PHOBOS ENCOUNTER EXPERIMENT DURING THE VIKING EXTENDED MISSION

By

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September 1974

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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16. Abstract
The Viking '75 Mission to Mars permits a truly unique opportunity to explore the natural satellite, Phobos, from distances measured in tens of kilometers. A preliminary feasibilility study has been made which shows that a science mission invloving a Phobos close encounter is technically feasible and within the capabilities of the current Viking design. For less than 20 m/s, the Viking Orbiter can provide approximately two 40-day periods of close observation of Phobos, with the first encounter period in January and the second in March, 1977. Multi-pass images of the entire satellite from nearly all aspect angles and with resolution on the order of 10 meters are possible. Close encounters will permit mass determinations to an accuracy of tens of percent. These experiments can be performed in series with the nominal mission; thus, providing complementary scientific information without compromising the original mission and science objectives.

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INTRODUCTION

The Viking '75 Mission to Mars permits a truly unique opportunity to explore the natural satellite, Phobos, from distances measured in the tens of kilometers. Because of the particular geometry currently planned for the Viking Mission orbit, the Viking spacecraft can be maneuvered to make repeated passes very close to Phobos in January and then again in March, 1977; that is, during the proposed extended Viking Mission phase. Multi-pass images of the entire satellite from nearly all aspect angles, and with resolution on the order of 10 meters are possible. Close encounters will permit mass determination to an accuracy of tens of percent. A preliminary feasibility study has been made which shows that the propulsive requirements are nominal, the orbit determination accuracy is adequate, and Phobos is within the scan platform pointing capability during portions of each encounter.

SCIENTIFIC CONSIDERATIONS

Recent Background. The first close-up photographs (Masursky, Pollack, 1972) of the Martian natural satellites by the MM '71 visual imaging system (VIS) produced new impedus to a topic quite in vogue almost a century ago. Initial analysis of these pictures indicated that both moons were of irregular shape, very dim, and heavily cratered. Immediate impressions from the data were that the current surface characteristics are largely determined by cratering and its accompanying fragmentation and spallation. Estimates of the mean radii were: Phobos, 10.9 ± 1.5km, Deimos, 5.7 ± .5km. First estimates of the surface age, based upon crater population, ranged from 10^9 years to as old as the solar system itself.

Recent reports (Pollack, 1973) extended the initial analysis by including estimates of the principal axes of the moons, providing additional confirmation of the moons' synchronous periods, and providing an interesting postulation of a surface regolith formed by repeated encounters of the moons with their own ejecta. From analysis of 40 photographs of Phobos (taken at ranges on the order of 7000 km) and 5 photographs of Deimos (taken at similar ranges) over a period of time of about 100 days, the synchronous rotation of the moons were calculated by observing changes in location of surface features. During this period of time, the same side of each moon faced toward Mars to within less than 5 degrees.

Triaxial shapes of the moons were determined using a limb fitting technique. Both moons were determined to have remarkably comparable shapes; wherein the ratios of the three axes of Phobos to the corresponding axes of Deimos are nearly a constant 1.8. The moons' flattening in the Mars-moon plane were determined to be .30 and .31 for Phobos and Deimos, respectfully. The moons' flattening perpendicular to the Mars-moon plane (that is, the plane containing the moon's motion) were determined to be .16 and .11 for Phobos and Deimos, respectfully. In terms of equivalent mean radii, the data yielded 11.5 km for Phobos and 6.4 km for Deimos, values slightly larger than first estimates. Estimates of the mass of the moons were given as 19.3 and 3.37×10^{18} gm for Phobos and

Deimos,respectfully. These were based upon an assumption of density of 3 gm/cc. However, no direct measurements of mass or density have been made.

Experiment Objectives. There are many mysteries surrounding the origin of the Martian moons. At first glance, the fact that the two moons have nearly identical geometric albedo (about .05) and almost identical shapes suggests a common origin. Following the hydrostatic equilibrium theories developed for the Moon (Jeffreys, Baldwin), first-order calculations for the shape of Phobos agree well with visual results of Pollack (TABLE I). On the other hand, the shape of Deimos is not consistent with hydrostatic theory owing to its relatively large distance from the planet. However, if the distance of Phobos is used in the calculation for the shape of Deimos, one obtains remarkably good agreement with the data, perhaps quite coincidentally, since for bodies of this size hydrostatic theory may not be applicable.

The MM '71 experiment has substantially improved our knowledge of the moons; however, many new questions have been raised, particularly on the origin of these moons. The nature and origin of the Martian moons could be the true Rosetta Stone for the origin of the Solar System; since, if these moons were formed out of primordial matters, they should, because of their relatively small size, retain their original chemistry and mineralogical composition (Burns).

Further investigations and more definitive data on the Martian moons are needed to confirm or reject origin theories. A short, but hardly exhaustive, list of the additional science information to be gained by a close Martian moon encounter by the Viking spacecraft is given below.

- Obtain a direct estimate of the mass and an improved figure determination. These new data will provide valuable new information on density which bears directly on the regolith and origin theories.
- Obtain improved values on the rotational characteristics of the moons to improve the estimate of the degree of synchronization. These data, combined with the size and mass data, may yield valuable information on moments of inertia and perhaps the density distribution. Further, non-accountable librations may provide bounds on the probability of asteroid collisions (Burns).
- Provide additional data to improve the ephemerides of the moons. These data, in conjunction with other Mars physical data obtained earlier in the Viking mission should provide valuable insights into Mars' internal structure.
- Provide additional and improved knowledge of the secular acceleration of the Moons (Pollack, 1973). Accurate Viking image data, taken about 5 years after MM '71 should provide further insight into the questionable (Burns) secular acceleration in the longitude of the Moons (Sharpless).
- Obtain high resolution measurements (about 150 m) on the surface thermal inertia. Data scans taken with the infrared thermal mapper instrument in conjunction with photographs should provide important surface property information. Perhaps these measurements can provide additional data to substantiate the existance of a regolith.

CELESTIAL MECHANICS CONSIDERATIONS

Orbit Geometry. The orbit geometry of Phobos and the VO is shown in figure 1. For simplicity Phobos is assumed to be in a circular, equatorial orbit. Neither of these assumptions will have a significant influence on the feasibility of the experiment. The VO-A orbit has an inclination of 33° and an argument of periapsis of 44° on July 4, 1976. In order for the spacecraft to pass close to Phobos, two conditions must be satisfied. First, the spacecraft orbit geometry must be such that the distance of the spacecraft from Mars is equal to the semi-major axis of the orbit of Phobos when the spacecraft passes through the orbital plane of Phobos; that is, the orbits in three dimensional space must intersect. The second condition is that the two satellites must be at this intersection point at the same time. A mathematical expression for the first condition can be derived from the conic equation relating radial distance (r) to the angular position in orbit (McCluskey)

$$r = \frac{a(1 - e^2)}{1 + e \cos f} \tag{1}$$

where a is the semi-major axis and e is the eccentricity and f is the true anomaly or angle measured from periapsis to the position in orbit. The spacecraft passes through the orbit plane of Phobos when $f = -\omega$ and $180° - \omega$. For the orbit paths to intersect, r must be equal to 9380, the semi-major axis of the orbit of Phobos. Thus the value of ω must satisfy one of the equations,

$$9380 = \frac{a(1 - e^2)}{1 + e \cos\omega}$$

or

$$9380 = \frac{a(1 - e^2)}{1 - e \cos\omega}$$

which are necessary and sufficient for orbit path intersection. Assuming the nominal values of a and e, the solutions for ω are: $\omega = \pm 96$ and $\pm 84^\circ$. The paths intersect as the spacecraft is ascending (south to north) when $\omega = 96^\circ$ and descending when $\omega = 84^\circ$.

As mentioned above, the value of ω in the VO-A orbit is 44°. However, there are perturbations of the orbit which cause ω to change with time. The major orbit plane perturbations are due to the oblateness of Mars which produces both a nodal regression and an apsidal precession given by (McCluskey),

$$\dot{\Omega} = -n(\frac{3}{2} J_2) \cos i (\frac{R}{a})^2 \frac{1}{(1 - e^2)^2}$$

$$\dot{\omega} = n(\frac{3}{2} J_2)(\frac{R}{a})^2 \frac{1}{(1 - e^2)^2} (2 - \frac{5}{2} \sin^2 i)$$

where J_2 (Born) is 1.96×10^{-3}, $n = 351^\circ$/day is the mean motion of the spacecraft, $e = 0.76$ is the eccentricity of the s/c orbit, $R = 3394$ is the radius of the Mars used as a reference for the gravity field expansion, $a = 20420$ km is the semi-major axis of the spacecraft orbit, $i = 33^\circ$ is the inclination. The orbital parameters n, a, e and i do not change substantially with time; thus,

$$\dot{\Omega} = -0.137\ ^{\circ}/\mathrm{day}$$

$$\dot{\omega} = 0.207\ ^{\circ}/\mathrm{day}$$

The argument of periapse will increase from the initial value of 44° to 84° in 193 days and to 96° in 251 days. Consequently, on January 13 and March 12, 1977 the orbit geometry is such that close encounters of the VO-A spacecraft and Phobos are possible. Similar analysis has been performed for potential encounters between VO-A and Deimos and VO-B with both natural satellites. The approximate encounter dates are shown in Table II. The most realistic opportunities are the two mentioned above and these are analyzed in detail below.

The geometry of Mars, Earth, Sun and the spacecraft orbit intersection with respect to the orbit plane of Phobos are illustrated in figure 2 for the January opportunity and figure 3 for the March opportunity. Refering to figure 2, the ascending node of the spacecraft orbit on January 13 will have a right ascension of about 97° and regresses 0.14 degrees per orbit. On January 13, the spacecraft passes through the orbital plane of Phobos near the orbital path as indicated by the dot on the line of nodes. Since ω increases from orbit to orbit by 0.207 degrees, the point where the spacecraft pierces the Phobos orbital plane continually moves inward. The radial change per orbit can be calculated by differentiation of equation (1),

$$dr = \frac{er^2 \sin f}{a(1 - e^2)}\, df$$

and evaluation of the differential with $f = \omega -$ [illegible] $df = d\omega = .207^{\circ}$. The result is $dr = 27$ km. Therefore, successive piercing points will be 27 km apart radially and 22 km apart longitudinally. Similar results are obtained for the March opportunity except the points move outward with time. Thus, if the phasing requirements can be satisfied, there will be multiple spacecraft-Phobos encounters in both January and March of 1977.

Relative Phasing. In order to insure repeated encounters the ratio of the two orbital periods must be a rational number. The orbital period of Phobos is approximately 7.65 hours and the nominal spacecraft orbital period is 24.61 hours. The ratio is 3.22. Rational numbers close to this ratio are 3, $\frac{13}{4}$, and $\frac{16}{5}$; however, the latter two ratios do not permit close encounters each spacecraft orbit. The maximum number of close encounters will occur for a ratio of 3 or a spacecraft orbital period of 22.95 hours. Repeated orbit positions will then occur every spacecraft orbit and every third Phobos orbit. An orbit period change from 24.61 to 22.95 hours can be performed for a velocity impulse of 12 m/s.

The only remaining geometric consideration is to assure that the spacecraft and Phobos simultaneously arrive at the point of near intersection. The relative orbital phase of the satellites will depend on the phasing of the spacecraft orbit which will in turn depend on the particular mission profile. However, the current uncertainties in the physical parameters that enter into the detail calculations and the complexity of the Viking mission profile make such calculations meaningless at this time.

Actually the initial phasing has no effect on the total propulsive requirements for the January opportunity, since the 12 m/s required to synchronize the two satellites can also be used to phase the satellites. The 12 m/s will produce a 1.7 hours change in period. Over a 5 orbit time internal such a change in period will permit more than a 360° change in the relative phase of the satellites. Thus, the first maneuver would be designed to reduce the orbital period from 24 61 to some value greater than 22.95, such that after 5 orbits the proper phasing is accomplished. The remainder of the 12 m/s will be used for the second maneuver which will synchronize the orbits.

The phasing and synchronization during March will require additional propulsion. In January, the satellites are in the vicinity of the descending node simultaneously and the March encounter requires that both be at the ascending node. The spacecraft takes [illegible] 2 hours to pass from the ascending to the descending node; whereas, [illegible] takes about 3.8 hours. Therefore, the total phasing error that must be corrected is less than two hours. If this phasing is performed over a five day period, the total propulsive requirements for a two maneuver transver will be about 6 m/s. Thus, the total for both opportunities will be about 18 m/s.

Error Analysis. The accuracy with which encounters can be planned and controlled is an important consideration and a preliminary analysis is given here. There are three distinct considerations; namely, how well can the orbit of the spacecraft be determined; how well can the orbit of Phobos be determined, and how well can the orbit of the spacecraft be controlled. The major orbit determination errors influencing the knowledge of the spacecraft orbit will be orientation of the orbit and the orbital period (Tolson). The orientation errors will be about 0.1° (O'Neil) which could produce a displacement relative to Phobos of 15 kilometers. The period uncertainty is important because it produces a secular increase in the error from one orbit to the next. The expected period uncertainty of about 0.1 sec. (O'Neil) means that the spacecraft passes through the orbital plane 0.1 seconds later (or earlier) each orbit. After 30 orbits this error would accumulate to 3 seconds. Thus Phobos would be about 6 kilometers farther along in its orbit than expected when the spacecraft passes through the orbit plane of Phobos. This error is consistant with the contribution from the orientation uncertainty discussed above; however, this estimate may be slightly conservative because the spacecraft will be in a 22.95 hour orbit and the periapsis will be at a new latitude, so the spacecraft will be experiencing a new Mars gravitational environment. In any case, the total orbit determination error is probably less than 25 kilometers.

The error in our knowledge of the orbital period of Phobos is 0.0021 seconds (Born) and therefore negligible over a few months period. Optical tracking of Phobos during the planetary approach phase and also during the orbital phase should reduce the along track errors to a few kilometers and the orientation angles should be known to a 0.1 degrees (Born). These errors produce position uncertainties in the orbit of Phobos that are the same order as the uncertainties in the spacecraft orbit.

The only other source of error to be considered is that introduced by the phasing and synchronizing maneuvers themselves. Since these maneuvers cannot be performed perfectly, they will introduce orbit errors. For such small maneuvers, the major effect will be to produce an error in the orbital period. For example, an 12 m/s maneuver with a 0.1% proportional error will produce a period error of about 6 seconds. This error will have the same effect as an orbit determination error in the period of the VO. However, a 6 second period error is unacceptable if very close encounters are required. Therefore, small propulsive maneuvers will be required to assure proper encounter geometry during the most critical phase of the experiment. With such small trim maneuvers, control of the orbit geometry should be about one to two seconds in period; thus, during the few most critical orbits the control error will be below 20 kilometers. Considering all three error sources, encounters as close as 40 kilometers should be relatively safe.

Encounter Geometry. One potential encounter scheme is illustrated in figure 4 for the January opportunity. The VO is targeted to pass exactly through the Phobos orbit on January 13 such that Phobos is 50 kilometers past the intersection point. This geometry assures that the illuminated, trailing hemisphere of Phobos will be viewed by the VO. The VO orbital period is initially designed such that, each time the VO passes through the orbital plane of Phobos, Phobos is 27 km farther back along its orbit. On January 15 the period is reduced by about 15 seconds so that Phobos moves back 54 km between successive VO passages. The points where the

VO descends through the orbital plane are illustrated by dots which are tied to the corresponding Phobos locations.

Recall that this is a descending node encounter and the VO has an orbit inclination of 33°. The velocities of the VO and Phobos are 2.65 km/s and 2.14 km/s. The relative velocity components are therefore 1.68, -0.42, and -1.11 in the radial direction (away from Mars), along the orbit of Phobos, and normal to the orbit plane of Phobos. The in-plane velocity of the VO relative to Phobos is illustrated in the figure. The relative velocity is parallel to the lines connecting the satellites on January 7 and 19, hence on these two encounters the VO will pass directly over the north and south poles, respectively. The VO-Phobos distances during polar passage will be about 55 km and 90 km respectively.

All of the encounters prior to January 13 have cone angles greater than 90°, and, since the VO passes north of Phobos, most of the flyby phase will be within the clock angle range. After January 13, the VO passes south of Phobos and some of the cone angles are below 90°. Spacecraft roll maneuvers will be required during many of these encounters. The solar declination is nearly zero during January so that both the north and south polar regions of Phobos are illuminated. Because of the synchronism between the orbital period and the rotational period of Phobos, only the trailing hemisphere will be illuminated during the January encounters.

The March opportunity, shown in figure 5, is designed similarly. The VO is phased to pass 50 km in front of Phobos on March 12, which assures that the leading hemisphere, now illuminated, can be scanned by the VO instruments. The relative velocity components are the same except the z-component is positive for these ascending node encounters. On March 5 the VO will again pass directly over the North Pole of Phobos at a distance of about 75 km. On March 14 the VO period is increased by 13 seconds so that the Phobos position remains invariant for all remaining VO passes. On March 19 the VO will again pass over the south pole at a distance of about 100 km. The VO scan platform pointing requirements are similar to the January encounters. Up through March 12 no rolls should be required, but after that time rolls will be required to look north toward Phobos.

A number of other encounter sequences can be imagined, and the optimum sequences can be developed once all the science requirements are defined. However, the above sequences have the following advantages:

(a) Complete coverage of Phobos with both hemispheres illuminated.

(b) Coverage from all aspect angles: looking down from both poles, looking from the direction of Mars and looking toward Mars, and looking head on at Phobos.

(c) Over half of the encounters will not require roll maneuvers.

(d) A number of very close encounters during both opportunities for mass determination of Phobos and increased resolution.

(e) On March 16 a picture of Mars rising over Phobos is possible.

Science Instrument Coverage. The field of view of the VIS is 26 x 54 milliradians. Thus, if the VO is within 850 km of Phobos, Phobos will fill the field of view. This condition will exist for over 40 days during both the January and March series. These extremely close encounters have the potential for very high resolution pictures of Phobos; however, there is no image motion compensation on the VO and the relative velocity is 2 km/s. At the point of closest approach, the entire relative velocity will contribute to smearing, so that at an exposure time of 0.01 seconds, the smear will be 20 meters. However, the smearing is approximately proportional to R/r where R is distance of closest approach and r is the distance at which the calculation is made. Thus very close encounters will have a rapidly decreasing smear as the distances from Phobos increases. The closest encounter is about 40 km, so that by the time the spacecraft is 150 km from Phobos, the smearing and pixel resolution are both about 5 meters. The best possible resolution will therefore be slightly less than 10 meters. There will be a blooming distortion but that is expected to be less than a meter.

If the spacecraft is expendable in March, an extremely close encounter could be planned, which if successful will essentially eliminate smearing and could return Ranger type pictures. This would also provide the optimum mass determination experiment.

The maximum relative angular velocity will be about 2.5°/sec for the closest encounters and is proportional to R/r^2. Again the velocity decreases rapidly with distance for close encounters. Since the maximum angular rate of the scan platform is 1°/sec, at most one picture per encounter, near the point of closest approach, will be possible for closest approach distances less than 100 km. Extensive analysis will be required to optimize these encounter sequences.

Mass Determination. As the spacecraft passes Phobos the gravitational field of Phobos will perturb the spacecraft orbit about Mars. An approximation to the amount of bending is obtained by assuming that the relative motion of the two satellites can be represented by hyperbolic conic motion. If Phobos has the same density as Mars, the change in velocity due to bending of the spacecraft trajectory will be about 42 mm/s for an encounter distance of 40 km. The effect varies inversely as the distance of closest approach. A second effect is a change in the total velocity as the spacecraft approaches and recedes from Phobos. The energy integral shows that the change in velocity would be 21 mm/s for an encounter distance of 40 km and again the effect drops off inversely as the distance. The geometry is nearly optimal in January to view the total effect of the bending in the Doppler data. The geometry is not as optimal in March; but most of the change in velocity magnitude will be seen in the Doppler data along with a small amount of the bending effect. The noise on the Doppler data is approximately 1 mm/s; thus, the signals will be easily detectable. Detailed error analyses are required to examine the effects of corrupting influences such as the Mars gravity field, encounter geometry uncertainties, etc. Mass accuracy in the tens of percent can probably be attained. Applying an expression developed for Asteriod flybys (Anderson) yields a comparable mass accuracy estimate. Optical tracking of Phobos will play an important role in eliminating the errors due to uncertainties in the relative geometry.

MISSION OVERVIEW

Figure 6 illustrates a possible preliminary mission timeline for the Phobos encounter experiment. The nominal end of mission for Viking 75 is November 14, 1976. Mars solar conjunction occurs on November 24, and it is expected that all spacecraft communication will be lost during that time period. It is assumed that fifteen days after conjunction the communications will be adequate to determine the VO orbit so that the phasing maneuver can be made on December 11. This maneuver will take less than 12 m/s and the VO orbital period will be between 24.6 and 22.95. The synchronizing maneuver will occur on December 16 and will use the remainder of the 12 m/s. At this time the distance from Phobos will be about 1000 km. The closest approach distance continually decreases to a minimum of about 40 km on January 13, 1977. An orbit trim is tentatively planned for January 13, 1977 to do the final phasing for the very close encounters. Detailed analysis will be required to define when such maneuvers should be executed and how many are required. Another orbit trim on January 16 changes the phasing again so that the VO will pass directly over the south pole of Phobos on January 19, 1976.

The March opportunity starts with a phasing maneuver of 3 m/s on February 15. The two orbit trims, which are performed in March, serve the same purpose as those in January. The total propulsive requirements for the mission will be less than 20 m/s.

SUMMARY

It has been shown that the Viking Mars Mission in 1976 will provide an unprecedented opportunity to gather important data on Phobos at essentially no extra spacecraft design costs. This serendipitous mission could provide data of great scientific value on the mass of Phobos and additional data on its figure, surface properties, and rotational characteristics. This study shows that a science mission involving a close Phobos encounter is technically feasible and within the capabilities of the current Viking design. For a ΔV of less than 20 m/s the Viking Orbiter can provide approximately two 40 day periods of close observation of Phobos with the first encounter period in January and the second in March, 1977. These experiments can be performed in series with the nominal mission; thus, providing complementary scientific information without compromising the original mission and scientific objectives. The data obtained from a multi-Phobos encounter experiment will add significantly to our total understanding of Mars, the environment of Mars, and the origin of the Solar System.

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TABLE I

		MM '71 DATA	ASSUMING* HYDROSTATIC EQUILIBRIUM	
PHOBOS	X,km	13.8 ± 1	13.2	
	Y,km	11.5 ± 1	11.0	
	Z,km	9.7 ± 1	10.3	ASSUMING DEIMOS AT 9380 km
DEIMOS	X,km	8^{+3}_{-1}	6.5	7.5
	Y,km	6.1 ± 1	6.4	6.1
	Z,km	5.5 ± 1	6.3	4.9

* Values used for these calculations are:

	Radius of Mean Equivalent Sphere	Mean Distance From Mars	Mass (Assuming 3gm/cc)
PHOBOS	11.5 km	9380 km	19.3×10^{18} gm
DEIMOS	6.4 km	23460 km	3.37×10^{18} gm

M♂ = 6.42×10^{26} gm

R♂ = 3394 km

TABLE II

ENCOUNTER DATES OF NATURAL SATELLITES AND VIKING SPACECRAFT

	PHOBOS	DEIMOS
VO-A	Jan. 1977	Nov. 1977
	Mar. 1977	Oct. 1978
	1979	1980
	1979	1981
VO-B	1984	Jan. 1978
	1984	1981
	1992	1987
	1993	1990

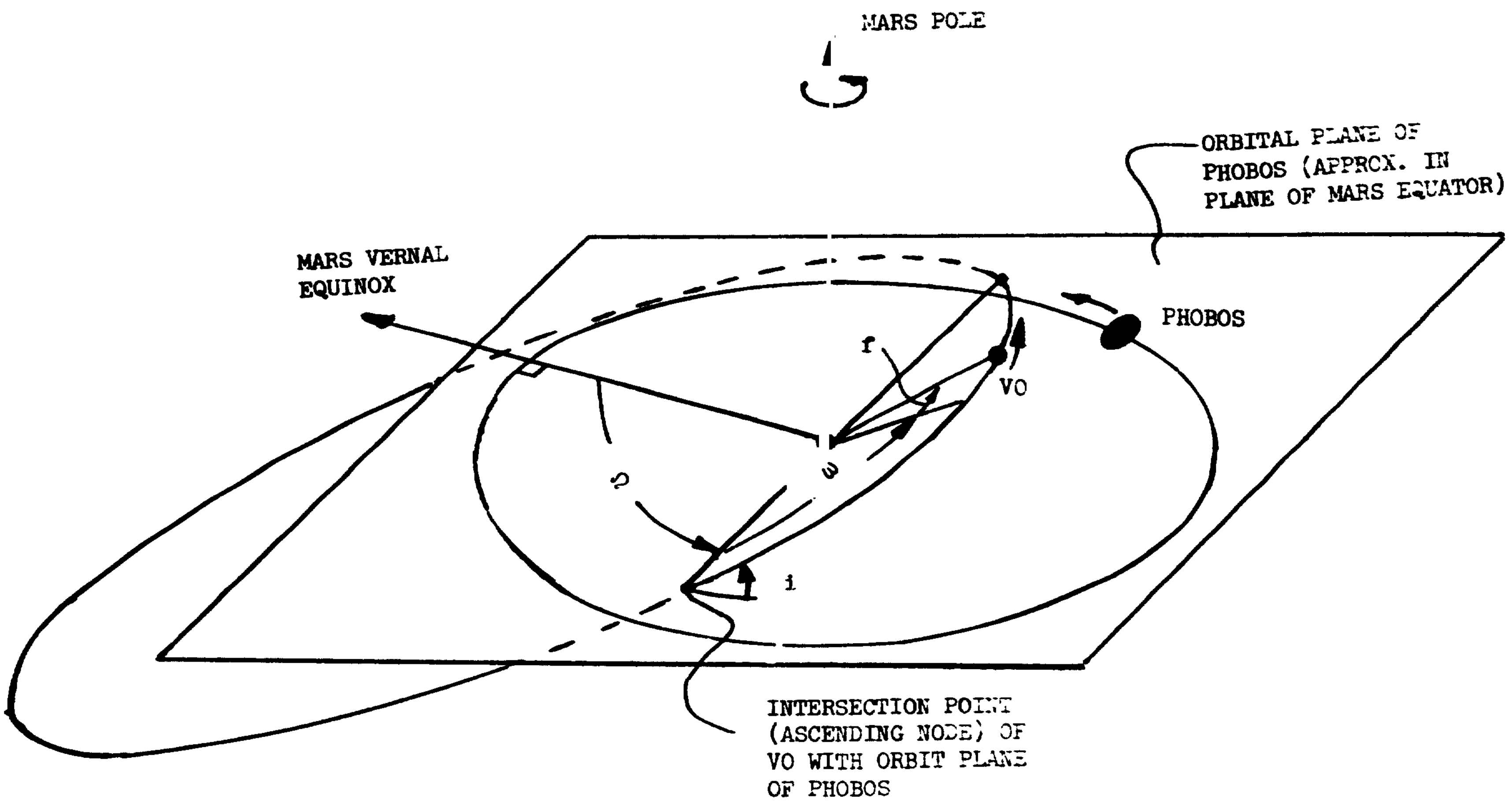

FIGURE 1: RELATIVE ORBITAL GEOMETRY BETWEEN PHOBOS AND THE VIKING ORBITER

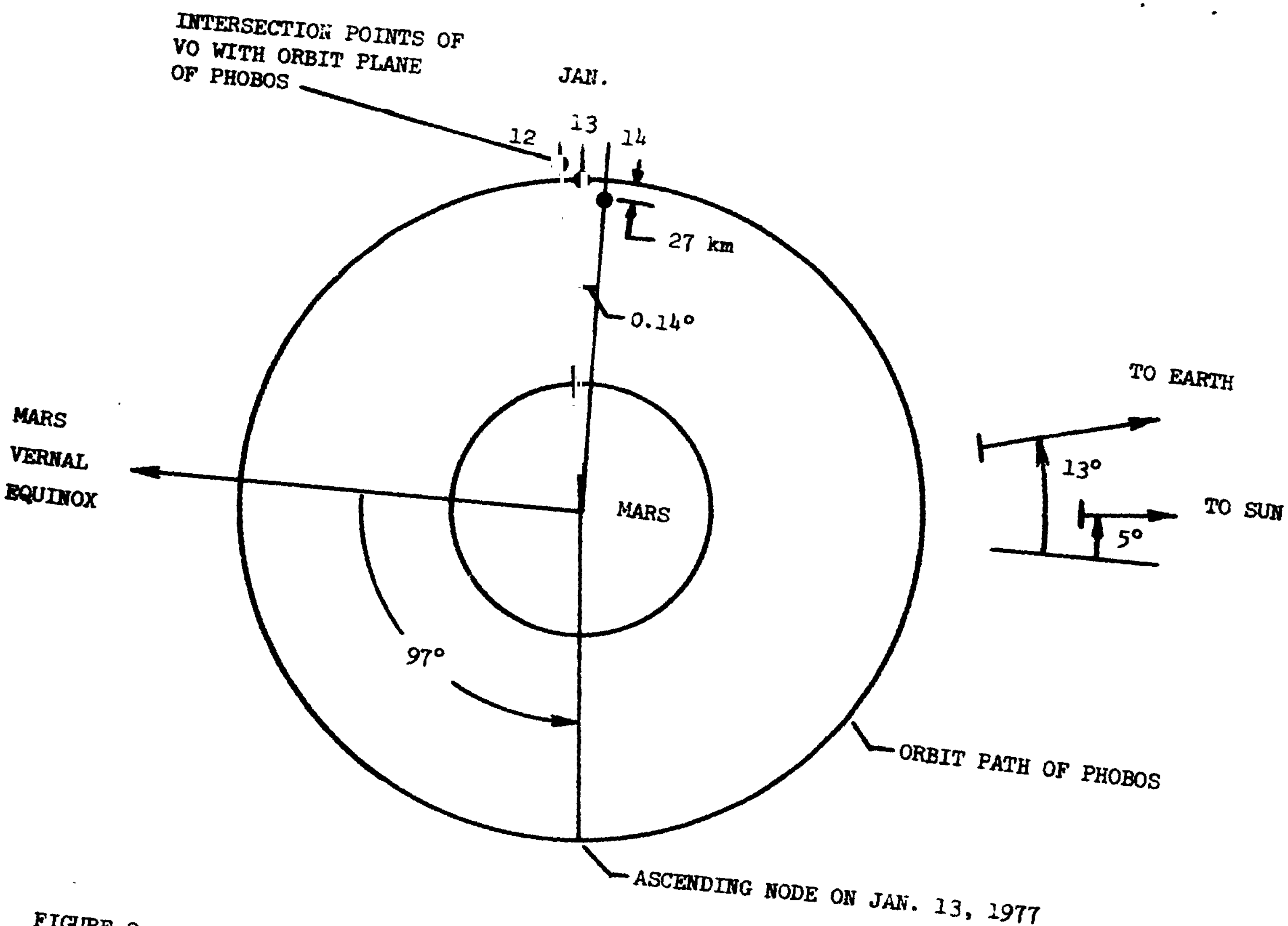

FIGURE 2. PHOBOS ENCOUNTER GEOMETRY IN JANUARY 1977

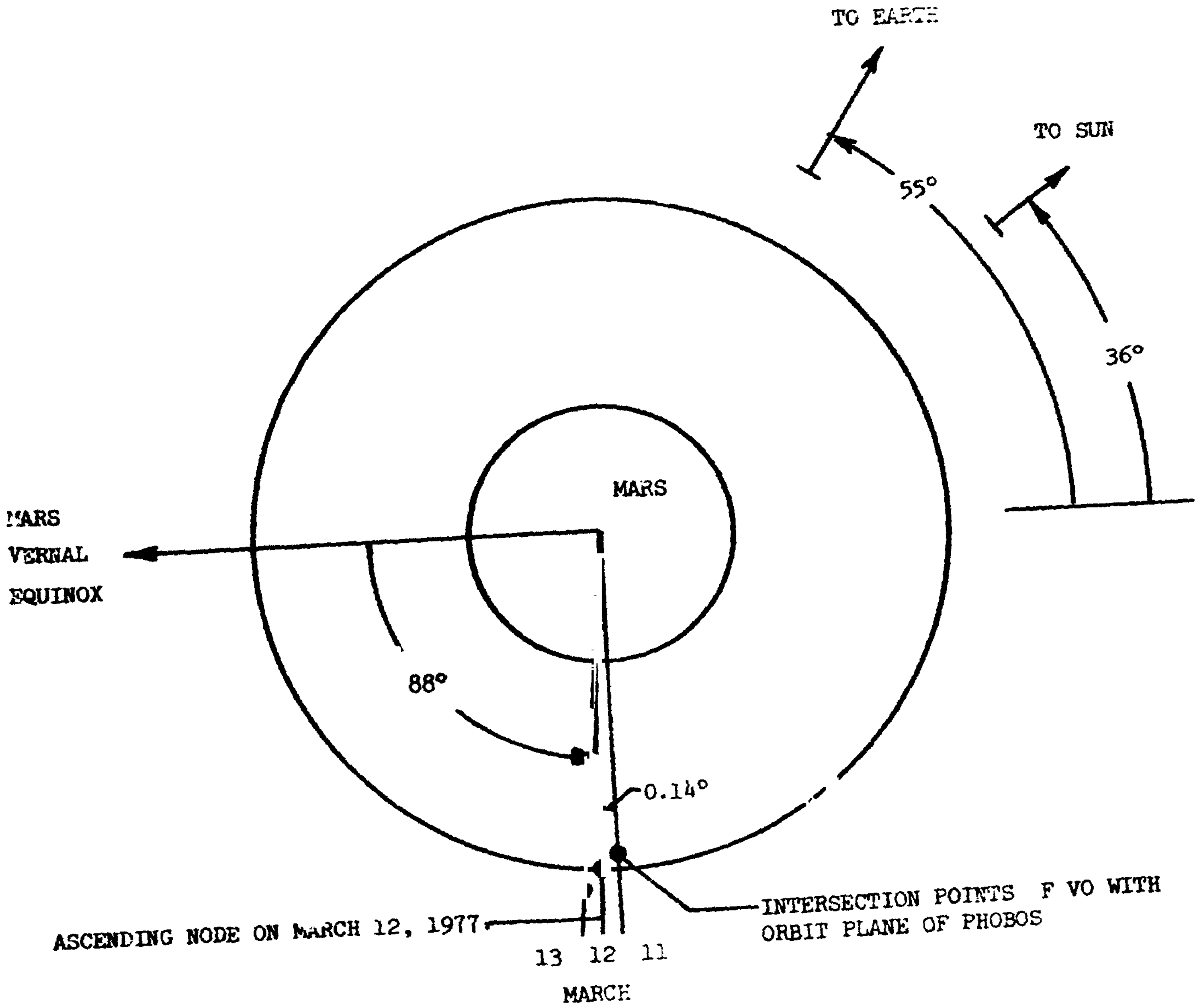

FIGURE 3. PHOBOS ENCOUNTER GEOMETRY IN MARCH 1977.

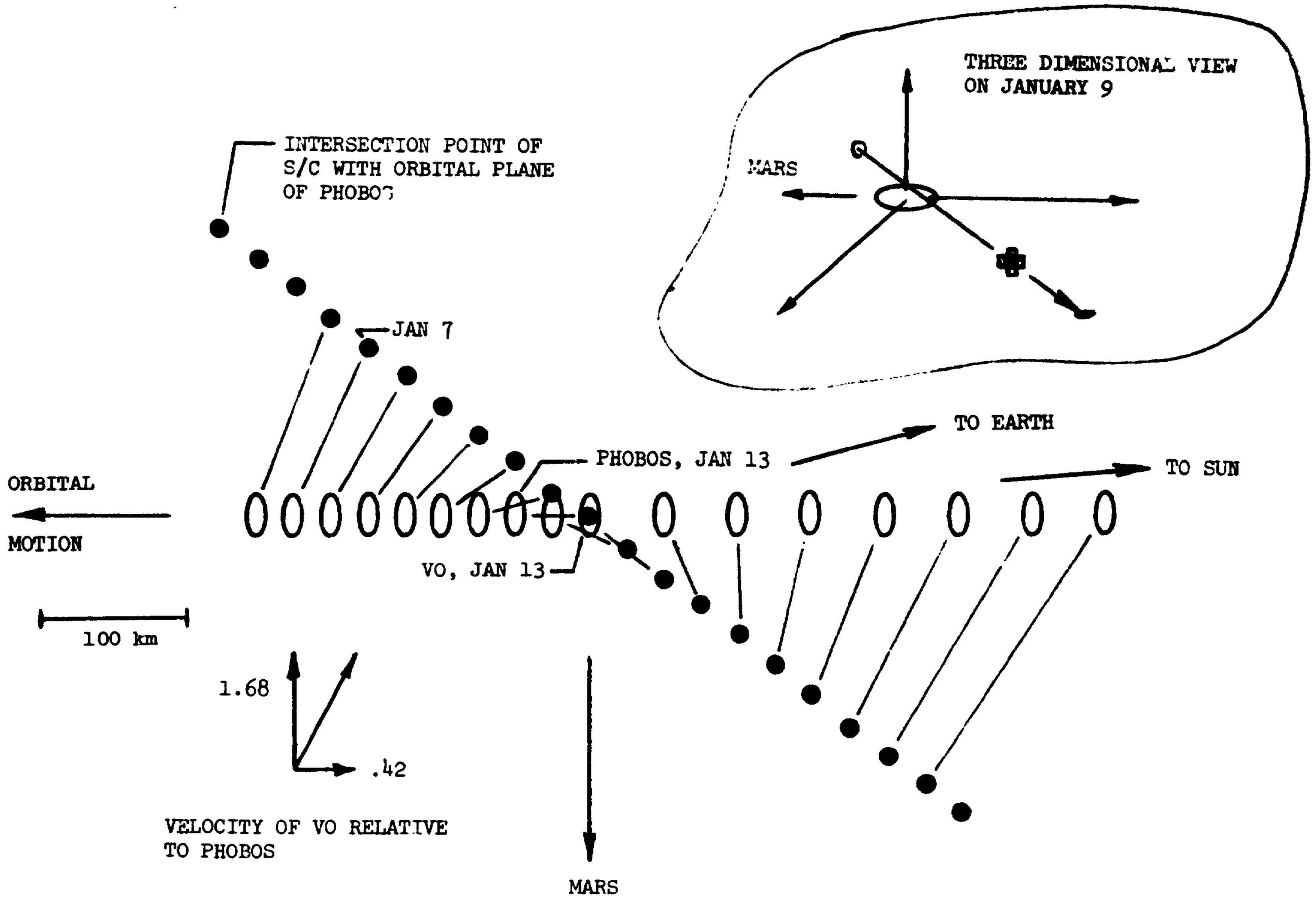

FIGURE 4. DETAIL ENCOUNTER GEOMETRY IN JANUARY 1977.

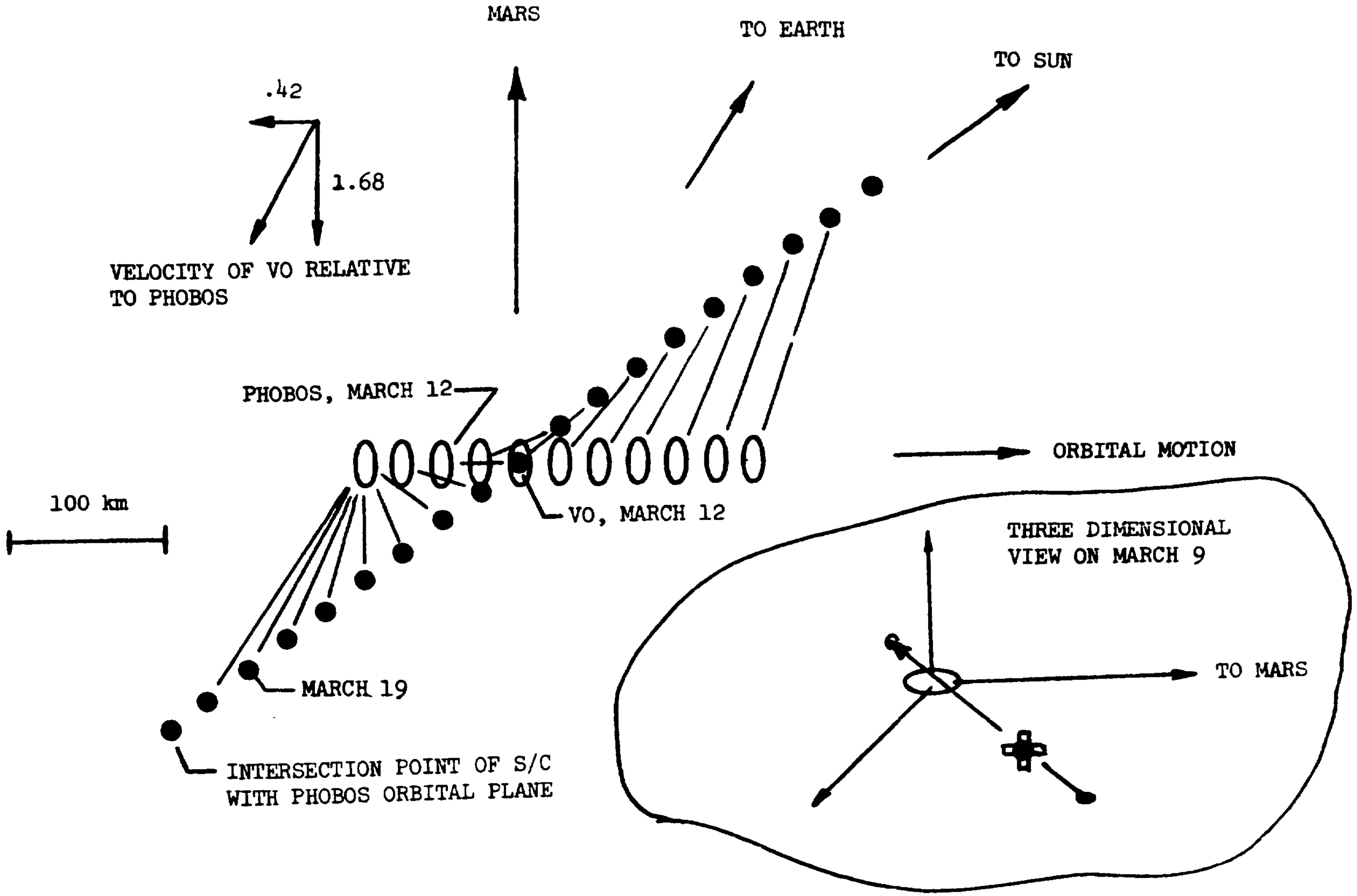

FIGURE 5. DETAIL ENCOUNTER GEOMETRY IN MARCH 1977.

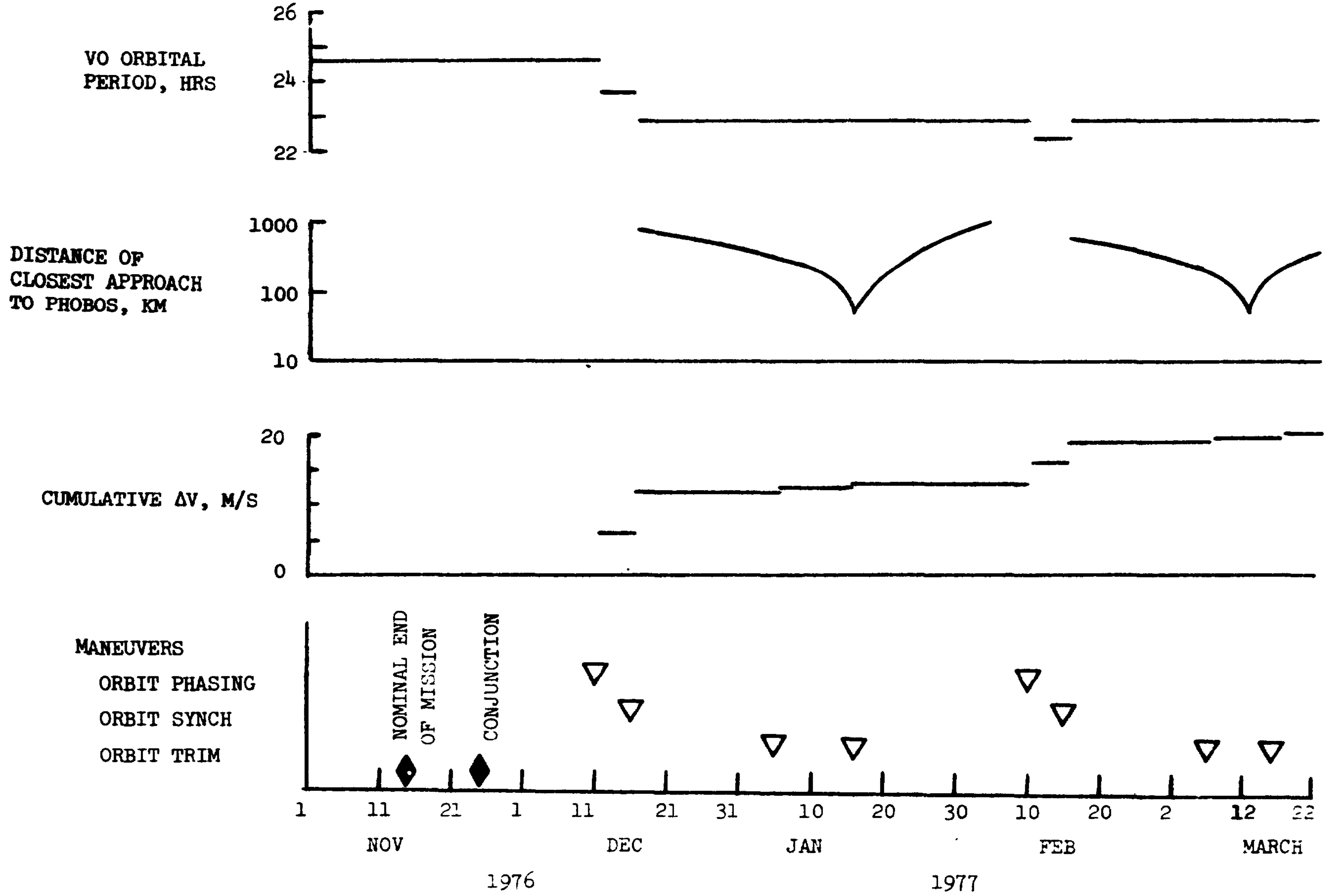

FIGURE 6. Preliminary Mission Timeline