

99942 Apophis Rendezvous Mission Opportunities

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Background

Apophis is a member of the Aten group of asteroids, a subset of asteroids with Earth-crossing orbits. Members of the Aten group have orbital periods less than one year. The Apollo group comprises the remaining asteroids with Earth-crossing orbits – those with orbital periods greater than one year.

Apophis was first identified in 2004 and was initially designated as 2004 MN4. Its finding created an immediate sensation in the media because its potential for impacting Earth was quickly noted. In order for an impact of a solar system body with Earth to occur, three conditions must be met:

1. The orbit of the body must cross that of the Earth, meaning that at times it is farther from the sun than is Earth and at other times it is closer to the sun than is Earth. This condition is met by all Earth-crossing objects.
2. At one of the two locations where the orbit of the body crosses the ecliptic plane (the plane defined by the orbit of the Earth about the sun), the distance of the body from the sun must equal the distance of the Earth's orbit from the sun. This condition, one would hope, is met by very few objects, but Apophis is one whose orbit nearly meets the condition. It is close enough that perturbations to the orbit caused by gravitational attraction of the planets can lead to future problems, even if the current orbit does not exactly meet the condition.
3. The Earth must be in this most unfavorable position at the precise time the solar system body crosses the ecliptic plane at the Earth's distance from the sun. This is a timing issue of extremely low probability; nevertheless, calculations based on the most accurate orbit measurements presently available predict a perilously close encounter of Apophis and Earth on April 13, 2029.

An impact of Apophis with Earth in 2029 has been ruled out. However, the anticipated close passage at about geosynchronous satellite altitude will alter the orbit of Apophis about the sun, possibly changing its membership from the Aten group to the Apollo group. The concern is that there is a possibility, albeit with a very small probability, that the orbit may be placed on a direct path to re-encounter earth in 2037 with more cataclysmic effects. Given the present uncertainties in the orbit of Apophis and the 23 years remaining for those uncertainties to propagate, it is impossible to determine at this time how serious the problem might be in 2037, or at some later close encounter. For this reason, many responsible individuals are calling for the development of plans to avert calamitous encounters in the future, and the focus is on Apophis because it is the object with the highest known potential to inflict major damage to the Earth and its population.

Various concepts for eliminating the threat of a collision with a solar system object have been suggested and some are being actively explored. Most of these concepts require sending a spacecraft to the object. This paper is offered as a contributed resource to assist those efforts. Specifically, windows offering the best opportunities to rendezvous with asteroid Apophis are identified and documented. Here, the word window implies the combination of departure and arrival date ranges that result in low propulsion requirements and the term “best opportunities” is defined in terms of those propulsion requirements, expressed as the sum of the Δv 's provided by the propulsion system at Earth departure and Apophis arrival. This sum is referred to as the total mission Δv . The Δv for Earth departure is defined as the change in speed required to break out of a 185 km circular orbit about Earth to place the spacecraft on a trajectory that intercepts Apophis on a given arrival date. The Δv at Apophis arrival is the difference between the spacecraft velocity on the heliocentric orbit at the time of arrival and the velocity of Apophis. Δv is readily converted to propellant mass, m_p , using the rocket equation:

$$m_p = m_s(1 - e^{-\Delta v/c})$$

where m_s is the spacecraft mass just prior to the injection maneuver, $c = g I_{sp}$ is the jet exhaust speed of the propulsion system, I_{sp} is the specific impulse and g is the reference acceleration of gravity at the Earth's surface (9.80665 m/sec^2). The identification of launch/arrival date pairs that lead to low values of the total mission Δv provides appropriate starting conditions for more detailed mission studies once specifics of the mission, launch vehicle and spacecraft have been defined.

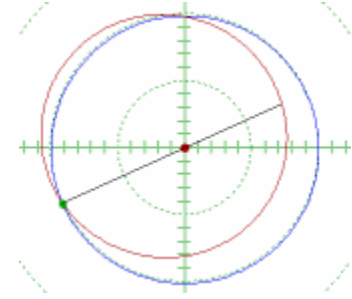
As a final point prior to proceeding with the analysis, we note that not all concepts for threat abatement require rendezvous with the target. For these cases, one will normally only be concerned with minimizing the departure Δv – a generalization that usually expands the window of the opportunities at reasonable propulsion levels. However, the opportunity windows identified for the rendezvous missions will typically be contained within the boundaries of those for flyby missions, so the information will be useful for both. If more detail is required, however, the same software used to produce the data to follow could also be applied to the flyby missions.

A wealth of reasonably current information about asteroid 99942 Apophis is available online at http://en.wikipedia.org/wiki/2004_MN4. This site also references other sites providing related content. Portions of the summary presented above were developed from these sources.

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Apophis' Orbit

The figure to the right displays the ecliptic plane projection of the orbits of Apophis (red) and Earth (blue). The black line through the center of the grid represents the line of nodes of the orbits – that is, the line at which the orbit planes of Earth and Apophis intersect. The line terminal represented with the green dot is the ascending node of Apophis orbit on the orbit of Earth and is the position corresponding to the near encounter in 2029. Note that Earth crosses the horizontal axis on the right side of the figure on the first day of autumn of each year and its motion is counterclockwise as viewed. Therefore, Earth passes the point of the upper orbit crossing around the first of each year and the lower crossing in the middle of April. So, the danger of its impact with Earth always occurs in mid-April.



The amount of propulsive energy required for trajectories between two co-orbiting bodies is cyclic with a frequency equal to that of successive alignments of the two bodies on the same side of the sun. The time between successive alignments is known as the synodic period of the two orbits, so good (low total mission Δv) mission opportunities normally occur once each synodic period and it is customary to refer to opportunities in terms of the date of the corresponding alignment.

The distance of Apophis from the sun ranges from a minimum of 0.7462 AU (perihelion) to a maximum of 1.0987 AU (aphelion), where one AU is the average distance of the Earth from the sun. The inclination of the orbit to the ecliptic plane is a mere 3.33 degrees and its period is 323.6 days. The synodic period of Apophis and Earth is 2,837.6 days (7.769 years), which explains why the next possible encounter with Earth following the 2029 passage is 2037. The synodic period is evaluated by dividing the product of the two orbital periods by their difference, so the synodic period is quite long when the two orbital periods are nearly equal.

A characteristic of low total mission Δv trajectories, which are often referred to as low energy transfers, is that departure occurs prior to an alignment of the two bodies and arrival occurs after the alignment. When the two orbital periods are substantially different, the penalty paid for trajectories that do not include the date of alignment are so severe that they are usually of little interest. On the other hand, when the two orbital periods are nearly equal, as in the case of Apophis and Earth, reasonable opportunities, separated at intervals roughly equal to the orbital periods, will exist both forward and backward in time from the date of alignment. This produces families of opportunities that are associated with, and surrounding, each alignment. Each successive opportunity within a family will, as it gets farther from the date of alignment, require more propulsion and eventually becomes of little interest. However, when this situation occurs in the case of Apophis, the early opportunities associated with the next alignment begin to be reasonable, so there will exist acceptable opportunities for missions to Apophis nearly every year.

Mission Classes

The calculation of trajectories between solar system bodies is accomplished by applying Lambert's Theorem to the configuration of the two bodies in question. In a nutshell, the theorem states that, given two points in space, there exists two orbits that join those points in a given transit time – one orbit in each direction in the plane containing the two points and the central attracting body (the sun). Associating the two points with the departure and target bodies, which themselves are revolving around the sun, we normally ignore the solution to Lambert's Theorem that opposes the direction of motion of the two bodies (referred to as retrograde orbits) because of the excessive amount of propulsion needed to establish the transfer orbit.

The theorem as stated above applies for travel angles less than one revolution about the sun. The theorem extends to multiple revolution orbits as well, stating that for any number, n , of full revolutions about the sun, there will exist two transfer orbit solutions in each direction with a given transfer time, provided the transfer time is greater than the minimum value required to accomplish the specified number of revolutions between the two bodies involved. The two orbit solutions that result for a given n will differ in period and eccentricity; we refer to the two possibilities as the long period and the short period solutions. Of course, the retrograde orbit solutions are ignored for multiple revolution trajectories as well because they are largely inaccessible from a propulsion standpoint.

Under normal circumstances, the plane of the transfer orbit will be close to the planes of motion of the two solar system bodies involved. However, as the transfer angle between two mutually inclined bodies approaches any multiple of 180 degrees, the geometry of the problem requires that the transfer orbit plane be highly inclined to the planes of motion of the two bodies. This imposes a sharp increase in the propulsion requirements necessary to establish the transfer trajectory and creates the distinct and well-known division between trajectories on each side of the demarcation. For transfers of less than 1 revolution, it is customary to refer to trajectories of less-than or greater-than 180 degrees as Type I and Type II transfers, respectively.

For multiple revolution trajectories, each of the long and short period solutions have their equivalents of Type I and Type II transfers. However, the range of departure and arrival dates yielding low energy transfers of long period Type II and short period Type I are often insufficient to provide an adequate window for a mission. Therefore, the primary focus of multiple revolution missions will usually be on long period Type I and short period Type II transfers. We refer to the various classifications of transfer trajectories as mission classes. Typical transfer trajectory profiles of three mission classes of importance to the Apophis rendezvous mission are shown in Fig. 1 below. In these diagrams, the orbit of Apophis is displayed in black, the orbit of Earth in blue, and the transfer trajectory in red.

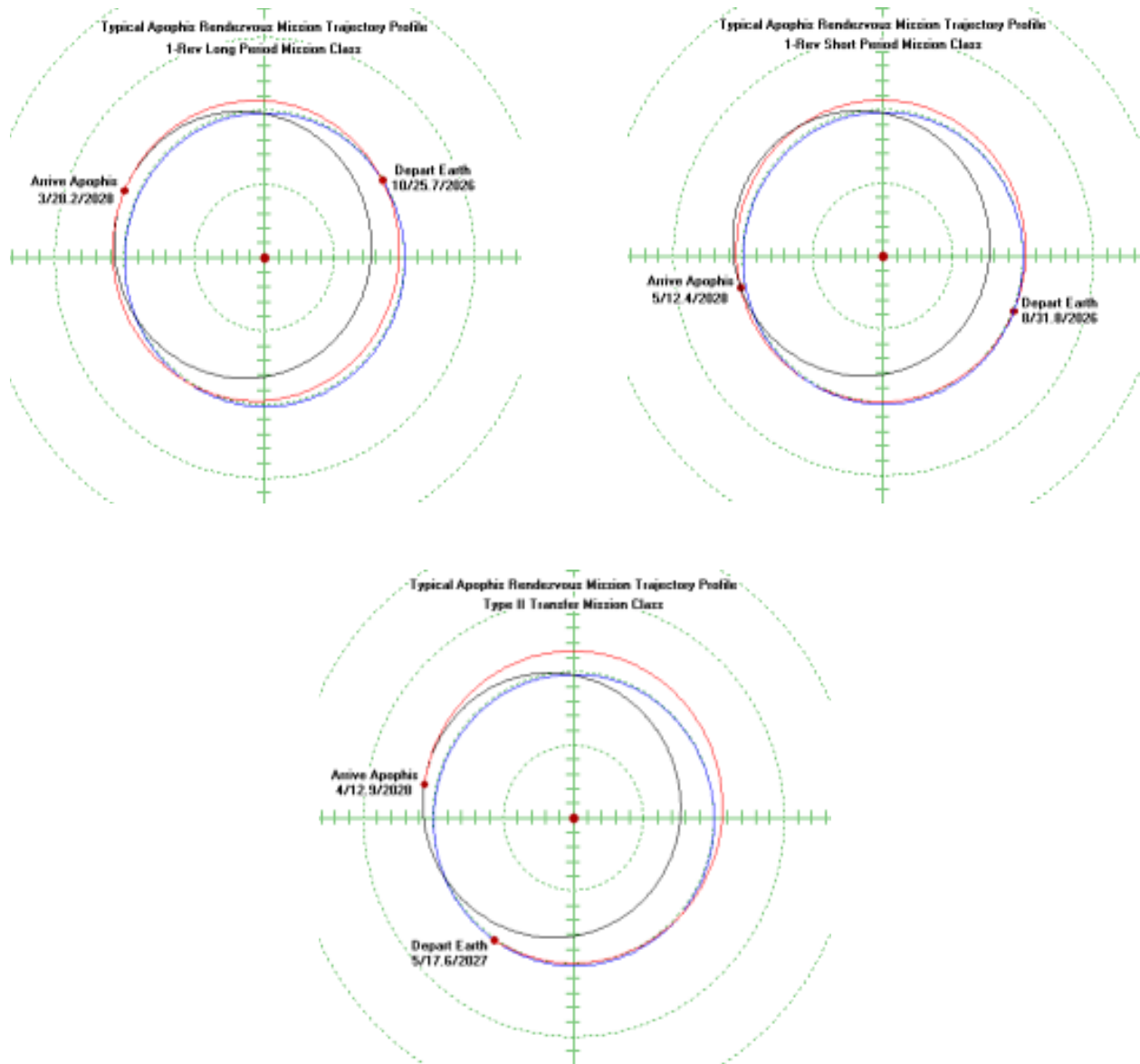


Fig. 1 – Typical Trajectory Profiles of the Candidate Mission Classes

As a final point, it is useful to note that the positions (and velocities) of solar system bodies are defined as functions of time by ephemerides. The implication of this with respect to Lambert's Theorem is that there will exist a single transfer trajectory of less than one revolution for any pair of departure and arrival dates. Similarly, for any number n of full revolutions about the sun, there may exist one long period solution and one short period solution for a given pair of departure and arrival dates. This observation is the basis for the presentation of various mission performance parameters on a grid of departure date versus arrival date, which allows for a clear visual definition of mission windows. These contour charts are occasionally called porkchop plots for reasons that become obvious when viewed.

Mission Opportunity Windows

Given the purpose of Apophis rendezvous, several mission opportunities preceding the close encounter in 2029 were mapped. Because it is thought that different threat abatement concepts may require arrival in different years, the data were organized in terms of arrival year. Specifically, mission opportunities for zero and one revolution were investigated. While equally good, or even better, solutions will exist for two or more revolution transfers, it is thought that interest in them will not be great because each additional revolution adds about one year to the flight time. It is relatively easy to create the additional information if interest in them should develop.

It is believed that mission data for arrivals during the 10-year period prior to the 2029 encounter is sufficient for the purposes prompting this paper. To support this period, it was necessary to consider two solution families – those associated with the 2021 and with the 2029 alignments. For the earlier solution family, arrival years ranging from 2020 to 2024 were assessed. For arrival years after 2024, low energy transfer trajectories disappear for this family unless one is to consider more revolutions. The earliest year of arrival of interest for solutions in the 2029 family is 2024, and the windows become increasingly favorable through 2028, after which they begin to diminish. Mission opportunities are presented by arrival year in Figures 2 – 11 that follow.

Contours of constant total mission Δv are displayed on the grid of departure date (on the horizontal scale) versus arrival date (on the vertical scale). Contours are shown for the same three values of total mission Δv in all arrival years. The values shown are 6 km/sec, 8 km/sec and 10 km/sec. Color codes of yellow, red and blue, respectively, differentiate the contours in all figures. However, in Figure 6 only, data are presented for both solution families, and the total mission Δv contours for 8 and 10 km/sec for the 2021 solution family are shown in cyan and magenta, respectively (no 6 km/sec contour exists for this arrival year).

In certain of the figures, contours displayed in black appear. These are not performance contours as are those of other colors. Rather, they represent regions in which no solutions are possible because the departure/arrival date combinations within the contours represent flight times that are too short to accommodate the required transfer angles between the two bodies. This author has found no mention of this interesting phenomenon in the literature and, in the absence of an official name for them, simply refers to them as exclusion zones; that is, regions where no multiple revolution trajectories are possible.

The interpretation of the contour plots is intuitive. Lower propulsion requirements may be associated with the interior contours for a given mission class and arrival year. Consequently, one would normally choose a departure date/arrival date combination that falls within a contour representing acceptable propulsion performance. The range of departure dates available within an acceptable contour represents the launch window afforded by that opportunity and total mission Δv capability.

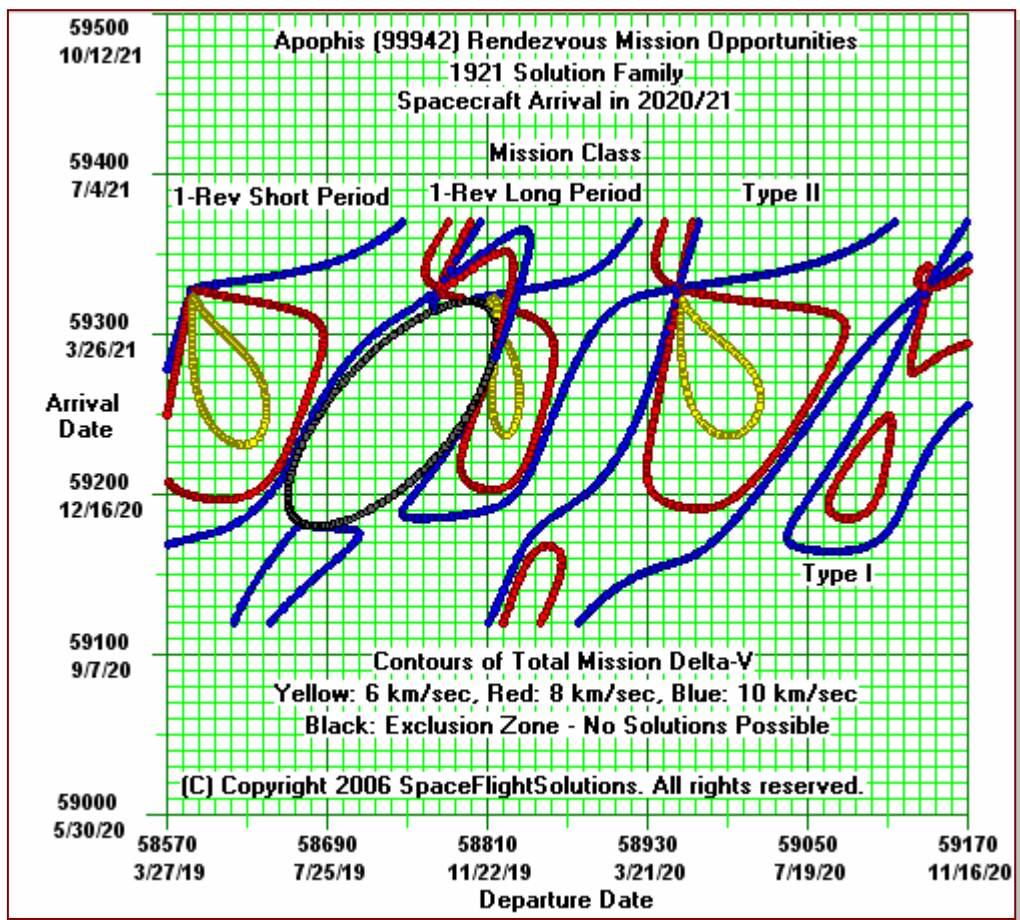


Fig. 2 – Total Mission Δv Contours for Arrival in 2020/21

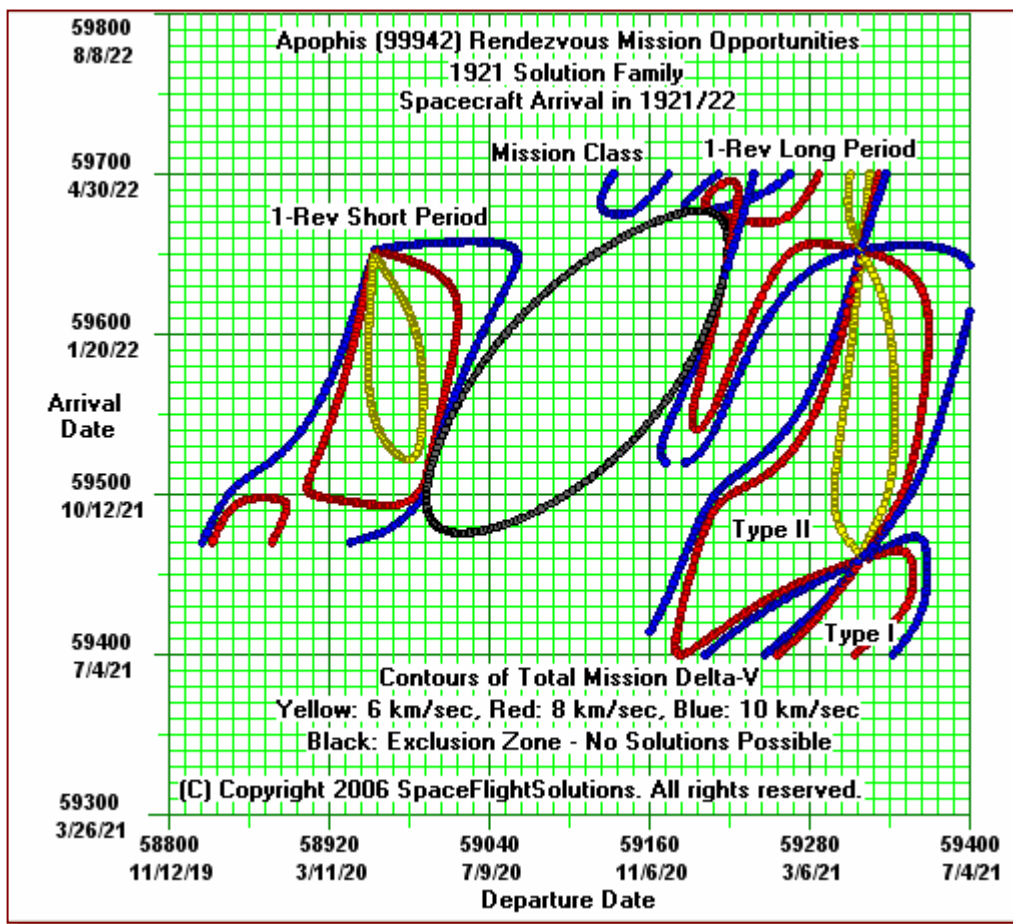


Fig. 3 – Total Mission Δv Contours for Arrival in 2021/22

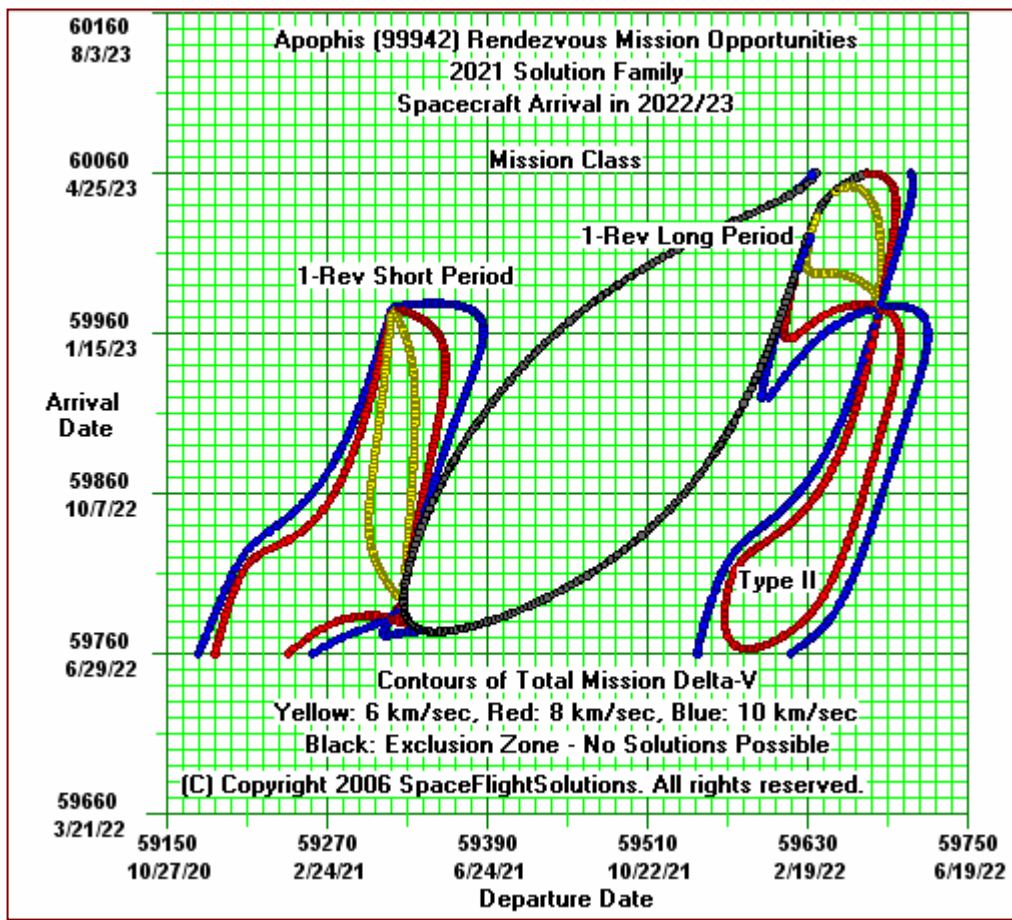


Fig. 4 – Total Mission Δv Contours for Arrival in 2022/23

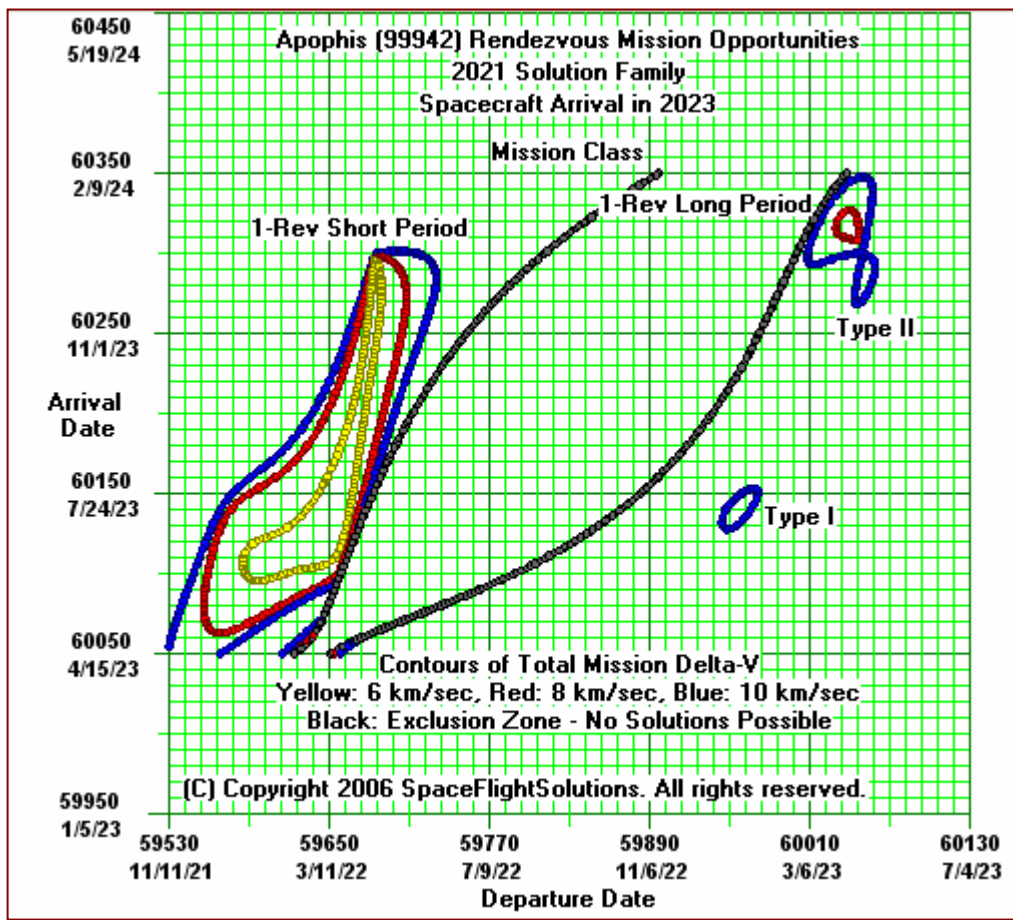


Fig. 5 – Total Mission Δv Contours for Arrival in 2023

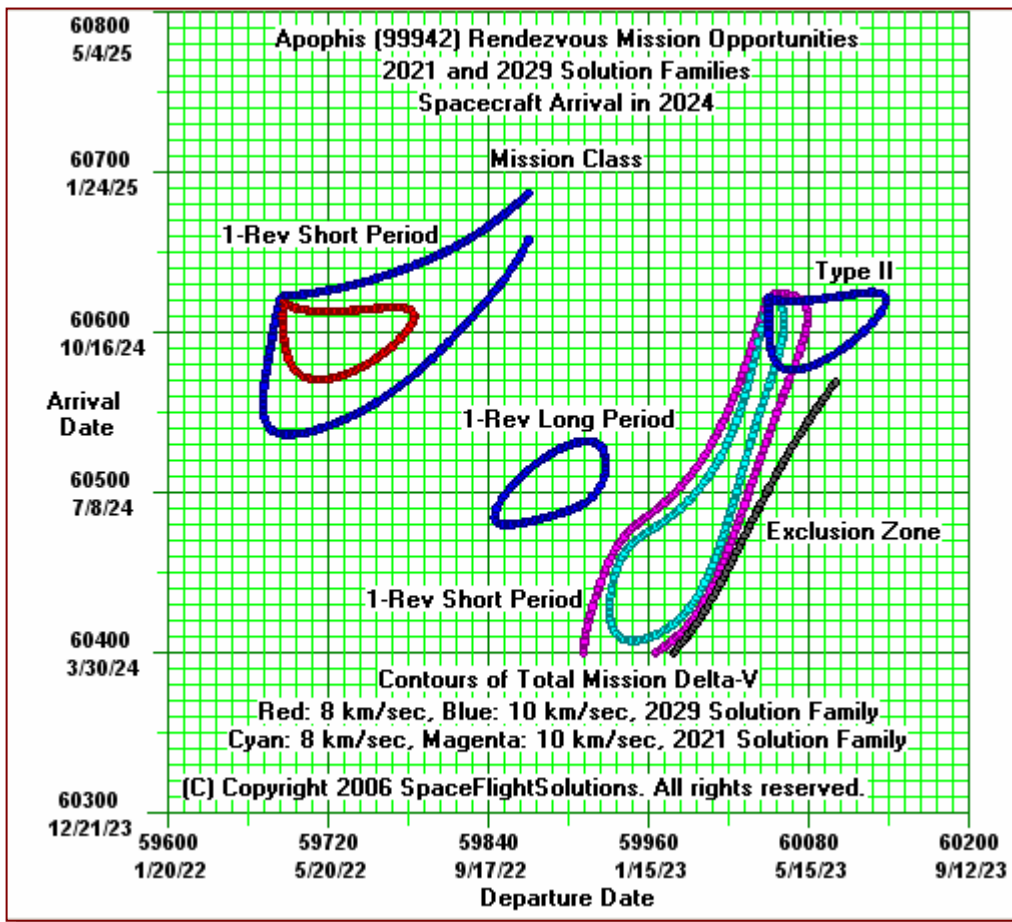


Fig. 6 – Total Mission Δv Contours for Arrival in 2024

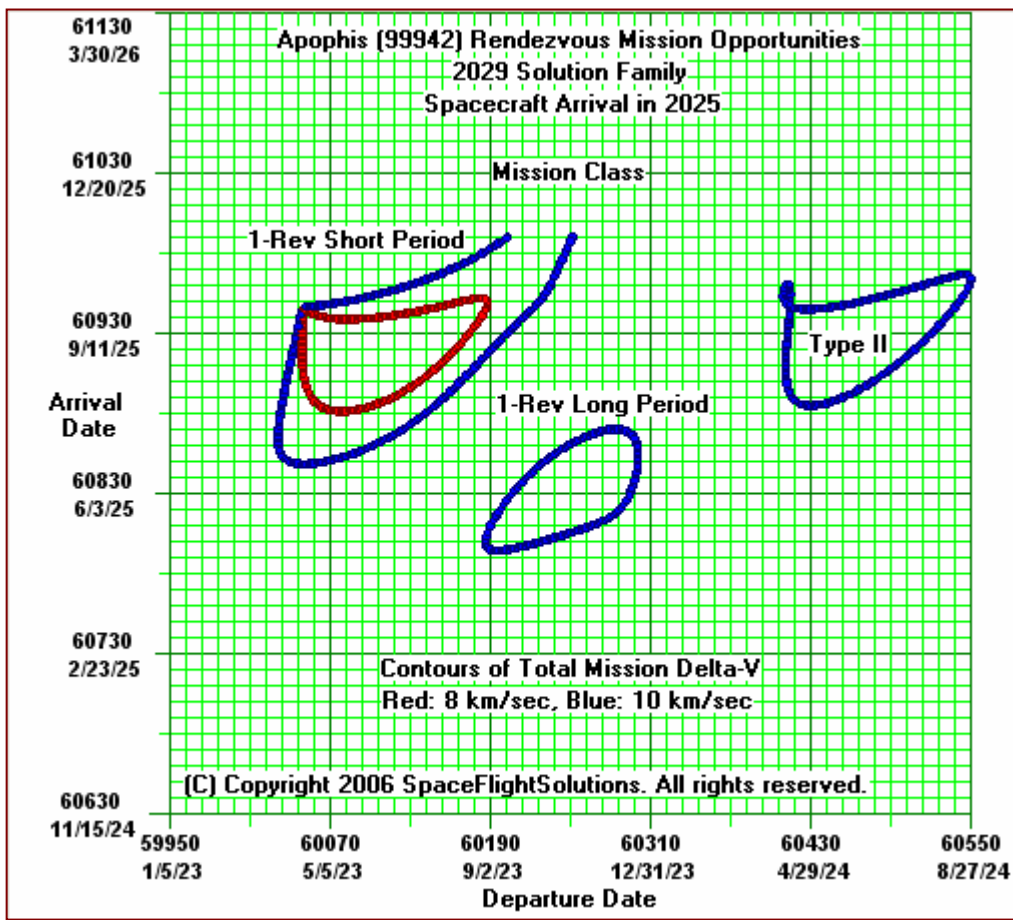


Fig. 7 – Total Mission Δv Contours for Arrival in 2025

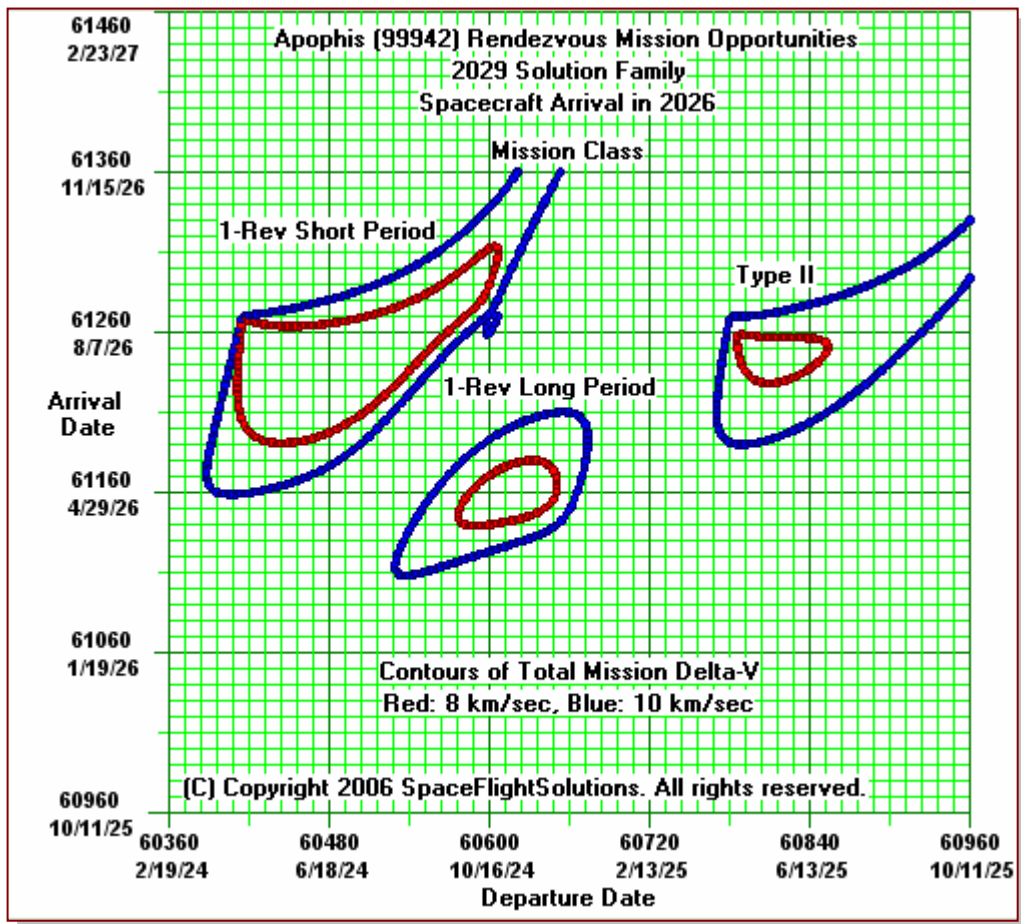


Fig. 8 – Total Mission Δv Contours for Arrival in 2026

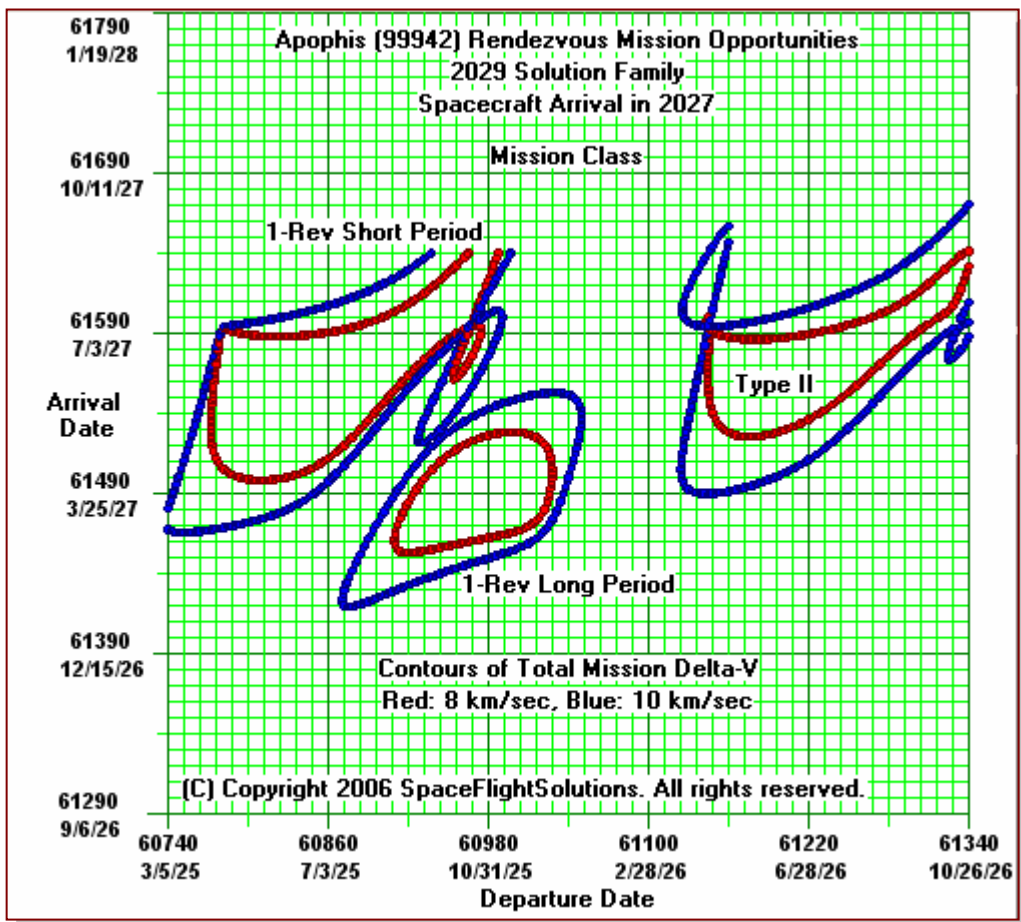


Fig. 9 – Total Mission Δv Contours for Arrival in 2027

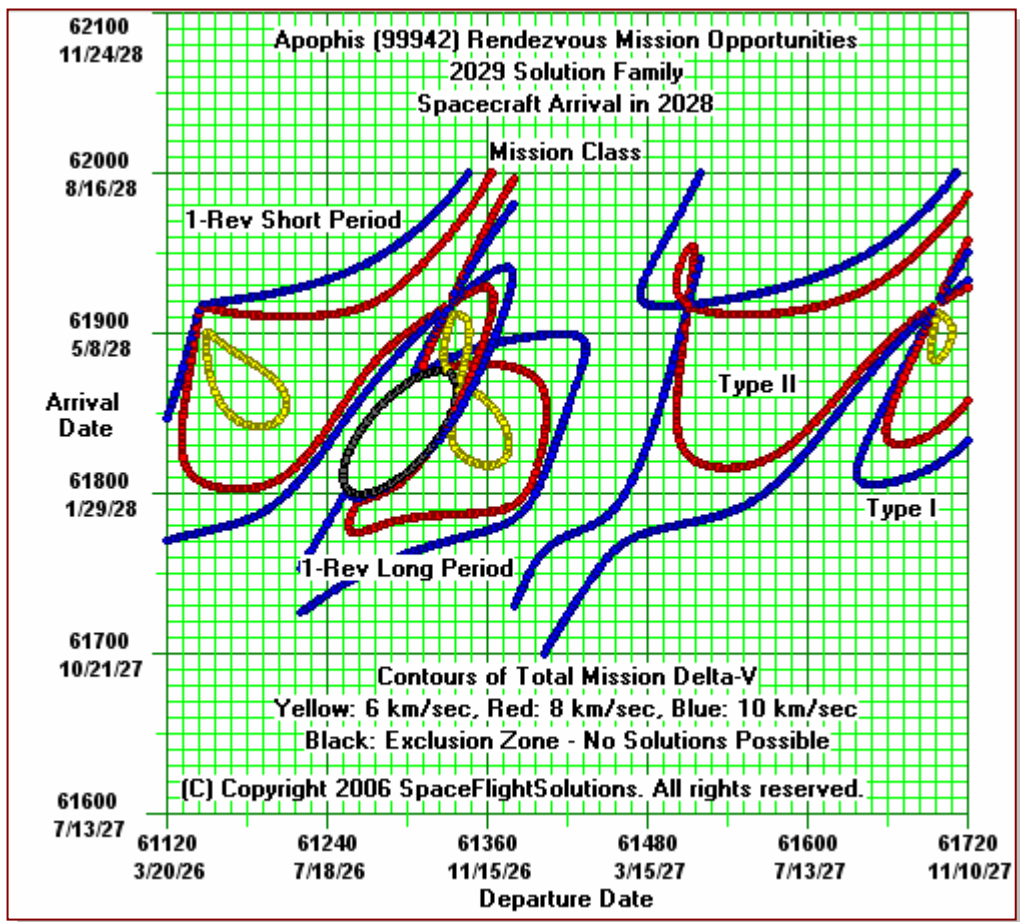


Fig. 10 – Total Mission Δv Contours for Arrival in 2028

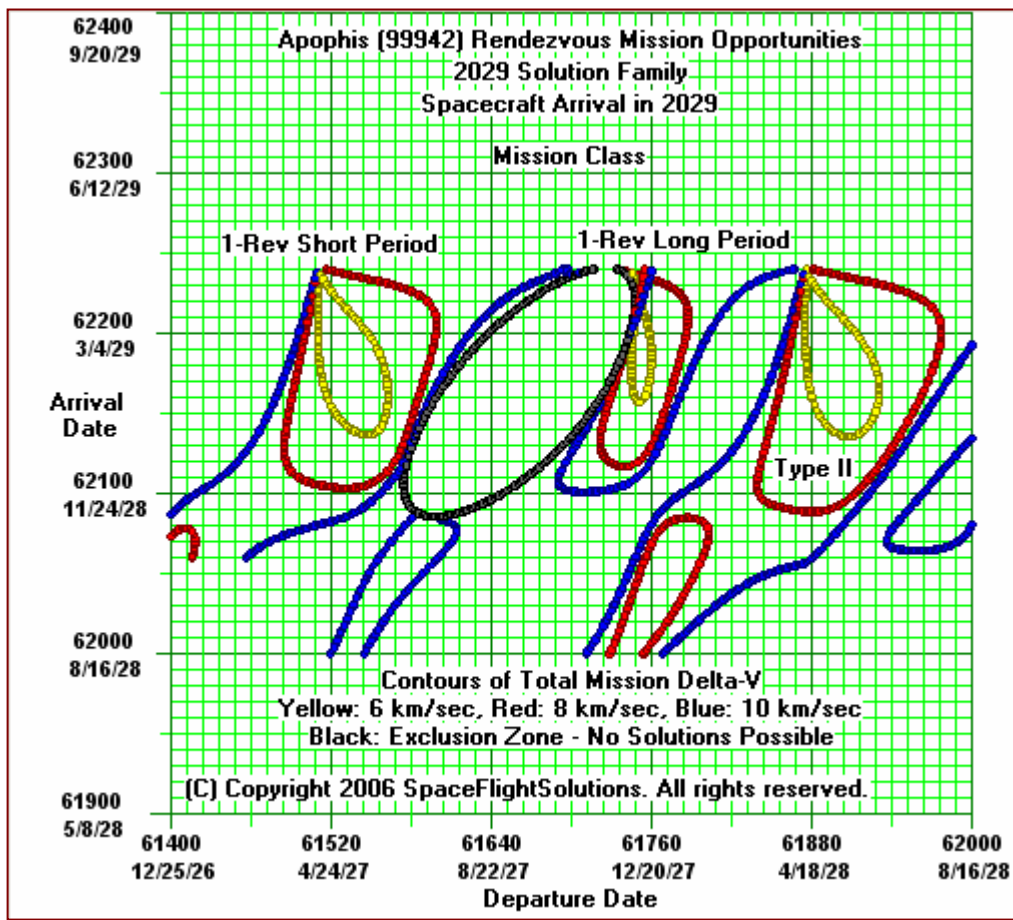


Fig. 11 – Total Mission Δv Contours for Arrival in 2029