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Extended opportunities of a mission to Sedna

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Abstract

The presented research is devoted to the determination and analysis of flight trajectories to the trans-Neptunian object Sedna. Sedna is a mysterious object moving around the Sun with an orbital period of about 11 thousand years. Origin of the object has been widely discussed. Currently Sedna approaching its perihelion which is about 75 a.u. and estimated to be in 2075-2076. This approach of Sedna opens up a huge amount of opportunities to study this unique object by sending a spacecraft and observing the object from a close distance. In this work the two possible ways of reaching Sedna are considered: a direct flight and a flight including gravity assist manoeuvres. Launch dates for the mission are chosen in 2029-2050 years. The gravity assist manoeuvres considered in the research can reduce the required value of ΔV and the flight duration. Manoeuvres near Venus and Earth, as well as Jupiter, Saturn and Neptune are considered. It is shown that for launch windows in 2029–2034, the use of the scheme of flight to Sedna with Venus — Earth — Earth — Jupiter gravity assists as a base, can significantly reduce the value of the total ΔV required to reach Sedna, under restrictions on the time of flight from 20 to 50 years. It is shown that 2053 seems to be the best time to start the mission using the Earth-Venus-Earth-Earth-Jupiter-Neptune-Sedna scheme because the launch in this year requires only about 5.8 km/s of the total ΔV at flight duration of 20 years. Also, we discuss possible expansions of the mission scenario by combining scientific missions to Sedna and another celestial bodies such as asteroids or another TNOs. Examples for such expansions were provided for five TNOs: three extreme TNOs, 2012 VP113, (541132) Leleakuhonua (former 2015 TG387), 2013 SY99) and two classical Kuiper Belt objects (KBO) (90482) Orcus and (20000) Varuna, as well as for the main belt asteroids (16) Psyche, (20) Massalia and (152) Hilda. The approach within which the flight to distant trans-Neptunian object as part of a scientific mission to Neptune also considered.

Keywords: Sedna, gravity assist manoeuvres, trajectories optimization, trans-Neptunian objects

Nomenclature

ΔV = characteristic velocity
ΔV_0 = launch ΔV from Earth
ΔV_Σ = total ΔV required for flight to Sedna
ΔV_α = ΔV near aphelion on Earth-Earth loop
SOI = sphere of influence
TOF = time of flight
SC = spacecraft
TNOs = Trans-Neptunian objects
LEO = low Earth orbit
ESed = direct flight Earth-Sedna
EJSed = Earth-Jupiter-Sedna
EVEEJSed = Earth-Venus-Earth-Earth-Jupiter-Sedna
EVEEJSSed = Earth-Venus-Earth-Earth-Jupiter-Saturn-Sedna
EVEEJNSed = Earth-Venus-Earth-Earth-Jupiter-Neptune-Sedna
EVEEJSNSed = Earth-Venus-Earth-Earth-Jupiter-Saturn-Neptune-Sedna
EJ-A = Earth-Jupiter-asteroid
EJN-A = Earth-Jupiter-Neptune-asteroid
VEGA = Venus-Earth Gravity Assists manoeuvre
VEEGA = Venus-Earth-Earth Gravity Assists
VEΔVEGA = VEEGA with impulse ΔV_α at aphelion of Earth-Earth loop

1. Introduction

Discovery of such objects as 2000 CR105, (90377) Sedna, 2012 VP113 and other like objects with aphelion more than 150 au (those objects usually are called extreme TNOs) might not only testify the existence of the Oort Cloud but also prove the existence of a hypothetical Ninth Planet in our Solar System [1]. Existence of this planet might be a reason for orbits of the extreme TNOs [2], [3].

The large deep space object (90377) Sedna is located far beyond the orbit of Neptune and thus is one of the many currently known TNOs. Sedna was discovered by American astronomers M. Brown, C. Trujillo and D. Rabinowitz in 2003 [4]. Little is known about this object; information about it is mostly speculative. The absolute stellar magnitude of Sedna is 1.56, the albedo is estimated at 0.32 ± 0.06. Based on these data, the diameter of Sedna can be estimated in the range of 1100-1300 km. According to estimates given in [5]–[8], the surface of Sedna has a rich, bright red color. The origin of such a shade may be associated with the presence of a layer of tholine or hydrocarbon sediment on the surface of this object [8]. Some researches suggests to which there may be an ocean under the surface of Sedna, heated by the internal heat of this object, generated by radioactive decay [9]. The orbital period of Sedna is more than 10 thousand years. At present, Sedna is approaching its perihelion, which opens up a unique opportunity to launch a SC to Sedna and study it at close range.

Flights to such distant objects as Sedna and 2012 VP113, are reasonable using gravity assist of the planets of the Solar System, i.e. with a flight near the planets in order to use their gravitational fields to increase the orbital energy of the spacecraft and purposefully change its trajectory. The article [10] shows results of studies of the trajectories of the flight to Sedna (as well as to four other TNOs) in 2015-2047. This article considers the Earth-Jupiter-Sedna flight scheme, i.e., the gravity assist manoeuvre only at Jupiter is assumed. The minimum values of the $\Delta V\Sigma$ (that is the sum of the characteristic velocity required for launch, as well as all manoeuvres in deep space and near planets), obtained by the authors, required to reach Sedna in 24.48 years, depending on the launch date, lie in the range from 7.2 (2045) to 11 (2023) km / s. Also, similar studies were carried out in [11]: flights to Sedna with a Jupiter gravity assist are considered and the values of the final mass of the spacecraft are compared when flying with high and low thrust.

The flight schemes with the gravity assist manoeuvres for the launch dates in 2029-2037 are analyzed. Each of the flight schemes includes a flight Earth-Venus-Earth-Earth-Jupiter or Earth-Venus-Earth-ΔV_α-Earth-Jupiter with a small impulse ΔV_α in the aphelion region. Such a manoeuvre makes it possible to reach Jupiter with ΔV_Σ only slightly exceeding the magnitude of the impulse ΔV_0 needed for the Earth-Venus flight when launching from a low Earth orbit: about 3.5-3.6 km/s (note that this value is the lowest among such values needed for a direct flight from Earth to any other planet). In addition, all considered schemes of flight to Sedna include a Jupiter gravity assist. Also flight schemes with the addition of Saturn and Neptune gravity assist are analyzed (Uranus can not be reached at the considered launch years).

For all the analyzed flight schemes, the optimal (in terms of the minimum ΔV_Σ value) trajectories are determined. Such flights have a long duration, therefore, restrictions on the duration of flights - 50 years - are also considered. As will be shown below, the best flight scheme depends on the launch date: for 2029, 2031 and 2037, the best one is EVEEJSed, for 2034 and 2036 EVEEJNSed; and in many cases, adding ΔV_α around the Earth-to-Earth aphelion slightly reduces ΔV_Σ. Moreover, with a flight duration of 25 years (i.e., approximately the same as that accepted in [10]), the value of ΔV_Σ is significantly less than in all cases of trajectories to Sedna considered in [10].

In some of the flights considered in the present article the spacecraft on the optimal trajectory approaches Jupiter at a relatively short distance during the gravity assist manoeuvre near this giant; in particular, in the scheme EVEEJSed at the beginning of the mission in 2034 and its duration of 30 years the spacecraft approaches Jupiter to an altitude of 4.2 thousand kilometers, and powerful radiation belts of Jupiter can be hazardous for the spacecraft electronic components. The article [12] gives an estimate of ΔV_Σ for the above option with restrictions on the minimum altitude over Jupiter up to 600 thousand kilometers. The estimation of the radiation dose received by the spacecraft during the Jupiter flight, depending on the thickness of the Al protective shield is given in [8]. Detailed estimates of the influence of the radiation hazard on the spacecraft electronic components during the passage of the SOI are given in [13], [14]. In particular, work [13] indicates that a safe passage of the Jupiter is possible with an orbital altitude of more than 130 thousand kilometers and inclination greater than 45 degrees. The authors of [14] show that a completely safe altitude will be 1 million km for any inclination.

A possible expansion of the mission to Sedna has also been proposed. In such a scenario, a flight takes place simultaneously to both Sedna and another TNO by separation of a small probe from the spacecraft. Such separation takes place during the Jupiter or Neptune flyby. After that the probe is directed to another TNO, the flight to which is possible without additional manoeuvres in the planetary SOI. Results are given for five TNOs suitable for this scenario, including three extreme TNOs 2012 VP113, (541132) Leleākūhonua (former 2015 TG387) and 2013 SY99 and two classical KBOs: (90482) Orcus, (20000) Varuna.

2. Mathematical methods

The method of patched conic, i.e., approximation of spacecraft trajectory by conic sections [*] [15]–[17], is used as a model of spacecraft motion. This method greatly simplifies the analysis and optimization of trajectories of flight and at the same time gives acceptable accuracy at the initial stages of mission design [16]. When using such a model, the *n*-body problem, which takes place when a body moves within the Solar System, is split into n-tasks of two bodies. The spacecraft trajectory segments within the two-body problem can be found by solving the Lambert problem (determining the orbit by two given positions and the flight time between them). There are many different methods for solving the Lambert problem; the method proposed in [18] is used in this paper.

After defining in this way the sections of the trajectories between each pair of celestial bodies, these sections are connected (patched) with each other as follows [12], [16], [17], [19]:

During the passage of the planet, the incoming and outgoing semi-hyperbolas, defined by the asymptotic velocities of approach to the planet and departure from it, respectively, are connected at their pericenters so that the tangents to them coincide. The modulus of the difference of velocity vectors at the pericenter of these hyperbolas is equal to the momentum ΔV needed to connect the approach and departure arcs of the trajectory. If the gravitational field of the planet is insufficient to rotate the asymptotic velocity vector from its incoming direction to its outgoing direction, additional impulse to rotate the velocity vector is required.

The trajectory optimization is done as follows: the intervals of launch dates for the Earth and the passage of each of the celestial bodies involved in the flight, which obviously contain the optimal dates, are set. Then the optimal trajectory, i.e. providing the minimum value of ΔV_Σ, is chosen from the whole set of trajectories, corresponding to the dates from these intervals. The advantage of this approach is that it allows one to easily impose any restrictions on the flight - for example, on the duration of each heliocentric arc or the flight as a whole, the altitude of the flight over the planets, ensuring radio visibility of the spacecraft from Earth during the flight of each celestial body, etc.

3. Theory and calculation

Flights are reasonable to carry out with the use of a powerful gravitational field of Jupiter: the gravity assist of this giant allows to significantly increase the orbital energy of the spacecraft and send it to the desired point of space. The optimal direct flight from Earth to Jupiter requires a characteristic velocity of at least 6.3 km / s, the duration of such a flight is about two years (such a flight was considered in [7, 8]). An Earth-Venus-Earth-Jupiter flight (i.e., a VEGA manoeuvre) can be used to reach Jupiter, but this flight has only a relatively small advantage over a direct flight to Jupiter in terms of the required ΔV, since a large additional active manoeuvre is required during the fly over Venus or Earth. The minimum ΔV is about 5.4 km/s, approximately 1 km/s less than a direct flight to Jupiter. At the same time, the flight time to Jupiter increases in comparison with a direct flight by about one and a half years, necessary for the implementation of the VEGA manoeuvre.

In our study in all cases of flight to Sedna considered the Earth-Earth-Earth-Jupiter flight scheme is used (application of the VEEGA manoeuvre, see Fig. 1a). The flight time between Earth-Earth loop is 2 or 3 years, i.e. the duration of the flight to Jupiter is increased by 3.5-4.5 years in comparison with a direct flight; however, as will be shown below, this increase is more than compensated by a significant reduction of the required ΔV_Σ. In the aphelion region of the Earth-Earth loop, a relatively small impulse ΔV_α can be applied (Fig. 1b), which in many cases decreases the value of ΔV_Σ; adding such a manoeuvre to the flight scheme was also investigated by the authors.

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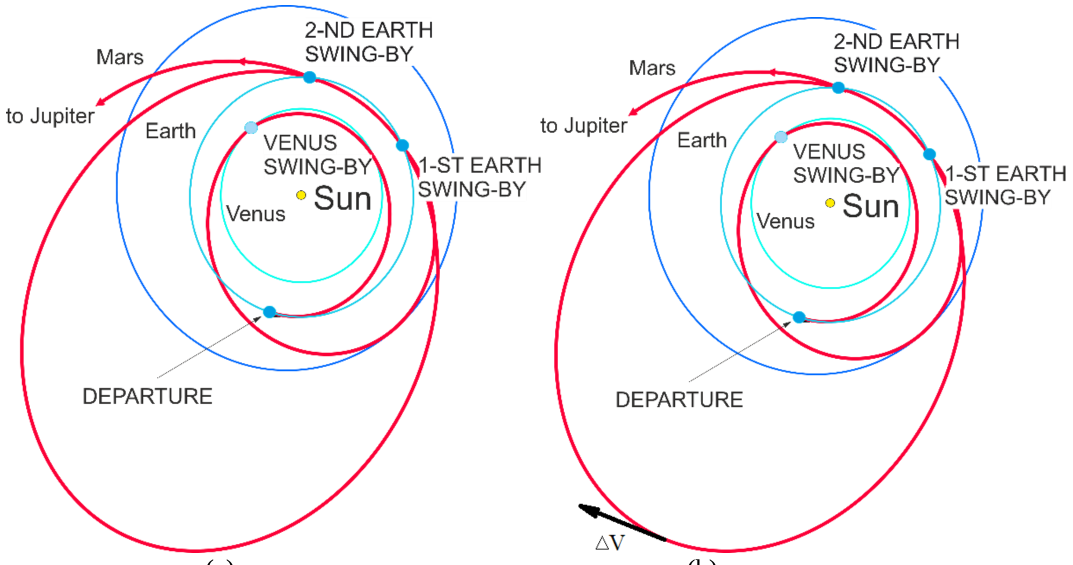
[*] In a more complicated version of the patched conic, the size of the planetary spheres of influence is assumed to be finite [36].



(a) (b)

Fig. 1. Illustrations of the manoeuvres: (a) VEEGA; (b) VEΔVEGA.

4. Results

4.1. Flights to Sedna using gravity assist manoeuvres

In this section we present the results of the analysis of optimal trajectories using various flight schemes and with constraints on the time of flight. We consider flights using Venus, Earth, and Jupiter gravity assists; we also consider the possibility and feasibility of Saturn and Neptune gravity assists. Below in the analysis of flights with gravity assist manoeuvres we will be limited to the duration of the flight and the value of ΔV_Σ, lying in the range of

$$\left.\begin{aligned}\Delta V_\Sigma &\le 8\text{ km/s}\\ \text{TOF} &\le 50\text{ yrs}\end{aligned}\right\}\qquad(1)$$

Notice, some trajectories that violate constraints given in (1) will also be analyzed. In particular, these are trajectories that make it possible to reach Sedna and other TNOs in 20 years or less. This case will be considered in more details in sec. 4.2.

The numerical characteristics of the flight schemes are presented in Table A.1. The table contains only some of the results of calculating a direct flight to Sedna (see [12], [19]), as well as flights using gravity assist manoeuvres, according to the above schemes, satisfying constraints (1) with step of 5-10 years in flight time; also for comparison, the estimates of ΔV_Σ obtained in [10] are given. In 2033, the flight according to the schemes EVEEJSed and EVEΔVEJSed is difficult to realize and requires high costs ΔV because of the close approach to the Sun at a distance of less than 20 million km, at the Jupiter-Sedna arc [12]. Adding a Saturn gravity assist to the EVEEJSed scheme allows us to increase the perihelion distance at the Jupiter-Saturn arc, if the flight time is more than 40 years. Therefore, only the flight according to the scheme EVEEJSSed with duration of 40 and 50 years is included in Table A.1; a detailed analysis of 2033 is given in [12].

As can be seen from Table A.1 (see Appendix) below, there is a local minimum of the ΔV_Σ when launching in 2031 and 2034 and using the EVEEJSed and EVEΔVEJSed flight schemes. The duration at which this minimum is reached is marked in the tables by two asterisks. At the beginning of the mission in 2029 such a minimum either does not exist, or is outside the 50-year duration of the flight.

Let us consider in more detail the optimal trajectories obtained for 2029 and 2034. When launching from Earth in 2029, the optimal flight schemes are EVEEJSed or EVEΔVEJSed; addition of Saturn and Neptune gravity assists does not lead to a decrease in ΔV_Σ. The dependence of ΔV_Σ on the time of flight is shown in Fig. 2.

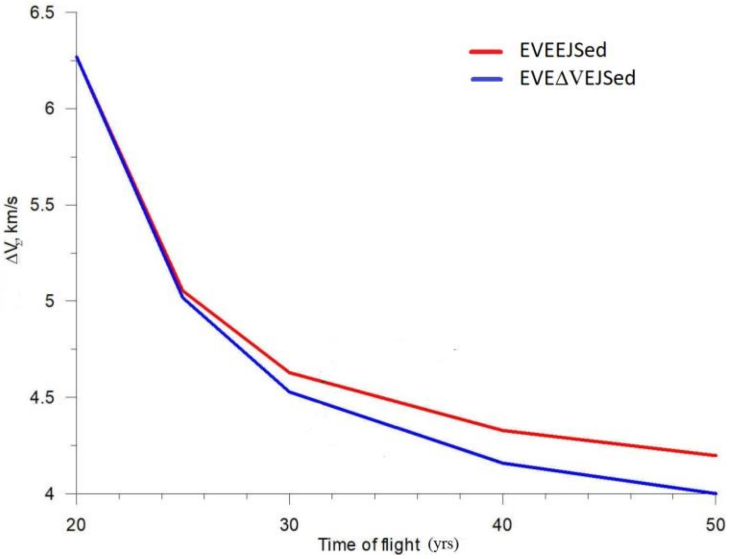


Fig. 2. ΔV_Σ versus the time of flight at the launch in 2029.

In 2034, on the optimal flight according to the EVEΔVEJSed scheme, the magnitude of the impulse at aphelion is negligible, so the values of ΔV_Σ and the flight trajectory in the EVEEJSed and EVEΔVEJSed schemes practically match, which is clearly seen in Table 1 and Fig. 3 (red curve). As can be seen in Fig. 3, the minimum ΔV_Σ value for both of these flight schemes is reached at a flight duration of just over 33 years, for the EVEEJNSed scheme at a flight duration of 38.5 years, and for the EVEΔVEJNSed scheme at a flight duration of about 42 years. These are some local minima; as calculations show, global minima are reached at flight durations well over 100 years.

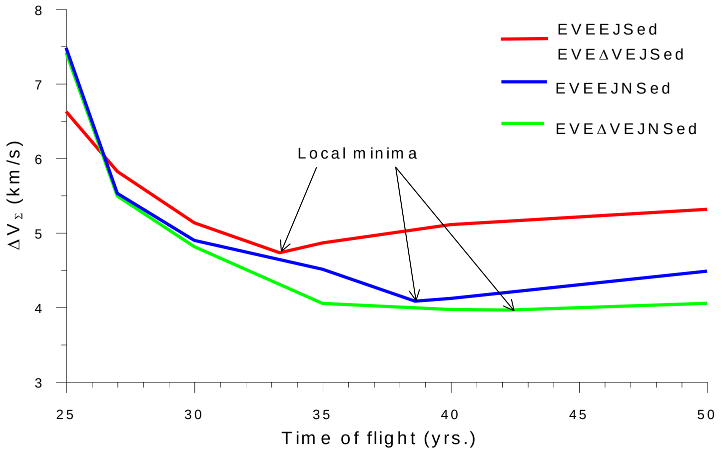


Fig. 3. ΔV_Σ versus the time of flight at the launch in 2034.

Fig. 3 shows that the curve corresponding to the EVEEJNSed flight pattern (blue curve) has a certain "hump" around the time of flight of 35 years. The authors have not been able to find out the nature of this.

Also, a problem of the close approach to Jupiter during its flyby deserves separate attention. As can be seen from Table 1, for the flight schemes in 2034, using EVEEJSed and EVEΔVEJSed spacecraft will fly at an extremely low altitude, which will inevitably lead to an increase in the radiation dose. However, as shown in [12], this danger can be eliminated by increasing the altitude of the flyby; however, as the altitude increases, the ΔV_Σ required for the flight to Sedna will unavoidably increase as well. For more information on the optimal EVEΔVEJSed and EVEΔVEJNSed flights in 2034, see [12].

As the results obtained (Table A.1) show, the use of gravity assist manoeuvres practically for all giant planets, except for Uranus, satisfies the imposed constraints (1) only when the time of flight is more than 35 years. And since 2034 ΔV_Σ begins to decrease with unchanged flight time (Table 1). This is due to the mutual synodic period of the Earth-Venus, Earth-Jupiter, Jupiter-Saturn, Saturn-Neptune systems. As an example, Fig. 4 shows the dependence of

ΔV_Σ on the flight time for 2037, which, with the same flight time according to the EVEEJSNSed scheme, showed better results than in 2034 and 2036 (Table A.1).

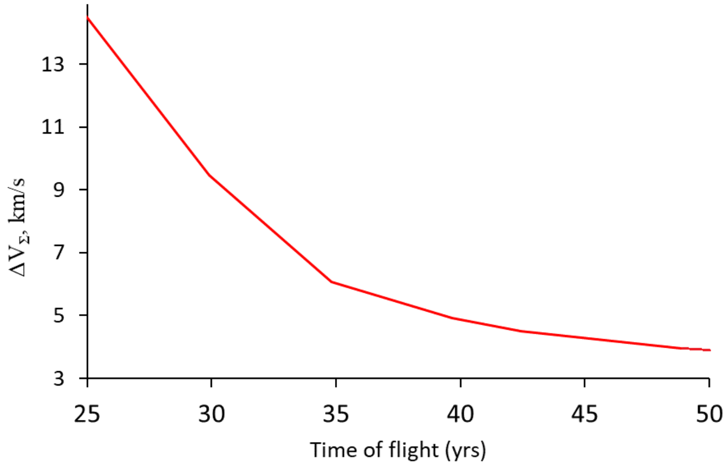
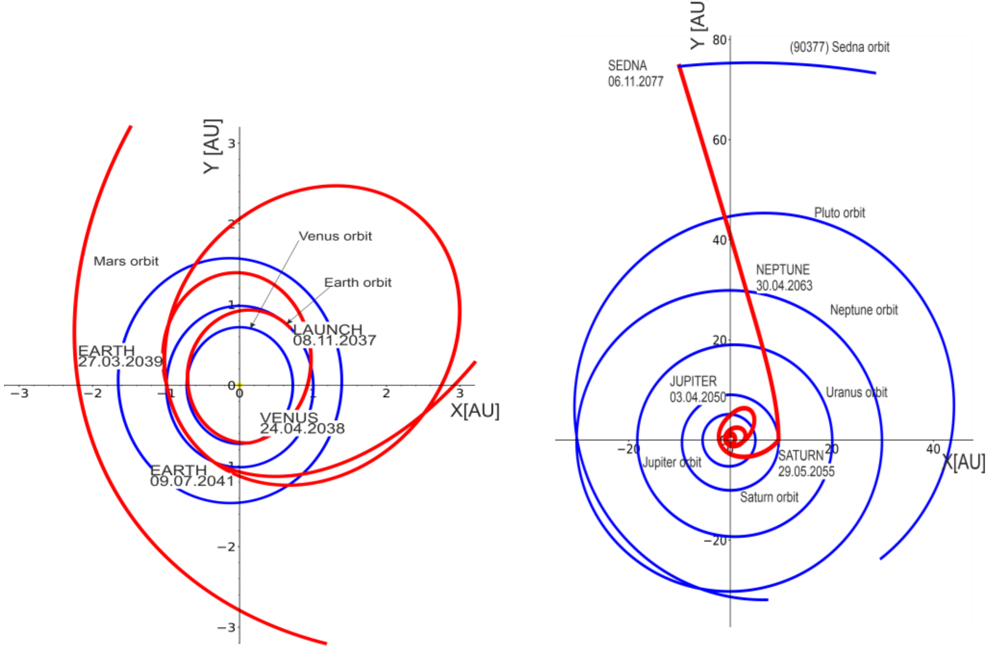


Fig. 4. ΔV_Σ versus the time of flight at the launch in 2037 by EVEEJSNSed scheme.

Fig. 4 shows that the dependence is monotonic, there are no extrema. When the time of flight is more than 35 years the ΔV_Σ satisfies the first part of the conditions (1). The flight to Sedna with a duration of 45 or more years occurs does not require any additional costs of ΔV on the whole path, i.e. only ΔV_0.

Since the dependence shown in Fig. 4 has no local extrema, let us show the optimal trajectory of the flight to Sedna of 40 years duration for the launch in 2037. According to Table A.1, the cost ΔV_Σ will be 4.89 km/s. Note that despite the long duration of the flight in this case, such a scheme allows us to fly around the almost all outer planets of the Solar system (except Uranus), and thus expand the scientific program of the mission to Sedna.

The trajectory and its main parameters are shown in Fig. 5 and Table 1 respectively.



(a) (b)

Fig. 5. The spacecraft trajectory for EVEEJSNSed scheme for the launch date 08.11.2037, in the projection on the ecliptic plane: (a) The trajectory of the spacecraft before the Jovian flyby; (b) The spacecraft trajectory after the Jupiter flyby.

Table 1. Trajectory parameters of the spacecraft during EVEEJSNSed flight for the launch in 08.11.2037.

Celestial bodies	Dates of launch and flyby of celestial bodies	Relative velocities near Earth and of flyby near celestial bodies, km/s	ΔV of launch, at aphelion and of flyby near celestial bodies, km/s	Height of the initial orbit and flyby above celestial bodies, 10^3 km
Earth	08.11.2037	3.25	3.71	0.2
Venus	24.04.2038	5.71	0	0.7
Earth	27.03.2039	10.17	0	5.9
Earth	09.07.2041	10.20	0.58	0.3
Jupiter	03.04.2050	11.49	0	4016.8
Saturn	29.05.2055	9.07	0.46	40.6
Neptune	30.04.2063	15.34	0	195.7
Sedna	06.11.2077	15. 27	-	0

In the EVEEJSNSed scheme with launch in 2037, the spacecraft will fly over Jupiter at an altitude of about 4 million km; at this distance the spacecraft will not suffer any radiation load.

4.2 Extended options of flight simultaneously to Sedna and other TNOs

The global practice of maximising the scientific output through expanding the research program of space missions is well known. For example, during the NEAR [20], [21] mission to the asteroid (433) Eros, it also approached the asteroid (253) Matilda, making it possible to determine its mass and obtain photos of its surface. There are also known examples of Galileo [22] (approaching (243) Ida and (951) Gaspra), Cassini–Huygens ((2685) Masursky) [23], Ulysses (passing the gas tail of comets C/1996 B2 (Hyakutake), C/1999 T1 (McNaught–Hartley), C/2006 P1 (McNaught)), and New Horizons [24] (TNO (486958) Arrokot flyby) missions, etc. This paper, on the other hand, has only one research target which is Sedna. Therefore, following the example of the mentioned missions, it is proposed to expand the scenario of the flight to Sedna.

One way of expanding the mission to Sedna could be to explore the planets and their satellites during gravity assist manoeuvres. Another way of expanding the mission scenario could be provided by including close encounters of small celestial bodies. In the paper [12], the main belt asteroids that could be encountered during the flight to Sedna were considered as potential additional targets. This paper proposes a different way of expansion, likewise in articles [25], [26], namely, to direct the spacecraft to Sedna and the other TNOs simultaneously. For that purpose, it is proposed that the spacecraft should consist of two modules: a vehicle to study Sedna and a small space probe, which could be separated from the main spacecraft during the last gravity assist manoeuvre and then directed to other TNOs.

The general optimisation scheme considered above will not be significantly changed. However, there is a specific feature of the algorithm used in this section. Like in the previous case, the model of patched conic approximation is used. Impulses needed during the gravity assist are described above in the text. One more impulse ΔV_s considered in this section is required for a separation of the probe from the main spacecraft and directing it to the other TNO. The ΔV_s value was calculated using the method described in [27]. Note that for implementation of the method the separation of spacecraft is considered to be on the SOI boundary of the last flyby planet.

Let us limit the magnitude of the separation impulse as follows:

$$\Delta V_s \leq 300 \text{ m/s} \tag{2}$$

No restrictions are imposed on the TOF to the second chosen TNO. But it is assumed that the flight to it takes place passively, i.e. without any additional manoeuvres. Nevertheless, the used optimisation process considers the manoeuvres of the probe inside the SOI. Hence all probe trajectories that requires active manoeuvres were removed in the final selection process.

A total of 5 suitable trans-Neptunian bodies were selected (Table 2), namely three extreme TNOs (2012 VP_{113} (‘Biden’), Leleākūhonua (former 2015 TG_{387}), 2013 SY_{99}) and two classical Edgeworth-Kuiper belt objects: (90482) Orcus and (20000) Varuna. The results for all flights satisfying constraints (1) and (2) are presented in Table A.2. The TOF to the second object is not limited and determined in the optimisation process at the criterion of minimum ΔV_Σ.

Table 2. Parameters of Sedna and the TNOs suitable for proposed mission expansion

TNO	d*, km	Orbital elements**,***						*T*, yrs
		q, AU	*a*, AU	*e*	*i*, deg	*Ω*, deg	*ω*, deg	
Sedna [4]	~1000	76.341	499.469	0.847	11.931	144.208	311.130	11,162.77
2012 VP_{113} [28]	~600	80.412	266.462	0.698	24.089	90.720	293.659	4,349.73
Leleākūhonua [5]	~300	65.172	1,210.470	0.946	11.655	300.795	117.648	42,115.24
2013 SY_{99}[29]	~250	50.080	792.110	0.936	4.216	29.526	31.718	22,293.92
Orcus [30]	761…917	30.155	39.110	0.228	20.584	268.725	72.701	244.60
Varuna [31], [32]	859×453	40.265	42.724	0.057	17.209	97.350	263.222	279.27

* d is TNOs diameter, estimated assuming albedo taken in https://ssd.jpl.nasa.gov/sbdb.cgi#top; **Orbital elements are given w.r.t. to Ecliptic plane J2000 Epoch; *** Orbital elements are given to 3rd. Accuracy order. Uncertainties of orbital elements are used as in https://ssd.jpl.nasa.gov/sbdb.cgi#top; Designations used in the table are as follows: *q* is the perihelion distance, *a* is the semi-major axis, *i* is the inclination, *e* is the eccentricity, *Ω* is the longitude of ascending node, *ω* is the argument of pericentre, *T* is the orbital period.

For example, the flight to Sedna and the sednoid 2012 VP_{113} (‘Biden’) using the EΔVEJSed scheme with the launch on 02.03.2029 and TOF (to Sedna) equal to 20 yrs is considered. The orbital diagram is shown in Fig. 6; the corresponding spacecraft’s trajectory parameters are shown in Table 3.

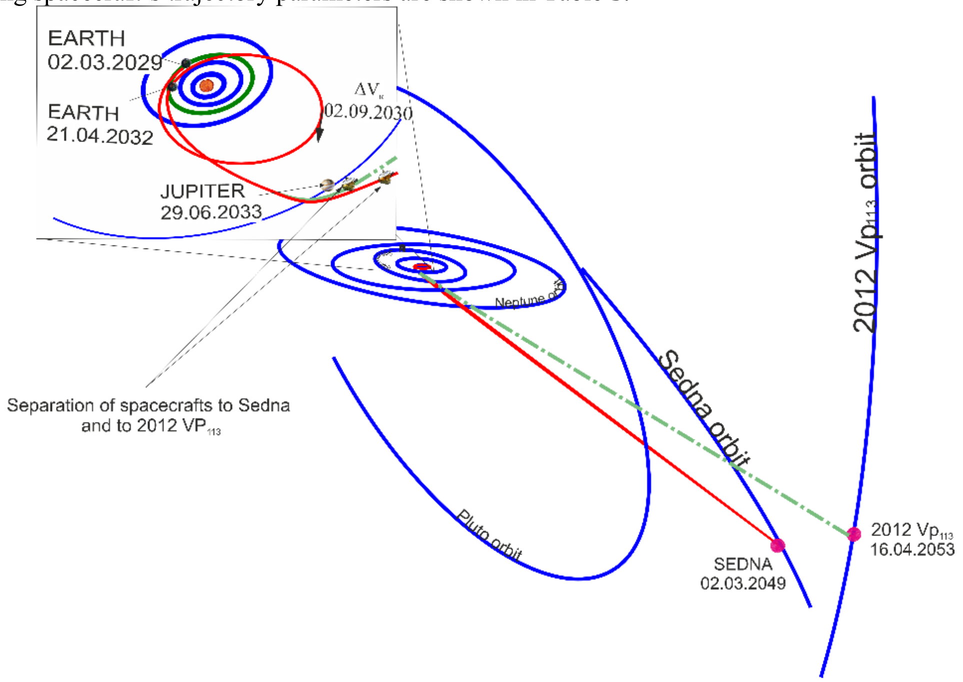


Fig. 6 Trajectory of spacecraft and probe flight to Sedna and 2012 VP_{113} for launch on 02.03.2029 using EΔVEJSed scheme

Table 3. The spacecraft and probe trajectory parameters to Sedna and 2012 VP_{113} using EΔVEJSed scheme for launch on 02.03.2029

Celestial bodies/deep space manoeuvres	Dates of launch and flyby of celestial bodies, dd.mm.yyyy	Relative velocities near-Earth and of the flyby of celestial bodies, km/s	ΔV of launch, at aphelion and of the flyby of celestial bodies, km/s	Height of the initial orbit and flyby above celestial bodies, 10^3 km
Earth	02.03.2029	7.02	5.28	0.2
ΔV_{α}	02.09.2030	10.64	0.60	-
Earth	21.04.2032	12.36	0.00	0.3
Jupiter (to Sedna)	29.06.2033	16.46*	0.48	3.7
Jupiter (to 2012 VP_{113})	29.06.2033	16.46*	0	56.3

Sedna (the spacecraft)	02.03.2049	22.44	-	0.0**
2012 VP_{113} (the probe)	16.04.2053	19.88	-	0.0**

* The value of incoming relative velocity is given.

**Approach to the object is assumed to be at any small distance

4.3 Flight to trans-Neptunian object (2012 VP_{113}) as an expansion for planet's exploration mission

Neptune Odyssey is now known to be NASA's mission to explore Neptune and its moon Triton. The mission is particularly unique, as the first and the last time Neptune was explored by a Voyager 2 in 1989 from a flyby trajectory. Of particular interest in this mission is the study of Neptune's moons, especially Triton, which the researchers suggest [33], [34] was captured by Neptune from the Kuiper Belt during a resonant approach to the ice giant. Also interesting is the study of Neptune's distant moons, which are virtually unobservable from Earth and near-Earth observatories because of their small magnitudes. The mission is expected to be launched in 2031; it is assumed to use the scheme of direct flight to Neptune, duration of the flight will be 12 years and $\Delta V_0 \approx 8.9$ km/s, as well as a flight to Neptune with Jupiter gravity assist. In the working group's report [34], the possibility of launching the spacecraft in 2031, 2033 and 2036 is considered.

Otherwise, as the study [35] has shown, a mission to the trans-Neptunian object 2012 VP113 (asteroid "Biden") is possible at about the same launch dates as a launch by the Neptune Odyssey program. This section analyzes a mission to 2012 VP113 with a gravity manoeuvre near Neptune for the launches in 2031 and 2033. It would be possible to combine a mission to Neptune and to the 'Biden' asteroid. At the same time, the vehicle proposed for the flight to 2012 VP113 might be used as an additional payload for the Neptune Odyssey mission. Such a vehicle (weighing no more than 200kg) could be designed by students worldwide and would thus serve as the first international vehicle to reach one of the Solar System's most intriguing objects.

Consider a flight to 2012 VP113 at launch in 2031, using the Earth-Neptune-2012 VP113 (EN-2012 VP113) scheme (Fig. 7, Table 4). The Earth-Neptune section repeats the Neptune Odyssey flight scheme, then near Neptune the probe is separated from the spacecraft and sent on a flight path to 2012 VP113.

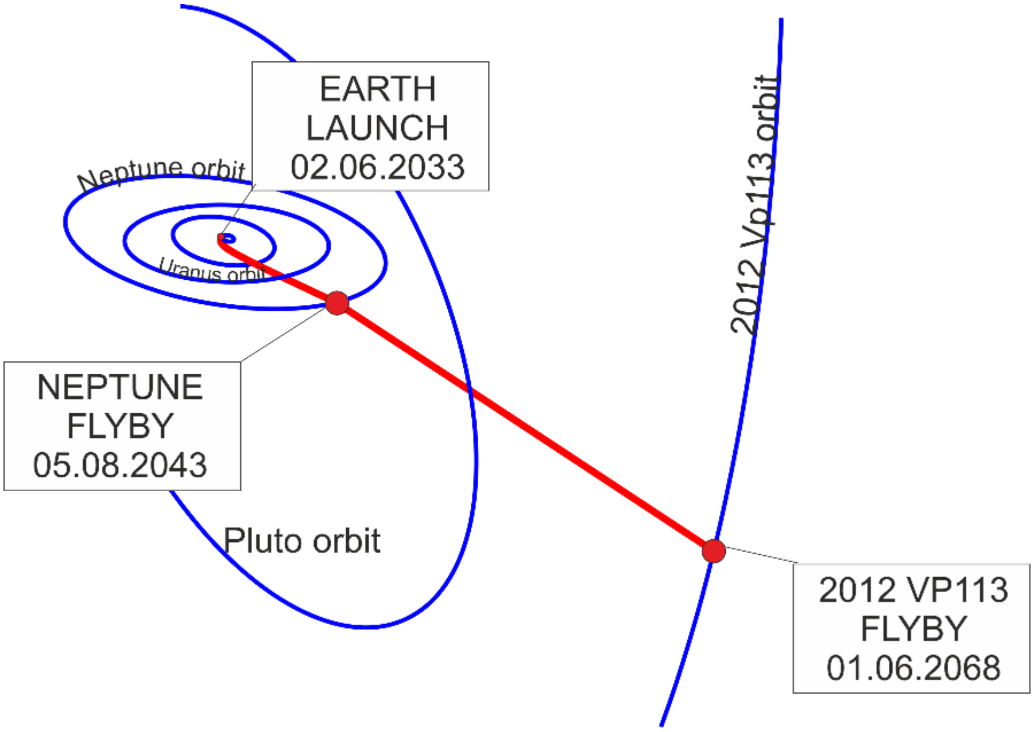


Fig. 7 The spacecraft trajectory and the probe flight to 2012 VP113 using EN-2012 VP113 scheme for launch in 2033

Table 4. The spacecraft and probe trajectory to 2012 VP_{113} using EN-2012 VP_{113} scheme for launch in 2033

Celestial bodies	Dates of launch and flyby of celestial bodies, dd.mm.yyyy	Relative velocities near-Earth and of the flyby of celestial bodies, km/s	ΔV of launch, at aphelion and of the flyby of celestial bodies, km/s	Height of the initial orbit and flyby above celestial bodies, 10^3 km
Earth	02.06.2033	13.30	9.88	0.2
Neptune	05.08.2043	11.50	0.00	42.1
2012 VP_{113}	01.06.2068	11.90	0.00	0.0

Note that in this case, trajectory of the probe (separating from the spacecraft for the flight to 2012 VP113) is passive (i.e., without additional impulses). Note that the flight time along the Earth-Neptune section differs significantly from the flight time adopted in work [33]. This is primarily because the developers of the project need to reduce the arrival velocity at Neptune, while in our case, its high value is optimal. Therefore, it is worth estimating the cost of flight to 2012 VP113 as part of the Neptune Odyssey flight scheme.

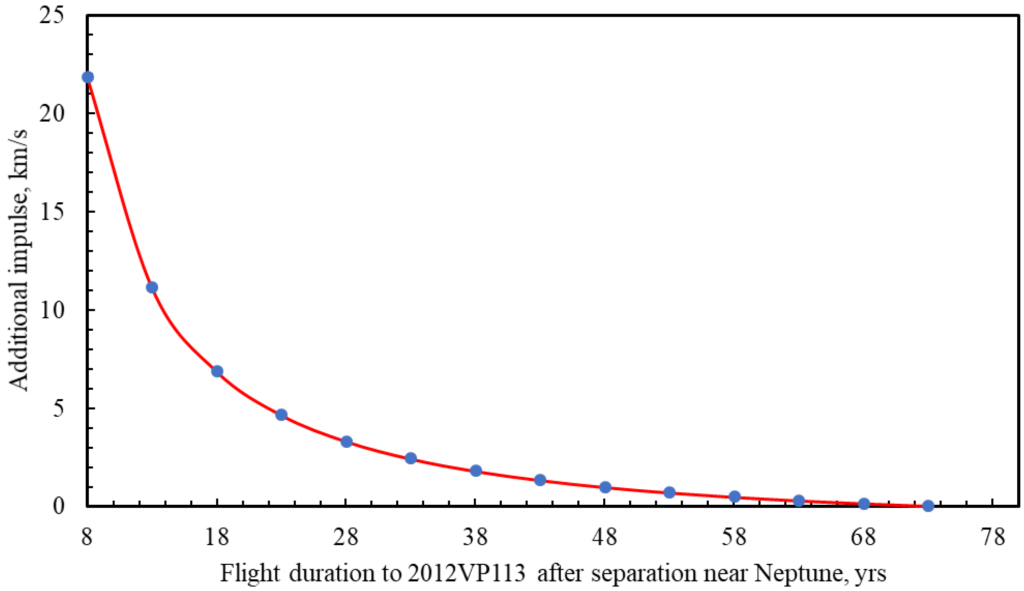


Fig 8. Additional impulse vs flight duration for flight to 2012 VP_{113} after separation near Neptune in 2049 (date of Neptune flyby)

In the Neptune Odyssey project description, the optimal direct flight to Neptune is with launch on May 31, 2033 and with a duration of about 16 years to reduce the incoming speed at Neptune. Under this scenario, let's consider the separation to 2012 VP113. To do so, we plot the dependence of the additional impulse vs flight duration for flight to 2012 VP113 (Fig. 8), which is the sum of the impulse applied to the spacecraft at the moment of separation from the main spacecraft on approach to Neptune, and the impulse applied in pericenter of the spacecraft's flyby trajectory near Neptune. Note that the optimal launch date has shifted from the date specified in [34] to 04.06.2033.

Note that an entirely passive flight is only possible if flight time on the Neptune-2012 VP113 section is of more than 65 years (Fig. 8). However, to reduce the flight time to the asteroid, it is possible to use electric propulsion using nuclear power as the main energy source, which requires separate consideration. Another more reliable way is to increase the flight velocity near Neptune, i.e., in the Earth-Neptune-2012 VP113 trajectory part. Still, this way requires higher braking into near Neptune orbit cost (~8.8 km/s for Neptune Odyssey; 11.5 km/s when flying to 2012 VP113) or usage of upper-atmosphere drag to decrease fuel costs.

Let's consider the flight to 2012 VP113 in the Earth-Jupiter-Neptune-2012 VP113 (EJN-2012VP 113) scheme at launch in 2031 (Fig 9, Table 5). In this scheme, the flight takes place with an additional manoeuvre near Jupiter at the Earth-Neptune trajectory part.

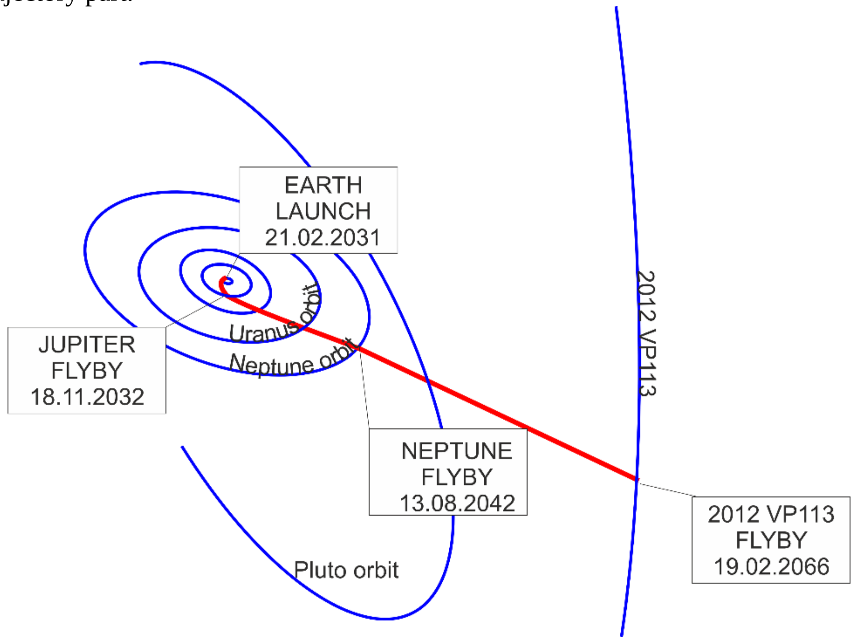


Fig. 9 Trajectory of the spacecraft and probe flight to 2012 VP$_{113}$ using EJN-2012 VP$_{113}$ scheme for launch in 2031

Table 5. The spacecraft and probe trajectory to 2012 VP$_{113}$ using EJN-2012 VP$_{113}$ scheme for launch in 2031

Celestial bodies	Dates of launch and flyby of celestial bodies, dd.mm.yyyy	Relative velocities near-Earth and of the flyby of celestial bodies, km/s	ΔV of launch, at aphelion and of the flyby of celestial bodies, km/s	Height of the initial orbit and flyby above celestial bodies, 10^3 km
Earth	21.02.2031	9.20	6.58	0.2
Jupiter	18.11.2032	9.00	0.00	540.2
Neptune	13.08.2042	12.10	0.00	53.9
2012 VP$_{113}$	19.02.2066	12.66	-	0.0

The Earth-Jupiter-Neptune-2012 VP113 scheme reduces the total ΔV comparing to scheme proposed in for flight only to Neptune, but its flyby velocity near Neptune is 600 m/s bigger than the scheme with a direct flight to Neptune. Also, the flight time to Neptune is shorter than in the Neptune Odyssey project.

5. Conclusions

As a result of the study of the possible flight schemes to the trans-Neptunian object (90377) Sedna were obtained and analyzed. Namely, the schemes including a series of gravity assists of the planets were considered.

Among all the launch dates in the interval under consideration, 2029 is the most favorable, since for the EVEEJSed and EVEΔVEJSed flight schemes this is the only year when the ΔV_{Σ} value satisfies condition (1) when the time of flight is shorter than 25 years; besides, for the time of flight not more than 30 years, this value is less than in the other launch years considered in the article.

In 2031 and 2034 for the mentioned schemes there are local minima of ΔV_{Σ}. In 2031 the minima are reached at the time of flight of 36.3 and 38.5 yrs. for the EVEEJSed and EVEΔVEJSed schemes respectively (see Table 1). In 2034 they are reached at 33.3 yrs. for the EVEEJSed and EVEΔVEJSed schemes and at 38.5 and 42.3 yrs. for the EVEEJNSed and EVEΔVEJNSed schemes respectively (see Fig. 3). Moreover, for the latter scheme, this minimum is 3.96 km/s which only slightly exceeds ΔV required for the Earth-Venus flight.

In 2034 and 2036, the Neptune gravity assist lowers the ΔV_Σ value comparing with the flight without this assist for the time of flight more than 27 years. For the scheme including Neptune gravity assist in 2034, there is a local minimum of $\Delta V_\Sigma \approx 3.9$ km/s for the time of flight of about 42 years, allowing to get practically free flight (i.e. without significant additional impulses on the trajectory) to Sedna.

Analysis of flight to Sedna in 2036 shows that the flight using the EVEEJNSed scheme requires less ΔV_Σ than EVEEJSed scheme, but for the launch in 2037, the opposite situation can be seen. The launch in 2037 by the EVEEJSNSed scheme allows flyby of three out of four outer planets with ΔV_Σ of about 4.89 km/s for the time of flight of 40 years.

As our research has shown, now there is a unique opportunity for a flight to such a distant object, using well known and previously used methods. In the year 2026 that we choose to launch the mission, it is possible to perform a flight with a low delta-v budget, which means that a large mass of research equipment can be transported to the 2012 VP113 object.

According to our research, a flight to the 2012VP113 object with no additional fuel consumption will take more than 30 years to perform. However, as the experience of already performed missions shows, such long flights are possible and provide the opportunity to explore other Solar System bodies from a flyby trajectory as well.

A reasonable question would be whether it is possible to orbit near Sedna or the sednoid 2012 VP113? However, the answer to the problem is not so obvious. Since the mass of the object is not precisely known, a braking impulse equal to the relative velocity of the spacecraft near the sednoid might be required to orbit the object. We should also note that even if it is impossible to enter into orbit around the sednoid, new data can also be obtained from a flyby trajectory, for example, like in the New Horizons mission.

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Appendix A

As can be seen from Table 1 below, there is a local minimum of the ΔV_Σ value as a function of the flight duration when launching in 2031 and 2034 and using the EVEEJSed and EVEΔVEJSed flight schemes. The duration at which this minimum is reached is marked in the tables by two asterisks. At the beginning of the mission in 2029 such a minimum either does not exist, or is outside the 50-year duration of the flight.

Table A.1. General characteristics of the considered flight schemes.

Launch year	Optimal date of launch, dd.mm	Time of flight, yrs	Scheme	ΔV_Σ, km/s	Velocity of Sedna flyby, km/s	Height of the Jupiter flyby, 10^3 km
2029	15.08	133	ESed	8.70	3.52	-
	09.11	20	EVEEJSed	6.27	23.60	201.0
	03.11	25	EVEEJSed	5.06	17.50	484.2
	02.11	30	EVEEJSed	4.61	13.64	791.7
	28.10	40	EVEEJSed	4.33	9.28	1256
	28.10	50	EVEEJSed	4.20	6.84	1514
	09.11	20	EVEΔVEJSed	6.27	23.60	201.0
	04.11	25	EVEΔVEJSed	5.02	17.50	482.7
	06.11	30	EVEΔVEJSed	4.51	13.71	781.0
	27.10	50	EVEΔVEJSed	4.00	6.84	1500
2031	2.08	30	EVEEJSed	5.06	23.12	3.6
	13.07	35	EVEEJSed	4.07	16.84	174
	6.07	36.25^{**}	EVEEJSed	3.97	15.68	292
	12.06	40	EVEEJSed	3.98	13.06	502
	2.08	30	EVEΔVEJSed	5.06	23.12	3.6
	10.07	35	EVEΔVEJSed	4.06	16.84	172
	2.06	38.51^{**}	EVEΔVEJSed	3.77	14.02	434
	2.06	40	EVEΔVEJSed	3.78	13.07	501
2033	29.01	40	EVEEJSSed	6.75	16.53	742.5
	23.01	50	EVEEJSSed	5.18	10.79	742.1
	06.05	24.48	EJSed [10]	7.45	15.06	733.5
2034	11.08	25	EVEEJSed	6.62	26.64	3.6
	9.08	30	EVEEJSed	5.13	19.08	4.2
	8.08	33.32^{**}	EVEEJSed	4.73	15.87	4.8
	8.08	40	EVEEJSed	5.11	11.70	3.6
	7.08	50	EVEEJSed	5.31	8.15	3.6
	11.08	25	EVEΔVEJSed	6.62	26.64	3.6
	10.08	30	EVEΔVEJSed	5.13	19.07	3.6
	8.08	33.33^{**}	EVEΔVEJSed	4.73	15.87	4.1
	7.08	40	EVEΔVEJSed	5.11	11.70	3.6
	7.08	50	EVEΔVEJSed	5.31	8.15	3.6
	7.08	25	EVEEJNSed	7.48	27.40	3.7
	30.07	30	EVEEJNSed	4.90	19.82	32.2
	5.08	38.6^{**}	EVEEJNSed	4.08	12.74	673
	29.07	40	EVEEJNSed	4.12	12.04	754
	3.07	50	EVEEJNSed	4.48	8.38	1079
	11.08	25	EVEΔVEJNSed	7.41	27.36	5.8
	31.07	30	EVEΔVEJNSed	4.81	19.72	90
	26.07	40	EVEΔVEJNSed	3.97	12.06	752
	22.07	42.36^{**}	EVEΔVEJNSed	3.97	10.96	873
	21.07	50	EVEΔVEJNSed	4.09	8.37	1062
	28.07	40	EVEEJSSed	6.47	17.55	99.5

	30.07	50	EVEEJSSed	5.06	11.18	90.7
2036	23.04	30	EVEEJSed	6.22	14.89	3.7
	23.06	25	EVEEJSed	6.40	22.94	46.3
	20.06	30	EVEEJSed	5.18	16.97	69.9
	14.06	35	EVEEJSed	4.64	13.27	109.8
	01.06	40	EVEEJSed	4.37	10.75	276.3
	29.05	50	EVEEJSed	4.20	7.65	380.9
	09.07	25	EVEEJNSed	6.91	23.73	3.6
	30.05	30	EVEEJNSed	4.74	17.80	80.5
	30.05	35	EVEEJNSed	4.19	13.95	136.8
	17.06	40	EVEEJNSed	4.11	9.28	3.7
	12.05	50	EVEEJNSed	4.02	7.96	516.6
	24.04	35	EVEEJSSed	7.05	21.70	2884.6
	25.04	40	EVEEJSSed	5.49	16.50	2702.1
	24.04	45	EVEEJSSed	4.79	12.99	2643.9
	24.04	50	EVEEJSSed	4.43	10.58	2648.1
	21.04	35	EVEEJSNSed	7.11	15.66	12708.7
	25.04	40	EVEEJSNSed	5.50	16.68	2672.5
	25.04	45	EVEEJSNSed	4.80	13.14	2579.0
	25.04	50	EVEEJSNSed	4.45	10.71	2554.3
2037	26.10	20	EVEEJSed	8.00	30.49	3.6
	13.10	25	EVEEJSed	5.74	21.27	3.7
	19.10	30	EVEEJSed	4.98	15.93	16.3
	20.10	38.22**	EVEEJSed	4.55	11.04	3.6
	23.10	50	EVEEJSed	4.58	7.35	291.0
	20.10	30	EVEEJSSed	6.45	24.97	3.6
	18.10	35	EVEEJSSed	5.27	18.13	16.2
	18.10	50	EVEEJSSed	5.00	16.06	15.9
	20.10	30	EVEEJNSed	6.45	24.97	3.6
	18.10	35	EVEEJNSed	5.27	18.13	16.2
	18.10	50	EVEEJNSed	5.00	16.06	15.9
	09.11	35	EVEEJSNSed	6.08	20.45	4028.1
	08.11	40	EVEEJSNSed	4. 891	15.29	4016.8
	04.11	50	EVEEJSNSed	4.05	12.21	5091.7
2046	23.06	24.48	EJSed [10]	8.59	14.15	1502.0

** Local minima

Table A.2. Catalogue of selected schemes providing exploration of both Sedna and another TNO simultaneously

Target TNOs	Scheme	Launch date, dd.mm.yyyy	TOF, yrs	ΔV_Σ, km/s	Date of separation, dd.mm.yyyy	Pericentre height*, 10^3 km	TOF_1**, yrs	ΔV_s***, km/s	V_e****, km/s
2012 VP_{113}									
	EJSed								
		01.04.2032	18	7.90	24.06.2033	55.0	19.8	0.020	19.91
		31.03.2032	20	7.42	24.07.2033	101.8	21.8	0.023	17.97
		10.05.2033	18	8.22	27.06.2034	429.4	21.2	0.039	18.04
		09.05.2033	20	7.87	21.07.2034	617.5	24.8	0.052	15.27
		22.06.2034	18	9.82	31.05.2035	1421.2	23.1	0.167	16.24
		20.06.2034	20	9.37	15.06.2035	1926.8	27.0	0.225	13.72
		26.01.2039	20	9.87	13.08.2045	3.6	30.7	0.034	12.81
	EJNSed								
		19.12.2040	20	8.63	11.08.2043	43.6	14.1	0.012	20.82
		19.01.2041	20	7.94	23.01.2045	51.0	13.4	0.014	21.87
		28.02.2043	18	8.86	22.02.2045	52.6	13.5	0.015	21.76

		28.02.2043	20	7.58	09.02.2045	87.8	15.6	0.019	18.73
		06.04.2044	18	7.65	07.07.2045	69.7	14.4	0.017	20.25
		04.04.2044	20	7.29	12.08.2045	110.6	16.6	0.022	17.56
	EΔVEJSed								
		27.02.2029	18	7.68	18.09.2033	244.9	26.5	0.01	14.45
		02.03.2029	20	6.36	29.06.2033	56.2	19.8	0.01	19.90
		15.04.2030	18	8.07	04.06.2034	282.5	18.3	0.01	21.15
		13.04.2030	20	6.92	17.06.2034	340.7	19.5	0.01	19.75
	EΔVEJNSed								
		03.05.2040	20	6.31	11.05.2045	40.82	10.6	0.013	23.41
		09.05.2041	18	8.99	20.05.2045	29.06	12.5	0.01	25.36
		05.05.2041	20	6.18	12.05.2045	54.84	11.6	0.015	21.67
		17.06.2042	18	9.08	11.06.2045	35.58	13.5	0.012	24.08
		13.06.2042	20	7.38	29.04.2046	62.28	12.2	0.016	20.58
Leleākūhonua									
	EJSed								
		01.04.2032	18	7.90	25.06.2033	757.0	19.5	0.176	16.03
		31.03.2032	20	7.42	24.07.2033	1163.1	24.9	0.23	12.07
		05.04.2044	18	7.85	22.07.2045	759.8	20.0	0.172	14.73
		05.04.2044	20	7.39	01.08.2045	867.3	21.4	0.18	13.58
	EΔVEJSed								
		27.02.2029	18	7.68	18.09.2033	1867.3	50.9	0.300	5.1
		03.03.2029	20	6.36	29.06.2033	753.5	19.5	0.200	16.0
		16.01.2038	20	9.10	09.09.2045	3.6	68.6	0.100	3.7
2013 SY$_{99}$									
	EJSed								
		27.01.2030	18	8.90	16.04.2033	39.1	49.0	0.060	3.82
		01.04.2032	18	7.90	24.06.2033	271.3	11.1	0.085	20.81
		31.03.2032	20	7.42	24.07.2033	399.2	12.5	0.095	18.28
		10.05.2033	18	8.22	27.06.2034	1,419.8	14.8	0.274	14.46
		05.04.2044	18	7.85	21.07.2045	169.2	11.3	0.070	19.70
		04.04.2044	20	7.39	01.08.2045	195.2	11.6	0.072	18.97
	EΔVEJSed								
		07.05.2030	18.0	7.31	01.08.2033	455.2	13.1	0.119	17.23
		07.05.2030	20.0	6.70	25.07.2033	417.3	12.7	0.106	17.82
		14.06.2031	20.0	7.17	24.06.2034	1,411.9	14.9	0.271	14.32
		06.03.2040	20.0	7.77	01.09.2044	119.6	43.8	0.056	4.04
		11.04.2041	20.0	8.72	03.10.2045	195.9	58.0	0.073	3.16
		10.05.2042	18.0	7.26	11.10.2045	491.6	15.4	0.127	13.62
		20.06.2043	18.0	7.61	09.06.2046	521.1	10.7	0.099	19.91
		18.06.2043	20.0	6.99	09.07.2046	788.0	12.8	0.129	16.33
	EΔVEJNSed								
		21.09.2041	20	9.21	11.05.2051	136.5	4.5	0.037	21.30
		14.05.2042	18	7.19	01.12.2050	108.4	4.1	0.034	23.71
		12.05.2042	20	6.47	11.09.2051	145.6	4.7	0.038	20.56
		21.06.2043	18	8.22	07.09.2051	114.6	4.3	0.034	22.62
		20.06.2043	20	7.58	01.06.2052	152.4	4.9	0.038	19.62
	EJNSed								
		19.12.2040	20	8.63	12.06.2050	127.1	4.6	0.035	21.19
		19.01.2041	20	7.94	21.01.2051	124.9	4.3	0.036	22.26
Orcus									
	EΔVEJSed								
		05.06.2029	18	9.06	06.07.2034	3.6	25.5	0.100	7.68
		25.02.2029	20	7.21	07.10.2033	3.6	38.0	0.100	4.27
		18.02.2030	18	7.33	14.10.2033	3.6	40.6	0.100	3.90
		10.04.2030	20	7.23	16.07.2034	3.6	25.7	0.100	7.63
		05.04.2031	20	7.40	15.07.2034	3.6	25.8	0.100	7.60
Varuna									
	EJSed								
		31.03.2032	18	7.92	14.07.2033	3.6	25.1	0.069	7.11
		31.03.2032	20	7.42	24.07.2033	10.9	26.5	0.078	6.60
		10.05.2033	18	8.22	27.06.2034	79.4	23.6	0.132	7.93

	08.05.2033	20	7.87	21.07.2034	92.7	23.1	0.142	8.06
	22.06.2034	18	9.82	31.05.2035	108.3	55.4	0.238	4.20
	20.06.2034	20	9.37	15.06.2035	131.8	55.1	0.269	4.01
	03.02.2038	20	9.82	26.12.2045	1,087.2	36.4	0.22	4.34
	06.02.2039	20	9.16	04.01.2046	1,166.7	39.7	0.223	3.87
	07.02.2040	18	9.80	01.12.2045	1,418.7	46.3	0.247	3.19
	09.02.2040	20	8.66	03.01.2046	1,319.2	45.2	0.234	3.30
EΔVEJSed								
	05.06.2029	18	8.25	24.04.2034	43.2	23.9	0.100	8.14
	16.04.2029	20	7.08	10.06.2034	67.6	24.6	0.100	7.67
	09.06.2030	18	7.83	06.05.2034	49.5	23.9	0.100	8.08
	13.04.2030	20	6.92	17.06.2034	72.3	24.4	0.100	7.70

* Height of the pericentre calculated for the probe trajectories after the probe separation

** TOF_1 is the time of flight after the probe separation to the TNO;

*** ΔV_s is the separation impulse at a distance of 80 mln. km from the flyby planet;

**** V_e is the flyby velocity near the second TNO.