RUSSIAN FEDERAL SPACE AGENCY
Central Scientific Research Institute of Machine Building

DESIGN OF THE FLIGHT SCHEME AND S/C NAVIGATION SUPPORT ENSURING THE GOALS OF THE DEMONSTRATION MISSION TO THE POTENTIALLY HAZARDOUS ASTEROID 2001 JV1

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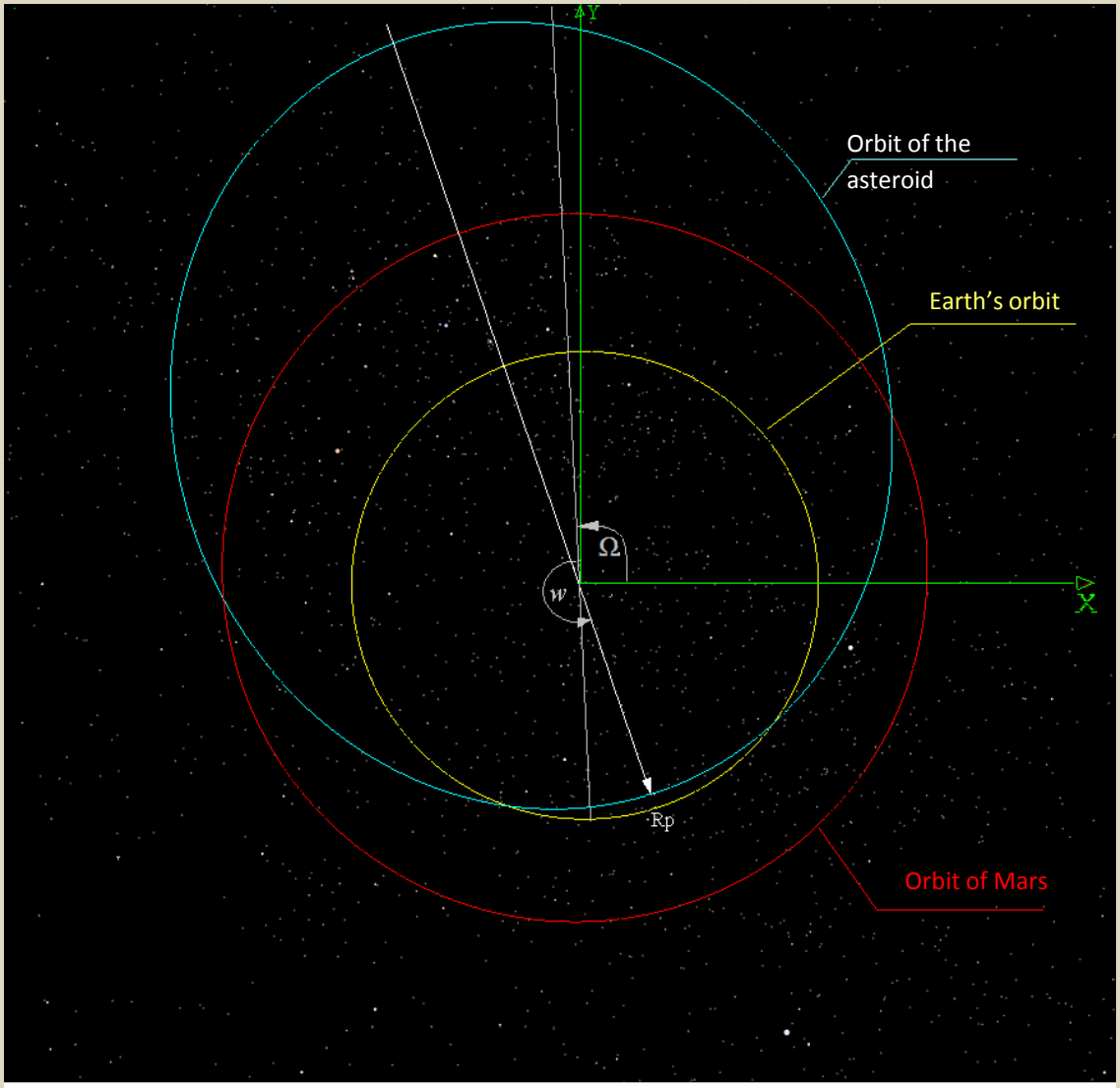
Characteristics of asteroid 2001 JV1 as a target of the demonstration mission



Orbit of the asteroid

Semi-major axis, *a*	1.705 AU
Perihelion, *q*	0.963 AU
Aphelion, *Q*	2.441 AU
Eccentricity, *e*	0.435
Orbital period, *P*	2.225 yr
Inclination , *i*	6.631°

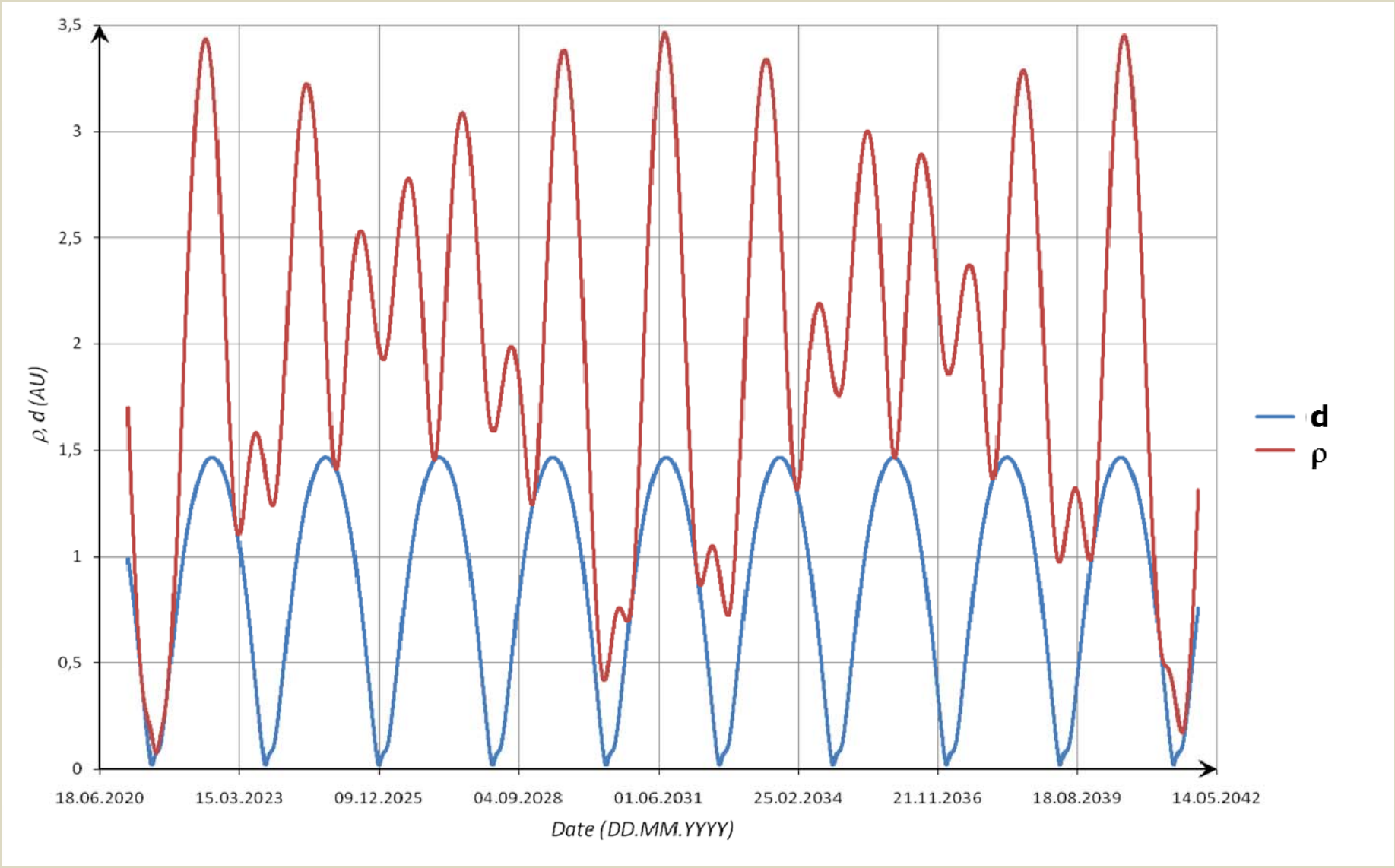
Asteroid – Earth Minimum Orbit Intersection Distance (MOID)

MOID ~ 0.021-0.023 AU

Physical Parameters

Size, ∅ ~	130 m
Mass, m_A ~	2.76×10^9 kg
Rotation period ~	29 h

Distances from asteroid 2001 JV1 to the Earth's orbit (d) and to the Earth itself (ρ)



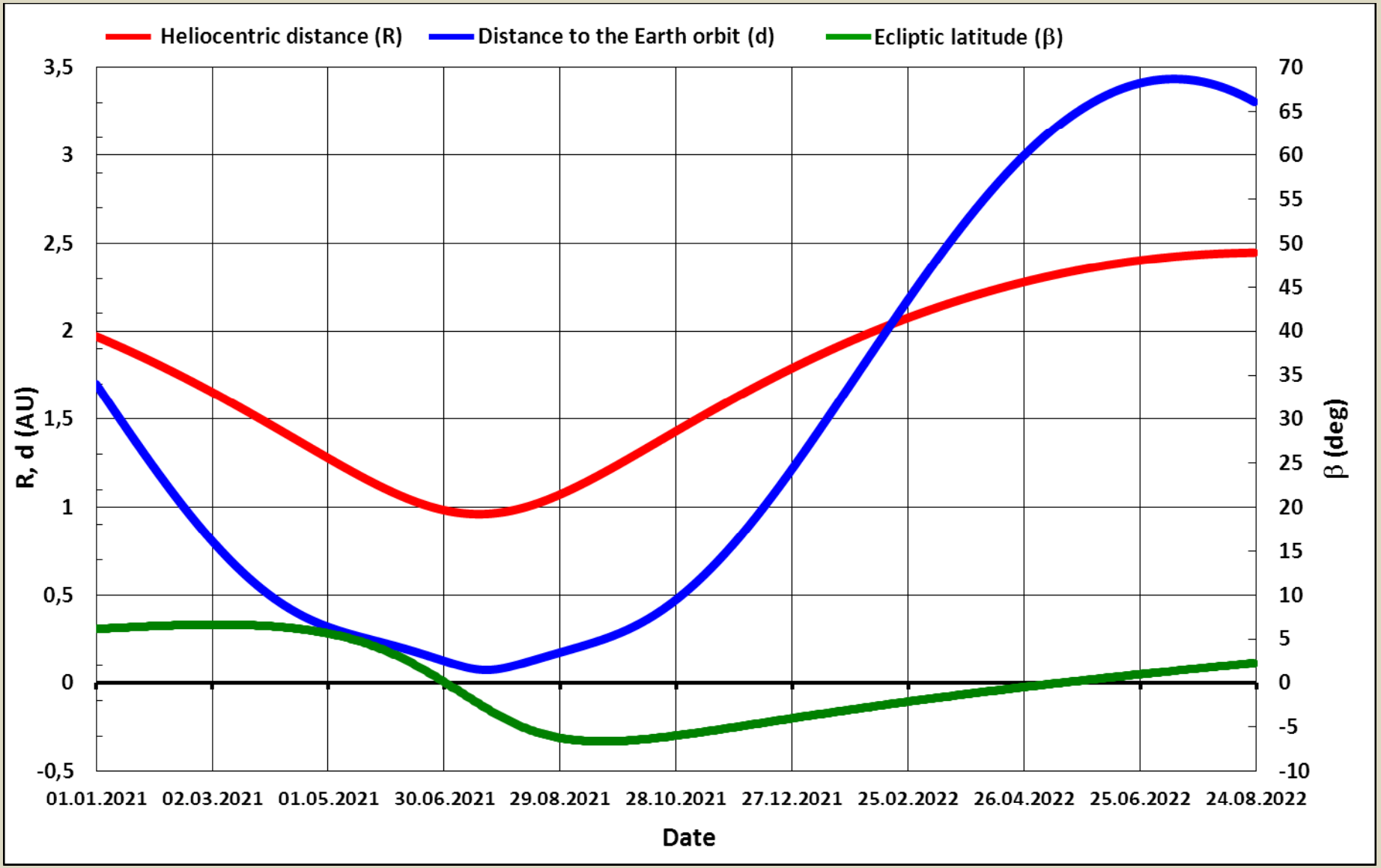
Goals and main principles of the hazardous asteroid blast deflection demonstration mission

- Technical demonstration of feasibility of the deflection of hazardous asteroid away from the Earth by means of the explosion of a special blasting assembly
- Registration and assessment of the asteroid orbit modification as a result of the given method action on a PHA
- Delivery of the S/C with a blasting device to the asteroid in the shortest time as it's possible
- Flight of the S/C in the vicinity of the target object with a small relative velocity
- Realization of a precise tracking of the asteroid and S/C by means of various onboard and ground based measurement facilities
- Choice of an appropriate conditions for realization of the explosion near the asteroid
- Power of explosion has to be corresponded to a change of the asteroid's velocity $\Delta V_A \leq 5$ cm/s

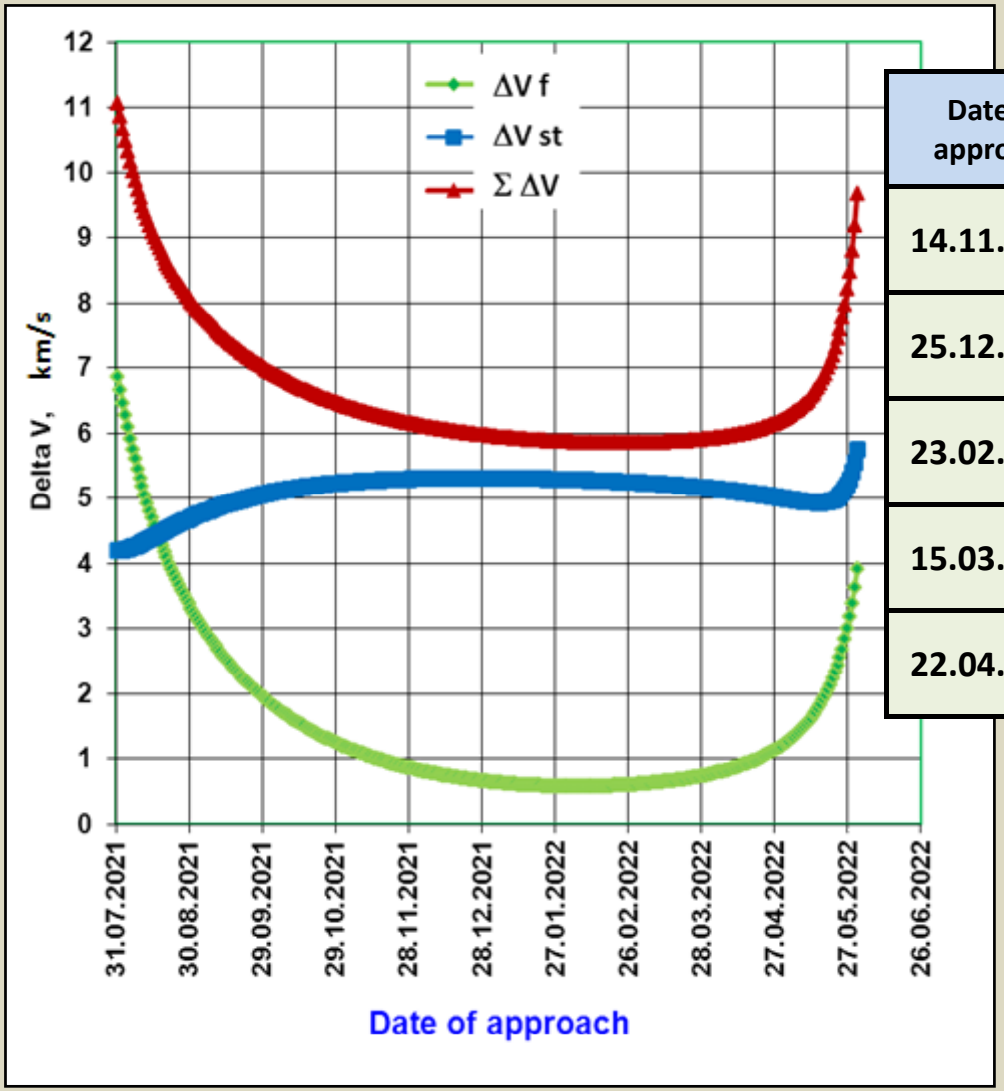
Base conditions of the mission realization

- S/C is inserted into an interplanetary trajectory with the help of the «Proton-M/Breeze-M» launch vehicle system
- S/C is designed on the basis of the tested platform, elaborated by the «Lavochkin Association»
- S/C mass after injection into an interplanetary trajectory makes $m_{s/c} \sim 2000$ kg, including a propellant budget $m_f \sim 700 \div 730$ kg
- Specific impulse of S/C propulsion system $I_{sp} \sim 304 \div 320$ s
- S/C escape velocity at infinity relative to the Earth has to be $V_\infty \leq 7000$ m/s
- S/C deceleration burn at the asteroid vicinity $\Delta V_f \leq 1000$ m/s

Asteroid 2001 JV1 motion characteristics for the nearest mission with launch window in 2021 year

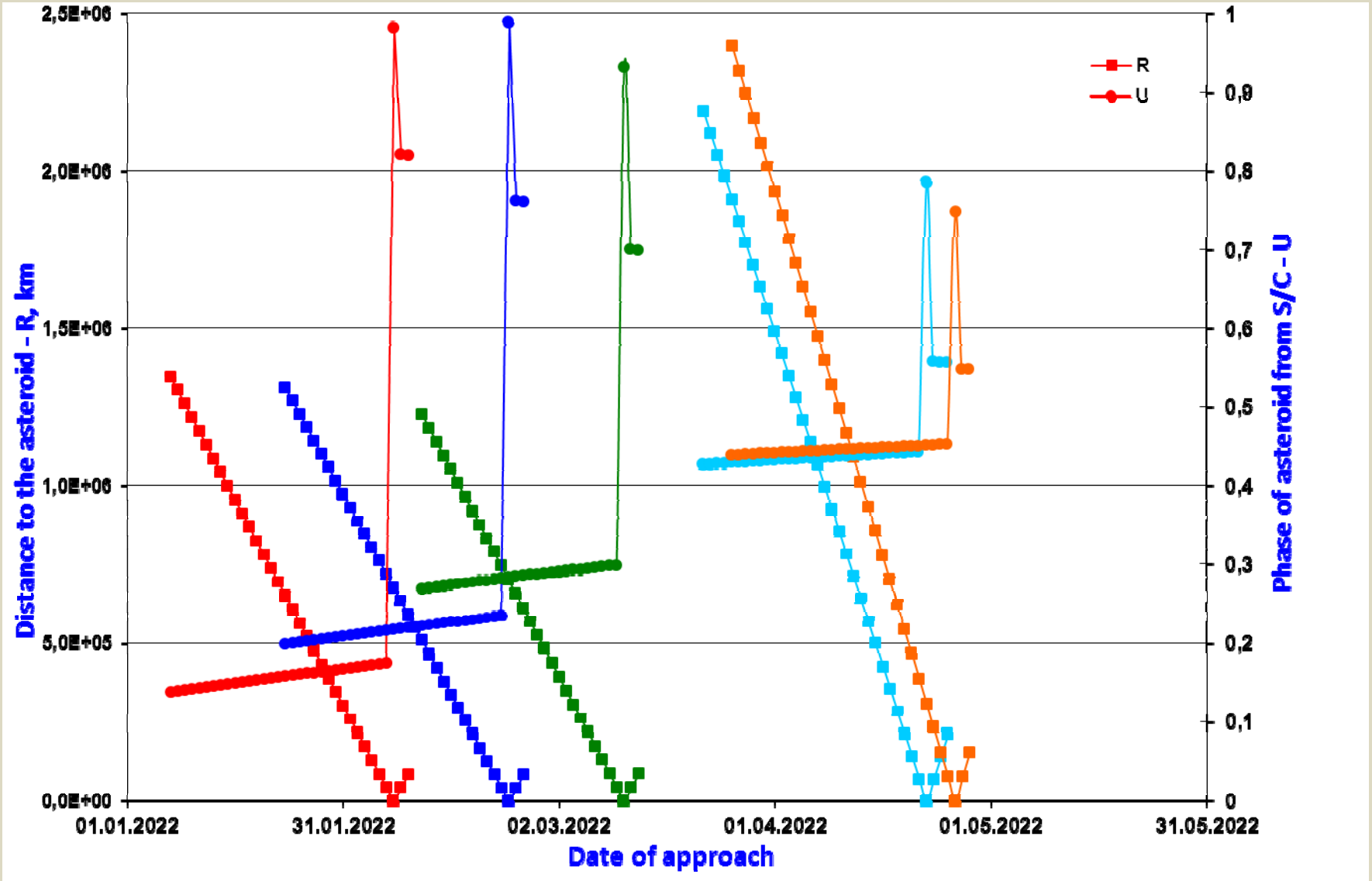


ΔV requirements for Earth-Asteroid 2001 JV1 transfer for launch at 28.06.2021 and different approach date

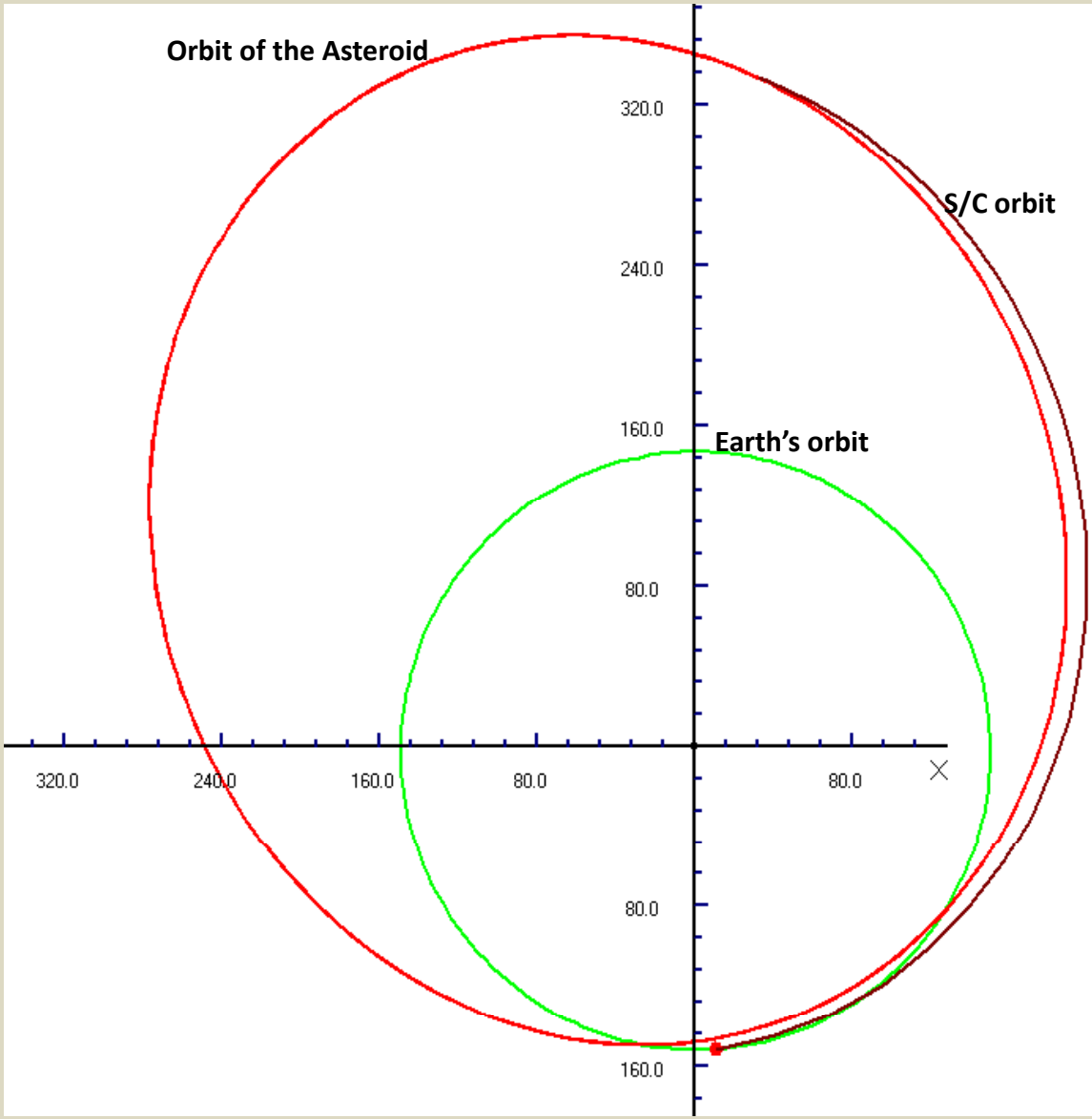


Date of approach	Transfer time, days	ΔV start, km/s	V∞ , km/s	ΔV final, km/s	Σ ΔV, km/s
14.11.2021	137	5.274	7.079	0.991	6.265
25.12.2021	178	5.312	7.150	0.656	5.968
23.02.2022	238	5.255	7.044	0.574	5.829
15.03.2022	258	5.207	6.956	0.638	5.845
22.04.2022	296	5.053	6.663	1.002	6.055

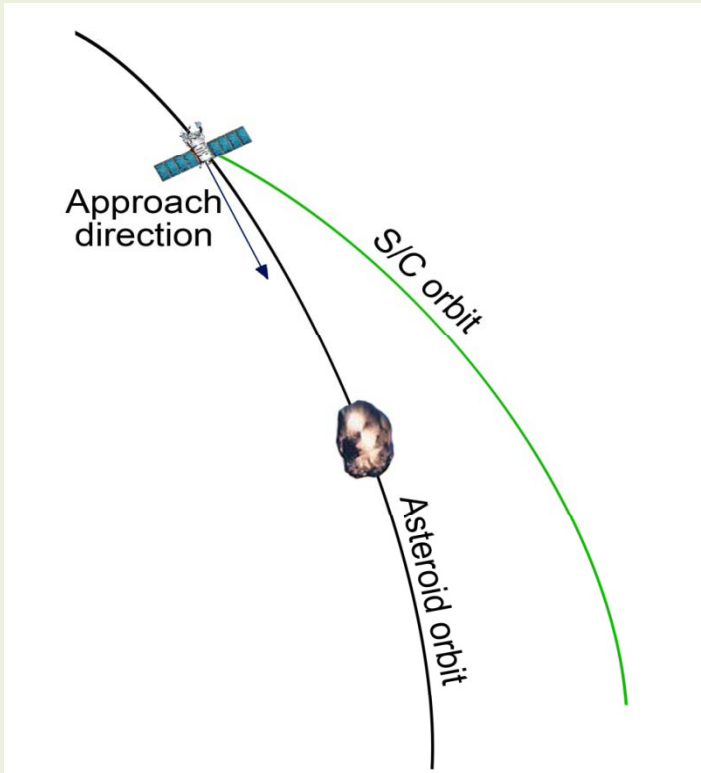
Conditions for onboard navigation at a final phase of transfer to the asteroid for different approach date



Heliocentric transfer orbit Earth-Asteroid 2001 JV1 at launch 28.06.2021



Final phase of inter-orbital transfer



Flight schemes nearby the asteroid

Asteroid's gravity sphere:

$$r_{sp}^{A} = R_{A}^{S} \times 0.45388 \times 10^{-8}\ AU \text{ // at } \quad R_{A}^{S} \approx 2.3\ AU \quad \Rightarrow \quad r_{sp}^{A} \approx 1.56\ km$$

Equations of S/C motion relative to the asteroid

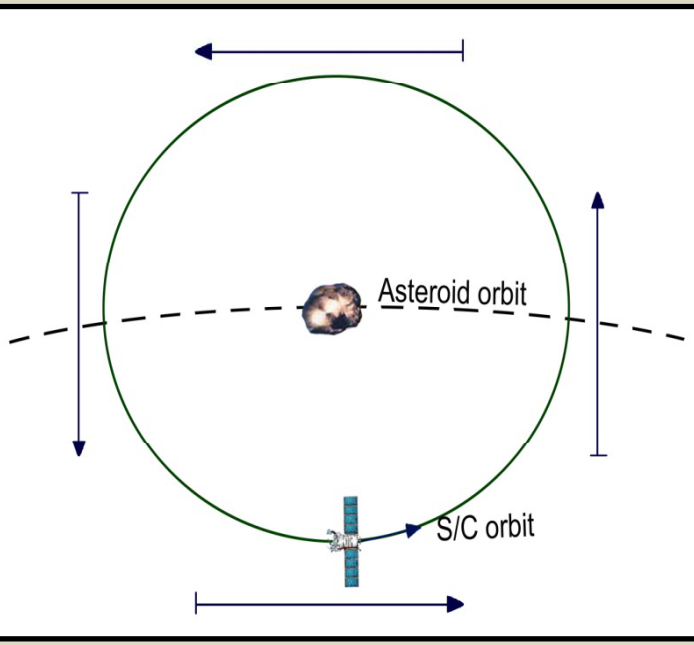
$$\ddot{\vec{\rho}} = \vec{F}_A + \vec{F}_S + \vec{F}_{add}$$

Time span where an approximation

$$\vec{\rho}(t) = \vec{\rho}_0 + \vec{v}_0(t - t_0) + \vec{a}\left((t - t_0)^3\right)$$

is valid at $v_0 \le 30 cm/s$

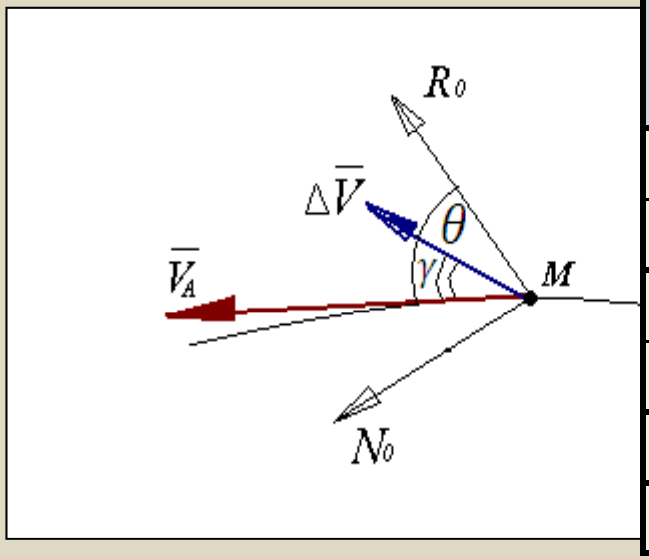
Distance from asteroid ρ, m	t-t0, min
300	≤ 16
500	≤ 27
1000	≤ 60



Characteristics of the asteroid's satellite orbits

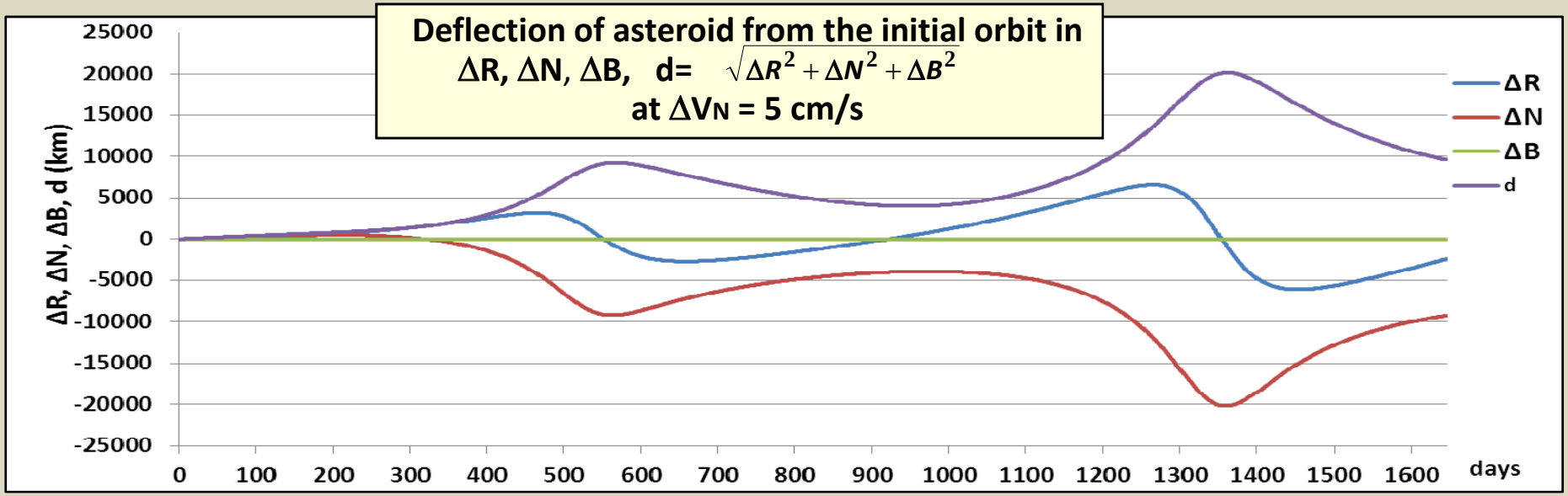
Radius of orbit, m	Orbital period, hour	Orbital velocity, cm/s
300	21.1	2.5
400	32.5	2.1
500	45.5	1.9

The choice of direction of ΔV$_A$ as a result of explosion



Direction and value of ΔV (cm/s)	Change of the orbital elements after explosion (new – old)					
	Δa, km	Δe	Δω "	ΔI "	ΔΩ "	Δt$_\pi$ s
ΔV$_R$ = 1	46.132	0.00000	0.169	0.000	0.000	33.803
ΔV$_R$ = 5	230.662	0.00000	0.845	0.000	0.000	169.017
ΔV$_N$ = 1	150.540	0.00000	0.211	0.000	0.000	50.919
ΔV$_N$ = 5	752.701	0.00000	1.056	0.000	0.000	254.596
ΔV$_B$ = 1	0.000	0.00000	-0.288	0.039	0.315	0.000
ΔV$_B$ = 5	0.010	0.00000	-1.439	0.196	1.575	0.000

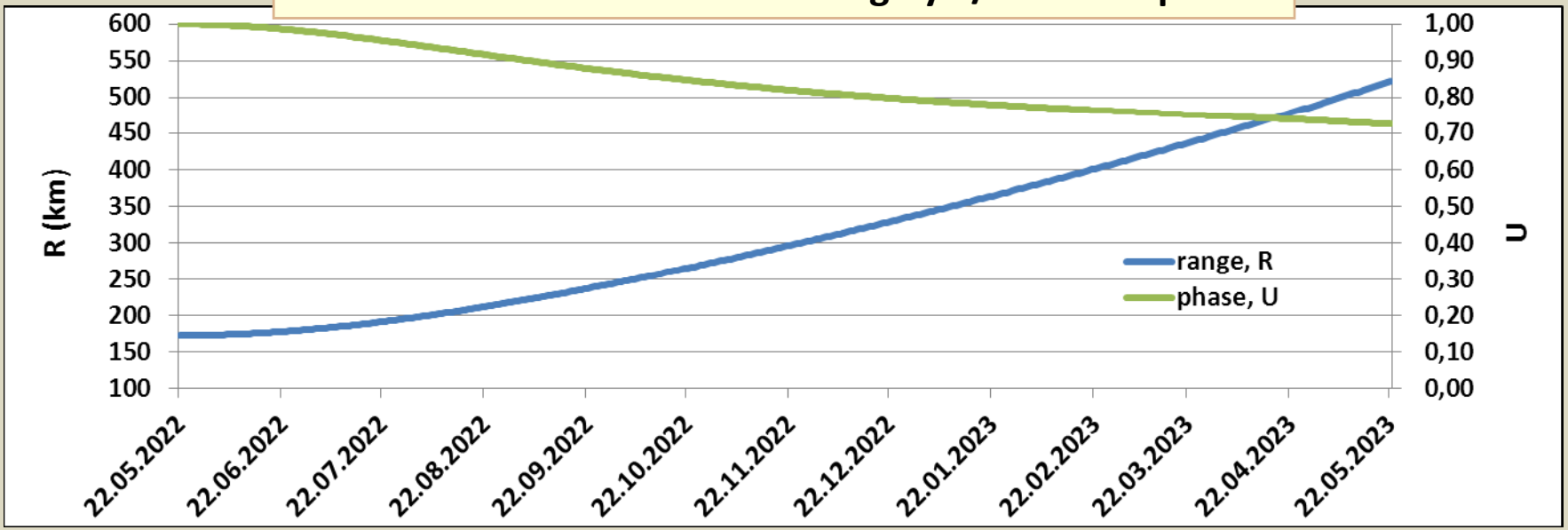
Deflection of asteroid from the initial orbit in ΔR, ΔN, ΔB, d= $\sqrt{\Delta R^2 + \Delta N^2 + \Delta B^2}$ at ΔV$_N$ = 5 cm/s



Days after explosion

Asteroid tracking by S/C and assessment of its orbit modification after blast deflection operation

Condition of the asteroid tracking by S/C after explosion



Asteroid orbit determination accuracy on the base of S/C onboard tracking measurements

Measurement arc	Type of observation	Measurement accuracy	OD accuracy				
			σ*a*, km	σ*e*	σ*R*, km	σ*N*, km	σ*B*, km
2 months	α, δ	σα = σδ = 1″	3500	0.12$_{10}$-4	8000	60	0.0002
4 months	α, δ	σα = σδ = 1″	200	0.74$_{10}$-6	460	3.0	0.0002
1 month	α, δ, D	σα = σδ =1″ D=100 м	0.01	0.12$_{10}$-9	0.02	0.0005	0.0003

Conclusion

The main results of the carried out researches :

- Potentially hazardous asteroid 2001 JV1 was considered as a possible candidate for a blast deflection demonstration mission
- Dynamics and singularities of the orbital motion and rendezvous with the Earth of PHA 2001 JV1 were investigated
- The concept and scenario of a blast deflection demonstration mission to a PHA are developed. The basic conditions for the mission realization with the help of available space techniques as well as the nearest launch window for a possible flight to the asteroid 2001 JV1 are determined
- The direct interplanetary Earth-asteroid 2001 JV1 flight scheme with a launch at 28.06.2021 and the end at 22.04.2022 (transfer for 296 days) was recognized as the most appropriate one for the given mission
- The scheme of a S/C approach to the asteroid, supplying with a slow rendezvous and accurate guidance of S/C on the target object, is offered. The possible mission profiles nearby the asteroid, including a flight on orbits around the asteroid were explored
- The dependence of the asteroid's orbit modification on a place and a direction of a velocity impulse ΔV_A, arising as a result of a blast effect, is determined
- The scheme of asteroid escort flight and its onboard tracking after explosion enable to fix and assess of a blast deflection effect within a mission frame was proposed

The obtained results justify a practical feasibility (from the ballistic and navigation point of view) of the blast deflection demonstration mission to the asteroid 2001 JV1 in the next decades