WORKSHOP REPORT
ASTRODYNAMICS OF INTERCEPTION

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Introduction

There exists a spectrum of possibilities for impact of near-Earth objects (NEOs) with Earth, ranging from an overwhelming, unpredicted disaster through objects whose orbits are so well-known that threats from them can be mitigated with certainty.

Warning time is the distinguishing factor among these different cases. Our interest does not exceed many decades on the high side, and is limited on the low side by that time [$t_{warning}$ < a few days] for which no astrodynamic response is possible.

Table I shows the way we divided the problem for consideration, beginning at the most favorable extreme, and working toward the less predictable cases in our discussion of interception.

Case 1

These are Earth-crossing asteroids (ECAs) with well-determined orbits. Error ellipsoid dimensions for the predicted Earth encounter are of the order R_E (or smaller), and, therefore, we can predict with reasonable confidence which apparitions will bring the asteroid into Earth impact. Here, we can predict positions precisely enough to allow warning times of decades or even centuries.

Some of the threatening objects are in highly inclined, highly elliptical orbits, and will require large ΔVs to intercept, but we can afford to use minimum-energy orbits. We can use the available time to carry out sufficient precursor missions to remove most uncertainties from the intercept. If $V_{intercept}$ of 25 km/s is acceptable, then it would be possible to fly a mission with a C_3 of 1 or 2 $(km/s)^2$. We can intercept the object at the intersection of the asteroid and Earth's orbits. Impulse is best imparted to asteroids other than Aten-types at perihelion, unless that is too close to the Sun for comfort. In the case of Aten-type asteroids, interaction is best at aphelion.

It is clear that programs treating Case 1 will have beneficial spinoffs for other NASA programs.

Case 2

These are newly discovered ECAs or short-period comets with significant non-gravitational forces having unpredictable temporal variation. In either case, orbital uncertainty reduces the lead time with which we can predict probable Earth impact to a few years.

Newly discovered ECAs have less certain orbits. Such objects will probably be faint, so the response must be more urgent.

Every available means should be employed to refine the orbit. Once determined to be a threat, much higher intercept velocities are likely to be required in this case. The C_3 needed could be enormously higher than in Case 1, and there is not the luxury of using an extra orbit to get a planetary flyby. On arrival at the target, the impulse delivered will be an order of magnitude larger than for Case 1. It is possible that a launch window might not exist for some reason, putting the object into Category 3. Success at the first attempt is critical for the intercept mission in this case, since failure may also have the consequence of changing the interaction into Case 3.

Case 3

Here the object is first identified as a threat when it is on a collision course with Earth. The object is typically a long-period comet approaching Earth. The most propitious scenario is discovery at a range of 10 AU at V=22 mag. It is likely to be 10 km or more in size to achieve this optimum case. At 5AU, much of the comet's light will be in the coma, making discovery much easier.

Newly discovered ECAs in this category are likely to be small bodies (less than a few hundred meters across), providing an adequate search for ECAs has been carried out previously.

Response in Case 3 requires an entirely different approach.

Launch is with shortest response time possible, and with the highest feasible velocity. Interception range is 0.1 – 1 AU, with a C_3 of 100 $(km/s)^2$, probably associated with a flyout time of about 1 week. The zone of feasible interception is probably within 0.1 AU in this case, whatever the intruder's orbit [see the Appendix to this report].

Case 4

With the present state of observational activity, this is by far the most likely scenario! The impactor could be a 5-km ECA. Extreme responses should be considered for this case, since astrodynamic response is very difficult or impossible.

APPENDIX

by

Joseph Gurley

The unique feature of the astrodynamic problem of intercepting an Earth-impact-threatening NEO is that the orbits of the NEO and of the Earth intersect at the ascending or descending node of the NEO orbit where the impact is predicted to occur.

Figure A1 shows a locally optimal maneuver to achieve a rendezvous with the NEO, starting from a low Earth orbit (LEO). A large impulse, essentially equal to the difference between the predicted Earth impact velocity of the NEO and the Earth orbital velocity of the spacecraft, is applied at the time Earth passes the nodal longitude. This injects the spacecraft into an orbit approximately matching that of the NEO, except for orbital phase and a small orbital period mismatch. This period difference is chosen so as to cause the two bodies to drift together, at which point an orbit trim maneuver completes the rendezvous. The total ΔV for this mission is typically in the range 7 – 18 km/s. The case 2 threat, with a warning time of only a few years, may require this type of interaction, perhaps modified to increase the drift rate at the cost of a higher orbit trim ΔV; this modification will decrease the time spent in the drift phase of the mission.

Figure A2 shows an alternative interception trajectory which reduces the mission ΔV by relaxing the rendezvous requirement and using a high-velocity approach, typically in the range 10 – 20 km/s. The interceptor is injected into a heliocentric orbit with a period slightly under or slightly over one year, at a point near the node of the NEO orbit (the point where impact with Earth is predicted to occur). Interception occurs at that same nodal point, several years later. A slightly modified version of this strategy may be useful against Case 2 threats, where mission ΔV is to be minimized, and the time available is tightly constrained.

An alternative low-ΔV strategy (Figure A3) uses multiple planetary gravity assist maneuvers to approximate a globally optimal transfer from LEO to a rendezvous with the target asteroid. This strategy is appropriate for high-impact-velocity Case 1 (long warning time) threats, whenever the defensive system requires either a rendezvous with the target object, or an interception far from Earth's orbit, e.g., at the perihelion point. For a rendezvous, the final gravity assist maneuver will generally be an Earth flyby at the node of the NEO orbit, to inject the spacecraft into a matching rendezvous orbit. The mission ΔV for this type of trajectory is the sum of the impulse needed to inject the vehicle into an interplanetary trajectory to the first flyby planet (probably Venus or Mars: estimated $\Delta V = 4 – 5$ km/s), and a small amount (probably < 0.5 km/s) for guidance and orbit trim maneuvers.

TABLE I: CASE DEFINITION

Case	$t_{warning}$	Action	Probability of Scenario for 1-km objects: Now	Probability of Scenario for 1-km objects: Future	Interaction Distance (AU)	Target ΔV (cm/s)	Object
1. Well-defined orbits – Precursor missions are strongly advisable for detailed evaluation	Decades	Long-term, VEGA-type missions	5%	95%	2	1	ECAs only
2. More uncertain orbits – Luxury of precursor mission may be absent – Intermediate warning time (but still urgent) – Object motion is affected by nongravitational forces	Years	Urgent response without much room for error			2	10 – 100 (more error) (less error)	Short-period comets Newly-discovered ECAs
3. Immediate Threat – Best scenario: discovery at 10 AU – Discovery initiates emergency	Months	Every available engineering measure Continue to refine the orbit			0.1 (comet) 0.1 – 1 (ECA)	> 1000	Long-period comets Small, newly discovered ECAs
4. You're hit before you know it!	0 – Days	Pray	95%	5%	0		Long-period comets & unknown ECAs

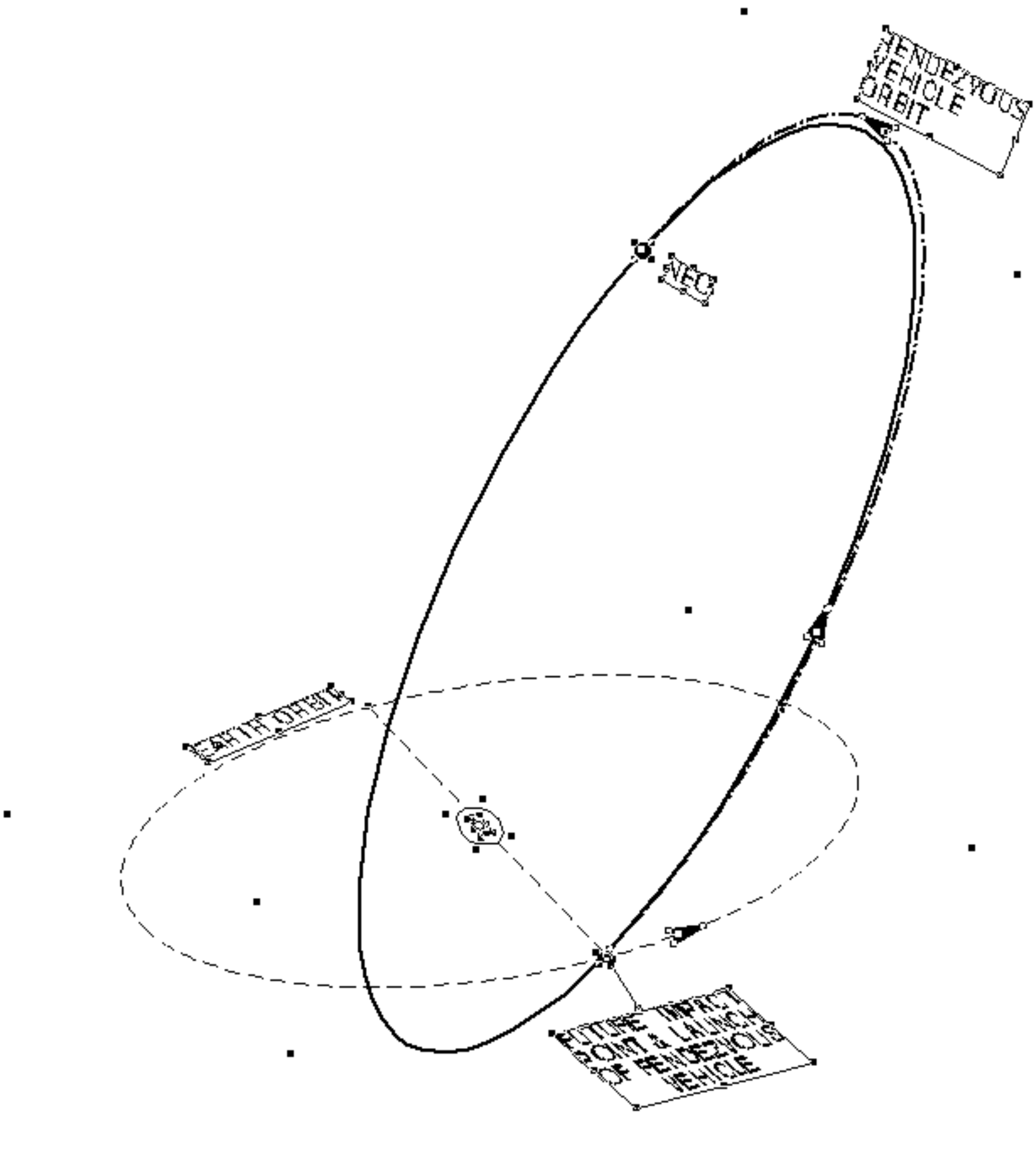

FIGURE A1
High-ΔV NEO rendezvous mission

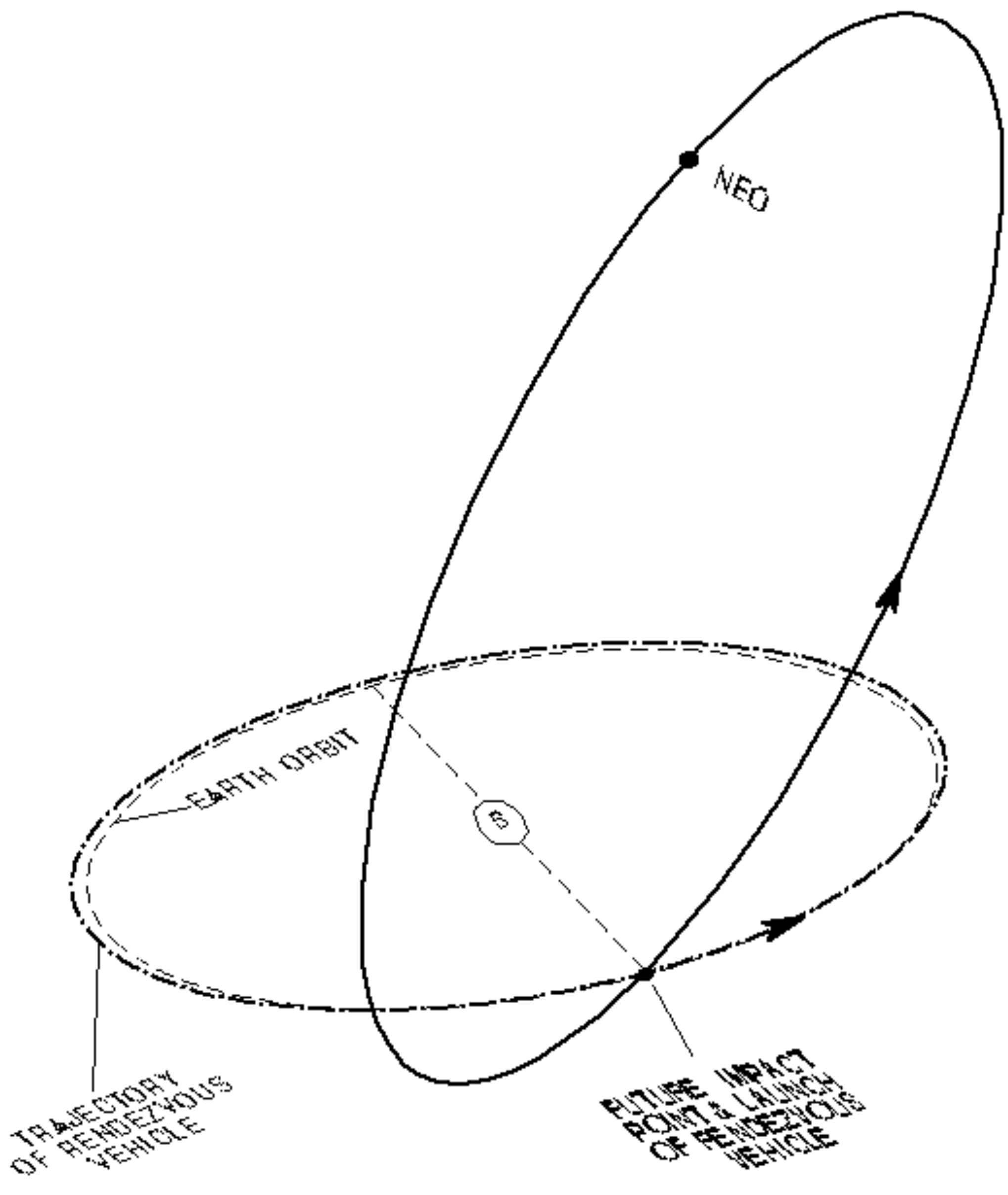

FIGURE A2

Low-ΔV, High Closing-velocity Interception
Interceptor orbital period is slightly greater or less than one year, in order to achieve phasing needed for early interception, several NEO orbital periods before Earth impact

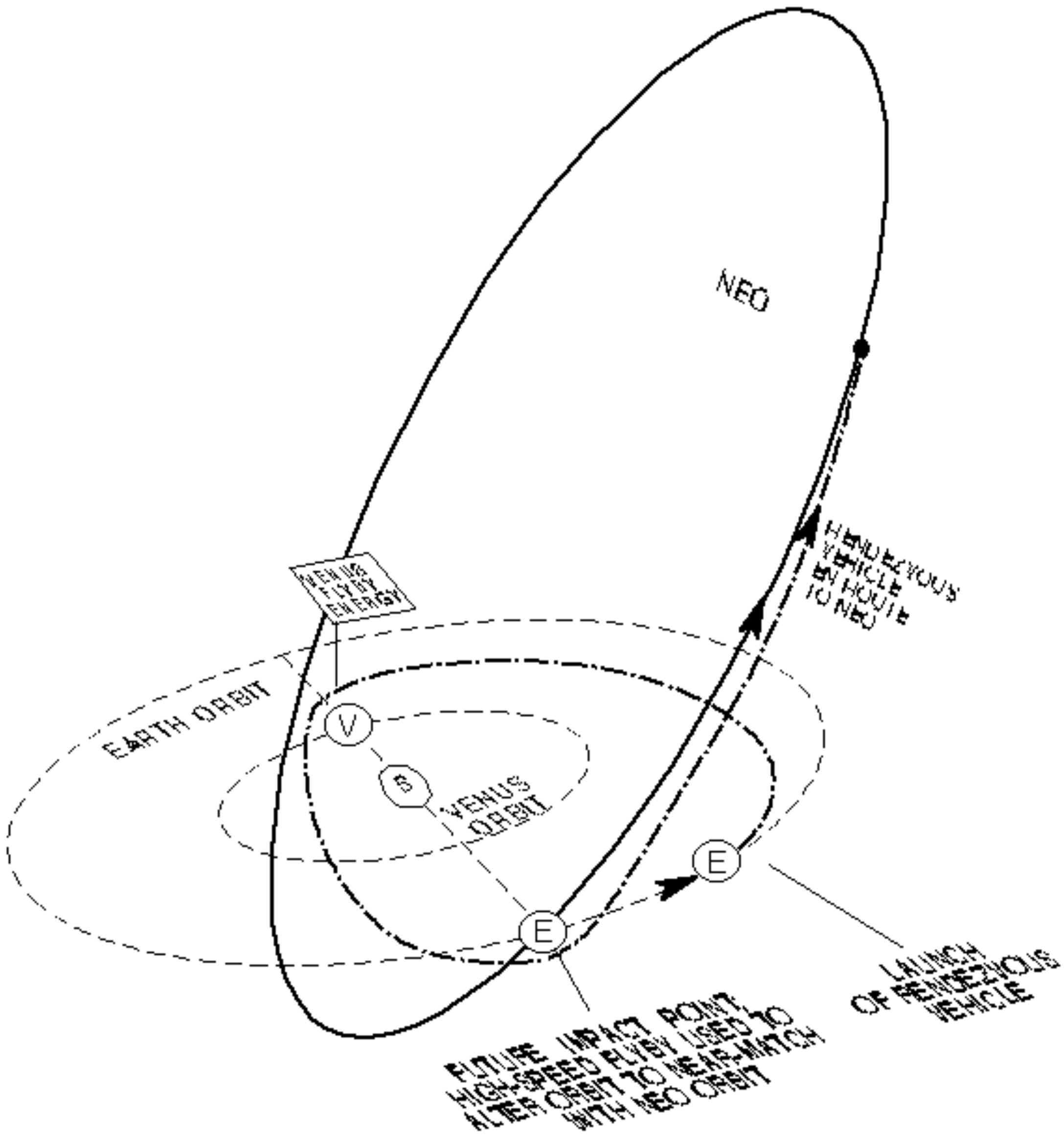

FIGURE A3

Moderate-ΔV rendezvous mission, using planetary flyby (in this case, Venus first and then Earth)