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The Near Earth Objects: possible impactors of the Earth/Les astéroïdes geocroiseurs : impacteurs potentiels de la Terre

Mitigation strategy

Andrea Carusi [a], Ettore Perozzi [b], Hans Scholl [c,*]

[a] IASF-INAF, Via del Fosso del Cavaliere 100, 00133 Roma, Italy
[b] Telespazio S.p.a., Via Tiburtina, 00156 Roma, Italy
[c] Observatoire de la Côte d'Azur, B.P. 4229, 06304 Nice cedex 4, France

Presented by Pierre Encrenaz

Abstract

There are three major options for mitigation of Near Earth Objects (NEOs). Deflection and disruption of NEOs require the development of new space technologies. A third option, the preparation of the target area on Earth to mitigate an impact, needs institutions for the required civil defense measures. The three options are complementary. Basic requirements for the presently most preferred strategy, deflection, are presented. ***To cite this article: A. Carusi et al., C. R. Physique 6 (2005).***

Résumé

Strategie de mitigation. Il y a trois options principales de strategies de mitigation concernant les objets géo-croiseurs (NEO ou Near Earth objects). La déviation ou la déstruction d'un NEO demande le développement de nouvelles technologies spatiales. La troisième option, la préparation d'une région à un impacte, demande la création de nouvelles institutions de protéction civile. Les trois options sont complémentaires. On présente les conditions techniques de base pour la stratégie la plus préférée, la déviation de NEOs. ***Pour citer cet article : A. Carusi et al., C. R. Physique 6 (2005).***

Keywords: Mitigation; Near Earth objects

Mots-clés : Mitigation ; Objets géocroiseurs

1. Introduction

Very generally, mitigation is an action to moderate the severity of 'something', which may cause disaster or damage. For instance, mitigation of floods, hurricanes, volcano eruptions means reducing or alleviating loss of life, injury and damage to property.

Mitigation of Near Earth Objects (NEOs) is an action to moderate the severity of an Earth impact. Three forms of mitigation are discussed: the preferred option is to intercept and to deflect a threatening NEO and transfer it onto a safe orbit, avoiding in the future a collision with Earth. A second option is the destruction of a threatening NEO which would result in a sample of much smaller objects causing less damage during an impact on the Earth. Thirdly, we may predict an impact and prepare

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[*] Corresponding author.
E-mail address: scholl@obs-nice.fr (H. Scholl).

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the target area on the Earth to survive the event as well as possible. All three options are complementary, depending on the predicted consequences of an impact, on the warning time of an impact, on the technical possibilities of corresponding national or international agencies mitigating a threatening NEO, and on the ability of governmental or private disaster-response systems.

Deflection of a NEO is presently the preferred option. This would require new and expensive systems and mitigation from space. As we will show below, the encounter of a spacecraft with a NEO appears technically feasible if the warning time before impact is not too short. On the other hand, the technological development of devices to deviate an asteroid are still in a very preliminary state.

2. Mitigation from space

2.1. Basic strategies

At the turn of the new millennium humans have achieved routine access to interplanetary space. The exploration of the Solar System carried out by remotely controlled spacecraft has shown that we are able to reach the farthest planets as well as those close to the Sun such as Mercury. However, approaching a hazardous small celestial body for implementing mitigation strategies from space still represents a technological challenge. In fact, in designing an interplanetary mission, it is not always possible to exploit the most convenient trajectories in space because of the limited energy budget provided by both the launcher and the on-board propulsion system. Gravity assist from the planets and/or the use of low thrust, high specific impulse engines (e.g. solar electric) are often needed to satisfy the mission requirements. This in turn introduces unavoidable side effects, such as increasing the duration of a transfer trajectory.

These difficulties apply in particular to the NEOs because of the wide variety of their orbital characteristics. From purely flight dynamic considerations an NEO can be more accessible than the Moon or more energy demanding than sending an orbiter around Jupiter or Saturn. Moreover, mitigation from space increases the number of mission constraints there being no choice on the target object nor on the time frame allowed for actually implementing a successful strategy.

There are two basic options for trying to avoid an object on a collision course with our planet:

(I) a continuous ‘gentle push’ applied to the celestial body which induces secular changes in its orbital parameters until a safe trajectory is achieved;
(II) a single energetic event with the aim of deflecting and/or destroying the potential Earth impactor.

The choice of either of the two strategies depends upon many factors, such as the length of the ‘warning time’ (the time span between the discovery of a dangerous object and impact), the size and the physical characteristics of the impactor (e.g. its internal structure), the availability of the technology required (e.g. deflection devices acting on the asteroid surface, artificial impact cratering, nuclear bombing). Whatever the case, evaluating the accessibility of NEOs is a key parameter for mitigation. From a dynamical point of view, mitigation type I implies the landing of a payload on the surface of a celestial body, thus corresponding to a *rendezvous* mission. A type II mitigation strategy aims to intercepting the target object with the highest mass of disruptive potential, which is the equivalent of planning a *flyby* trajectory at one of its nodes.

In this respect, the classical results on the accessibility of celestial bodies obtained by Walter Hohmann at the beginning of the 20th century [1] can be extended to the eccentric and inclined orbits of NEOs [2]. An *H-plot* analysis [3,4] is then used to give an overall picture of the accessibility of the whole NEO population, thus allowing us to discuss the feasibility of different mitigation techniques in the light of mission analysis considerations.

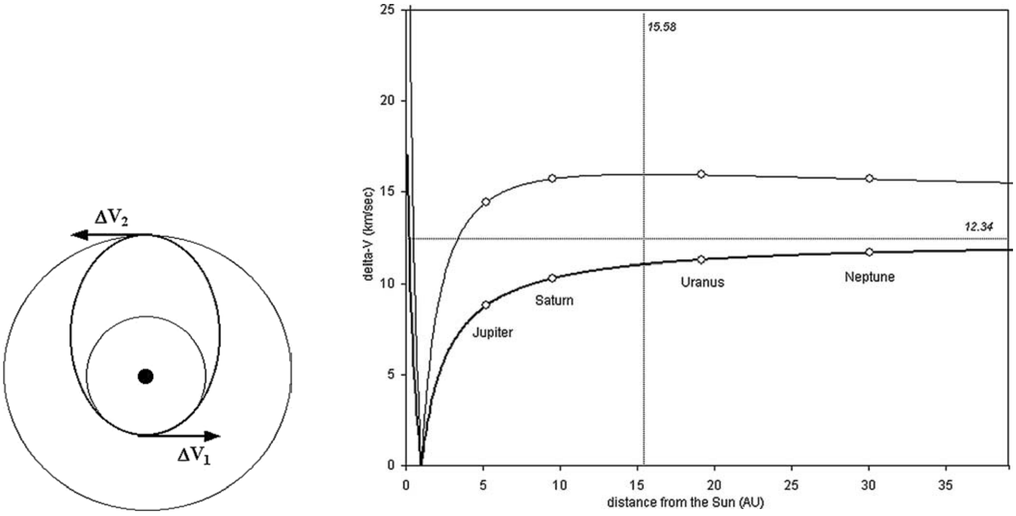
2.2. Accessibility

The Hohmann transfer strategy is widely used for assessing the accessibility of celestial bodies because it foresees two simple orbital manoeuvres whose magnitude can be straightforwardly computed from basic Keplerian motion [5]. First we consider the ‘planetary case’, i.e. a transfer between circular and coplanar orbits. Assuming that the radius of the target orbit is larger than that of the departure orbit (Fig. 1(a)), the first manoeuvre injects the spacecraft into a trajectory whose apocentre is tangent to the target orbit. The second manoeuvre – applied upon reaching the apocentre of the transfer orbit – increases the velocity of the spacecraft of the exact amount needed for circularization. Adding up the ΔV contribution of both manoeuvres, a reliable estimate of the energy requirements needed for performing such a rendezvous mission (i.e. at encounter the spacecraft must have the same orbital velocity, and thus the same orbit, as the target) is obtained.

More generally, assuming that the radius of the departure orbit is unity, the Hohmann strategy can be expressed by the function:

$$\begin{aligned}\Delta V &= \Delta V_1 + \Delta V_2\\ &= \mu^{1/2}\bigl[2^{1/2}\bigl(1 - 1/(1+r)\bigr)^{1/2} - 1\bigr] + \mu^{1/2}\bigl[(1/r)^{1/2} - 2^{1/2}\bigl(1/r - 1/(1+r)\bigr)^{1/2}\bigr] \qquad (1)\end{aligned}$$

where r is the radius of the target orbit and μ is the gravity parameter.



(a) (b)

Fig. 1. (a) Orbit diagram of a Hohmann transfer. The spacecraft, initially on a circular orbit, is injected by an impulse of magnitude ΔV_1 into a transfer ellipse whose apocenter is equal to the radius of the target orbit. Upon reaching it, a ΔV of the exact amount needed for circularization is applied. (b) In an H-plot the two curves give a graphical representation of the Hohmann transfer strategy in the Solar System. The bold lines correspond to the ΔV needed to leave the orbit of the Earth on transfer ellipses of increasing aphelion (right branch) or decreasing perihelion (left branch) distances. The thin line represents the total ΔV budget ($\Delta V_1 + \Delta V_2$) for performing a 'planetary' rendezvous mission. Note the extremely high requirements needed to reach the inner Solar System. Open circles indicate the objects already visited by spacecrafts or for which realistic mission profiles have been computed. The NEO sample is that provided by the Minor Planet Center, updated to 8 June 2004 and including 2825 objects.

If the departure orbit is that of the Earth, a graphical representation of performing 'planetary' transfers throughout the Solar System (hereinafter called the H-plot) is obtained by plotting the ΔV magnitude as a function of the target distance. Varying continuously the radius of the target orbit while keeping fixed at 1 AU that of the departure orbit, the Hohmann strategy translates into the two curves of Fig. 1(b) representing low velocity flyby (ΔV_1) and minimum energy rendezvous missions (ΔV), respectively.

It is interesting to note that studying the ΔV function (1) and its derivative:

$$\begin{aligned}\delta/\delta r\,\Delta V = {}&\frac{1}{2}\mu^{1/2}\big[2^{1/2}\big(r/(1+r)\big)^{-1/2}\big(1/(1+r)^2\big) - r^{-3/2}\\&- 2^{1/2}1/\big(r(1+r)\big)^{-1/2}\big(1/(1+r)^2 - 1/r^2\big)\big]\end{aligned} \tag{2}$$

some additional information useful for mission design is found. Both, Eq. (1) and the ΔV_1 curve tend to the same limit for orbital transfers of increasing size:

$$\lim_{r>inf} \Delta V = \mu^{1/2}(2^{1/2} - 1). \tag{3}$$

This limiting value turns out to be equal to 12.34 km/s, which corresponds to the Solar System escape velocity. Moreover, as shown in Fig. 1(b), before starting to decrease towards this limiting value, the ΔV function (1) reaches an absolute maximum. From Eq. (2) it is possible to compute that it occurs at a distance of 15.58 AU, which represents the highest ratio between the semimajor axis of the final orbit to that of the departure orbit which guarantees that the Hohmann mission profile is also a minimum-energy transfer trajectory [5].

The Hohmann formalism can be used as a basic targeting strategy for reaching also the eccentric and inclined orbits characterizing most NEOs by properly rearranging the order and the magnitude of the orbital manoeuvers. Results are displayed in Fig. 2, which has been obtained plotting the aphelion distance of each object versus the total velocity change needed to transform an initially zero inclination circular 1 AU orbit into one identical to that of the target. Should a NEO have an eccentric coplanar orbit tangent at perihelion or aphelion to that of the Earth, the corresponding point would be located along the reference solid lines – its orbit being identical to the intermediate Hohmann transfer trajectory. Any displacement is a measure of the additional energy needed to lower or rise the perihelia, as well as changing the inclination. The distribution of NEOs in the H-plot obtained in this way clearly shows that they are widely dispersed in terms of ΔV.

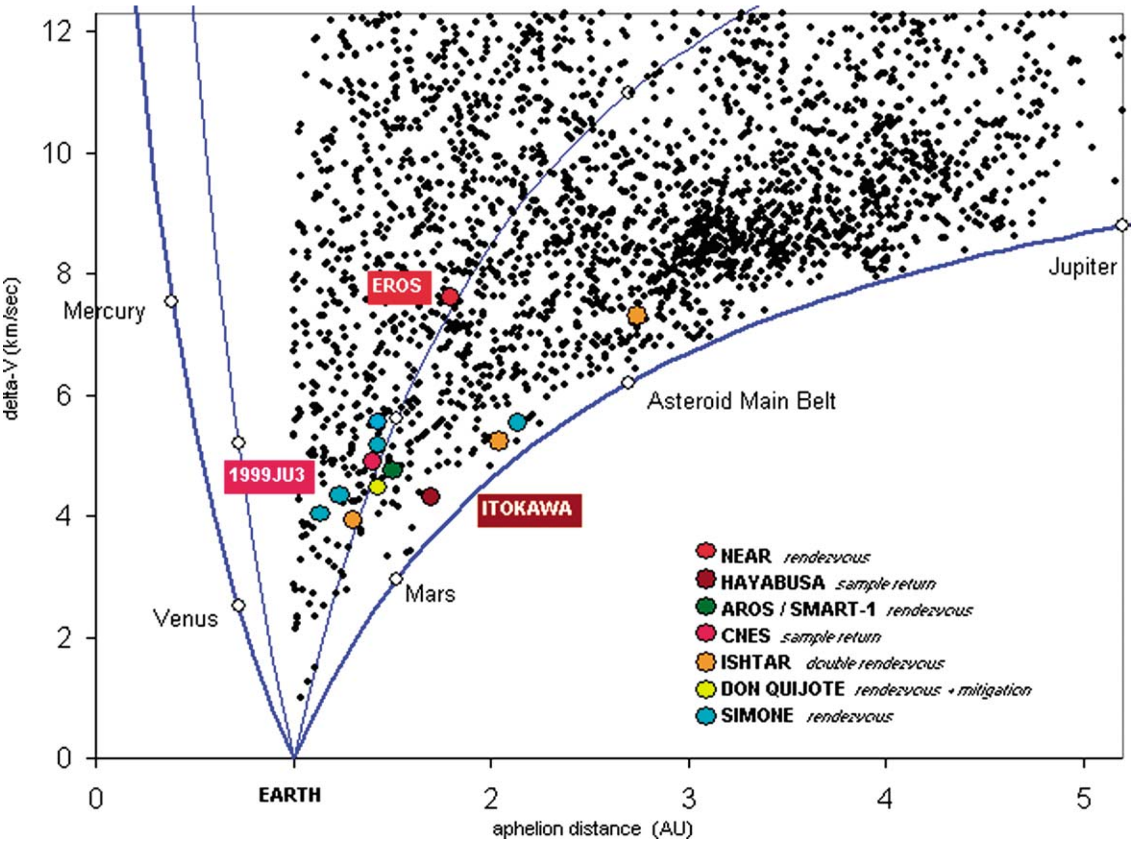


Fig. 2. The region of the H-plot where most NEAs are found is bounded on one side by the Solar System escape velocity and on the other side by Jupiter's distance from the Sun. Circles of different colours identify the objects either already visited by spacecrafts or for which realistic mission profiles have been computed. The NEO sample is that provided by the Minor Planet Center, updated to 8 June 2004 and including 2825 objects.

This dynamical framework has the advantage of being independent from the launch scenario: Earth phasing, the different capabilities of the launchers and/or the use of intermediate parking orbits make often it difficult to carry out meaningful comparisons among different missions to different targets. The ΔV values used for filling the H-plot are instead a self-consistent data set representing the lowest figures achievable when both ideal phasing occurs (corresponding to the most favorable launch window geometry) and ideal orbital manoeuvres (i.e. strictly impulsive) are performed.

In Fig. 2 the objects selected as targets for NEO space missions (past, present and under study) have been also indicated. In particular, Eros has been extensively orbited by the NEAR-Shoemaker mission, dust samples of Itokawa will be returned to Earth by the on-going Japanese Hayabusa mission, while 1999 UJ3 turned out to be the best candidate for a sample return mission to a primitive C-type object within the framework of a proposal to CNES [4].

The distribution shows that no target beyond 8 km/sec has been taken in consideration until now, thus defining the 'present technological level' for rendezvous missions. This implies that a large fraction of NEOs are out of reach for mitigation type I when optimal direct transfer trajectories are foreseen. An hazardous object can in fact be found everywhere in the H-plot because its collision path is determined only by the time evolution of the so-called Earth MOID (minimum orbit intersect distance). Exploiting repeated Earth and/or Venus gravity assist trajectories and, to a minor extent, the use of weak stability boundary Earth escape trajectories, can help to overcome this difficulty [6], although at the cost of longer mission duration. This adds a further difficulty to the possibility of exploiting the dynamical evolution of NEOs and in particular the effect of close encounters with the terrestrial planets for amplifying the effect of very small deflection manoeuvres [7].

The feasibility of intercepting an object when it crosses the ecliptic (type II mitigation) is more easily assessed. A nodal flyby mission does not require performing inclination manoeuvres which are most demanding in terms of energy budget. Furthermore, NEOs are intrinsically accessible from Earth because most of them have at least one node at an affordable distance. In particular, it is possible to show [8] that the rather extended region of space between the orbits of Venus and Mars is reachable with a best case ΔV as low as 3 km/sec. This favorable situation is summarized in Fig. 3, which shows the distribution of the nodal

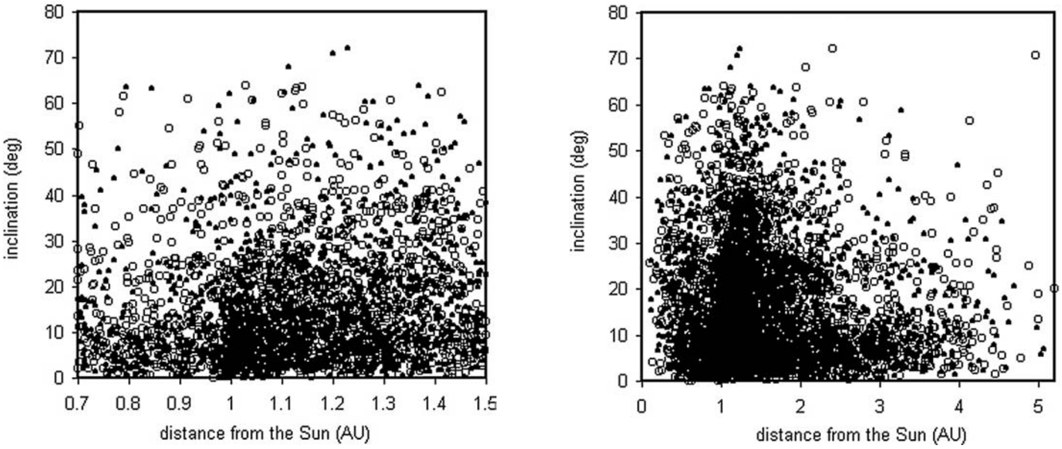


Fig. 3. The location of the ascending (full circles) and descending (open circles) nodes of all NEOs are displayed as a function of the inclination of the corresponding orbits. The concentration of nodal distances between the orbits of Venus and Mars (left plot) is evident on a wider scale (right plot). Note the large number of high inclination objects. The NEO sample used is the same as in Fig. 2.

distances of all known NEOs. Only 8 objects out of 2825 have one of the two nodes more distant than Jupiter, while 87 percent of them has at least one node falling between Venus and Mars.

2.3. Space missions

Precursor missions devoted to mitigation from space are focused on scientific as well as on technological issues. Measuring the physical characteristics of NEOs (e.g. density, internal structure, porosity) is a basic requirement for evaluating the efficiency of any proposed deflection strategy. Testing the accessibility of potentially hazardous NEOs provides the necessary operational context for in situ actions or high velocity intercept of the target.

Within this framework, the European Space Agency has recently carried out some NEO space mission preparation studies where mitigation plays a major role [9]. The aim in fact was not focused on science but in determining the priorities for risk assessment and reduction from space. Therefore a mitigation-driven selection procedure has been set up and six mission proposals were awarded a phase-A system level study. Eventually, a panel of experts recommended the scenario proposed by the *Don Quijote* mission concept [10]. It foresees a spacecraft orbiting a near-earth asteroid while another is independently sent on an impact trajectory toward the same object. In doing so, many important issues are addressed at the same time: the physical characterization of the target, its accessibility for both mitigation strategies (type I and II) and a deflection experiment whose outcome can be directly measured with high accuracy.

3. Mitigation options

3.1. The basic requirements

The purpose of any action aimed at deflecting or destroying an object on a collision course with the Earth is to avoid impact. This is a unique case among natural disasters because in this case it is possible, in principle, to completely eliminate the problem. As a matter of fact, the only possible response to more usual catastrophes is to forecast them and evacuate the threatened area: people would then be safer, although the level of destruction to properties and infrastructure would not be diminished. In case of an impending impact, on the other hand, deflection or destruction of the projectile simply means that the impact would not take place.

In order to reach the desired goal, however, mitigation techniques must acknowledge a few basic requirements:

- certainty of the desired result;
- flexibility of the associated manoeuvres;
- minimization of the required energy budget.

The first requirement is rather obvious, but it implies that the technique used be tested in advance in order to be sure that it is capable of obtaining what is needed. The implications of this requirement will be discussed in the next section.

The second point concerns the substantially inevitable possibility of failure. Given the enormous consequences that such failure could have, it is necessary for any mitigation method to have a high degree of flexibility, including the possibility to recover the mission at a later time.

The third requirement may seem less important: in case of a certain impact with high consequences every effort would be made in order to avoid it irrespective on the cost, both in energy and money. However, it should be noted that techniques requiring a great amount of energy, such as those using nuclear devices, may be difficult or unsafe to handle and that possible malfunctions may even make the situation worse.

3.2. Fulfilling the basic requirements

It is important, when discussing the mitigation techniques, to take always into account the above discussion. It is therefore useful to examine what are the methods that fulfill the requirements mentioned.

An impending impact is avoided when either the projectile is fragmented to the point that fragments hitting the Earth are small enough to be stopped by the atmosphere, or the path of the object is deflected so that it misses the planet. There are, in other words, only two techniques: destruction or deflection.

The first technique could be acceptable depending on the size of the impactor and on the warning time, as previously defined; while a small, loosely-bound object (a small comet, for example) might be fragmented to the desired point, this is much less sure for a sizable object (of the order of some hundreds of meters), or for stony, non-compact objects. In the latter case a substantial fraction of the energy would be spent in separating the major components that would continue their path, although independently, and would hit the Earth anyway if the time to impact is short.

The second technique is also strongly linked to the size of the object and again dependent on the length of the warning time. In fact, in order to change the dynamical state of the projectile the impulse needed is proportional to the desired velocity variation, and therefore depends on the mass of the object. However, the ΔV required for an effective deflection is a non-linear function of time, due to the Keplerian motion, thus depending on the orbital parameters of the impactor. Therefore, in order to compute the amount of ΔV needed for deflection at a given epoch, it is important to know *with great accuracy* the dynamical 'future history' of the impactor, and to study whether it is possible to take advantage of it.

In conclusion, both options have their merits and their drawbacks, and the final choice would depend basically on the warning time. However, it seems more useful to fully explore the concept of deflection because this technique has a greater possibility to fulfill all the three requirements at the same time.

3.3. An example of simulated deflection

Deflection is much simpler to model than destruction. Whatever the method used (kinetic energy, mass drivers, solar sails, stand-off nuclear blasts) the common concept is to transfer linear momentum to the object so that its orbital velocity is increased or decreased. In this way the orbital semimajor axis, which depends on the velocity, is also changed. The change in semimajor axis, in turn, produces a change in the orbital period giving rise to a temporal shift at encounter that accumulates with time. In other words, the object comes to the impact point either too early or too late, and the impact does not take place.

The technique is conceptually very simple, but it stands on the possibility to transfer linear momentum to the impactor early enough, and in a sufficient quantity, to transform the temporal shift in a spatial shift of at least one Earth radius: on the target plane the path of the incoming object will then be outside the circle representing the Earth.

Many simulations have been done of this kind of manoeuvre [7,11,12], and all of them show that a deflection is possible, even for large objects, provided that a sufficiently long warning time is available.

As an example, Fig. 4 shows the results of the simulated deflection of a fictitious object called Aramis. This computation was made in the framework of a case study for testing different mitigation options [12]. The orbital evolution of the object was computed backwards in time for 50 years, and then followed forwards until the impact date, applying a variable ΔV at different times during the evolution. The graph in Fig. 4 represents the velocity variation (in meters per second, log notation) necessary for the object to miss the Earth. Two impulses were applied along track in opposite directions because the reference impact trajectory, at the time of impact, usually does not pass through the center of the Earth, and therefore it is easier to deflect the object in one direction instead of the other.

Aramis is an Apollo object, whose perihelion is just inside the Earth orbit. The plot in the figure shows that the ΔV necessary for deflection applying the impulse 50 years before impact is, in the most favourable case, about -3.8 (in log notation), i.e., less than a millimeter per second. This value remains almost constant for a long time: at the sixth perihelion passage since the beginning of the integration it is still -3.7. The manoeuvre needs to be done at perihelion to maximize the effect.

The computations done so far have shown that there are more favourable cases. When the orbit of the projectile is in resonance with that of the Earth the impact encounter is usually preceded by another encounter a few years before. This kind

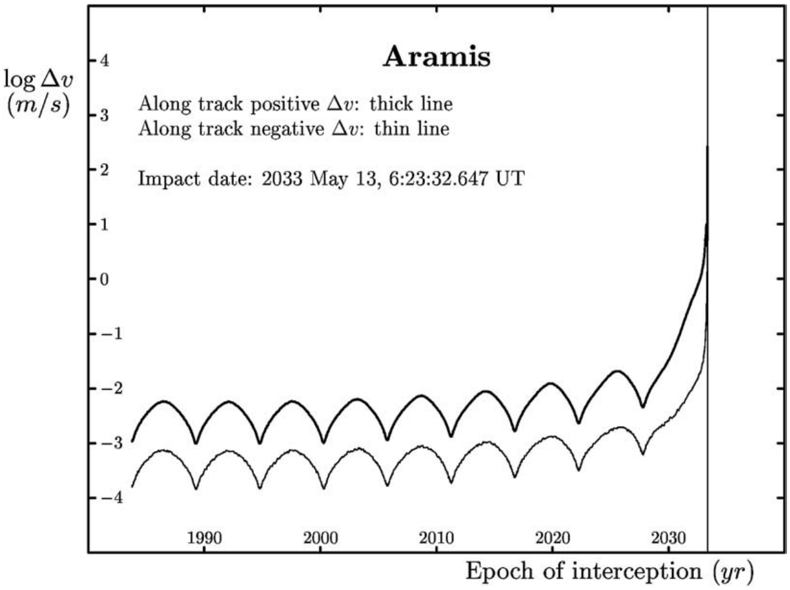


Fig. 4. Simulation of the deflection of the fictitious object Aramis.The two curves give the ΔV (in log notation) necessary to modify the orbit so that the impact does not take place, as a function of the Epoch of interception at which the manoeuvre is done. The vertical line on the right is the impact date.

of occurrences has been called a ‘resonant return’ [13]; if a deflection manoeuvre is done before the pre-impact encounter, the ΔV needed may drop down by one or two orders of magnitude, making the deflection even easier.

The deflection technique, when applied a few decades before impact, is perfectly fulfilling the basic requirements. In fact, the manoeuvre may be repeated at every perihelion passage, providing a many opportunities for correcting wrong operations, thus making the process very flexible. Moreover, the amount of energy required for every impulse may be rather low, or it may be provided in a more or less continuous way at a very low rate.

The only drawback of this scheme is that it is necessary to identify the impact well in advance. This is not impossible with present day techniques, but it requires a continuous monitoring of potentially hazardous objects.

4. International context

The subject of NEO impacts, and of their possible consequences on Human society, has also been widely discussed in the past ten years or so in the international, non-scientific community. These discussions have led to several Resolutions and Reports addressing the national governments and asking to deepen the study of the problem also from a Civil Defence point of view (see, e.g., Council of Europe, 1996, UN-COPUOS, 1999, OECD, 2003).

This growing awareness is based on the findings of the scientific community, but extends beyond scientific research. In fact, even if scientists begin to be able to predict impacts well in advance (50–100 years), nothing has been done to date to study possible counter-measures; most probably the next impact will be of an object of modest size and it will probably be undetected until the last moment. With a warning time of, say, one month it is impossible to plan a mitigation space mission and every effort would then be devoted to plan the evacuation of the targeted area. This is not a problem for scientists, but for national Civil Defence systems.

On the other hand, the possibility to predict an impact decades in advance has already triggered a number of conferences and workshops on the subject of space mitigation. These have been usually international in character, because it is clear that the impact threat cannot be confined to, nor addressed by, a single country. Two such conferences have been held in the United States: the first in Arlington (2002) and the second in Orange County (2004). In both cases technical and social aspects have been discussed together by the convened people, putting the foundations for a close collaboration among different disciplines and institutions. However, the big question is still there: should we *build and test* mitigation devices? and, if yes, who is going to do this?

At the beginning of the 1990s the most usual answer was: no. There was indeed the suspect that several military circles were trying to ‘jump on the bandwagon’ of the asteroid scare in order to continue the design and production of nuclear weapons, and the scientific community was seriously considering the so-called “Deflection Dilemma’: every device designed to deviate an asteroid *away from* Earth could be used to move an asteroids *towards* the Earth. The Deflection Dilemma has never been solved, but is now to some extent superseeded by a Deflection Dilemma 2: if we design a mitigation system, but never try it, it will most probably fail when really needed.

At this time the most common opinion is that we should actually test some of the ‘soft’ techniques, like kinetic energy. As mentioned above, ESA has already studied a mission to try the deflection of an innocuous object, and similar initiatives are under development elsewhere (for example by the B612 Foundation).

On the other side of the problem (mitigation of the consequences of an impact) international initiatives, especially that of the OECD, are slowly pushing national agencies to take the issue seriously. It is in this context that the International Council of Science (ICSU) has organized a workshop (Tenerife, December 2004) to discuss the impact problem not only from an astronomical or palaeontological point of view, but also involving scientists and representatives of other disciplines, such as economists, sociologists, politicians. The purpose is to favour the development of deeper awareness that this natural disaster has to be treated like the others: trying to predict its occurrences and to minimize its effects on Human society.

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