THE DEFLECTION DILEMMA:
USE VS. MISUSE OF TECHNOLOGIES FOR AVOIDING INTERPLANETARY COLLISION HAZARDS

Alan W. Harris
Jet Propulsion Laboratory, Caltech

Gregory H. Canavan
Los Alamos National Laboratory

Carl Sagan
Cornell University

Steven J. Ostro
Jet Propulsion Laboratory, Caltech

5 November 1993
7 Manuscript pages
4 Figures
1 Table

ABSTRACT

A system capable of deflecting a Near-Earth Object (NEO, an asteroid or comet in Earth-approaching orbit) out of an Earth-impacting trajectory could also be used to deflect a non-menacing NEO so it impacts the Earth. We calculate the expected frequency of opportunities to misuse a deflection system as a function of NEO diameter, the capability of the putative deflection system, and the fraction of the full Near-Earth Asteroid (NEA) population that is known. Our principal result, which is nearly independent of other assumptions, can be simply stated: the frequency of opportunities to misuse a deflection system, for NEAs of a given size, is $\sim 100(\Delta v)^2$, or $\sim 1/t_r^2$, times the natural impact frequency with the Earth of NEAs of the same size. Here Δv is the deflection velocity in m/sec that a hypothetical system is capable of achieving; equivalently, t_r is the time in years that the given system needs to deflect an object by one Earth radius, *i.e.* the response time required in legitimate use, For a system that would be effective against objects discovered only days or weeks before impact, opportunities for misuse might be so frequent as to be continuously present, For a less capable system, the frequency of opportunities for misuse may be only once a century or less, but still more frequent than the need to use it, Unwillingness or inability to develop a deflection capability in advance of need leaves us vulnerable to that fraction of NEO impacts by bodies (mainly long-period comets) that may not be discovered with enough lead time to construct a defensive system. But the potential for misuse of a system built in advance of an explicit need may in the long run expose us to a greater risk than the added protection it offers, This is the deflection dilemma.

I. INTRODUCTION

In its annual motion about the Sun, the Earth moves through a cloud of asteroids and comets in orbits which cross the Earth's, the near-Earth objects (NEOs). Occasional collisions with members of this population are inevitable. Once we recognize that collisions with NEOs larger than a few hundred meters in diameter could threaten the global civilization, means for mitigating this threat seem clearly worth considering. Deflection methods which have been discussed (*cf.* Ahrens & Harris 1992, and in this volume; Canavan, in this volume) include mass driver engines propelling reaction mass into space, high speed collisions, and sub-surface or stand-off thermonuclear explosions. These same capabilities can in principle be used to alter the orbit of an object on a non-intercepting trajectory so that it does impact the Earth. Some have warned (Sagan 1992) that through negligence, fanaticism, or madness, the technology to deflect asteroids and comets might be used to generate a global catastrophe on a time scale much shorter than the waiting time for the natural catastrophe that this technology is intended to circumvent, Those who *take* seriously a probability of 10^{-3} in a century of a catastrophic asteroidal impact must surely take seriously, say, a probability of order unity in a century that an opportunity will exist to misuse deflection technology to cause such an impact, The cure, it is suggested, may be worse than the disease,

In this chapter, we calculate the expected frequency of opportunities to misuse a deflection system as a function of NEO diameter, the capability of the putative deflection system, and the fraction of the NEA population that is known -- that is, the number of nearby bodies available for misuse. We find that opportunities to misuse a deflection system are much more frequent than are occasions to use it for its intended purpose. That result is very robust in that it depends on very few auxiliary assumptions. It is expressly not our purpose here to discuss the plausibility that some nation or group might seize an opportunity to deflect an NEO toward the Earth. Nor do we address in any detail the technical feasibility or cost of developing a deflection system. Such systems are physically quite possible in terms of energy and momentum considerations, so the potential capability to develop and misuse such systems must be taken seriously.

II. OFFENSIVE USE OF A DEFLECTION SYSTEM

Consider a system capable of deflecting an asteroid by a velocity increment Δv. According to Ahrens and Harris (1992, *this book*), in a time $t < P/2\pi$ (where P is the period of the asteroid) the displacement is $\sim(\Delta v)t$. For $t > P/2\pi$, the displacement *along-track* is $\sim 3(\Delta v)t$, and *across-track*, $\sim(\Delta v)P/2\pi$. Thus the requirement that such a system be capable of deflecting an incoming asteroid by a distance of the order of the Earth's radius, R_E, requires a response time t_r for applying Δv of:

$$t_r \approx \frac{R_E}{\Delta v} \qquad\qquad t_r < P/2\pi, \tag{1a}$$

$$t_r \approx \frac{R_E}{3\Delta v} \qquad t_r > P/2\pi. \tag{1b}$$

In the case of $t_r > P/2\pi$, we have assumed a displacement along-track because it is most efficient. Note that the above relations between t_r and Av are very conservative. Because of inevitable uncertainties in the exact trajectory of a threatening object, one would no doubt want to deflect it by a comfortable margin, perhaps several Earth radii; thus a realistic value of t_r for a given value of Av, or vice-versa, might be several times larger than given by the above expressions.

Now Consider the possibility of offensive misuse of the same system. In a time T, by how far might the same system displace an available asteroid toward the Earth? 'This case differs in one subtle way from the above, because the option to displace along-track instead of across-track is not a free choice -- one must displace the asteroid in a prescribed direction to hit the Earth, Or to consider the matter in reverse, the areal phase space from which an asteroid could be diverted from its natural course so it hits the Earth has an across-track dimension

$$\delta_\perp \approx \Delta v\left(\frac{P}{2\pi}\right), \tag{2a}$$

and an along-track dimension

$$\delta_\parallel \approx 3(\Delta v)T \tag{2b}$$

In this case, we have assumed that $T > P/2\pi$. Thus the area of the phase space from which one might choose potential deflectable asteroids is

$$A - \pi\delta_\perp \cdot \delta_\parallel \approx \frac{3}{2}\Delta v^2 PT. \tag{3}$$

The collisional cross-section of the Earth, allowing for the gravitat tonal focusing of bodies approaching at about 10 km/sec, is $A_E \approx 2\pi R_E^2$.. The ratio A/A_E *is* equal to the frequency with which an asteroid passes within a divertable range of the Earth (for a system capable of diverting by Av) to the natural frequency of collisions with the Earth of objects of the same size. In other words, this is the ratio of the chance that a system *could* be misused to the chance that it would be needed for the legitimate task of diverting an asteroid. One further factor might be taken into account. The collision frequency of asteroids hitting the Earth does not depend on whether or not we know about them. But only asteroids discovered in advance are available for deflection toward the Earth, Thus the ratio of "chance to misuse" to "need to deflect" is $\Omega \approx fA/A_E$, where f is the fraction of the asteroid population in question which has been discovered and tracked:

$$\Omega = \frac{\text{Chance to misuse}}{\text{Need to deflect}} \approx \frac{fA}{A_E} \approx \frac{3f\Delta v^2 PT}{4\pi R_E^2} \tag{4}$$

For purposes of discussion, we evaluate the above expression, using a typical NEA orbit period, $P \sim 4$ years, and misuse deflection time, $T \sim 4$ years. An upper limit to T is about 10 years, a time in which other nations could detect a deflection and have time to develop their own countermeasures. Thus we obtain:

$$\Omega \approx 100 f\Delta v^2, \tag{5}$$

where Av is in m/sec. We can express the above ratio in terms of the required response time, t_r, for legitimate use of the hypothesized system, by substituting Eq. (1a) or (1b) into (5):

$$\Omega \approx \frac{(0.4 \text{ to } 4)f}{t_r^2}, \tag{6}$$

where t_r is in years. Within the parentheses, the coefficient 0.4 applies for short response time ($t_r < P/2\pi$ -0.5 year), and *4* for longer response times, with a smooth transition in between

Figure 1 is a plot of Q vs. Av from expression (5), for-f= 1. We will discuss other values of f in Sect. IV, below. The equivalent scale in units of t_r across the top of the figure is derived from Eqs. (1a) and (1b) blended smoothly between short and long t_r. It is noteworthy that for a defense system with a response time t_r of the order of 1 year, *the frequency of opportunities for misuse is about the same as the frequency of situations requiring the use of such a system.* This result is independent of almost all assumptions, such as the collision frequency itself. For even shorter response times (that is, systems capable of larger Δv), the frequency of opportunities for misuse can greatly exceed the frequency of need to use such a system.

III. DEFLECTION VELOCITY

What is a plausible range of possible deflection velocities that may be achievable by a deflection system? Ahrens and Harris (1992, and in this book) estimate that even employing the technologically easiest method, stand-off nuclear explosions, a 1 km asteroid can be diverted ~1 m/sec with an explosive energy of about 1-10 MT. The deflection velocity Δv is proportional to the explosive energy and inversely proportional to the asteroid mass, thus:

$$\Delta v \approx \frac{E}{3D^3}, \tag{7}$$

where E is the explosive energy in megatons and D is the asteroid diameter in km,

It is not possible to apply a single impulse Δv greater than about the object's surface escape velocity without disrupting the body rather than deflecting it in one piece. The surface escape velocity from a sphere of diameter D is

$$v_e = \left(\frac{2\pi G\rho}{3}\right)^{1/2} D \approx (0.65\ \text{m/sec})(D\ \text{in km}) \tag{8}$$

One can imagine using multiple impulses. Indeed, for accurately "herding" an asteroid toward the Earth, this would be a necessity. Thus the maximum deflection velocity achievable is:

$$\Delta v \approx n\, v_e \approx n\,(0.65\ \text{m/sec})(D\ \text{in km}), \tag{9}$$

where n is the number of impulses applied. At least a few impulses would be required just to achieve the needed accuracy, and more than a few hundred might become impractical.

In Fig. 2, we have plotted the limits on Δv derived from Eqs. (7) and (9), as a function of asteroid diameter, for E = 10, 100 and 1000 MT total explosive energy, and for n = 5, 50 and 500 impulses, in the following discussion, we will take E = 100 MT and n = 50 to define a nominal limit on Δv vs. diameter (solid line in Fig, 2), but results for other assumptions can be easily derived from the figures. We note that sizable values of Δv (> 1 m/sec) can be obtained for large asteroids (D > 1 km) with only a few 10 MT weapons, such as were once the mainstays of the U.S. and Soviet nuclear arsenals,

IV. POPULATION OF NEAS AVAILABLE FOR MISUSE

In order to apply a system to deflect an asteroid toward the Earth, one must discover and track enough bodies to have an available divertable asteroid in a reasonable amount of time. How many such bodies might one expect to be available? Using estimates of the total population of NEAs vs. size (Morrison, ed. 1992; Rabinowitz *et al.*, this book), we have derived the differential populations in factor-of-two size bins for all NEAs larger than 50 meters in diameter. Taking the *Spaceguard* survey (Morrison, ed. 1992 and Bowell and Muinonen, in this book) as a representative example of a possible search program, we have computed the number of NEAs in each size bin that would be discovered as a function of time. From the graphs and tables given in the above references, we find that the fraction f, or completeness of the survey, can be well represented as an exponential function:

$$f = 1 - e^{-t/t_0}, \tag{10}$$

where t is time and t_0 is the characteristic time scale of discovery. Table 1 lists the results of these analyses, The collision frequencies listed are estimated as (total number in size bin) . 4.2 x 10^{-9} years^{-1} (*cf.* Rabinowitz *et al.*, this book). The final column is the fraction f, which appears in Eqs. (4), (5) and (6).

Table 1. Number of NEAs **and number discovered in 10 years** by *Spaceguard.*

Diameter Range km	Total Number of NEAs	Collision Frequency $(\text{years})^{-1}$	Characteristic time scale of discovery, t_0, years	Number Discovered after 10 years	Fraction, *f*, discovered after 10 years
0.05-0.10	1,700,000	7.1×10^{-3}	2400	7,100	0.042
0.1 -0.2	250,000	1.1×10^{-3}	470	5,400	0.021
0.2 -0.4	50,000	2.1×10^{-4}	130	3,600	0.073
0.4 -0.8	11,000	4.8×10^{-5}	43	2,400	0.207
0.8 -1.6	2,600	1.1×10^{-5}	14	1,400	0.523
1.6 -3.2	700	2.9×10^{-6}	4.5	620	0.89
3.2 -6.4	60	2.5×10^{-7}	1.5	60	1.0
6.4 -12.8	5	2.1×10^{-8}	0	5	1.0

Note the flatness of the discovery spectrum. Over a range of one order of magnitude in diameter, from -0.1 to -1.0 km, the population of NEAs varies by nearly three orders of magnitude; yet the number of NEAs discovered after 10 years varies by only a factor of 5. A fair fraction of this decrease with increasing size is due to the asymptotic approach to completeness in the larger size bins.

From the results in Table 1, we can estimate the frequency with which objects over a range of sizes might be divertable toward the Earth, as a function of the capability of a putative deflection system. Figure 3 is a plot of that frequency, using the assumed results of a ten-year *Spaceguard* survey as an illustration, Note that over the range of size from -0.1 to -1,0 km, the relative frequency of possible misuse at any given value of Av varies by only about one order of magnitude. For each size object considered, we have indicated the limiting value of Av from Fig. *2* (solid dots for $n \leq 50$, open circles for 1,'<100 MT).

Finally, one can estimate the frequency of opportunities to misuse a deflection system as a function of survey completeness. Using Eq. (10) and the data in Table 1, we have computed this frequency as a function of duration of a S@cegurwd-level survey, for each size bin, assuming the limiting values of Av shown in Fig. 3. One should not take the time scale literally, since time intervals toward the right side of the plot are long compared to the expected rate of advance of technology. At the left margin, we see the frequency of opportunities to misuse a deflection system with our *present* level of survey completeness and at the right margin the frequency given *complete* knowledge of the NEA population in each size bin. Figure 3 can be thought of a "snapshot" cutting across Fig. 4 (*cf.* the dots in the two figures), to show the dependence on Av at a given time. We note, for example, that the opportunity to deflect a 1 km NEA into an Earth-impact trajectory presents itself today only about once a century (or 10-2 a year), while after a decade of a *Spacegumd-level* survey opportunities present themselves about once a year.

It may be instructive to consider a couple of cases based on presently known NEAs. Yeomans and Chodas (*this book*) list all known Earth approaches by comets or asteroids to within 10 lunar distances for the interval 2001-2200. In addition to the closest approach, they list the minimum separation of the orbits at the time of encounter, necessary for estimating $\Delta v_\perp$ -- -the cross-track deflection velocity required -- which is generally the larger component. The asteroid 4179 Toutatis will pass within about 0.01 AU from the Earth in 2004. The two orbits miss each other by only 0.006 AU, requiring (from Eq. 2) $\Delta v_\perp \approx 45$ m/sec. This could be applied as little as a year in advance. The along-track adjustment required to cause a collision is only $\delta_\parallel \approx 0.008$ AU, so from Eq. (2b), $\Delta v_\parallel \approx 1$ m/sec if applied 10 years in advance, but is still only a fraction of $\Delta v_\perp$ even if applied only 1 year in advance. Toutatis is -4 km in diameter. Thus, by Eq. (7), the total explosive energy required to deflect it by -50 m/sec is $\sim 10^4$ MT. This is an aggregate yield about equal to the present global stockpile of nuclear arms. Referring to Fig. 4, note that for bodies as large as 3.2-6.4 km in diameter, our present knowledge of the population is nearly complete, so further surveying will not change the statistics much. From Fig. 3, note that the 3.2-6.4 km diameter line at a Av of 50 m/see indicates a frequency of possible misuse of about once per 10 years. Hence the upcoming close pass of Toutatis by the Earth represent about an expected level of opportunity for misuse of a deflection system on a very large NEA.

Another example is 1991 OA, an asteroid -1 km in diameter, which will pass within 0.015 AU of the Earth in 2070. What makes this close approach unusual is that it is the closest to intersection of the Earth's orbit with that of any other known object in the next century, 0.003 AU, and hence has the minimum $\Delta v_\perp$, -23 m/sec, needed to cause a collision. The impulse required to deflect 1991 OA into an impact trajectory can be delivered by only -60 MT. From Fig. 4, the frequency of opportunities to deflect an object this size toward the Earth with a 100 Ml delivered impulse should occur about every 50 years, with our present knowledge of the population. This is again consistent with the fact that the "best" deflection opportunity now known occurs in 2070. However, note that with complete knowledge of the population, an opportunity to deflect a 1 km asteroid toward the Earth with 100 Ml total impulse would occur every few years.

V. CONCLUSIONS

The possibility of misusing a deflection system depends strongly, and almost solely, on the capability of such a system (i. e., on the deflection Av it is able to achieve or, equivalently, on the minimum response time, t_r, it requires).

1. A system of very low capability (Av $\leq$ 0.1 m/sec), such as might suffice to deflect NEAs discovered long in advance of a collision event, poses minimal threat of being misused to deflect asteroids toward the Earth. On the other hand, the response time t_r required to move an asteroid away from the Earth with such a limited system is > 1 year, thus calling into question the need to build such a system in advance of a discovery of an object on a collision trajectory.

2. A system of moderate capability, Av - 1 m/sec, would have potential application for protecting against long-period comets, where the response time is about a year or less. The probability that such a system could be misused is small, but is about 100 times greater than the probability that it would need to be used,

3. A highly capable system, able to deflect an object with only a few days' warning, coupled with a *Spaceguard*-level search for NEAs, presents a virtual continuum of opportunities for misuse. Such a high-capability system is not required for deflection of large long-period comets (see 2 above). Its only legitimate application would be for very fast response to approaching small asteroids. Since such small objects constitute only a very small fraction of the NEO collision hazard, and since a deflection system effective for such objects has significant potential for misuse, it appears imprudent to build such a system -- at least at this time.

Beyond protecting the Earth against impacting NEOs, there are other benign motivations for developing an asteroid orbital engineering capability. Some authors (*e.g.* O'Leary 1977; Gaffey and McCord 1977) have proposed doing so to utilize mineral resources in asteroids, and Herrick (1979) suggested a scenario for crashing a part of the asteroid 1620 Geographos into Central America, to excavate a new Atlantic-Pacific canal. We must caution that any such orbital engineering systems present the same or greater risk for misuse or accidental mishap as a defensive deflection system,

ACKNOWLEDGMENTS

We are grateful to Joseph Burns, David Morrison, Bruce Murray and Eugene Shoemaker for helpful comments. The work at JPL was supported under contract from NASA. C.S. was supported by NASA Grant NAGW 1870.

REFERENCES

Ahrens, T. J., and A, W. Harris (1992) Deflection and fragmentation of near-Earth asteroids. *Nature* 360, 429-433.

Gaffey, M. J., and T.B. McCord (1977) Mining outer space. *Technology Rev. 79,3-11.*

Herrick, S. 1979. Exploration and 1994 exploitation of Geographos. In *Asteroids*, ed. T. Gehrels (Tucson: University of Arizona Press), pp. 222-226.

Morrison, D., ed. (1992) *The Spaceguard Survey.* Pasadena: NASA/JPL, 66pp.

O'Leary, B. (1977) Mining the Apollo and Amor asteroids, *Science* **197, 363-366.**

Sagan, C. (1990) Between Enemies, *Bull. Atomic Scis. 48, 2.4-26.*

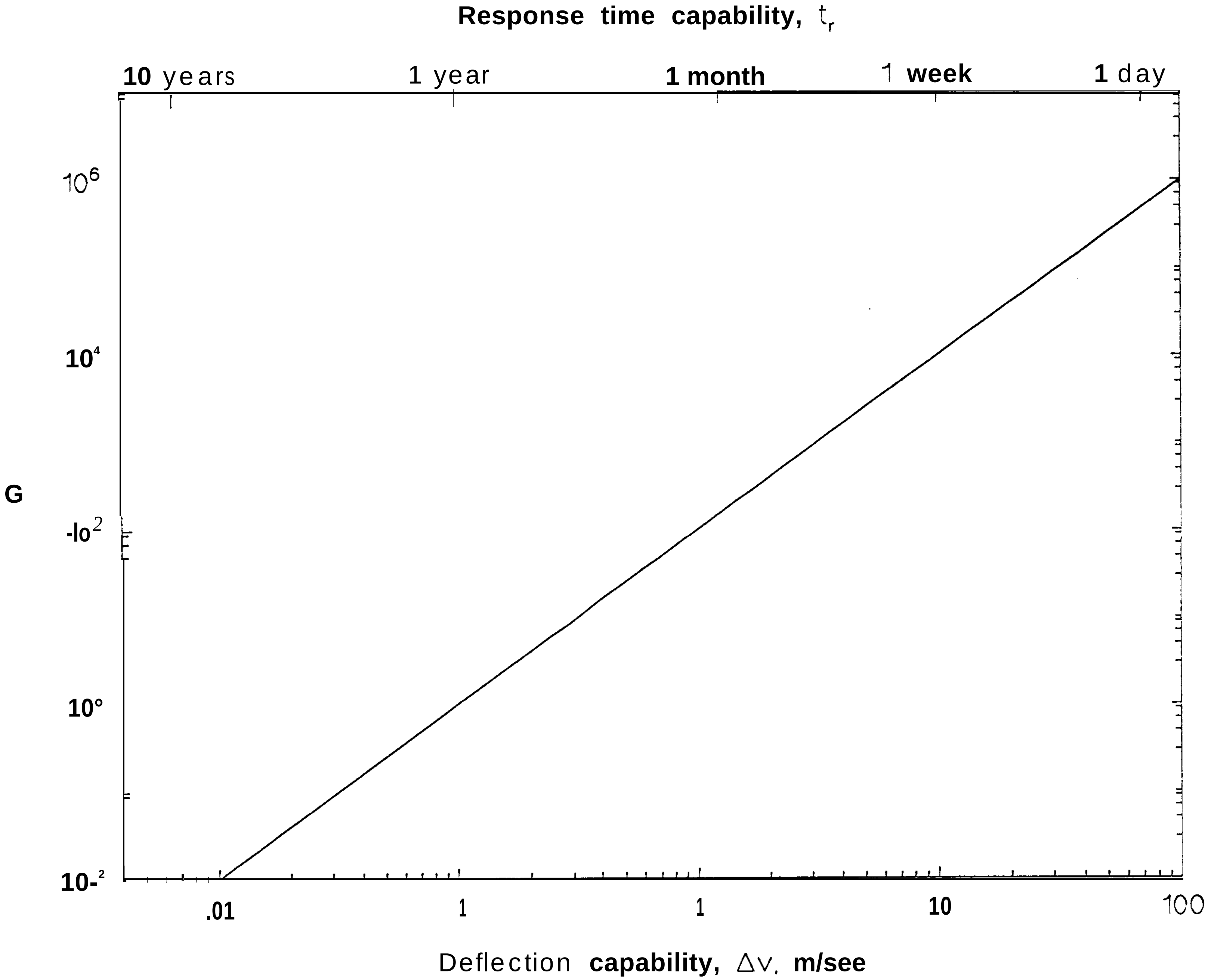
FIGURE CAPTIONS

1. The ratio Ω of the frequency of opportunities to misuse a deflection system to the frequency of occasions requiring the use of such a system, as a function of the capability of the system in terms of the Av it is capable of delivering to an asteroid (bottom scale) or, equivalently, the time t_r required to move an asteroid by one Earth radius at that Av (top scale),

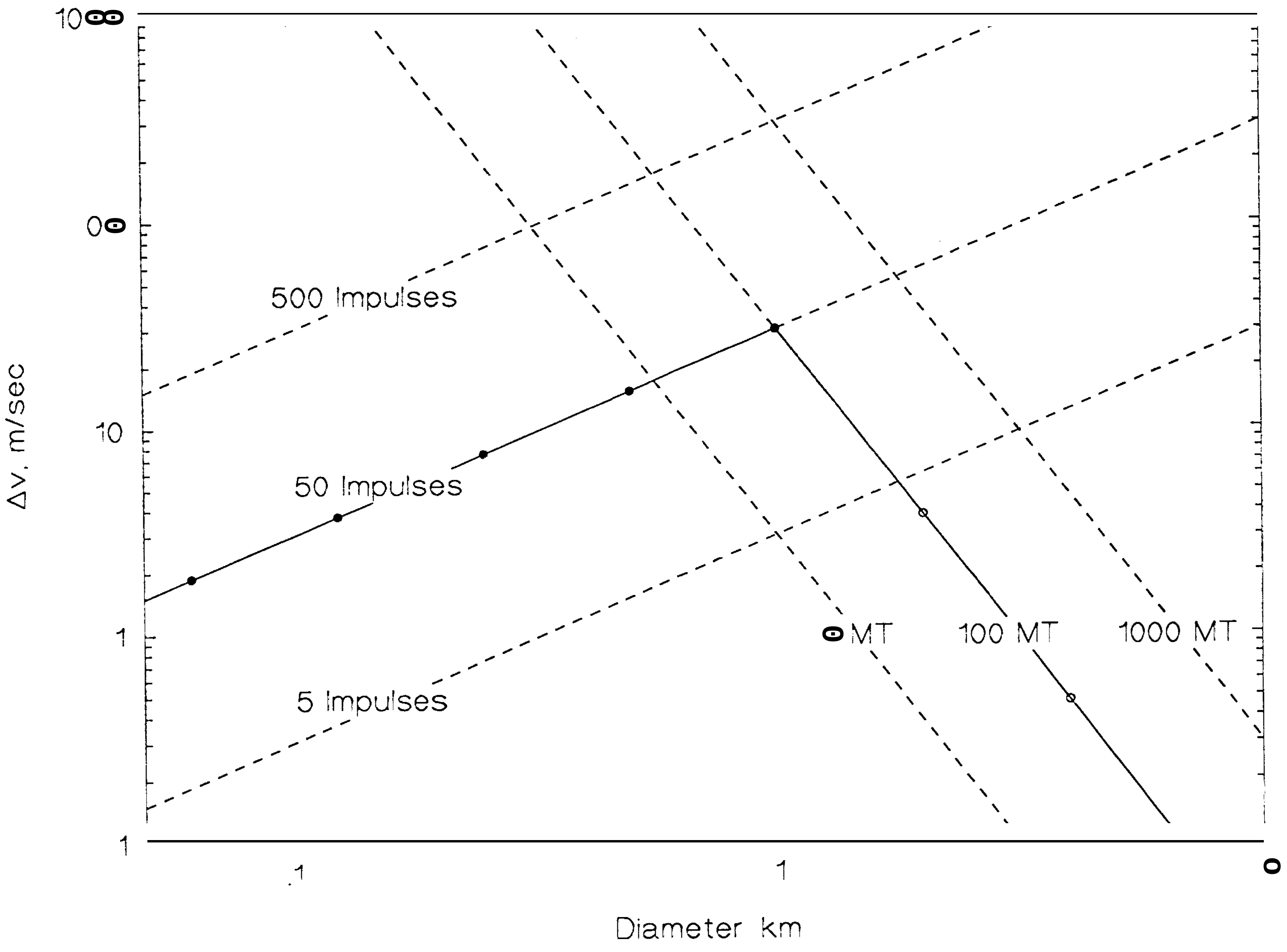
2. Limits on deflection velocity Av imposed by the number of impulses n required (such that each individual impulse is less than the surface escape velocity of the object), and the total explosive energy E required to achieve the deflection. In the discussion, we assume nominal limits of $n = 50$ impulses and $E = 100$ MT (solid lines). Values for each of the size objects considered in Figs. 3 and 4 are indicated by dots.

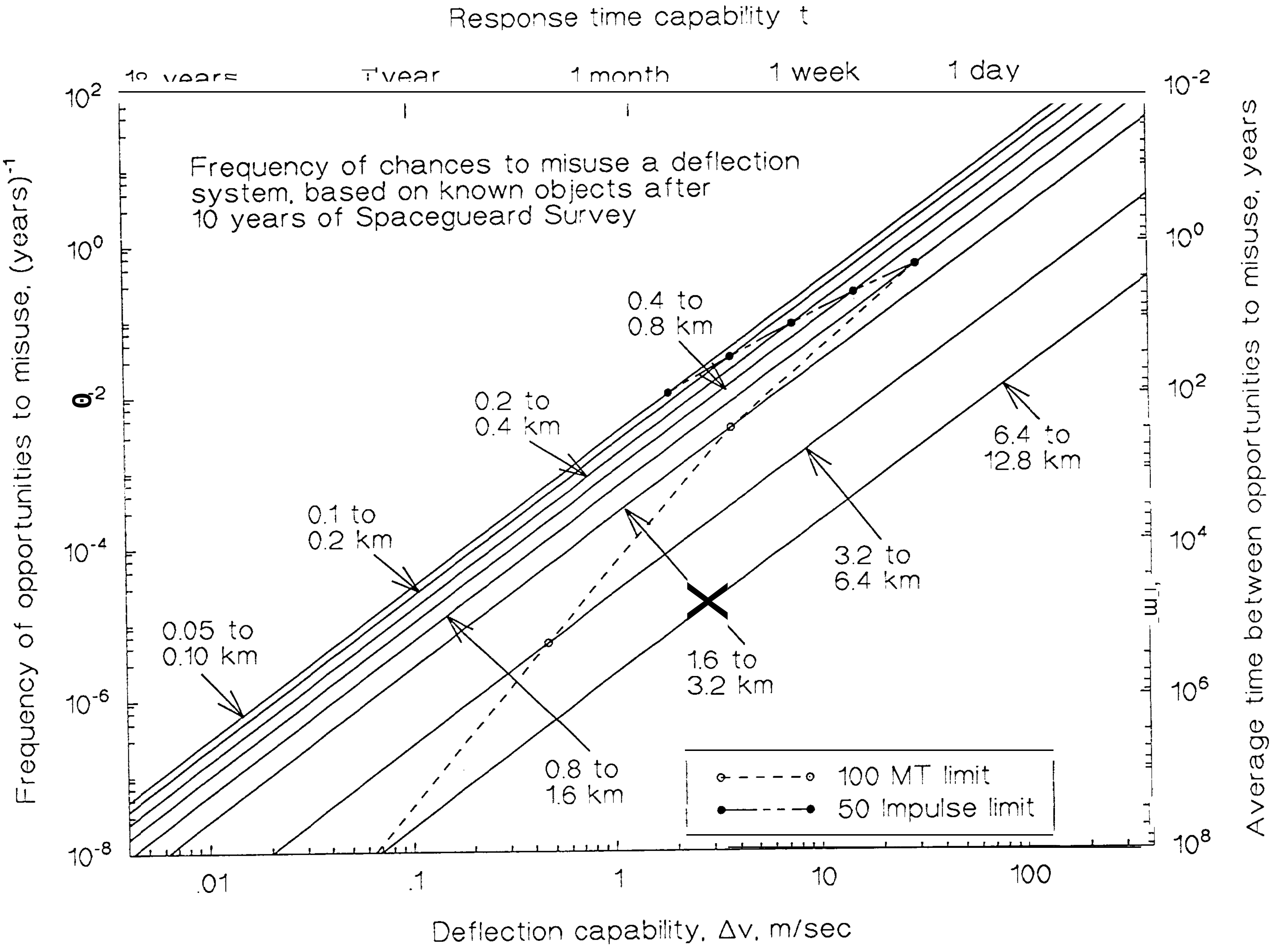
3. The frequency of opportunities to misuse a deflection system for various NEA diameters vs. the deflection capability Av or, equivalently, the deflection response time, t_r. We indicate, from Fig. 2, the maximum deflection velocity for each size object that can be achieved by 50 impulses (filled circles), or by 100 MT total explosive impulse (open circles). This plot is based on the fraction of the NEA population which could be discovered in 10 years by the *Spaceguard* survey.

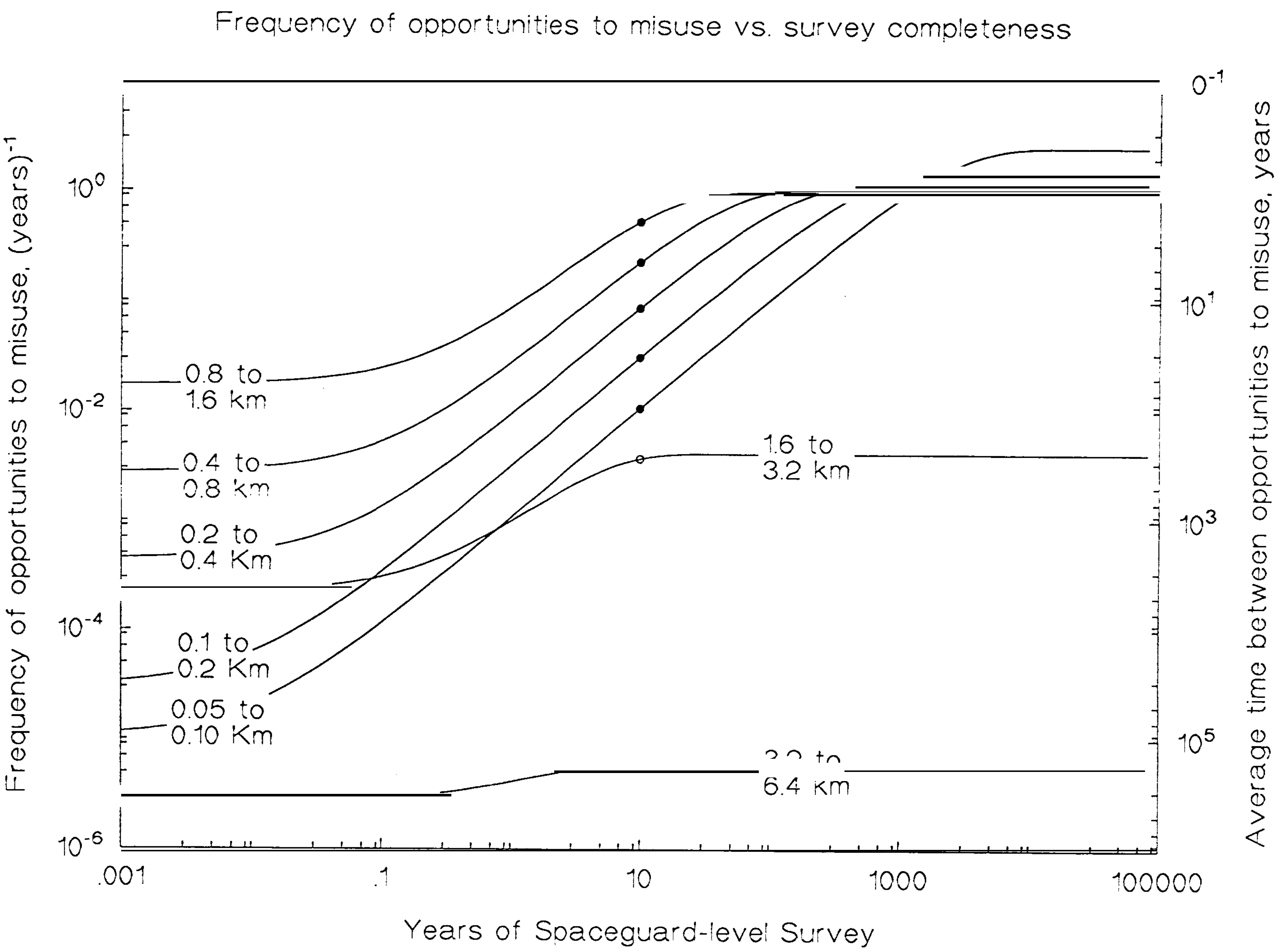
4. The frequency of opportunities" to misuse a deflection system for various NEA diameters vs. the completeness of discovery of the NEA population, parameterized in terms of the *Spaceguard* survey estimated performance. For each size bin, we have taken the maximum Av as given in Figs. 2 and 3. The left margin corresponds to present-day knowledge of the population, and the right margin to complete knowledge.


Response time capability, t_r
10 years
1 year
1 month
1 week
1 day
G
10^6
10^4
$-lo^2$
10^0
10^{-2}
.01
1
1
10
100
Deflection capability, Δv, m/see

Δv limits imposed by number of impulses and total energy




Response time capability t
10 years
1 year
1 month
1 week
1 day
Frequency of chances to misuse a deflection system, based on known objects after 10 years of Spacegueard Survey
Frequency of opportunities to misuse, (years)⁻¹
10²
10⁰
0⁻²
10⁻⁴
10⁻⁶
10⁻⁸
Average time between opportunities to misuse, years
10⁻²
10⁰
10²
10⁴
10⁶
10⁸
0.05 to 0.10 km
0.1 to 0.2 km
0.2 to 0.4 km
0.4 to 0.8 km
0.8 to 1.6 km
1.6 to 3.2 km
3.2 to 6.4 km
6.4 to 12.8 km
100 MT limit
50 Impulse limit
.01
.1
1
10
100
Deflection capability, Δv, m/sec


Frequency of opportunities to misuse vs. survey completeness