Steps Toward Impact Mitigation: New Approaches for NEO Detection and Characterization

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The end of the cold war has coincided with widespread perception of the reality of the NEO impact threat. There now exists a unique opportunity to greatly advance the capabilities for detecting, characterizing, and interdicting NEOs through the use of previously unavailable technologies and strategies. Some examples of candidate "high-tech" approaches will be described. The desirability of an international effort based upon coordination of ground and space-based assets is evident.

Introduction

Having chaired the NASA/DoE Near Earth Object Interception Workshop at Los Alamos National Laboratory in January, 1992, I'm particularly delighted to see how mutual understandings have progressed in the three years from Los Alamos to Livermore. Scientists from many different countries and disciplines who formally seldom interacted are now working side-by-side on the problem of Planetary Defense. Happily, these new collaborations encompass both civilian and defense communities and also unite our efforts across international borders.

The emergence of some of the remarkable "SDI" technologies into the unclassified world also represents very significant progress. The mostly-successful Clementine mission was vital in showing an easier path to future capabilities. Other capabilities that formally were classified secrets are now becoming available to address the Near Earth Object (NEO) threat. All of this progress is due to the hard work and deft diplomacy of numerous people, many of whom are at this meeting.

In this paper I want to share some perceptions about a potpourri of loosely related topics that are collectively very important and must be attacked in depth in order to achieve a true planetary defense. I will propose some new approaches, both observational and experimental, that can expedite progress. I am motivated by a belief that advanced concepts are readily achievable that go beyond incremental, "business as usual" approaches to detection and mitigation. I believe that innovative concepts and technologies can yield highly effective capabilities that are less expensive, more quickly realizable, and much broader in application than what has been considered to date.

While constraints such as budget limitations and perceived immaturity of present technologies seem to fore-ordain very gradual evolution toward effective mitigation capabilities, the true complexity of the NEO mitigation challenge gets swept under the rug in the process of being prudent. For example, if we are serious about defending the Earth, we have to take seriously the fact that there will always be a need for "short fuse" reaction capabilities -- things that can be done quickly to respond to short-warning threats. This will be particularly true during the next several decades, during which the number of unknown NEOs will greatly exceed the number of known ones, and the technologies for long range detection and mitigation will be immature. In order to develop capabilities to effectively mitigate the threat of NEOs, we must first increase greatly our knowledge of their physical properties and, second, graduate as soon as possible to numerous, systematic non-nuclear experiments to destroy or perturb a variety of objects. With this in mind, I want to try to point the way toward approaches that can accelerate our reaction times and simplify missions while also expanding our knowledge base by orders of magnitude.

At present, most attention is focused upon very large "doomsday" objects, which are rarely encountered in both space and time. Thus, present ideas revolve around searches for large objects covering many years, punctuated by occasional missions to explore and/or perturb well-known large objects. Paradoxically, I believe that the required quick-reaction capabilities will develop from a better approach to detection and experimentation focused upon the very large population of very small, periodic asteroids that are constantly passing near the Earth. They can provide a readily accessible experimental arena that will permit the development of effective mitigation strategies in scaled-down, frequent tests of interception hardware and methods.

I will describe a new strategy based upon a spacecraft called ARGUS which directss ground-based radar and optical astronomy resources with very high efficiency. ARGUS will also discover all of the large objects targeted by other search strategies, but quicker andwiith more comprehenive results. Interestingly, GUS may also make it possible to easily capture small velociinto Earth orbitsCin the huge stable regions L4 and L5 on the lunar orbit, where detailed experiments and analyses will become feasible.

Difficulties of Interception of Random Large NEOs

In an actual mitigation mission, it would be desirable to rendezvous with the target object far from the Earth so that small perturbations imparted to the object can integrate to large miss-distance at the Earth. To do this, however, requires very precise information about very faint objects whose characteristics must be well known years in advance. (Such information permitted the spectacular fly-by photographs of the main-belt asteroids Gaspara and Ida by NASA's Galileo spacecraft now in route to Jupiter.) The problem of how to intercept randomly occurring objects such as long period comets is very different from the question of how to deal with periodic NEOs whose orbits can be well determined so that we can plan research and interception missions at leisure. I don't feel that adequate attention has been given to the vast difference in technological capabilities needed to address these two types of threats. Comets may comprise more than 25% of the overall threat, particularly when their higher velocities are included in the threat analysis.

For missions to encounter randomly-occurring Earth-threatening objects, the word "rendezvous" is vastly optimistic; it should be "fly-by" or "impact", because generally the energy required to actually match the spacecraft velocity with that of the object would be very large. A low delta-V spacecraft, meaning essentially that it possesses relatively low fuel mass compared with the mass of the payload, will necessarily be confined closely to the plane of the Earth's orbit (see Figure 1). The spacecraft must be launched so that it arrives at the right place and the right time to encounter the NEO as it crosses the ecliptic plane. That will usually result in a high-speed encounter with a very short visit duration. If the mission is merely to gather data on the object, the data must be obtained very quickly. To destroy the NEO or deflect it from its initial orbit, the encounter would have to be executed with great precision.

If a high delta-V spacecraft were available, it might be possible to launch into the orbital plane of the NEO, changing from the plane of the Earth's orbit (Figure 2). Better options would then become possible. If enough time is available, the spacecraft can eventually achieve a true rendezvous. The best place to perturb an NEO to cause it to miss the Earth is at perihelion, where maximum change in its velocity vector will occur per unit of energy delivered to the NEO.

Of course, if unlimited time is available, gravitational deflections from encounters with one or more planets can change the orbit effectively even with modest delta-V (Figure 3). But, it is clear that such leisurely approaches will not apply in the general NEO defense case.

True planetary defense must deal with a very large parameter space. Comets must be included, which may comprise one tenth to one fourth of the overall threat, or even more if the consequences of their higher kinetic energy are included. Comets could be encountered having diameters greater than 10 kilometers, velocities up to about 70 kilometers per second, and warning times that may range from zero up to 1,000 years. -- The great majority of asteroidal Earth-threatening objects are also hard to deal with in a timely way because they are small and faint, and therefore quite hard to find, even though their velocities are considerably lower than some of the comets. The chart shown in Figure 4, adopted from the Spaceguard study, emphasizes the latter fact. This chart shows the expected results from 25 years of observations with that proposed ground-based system: If, indeed, the survey could reach to the twenty-second stellar magnitude, after a few years the catalog would be about 90 percent complete for one-kilometer diameter asteroidal objects having regular, relatively short period orbits. For half-kilometer objects it would be perhaps 70 percent complete. Smaller objects fall precipitously off the bottom of the chart, being undetectable except in small percentages because of their faintness; and there are much vaster numbers of smaller objects.

Therefore, the detailed physical and ies oftthettotal population m ass, m cdtion, rand orbital distribution of Earth-threatening objects will remain inaccessible and incomplete if based on data exclusively from ground-based surveys of larger, less numerous objects unless the data is accumulated over hundreds of years. Obviously, no data on material reactions will be accumulated without actual in-space experiments; and ,to be meaningful, such experiments must be performed on as large a sample of the population as possible.

Reconsidering the Importance of Small NEOs

I think that this large deficit of information is unacceptable. While we all agree that large objects are the ones to worry about in terms of global extinction events, the key to understanding the large objects may well lie in the vast hidden data of the smaller objects. The steep power law characterizing the size distribution indicates that there are millions of NEOs at the 10 meter diameter level. Very few of these would survive the Earth's atmosphere to produce damage at the surface; but, in space, they can provide a wealth of vital data. A thorough census of the small objects, gathered in the course of seeking the large "Earth Destroyers", can reveal the answers to many questions such as: (1) What are the relative percentages of heavy metal objects, icy comet fragments, hydrated relicts of the solar nebula, carbonaceous chondrites, and dry achondrites in the total population passing near the Earth? (2) What is the total distribution of orbital state vectors? Are there bunching effects in phase space that will change the frequency of impacts over time? Does the pulsating potential well created by the Moon orbiting the Earth drive such bunching? (3) Is there a gaussian "tail" of low velocity NEOs that we can easily reach as they pass through the Earth-Moon system? Are they sometimes quasi-trapped in the Moon's L4 and L5 Lagrange regions?

The consequences for world-wide catastrophe decrease as impacting object sizes fall below the kilometer/half-kilometer diameter range. In spite of lower expected mortality from smaller (but much more frequent events), this does not mean that the potential for locally terrible consequences from smaller objects should be ignored. The people who are paying for our efforts are concerned about massive carnage on any scale, particularly in the near term; and we must be able to give honest assurance that we are working to avoid catastrophes of all magnitudes.

Among the most important pieces of work inspired by our 1992 Los Alamos workshop was the work of Hills and Goda[1] (Figure 5), who calculated the effects of energy dissipation by impacts of objects in the 10 to 500 meter diameter range. They have achieved quantitative understanding of how stony and metallic impactors break up and what the radius of destruction in kilometers is as a function of the size of the object. A stony object 200 or 300 meters in diameter would essentially annihilate an area the size of Connecticut. I do not believe that we could find objects this small with any reliability using the proposed Spaceguard system. Even if we did find them fortuitously in a terminal-orbital phase, I do not believe that we could react quickly enough to evacuate Connecticut in the short warning time that a strictly Earth-based system would provide. Over the centuries, we are involved in a "crap shoot" situation, where it's the roll of the cosmic dice that determines what gets hit. Surely it must be our responsibility to find ways of preventing even these very rare but potentially enormous tragedies from smaller, but much more frequent, impactors.

The Tunguska impact in 1908 did give us quite a real lesson in the effects of a small comet in the 50-100 meter diameter range. The Spaceguard report showed the lethal area of about four pounds per square inch over-pressure: Figure 6 shows the way the trees were laid down from that event compared with the areas of New York City and Washington.

Further work has been reported on tsunamis caused by impacts. These can also be very profound events. On the eastern seaboard of the United States, for example, there is evidence that there was a tsunami within the last 100,000 years that devastated everything from the coast of North Carolina and Virginia all the way to the edge of the Piedmont plateau. If this occurred now, millions of people would die. Air-burst events like Tunguska don't leave any significant geologic signatures and indeed may be washed away within a short time even on the scale of human history. But tsunamis leave much longer lasting signatures that may provide better understanding of "smaller" events.

So, we have to continue to refine the definition of the threat. We have to find out truly what the full significance of these small objects is and where you draw the line between no concern whatsoever and active concern. Basically, I believe that we can easily build a new type of detection system that will be able to garner an essentially complete census of all periodic NEOs down to ten meter diameters. This system will, of course also find all of the large, periodic "extinction-class" objects over several years of operation. The fact that the small objects are so much more numerous suggests that they are, by far, the easiest to use in active experiments to enable us to develop the ability to intercept and mitigate.

Need for Interactive Mitigation Experiments

The past decade has seen the advent of the first images of both comet nuclei and asteroids, which typically turn out to be quite elongated in form. First, the pictures of the nucleus of comet Halley revealed a peanut-shaped object 21 kilometers long and about 8 kilometers in diameter. Then the pictures of the main-belt asteroids Gaspra and Ida taken by the Galileo spacecraft revealed highly elongated, irregular objects. -- Concurrently, radar imaging of smaller, closer NEOs have shown Castalia (see Figure 7), Toutatis, and Geographos also to be very elongated or double.

Consider a hypothetical experiment to perturb Toutatis, shown in Figure 8. Where would you hit it? An impulse near one end would probably cause it to spin like a dumbbell, possibly separating it centrifugally. Hitting it near the middle might break it into two or more objects. Then you'd have to have more payloads available to deal with the fragments. We are in a state of profound ignorance as to having reasonable abilities to predict what the actual reaction would be. There is a strong case for non-nuclear ein pactme pex ents o n small NEOs in the not-distant future. At the very least, we will get data on evhether ith reaobj as socts ie or bur tsa part as dust To oathis, however ewill require careful advanced set-up of the interceptors and real-time detection of large numbers of small NEOs in order to find one that we can reach in a timely way.

If we achieve expanding capabilities in space in the next two decades, it is quite possible that some significant experiments can be done. In addition to answering the three classes of questions previously mentioned crning NEO icals properties rbitaldynamio we will be abl to fi d some ideal targets for controlled experiments. Existing data suggsts that, at any given time, there aapproxiate ly 100 NEOs larger than 10 meters in diameter passing through a spherical volume centered on the Earth with n usiö of e million kilometers. This motivates me to p ppose a new set of detection technologies that will, a rrelaveiv ldwlccwt, be able to find and characterize 100% of such objects in real time, leading to capabilities for numerous quick-reaction perturbation experiments in the first decade of the new millennium. The proposed system exploits the best of both worlds: space-based detection and ground-based data augmentation.

A New "High-Tech" Detection Strategy

ARGUS Spacecraft

By borrowing from formerly defense-oriented technologies, we can build a versatile, low cost new spacecraft that can be stationed at the L1 point between the Earth and the sun -- about 1 ,5 million kilometers toward the sun (Figure 9). It has been named "ARGUS", for Asteroid Research Global Unbiased Surveyor (Figure 10). It can be built on many of the same technologies that were integrated into Clementine: "smart" visible and infrared focal plane sensors and state-of-the-art onboard computing technologies. The ARGUS spacecraft at solar L1 with a 3 degree field of view and 32 degree field of regard in circular scan mode will detect all 10 meter or larger diameter NEOs passing through the vicinity of the Earth with nearly 100% success probability. At an average speed of 20 kilometers per second, typical NEOs would be tracked for more than half a day -- sufficient to hand them off to any observers on Earth equipped with radar and optical telescopes. They can then do a thorough and complete job of analyzing the detailed properties of essentially all of our visitors..

What characteristics are required for the spacecraft to find these faint objects? Detailed photonic analysis by a team at Marshall Space Flight Center headed by Max Nein has confirmed the capabilities of the proposed suite of technologies. The largest departure from Clementine technology is the need for a low-weight primary reflector 1.5 meters in diameter. This does not need to be a very precise or expensive reflector. Since the resolution will be limited by the pixel size, the primary reflector can be made with composite materials and integrated with the light-weight spacecraft technologies now available. The probable "push-broom mode" CCD sensor observes the distant stars to 21st magnitude. The spacecraft is self-stabilizing because the on-board computer recognizes the star field. It has smart computer technology using a four gigabyte, all solid state processor that reports only moving objects that come into the field of view, leading to very modest data transmission requirements. I believe all of this can be done economically and quickly based upon technology that now exists.

Free Electron Maser Radar for 3 mm Wavelength

Radar, as we have seen, can image NEOs. It can also measure their state vectors to high accuracy, thus pinning down the orbits precisely. Moreover, radar can probably distinguish among metallic, icy, and dry, stony objects. In addition to all of these advantages, it can readily hand off the detected objects to optical and infrared astronomers for detailed studies.

One thing that radar cannot do well is whole-sky searches because there is too much sky for too few radars. This is why the ARGUS spacecraft is needed to hand off each detection to the ground-based radar for refinement. Also, radar is an inverse fourth-power device, which requires very high peak power pulses and/or very narrow beam width to achieve long ranges and high signal-to-noise. Narrow beam width is obtained by having the largest possible antenna in terms of the wavelength of operation. Super high power at short (millimeter) wavelengths has hitherto been restricted by available technology. Both of these requirements (i.e. high peak power and large, fully steerable antenna) can now be met by excellent new technologies that are completely within the state-of-the-art.

Millimeter wavelength astronomy has driven antenna technology to 30 meter diameters with surface accuracy of 100 micrometers (rms) or better. The cost of these antennas is surprisingly low. So it is easy to build an antenna for 3 mm wavelength for about $6 million that has higher gain than the Arecibo system and is fully steerable.

How, then, can we achieve very high peak power pulses? The answer is to use free electron coherent emission technology, which has been undergoing many generations of development in the past 20 years. Basically, you need a compact, modest-cost high-current electron accelerator and a row of alternating magnets known as a "wiggler". (Figure 11) The electromagnetic wave length that emerges from the wiggler is inversely proportional to the square of the relativistic energy of the electrons: 6 Mev electrons will produce copious radiation at 3 mm.

At NASA, in a joint program with the Ballistic Missile Defense Organization, considerable effort has been put into developing reliable ways of building a new type of compact, high current accelerator. (Figure 12) Each of the illustrated modules produces one million electron volts at 500 amperes using all solid-state silicon technology, and they have demonstrated billions of pulses without missing a tick. This is totally new territory in terms of accelerator technology that is both reliable and inexpensive. One module costs $450,000 to build. The entire free electron maser for the asteroid radar would cost under $10 million. (Six accelerator modules are required, plus the cathode and wiggler and a building to house it.). Coupled with the magnetic wiggler technology developed at the Lawrence Livermore National Laboratory, this system will produce peak power pulses on the order of 10 gigawatts with duration of 50 nanoseconds at a rate of 500 pulses per second. One such radar in the northern hemisphere and one in the southern will be sufficient to image and fully determine the orbits of all objects discovered by the ARGUS spacecraft.

Help from Russia

There is yet another tantalizing near-term opportunity for NEO search and diagnostics that presently needs political talent more than technical talent to realize it. Figure 13 is unfortunately a very poor picture which proves that truth is stranger than fiction. Those of you who read Tom Clancy's book, The Cardinal of the Kremlin, back in 1986, remember that the scene of the action was a place in Tadjikistan which was supposed to be a ground-based laser site. After a lot of ruckus about this, Pravda published this picture of this site on top of Mt. Sanglak, which is about 50 kilometers south of Dushanbe. It's an excellent site, 7,000 feet above sea level, with superb weather the year around. There are ten domes, six of them in one cluster and four more in a second group -- probably an arrangement for detailed imaging and ranging of space objects of all sorts. The site was still under construction in 1986 when Figure 12 was taken.

This is clearly a state-of-the-art optical facility in the world, and it is eminently capable of advancing the NEO search. Each dome contains a telescope between 2 and 3 meters aperture, and they could easily be equipped with the latest imaging technology. You could, for example, put a "staring-mode" sensor on each of the telescopes and look in ten different directions at once. It also could have stereo and phased-array capabilities so that objects could be imaged at high resolution. Combined with a pulsed laser capability, active imaging from this site would also be possible.

The unfortunate fact is that there is now a very unstable political situation in Tadjikistan. Perhaps international attention to the significance of this site for NEO research might help to stabilize that unhappy situation. I am told that Russia would very much like to see that happen. Given enough motivation from clearly beneficial activities such as the protection of the world from impacts, perhaps this could become a unifying principle to do something constructive for all people. Maybe NEO researchers could get a foothold there and establish this as an enclave that would be protected and woul de the search to go forward at a much accelerated pace. So, this something that I would propose as a topic for a lot more international discussion. Mount Sanglak and other former Soviet facilities provide very real potential opportunities, and they can certainly play a vital role in achieving our fondest hopes for NEO progress.

No Malicious Use of NEOs

There is one final matter that I want to address. At the 1993 Tucson meeting, the question was raised by Carl Sagan as to whether anyone who developed the means of deflecting an object might not do it with malice aforethought so that they might dump an NEO in the backyard of their enemies. In view of what I've said about the unpredictable occurrences of these objects, the unknown center of mass, the unknown questions about whether they're going to come apart into many pieces if you try to do something, such hostile acts seem extraordinarily unlikely as well as unwise.

Suppose we knew that an object was going to collide at the point indicated in Figure 14. The best estimate of the impact point would be surrounded by a circular error probability. If you undertook to deflect the object, you would try to make it miss the Earth by at least three Earth radii because you can certainly expect an additional large gaussian error probability for any action that you undertake. No matter what you do, unquestionably you will want to do it so that you've allowed for several standard deviations from all potential sources of error. The residuals are always going to be very large.

If you had in mind dumping this NEO in your enemy's backyard, it would just as likely land in your own backyard or in some other even less desirable place. In addition to that, I think it's fairly obvious that it's much easier to send a "nuke" directly to your enemy's backyard than it is to try to go all the way out to an asteroid in order to accomplish the same nasty thing. So, concentration should be on eliminating war rockets and eliminating "nukes" for hostile purposes rather than curtailing development of abilities to deal with NEOs that will surely eventually pose a real threat to innocent people on Earth.

At the same time, we must, of course, reflect on the problem of just how far it is prudent to go with elimination of nuclear devices. In building nuclear weapons, the superpowers have developed over the past 50 years the most sophisticated technology in the history of the world. Sustaining it requires an enormous infrastructure. Let's hope for the best and suppose we will have a peaceful world, a world of nuclear disarmament. Still do we want to keep some of these capabilities against the inevitable impact threat? Do we want to preserve the know-how, the ability to build these things in order to protect against the ultimate cosmic disaster? This is a policy issue of international importance that we all need to think about. It is not a simple issue.

Conclusions

The key initial requirement is for a complete survey of Near-Earth Objects, and I emphasize "complete." The level of that survey should be extended down to 10-50 meter diameter objects so that we have a full sample of population density versus size, orbital dynamics, and physical properties of all short period (i.e. <10 years) objects. We must increase the detection range and time so that we can send diagnostic probes to a variety of different objects. Further, we must continue with precursor activities to expand the knowledge base of comets and other long period objects in any way we can. Test deflections and disruptions using non-nuclear means must be attempted as soon as possible on the small and frequently detectable objects that safely visit the earth in droves and pose no threat. A new detection spacecraft named ARGUS has been proposed that, together with a new type of ground-based radar and ground-based optical facilities, can achieve the required detection capabilities to complete the survey and hand off to interceptor probes with very cost-effective hardware and operations. I think that these things must be done expeditiously if we're really serious about trying to defend the Earth.

Figure 1

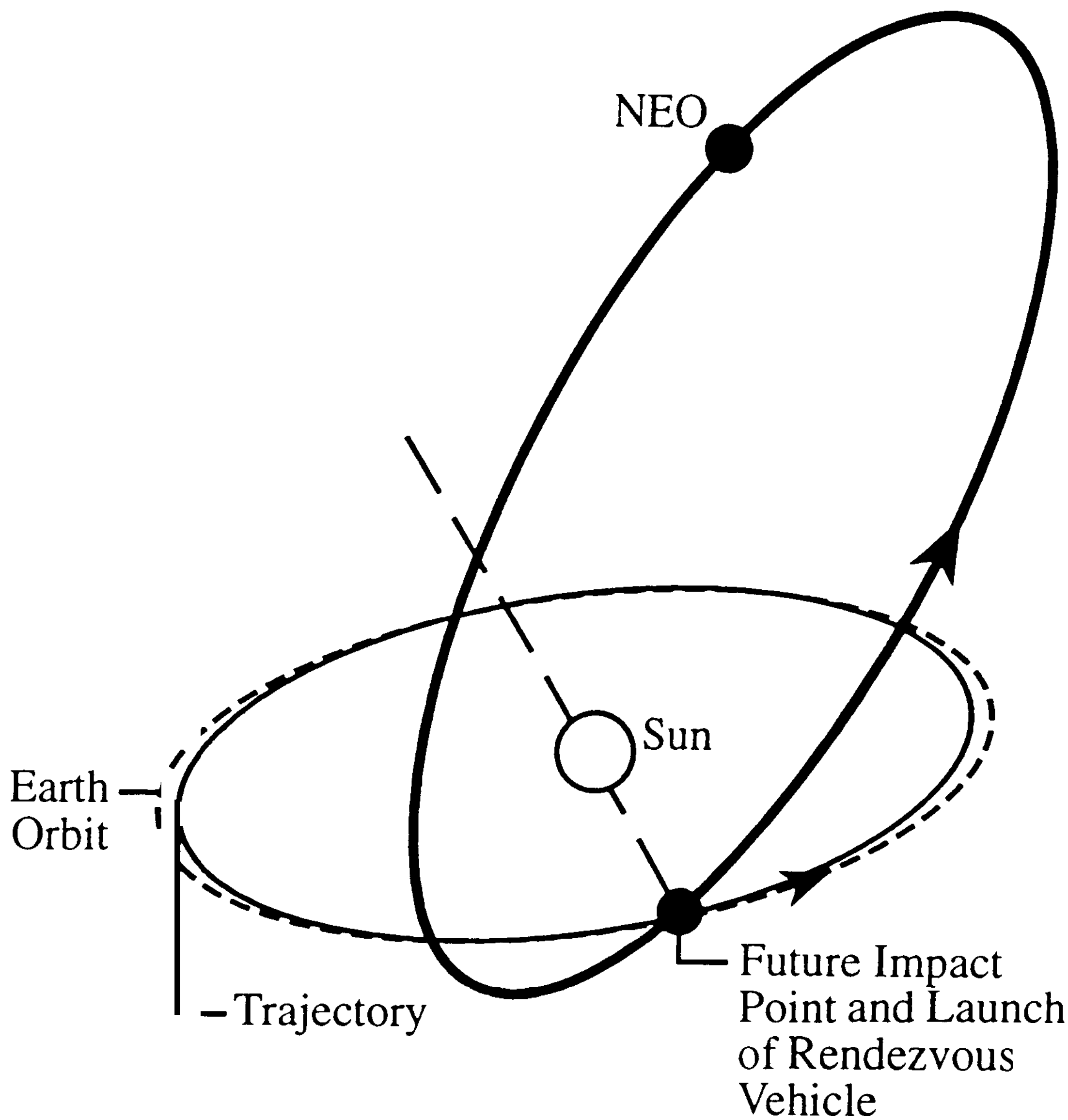


Figure 1: Low-ΔV, high-closing velocity interception. Interceptor orbital period is slightly greater or less than one year in order to achieve phasing needed for interception. Several NEO orbital periods must be available before Earth impact.

Figure 2

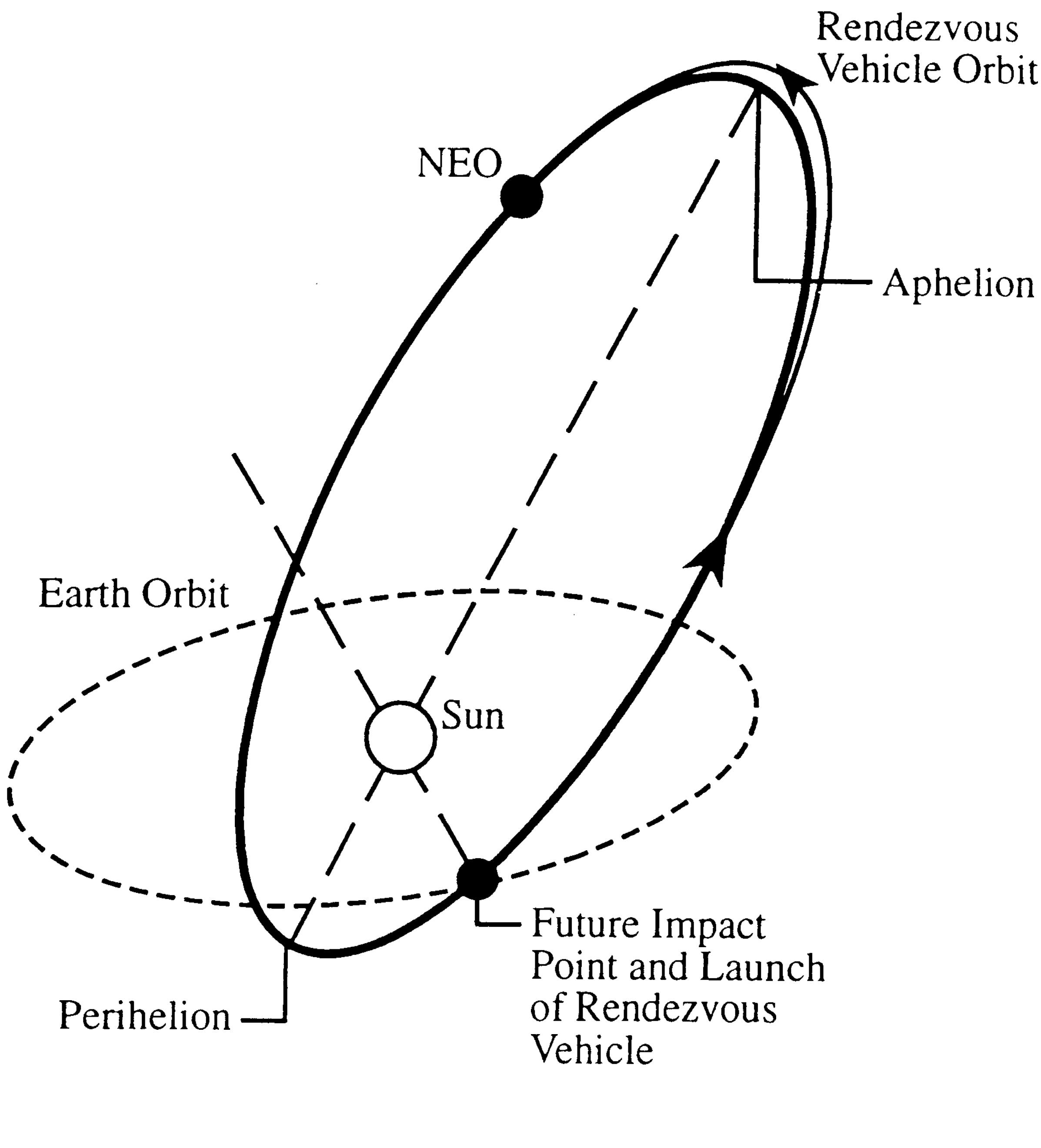


Figure 2: High-ΔV NEO rendezvous mission.

Figure 3

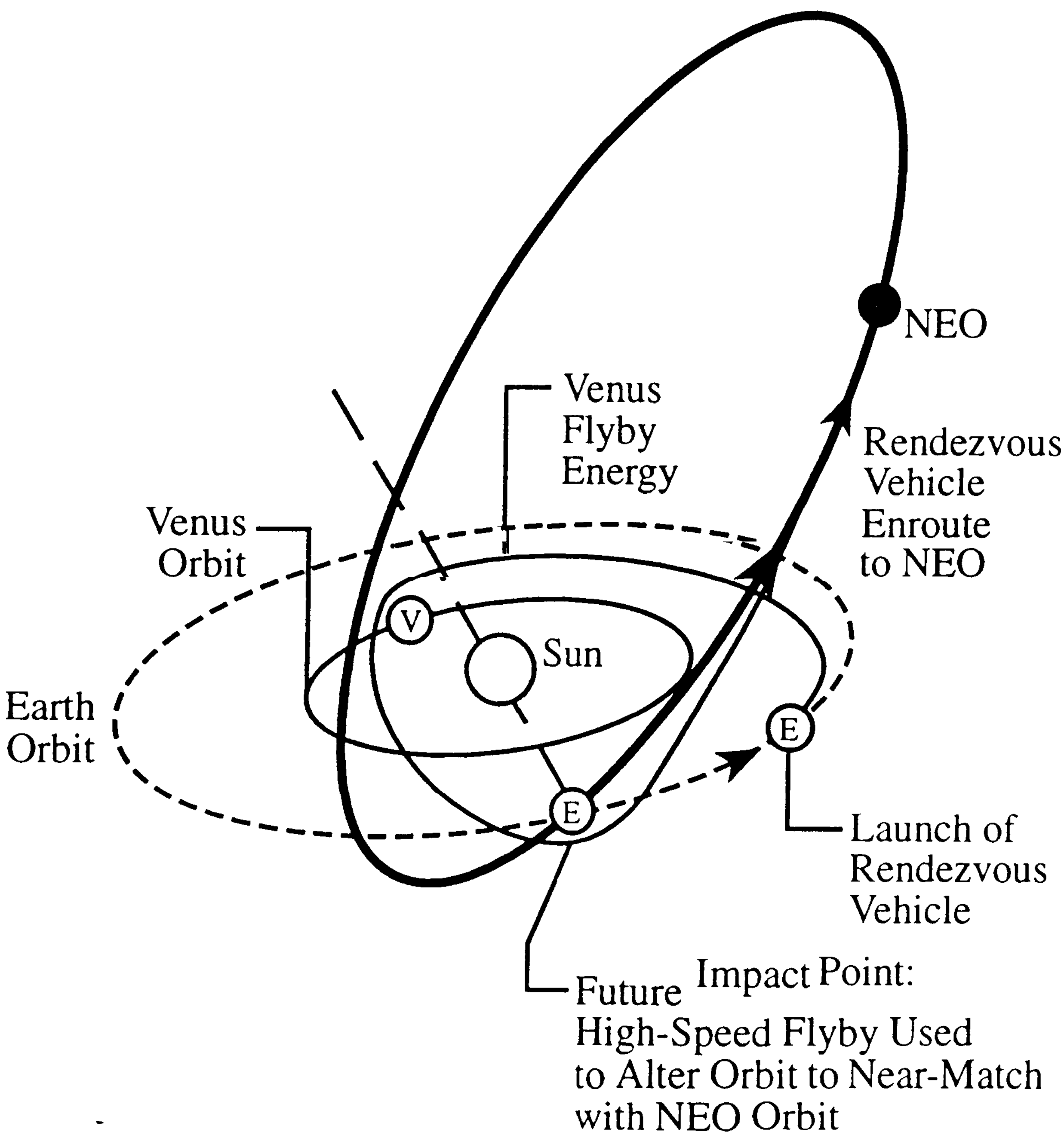


Figure 3: Moderate-ΔV rendezvous mission, using planatary flyby (in this case, Venus first and then Earth).

Figure 4

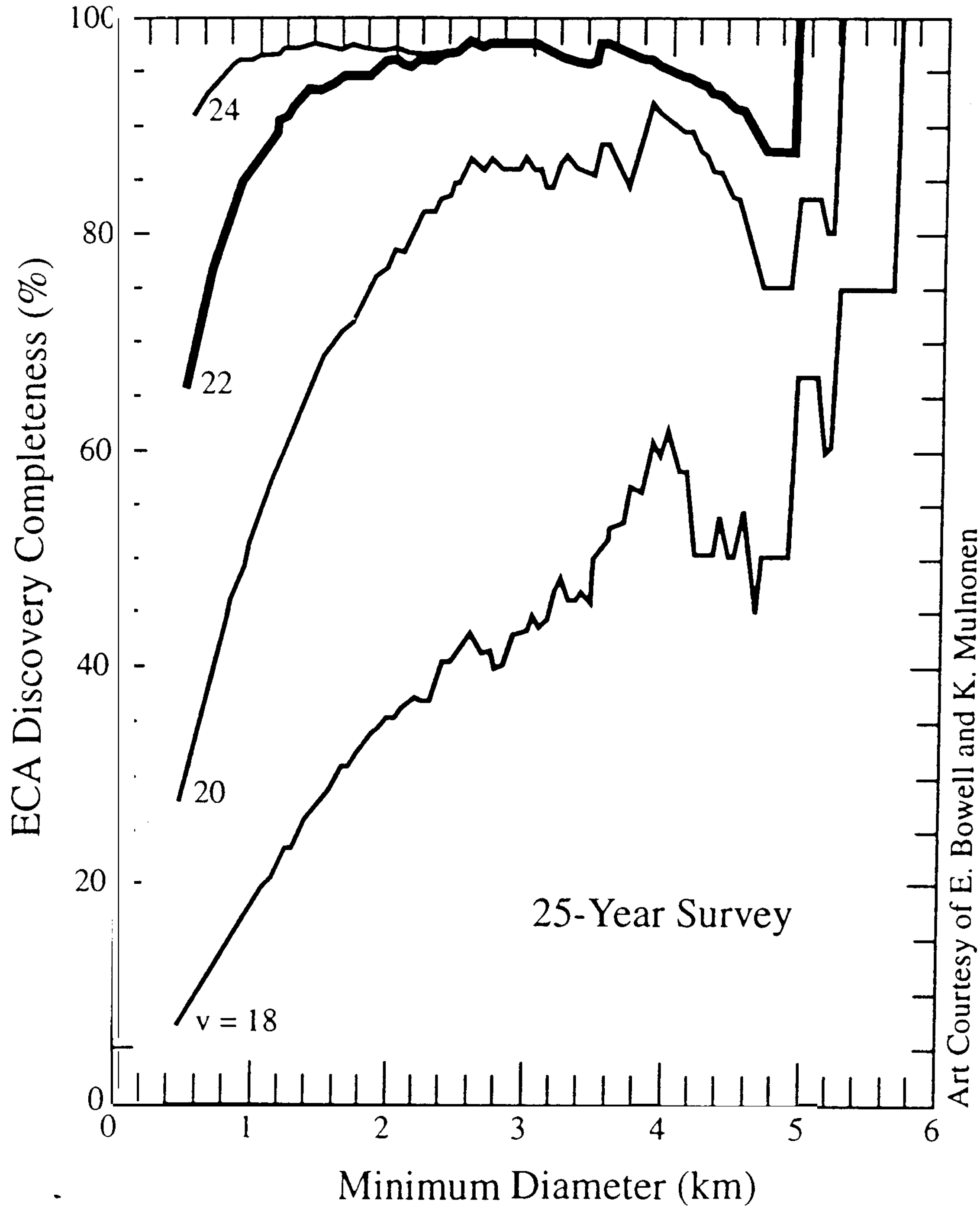


Figure 4: ECA discovery completeness as functions of threshold diameters and limiting magnitude V for the standard survey region (see text). In the bias-corrected model population examined, several large ECAs went undetected throughtout the survey, even at faint V.

Figure 5

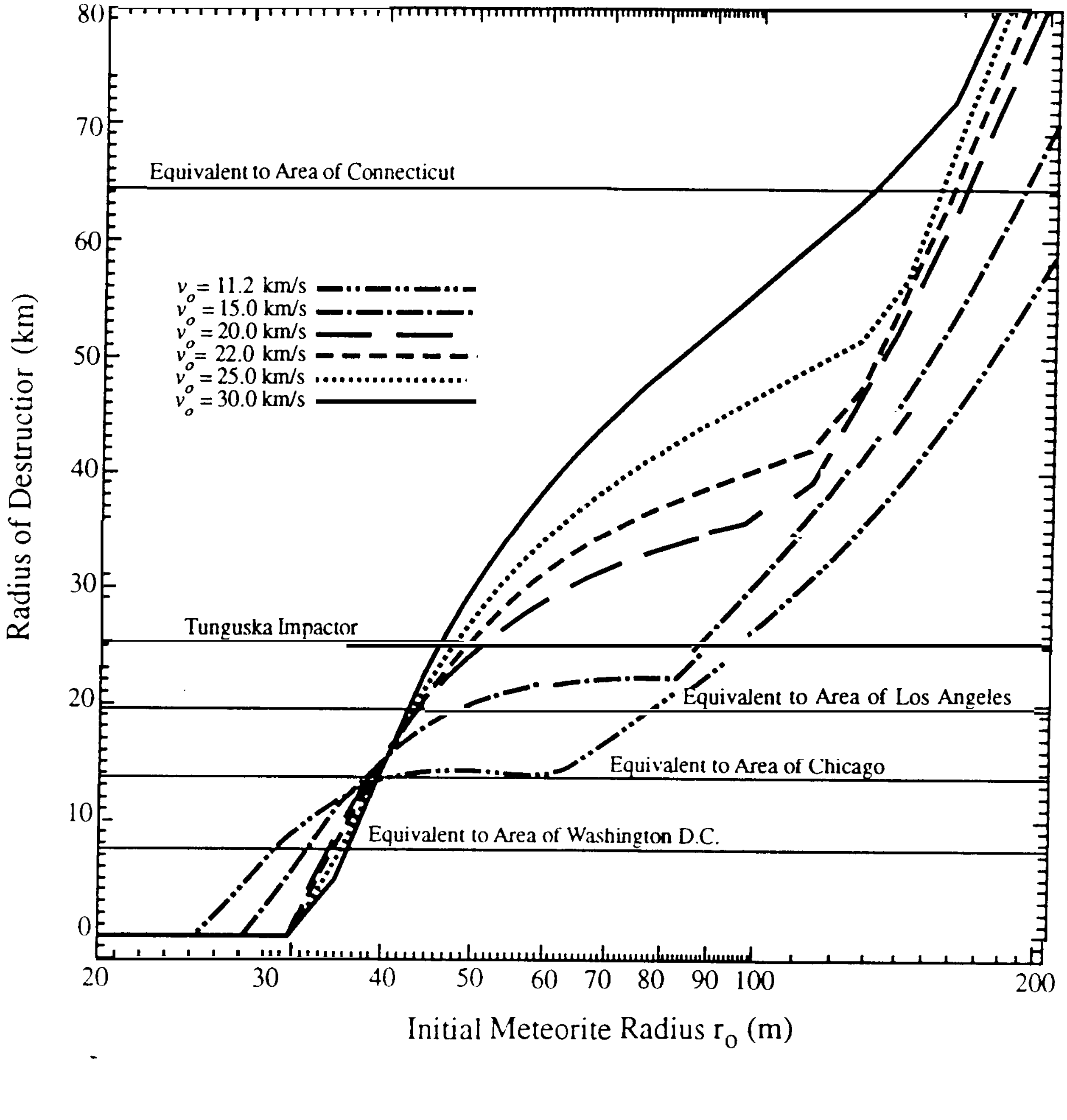
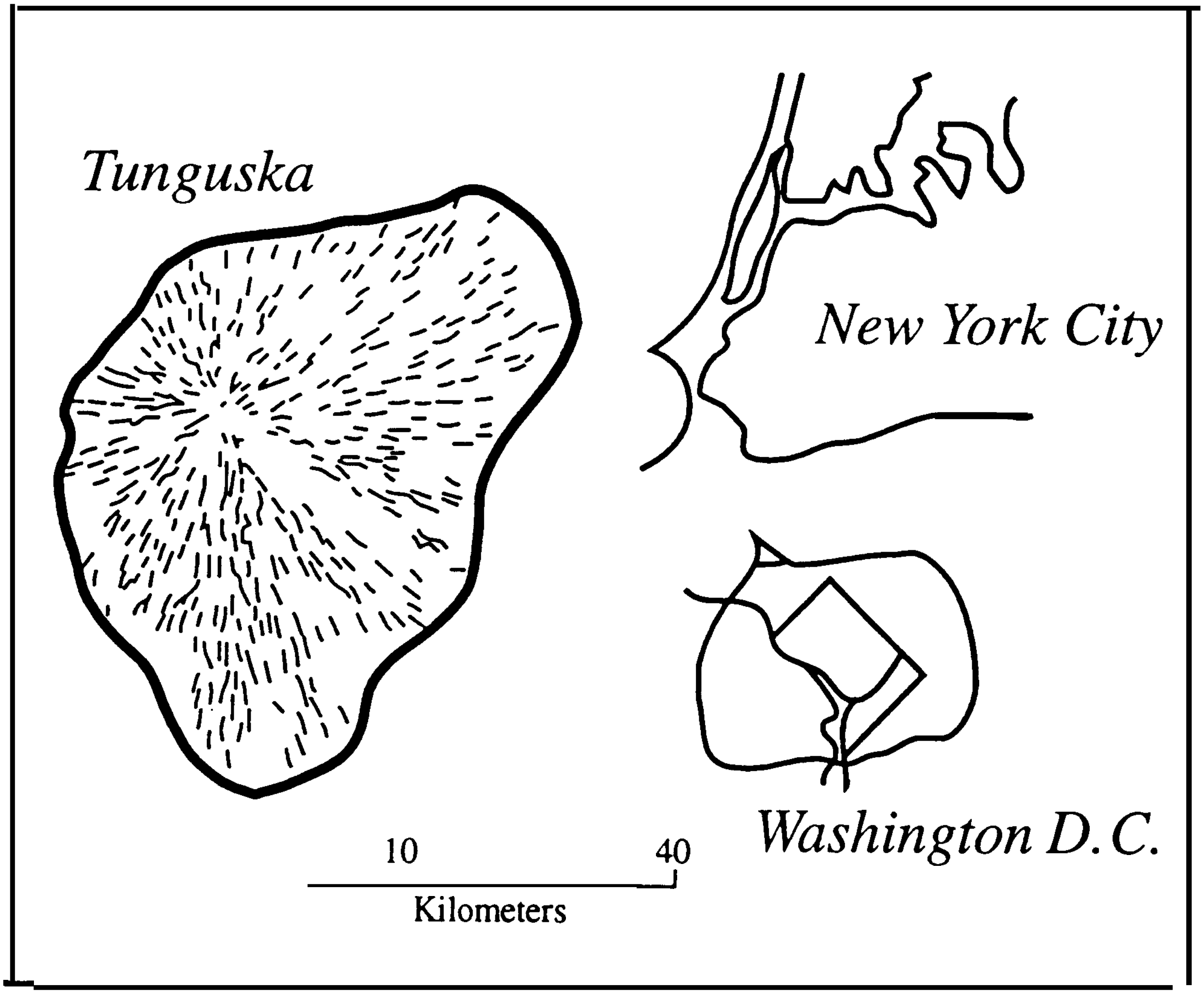


Figure 5: Stony meteriote radius of destruction as function of size and impact velocity.

Figure 6



Art Courtesy of John Pike

Figure 6: Tunguska in Perspective

Figure 7

Asteroid 1989 PB

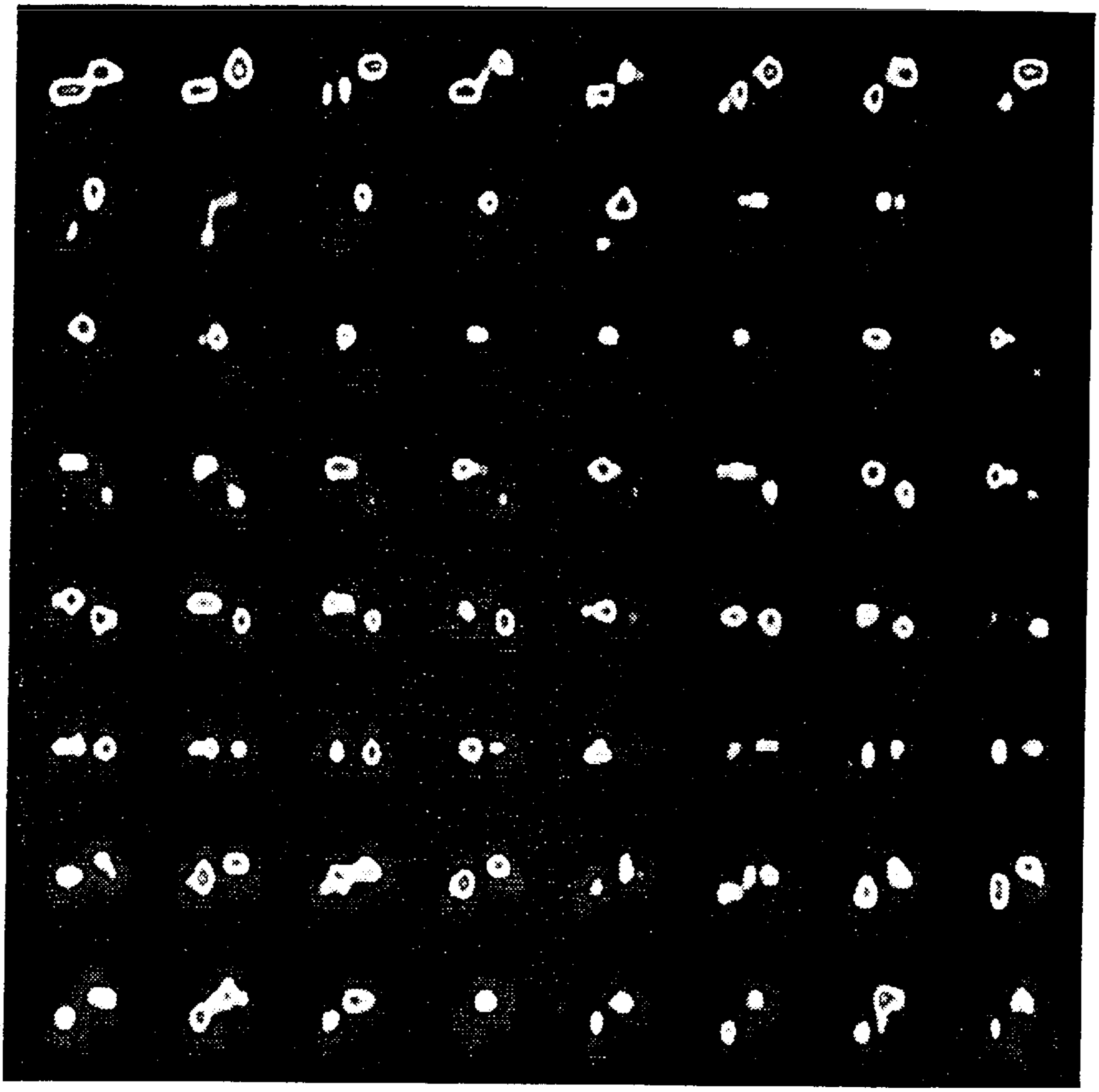
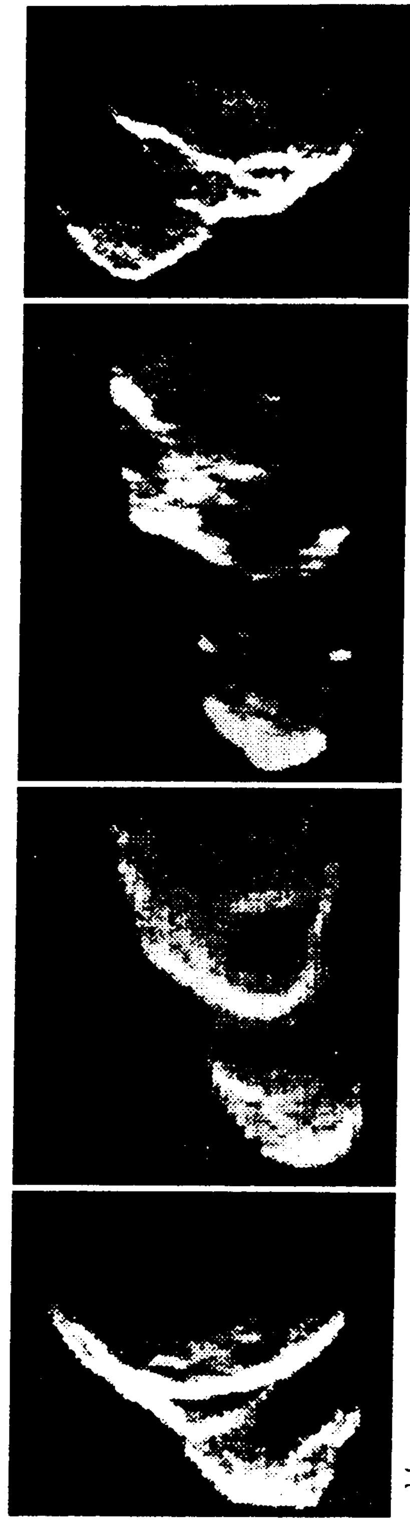


Figure 7: Radar images reveal 1989 PB to consist of two distinct, half-mile-diameter lobes that appear to be in contact. It seems likely that the lobes once were seperate and that they collided gently to produce the current "contact-binary" shape.

Reference: S. J. Osrto, J .F. Chandler, A. A. Hine, I. I. Shapiro, K. D. Rosema, D. K. Yeomans.
Radar Images of Asteroid 19S9 PB. *Science* 248, 1523-1528 (June 22, 1990).

Figure 8



January 4, 1993
Toutatis RadarImages

Figure 8: These are radar images of asteroid 4179 Toutatis made during the object's recent close approach to Earth. The images reveal two irregularly shaped, cratered objects about 4 and 2.5 kilometers (2.5 and 1.6 miles) in average diameter which are probably in contact with each other.

TRANSFER TRAJECTORY TO HALO ORBIT AT EARTH/SUN L_1

ISEE-3 / Ice Comet Mission Launched August 12, 1978

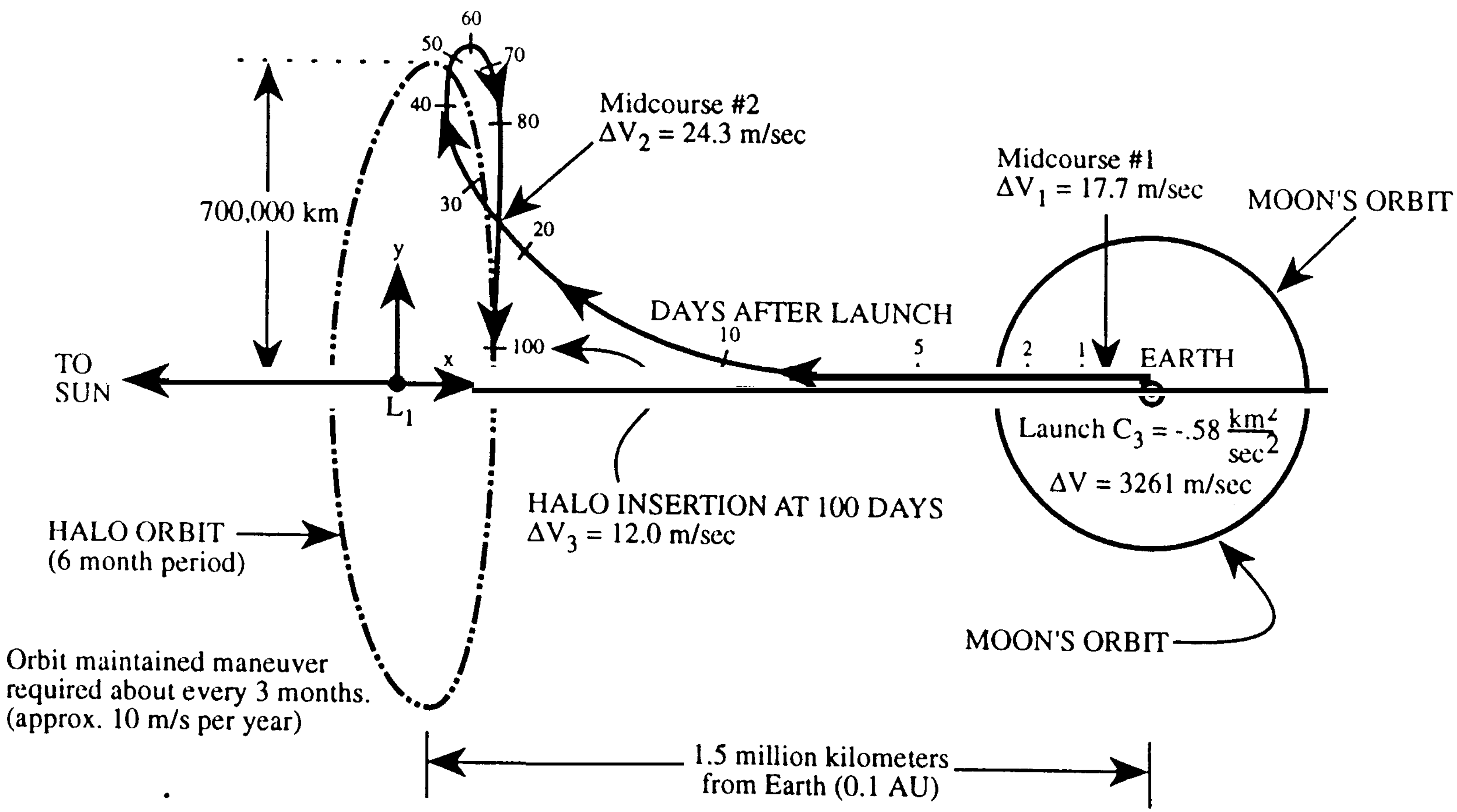


Figure 9 Reference: J. McCarter - NASA Marshall Space Flight Center.

Figure 9

ARGUS

Deployed Configuration

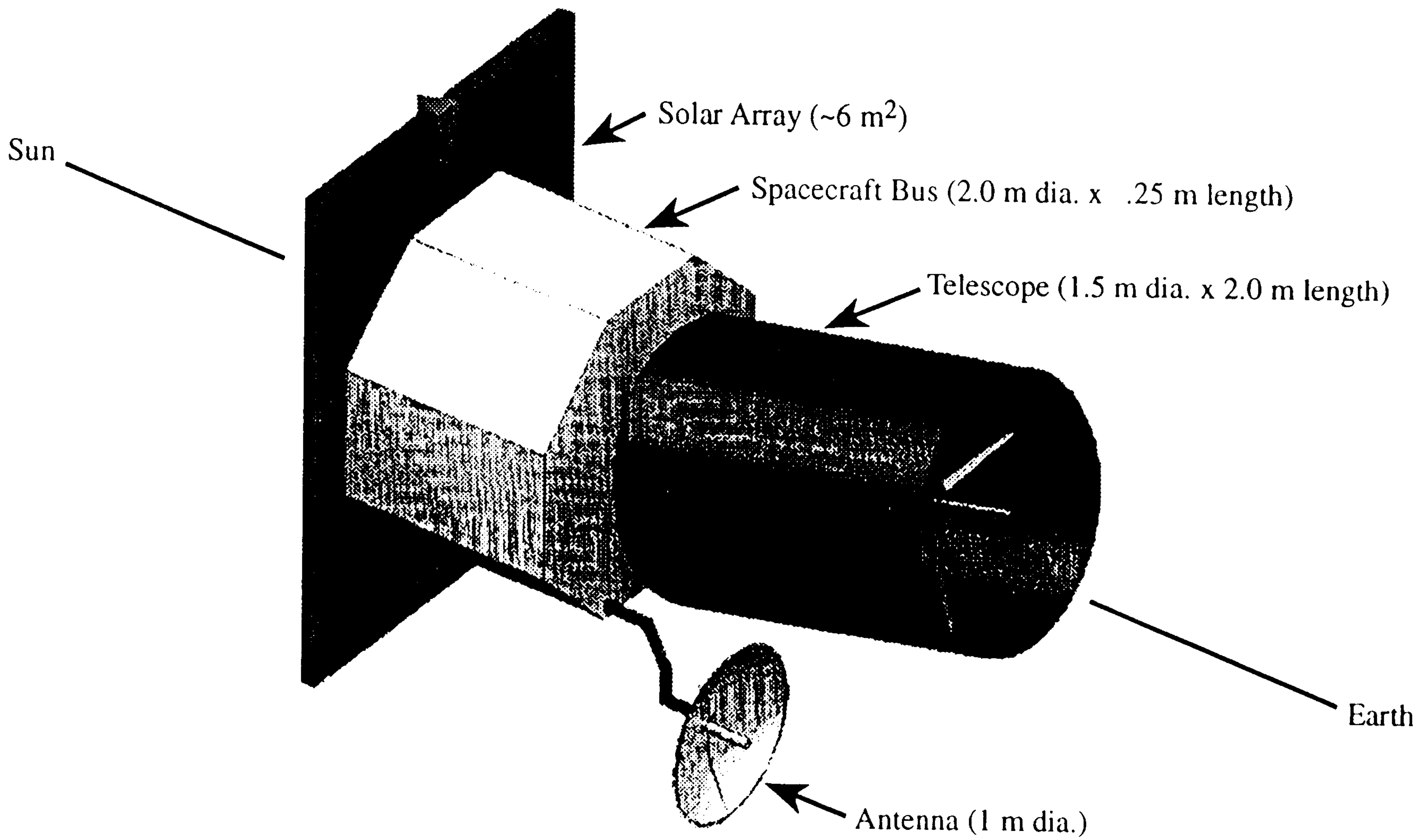


Figure 10: NASA/MSFC, PD23/Sharon S. Fincher, January 19, 1995.

Figure 10

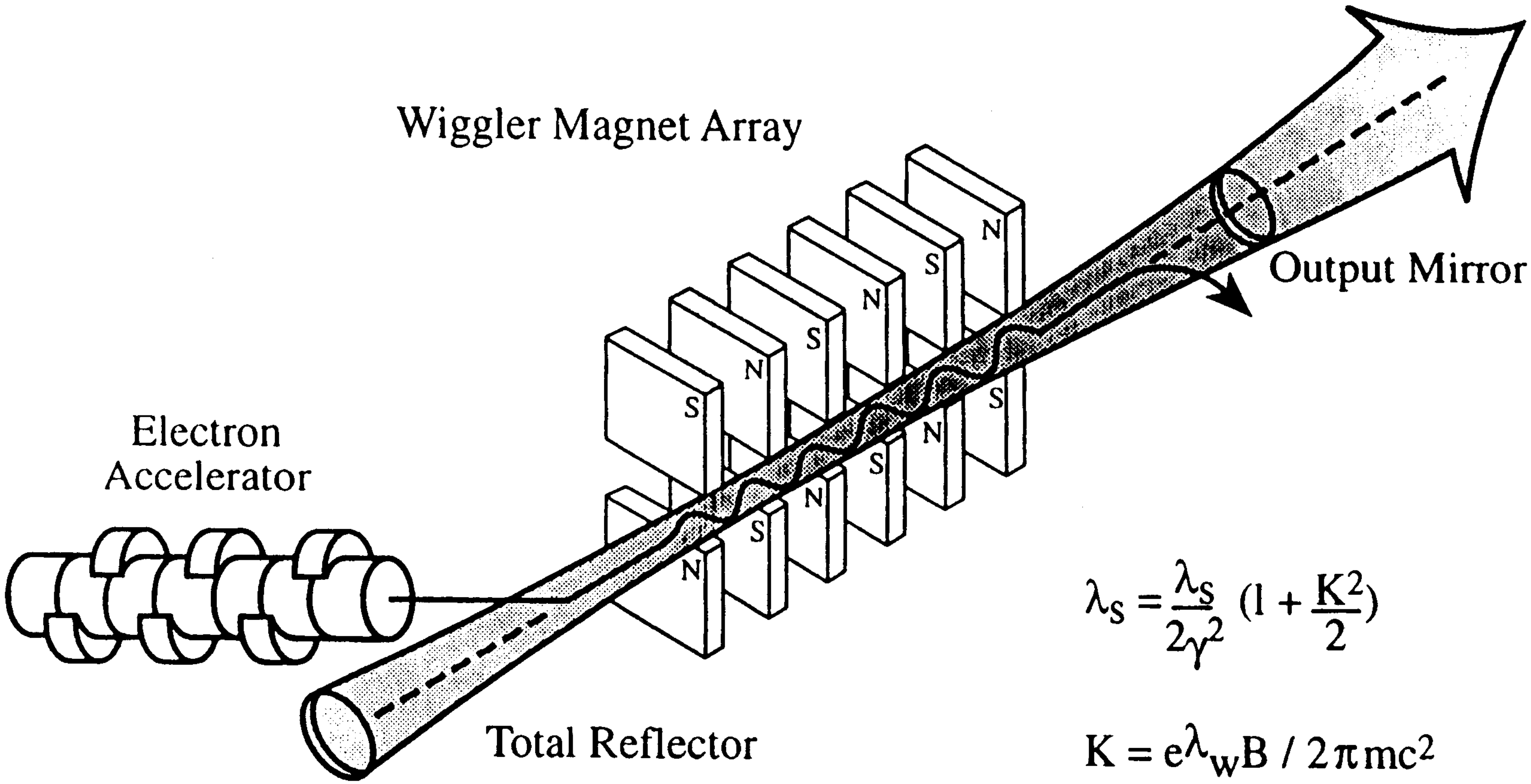


Figure 11

Figure 11: Basic elements of a Free Electron Laser. The accelerator must deliver 500 ampere pulses at 6 Mev to generate 3 mm wavelength for the NEO radar application.

Figure 12

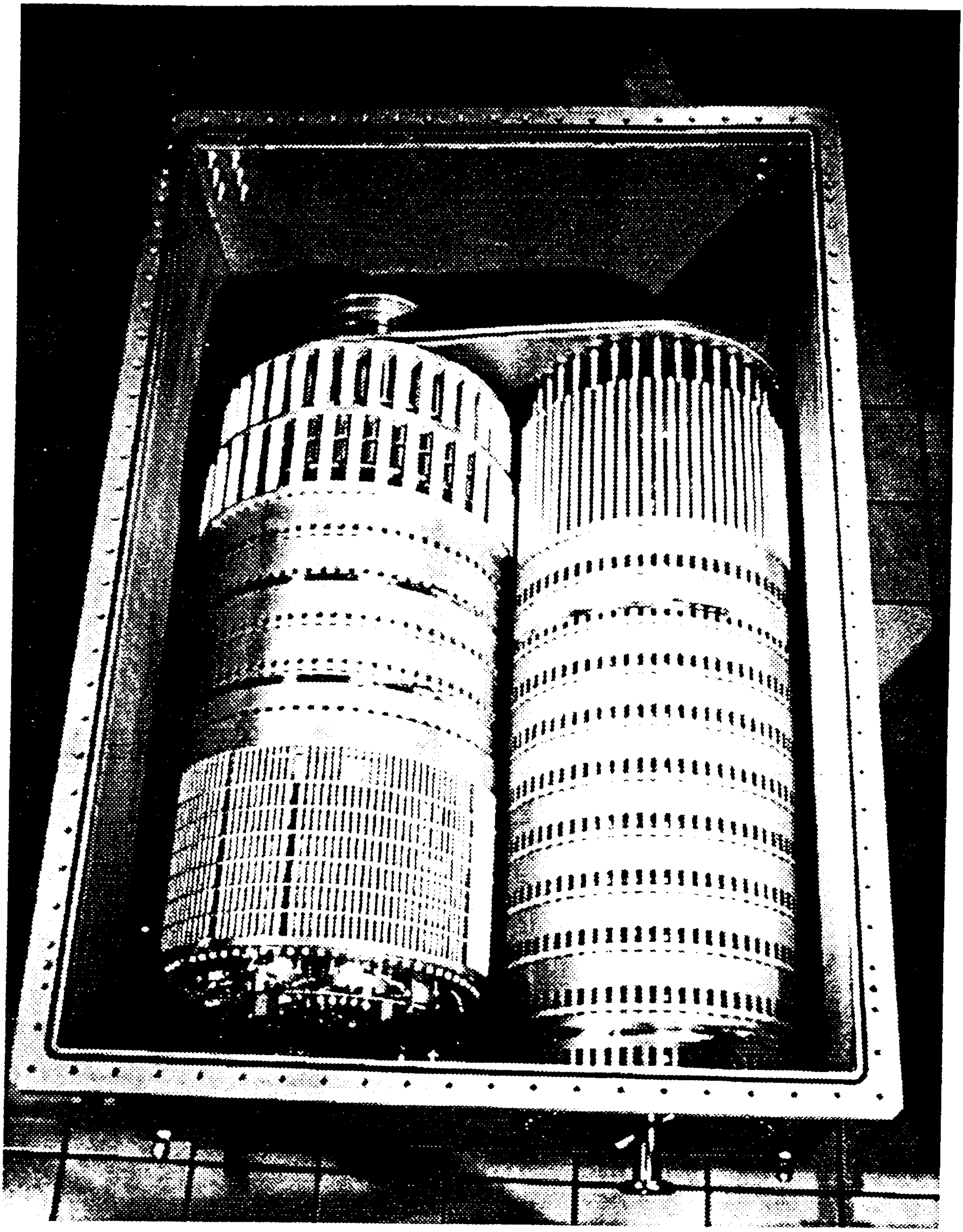
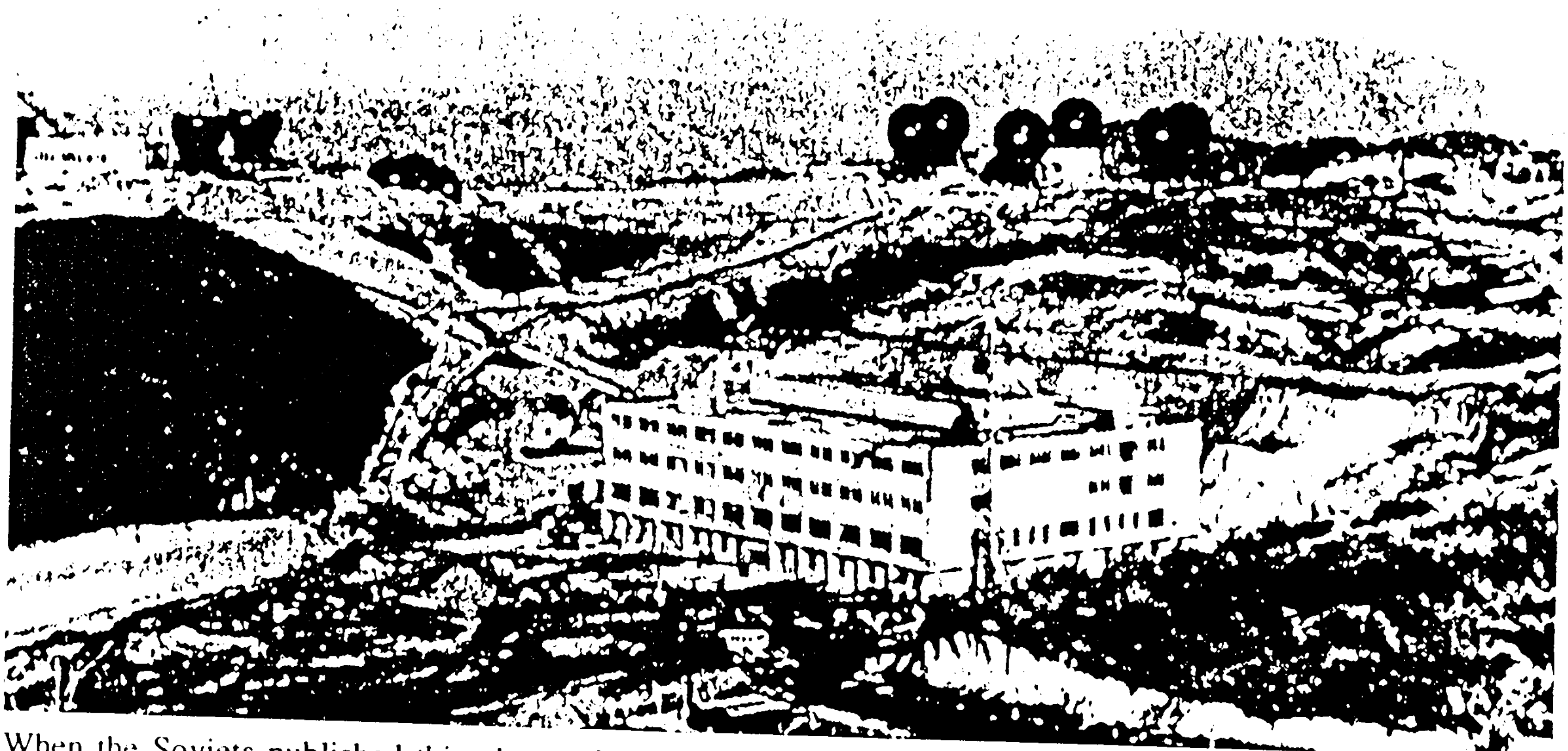


Figure 12: Compact, all solid-state electron accelerator module developed by Science Research Laboratory, Inc. in a joint NASA-SDIO project. Six such modules would power the 3 mm wavelength NEO radar.

Figure 13



When the Soviets published this photo of their space-tracking facility at Dushanbe, they maintained that its purpose is to track satellites. The amount of power supplied by a nearby hydroelectric dam, however, exceeds that needed solely for satellite tracking. It may in fact be used to generate high-energy laser beams for antisatellite missions.

Figure 13: Pravda photo of Russian space tracking station reproduced in U.S. Dept. of Defense annual review, "Soviet Military Power, 1988". Original caption is included.

- Must Achieve Several Standard Deviations
- Residuals Always Will Be Large

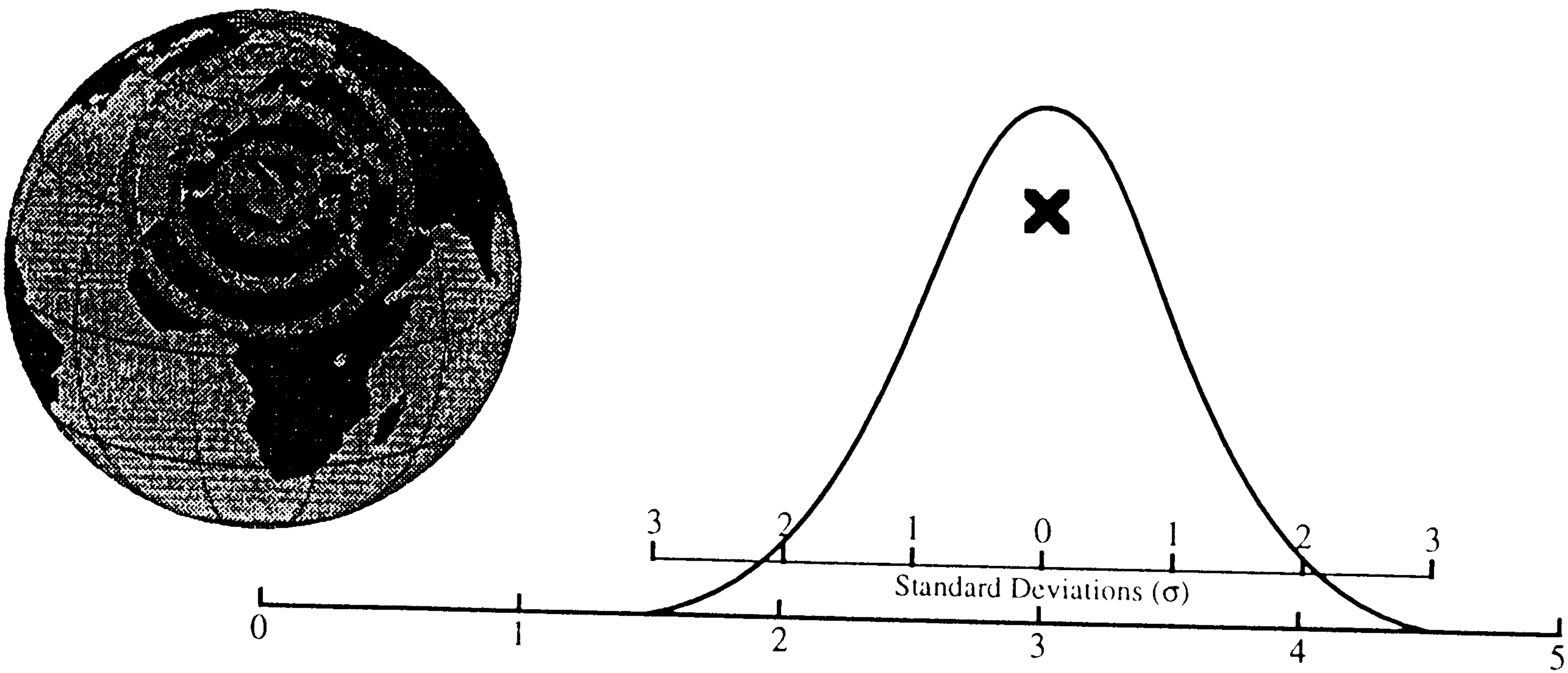


Figure 14

Figure 14: Unpredictable errors will be decisive in NEO deflections. There will be uncertainties in the predicted impact point plus large uncertainties in the reaction of the NEO to perturbation efforts. These errors will render malicious use of NEO impacts highly unlikely.