ABSTRACTS

Sizes and structures of comets and asteroids: What is worth mitigating, and how?

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Once every 20,000 years, a huge rock mass slams into an ocean basin with little or no warning, generating a tsunami with wave energy equivalent to ~3 gigatons of TNT. Hundred meter high waves propagate across the impacted ocean basin, obliterating coastal cities in their wake. Hundreds of millions of lives are lost, and the cost in purely economic damage is in the trillions of dollars. Yet we do almost nothing about it.

I am talking about volcanic island landslides. Waves spawned by once-per-20,000 year collapses of volcanic mountain flanks (Cumbre Vieja, Kilauea, etc.) are about the same wave energy as would be spawned by a 600 m diameter asteroid (S. Day, pers. comm. 2002). Interestingly, 20,000 years is also about the mean recurrence interval for 600 m NEO impacts. Smaller island collapses (e.g. Ritter Island, 1888) are certainly more frequent than Tunguska-type airbursts, and probably cause at least as much potential harm. And the largest volcanic events, such as the Siberian flood basalts which may have conspired to end the Permian, are about as rare and evidently as deadly as the largest impact events in the present solar system.

These numbers are all quite rough, and the parallels not entirely satisfactory (for instance, asteroids can hit suddenly and anywhere). But it helps objectively constrain our concern with NEOs. They do represent the one potentially catastrophic natural disaster that we think we can mitigate, yet mitigation has its own costs and risks, and if those costs overwhelm the costs of the underlying fundamental research, and if those risks outweigh the hazard they are aiming to subdue, there is little point. At some small diameter, we all agree, mitigation is not worth the trouble. What size is that? In my talk I hope to address this with some precision, or at least with some geophysical motivation.

Any proposed mitigation scenario will be enormously expensive to develop; $10G (~15% the cost of Space Station) is probably a fair estimate of the cost to deflect or disrupt a 300 m diameter NEO with appropriate lead time. In comparison, ~3% of this amount would support a Discovery-class telescope interior to Earth (orbiting at Venus L2, say) capable of telling us with near certainty in two decades that nothing out there larger than 300 m is going to hit us before the next century. Of course, we face a ~1/500 chance of learning bad news instead of good from such a survey - i.e. that we need to prepare for a 300 m impact before 2100 - but then we'll know. From a purely fiscal perspective, it makes 500/3% = 2.10^4 times more sense to pursue advanced reconnaissance of NEAs, than to pursue any engineered mitigation solution before its time. Reconnaissance is such an enormous bargain that any money spent elsewhere, if taken from the same pool of funds, is folly. This argues strongly for putting the NEO search in a protected budget, so that it does not compete with vastly more expensive, and in the end probably unnecessary, initiatives related to hazardous NEOs.

Yet we do speculate "what if 2002 NT7 was headed our way in 2019". Thermonuclear asteroid mitigation - perhaps our best hope in that one-in-a-million dire circumstance with such little lead time – can easily be developed alongside existing weapons testing and development programs. Indeed, research in this area can be continued, and even promoted, in a manner that affirms Article IV of the Outer Space Treaty (prohibiting weapons in space) and which affirms the present Comprehensive Test Ban Treaty. Thermonuclear weapons design is done in the modern era by computer modeling, coupled with field- and lab-testing of individual deployable components in a manner that does not yield an explosion. Of particular relevance is the United States Department of Energy Accelerated Strategic Computing Initiative which oversees modeling efforts using the world's fastest supercomputers to perform high-fidelity simulations running advanced 3D thermophysical and nuclear reaction codes. DoE-ASCI is a well-established and well-funded research program that is already perfectly suited to oversee model development and testing of any thermonuclear asteroid mitigation scenario, alongside the DoE's banner goal to "shift promptly from nuclear test-based methods to compute-based methods" (see http://www.lanl.gov/asci/asci.html).

One need not be branded a blind optimist to presume that advanced and benign, perhaps even profitable technologies for NEO mitigation shall be developed in the coming centuries, so that thermonuclear asteroid mitigation never happens. In the year 25,000 - the average time between now and the next 300 m asteroid strike - we will presumably have better tools. But in the interim we can learn the detailed effects of high energy explosions on asteroids by combining existing models for asteroid impact disruption with national security computations related to weapons performance.

But a model is only as good as its boundary conditions, and any mitigation modeling program would have to be complemented by extensive field reconnaissance of asteroids and comets. Which brings us back to the scientific requirements that are the subject of this conference: how do we adequately characterize an asteroid's geology.

Rational NEO mitigation priorities are therefore approximately as follows: (1) Link NEO impact predictions to existing warning centers, as this can be done at almost zero cost immediately (e.g. http://www.prh.noaa.gov/pr/ptwc/aboutptwc.htm). (2) Complete the NEO catalog down to about 300 m, for about $300M, within about 30 years. (3) Determine detailed geological characteristics, for a wide range of comets and asteroids, down to sizes of a few 100 m. The latter folds in superbly with the goals of solar system exploration, especially since we now know that NEOs are objects from the main belt and beyond, delivered to our doorstep for free.

These priorities alone are going to represent an uphill but worthy battle for tax dollars. Going another step - trying to deploy intervention mitigation at this time, beyond the conceptual stage - will be a dramatically unsound investment until these first three steps are complete, and may in fact hinder their timely completion by competing for funds. Moreover, and perhaps most seriously, it may elicit a suspicion regarding the honest goals of planetary science, if comparable plans are not also laid out for volcanologists to mitigate the impending collapse of Cumbre Vieja.

Lander and Penetrator Science at NEOs

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Some of the surface or sub-surface investigations needed to support Near-Earth Object risk assessment and mitigation demand contact with the surface. This talk will look at some of the conceivable experiments for which this is the case and will highlight existing technologies and concepts applicable to missions to the surfaces of comets and asteroids. Current capabilities will be described and recommendations made concerning technology development. Possibilities for surface missions include destructive impacts, passive projectiles, payload-delivery penetrators, soft landers, touch-and-go measurements, end-of-mission landings and various concepts for surface or sub-surface mobility. The low gravity environment means that a 'surface mission' may in some cases be achievable with a spacecraft hovering at very low altitude, rather than actually landing.

Advances in Groundbased Characterization of the NEO Population

Richard P. Binzel (MIT)

Over the past decade the growth in groundbased measurements of NEO physical properties has struggled to keep pace with the increase in their interest and their discovery rate. Physical parameters (such as their spectroscopic, shape, and rotation properties) were known for only a few dozen NEOs in 1990. By 1998 measurements were in hand for about 100 objects. Today the current sample is nearly 300 objects. These studies are revealing the population to be diverse and in some cases seemingly bizarre, as material strength and gravity compete to form and hold NEOs in stable shape and rotational configurations.

Beyond the opportunity to study the structural nature of the smallest observable solar system bodies, the scientific rationale for studying near-Earth objects also focuses on understanding the relationships between asteroids, comets, and meteorites. Through the analysis of a large sample groundbased spectroscopic and albedo measurements, we are beginning to achieve good constraints on the actual compositional and size distribution of the NEO population. These are giving insights to the main-belt and extinct comet source regions for NEOs. We are also making substantial progress in directly relating NEOs in space to their hand samples studied as meteorites in the laboratory. It is the combined knowledge of size, shape, internal structure, and composition that are most critical to addressing how to effectively mitigate the possible impact threat posed by any particular object.

As our basic understanding of the NEO population and its origins has advanced, so to has the level of scientific questions we can ask. Is there evidence for groupings (or "families") of NEOs that pinpoint common collisional or dynamical origins? Are there "streams" of NEOs that may favor delivery of particular types of meteorites relative to others? Is the subset of "potentially hazardous objects" (PHAs) representative of the total NEO population? Which NEOs are the "best" for spacecraft exploration in terms of both accessibility and intrinsic scientific interest (taking into account such factors as unusual structure or composition)?

While the first level of questions about the nature of NEOs can be (and is being) addressed by "random" statistical surveys of the population, the more advanced questions require directed studies of particular NEOs. Directed studies are inherently more difficult because almost any given NEO makes infrequent passages near the Earth that provide favorable opportunities for observation. In most cases objects are discovered BECAUSE they are making a particularly favorable apparition and the best opportunity for performing physical studies is immediate to the time of discovery. The groundbased telescope time and aperture requirements for such directed studies of specific NEOs is quite different from the statistical studies that have been carried out to date. Nearly dedicated access to a modest (4-m) aperture telescope is required for thorough characterization of discoveries and select opportunities with large (6-10m) telescopes are required for characterizing specific objects of high interest.

Understanding the Distribution of Near-Earth Objects

William Bottke (SwRI), Alessandro Morbidelli (Obs. Nice)
and Robert Jedicke (U. Arizona)

The orbital and absolute magnitude distribution of the Near-Earth Objects (NEOs) is difficult to compute, partly because known NEOs are biased by complicated observational selection effects but also because only a modest fraction of the entire NEO population has been discovered so far. To circumvent these problems, we have used numerical integration results and observational biases calculations to create a model of the NEO population that could be fit to known NEOs discovered or accidentally rediscovered by Spacewatch. This method not only yields the debiased orbital and absolute magnitude distributions for the NEO population with semimajor axis a < 7.4 AU but also the relative importance of each NEO replenishment source.

We list a few of our key findings here, with a full accounting given in Bottke et al. (2002a, Icarus 156, 399). Our best-fit model is consistent with 960 +/- 120 NEOs having absolute magnitude H < 18 and a < 7.4 AU, with approximately 55% found so far. Our computed NEO orbital distribution, which is valid for bodies as faint as H < 22, indicates that the Amor, Apollo, and Aten populations contain 32%, 62%, and 6% of the NEO population, respectively. We estimate that the population of objects completely inside Earth's orbit (IEOs) arising from our NEO source regions is 2% the size of the NEO population. Overall, our model predicts that 37 +/- 8%, 25 +/- 3%, 23 +/-9%, 8 +/- 1%, and 6 +/- 4% comes from the nu_6 resonance, the intermediate-source Mars Crossing (IMC) region (i.e., a population of Mars-crossing asteroids with perihelion q > 1.3 AU located adjacent to the main belt), the 3:1 resonance, the outer main belt, and the Jupiter-family comet region, respectively. The influx rates needed to replenish the NEO population and the identification of extinct comets in the Jupiter-family comet region will also be discussed.

Applying the results of this model, our team has also developed a method for determining the debiased albedo/orbital distribution of the NEOs (Morbidelli et al., 2002, Icarus, in press). Our work shows that an observationally complete NEO population with diameter D > 0.5 km should contain 53% bright objects (e.g., S-type asteroids like 433 Eros) and 47% dark objects (e.g., C-type asteroids like 253 Mathilde). By combining our orbital distribution model with our albedo distribution model, and assuming that the density of bright and dark NEOs is 2.7 and 1.3 g cm^-3, respectively, we estimate that the Earth should undergo a 1000 megaton (MT) collision every 64,000 years. On average, the bodies capable of producing 1000 MT blasts are those with H < 20.5; only 18% of them have been found so far.

We have also combined our debiased NEO population results with a survey simulator in order to investigate the time needed by existing NEO surveys to find 90% of the NEOs larger than 1 km diameter. In our most realistic survey simulations, we have modeled the performance of the LINEAR survey over the 1999 -2000 (inclusive) period (Jedicke et al. 2002, Icarus, in press.). Tests indicate that our survey simulator does a reasonable job at reproducing LINEAR's NEO detections over this time frame. For this reason, we have some confidence that extending our simulator results into the future will also produce realistic results.

Our results indicate that existing surveys (as of January 2001) will take another 33 +/- 5 years to reach 90% completeness for D > 1 km asteroids. Our predicted timescale to reach the Spaceguard goal is longer than other recent estimates because our undiscovered NEOs have a very different orbital distribution than our discovered NEOs. Conversely, advances in survey technology over the last 6-12 months have allowed LINEAR to improve their limiting magnitude (J. Evans, personal communication), such that they can now find fainter objects than they could as of January 2001. We are still investigating the implications of their changes (and improvements made to other NEO surveys), but our test results suggest that the Spaceguard goal could be achieved as soon as 2014, better than the 2035 estimate given above. We believe this issue will need to be continually revisited over the next several years as surveys get better at finding NEOs.

We have not yet attempted a cost-benefit analysis, but our results suggest that a local-area network of telescopes capable of covering much of the sky in a month to limiting magnitude V ~ 21.5 may be administratively, financially, and scientifically the best compromise for reaching 90% completion of NEOs larger than 1 km diameter by 2008. We find that distributing survey telescopes in longitude/latitude may produce a 25% savings in the time needed to reach the Spaceguard goal. This value can be used to assess the relative merits of a southern hemisphere NEO survey against factors like cost, time needed to reach operational status, etc. Our results also indicate that a space-based satellite survey on an orbit inside Earth orbit (e.g., perihelion near Mercury) would offer significant advantages over terrestrial surveys, such that a Discovery-class mission to discover NEOs might be warranted.

For more information on these topics, please go to:
http://www.obs-nice.fr/morby/ESA/esa.html

What we Know and Don't Know about Asteroid Surfaces

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One of the most fundamental aspects of mitigating an impact threat by moving an asteroid involves physical interaction with the asteroid. Whether one is bathing the asteroid surface with neutrons, bolting an ion thruster or mass driver onto the surface, or trying to penetrate the surface in order to implant a device below the surface, we need to understand the physical attributes of the surface. Of course, we must understand the surface of the particular body that, most unluckily, is eventually found to be headed for Earth. But, in the meantime, it will advance our ability to design experiments and understand data concerning the particular body if we have thought, in advance, about the range of surface properties we might encounter.

We already know, from meteorite falls, that asteroidal materials can range from strong nickel-iron alloy (of which most smaller crater-forming meteorites, like Canyon Diablo, are made) to mud-like materials (like the remnants of the Tagish Lake fireball event). But the diversity could be even greater, especially on the softer/weaker end of the spectrum, because the Earth's atmosphere filters out such materials. That is why many meteoriticists doubt that we have any macroscopic meteorites from a comet. We could readily expect some icy, snowy, frothy, and dusty materials on the surfaces of asteroids and comets, and perhaps still stranger materials (e.g. with the structure of styrofoam).

A common framework for thinking about asteroid surfaces is to extrapolate from our very extensive knowledge of the lunar regolith. Indeed, there is a considerable literature concerning asteroid regoliths (mostly published in the 1970s and 1980s) based on theoretical extrapolation from lunar regolith models and on inferences from what are termed "regolith breccia" meteorites. These studies suggested that we should expect both similarities and differences from our lunar experience, for asteroids several km in diameter and larger. Less thought was given to smaller asteroids, except that at small sizes there must eventually be a transition to a "bare rock in space."

The Earth-approaching asteroid Eros is large enough that it was expected to have a roughly lunar-like regolith, although perhaps somewhat coarser and less well mixed. A major surprise from the NEAR Shoemaker mission to Eros is that its surface is totally unlike the Moon's, particularly at spatial scales of centimeters to tens of meters – just the scales relevant for human interaction with an asteroid. The Moon is covered with a well-churned regolith (basically a sandy soil, with occasional larger rocks and boulders, especially near recent craters large enough to have penetrated the several-meter-deep regolith down to bedrock), and its surface is characterized by innumerable small craters. Eros, on the other hand and despite its lunar-like appearance at spatial scales larger than ~100 meters, has been found to have relatively few craters tens of meters in size, and almost no craters cm to meters in size. Instead, the surface of Eros is dominated by countless rocks and boulders, except in localized flat areas (nearly devoid of both craters and rocks) that have been called "ponds".

The lesson is that extrapolations from meteoritical and lunar studies proved wrong. Evidently, our generalized understanding of the processes that shape asteroid surfaces is wrong in one or more fundamental ways. The way that we can really tell what an asteroid surface is like is to measure it directly rather than to theorize about it.

It is tempting to draw inferences from the NEAR Shoemaker data about what the surfaces of asteroids, or at least of S-type asteroids, are like. Indeed, it is the best evidence that we have. But, as indicated above, the NEAR Shoemaker surprises are not yet understood, although some hypotheses have been offered. And there is much that we don't know. The ponds are thought by many to be deposits of fine particulates (e.g. electrostatically levitated dust), but our best resolution is only a couple of cm and we do not even know for sure that these surfaces aren't solid and hard. Although the NEAR Shoemaker spacecraft landed on Eros' surface, we never got to see the gouges it may have made.

Even once the NEAR Shoemaker data are thoroughly analyzed, it is not clear how relevant the interpretations will be for asteroid mitigation, which will certainly involve much smaller bodies. In terms of self-gravity, the multi-hundred-meter body we might want to deflect from Earth impact is as different from Eros as Eros is from the Moon. These bodies will likely have essentially no modern regolith on them at all. But there may be legacy regoliths, evolved on the larger bodies from which the small bodies were formed...or almost any kind of unexpected structure.

Impact probabilities and lead times

Steve Chesley (JPL/Caltech) and Tim Spahr (CfA, Harvard Univ.)

The most important requirement, scientific or otherwise, for any impact mitigation is the recognition of the hazard, since, in the absence of a perceived impact risk, there is neither the incentive nor the capability to address the threat. Therefore, the success of any potential mitigation effort will rely heavily upon our ability to discover, track and analyze threatening objects. In this presentation we will consider the effectiveness of the present surveying and monitoring capabilities by bombarding the Earth with a large set of simulated asteroids that is statistically similar to the impacting population. Our aim is to see how many of these impactors might be recognized as threatening, and what is the reliability and expected lead time for such recognition.

To begin, we form a large set of "typical" impactors. For this purpose we use the debiased NEA population model developed by Bottke et al. (2000, Science 288, 2190). Starting with a very large population of NEAs we derive a set of 1000 impactors by first reducing the population to those for which the minimum orbital separation, or MOID, is low enough to permit an impact. Impactors are sampled from this low MOID set according to the fraction of their orbital period that they spend within the Earth-capture cross-section of the Earth's orbit, a value that can range from as much as a few percent for Earth-like orbits down to 10^-9 for low-MOID cometary orbits. This sampling approach allows for the more hazardous orbital classes, such as low inclination, Earth-like or tangential orbits, to have appropriately increased prominence among the simulated impactors. The orbital characteristics of the impacting population are important from a mitigation perspective in terms of both discovery and deflection efforts and these issues will be addressed.

Given a set of impactors one can ask whether and when they would be discovered by various NEO surveys with differing sky coverages and brightness limits. To approach these questions we run survey simulations, recording detections for various object sizes. This allows us to infer the distribution of warning times as a function of size. If there is a warning before an impact, the warning time will generally be measured either in years or else in weeks. In the former case mitigation by disruption or deflection of the object may be feasible, while in the latter case mitigation will be limited to evacuation of the impact region, etc. Detectability at the final apparition is often very challenging since the objects will tend to have rather slow sky-plane motion and will generally be located far from the heavily-searched opposition region. This means that in many cases, especially for the smaller objects, if a last-minute detection does occur it is not likely to be until the object is close enough for the parallactic motion to be detectable, generally a few weeks before impact.

The detection lead time is important in determining the time available for mitigation, but it is not the only factor. There is some delay between the discovery of the asteroid and the recognition that it poses a threat worthy of mitigation. The idea of continually monitoring the ever-evolving asteroid orbit catalog for possibilities of impact is fairly new, and the first automatic collision monitoring system was fielded less than three years ago. Today there are two independent and parallel systems, at JPL and the Univ. of Pisa, that are operating continuously to scan for potential impacts. These efforts have been very successful at detecting potentially hazardous future encounters for newly discovered asteroids and reporting the results to the NEO community. Follow-up observers have responded enthusiastically with observations that permit the hazard assessment to be refined and usually eliminated. We will consider a few impact case studies to understand how rapidly after discovery the probability of an impending impact can be expected to increase as time passes, and in particular to understand how this affects the lead time for mitigation.

Optimizing the orbital interception and deflection of hazardous NEOs

Bruce Conway (U. Illinois)

Thermophysical properties of comets and asteroids inferred from fireball observations

Mario Di Martino
INAF - Osservatorio Astronomico di Torino

Fireballs are very important events to derive basic physical information on near-Earth objects in a size range for which detection using conventional astronomical techniques is particularly difficult. The observable features of these events give relevant information about the physical properties of their parent bodies, and their likely origin. This may be important, for instance, to better evaluate the relative abundance of bodies having a likely cometary origin.

At the same time, a better estimate of the frequency of fireball events can put essential constraints on the general trend of the NEO size distribution, by providing data referring to an interval of the mass spectrum that is very poorly known at present. The major problem in fireball observations, however, is that currently only a minor fraction of the events are actually detected and recorded, and detections occur mostly in the form of serendipitous discoveries made by satellites devotedto other purposes. The situation can drastically improve if dedicated observing facilities will be developed. Due to the large areas of sky to be monitored for efficient fireball detection, the development of dedicated space-based facilities is strongly needed.

Mission Concepts for NEO Characterization

Richard Dissly and Rich Reinert
Ball Aerospace & Technologies Corp.

The scientific characterization of potentially hazardous Near Earth Objects will require a series of spacecraft missions to fully address the measurements required for the optimized implementation of any mitigation strategy. In addition, current surveys of the NEO population can benefit tremendously from space-based observational missions. This talk will cover both reconnaissance and survey mission concepts.

Mission concepts will be discussed in reference to the scientific questions they are designed to address. Measurement implementation strategies drive mission design some examples:
* What measurements can be made remotely?
* What measurements require a part or all of the spacecraft to contact the body?
* Is the contact on the surface or sub-surface?
* Is the contact long-term or an ephemeral event?

Future mission architectures so categorized will be compared to previous and current mission designs. The discussion will assess the technical maturity of future concepts and make preliminary estimates of the associated costs. This talk will also address technology developments that can facilitate suggested measurements.

Scientific Requirements for Enabling Future Technologies
Alan W. Harris, JPL

I am, at present, an observational astronomer, specializing in physical observations of asteroids, especially of the Near-Earth variety. It therefore seems likely that I should advocate intensive physical observations of NEAs in order to characterize the one that may get you. Instead, however, I will argue that we already know the range of physical properties of NEAs well enough that the problem with respect to mitigation is not a lack of knowledge of the range possible NEA properties. Instead it is our lack of knowledge of the specific properties of the one with our name on it: its size, mass, density, composition, material strength, whether it is one body or two, and so forth. We know that NEAs range from meteoroids to dinosaur-killers ten or twenty kilometers across, from near dust balls to solid iron, from spheres to long skinny pencils-in-the-sky and even binary objects. The only way we can know the specific properties of the one with our name on it is to find it. Additional physical studies will not do much to narrow down the range of possibilities, so if one insists on being prepared, one must simply deal with the entire range of possibilities of sizes, orbits, and physical states of the entire population, which we actually know quite well enough. Thus surveys must remain the most important astronomical endeavor relating to the impact hazard.

That being said, I will advocate continued, and hopefully increased, physical studies for two reasons. First, the survey discoveries currently being made represent a superb opportunity for scientific investigations apart from the hazard issue. It borders on criminal neglect to not take advantage of these opportunities for physical studies for their scientific return alone. Consider that NASA has spent, and continues to spend, hundreds of millions of dollars on missions to obtain high-resolution images of small bodies. Ground-based radars are capable of yielding comparable quality results (perhaps somewhat inferior in resolution but superior to flybys in time resolution), e.g. from the recent (future as I write this) close passage of the newly discovered 2002 NY40 in mid-August. Most of what we know about NEA binaries has been gleaned by rapid-response observations of recent discoveries. This is 100% true of the many tiny super-fast rotators found. We would not even know this population exists if it weren't for rapid follow-up observations (and some raving speculations of theorists).

The second justification of physical observations does have indirect application to the hazard issue. In order to characterize the NEA population as it is discovered one must obtain at least a statistical sample of properties. The most fundamental physical parameter is size, characterized most simply by absolute magnitude H. Even this is not well determined by the surveys and should be refined by well-calibrated photometric observations. Since absolute magnitude is the fundamental metric for tracking progress of the survey, this much should be done for every discovered object. In addition, at least a statistically significant sampling of other properties, spectra and radiometric albedo, should be undertaken so as to "calibrate" the transformation from sky brightness to a reasonable estimate of physical size of objects.

Returning to the matter of enabling mitigation technology, I will not speculate on how to kill an asteroid, other than to posit that it will require rendezvous. In the distant past, I naively speculated that one might deflect an asteroid by a standoff nuclear blast, causing spallation of a surface layer leading to recoil of the main body. It now appears very likely that most NEAs larger than a couple hundred meters in diameter are not monolithic and indeed are almost certainly disjoint "rubble piles" of some sort or another. Spallation is not likely to work. Any other method of deflection I can imagine will require rendezvous. Thus we should consider the requirements of rendezvous missions, not simply flyby ones.

In another life, I was (maybe still am) a celestial mechanic, so I will next speculate a bit on "getting there." It has often been said that NEAs are the easiest targets in the solar system for space missions. This is especially true for flyby missions to an asteroid on a collision trajectory with the Earth. Given a few orbits in advance, all you have to do is barely escape the Earth and park in an orbit with a slightly different period to move ahead or behind the Earth's position in orbit as needed to effect the close flyby (or impact). This has led some folks to speculate that a cheap mitigation system could be put together out of a few spare ICBMs and standard nukes already on hand. I maintain this is so unlikely to be effective that it should not be contemplated or advocated.

For rendezvous missions, NEAs are only easy targets if you get to choose the target; e.g. 4660 Nereus is unquestionably an easy rendezvous target. Unfortunately, if nature chooses the target for you (the one with your name on it), it is not likely to be easy. Simplistically, the velocity needed to match orbits with such an object is approximately equal to the impact velocity it will have when it hits (hopefully achieved at least a few orbits sooner). The mean (RMS) impact velocity of NEAs for actual discovered orbits is around 20 km/sec. I once heard no less an authority than Werner Von Braun himself declare that a Saturn-V could send a Volkswagen to Pluto, which is a similar delta-v task to a rendezvous with an "average" NEA. It is not a task suitable for a surplus ICBM to achieve such a launch velocity (15 km/sec plus Earth escape). Indeed, with chemical propulsion current launch vehicles couldn't get much more than a shoebox to such a velocity. There are tricks to reduce the launch energy requirements, such as gravity assist trajectories, but these are time consuming and have limitations. Thus it seems to me that the most important "enabling technology" for impact mitigation is the development of advanced high-energy propulsion systems. We must first enable simply getting there before worrying over much about what to do when we arrive.

I must conclude, however, that even "getting there" is not cheap and simple, and combined with the extraordinarily low probability of needing to "get anywhere," it seems to me unjustified to do more than paper studies in advance of the actual discovery of a threatening NEA. High-energy propulsion systems are probably worth developing for other reasons (like going to Pluto without rebuilding a Saturn-V), but the impact hazard by itself hardly justifies doing so.

Ceterum censeo machinas ad sidera errantia deflectenda struendas non esse.

Scientific Requirements for Understanding the Near-Earth Asteroid Population

Alan W. Harris
DLR Institute of Space Sensor Technology and Planetary Exploration, Berlin

A vital prerequisite for the development of an effective mitigation strategy for hazardous near-Earth asteroids (NEAs) is a thorough understanding of their physical nature and mineralogical composition. The deflection of an object on collision course with the Earth would require the use of considerable force, the successful application of which would depend on prior knowledge of parameters such as mass, shape, strength, and structure. Recent experience has shown that much can be learned about individual objects from fly-by and rendezvous missions and such missions would play the dominant role in gathering mitigation-relevant information once a dangerous potential impactor had been identified, provided sufficient time were available before the impact.

In the meantime, it is important to study the NEA population in general to enable the most likely physical characteristics of a potential future impactor to be anticipated as accurately as possible. Groundbased, airborne, and satellite observatories offer a wide range of techniques with which large numbers of near-Earth asteroids can be remotely sensed, including lightcurve measurements, visible to thermal-infrared photometry, visible to near-infrared reflectance spectroscopy, and radar. The merits of techniques most useful from the point of view of NEA hazard assessment and mitigation, and the type of information each can provide, are discussed. The interdependency of the interpretation of data from the various observing techniques is emphasized.

Geology of asteroids: Implication of spin states regarding internal structure and some implications of that structure on mitigation methods.

K. A. Holsapple, University of Washington

The design of asteroid and comet collision mitigation strategies depends crucially on knowledge of the body's internal structure and mechanical properties; but those are poorly known. While we have clues, definitive information eludes us. Planning for mitigation requires focused efforts; not only for discovery, but also methods for the determination of internal structure and properties, and the study of the science of proposed deflection or disruption methods.

A natural approach to looking for such clues about the makeup of asteroids is to study the implications of their observed size, shape and spin. Those properties are available from the analysis of the lightcurves of well over 1000 asteroids, including about 100 NEA's.

An asteroid's size, shape and spin produces internal stresses from the gravitation and rotational forces. In turn, the asteroid must be sufficiently strong to resist those stresses. Thus, a minimum strength can be deduced by an analysis of those internal stresses. Knowledge of that required strength gives constraints on the internal structure.

I have obtained closed-form algebraic expressions that give equilibrium stress states as a function of size, ellipsoidal shape and spin (Holsapple, 2001). Further, those equilibrium states must also satisfy constraints of stability, which further narrows the possibilities (Holsapple, 2002). The stable states of equilibrium are then compared to strength models to determine the required strength. Geological materials are mostly modeled as granular materials with a Mohr-Coloumb strength, in which the allowable shear strength is related to the confining pressure, that relation depending on the cohesion (strength at zero confining pressure) and the so-called angle of friction.

The results are surprising: almost all known asteroids are within the limits allowed by a cohesionless material with some reasonable angle of friction. Further, most are well within the limits for relatively low angles of friction, on the order of 20?. As a result, while we cannot rule out the possibility of additional strength, all of those asteroids need only have the strength of a porous rubble-pile granular structure.

If indeed many bodies do have such a rubble-pile structure, we must study the implications of such a porous structure on proposed mitigation schemes. Even if the gross properties of an asteroid are not those of a rubble-pile, the presence of a porous regolith may also have a dramatic effect on mitigation.

I also present some calculations emphasizing the importance of porosity on proposed (Ahrens and Harris, 1994; Melosh et al., 1994) mitigation methods. Methods utilizing surface and buried nuclear or chemical explosions may be reduced in effectiveness by a factor of five or so by porosity. Methods using the kinetic energy of an impactor may also reduced in effectiveness by a factor of five. Even more dramatically, methods using energy deposition and blow-off may be reduced by a factor of 103 in effectiveness. For example, the use of a standoff nuclear weapon in the megaton range would not have any appreciable effect on diverting a 10km porous-surface asteroid or comet.

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ABSTRACTS

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Human Exploration of Near-Earth-Objects

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The scientific requirements of future mitigation technology

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Introduction: Currently, various ideas for the diversion and/or disruption of potentially hazardous objects (PHO) exist. Among them are systems that are technologically feasible at present, e.g. kinetic energy impactors and nuclear explosives. Others are currently not available within the designated size but might be possible with some effort, e.g. propulsion systems (chemical, nuclear), and solar concentrators. Some systems seem to be too far off to be realized within the next decades such as mass drivers, solar sails, and surface layers (Yarkovsky effect). Besides, there are also futuristic technologies such as laser systems, eater, "cookie cutter", and the use of antimatter. The use of mass drivers as well as solar sails would probably demand for large and heavy mechanical structures and might thus never become realistic mitigation options. The same can be expected from the utilization of the Yarkovsky effect. Further, the application of kinetic energy impactors or nuclear explosives might even worsen the situation in case of an unintended disruption of the NEO, which could cause multiple impacts on Earth (firestorms). Here, two mitigation concepts will be discussed that could become attractive alternatives in the mitigation of hazardous objects: the solar concentrator system and the magnetospheric propulsion.

Solar Concentrator: The application of solar concentrators for NEO mitigation was discussed first by Melosh et al. [1]. The basic idea of this technology is to concentrate solar radiation onto the NEO surface with a lightweight (parabolic) reflector. Depending on duration and intensity of illumination, the material within the spot will be heated up and vaporizes. The evaporated material accelerates to a speed of about 1 km/s and delivers an impulse to the NEO. Although the generated thrust is small (order of magnitude: 10^1 to 10^2 N) it will suffice to deflect the NEO from its collision course with Earth if sufficient lead-time is given (years). Such a system could be operated for the duration of several months, which would lead to a slight increase in semi-major axis of the hazardous NEO. For technology demonstration a small satellite could be built within short time. When equipped with instruments, e.g. mass spectrometer, material properties of the target NEO could be studied at same time.

Magnetospheric Propulsion: The idea of magnetospheric propulsion is related to the solar sail concept concerning that both tap the ambient solar energy to provide thrust to a spacecraft. But, solar sails suffer from their mechanical structure – if large spacecraft or even small asteroids have to be propelled, physical limits will be reached, e.g. the system mass and problems accompanied by deploying that large structures. Thus, Winglee et al. [2] invented a revolutionary propulsion concept for interplanetary space missions (named Mini-Magnetospheric Plasma Propulsion - M2P2). This system creates a magnetic bubble that will intercept the solar wind. At a distance of 1 AU the solar wind particle density is about 6 cm^-3 moving at a speed of about 300 to 800 km s^-1. This results in a constant dynamic pressure of 2 nPa. If the magnetic field cross section is large enough a continuous force (order of magnitude: 10^1 N) could be provided. We propose to use such a system for NEO diversion. Although the generated thrust is low, this system could be operated for a long duration (several months) to divert a PHO.

Summary: Both technologies, solar concentrator and magnetospheric propulsion, could be developed within short time. For demonstration the systems could be scaled to small satellites (about 200 kg). An overview of both systems, relevant physical parameters for the interaction, a brief conceptual analysis, and examples for orbit diversion will be presented.

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Peering inside NEOs with Radiowave Tomography
Wlodek Kofman

The radar technique has been successfully applied for many years for Earth and planetary observations, while the tomography has been used for many years in medical studies and in non-destructive analysis of materials.

The Synthetic Aperture Radar is a good example of the use of the radiowave imaging inverse scattering technique in radar application. The idea to use radiowave sounding to study the interior of comets is applied in the CONSERT experiment for the ROSETTA mission.

In this presentation, we start with a discussion on the ability of the radar tomography to observe the interior of asteroids. Then, after a description of the relevant radar parameters necessary to define in a very general way the radar designed for this purpose, we discuss the principle of Radar Transmission and Radar reflection tomography and compare these two methods, discussing their differences. With the example of the CONSERT experiment which was developed for a cometary mission, and which will be launched in January 2003 on the ROSETTA mission, we show how the transmission tomography is used. The CONSERT system is briefly described; simulation results of the inversion methods, and how to infer the interior of the comets from measurements, are shown.

The propagation of the waves in the material medium is addressed with special attention concerning the attenuation coefficient in the cometary and asteroid materials covering their likely composition. This parameter is essential for the determination of the frequency and bandwidth of the radar. It is thus clear that for asteroid interior peering, we should use low frequency radars, surely below 50 MHz, and even this will not guarantee a total penetration. The monostatic reflection radar tomography is probably the only solution.

The accuracy of the satellite positioning relatively to the surface of the object, which has to be very high, of the order of a fraction of the wavelength, is an additional argument for the use of low frequency radars. We discuss the expected radar performances and show that for small kilometric bodies, the radar reflection tomography is a good approach to study the interior of asteroids.

Finally, radar specifications are proposed.

Geophysical Constraints on NEO Mitigation Strategies

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The success of any proposed mitigation strategies depends on two major factors: How massive is the NEO and how much lead time do we have? A secondary issue is what is the NEO made of and how are its various parts arranged.

The essential object of deflecting an asteroid or comet away from an impending impact with the Earth is to change its velocity. Given the astronomical distances likely to separate the NEO from the Earth at the time the threat is discovered, only a small velocity change (perhaps a few cm/sec) is necessary, but even such small changes are difficult to achieve for objects 1 km or more in diameter, which may have masses in the range of 10^12 kg. The direction in which the velocity impulse is applied is important for orbiting objects. An impulse in the direction of the orbital motion is much more effective in changing the position of an object than an impulse in any perpendicular direction. Deflection scenarios range from a single impulse delivered long before the impact, such as the jolt delivered by a nuclear explosion or impact of another asteroid, to long-duration low accelerations delivered by solar evaporation or a mass driver. In any case, the deflection process is likely to be limited by the energy available, not the reaction mass available, so the optimum use of the available energy is to move as much mass as possible, not to eject it at high speeds.

The success of a given deflection strategy may depend strongly on the physical and chemical nature of the NEO. The methods envisioned for deflecting a solid silicate rock may differ considerably from those effective against a porous aggregate. Recent spacecraft studies indicate that the density of asteroids runs the gamut from nearly solid silicates (Eros) to highly porous aggregates (Mathilde). Theoretical cratering studies and limits on rotational period suggest that most asteroids larger than a few km in diameter are thoroughly fractured by smaller impacts. The effective strength of any given NEO may thus vary over a wide range, especially if it is composed of mechanically independent blocks, or even possesses a satellite, as do about 15% of NEOs. Even stony asteroids may contain volatiles that could affect the success of some deflection scenarios. These considerations make it important to implement a program in which determination of the physical and chemical properties of NEOs are a major component of any large-scale deflection strategy.

Science and Public Perception (panel)

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Impacts are different from other more familiar hazards. The impact risk is primarily associated with extremely rare events – literally unprecedented in human history. They are the extreme example of a hazard of low probability but immense consequences. Although there is a chance of order one in a million that each individual will die in any one year from an impact, it is not the case that one out of each million people dies each year from an impact. Further, impacts threaten not just individuals but civilization itself. For many people, impacts are therefore a greater concern than is implied by simple numerical risk estimates, since a large impact could destroy much that is uniquely human. Others, of course, prefer (perhaps unconsciously) to play the odds, based on the very low probability that any major impact will occur within our lifetimes.

Scientists (aided by Hollywood) have succeeded in alerting the world to the existence of an impact hazard, and astronomers have successfully undertaken the Spaceguard Survey, focused (so far) on the threat of global disaster from collision with a NEA of diameter greater than 1 km. We have not yet established any goals beyond 2008. Should we continue the present survey to push the completeness limits for large asteroids to 95% or 99%? Should we raise the bar and build the larger telescopes that will be required to achieve completeness at smaller sizes, say 300 m? Or should we begin to develop technology to change the orbits of asteroids? To answer such questions, the NEO science community needs to engage in active dialog with other professionals with greater experience in disaster mitigation and national security. We need to consider the societal context of NEO searches and of approaches to mitigation. These social and political considerations will play an important role in determining what priority will be placed on protecting our planet from cosmic impacts.

We also have a responsibility to the public. Every few months this issue is thrust into the public spotlight, usually by a report that a newly-discovered asteroid poses (temporarily) some low-probability hazard of colliding with the Earth. There is a temptation to play up such stories, even though most scientists realize that the issue will likely evaporate when a few more observations are made. Some members of our community like to appear on TV, and others feel this is a good way to garner public support for our work. We need to ask ourselves if it is really to our advantage to use these opportunities to gain media and public attention, especially when we know the risk is actually extremely small. There is a serious potential down-side if we cry "wolf" too often. Our credibility is at stake, and hence our ability to inform the public and perhaps to influence the decision makers.

We also need to be concerned about confusions between large impactors and small ones. Understanding kiloton-energy bollides that explode in the atmosphere is important, but this is entirely different from the search for dangerous asteroids. Similarly, there is an orders-of-magnitude difference in the hazard from large asteroids (larger than a couple of kilometers) and that from smaller, Tunguska-class impacts that have no global consequences. When we blur these distinctions, we confuse the public and sometimes even ourselves. An example is the recent interest in establishing a government coordinating and warning center. The implication of this suggestion is that we will have many warnings to issue. I don't think so. The frequency of even the smallest impacts that do surface damage is no more than one per century. Even with a perfect survey, the warning center might therefore issue fewer than one warning per human lifetime.

Does this make sense? These are all issues of public communication, but they ultimately depend on our own ethical commitment to deal with the impact hazard in a responsible, honest way.

Radar Reconnaissance of Potentially Hazardous Asteroids and Comets

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Groundbased radar is an intelligence-gathering tool that is uniquely able to reduce uncertainty in NEO trajectories and physical properties. A single radar detection secures the orbit well enough to prevent loss of newly discovered asteroids, shrinking the instantaneous positional uncertainty at the object's next close approach by orders of magnitude with respect to an optical-only orbit. This conclusion, reached initially by Yeomans et al. (1987) through Monte Carlo simulations, has been substantiated quantitatively by comparison of residuals for radar+optical and optical-only positional predictions for recoveries of NEAs during the past decade (Ostro et al. 2002).

Integration of an asteroid's orbit is afflicted by uncertainties that generally increase with the length of time from epochs spanned by astrometry. Eventually the uncertainties get so large that the integration becomes meaningless. The duration of accurate orbit integration defines our window of knowledge about the object's whereabouts. Presumably we want to find out if any given NEO might threaten collision, and if so, we would like as much warning as possible. Radar extends NEO trajectory predictability intervals far beyond what is possible with optical data alone, often approaching the end of this millennium (e.g., 1999 JM8; Benner et al. 2002).

For 2002 FC, an eight-week arc of discovery-apparition optical astrometry could not reliably identify any close Earth approaches before or after 2002, but with Arecibo astrometry from May 24 and Goldstone astrometry from June 6 (the object's last radar opportunity until 2040), close approaches could be identified reliably during the 1723 years from 488 to 2211. At this writing, with a much longer, 3.3-month optical arc, the corresponding intervals are 1951 years with radar (464 to 2415) and 137 years without it (2002 to 2139).

For asteroid (29075) 1950 DA, analysis of the radar-refined orbit (Giorgini et al. 2002) revealed that there will be a possibly hazardous approach to Earth in 2880 that would not have been detected using the original half-century arc of pre-radar optical data alone. This event could represent a risk as large as 50% greater than that of the average background hazard due to all other asteroids from now through 2880, as defined by the Palermo Technical Scale (PTS value = +0.17). 1950 DA is the only known asteroid whose danger could be above the background level. The uncertainty in the probability of a collision in 2880 is due mostly to uncertainty in the Yarkovsky acceleration, which depends on the object's shape, spin state, and global distribution of optical and thermal properties. This example establishes the fundamental inseparability of asteroid physical properties and long-term prediction of their trajectories: if we take the hazard seriously, physical characterization must be given high priority.

For most NEAs, radar is the only Earth-based technique that can make images with useful spatial resolution (currently as fine as ~10 m). With adequate orientational coverage, delay-Doppler images can be used to construct geologically detailed three-dimensional models (e.g., Hudson et al. 2000), to define the rotation state, and to constrain the internal density distribution. The wavelengths used for NEAs at Arecibo (13 cm) and Goldstone (3.5 cm), in combination with the observer's control of the transmitted and received polarizations, make radar experiments sensitive to the surface's bulk density and to its roughness at scales larger than a centimeter (e.g., Magri et al. 2001). The fact that NEAs' circular polarization ratios (SC/OC) range from near zero to near unity means that the surfaces of these objects are extremely variegated. In many cases, NEA surfaces have more severe small-scale roughness than that seen by spacecraft that have landed on the Moon, Venus, Mars, or Eros (whose SC/OC is near the NEA average of ~0.3).

Radar-derived shape models of small NEAs open the door to a wide variety of theoretical investigations that are central to a geophysical understanding of these objects. With realistic models, it is possible to explore the evolution and stability of close orbits (e.g., Scheeres et al. 1998) with direct application to the design of spacecraft rendezvous and landing missions. Given information about the internal density distribution, one can use a shape model to estimate the distribution of gravitational slopes, which can constrain regolith depth and interior configuration. A shape model also allows realistic exploration (Asphaug et al. 1998) of the potential effectiveness of nuclear explosions in deflecting or destroying hazardous asteroids.

The most basic physical properties of an asteroid are its mass, its size and shape, its spin state, and whether it is one object or two. Radar is uniquely able to identify binary NEAs, and at this writing, has revealed six (Margot et al. 2002 and references therein, Nolan et al. 2002), all of which are designated Potentially Hazardous Asteroids (PHAs). Analysis of the echoes from these objects is yielding our first information about the densities of PHAs. Current detection statistics suggest that between 10% and 20% of PHAs are binary systems.

The risk of a civilization-ending impact during this century is about the same as the risk of a civilization-ending impact by a long-period comet (LPC) during this millennium. At present, the maximum possible warning time for an LPC impact is probably between a few months and a few years. Comet trajectory prediction is hampered by optical obscuration of the nucleus and by uncertainties about nongravitational forces. Radar reconnaissance of an incoming comet would be the most reliable way to estimate the size of the nucleus (Harmon et al. 1999) and would be valuable for determining the likelihood of a collision.

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Close Proximity Operations at Small Bodies: Orbiting, Hovering, and Hopping

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Central to any characterization or mitigation mission to a small solar system body, such as an asteroid or comet, is a phase of close proximity operations on or about that body for some length of time. This is an extremely challenging environment in which to operate a spacecraft or surface vehicle. Reasons for this include the a priori uncertainty of the physical characteristics of a small body prior to rendezvous, the large range that can be expected in these characteristics, and the strongly unstable and chaotic dynamics of vehicle motion in these force environments. To successfully carry out close proximity operations about these bodies requires an understanding of the orbital dynamics close to them, a knowledge of the physical properties of the body and the spacecraft, and an appropriate level of technological sensing and control capability on-board the spacecraft. In this talk we will discuss the range of possible dynamical environments that can occur at small bodies, their implications for spacecraft control and design, and technological solutions and challenges to the problem of operating in close proximity to these small bodies.

Mission operations in low gravity, regolith and dust

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Introduction

Scientific investigations should be a component of impact mitigation studies because knowledge of the nature of the asteroid is necessary for the development of deflection techniques and predicting the effects of atmospheric and terrestrial impact. We are developing a proposal for the Hera mission, as mission to reconnoiter three asteroids and take samples from three locations on each. We are interested in the asteroid-meteorite connection and all this has to imply for the origin and evolution of the solar system and the relationship between our Sun and other stars. In these connections, we have performed experiments with simulated regolith and dust on NASA microgravity facility (the KC-135), which should also provide insights into mission operations in low gravity, regolith, and dust.

The Microgravity experiments

The aircraft lies about forty parabolas in a 2.5-hour flight in groups of 10 separated by 10 minutes of flat flight. Each parabola is about 2 minutes duration and can be considered as having four phases, positive gravity (during climb), negative gravity (when objects in the plane continue to climb when the plane reaches the top of the parabola), microgravity (as the plane descends at almost free-fall) and recovery (as the plane comes out of descent). The duration of microgravity is about 25 seconds. We conducted experiments during three campaigns, flying twice in each campaign, for a total of 240 parabolas.

During the first campaign, 317 one-inch Plexiglas tubes filled with various sand and iron mixtures were flown. Separation of iron and sand was determined from image analysis of photographs of the tubes after flight and from the measurements of removed samples. For the second campaign, two six-inch diameter Plexiglas cylinders containing sand iron mixtures in approximately chondrite grain sizes and proportions were observed with digital cameras The separation of iron and sand was noted and any structures resembling the ponds on Eros were looked for. The third campaign was essentially a test of the Honeybee Robotics touch-and-go surface sampler. This device consists of two counter-rotating cutters that eject material into a cylindrical container with front doors, to allow collection, and a trap door below to allow ejection into the spacecraft container. The collector was mounted on a vertical rail inside a double walled enclosure and attempts were made to sample four surface stimulants, sand, sand and iron mixtures, sand and gravel mixtures and concrete. It is particularly helpful to compare the test results in microgravity with the results in the laboratory.

Some results

The major result of the three campaigns, in terms of implications for mission operations on the surfaces of asteroids and comets were:

- Particle size sorting of the surface material occurs readily.

- Segregations that occurred early in the process are retained during considerable amounts of subsequent activity

- It was difficult to "see-through" the periods of negative g, which are an artifact of the KC-135 tests and would not be present during sample collection on an asteroid. A collector that works well on the ground worked far less well under microgravity conditions where movement of the disturbed surface in all directions but mostly away from the collector was a big problem. Clogging of moving parts in such a dusty environment was also a problem.

Lessons for mission operations on asteroids

- Limitations of KC-135 tests. In our experiment in the plane, it has been difficult to "see through" the negative-g phase, and attempts to retain the sample as the plane transitions from positive g to microgravity were difficult given the time and physical constraints operative. It might be better to use drop towers (although they only provide typically 5 seconds of microgravity) or the Shuttle (which is expensive).

- Most methods of sample collection will produce segregations in unconsolidated surface materials that would seriously degrade the scientific value of the samples. The surface will be easily disturbed and material distributed widely. Segregations produced early in the collection process can be retained after fairly large amounts of subsequent mechanical agitation. Therefore (1) the collector should disturb the surface as little as possible, (2) attempts should be made to collect rocks (or clods) as well as dust and fine regolith.

- During the development phase of equipment designed for operation on an asteroids or comets, it is probably safe to assume that the collector will perform to a much lower efficiency than on Earth, where gravity retains material and where we have ample experience. With this in mind, sample collectors with the minimum of moving parts and with as much dust protection as possible are preferred, and collectors which cover or retain the surface materials as they are collected stand the best chance of success of recovering the most scientifically valuable samples.

Seismic Investigations of Asteroid and Comet Interiors

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For a Near Earth Object on a potential collision course with Earth, any mitigation technique will require a knowledge of the composition and structure of the NEO. In particular, the density, strength, and cohesiveness of the NEO, either an asteroid or a comet, will be required. Quantitative information about the internal composition and structure of an asteroid or comet can be obtained through active seismology. Active seismology requires a source of the seismic disturbance and detectors (geophones or seismometers) to measure the sound waves produced in the asteroid or comet body. There are two approaches to producing seismic waves: explosive charges and impactors. The active seismology program conducted on the Apollo 14, 16, and 17 flights used both. On each of the flights the astronauts carried explosives, either to be launched in a grenade launcher or to be placed by hand as seismic source. On two of the flights a hand-held thumper consisting of exploding bridge wires was also used as a seismic source. These experiments allowed a partial determination of the structure of the lunar surface in the vicinity of the landing site. Also, information about the Moon's structure was gleaned from the seismic traces produced by the impact of the LMs and SIVBs. Some of these results will be reviewed. Next, given a size of an asteroid or comet and some assumptions about composition, the requirements for explosive charge size or impactor momentum in order to obtain signals that can be measured by various seismometers will be discussed. The size of the charge ties into the coupling between the explosive and the surface material of the asteroid or comet. Experiments are being performed to examine the coupling of small explosive charges with relation to depth into the surface. Large increases in efficiency result. The corresponding impulse loadings from impacts will be discussed, including what size impactors and impact velocities lead to similar seismic signals. Information about the required loading on the surface is then available as input for mission design, and well as determining seismometer sensitivity requirements.

Military perspectives on asteroid impact mitigation

Pete Worden (USAF)

Techniques for the structural investigation of aggregate bodies and Summary of Muses-C

Hajime Yano (ISAS)