NASA/CP–2008-214579

Workshop Report On Low-Cost Missions To Explore Near-Earth Objects (NEOs)

Compiled and Edited by:

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Report of a workshop
sponsored by and held at
NASA Ames Research Center
Moffett Field, California
on October 20-21, 2007

May 2008

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National Aeronautics and
Space Administration

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Moffett Field, California 94035-1000

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Executive Summary

The motivation for characterizing Near Earth Objects (NEOs) centers around four principal objectives: (1) a wide range of science objectives, such as understanding the physical characteristics and impact/collisional histories of the NEO population; (2) a defense objective to identify the dynamical state and interior structure of NEOs, should it be necessary to develop countermeasures to avoid a collision; (3) a piloted mission objective, since these objects could be potential stepping stones in NASA's exploration objectives; and (4) a resources objective, looking forward to a time when raw materials could be obtained in space. The majority of the presentations and discussions at this workshop were focused on Near Earth Asteroids (NEAs).

Strategies for characterizing NEAs include orbital reconnaissance, radar imaging to characterize the deep interior, seismic probes and landers, and sample return. These four strategies give complementary information about NEAs.

Flybys of NEAs were considered to be of limited use, since we already have radar images of NEAs that pass close to the Earth. However, inexpensive fly-bys might be useful to study comets and could be considered for missions of opportunity to explore objects of special interest. However, for comets the science objectives are much better attained using rendezvous spacecraft.

The most powerful general exploration approach is with orbiting or rendezvous spacecraft. Since most of the information on shapes, topography, spin state, gravity field, etc. can be obtained with multispectral imaging, very useful missions can be flown with quite small payloads, consisting only of imaging and lidar, and taking full advantage of a maneuverable spacecraft that can explore the asteroid for a long time from a range of distances and viewing geometries. Ideally one would also like to add a visible and near-infrared spectrometer, especially to observe low albedo objects that have small, narrow water of hydration features.

One of the preferred mission profiles was to use a reconnaissance spacecraft already in orbit around the NEA to observe an impact by another spacecraft. This approach permits observation of all three phases of the impact, namely the impact flash, the ejecta curtain, and the target crater. Since the crater forms rather slowly because of the low gravitational field of the NEA, the greatest information is derived only from having another spacecraft in close proximity to the NEA for all three phases of the impact. For example, crater formation would take approximately 20 minutes for a 300-350 m diameter asteroid, assuming a 2000 kg impact at 5 km/s (see later discussion).

Lander missions are also an important element of NEA exploration because they permit unique measurements, such as in-situ composition and chemistry measurements, and seismic sounding measurements that reveal the internal structure and density distributions. The workshop participants recommended an orbiter/lander/hopper flight profile for the lander mission, where the spacecraft would first rendezvous with the NEA and enter orbit to conduct a remote survey of the

NEA's size, shape, and gravity field. The lander would then drop to the surface and could "hop" to other locations to obtain a representative sampling of the NEA. Seismic sounding measurements could be accomplished through deployment of probes across the surface of the NEA.

One of the main focuses of the workshop was how to leverage low-cost small satellite missions. Low-cost mission strategies are needed if we are to explore a representative sample of these diverse objects. The potential advantages of smaller, modular spacecraft are lower mission cost (<\$100M), shorter development schedules (<24 months), and lower mass (<300 kg). This approach could enable faster learning cycles and an ability to implement new technologies sooner. Low-cost missions make sense especially in cases where the NEAs can be reached with modest launch costs using, for example, Minotaur-class launch vehicles, or can fly as secondary payloads or missions of opportunity. Cost savings are also achieved by selecting very limited science instruments, and by procuring the basic spacecraft bus in multiple lots to realize economies of scale.

Another subject discussed at the workshop was a recent informal NASA study of the technical feasibility of piloted missions to NEAs using the Crew Exploration Vehicle (CEV). Possible launch vehicles for NEA missions include the Atlas 5 (heavy), the Delta IV (heavy), and the Ares family of rockets. The study included an identification and assessment of candidate target NEAs with science justification. One of the outcomes of the study was the realization of the relatively small number of assessable known asteroids. Therefore, one of the priorities going forward is to identify the NEA population down to smaller sizes. This will increase the number of targets accessible by both low-cost small satellites and human piloted missions.

Workshop Report On Low-Cost Missions To Explore Near-Earth Objects (NEOs)

Stephanie Langhoff[1] and David Morrison[2]

Ames Research Center

I. Introduction

A workshop entitled "Low-cost Missions to Explore Near-Earth Objects (NEOs)" was held at Ames Research Center on 20-21 October 2007. This workshop is part of series of informal weekend workshops hosted by the Ames Center Director, Pete Worden. The organizers were David Morrison (Interim Director of the NASA Lunar Institute) and Stephanie Langhoff (Ames Research Center Chief Scientist). The workshop agenda was structured to bring together the science and engineering communities who have a common interest in small body missions, but rarely talk to each other. The environment of an informal workshop helps to break down walls that inhibit communications between these groups. Approximately 55 persons representing the government, industry, and academic communities attended (see list of attendees). In practice, the workshop focused on Near Earth Asteroids (NEAs), with only a few mentions of possible comet missions.

The agenda blended five major themes: (1) the scientific importance of characterizing small NEAs and the kinds of science measurements and instruments that are needed. This discussion included summaries of what is currently known about NEA populations and orbital statistics. (2) How to get to NEA targets, including direct vs. gravity-assist trajectories, and NEA rendezvous opportunities and proximity operations issues. (3) Current missions that have flown and feasibility studies for future missions. (4) Low-cost and small satellite concepts, especially as secondary payloads and missions of opportunity. (5) Piloted missions to NEAs, especially using future launch and Crew Exploration Vehicle (CEV) assets. Fifteen-minute papers covered the above topics, with plenty of time for discussion. The Program Organizing Committee (David Morrison and Stephanie Langhoff (co-chairs), Erik Asphaug, Dan Durda, Bob Farquhar, and Pete Klupar) was responsible for the selection of speakers. The final afternoon was devoted to interactive discussions, organized around three key questions that the workshop participants could explore in smaller breakout sessions.

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II. Characterization of Small NEOs

The first presentation in the morning session, given by David Morrison, was entitled “NEO Background: Surveys and Science.” He began by defining several terms that would be used throughout the workshop. A Near Earth Object (NEO) is defined to be any small object (comet or asteroid) that has its perihelion inside 1.3 astronomical units. A Near Earth Asteroid (NEA) is defined to be all NEOs that are not comets, where the primary distinction is composition, that is, the presence of frozen volatiles near the surface. It was noted that NEAs come primarily from the main asteroid belt, generally by a process of collisional breakup followed by dynamical transport. The dynamical lifetimes of NEAs are on the order of 100 million years. Asteroids (NEAs) were the main focus of the presentations and discussion at the workshop.

Morrison briefly discussed the progress of current NEA surveys and the issues associated with expanding these surveys, which has been requested by Congress. This is later discussed in more detail by Alan Harris. Morrison noted that currently four approximately one-meter telescopes are discovering most asteroids. The current Spaceguard Survey should eliminate 90% of the impact risk by the end of this decade. Extending the survey to smaller diameter asteroids will take larger telescopes such as the proposed Large Synopic Survey Telescope (LSST).

In his presentation, he elaborated on what we now know about NEAs. We have found 100% of extinction-level objects (diameter (D) > 5 km), 80% at diameter > 1 km, but only 1% at D > 100 m. Planetary radars such as Arecibo and Goldstone have provided precise orbits for more than 30 NEAs. For a smaller number of NEAs, we have images, spin axis, size, shape, moments of inertia, radar reflectivity, and in many cases, the discovery of a satellite body. Ground-based telescopes have provided size estimates (within a factor of two) and estimates of dominant mineralogy. Space missions, for example, the NEAR-Shoemaker mission that orbited and landed on Eros, and the Hayabusa rendezvous and touchdown to sample Itokawa, have provided more detailed characterization (see later discussion). However, there is much more to learn about NEA populations, diversity, surface characteristics, interior structure, origin, composition, and collisional and dynamical history.

The motivation for characterizing NEAs centers around several principal objectives: (1) science objectives to understand the population of impactors that have contributed to the volatile inventories of the terrestrial planets, to ground truth the ground-based meteoritic data, and to gain insight into the impact/collisional histories and general physical characteristics of the overall NEO population; (2) a defense objective to identify the dynamical state and interior structure of a diverse set of NEAs, should it be necessary to develop countermeasures to avoid a collision; (3) a piloted mission objective, since these objects could be potential stepping stones in NASA’s exploration goals; and (4) a resources objective, since NEAs could become a major source of raw materials for a future space-based economy. Potential characterization approaches include Earth-based radar and spectrophotometry, and flyby, rendezvous, lander, impactor, and sample return missions. The relative merits of these approaches were discussed in later sessions.

Erik Asphaug's talk "Geophysics Measurements and Missions" was a science-based review focused on the interior structure of NEAs, most of which appear to be rubble piles with large void spaces. Asphaug used radar and spacecraft data to illustrate surfaces (regoliths, slopes, mobility of fine material) and interiors (mechanical properties of rubble piles). He recommended probing interiors with Electro-Magnetic (EM) sounding or impacts, as observed from a rendezvous spacecraft. He noted an uncertainty of four orders of magnitude in estimates of the energy required to disrupt a rubble pile asteroid, a critical issue if it is necessary to deflect an asteroid for hazard mitigation.

There is considerable evidence that asteroids are rubble piles, that is, they are loosely held together, and are macroscopically porous compared with meteorite analogs. It has been suggested that rubble piles may be the natural end state of asteroids on the basis of the "survival of the weakest". In other words heavy bombardment, if noncatastrophic, will produce a rubble pile, and rapid shock attenuation allows a rubble pile to withstand subsequent bombardment. Thus asteroids may be fossils from the very early and violent solar system.

The types of NEAs were discussed along with the interesting science questions associated with each type. Since Arecibo and Goldstone radar along with optical observatories characterized many NEAs, a well-characterized asteroid could be selected as a mission target. Four spacecraft mission strategies were proposed for characterizing NEAs: (1) close in reconnaissance (~50 m); (2) radar imaging to characterize the deep interior; (3) blast experiments to gain insight into the morphology; and (4) seismic probes and landers. These four strategies give complementary information about NEAs. Technology is sufficiently mature to characterize the geophysics of these objects. However, new low-cost mission strategies are needed if we are to explore a representative sample of these diverse objects.

Tony Colaprete, Principal Investigator of the Lunar Crater Observation and Sensing Satellite (LCROSS) team, discussed how impact studies could be used as a means to study interior mechanics, structure, and composition. Data and simulations from Comet Tempel 1 (Deep Impact) and the Moon (LCROSS) were used to illustrate how observations of an impact (the flash, plume, and crater morphology) could be interpreted.

Colaprete noted that while impact studies can be used to determine the compositional and mechanical properties of targets, to derive the greatest information, one must observe the three phases of the impact, namely the impact flash, the ejecta curtain, and the target crater. Since the crater forms rather slowly due to the low gravitational field of the NEA, the greatest information is derived from having another spacecraft in close proximity to cover all three phases of the impact. To further quantify the formation times, calculations were carried out for a 2000 kg impact at 5 km/s at targets of varying gravity (private communication, Colaprete). Figure 1 shows the crater formation time(s) versus target gravity. For a 300-350 m diameter object, crater formation time is predicted to be on the order of 20 minutes.

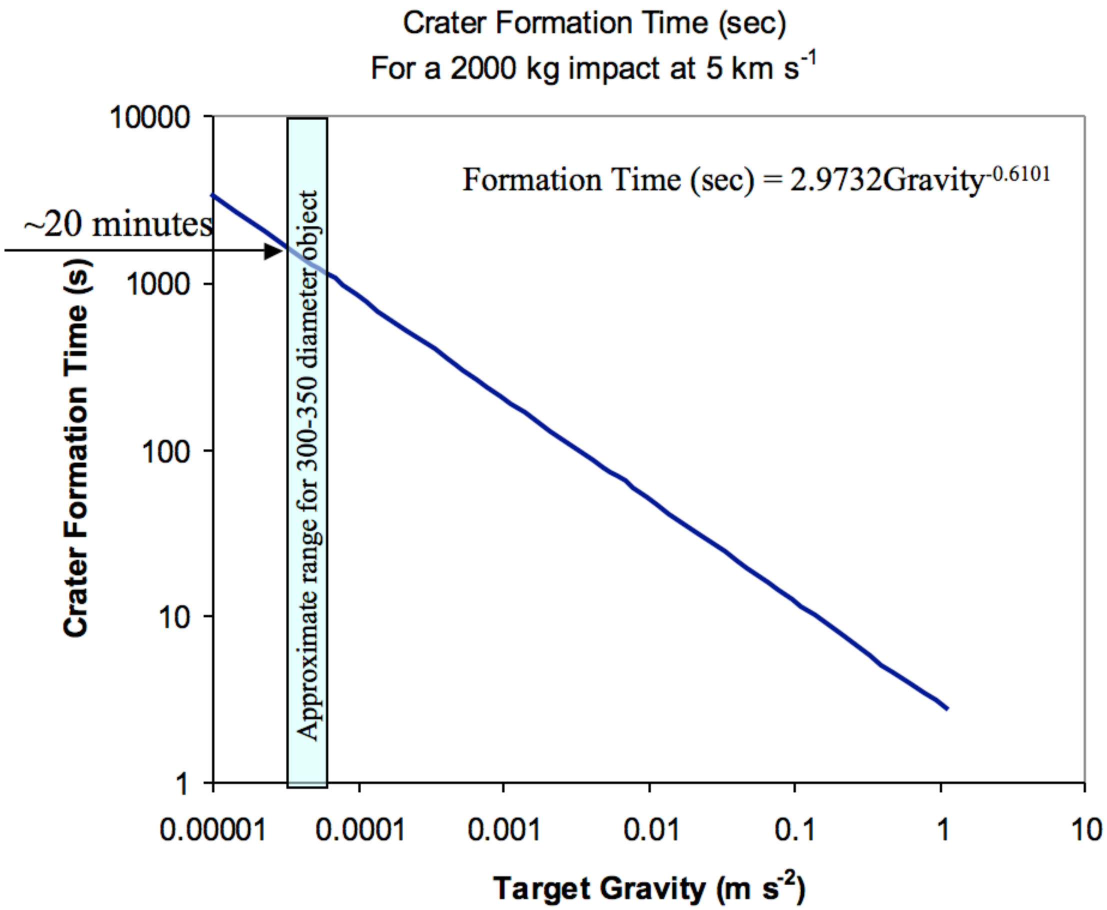

Figure 1. Crater formation time(s) versus target gravity.

In the first phase of the impact, observations must be made of both the visible and the near-infrared (NIR) component of the flash to determine the composition of the target material and the fraction of the impactor that vaporizes. The total energy that is released is sensitive to target properties such as material strength, density, and water content. The shape of the blackbody emission of the vapor cloud reflects the penetration depth and changes in material competence. After the flash, target material is ejected outward on ballistic trajectories forming an ejecta curtain. By measuring the evolution of the spectral brightness, one learns about the particle density, composition, size and shape, which in turn depend on the morphology of the target. The final phase of the impact occurs when the bulk of the ejecta "settle" exposing the fresh crater. The morphology of the resulting crater is sensitive to the strength, composition, and structure of the target.

The advantages of impacts include providing insight into the compositional and mechanical properties of the target by excavating a fresh crater, the creation of high-contrast spectral scenes that can be observed remotely, and it can be relatively inexpensive. Disadvantages include its transient nature, limited sampling, and the uncertainties in impact point that can complicate the decisiveness of the results.

Alan Harris reviewed the ways in which NEA populations are estimated from incomplete data. Surveys are complete for D > 3 km, but very sparse at the 100-m level. To find optimal targets for NEA rendezvous missions, it is necessary to understand NEA populations and orbital statistics. Harris discussed the current state of our understanding and the prospects for the future. He discussed several methods to estimate populations. The first method is to just find them all. This currently works for only the largest NEAs, e.g., we have found all NEAs > 5 km. Two other approaches are to estimate completion from the re-detection ratio, or from the relative completion of a survey model. The most important aspects of a survey model are the distribution of orbits and the duration of the simulated survey, because these two aspects determine the relative detectability of NEAs. The best representation of model populations was found to be in terms of the parameters inclination, perihelion, and aphelion. They used a probability distribution in these three parameters for the largest known objects in a size range that appears to be nearly complete to bootstrap to a smaller size. This assumes the populations are homologous with respect to size and that the quality of the distribution is dependent on the completeness in the largest sizes. The details of the simulations are beyond the scope of this report.

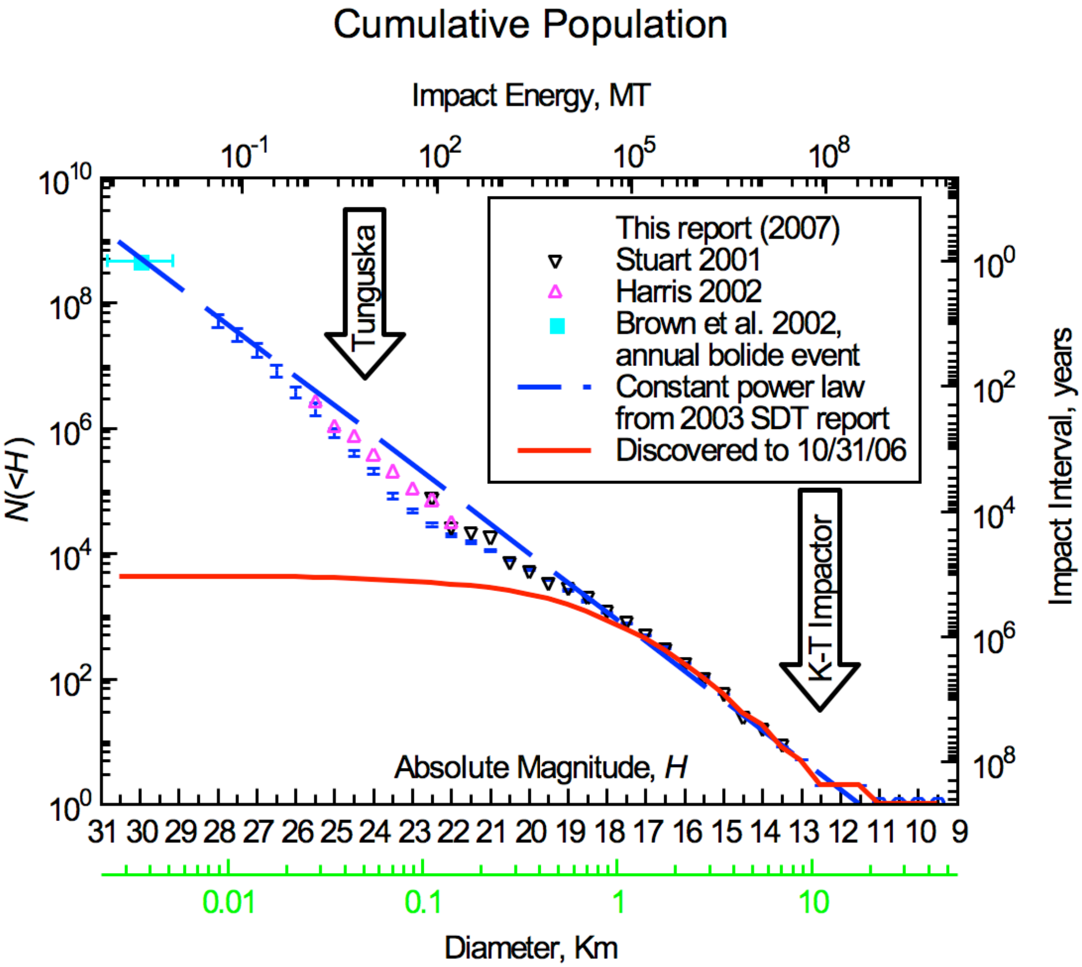

Figure 2. Our current knowledge of the population distribution.

Our current knowledge of the population distribution is shown in figure 2. Plotted on the bottom are the absolute magnitude (H) and the estimated diameter (km). On the left is the number (on a log plot) of NEAs brighter than a given magnitude. On the right is the estimated impact frequency in years and at the top, the estimated impact energy in megatons. Estimates of the K-T impactor and the Tunguska event provide some qualitative insight into magnitude. The red curve, which depicts the number of objects currently observed, shows that a significant fraction of the population has been observed only for the largest objects. The dashed blue line gives an estimate based on a constant power law. Interestingly, recent results from the Spaceguard Survey indicate a real departure from a power-law in the numbers of NEAs in the 100-200 m size range. This discontinuity in the size-frequency appears to correspond closely to the size limit of the rotational "spin barrier", which is presumed to be the transition from rubble pile structure to monolithic structure. Relative to the situation when the Congress asked for a survey to retire most of the risk from sub-km impactors, these new results suggest that we have already removed some 70% of the risk by this revision in the population of sub-km NEAs.

Two factors that affect the ease of rendezvous are the encounter velocity and the spin rate of the target. The launch velocity in excess of the escape velocity is small for a flyby or impact trajectory to an Earth-crossing asteroid. The difference in velocity (delta-V) in excess of escape velocity to rendezvous is approximately equal to the Earth encounter velocity. Thus, a rendezvous could be quite easy if you are allowed to choose the target, but quite difficult if Nature chooses it for you. Landing on a small asteroid is also complicated by high spin rates. Most asteroids smaller than 100 m are spinning so fast that acceleration at their equator is reversed (points up). The number of good rendezvous targets with low delta-V is currently limited, but should grow as our knowledge of the NEA population improves.

Richard Dissly discussed a Ball Aerospace Discovery class mission to rendezvous with a NEA and then deploy multiple small autonomous probe/landers to the surface. He noted that the same basic information on composition and structure is needed for science, hazard mitigation, and resource exploitation. Currently we do not know how low-g bodies respond to mechanical excitation (e.g., impacts), what the aggregate size distribution is in the interior, what the role of electrostatics is in controlling surface character, and how the uniformity changes with depth. Contact measurements are critical for understanding the mechanical properties such as cohesion and strength, and for measuring near-field forces. Therefore, the mission measurement goals are to understand the aggregate size distribution, how the regolith ejecta redistributes after an impact, how an NEO physically responds to impacts, and the role of electrostatics in shaping the surface.

He described a low-risk scalable mission design that addresses the above measurement goals. The mission would be carried out using a relatively small spacecraft and a set of small probes to touch the surface. Risk is reduced by using multiple, identical probes. The mission design is scalable, since it can access multiple rendezvous targets by increasing the delta-V capability of the carrier spacecraft and the number of probes. The design is a logical follow-on to the NEAR-Shoemaker and Hayabusa missions. He described Ball's asteroid surface probe that was battery powered and used cold gas thrusters for hopping to new locations. The probes would be equipped with cameras, accelerometers, X-ray fluorescence, and Langmuir instruments to study mechanical excitation and the aggregate size distribution of the interior components. Dissly gave a concept overview on how the asteroid surface probe could navigate on the surface of Eros. The probe would free-fall from the carrier spacecraft, and has enough fuel for five hops on the surface. Deceleration upon impact of the probe would provide information on regolith elasticity, and imaging would provide information on the local particle size with millimeter resolution in the near field. Local elemental composition would be provided using X-ray fluorescence.

The mission design includes a cratering experiment with some of the probes on the surface acting as a limited seismic network. By exploding small charges at the surface, detailed seismic profiles of the interior can be obtained, as well as observations of the disturbance of the regolith. The primary uncertainties involve the coupling of the probes with the surface, and hence, the ability to excite the interior and to measure this seismically. In microgravity, it would be easy to eject the probes with small disturbances. He ended his presentation by discussing the limitations of the mission design, e.g., the implementation requires a carrier spacecraft with a few km/s delta-V to rendezvous.

III. How to Get to NEA Targets

The second theme of the workshop was focused on navigation issues, and what were the current and future best targets for missions. Howard Eller spoke about potential new missions to several classes of asteroids, building on the proven technology that is being deployed on the LCROSS mission. Relatively low cost (<$100M) is achieved by launching these asteroid missions as secondary payloads using the available family of expendable launch vehicles such as Atlas and Delta rockets. Power would come from solar cells, and these might provide enough energy for a small ion drive engine when operating inside the Earth's orbit. He discussed a number of science-driven candidate secondary-payload asteroid missions. Examples included what we could learn about the event that created the Earth-Moon system from visiting an object that may have originated in that system, and an impactor or orbiter/lander mission to a Type-C NEA to determine whether they are rubble piles or solid bodies. He envisioned a series of 2-2.5 year development time missions that begin and launch yearly or every other year. Each mission would increase in complexity. As an example Eller suggested the following sequence of missions.

1. Type-C Asteroid flyby/impactor—e.g., 1992 NA
2. Impact an asteroid in an Earth-like or Horseshoe orbit—e.g., 2000 PH5 or 2003 YN107
3. Type-M Asteroid Orbiter/Lander—e.g., 1986 DA
4. Sample Return—e.g., from 2003 YN107 or 2000 PH5

Drawing on a lifetime of experience in deep space navigation, Bobby Williams (now at KinetX) emphasized that it is challenging to operate at great distances from Earth, and that one must proceed slowly and carefully. He discussed navigation strategy for flyby, orbiter and sample return missions. Unlike planetary orbiter missions, navigation to NEAs depends on rapid estimates of asteroid physical parameters such as spin state, shape, and gravity field. Therefore, orbit determination and trajectory correction maneuver strategies need flexibility and feedback during critical mission operations. This becomes more crucial as the proximity of operations increases, e.g., for landing or touch-and-go missions. He discussed the different types of tracking mechanisms and their relative strengths. These included Deep Space Network (DSN) radio metric tracking, optical navigation by imaging the target against a star background, and optical (laser) or radio reflection measurements. He noted the necessity of minimizing unmodeled accelerations on approach and the need for propulsive maneuver accuracy. Also he noted the requirement to thoroughly understand spacecraft accelerations from solar radiation pressure, which is comparable to the gravity field of the asteroid for such small targets.

For encounter and rendezvous missions, it is necessary to reduce relative velocity to capture speeds (m/sec) at the target. This requires a sequence of three to four maneuvers with each maneuver being 10-50% of the previous maneuver. He described the experience of NEAR-Shoemaker at Eros, when several months were spent gradually shrinking the orbit (by a factor of 2 steps) with detailed feedback from each step and associated improvement in the knowledge of the asteroid topography and gravity field. Orbital missions require both Doppler and optical data, and autonomous control generally requires a wide field-of-view (FOV) camera. It is critical to avoid unstable orbits, which generally require retrograde orbits within 4 asteroid radii. Sample return missions require Doppler, optical, and possibly altimeter tracking data. On landing or touch-and-go missions trajectory prediction accuracy is critical to meeting touchdown requirements. In conclusion, trajectory control at small targets depends on accurate dynamical models, spacecraft propulsive maneuvers, and tracking data. The required mix of DSN tracking, optical navigation, and altimeter measurements depends on mission type and asteroid characteristics.

David Dunham discussed possible sample return and low C3 (the hyperbolic excess over escape speed squared) rendezvous possibilities. The information is based on the currently known NEA population database that is kept on the JPL NEO website. Dunham discussed the details of calculating NEA orbits and suggested that the JPL orbit files on the Internet be reformatted to make such computations easier. Steve Chesley noted that, in fact, such data are available now from JPL if requested. Dunham has calculated rendezvous trajectories to a number of interesting NEAs including Apophis. He ended his presentation by discussing one possible design for a near Earth asteroid rendezvous spacecraft. The science payload contained a multispectral imager, near-infrared spectrometer, x-ray spectrometer, laser altimeter, and a magnetometer.

Regan Howard spoke about Orbital's vision for a low-cost mission to Apophis. This Potentially Hazardous Asteroid (PHA) is particularly interesting because of its close approach (7,000 km inside the GEO orbit) to Earth on April 13, 2029, and the very small probability that it could impact Earth in 2036. It is of interest, therefore, to characterize this asteroid more fully. The rendezvous mission he described would depart Earth in May 2012 with 309 days flight time and an achievable C3 of ~8.3 km^2/sec^2. The mission would launch from Wallops on a Minotaur V. The spacecraft would be relatively low cost and use proven technologies to minimize risk. The total cost for launch and spacecraft with ~20 kg payload would be on the order of $1M. One downside to the mission is the large rendezvous delta-V.

Malcolm LeCompte discussed a study of human NEA rendezvous missions using the Orion Crew Exploration Vehicle. The study showed that human exploration of NEAs is feasible using Constellation and EELV spacecraft. The easiest presently known target is 2000 SG344, with launch opportunities in 2028 and 2029. Overall, they identified 3 targets and 4 opportunities for missions between 2020 and 2030. This represents less than 1 percent of the more than 500 close approaches. Thus, it can be inferred that human sprint missions are not feasible to the vast majority of NEAs by any foreseeable form of chemical rocket propulsion due to the large C3s required. Al Harris noted that the lowest-energy targets have the lowest velocity as they pass Earth because they are in Earth-like orbits. These also have very long synodic periods, often more than 6 years, which can be a problem in obtaining required precursor data needed to plan a piloted mission. Further characterization of the NEA population will hopefully identify additional assessable targets.

IV. Current Mission Concepts

One of the highlights of the meeting was Hajime Yano's presentation on the Japanese Hayabusa mission to the sub-km NEA Itokawa, a presentation that included discussion of the challenges of operations near a small, highly irregular NEA. Full autonomy was required for operations near the asteroid, and each mission phase had to be modified and practiced after the spacecraft reached the asteroid.

To summarize the Hayabusa (MUSES-C) mission profile, it was launched on May 9, 2003 and rendezvoused with Itokawa on September 12, 2005 after an Earth gravity assist. The sampling and landing phase was November 19 and 25, 2005. The spacecraft departed the asteroid on April 25, 2007 and is scheduled to return to Earth in June 2010, with an entry capsule targeted to land in Australia. In addition to exploring an asteroid, the Hayabusa mission was used to establish technologies for deep space round-trip explorations. For example, it is using an ion engine system for interplanetary cruise and autonomous navigation and control by image processing. The mission demonstrated surface sample collection from a microgravity body and will hopefully demonstrate direct Earth re-entry from interplanetary space in the heritage of Genesis and Stardust.

The on-board scientific instruments included a sampler to collect surface samples, an optical camera, a laser altimeter to study the surface topology, a near-IR spectrometer (0.82-2.10 micrometer) to study surface mineralogy, an X-ray fluorescence spectrometer to study global surface composition, and cameras and heat probes to study the regolith condition and surface thermal properties.

The mission defined all of the fundamental parameters of Itokawa such as orbital elements, its size and principal axis, its rotational period, mass and bulk density. The asteroid is observed to have measurable variations in both color and albedo. Spectroscopic studies demonstrated that Itokawa fits with the LL chondrite class of meteorites, but the possibility that they may be primitive chondrites meteorites has not been ruled out. No substantial regional variation is found, indicating homogeneity in composition. The co-existence of both bright and dark materials on the surface may indicate that seismic shaking and other processes due to impacts or planetary encounters removed a part of the dark and boulder-rich surfaces.

There were a number of lessons learned from this so-far extremely successful mission that are worth emphasizing in this report:

1. Expect the unexpected—pre-arrival information is limited
2. Prepare with many rehearsals—rehearsals are necessary to maximize fuel and schedule —full autonomous navigation is not easy, especially with ~34 minutes delayed communication.
3. Understand microgravity—microgravity is not zero gravity—the smallest asteroid still pulls down your spacecraft and solar radiation pressure is important at some altitudes.
4. Know your enemy—global mapping for creating a 3-D shape model is a top priority during the observational period, and sample site characterization is vital for both mission safety and scientific gain.

5. Treat the whole spacecraft as an integrated sampling device—one must be prepared for any surface conditions, and pin-point landing accuracy is important
6. Build the best team in the world—success depends on the capability of the operation team.

Yano ended his presentation by talking about follow-on missions and international collaboration. The Hayabusa-2 mission will be the first rendezvous and sample return from a C-type asteroid. The target asteroid is 1999 JU3 with launch in November of 2011. He also discussed briefly the Hayabusa Mk-II (Marco Polo) mission to recover samples from a D-type asteroid or a comet like Wilson-Harrington. Yano also showed a beautiful 30-minute film of the Hayabusa Itokawa mission made for Japanese TV.

Julie Bellerose presented a mission design for travel to a binary asteroid system. It is estimated that 15% of NEAs are binaries. She presented a case study using an ellipsoid-sphere approximation to the binary system 1999 KW4. It is an extreme environment, because the primary (Alpha) spins very close to its disruption rate. Because of its rapid rotation, the lowest point on Alpha is at the equator, which is the furthest point from the body's center. Any loose material spun off Alpha is trapped by the secondary (Beta). Beta is stable and rotationally locked with Alpha. The mission design included six phases: (1) insertion into a reconnaissance orbit; (2) approach to Beta; (3) surface investigation of Beta; (4) transition to Alpha; (5) surface investigation of Alpha; and (6) rendezvous and return. The reconnaissance orbit was retrograde with an inclination of greater than 150 degrees for stability. The only entrance/exit region is through the L3 Lagrange point (see fig. 3). Surface packages are ejected from the back of the spacecraft, which stays on its retrograde orbit for communication. The surface of Beta is explored using "hoppers" and surface navigation using optical sensors and star trackers. Transfer from Beta to Alpha is challenging due to their relative spin rates. Alpha is also explored using "hoppers", which can hop with sufficient energy and rendezvous through L2 with the spacecraft. She showed an impressive video of the 1999KW4 binary with its rapidly spinning primary.

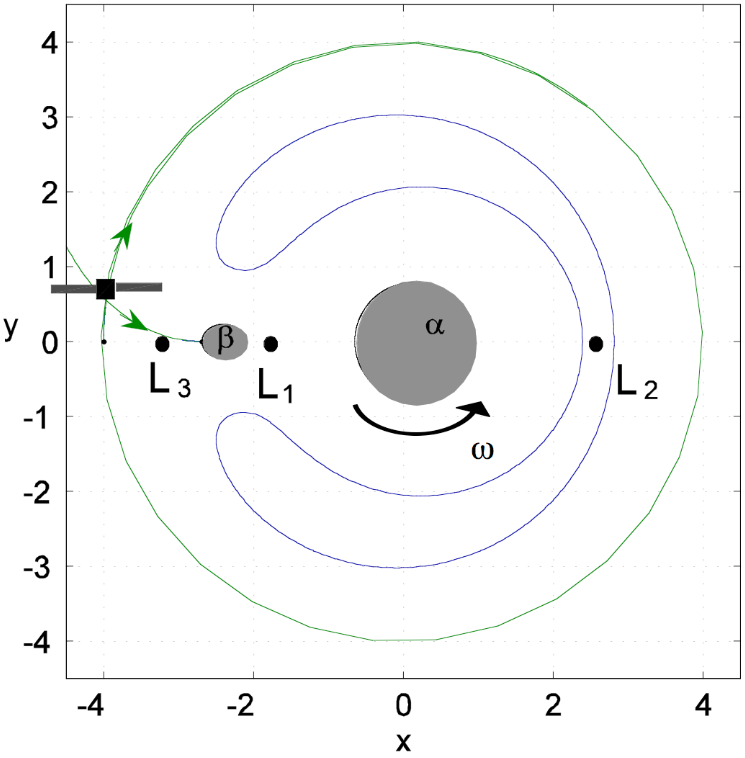

Figure 3. Approaching the Binary by L_3 to Beta.

Steven Chesley spoke about the feasibility of an add-on asteroid impact deflection mission. The impactor spacecraft would not launch until the observer spacecraft had successfully rendezvoused with the asteroid. While the impactor was enroute, the observer spacecraft would characterize the asteroid (spin, size, and shape) and accomplish primary mission goals such as mapping, sample collection, radio science, radar tomography, etc. Before impact, the observer spacecraft would assume a safe distance to observe the impact. In the weeks that follow impact, the observer spacecraft would characterize the crater, monitor the orbital dynamics of the ejecta, and measure the net impulse associated with the impact. Just about any NEA rendezvous mission could serve the role of observer, for example, ESA's Marco Polo or Don Quijote missions, JAXA's Hayabusa 2 mission, or NASA's OSIRIS mission.

Key feasibility issues were addressed in Chesley's presentation, such as, can we reach the asteroid with a small spacecraft at high impact velocity and with reasonable flight times? Can we hit a small (~200 m) NEA? Can we measure its deflection? These impactors can be launched as secondary payloads but require kick stages and perhaps solar electric propulsion to reach their targets and hit at high speeds. A straw-man mission was discussed based on the Don Quijote schedule and target. Terminal guidance of the impactor is critical. Compared to the Deep Impact mission, we have the advantage of detailed shape and spin models for the target from the observer spacecraft. However, the target is smaller and the encounter velocity is higher, and using the JPL autonomous navigation software for terminal guidance and existing optical cameras, studies showed that impact-targeting errors could easily be held below 100 meters. Measuring the deflection of the asteroid (net impulse) is complicated by the poorly constrained ejecta response, and the direction depends on the surface normal at the impact location. However, the ability to measure sub-mm/s deflections in the days/weeks that follow with radio and optical tracking makes measuring the deflection feasible.

Larry Lemke discussed the mission concept and current status of the European Space Agency (ESA) Don Quijote Mission. The purpose of the mission is to characterize and modify the orbit of an NEO representative of the potentially hazardous class. The characterization metrics are to determine the mass, shape, binarity, rotational state, velocity, composition and structure. The deflection metrics are to change the semi-major axis by more than 100 meters with an accuracy of 1/10 the deflection magnitude. The mission concept calls for two spacecraft—an orbiter carrying a small autonomous surface package, and an impactor. The orbiter spacecraft, Sancho, was to arrive at the target six months earlier than the impactor, Hidalgo, to observe before and after impact to determine the amount of momentum transfer. Instruments include a visible imager, laser altimeter, near-infrared spectrometer, and a thermal radiometer. The impactor spacecraft was to impact an asteroid of approximately 500 m diameter with a speed of about 10 km/sec.

To date, the Don Quijote mission has not been approved for flight. While the orbiter spacecraft fits well with the technical capabilities of ESA, the impactor spacecraft is problematic, since it would require a terminal guidance camera and an optics development effort, as well as a Russian launch. Therefore, ESA is looking for a non-ESA partner to fly the impactor. While ESA is still considering a Sancho-like mission, the contribution of an impactor and an Autonomous Surface Package-Deployment Engineering Experiment (ASP-DEX) to make measurements with "contact" instruments (e.g., Mossbauer, microscope, and camera) could restore the full functionality of the original Don Quijote mission.

Al Tadros and Andy Turner discussed Space Systems/Loral NEO Scout mission concept. The Scout is a modest mass (<100 kg) low-cost mission that would fly as a secondary payload on a commercial launch. Estimated launch costs are <$10M. The NEO Scout would reach GEO Transfer Orbit (GTO) on the commercial mission, with an ability to achieve 1- to 3-km/sec delta-V towards the target. The main advantage of the concept is that the mission can be flown much more cheaply by leveraging launch costs. Although the commercial spacecraft drives the launch schedule, some flexibility in schedule exists. The NEO Scout would observe an impact with the target using a separate copper impactor that is part of the ~20 kg payload. They also briefly discussed a follow-on NEO Inspector mission that would rendezvous with an NEA and then perform a global survey at close range and possibly extract samples for on-board inspection.

V. Low-Cost and Small Satellite Mission Concepts

At the beginning of the second day of the workshop, focus changed to discuss the potential for NEO missions using small spacecraft. Butler Hine discussed an NEA Rendezvous mission concept using small spacecraft with a common modular spacecraft bus. The key advantages of smaller, modular spacecraft are lower mission cost (<\$100M), shorter schedules (<24 months), and lower mass (<300 kg) with correspondingly lower launch costs. This enables more missions, faster learning cycles, and an ability to implement new technologies sooner. Overall program risk is reduced by providing several flight opportunities for critical instruments. Drawbacks of smaller spacecraft include elimination of some missions, higher individual mission risks, and use of "yet to be proven" launch vehicles. Flying as a secondary payload also reduces mission flexibility. The modular bus design enables both orbital and lander configurations with variable payloads.

The spacecraft is designed to fly within the shroud of either the Falcon 1 or the Minotaur V. The propulsion system runs on monomethyl hydrazine with nitrogen tetroxide as the oxidizer. A mission concept was presented using the common bus configuration and a Falcon-1 launch vehicle. The spacecraft was designed to rendezvous with an NEO target with a delta-V of ~3 km/sec. The spacecraft had a mass of 56 kg and the instrumentation consisted of a multispectral imager and either a laser or radar altimeter.

Robert Meurer discussed the low-cost responsive space modular bus that has been developed at Alliant Techsystems (ATK), and how it might enable low-cost missions to NEAs, from remote sensing and flybys to rendezvous, orbiting, and landing. Advantages of their bus include compatibility with Minotaur and other expendable launch vehicles, flexible launch mass contingent upon payload accommodation, precision pointing, robust power capability, and high-speed onboard processing. The bus can be configured with an optional add-on propulsion module. One interesting idea was to include an ion drive that uses the same fuel (hydrazine) as the chemical rockets, thus allowing a choice of propulsion at different phases of the mission. He illustrated the capabilities of the spacecraft bus by describing the successful Time History of Events and Macroevents during Substorms (THEMIS) mission. The THEMIS mission architecture, which consisted of a constellation of 5 satellites, demonstrated the multi-launch capability and modular design that enables scalable performance. The build and test phase of the mission required about 15 months. Thermal design allows the spacecraft to survive in a wide range of thermal environments. It is also adaptable to other instrument suites, making it an ideal platform to reach multiple asteroid targets.

Hugo Sanchez, a graduate student at UC Berkeley, discussed his recent project to design a nanosat to study Apophis. His talk focused on the challenges of doing an NEA mission for \$10 million rather than \$100 million. The design criteria were to build a scientifically capable inexpensive satellite (\$10-15M), with sufficient power (50 watts) and reasonable payload (5-10 kg) that was fast enough to rendezvous (1-2 km/s delta-V), and that was reliable (high technology readiness level of 7+). His mission, called the Near Earth Object Nanosat (NEON), has a goal of tracking and characterizing Apophis. The first phase will be to conduct a two-month orbital study using an imager, spectrometer, and altimeter. The second phase is to orbit Apophis to provide tracking. The total spacecraft and integration costs flown as a secondary are less than $6M with a schedule of 24 months to completion. The capabilities of the satellite include 21 kg total mass, deployment into GTO orbit, and payload power of 9-10W. In the first phase of the mission there will be a small imager for optical characterization. In the second phase the requirement is a high-power tracking payload. The satellite utilizes a high-performance propulsion system to achieve delta-V > 1.6 km/sec.

However, this preliminary design suffers from several shortcomings. A delta-V of 1.6 km/sec from GTO is still not enough for rendezvous. Also, 10W power is not enough for communication (25+W is needed at 0.3 AU), and finally, one instrument, an imager, is not sufficient to adequately characterize the asteroid. However, the study provides useful data in helping define the minimal cost needed for a mission to Apophis using current technology. Sanchez ended by looking at different trade-offs to add functionality to the mission. Lighter and cheaper instruments are one key driver. Launch efficiency is another, e.g., deploying multiple probes on a single launch. He concluded that technology is already close to capable of performing the mission for $10M.

Stanley Kennedy discussed micro- and nano-sat enabling technologies. He noted that Lockheed Martin has interest in both micro-sats and nano-sats, but this experience is largely limited to Earth-orbiting spacecraft. He described two of Lockheed Martin's spacecraft, the micro-sat (LM300), which has a wet mass of 140 kg, and the nano-sat (LM100), which has a mass of 25-50 kg.

VI. Piloted Missions to NEAs

Rob Landis talked about a technical feasibility study of piloted missions to NEAs using the Crew Exploration Vehicle (CEV). Possible launch vehicles for NEA missions include the Atlas 5 (heavy), the Delta IV (Heavy), and the Ares family of rockets. The objectives of the study were to examine the flight elements of the Constellation Program in order to best utilize the CEV (Orion) and Ares launch vehicles for NEO missions. This included an identification and assessment of candidate target NEOs with science justification. One of the outcomes of the study is the realization of the relatively small number of assessable known asteroids. The 2006 status of known (current) NEA population is shown in figure 4. Thus part of the presentation was an assessment of the number of known NEAs and a discussion of the NEA Program's next generation search. The NEA Next Gen Search (2008-2021) is expected to be at 100 times the current discovery rate. The PanSTARRS-4 survey under consideration is estimated to find more asteroids in the first month of operation than are currently known. By 2021, it is expected that ~20,000 potentially hazardous objects (PHOs) (140 m and larger) will be found. Many of these PHOs could be possible targets for a crewed NEA mission. Landis presented a number of crewed mission concepts that could take place in the 2015-2030 time frame. The feasibility of any mission depends greatly on the orbital phasing and the delta-V required for rendezvous to the NEO.

He noted that there was significant value in human exploration of NEAs. Of particular note is to assess the resource potential of asteroids for exploration and commercial use, and to demonstrate the utilitarian nature of the Constellation Program. He noted a logically elegant cycle of quantify-

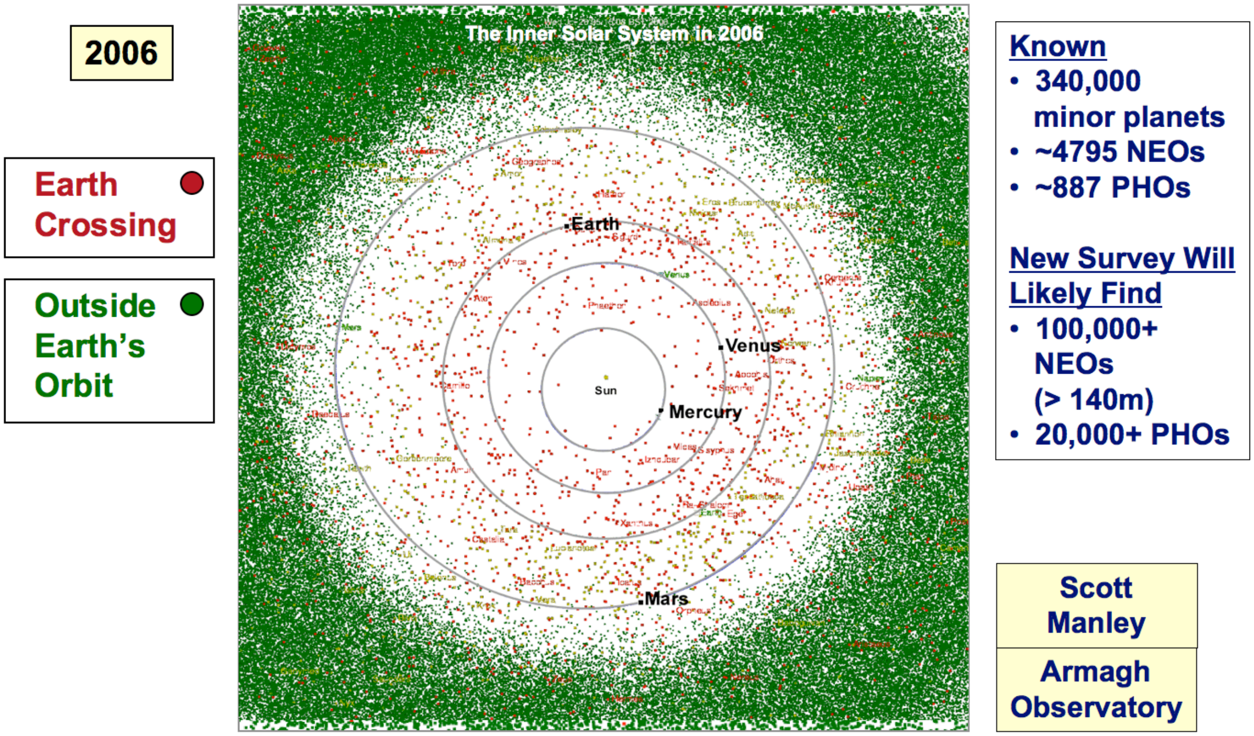

Figure 4. History of known (current) NEO population.

ing and tracking NEAs, assessing their impact threat, selecting an assessable target, visiting and conducting studies around asteroids, and while learning to deal with the threat, exploiting asteroid resources in future exploration efforts.

Paul Abell continued the discussion of piloted flights with an emphasis on precursor robotic missions. He noted that prior to sending a piloted mission to a NEA, a robotic precursor mission is required to obtain basic reconnaissance to assess potential hazards that may pose a risk to both crew and vehicle. Furthermore, assessing the surface maximizes mission efficiency of follow-on piloted missions using the CEV. As an example, he noted the difficulty in finding a good landing site on Itokowa during the Hayabusa mission. Abell noted that precursor mission instruments should include a high-resolution, optical camera for surface identification, navigation, characterization, and optical mapping. Additionally, Laser Imaging Detection and Ranging (LIDAR) should be included for topographical mapping, a visible and near-IR spectrometer for compositional investigation, and a small lander package for characterizing the surface.

CEV mission objectives include sample return, the determination of the internal structure of the target, and demonstration of in-situ resource utilization applications for water production or metal extraction. CEV mission instruments would likely include a tele-operated robotic rover, a multi-wavelength radar system, small instrument packages for surface deployment, and of course, the human crew that would interact with the surface. While human missions are currently limited to a few accessible NEOs, it was emphasized that precursor missions could be done at relatively low cost and should be sent to a variety of objects. This would not only be for basic reconnaissance of potential human mission targets, but also to characterize the diversity of geologic materials that exists within the NEO population. Evidence from the terrestrial meteorite collections suggests that materials from at least 120 different asteroid parent bodies has made its way to Earth.

Robert Farquhar discussed the recent International Academy of Astronautics (IAA) study to compare different approaches for human exploration beyond low-Earth orbit leading ultimately to the human exploration of Mars. He described an ongoing IAA study of an elaborate space architecture making use of spacecraft in halo orbits around the Sun-Earth L2 point. In addition to using such orbits for human-tended observatories, he advocated them as a staging area for low-energy piloted missions to NEAs, Phobus, and Mars, bypassing the Moon entirely. A basic assumption of the study was that the Crew Exploration Vehicle (Orion) and the crew launch vehicle (Ares-1) would be developed. The factors that were used to compare the IAA study to the current Vision for Space Exploration (VSE) were science value, cost effectiveness, mission risk, flexibility, sustainability, and possible extension to other exploration destinations. Farquhar showed several mission scenarios that involved rendezvous with NEAs using the Interplanetary Transport Vehicle (ITV). In the IAA vision for space exploration, the ability to rendezvous with and use NEAs and the Moons of Mars for space operations takes on much added significance.

Bruce Damer showed his visualization of a piloted flight to a NEA, and also a beautiful clip on asteroid impact from the Rose Planetarium's current show on cosmic impacts (created by Carter Emmet). Damer has had excellent media coverage, including a cover story in Popular Science.

VII. Breakout Sessions

In the afternoon, the workshop participants broke into three separate groups to address three questions in more detail, namely: (1) What are the minimum cost, high-science-value missions? (2) What information or technology is missing to enable such a mission? (3) Would this approach be suitable for a 2013 mission to Apophis? Group 1 was tasked with impactors (alone or with other elements), group 2 with orbiter, rendezvous, and flyby missions, and group 3 with lander missions (both in the short and long term). In addition, each group was to discuss and make recommendations on the advantages and challenges of low-cost missions.

GROUP 1: IMPACTOR MISSIONS TO CHARACTERIZE NEOS

Chris McKay chaired the first group charged with discussing potential impactor missions. The group's mantra was "Hit them before they hit us!" The group first identified both basic science and applied science reasons for wanting to characterize NEOs. The basic science reasons included measuring NEO physical characteristics and understanding their mineralogical and chemical composition, deciphering the relationships among asteroids, comets, and meteorites, and understanding the formation and geologic histories of NEOs. The applied science goals were to understand the NEO surface physical properties to aid the design of impactors, to understand the bulk properties of NEOs to allow modeling of their response to impacts, detonations or external forces, to determine the diversity in the NEO population with respect to mechanical and bulk properties, to provide calibration for remote Earth-observations, and to better understand the physics of low gravity hyper-velocity impacts.

The group considered four mission designs in order of increasing complexity. The simplest is to observe a single spacecraft (impactor) from the Earth, such as the Lunar Prospector end-of-mission crash into the Moon. Unfortunately, the spatial resolution was inadequate to observe either the plume or crater by a factor of 10^4. The next level of complexity is to employ two spacecraft, an impactor and an observation craft, which could be either a flyby or impactor (e.g., LCROSS where the observation craft also impacts). The group felt that observing the newly formed crater had priority over viewing the impact flash.

Another more complex two-spacecraft mission concept is to have an orbiter as one of the spacecraft. The orbiter could be pre-existing from another agency or a mission of opportunity. The impactor would need only a navigation camera to be able to hit the target. The orbiter would be equipped with a high-speed photometric camera for plume dynamics and mapping, cameras for a high-resolution mapping of the crater, and a near-IR spectrometer to measure mineralogy and composition. The orbiter would be able to observe the impact flash, the plume, and the resulting crater. The group considered this mission concept with an impactor and pre-existing orbiter (Don Quijote mission design) to be the best.

The group considered an additional mission design using three or more small spacecraft (two flybys: one for the plume and one for the crater). The first flyby spacecraft would be equipped with a high-speed photometric camera for plume dynamics and mapping, and the second flyby spacecraft would be equipped to map the crater for composition and possibly internal structure. This was considered to be a reasonably good mission design and one that might lend itself to cost savings by utilizing small spacecraft.

In terms of cost-benefit ranking, the orbiter/impactor model ranked highest, especially if the cost was shared between organizations. For example, in the Don Quijote mission, ESA would build the orbiter and an external partner would contribute the impactor. Three small spacecraft on one launch (one impactor and two imagers) would also be cost effective. Judging from the LCROSS model, the group felt that it would be possible to launch an impactor and a flyby spacecraft for <$100M plus launch costs.

The group did not feel that a 2013 impact mission to Apophis was appropriate, considering the sensitivity of the target. Although highly unlikely, a low-impact-momentum collision could knock the object into the keyhole. This probably could not be done as a secondary mission because of the limited launch window. However, the group felt that if sufficient delta-V were available and the size and rotation of the target was in acceptable range, such a mission could be accomplished by 2013 if it began soon.

GROUP 2: FLYBY, RENDEZVOUS, AND ORBITER MISSIONS

Group 2 was co-chaired by David Dunham and Pete Klupar. They approached the problem with a mission cost target of less than $100M, but preferred the $30M to $50M range. They also began by identifying the key science drivers. They noted that in-situ exploration of diverse NEOs is needed as "ground truth" for remote sensing, to investigate what caused the differentiation of some asteroids, the distinction between small asteroids and extinct comets, and the population of impactors that have contributed to the volatile inventories of the terrestrial planets. Other exploration objectives include investigating the size, shape, and dynamical state of diverse small NEAs, calibrating the Yarkovsky effect (the force acting on a rotating body in space caused by the anisotropic emission of thermal photons, which carry momentum), exploring the regolith and interior structure, and evaluating the probable response to ballistic impact.

They noted that flybys can be achieved with current technology, but provide only a few seconds of high-resolution data. They can provide the first close-up images of shape, large-scale morphology, boulder population, scars of past break-up events, small moons, and other evidence of their physical nature and recent collision history, but they are unable to determine mass, density, gravity field, thermal properties, or detailed topography. They are most useful for active comets (where a flyby can measure extended atmosphere), for NEO associated with meteoroid streams (where a flyby can confirm the object as being a dormant comet), or for classes of NEAs that cannot be reached by radar or by rendezvous missions. However, data return is many orders of magnitude less than from rendezvous missions. A flyby could be suitable for a 2013 mission to Apophis, because of its high public outreach value.

Rendezvous/orbiter missions are an excellent means of characterizing NEAs. They can provide detailed observations for as much as a year (as compared with a few seconds for a flyby). Rendezvous/orbiter missions are also valuable in conjunction with either impactors or landers, because they provide several months of orbital examination of the target. A basic rendezvous payload would consist of a camera with an imaging resolution of centimeters to 10's of meters and a 0.4 to 3.5 microns spectrometer with a resolution of 100. They scoped out a 2013 rendezvous mission to Apophis that could be launched for $50M, although no detailed cost analysis could be done within the limited time available. Their main conclusion was that we currently have the technology for such a mission.

GROUP 3: NEO LANDER MISSIONS

Randy Correll chaired Group 3, which was tasked with lander missions. They assumed that launch and deep spaceflight are provided by any of several low-cost concepts briefed during the workshop. Additionally, they made rough estimates of cost from data presented at the conference and space mission component cost data developed by NASA Ames. They were able to design a lander mission within the 100 kg mass and $30M cost constraints, with the caveat that a more detailed study is required to verify cost credibility.

When considering which lander missions to pursue, the focus must be on both science value and affordability. To assess the science value, the group focused on what landers can do that remote sensing couldn't. There are two types of measurements that are enabled by contact with the surface, namely, in situ composition and chemistry measurements to correlate with the remote sensing spectrum and meteoritic data, and seismic sounding measurements that reveal the internal structure and density distributions important for scientific understanding and for possible impact mitigation considerations.

For the composition and chemistry mission, they recommend an orbiter/lander/hopper flight profile where the spacecraft first rendezvous with the NEA and enters orbit to conduct a remote survey of the asteroid's size, shape, and gravity field. For low-cost missions, this survey would be minimal, with the majority of instrumentation being dedicated to surface measurements. The instrument suite would include visible cameras, grinding tools, laser ablators, and the relevant spectral or elemental identification detectors, Langmuire probes, and electromagnetometers. After the orbital survey is complete, the spacecraft would touch down on the surface to take appropriate measurements with its instruments. The lander then hops or levitates to other locations using its primary propulsion system and builds up a spatially diverse collection of in-situ data. This type of mission is essentially a poor-man's sample return mission but keeps mission mass, complexity, and cost down by avoiding the return flight and re-entry to Earth. While previous surface missions to Mars have used a variety of in-situ ablation and characterization instruments, it would be necessary to assess if these instruments are truly adequate in providing decisive science data not obtainable via remote sensing, and whether they can be used effectively in a micro-g environment. Lastly, the spacecraft could remain on the surface with some type of legacy functionality such as a transponder/beacon for precise orbit determination from Earth.

Seismic sounding measurements could best be accomplished through a network of probes deployed across the surface of the asteroid. The probes could be simple devices comprised of accelerometers, communications, batteries, and pyrotechnic charges. The spacecraft would first orbit the target to complete an initial survey and then deploy the probes, which could simply free-fall in the low-g environment to the surface. The probes' locations would be fixed through triangulation of their beacon signals by the orbiting dispenser/communications-relay spacecraft. Finally, a sequence of detonations and measurement cycles begin: one probe is commanded to detonate, the others collect the seismic data, and this is continued until all the probes are expended. The collection of seismic data would be accomplished within approximately 100 hours of probe battery life. Additional study needs to be undertaken to ensure probes could adequately couple to the surface to ensure seismic data collection and interpretation, and also that the detonations will be coupled enough to excite seismic activity (as opposed to simply launching the probe back into space).

For a 2013 mission to Apophis, this group recommended the seismic sounding mission for two reasons: (1) Apophis is of a NEA class fairly well characterized, and little additional insight would be gained by in situ measurements; and (2) the 2029 close-approach of Apophis with the Earth, where it will be subject to substantial tidal stress, will make understanding of its structural properties of great interest to the scientific community and to the general public.

Agenda

Workshop Report On Low-Cost Missions To Explore Near-Earth Objects (NEOs)

DAY ONE – Saturday, October 20, 2007

Time	Dur. (min)	Description	Speakers & Discussion leaders
8:00	30	Breakfast	
8:30	5	Logistics	Stephanie Langhoff
8:35	10	Welcome/objectives	Pete Worden
8:45	15	Introduction of participants	
Theme: Characterization of small NEOs Session Chair: Chris McKay			
9:00	15	TALK: Science Measurements needed for NEOs	David Morrison
9:15	15	TALK: Geophysics Missions/Instruments	Erik Asphaug
9:30	20	Discussion	
9:50	15	Break	
10:05	15	TALK: Impact Studies of NEOs to Determine Compositional and Mechanical Properties	Tony Colaprete
10:20	15	Discussion	
10:35	15	TALK: NEO Populations and Orbital Statistics	Alan Harris
10:50	15	Discussion	
11:05	15	TALK: Small Surface Probes for the In-situ Characterization of Asteroids and Comets	Richard Dissly
11:20	15	Discussion	
11:35	55	Lunch	
Theme: How to get to NEO targets Session Chair: Robert Farquhar			

12:30	15	TALK: Trajectories to Quasi-Earth, M-Class and C-Class asteroids	Howard Eller
12:45	15	Discussion	
13:00	15	TALK: Navigation to NEOs	Bobby Williams
13:15	15	Discussion	
13:30	15	TALK: NEO Rendezvous Opportunities	David Dunham
13:45	15	Discussion	
14:00	15	TALK:Low Cost Access to 99942 Apophis	Regan Howard
14:15	15	Discussion	
14:30	15	TALK: Near-Earth Asteroid Rendezvous Missions with the Orion Crew Exploration Vehicle	Malcolm LeCompte
14:45	15	Discussion	
15:00	20	Break- Birthday celebration	
Theme: Current mission concepts for NEOs Session Chair: Dan Durda			
15:20	20	TALK: The Hayabusa Mission to Itokawa	Hajime Yano
15:40	20	Discussion	
16:00	15	TALK: Dynamics and Mission Design for Travel to Binary Asteroids	Julie Bellerose
16:15	15	Discussion	
16:30	15	Talk: Feasibility Study for an Add-on Asteroid Impact Deflection Mission	Steve Chesley
16:45	15	Discussion	
17:00	15	TALK: Don Quixote Mission: Opportunities for International Collaboration	Larry Lemke

17:15	15	Discussion	
17:30	15	TALK:NEO Scout	Alfred Tadros
17:45	15	Discussion	
18:00		Adjourn- Wine and Cheese social	
19:00		DINNER: Chef Chu's, 1067 N San Antonio Rd. Los Altos	

DAY TWO – Sunday, October 21, 2007

Time	Dur. (min)	Description	Speakers & Discussion leaders
8:00	30	Breakfast	
Theme: Low-Cost and Small-sat Mission Concepts Session Chair: Pete Klupar			
8:30	15	TALK: Small Spacecraft NEO mission	Butler Hine
8:45	15	Discussion	
9:00	15	TALK: Very Low Cost Bus for NEO Missions	Robert Muerer
9:15	15	Discussion	
9:30	15	TALK: Small Sat Mission to Apophis	Hugo Sanchez
9:45	15	Discussion	
10:00	15	TALK:Micro and Nano-Satellite Enabling Technologies for Primary/Secondary Low-Cost NEO Missions of Opportunity	Stanley Kennedy, Jr.
10:15	15	Discussion	
10:30	15	Break	
Theme: Piloted Missions to NEOs Session Chair: Ed Lu			

10:45	15	TALK:Piloted Missions to Near-Earth Objects Using the CEV:Operational Outline and Constellation Goals	Rob Landis
11:00	15	Discussion	
11:15	15	TALK:Scientific Exploration of Near-Earth Objects: Precursor and CEV Mission Objectives	Paul Abell
11:30	15	Discussion	
11:45	15	TALK: Studies by the IAA on Human Missions to NEOs	Robert Farquhar
12:00	15	Discussion	
12:15	15	TALK: Design for a Human Mission to a Near Earth Object	Bruce Damer
12:30	60	Lunch	
Breakout Sessions			
13:30	5	Introduction to breakouts	Langhoff/Morrison
13:35	90	Breakouts on research questions and approaches: Advantages and Challenges of Three Classes of Missions (a) Impactors (b) Rendezvous (c) Landers	Chairs: (a) Chris McKay; (b) David Dunham and Pete Klupar; (c) Randy Correll
15:05	15	Break	
15:20	30	Reporting of breakout groups	
15:50	40	DISCUSSION: Research priorities-where do we go from here?	Pete Worden
16:30		Adjourn	

List of Participants

NAME	AFFILIATION
Paul Abell	NASA JSC / Planetary Science Institute
Erik Asphaug	UCSC
Julie Bellerose	University of Michigan
Michael Bicay	NASA Ames
James Bremer	ATK Space
Steve Chesley	JPL/Caltech
Anthony Colaprete	NASA Ames
Silvano Colombano	NASA Ames
Randy Correll	Ball Aerospace
Bruce Damer	DigitalSpace Corporation
Vince Deno	Millennium
Richard Dissly	Ball Aerospace
David Dunham	Johns Hopkins/Applied Physics Lab.
Daniel Durda	SwRI / NASA HQ
Howard Eller	Northrop Grumman Space Technology
Kenny Epstein	Ball Aerospace
Robert Farquhar	KinetX, Inc.
Craig Gravelle	AeroAstro
Alan Harris	Space Science Institute
Butler Hine	NASA Ames
John Hines	NASA Ames
Regan Howard	Orbital Sciences Corp
Dave Huntsman	NASA/GRC
Tomoko Ishihara	SETI Institute
BJ Jaroux	NASA Ames
Petrus Jenniskens	NASA Ames
John Karcz	NASA Ames
Stanley Kennedy	Lockheed Martin
Peter Klupar	NASA Ames
Rob Landis	NASA Johnson Space Center
Stephanie Langhoff	NASA Ames
Malcolm LeCompte	Elizabeth City State University
Larry Lemke	NASA Ames
Creon Levit	NASA Ames

List of Participants

NAME	AFFILIATION
Jack Lissauer	NASA Ames
Edwar Lu	Google
William Marshall	NASA Ames
Kevin Martin	SAIC/NASA Ames
Chris McKay	NASA Ames
Robert Meurer	ATK Space
Tom Meyer	Boulder Ctr for Science and Policy (BCSP)
Julie Mikula	NASA Ames
John Miles	LMCO
Joseph Minafra	Lockheed Martin
David Morrison	NASA Ames
Kevin Parkin	NASA Ames
Pat Patterson	SDL
Hugo Sanchez	Ames Co-op Student
Robbie Schingler	NASA Ames
Alfred Tadros	Space Systems/Loral
Domenick Tenerelli	LMCO
Andrew Turner	Space Systems/Loral
Alan Weston	NASA Ames
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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
05/015/2008

2. REPORT TYPE
Conference Proceedings

3. DATES COVERED *(From - To)*
10/20-21/2007

4. TITLE AND SUBTITLE
Workshop Report on the
Low-Cost Missions To Explore
Near-Earth Objects (NEOs)

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
292487.01.01.02

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
[1]NASA Ames Research Center, Moffett Field, CA 94035-1000
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8. PERFORMING ORGANIZATION REPORT NUMBER
A-080002

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington D.C. 20546-0001

10. SPONSORING/MONITOR'S ACRONYM(S)
NASA

11. SPONSORING/MONITORING REPORT NUMBER
NASA/CP–2008-214579

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified — Unlimited Distribution: Nonstandard
Subject Category: 12, 90
Availability: NASA CASI (301) 621-0390

13. SUPPLEMENTARY NOTES
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14. ABSTRACT

A workshop entitled "Low-cost Missions to Explore Near-Earth Objects (NEOs)" was held at Ames Research Center on 20-21 October 2007. The agenda blended five major themes: (1) the scientific importance of characterizing small Near-Earth Asteroids (NEAs) and the kinds of science measurements and instruments that are needed. This discussion included summaries of what is currently known about NEA populations and orbital statistics. (2) How to get to NEA targets, including direct vs. gravity-assist trajectories, and NEA rendezvous opportunities and proximity operations issues. (3) Current missions that have flown and feasibility studies for future missions. (4) Low-cost and small satellite concepts, especially as secondary payloads and missions of opportunity. (5) Piloted missions to NEAs, especially using future launch and Crew Exploration Vehicle (CEV) assets.

15. SUBJECT TERMS
Near-Earth Asteroids, low-cost small satellite missions, NEA mission concepts

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Stephanie Langhoff
Unclassified	Unclassified	Unclassified	Unclassified	35	19b. TELEPHONE *(Include area code)* (650) 604-6213