Surveying the inner Solar System

**A White Paper Submitted to the 2010 Decadal Survey Committee,
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Summary: The so-called *Spaceguard Survey*, utilizing telescopes in the ~1 m size range, has cataloged most of the largest (D > 1 km) NEOs thereby allaying >90% of the near-term impact hazard. A next generation survey, utilizing larger telescopes such as the LSST recommended in the last Decadal Survey and currently under construction, will be capable of reducing the residual risk by yet another order of magnitude (unless it should happen to find one on a collision course). Aside from risk reduction, the current survey has made or enabled scientific discoveries that have revolutionized our view of the asteroid belt and of the solar system itself, and the next generation survey stands to continue yielding rich scientific rewards. Thus, continuing the survey of the inner solar system is worthwhile on scientific grounds alone.

Introduction & background

In 1991-92, NASA commissioned a study on the hazard from Near-Earth Object (NEO) impacts. The resulting report, titled *The Spaceguard Survey* (David Morrison, Chair) recommended a system of several multi-meter telescopes to accomplish the task of finding most Earth-crossing asteroids larger than 1 km in diameter that could lead to a global climatic catastrophe resembling "nuclear winter" if one were to impact the Earth. In 1998, NASA adopted the task of finding 90% of such objects within ten years. Now, at the conclusion of that ten-year period, the various instruments employed in the survey (about half a dozen at any one time, all under 2 m aperture) have successfully found and cataloged an estimated 84% of such objects, in the process retiring, in the short term, more than 90% of the impact threat for the next half century or longer. That is, the present survey has certified that none of the 84% of the objects found have any significant chance of impacting in the next half century, thus the risk from that fraction of the population can be thought of as "retired", for the short term. The reason that constitutes more than 90% of the risk is that an even higher fraction of the largest, and hence most damaging, bodies have been found.

In 2002-3, NASA commissioned another study, asking what the next generation goal should be. The report that came out of that study recommended a next generation survey that would achieve 90% completion of all NEOs larger than 140 m diameter within a period of 10-20 years. A motivation for this goal was that the initial Spaceguard Survey was expected to retire about 90% of the impact risk, so a reasonable next goal could be to further reduce that by another order of magnitude, which the 90% to 140 m was projected to do. That goal was adopted in a Congressional mandate in 2005, specifically calling for it to be reached by 2020, and calling for NASA to report by December 2006 on cost-effective means of achieving that goal in that time.

As these various studies and surveys progressed, technology also progressed, as demonstrated by the fact that the initial *Spaceguard Goal* was achieved, or nearly so, with 1-2 m telescopes rather than the network of six 2.5-m telescopes that report recommended. Also during this time period, the last Decadal Survey of the NAS/NRC took note of this advancing technology and the ability now to survey the whole sky to unprecedented depth and in only a few days, allowing a "cinematic" view of the heavens. Among the recommended projects for the decade was the Large-aperture Synoptic Survey Telescope (LSST), with one of the primary missions to approach, perhaps even reach, the Congressionally mandated goal of 90% completion to 140 m diameter objects, although perhaps not quite by 2020.

Know the enemy: The NEO population

Although the possibility of a catastrophic impact of an asteroid or comet with the Earth has been recognized for decades and even centuries (Edmund Halley articulated the possibility in his publication of the orbit of the comet that now bears his name), one must discover a sample of the population of NEOs over the range of size of interest and map out the distribution of orbits in order to estimate the population and quantify the hazard in terms of impact frequency. Finding large long-period comets with enough lead time to do anything about them is far beyond current technology. Fortunately, comets constitute only a small fraction, not more than a few percent, of the total hazard. Thus, we will focus on Near-Earth Asteroids (NEAs) from here on. Figure 1 is the result of my recent study for NASA of the NEO population. At the largest end of the distribution, there are only a few NEAs the size of the impactor that killed the dinosaurs (~10 km in diameter), and we have no doubt found them all, except for long-period comets. As can be seen in Fig. 1, we have likely found essentially all NEAs larger than just a few km in diameter. We know this because we do not find any new ones; we just keep re-detecting the known ones over and over.

In the size range from ~1 km down to ~100 m, we can estimate the total population by the re-detection ratio. This ratio must be corrected for the fact that not all asteroids are equally easy to detect, and any survey is bound to find more of the easy ones first, so the actual completion will be less than the raw re-detection ratio. Reasonable correction factors can be estimated using computer simulations of actual surveys with known distributions of orbital parameters. These same computer models can be used to estimate relative detection efficiency of a survey and extend the population estimate to even smaller size NEAs where too few or even none are being re-detected.

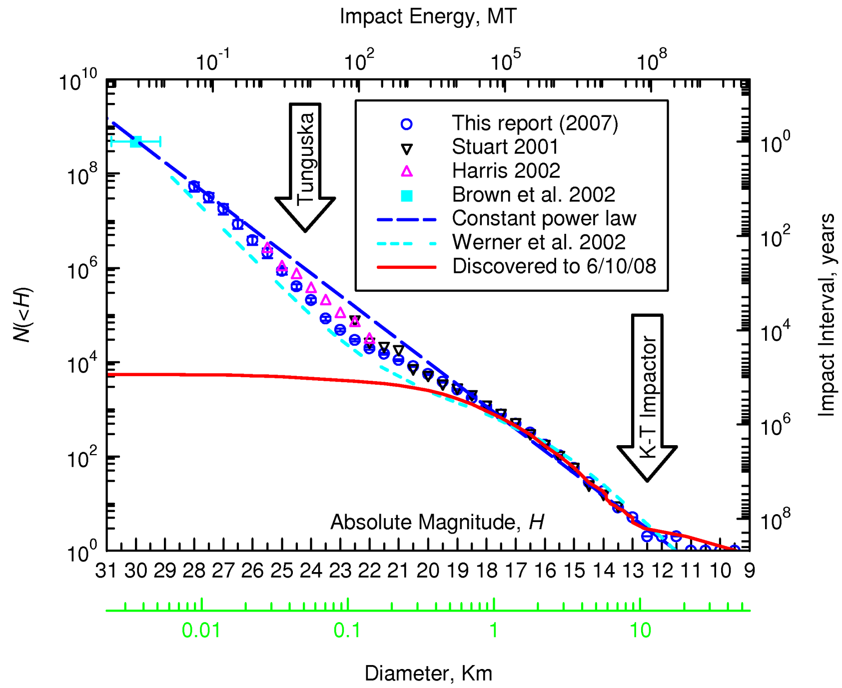

Figure 1. Cumulative number of NEAs brighter than a given absolute magnitude *H*, defined as the *V* magnitude an asteroid would have in the sky if observed at 1 AU distance from both the Earth and the sun, at zero phase angle. Ancillary scales give impact frequency (right), impact energy in megatons TNT for the mean impact velocity of ~20 km/sec (top), and the estimated diameter corresponding to the absolute magnitude *H* (second scale at bottom).

The main thing to note in Figure 1 is the dip in the currently estimated size-frequency distribution (blue symbols) in the size range from about half a km in diameter down to only 20-30 m diameter. The 2003 NASA report, in which the "next generation survey" goal was first articulated, used a straight-line population model (blue dashed line in Fig. 1) to estimate the NEA population and consequent impact hazard. This particular choice represents very well the population in the size range primarily addressed by the ongoing *Spaceguard Survey* ($D > 1$ km) but in fact over-estimates the population by a factor of 3 or so in the range of primary concern for the next generation survey, extending down to ~100 m.

The impact "kill curve"

The potential damage from a cosmic impact can be divided into four categories, with some overlap in size range of each. Below a certain size, currently thought to be around 30 m diameter (energy up to a megaton or so), incoming bodies explode high enough in the atmosphere that no ground damage occurs in the form of a blast wave. Sonic booms may break a few windows and there is some minimal risk from falling meteorites, but so far not a single death has been firmly documented in all recorded history from falling meteorites. In the next size range extending up to 100-150 m or so (100 MT), most of the impact energy is released in the atmosphere, resulting in ground damage more or less similar to a large nuclear blast. Over land, this has the potential to create major devastation, as can be seen by the scar of the Tunguska event of a century ago, although fortunately it happened in a remote area and no human fatalities are documented. Over sea, such an event likely would not cause any damage. Even larger events in which the incoming body would reach the ground still traveling at cosmic velocity would of course cause even greater damage over land, but it is expected that the larger risk in this size range is from tsunami from impacts occurring into the ocean. At some size, variously estimated between 1 and 2 km diameter, it is expected that the impact event would lead to a global climatic catastrophe due to dust lofted into the stratosphere, with the possibility of "ending civilization", perhaps killing a quarter or more of the human population from famine, disease, and general failure of social order. The eventual number of deaths from such an event would vastly exceed those killed immediately by the local blast damage. The global atmospheric catastrophe would occur even for an ocean impact, since such a large body would punch right through even a deep ocean to form a crater and loft debris into the atmosphere.

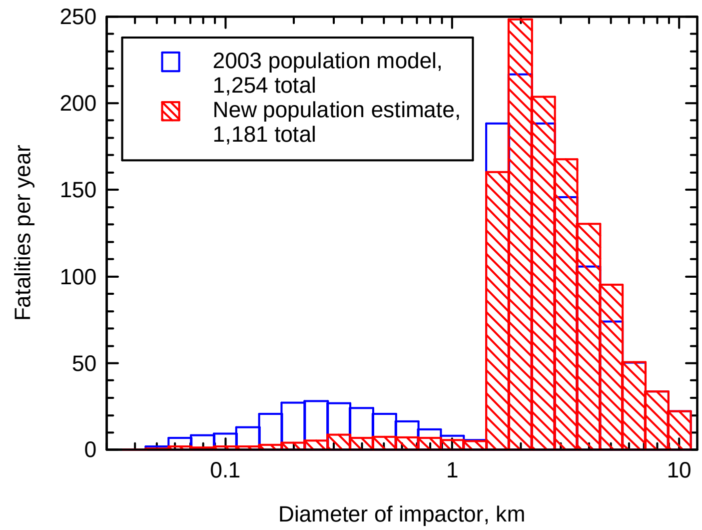

Figure 2. Intrinsic impact risk vs. size of impactor, before surveys retired any of the risk.

Multiplying the expected deaths per event by the frequency of events of a given size, one can estimate the "fatalities per year" from impacts as a function of size. Even though impact events don't occur every year, or even in a century, this is a useful metric to assess their importance. Figure 2 is a histogram showing this, for the intrinsic impact hazard, before any NEAs were discovered. The blue bars show the fatality estimates using the nominal (straight line in Fig. 1) population model used in the 2003 NASA study. The red bars are the estimates using the same "kill curve" vs. size, but for the most recent population estimate (blue plot points in Fig. 1). The total number of estimated fatalities is nearly the same for the two population estimates, but the revised rate from small size impactors is about three

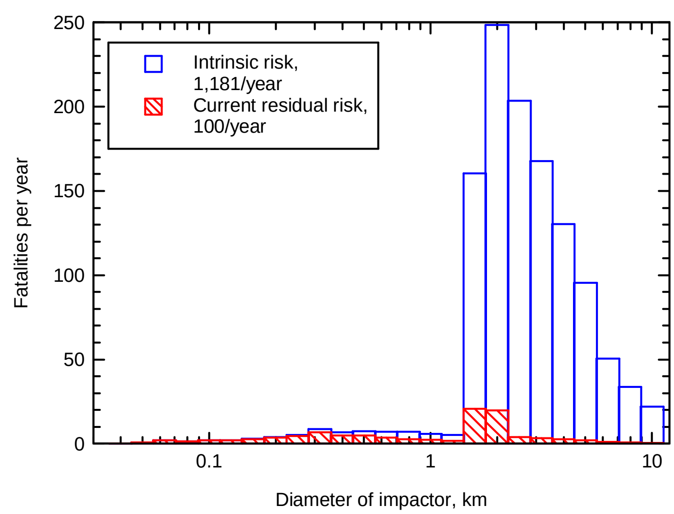

Figure 3. Impact risk, before any NEAs were discovered, and at present level of survey completion.

times less than before, as expected due to the "dip" in the new population estimate.

As NEAs are discovered and cataloged, we are able to determine if any one of them will impact the Earth, and when. So far, no discovered NEA has a significant chance of impact in the next 50 or so years, so we can think of that fraction of the impact risk as "retired" for the short term. Figure 3 shows the impact risk again, this time for the same population estimate, but "before and after", for the current level of survey completion.

Where are we now? Where are we going?

Table 1 summarizes the impact hazard, breaking out the components according to small land impacts, medium size tsunami-generating ocean impacts, and large size impacts leading to global consequences. Interestingly, the new population model has not changed the intrinsic risk estimate significantly, but it does lead to a reduction of about a factor of 3 in both the small and medium-sized impact hazard, the size range primarily targeted by the next generation survey. Comparing the intrinsic risk, for either the SDT population or the new population, with the residual risk at the current level of completion (next column over), we can see that the risk from global catastrophe has been dramatically reduced, so that the residual risk is about evenly divided between large (global) and smaller impacts. In the last column, I have projected ahead, using model completion curves, to estimate the remaining risk after the "Congressional mandate" goal of 90% completion down to a size of 140 m diameter is achieved. One can see that even then, the small residual risk from a global event (by then the fractional probability that even one object larger than 1 km in diameter remains undiscovered) remains a substantial fraction of the risk. Some final matters regarding the above charts and table should be noted. Not all of these "fatality" estimates represent actual fatalities. In earthquake-generated tsunami, only about 10% or less of people living in an inundation zone actually die in the event, the rest evacuate or are rescued. The fraction is probably no greater for an impact tsunami, so the Tsunami fatality numbers should perhaps be divided by about ten. Secondly, there is the risk from comets, which the surveys do not mitigate. It was estimated in the 2003 NASA report to be about 10 fatalities/year, in the "global" category, so that number is included in a separate line of the table. Finally, these numbers are estimates for worldwide fatality rates. For the U.S. only, all numbers should be divided by ~20. Thus, at present, the residual impact risk within the United States is only a few per year; meeting the Congressional mandate will reduce it to less than one.

Table 1. The impact hazard (fatalities/year), past, present and future.

Class	<D>, km	SDT Population	New Population	New Pop, current compl	New Pop, Next Gen
Land	0.05-0.15	61	23	11	4
Tsunami	0.15-0.70	182	59	35	3
Global	>1.5	1011	1098	54	11
Comets	>1.5	10	10	10	10
Total		1264	1191	110	28

Science from or enabled by the NEO survey

Confronted with the above low numbers for the remaining risk from impacts, it is natural to wonder if it is worth continuing surveys to further reduce the risk. My personal opinion is "yes, it is worth continuing the survey, but not for the sole purpose of risk reduction." Unlike fishing where you "throw the small ones back", we keep everything, and not just the NEOs. In the process of cataloging NEOs, we reap a rich harvest of science, both by mapping the full asteroid population throughout the solar system, but also by enabling a broad array of physical studies by providing targets for study by photometry, spectrophotometry, thermal IR, radar, and so forth. These studies have revolutionized our understanding of the small bodies in the solar system, and of the solar system itself. In a sense, the NEO survey is like a "whole life" insurance policy: it rewards us even if we never find a single "killer asteroid". In what follows, I offer some examples of scientific results, not intended to be comprehensive, which have been either the direct result of or enabled by surveys, that have revolutionized our understanding of the physical processes shaping our solar system.

The "HDTV" picture of the asteroid belt. Prior to the surveys, our view of the asteroid belt was like a snowy black and white TV image from the 1950's. Today we have the equivalent of "HDTV", in color, thanks to the hundred thousand known asteroids observed by the Sloan Digital Sky Survey, most of them discovered by the current surveys. In Fig. 4, resonance gaps and family clusters are clearly visible, with individual families showing uniform color as expected from common collisional genesis. More detailed studies reveal the subsequent drift of objects in the different families. The next generation surveys will be the equivalent of a 10-megapixel view of the asteroid belt. One can only speculate what that will reveal.

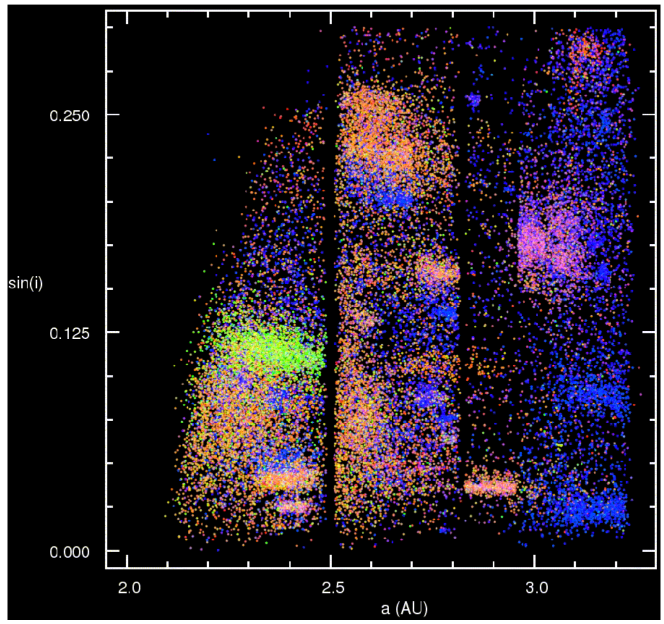

Figure 4. The asteroid belt in color from SDSS data. Parker, et al. *Icarus* **198**, 138-155, 2008

Radar images of asteroids. The images in Figure 5 show the actual visual perspective of the binary asteroid (66391) 1999 KW4 as seen from Earth during the time of the radar and optical observations. The mutual eclipses were actually detected and monitored in lightcurves. The full resolution reconstruction is actually far more detailed than these images. Passes close enough to the Earth for detailed radar imaging are rare for any given asteroid, but thanks to the surveys (this one was discovered by LINEAR), opportunities are now frequent, and will become even more plentiful with the next generation of surveys. Ostro *et al.*, *Science* **314**, 1276-1280 (2006).

Figure 5. Shape and configuration of (66391) 1999 KW4, reconstructed from radar data.

Binaries galore. The first satellite of an asteroid was discovered in Galileo spacecraft images of (243) Ida just fifteen years ago this month (February, 1994). Since then a total of 170 satellites have been found about small bodies of all kinds, NEAs, main-belt asteroids, Jupiter Trojans, and TNOs. They have been found by a number of techniques and instruments: radar, photometric lightcurves, adaptive optics, and HST, in addition to the one found by spacecraft encounter. Many of the main belt and near-Earth asteroid binaries are asteroids first discovered by the current surveys. The next generation surveys will probe to much smaller sized asteroids, allowing us to see if tiny monolithic "boulders" have satellites.

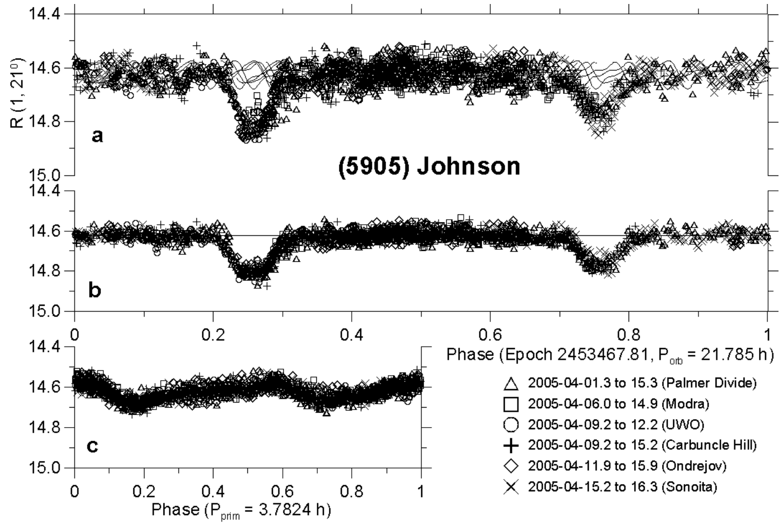

Figure 6. A small main-belt (Hungaria) asteroid binary detected by mutual eclipse phenomena observed in its lightcurve. The top two plots are composited with the period of the satellite, 21.8 hours, the top one as observed and the middle one with the rotational lightcurve subtracted out. The bottom curve is the rotational lightcurve (the part subtracted), plotted with that period, 3.78 hours. This binary was discovered by Brian Warner, as an amateur astronomer, using a "backyard telescope" and commercial CCD camera.

Yarkovsky Effect evolution of families. Our increased resolution view of the asteroid belt as shown in Figure 4 has allowed us to observe the drift of small asteroid orbits due to the Yarkovsky radiation pressure effect. The time delay between "noon" and maximum temperature of the "day" results in gentle thrusting in the direction of orbital motion for prograde rotation, or opposed to that direction for retrograde rotation, leading spiraling out or in, respectively. Figure 7 illustrates this effect for the Hungaria collisional family. The expected width of the family from the collisional disruption alone is only as wide as the green line in the middle. The present width is due almost entirely to Yarkovsky drift, the rate being inversely proportional to size due to the increasing area-to-mass ratio. The observed width of the family, indicated by the red lines, leads to an estimate of ~0.5 Gy since the family-forming collisional disruption. The next generation surveys will push the limits of the

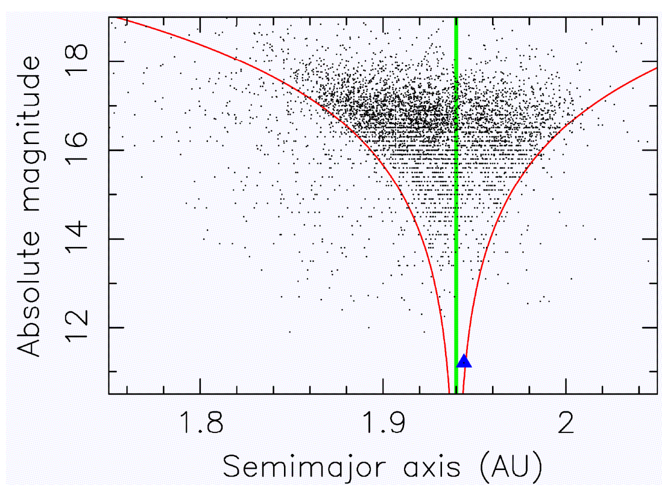

Figure 7. The Hungaria asteroid family, showing the increasing spread in semi-major axis with decreasing size (increasing absolute magnitude). The position of Hungaria itself is indicated with the larger triangular plot point. Warner, *et al.*, *Icarus, in press.*

cataloged family several magnitudes fainter, allowing us to see what happens when the spreading reaches the resonance boundaries of the Hungaria zone.

Comets in asteroid orbits and asteroids in comet orbits – blurring the distinction. Recently, several objects in ordinary main-belt asteroid orbits have been seen to exhibit comet-like coma and tails. Conversely, the surveys have discovered a number of asteroids in comet-like orbits. Some of these have approached the sun close enough that even a low level of volatile content should have resulted in cometary phenomena. These objects are likely the result of Jupiter ejecting some primordial asteroids into the Oort Cloud, just as it did material from outside of its orbit. How the "asteroidal comets" came to be is more of a mystery. The next generation survey will undoubtedly uncover more members of both of these strange classes of objects, and maybe reveal their origin and nature.

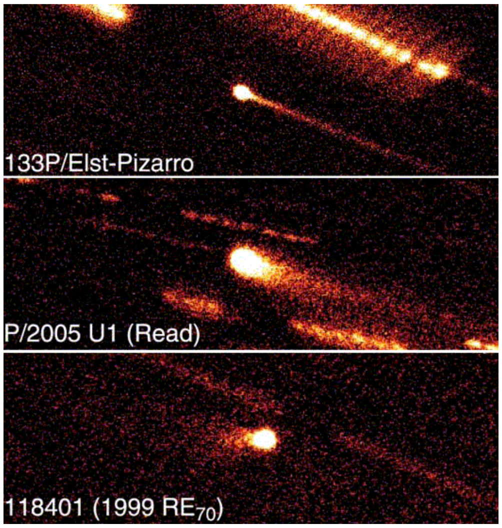

Figure 8. All three of these bodies are in ordinary "asteroidal" orbits in the outer main belt, a = 3.1-3.2 AU; e = 0.15-0.25; i = 0.2-1.4°; indeed falling in the orbital range of Themis family asteroids. Hsieh and Jewitt, *Science* **312**, 561-563, 2006.

Connecting asteroids to meteorites. On October 6, 2008, a very small asteroid was discovered by the Catalina Survey that entered the atmosphere over Sudan the next day, dropping meteorites on the desert below. Physical observations (spectral data, lightcurve observations) were obtained, as well as a good heliocentric orbit. For the first time, we have directly linked an asteroid in space with meteorite specimens on the ground. This will no doubt become commonplace with the next generation survey, promising to bring new insights into the asteroid-meteorite connection.

Conclusion

The *Spaceguard Survey* has been a remarkably successful endeavor. In ten years, it has reduced the short term (~50 years) residual risk from impacts on the Earth by an order of magnitude, and in particular has mostly erased the disturbing possibility of a disaster of unprecedented proportion that could bring an end to civilization. What remains is mostly in the range of other major natural disasters, like floods, tsunamis, and earthquakes that can cause perhaps a million fatalities, but not likely end civilization. Continuing the survey with still larger and more capable instruments, detectors and computers will further reduce the impact risk. At some point, the question comes whether it is worthwhile to further reduce the impact risk. The most important point we make in this white paper is that the scientific returns, which come hand-in-hand with the impact hazard survey, are in themselves well worth the cost, and promise to continue being so into the next generation survey.