NEO Survey: An Efficient Search for Near-Earth Objects by an IR Observatory in a Venus-like Orbit

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Abstract. In 2003 NASA commissioned a Science Definition Team (SDT) (Stokes, *et al.*, 2003) to study the threats posed by Near-Earth Objects (NEOs), recommend efficient methods for detecting NEOs down to 140 meters in diameter, and suggest conceptual mitigation techniques. In this same time frame, Congress set the goal of cataloguing 90% of all NEOs down to 140 meters diameter by 2020. The SDT concluded that the infrared passband from ~5 to ~11 microns is the best for finding NEOs; that an aperture of 50 centimeters is sufficient; and that locating a NEO-finding observatory in a Venus-like orbit is ideal. Since then, NASA and its industrial partners (such as Ball Aerospace) have flown two very NEO-relevant deep-space missions—the *Spitzer Space Telescope* and *Kepler*. Herein, a high-reliability, credibly-costed design is presented based on *Spitzer* and *Kepler* that meets the 90%/140-m/2020 requirements for about $600M. This design will also detect about 85% of all >100 meter NEOs, about 70% of all >65 meter NEOs, and about 50% of all >50 meter NEOs. These smaller NEOs constitute a newly recognized threat regime that cannot be efficiently found from the ground.

Keywords: Near-Earth Objects, Spacebased NEO Survey, Infrared NEO Detection, Venus-Like Orbits for NEO Detection, Planetary Defense, Low-Altitude Airbursts, Requirements of the George E. Brown Bill, PDC in Grenada, Spain.
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INTRODUCTION

This conference is apparently the first to focus in detail on the astrosociological aspects of Near-Earth Objects (NEOs). NEOs are a complex population of objects, composed of a variety of materials that enter the inner solar system in very dynamic orbits with a full range of inclinations. NEOs follow a power-law in their size-frequency distribution, so that the most threatening (large) objects impact the Earth very infrequently compared to the much more frequent impacts by smaller, less damaging, objects. NEOs are perhaps the only astronomical objects which make astronomy relevant to the average person. A surprising percentage of the general population is aware of NEOs, at least as a concept, and cares about them because of one thing—impacts—which is perhaps the defining astrosociological concern. And yet, Congress and the relevant government agencies are doing relatively very little about them. This is because NEOs (and their impact threats) are not deemed scientifically interesting enough by Congress and the relevant government agencies (generally NASA for spacebased surveys and the National Science Foundation for groundbased surveys) to justify the extra funds needed to find impactors by means of a thorough, fast, efficient and sensitive survey. But as we will show, a spacebased, infrared, NEO survey mission would provide the most efficient way to find the vast majority of the threatening NEOs. To the interested onlooker, it seems like the processes of NEO discovery and mitigation should reside within the capabilities of the world's space agencies.

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Crucial to the politics of NEO searches is the size-frequency distribution, which until the past two or three years has statistically indicated that the next significant impact is not likely for maybe 1,000 years, enough time for the groundbased community to find most of the NEOs with diameters roughly larger than 100 meters. However, M. Boslough (2009), of Sandia National Labs, has recently changed this argument by applying supercomputing-based numerical codes, used to model nuclear detonations, to the enigma of the Libyan Desert Glass (LDG) event. Boslough concluded that a 100-meter-class NEO disintegrated in the air far above the Saharan desert, with all of its kinetic energy and momentum continuing downwards as something informally referred to as an "air hammer." When this air hammer struck the Earth's surface, the entrained fireball initially had core temperatures on the order of 5,000 kelvin. The fireball portion of this complex event then spread laterally to about 20 kilometers in diameter. The air hammer also produced a hypersonic blast wave that extended radially for perhaps 50 kilometers. The fireball portion of the interaction remained on the ground for about 40 seconds and melted a patch of sand some 15 kilometers in diameter and several centimeters thick to produce the Libyan Desert Glass. Occasional expeditions to the site collect 100s of kilograms of the glass and sell it on the internet for a few dollars a gram.

Boslough (2009) also modeled the 1908 Tunguska event and rescaled the estimated size of the Tunguska body downwards from ~80 meters to ~30 meters. At this new size, the mean interval between impacts is 150 years. Here is where the astrosociology of this paper's contents becomes pertinent—

This newly recognized threat régime (diameter >30 meters) contains far more objects than the diameter >140 meter NEOs. This 140-meter threshold arose circa 2003 when the United States Congress set the goal of compiling a catalogue complete to 90% by 2020 of all NEOs larger than 140 meters in diameter. This 90%, 140 meter, 2020 set of goals was named in honor of George E. Brown (GEB). Merging the GEB goals to Boslough's (2009) work gives two results. The first is that all the 1,000-year-interval arguments no longer work. Instead, the mean interval between serious impacts is roughly 150 to 200 years. This shortened mean-interval forcefully argues for an efficient and timely NEO survey being completed in the next few years. Next (and this point is both subtle and powerful), typical arguments against performing a spacebased survey usually begin by a person saying something like-- "Yes, an event similar to Tunguska might happen in the next 100 years, but so what? Roughly six percent of the Earth's surface is populated, so the next event is likely to be a non-event in terms of fatalities."

However, even though ~6% of the Earth's surface is populated, the world's widely distributed infrastructure is vastly larger and extremely vulnerable to the physics of Boslough's (2009) modeled airbursts. A typical LAA airburst could create a cascade of failures across many distributed and interconnected networks which would be extensive, unpredictable, and impossible to quantify. Additionally consider the following: Suppose a large-scale airburst occurred above the Indian Ocean and killed no one. The resulting psychological trauma around the world could create panic on an unprecedented scale, panic which would at least ripple though the global financial markets. And if such an airburst happened without warning in places like the Middle East, or the much larger, and nuclear-armed areas of Asia or Russia, the resulting response could initiate a chain of human events resulting in severe military action. It's this nonlinear psychological aspect that needs addressing in this conference because its message has been overlooked in the past. Most risk analyses done to date have only considered what can be quantified—the immediate body count and all the property damage arising from the initial impact. Perhaps this conference should place an added emphasis on the world's vastly extended infrastructure and its interdependency, as well as the realities of large-scale human reaction to a sudden and catastrophic airburst vent.

The key to mitigation is discovery. And the fastest possible method for finding NEOs is to look for them in the thermal-infrared band from ~6 to ~11 microns with a telescope having an aperture of 50 centimeters that is located in a Venus-like orbit with a semi-major axis of about 0.7-AU. Such a system is presented in this paper and is based on experience gained from two very relevant, deep-space missions: the infrared Spitzer Space Telescope and the large-aperture Kepler mission. Both systems are currently operating and exceeding specifications in deep space. Because the design presented herein is closely based on these two flight systems, the mission described in this paper has a robust cost estimate due to the use of actual final costs for nearly identical systems. Every aspect of this design is a *lowering* of complexity compared to its flight-heritage program element.

A detailed computer model of the flight system and the NEO search process was created by Ball Aerospace to guide the development of this observatory. The main details of this model are included below. The Ball model has been compared against a similar model built for the same purpose by the Jet Propulsion Laboratory (JPL) circa 2003, as well as to another similar model developed by the Large Synoptic Survey Telescope (LSST) for its own purposes. (LSST is not yet in any funding queue, and if built would take perhaps 15 to 30 years after first light to complete the GEB-level mission). Recently, the integrated Ball model, which evaluates only flight systems, has been uploaded into the groundbased-only LSST model, thus providing the community with an improved model that can compare any mission design in any orbit in any passband. The Ball-LSST model has been compared (as separate elements) against the JPL model using test objects, and then with simulated missions, and all three models converge on the same results.

All of this modeling supports the 2003 Science Definition Team's (SDT) conclusion that a half-meter, infrared system operating in a Venus-like orbit, by itself, will find 90 percent of all the greater than 140 meter diameter NEOs in just over seven years. While doing so, it will also find about 70 percent of all the greater than 100 meter diameter NEOs and about 50 percent of all the greater then 50 meter diameter NEOs. Adding a groundbased visible light telescope such as Pan-STARRS1 to this spacebased infrared mission reduces the time-to-90% completion from a little over seven years to a little over five years. It is especially relevant that deep-space-based infrared is the only approach that will meet the performance levels stated above regarding the smaller NEOs, and is the only design that finds them in such numbers at such a high rate. Note well that these smaller NEOs constitute Boslough's (2009) newly discovered threat régime.

If, as moral societies wishing to mitigate the threat of a large-scale loss of human life, unforeseen economic disruption and massive physical infrastructure damage, coupled to the unpredictable reaction of societies to such a trauma, we look at the NEO situation from this new perspective, then for the first time in human history NASA and its industrial base (or ESA and its technical base) have the unprecedented chance, for close to \$600M, to deterministically answer the question: are we safe for the next 100 years? If we are, then we, as a population, will have at least attained an extensive data set regarding NEOs for future use. If we are not, then any mission like the one described herein becomes the first vital link for preventing a natural disaster of this scale—the only kind of natural disaster of this scale which humans can prevent, at least in principle. Stated another way, with enough warning time, humans can move an impact off the Earth, thus mitigating a global, life-altering threat. But like treating cancer, the key to survival is early discovery. A mission such as this one represents the fastest possible means to discover, initially track, and then successfully mitigate the threat.

This is no longer an arcane scientific discussion—this is now a matter of doing something relatively small and affordable that can act as an insurance policy for everyone on Earth, or in the safest outcome will yield a very large data set about NEOs for future work.

CONCEPT OF OPERATIONS (CONOPS)

Figure 1 shows the basic CONOPS and illustrates the greatly expanded search region available from a Venus-like orbit compared to any groundbased option. The depicted orbits are to scale, and the red ellipse is the nominal Venus-like orbit having a semimajor axis of 0.7 AU with an orbital period of ~206 days and a synodic period of ~514 days (vital for discovering dangerous NEOs having roughly Earth-like orbits, as discussed later). The Venus-like orbit is very important and distinguishes the *NEO Survey* CONOPS because it is the orbit in general that's important, not the location along the orbit. For example, the proposed *NEO Survey* orbit is preferred to any Venus-Lagrangian orbit or Venus-capture orbit because the flyby orbit is easier and safer to obtain through a single, unpowered, low-criticality, one-time flyby of Venus as opposed to a series of complex orbital-insertion burns. The mission's final results are not sensitive to the orbit's final details as long as the final orbit is roughly within the 0.8 AU by 0.6 AU boundaries.

Figure 1 shows that the *NEO Survey* design has a 200 degree full-opening-angle field of regard (FOR), slightly more than the entire anti-Sun hemisphere. A 24-day observing cycle is presumed with two pairs of visits to all areas in the FOR. However, the final cadence is a function of which sky-tiling pattern is implemented. *NEO Survey's* 2 degree by 5.5 degree field of view (FOV) scans the sky at 165 square-degrees per hour and completes its mission in 7.5 years, or 5.5 years with the addition of a single groundbased asset such as Pan-STARRS-1. *NEO Survey* operates in a step-and-stare mode with 3 minute exposures and 1 minute to step-and-settle to the next field, a routine level of agility and stability for modern spacecraft.

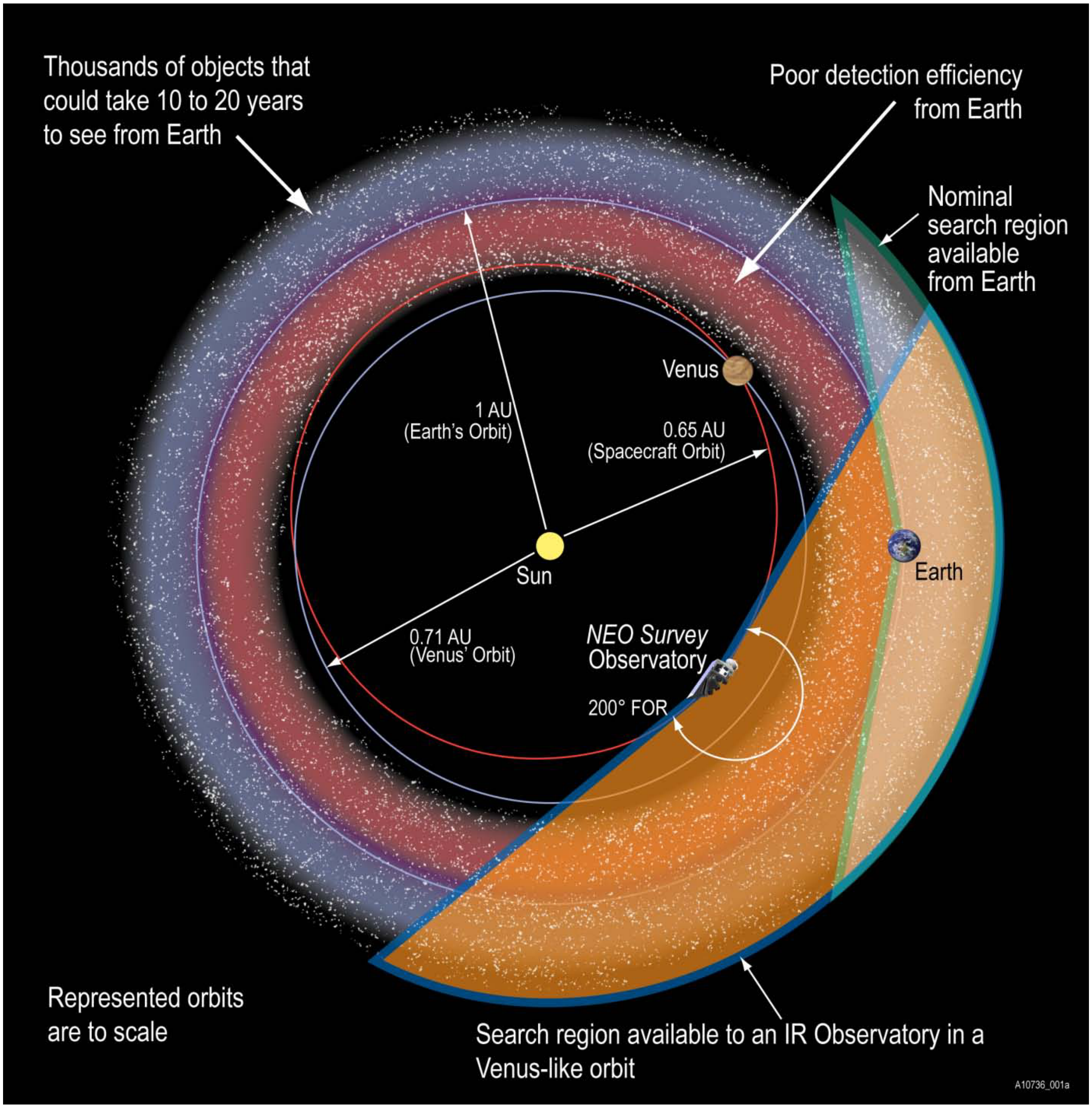


FIGURE 1. Illustrates the *NEO Survey* field of regard and the advantages of a Venus-like orbit.

Figure 2 is a computer generated rendering showing how the system is designed to always keep the solar shield and the solar cells pointed in the Sun-line direction, and the instrument always in the shade for passive cooling, and the line-of-sight always in the anti-Sun hemisphere.

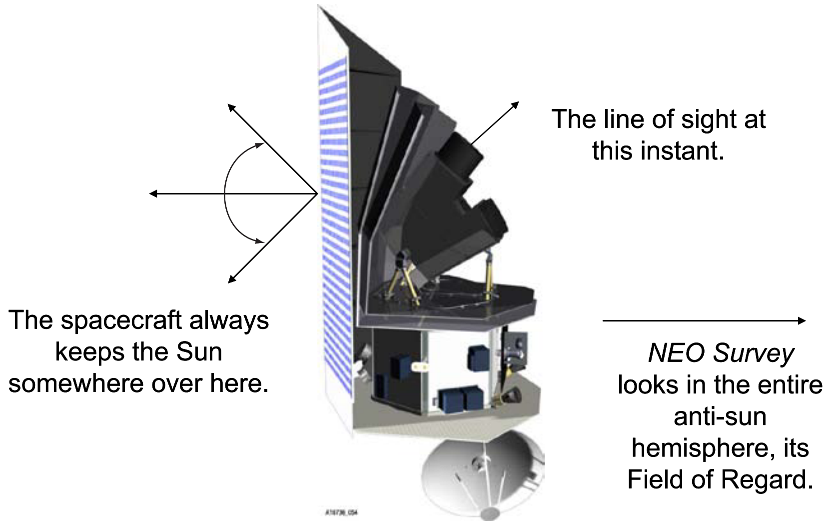


FIGURE 2. Illustrates the tilting of the instrument's line of sight (LOS) with respect to the anti-Sun line to facilitate the design of the solar arrays and the thermal management system.

WHY THIS MISSION? WHY NOW?

Groundbased searches at visible wavelengths are nearing 90% completeness for NEOs having diameters greater than 1,000 meters. Extending the effort down to diameters of 140 meters, and smaller, is very challenging from the ground due to visible albedos of ~20% or less, unfavorable phase functions in reflected light, and difficulties observing near the Sun. Use of a dedicated mid-infrared telescope in a Venus-like orbit greatly improves the search efficiency for several reasons such as NEOs in small orbits can be observed at larger solar elongation angles than from the Earth and most of the radiated energy from NEOs emerges in the thermal infrared, meaning that the phase function of infrared (thermal) emission is more favorable than for reflection at visible wavelengths. *NEO Survey* also accesses a greatly expanded near-Earth region in the FOR as discussed next.

Any NEO in roughly an Earth-like orbit will approximately have an Earth-like period and will be hard to detect from the ground for many reasons. For example, if a nearby NEO has an orbit that is similar to, but is 5% different than the Earth's, then its next Earth-approach will happen in 20 years. During the vast bulk of these 20 years, this NEO will reside in the daytime sky and be unobservable from the ground. Yet when it returns, it will very likely come at the Earth from the daytime sky with little or no warning. But from a Venus-like orbit all such objects are easily detectable on the scale of ~520 days. Thus, 10 to 15 years of advanced warning could be given, time that is vital for any mitigation mission to succeed.

As reviewed in the Introduction, recent work by Boslough (2009) shows that the impact-physics of NEOs having diameters in the 30-100 meter range has been seriously misunderstood due to a process he named a Low-Altitude Airburst (LAA). In an LAA event, the main body of the NEO physically comes apart at high altitudes (~10 to ~80-km), but the object's mass and kinetic energy are conserved as a fast moving, loosely aggregated, collection of particles that entrain a column of air which reaches the ground as "air hammer." Boslough's work shows that the air hammer from NEOs as small as 30 meters will inflict significant damage on the ground, as was seen in the 30-meter-class Tunguska event. Boslough has also shown that an LAA from a ~100 meter diameter NEO melted sand into glass across a region about 10-km in diameter during Libyan Desert Glass impact ~35 million years ago. During this event the LAA-induced fireball settled onto parts of modern Egypt and Libya for about a minute with temperatures approaching 5,000K—hotter than the Sun's surface. Additionally, the hypersonic blast wave from this event perhaps extended eighty kilometers from the melt zone. Boslough has also shown that the interaction of an LAA with the ocean's surface is much different from that of a large object striking offshore, therefore the tsunami risk from an LAA event is not well understood, either, but is different than previously thought. Therefore any survey instrument capable of searching well below the GEB limit of 140 meters is quite valuable. The *NEO Survey* concept shown here captures about half of the >50 meter-class NEOs in its 7-year mission, and the completion rate increases rapidly with increasing diameter up to the design goal of 90% for all 140 meters, and larger, objects.

Derating the Tunguska object from ~80 meters to today's ~30 meters greatly decreases the mean impact interval from ~1,000 years to ~150 years. Given that Tunguska happened 101 years ago, the next impact is arguably 50 to 100 years away, so why the urgency?

From contract start, it would take an experienced aerospace contractor about 3 years to build and launch *NEO Survey*, and then 7 more years (worst case) to complete the catalogue, or 10 years to completion. Assume for the moment that near the end of this period of 10 years, a 50-meter diameter NEO is discovered having an impact date in 50 years. What does this mean?

Groundbased systems could easily miss such an object for an apparition or two, resulting in perhaps a few years, or perhaps a few months of warning time before impact. If, by remote chance, it was determined that the strike location was close to a high-density human population, it would force the evacuation of millions of people from a large geographic area and would produce a long-lasting, global sociological disruption that would eventually outweigh the immediate harm resulting from a large-scale loss of human life and damage to a distributed infrastructure. And since there is no predicting the reaction of populations or their governments to such a trauma, such an incident could possibly trigger a chain of events resulting in military action of unforeseeable severity. Clearly, the effect of such an event on the global economy could also be large compared to the cost of flying a sensitive and efficient NEO cataloguing mission. Consider also the value of finally having a *deterministic* answer to the question: "Are we safe for the next few hundred years?" as opposed to the present case of arguing from statistics.

If *NEO Survey* found an incoming NEO with a warning time of only 50 years, what would it take to execute a successful mitigation effort, and how long would that effort last? To begin with, it would take a year or two for groundbased assets to do detailed follow-up orbital refinements. Then, a space mission to the object would be required for in-situ characterization because all conceivable mitigation techniques require detailed knowledge of the object's composition, mechanical properties, spin state, whether it has a moonlet, and so on. Only then could the appropriate mitigation solution be chosen and negotiated in a global political setting. It would then take an additional 10 years, approximately, to design, build, fly, and complete the mitigation task. Additionally, the results of any mitigation action would have to be closely monitored, and perhaps a second mitigation mission would be required to produce the desired final result.

These timelines are in series and mean that 50 years of lead-time is almost tomorrow. Reliance on groundbased assets to find these smaller NEOs over a period of decades ignores the threats LAAs represent to the modern world. Additionally, the longer the warning time becomes, the less delta-vee is needed to move an impact off the Earth, simplifying the mitigation effort. For example, the difference between 10 years and 20 years of warning time could enable a passive mitigation option compared to a nuclear option.

WHY THE THERMAL INFRARED?

Objects at ~0.8 to ~2.5 AU of solar distance have equilibrium temperatures in the range of 170K-300K, which makes the 5 to 11 micron band ideal. The thermal inertia (Delbo *et al.*, 2007) of NEOs, when coupled to their rapid spin rates, means that most NEOs have modest temperature variations across their surfaces. Thus, the solar phase angle problem that plagues any whitelight system when looking far off the anti-Sun line is much milder in the infrared: a large advantage. This is especially true for objects at or inside solar quadrature where many threatening NEOs in Earth-like orbits reside. Although higher sensitivity improves NEO search capability, larger apertures typically have smaller FOVs, and therefore slower survey speeds. Since this mission's full FOR must be covered about 4 times in 24 days, the Ball model shows that survey completeness declines for apertures larger than 50 cm in the infrared. For the visible light options that were studied and discarded, this decline occurred for apertures beginning at about 150 cm. The Ball model also indicates that the difference between hypothetical systems such as Pan-STARRS-4 and LSST is relatively minor in terms of catalogue completeness within the timescale defined by the GEB goals. After a modest aperture is reached, what dominates is the 2-D area of sky searched per unit time, not the 3-D volume of searched space. This is an unintuitive result for most astronomers who are accustomed to seeing more by looking deeper. Moving NEOs are unique in this regard, something that takes a good system model to grasp.

THE BALL AEROSPACE & TECHNOLOGIES SYSTEM MODEL: WHAT IT IS AND HOW IT WAS USED

To guide the development of *NEO Survey*, Ball Aerospace developed a system model that includes all the relevant physics: NEO orbital motion; detector performance including dark current, read noise, and quantum efficiency; sky brightness as a function of observatory location and pointing direction; the observing cadence; the signal-to-noise ratio for a detection (set at 6); the FOV; and the FOR. The model uses the 1,280 synthetic orbits developed by Bottke, *et al.* (2002), with a realistic set of sizes. Morbidelli's *et al.* (2002) bimodal, visible-albedo distribution was used, where 78% of the simulated NEOs have a visible albedo of 20%, and the rest have 6%.

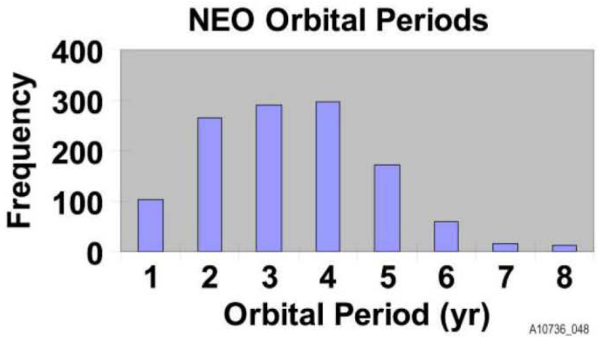
Initially, the model was used to investigate, and eventually discard, a wide variety of Schmidt-based variants of the *Kepler* photometer now on-orbit and operating very well. When these failed, several visible-light Cassegrain designs were considered. The visible band was finally discarded and variants of the all-reflective *Spitzer Space Telescope's* Cryogenic Telescope Assembly (CTA), with which *NEO Survey* shares much heritage, were studied.

For the visible light studies, a very small point-spread-function (PSF) was used that ultimately did not work due to off-axis performance as well as chromatic aberrations in all the Schmidt-based designs, even those containing a very large and complex field-flattening lens assembly located just in front of the focal plane array (FPA). Various time-delayed-integration (TDI) schemes and FPAs having enormous numbers of pixels were considered, some approaching a gigapixel in size. It was eventually discovered that the phase-space of NEO-search solutions is overwhelmingly dominated by the fact that NEOs move relatively large angles on the sky during the time needed to detect them, typically between 30 and 200 seconds. For a physically small PSF, all the signal photons at one instant from a given NEO arrive on a single pixel, which is desired. However, in a few seconds, the NEO's Keplerian motion smears these signal photons across several pixels, which is undesired. Opening the pixel size to deal with the smearing problem means the sky background increases dramatically and the system fails again. By exploring the phase-space between these two trades, it was realized a PSF of a couple of arcseconds is needed to cope with the smearing, and pixel sizes of a few tens of microns are optimal for sky brightness.

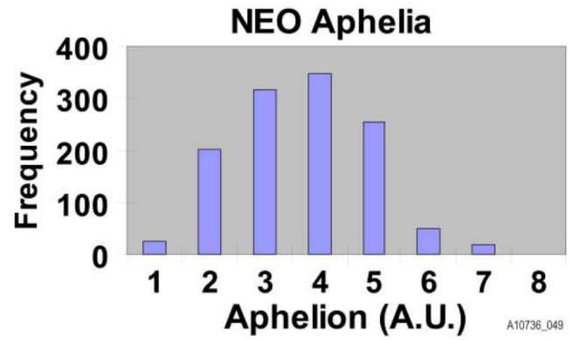
The Ball model helped the design team choose a cut-off wavelength of 10.5 microns to control the FPA's dark current. The Planck blackbody curve coupled to typical NEO temperatures within the detection range set the cut-on wavelength at 6 microns. Infrared detectors that work well in this spectral range are commercially available, which was not true at the time of the SDT. Similar detectors are flying successfully on the *Hubble Space Telescope*, proving their flight readiness. The model was also used to set the upper limit of the telescope's on-orbit temperature to 65K and to set the FPA's operating temperature to 40K, achievable with a flight-proven high-reliability 2-stage Stirling-cycle cryocooler that is discussed later.

ORBITAL PHASING: THE CRITICAL FACTOR

Perhaps the most surprising result of running the Ball model against numerous system architectures was the realization that after some modest aperture is reached (50-cm in the thermal infrared and ~150-cm in the visible), the Keplerian motion of the NEOs becomes the dominating factor in the cataloging rate. Figure 3a and 3b reveals the source of this system-level driver. These two histograms show that most NEOs, most of the time, are too far from the Sun to be seen by any system. A typical NEO is only bright enough to be detected for about 10% of its orbital period. Thus, many NEOs will brighten, pass around the Sun, and quickly leave before any observatory sees it. The Y-axis numbers are those populations in the Bottke model. For the real NEO population, these would be percentages of the actual population. Figure 4a and 4b shows the final cataloguing rate as a function of time and two size-classes of NEOs. It also shows the usefulness of adding a single observatory in an uncorrelated orbit to the system, such as the groundbased Pan-STARRS-1 system, which improves the phasing problem and shortens the catalogue completion time (blue curves) from about 7.5 years (4a) to about 5.5 years (Figure 4b).

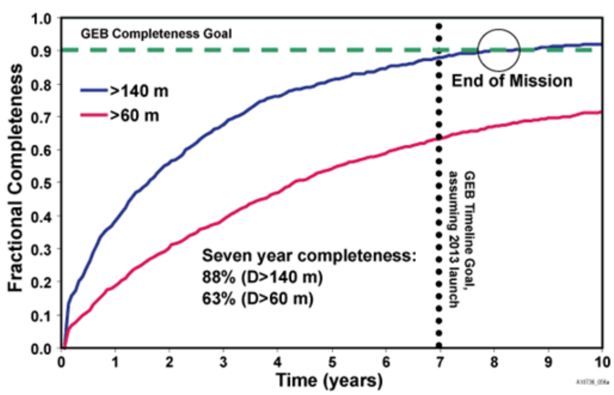


(a)

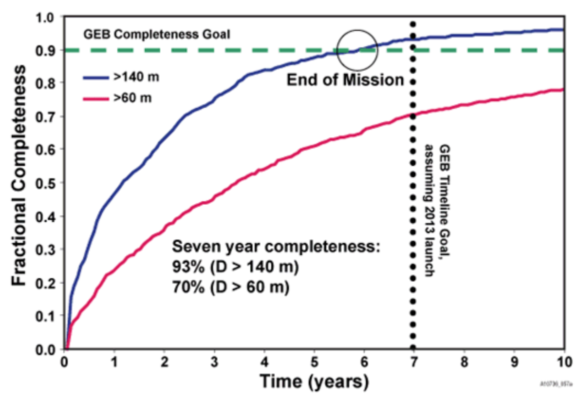


(b)

FIGURE 3. **(a)** Orbital Periods in histogram bins, shows how Kepler's Laws drive any efficient NEO surveying mission to requiring at least five, and perhaps 7.5 years to complete its catalogue and **(b)** NEO Aphelia in histogram bins, reveals that the vast majority of NEOs spend most of their orbital periods at heliocentric distances too great to be seen by any credible survey system at any given time, either groundbased or spacebased. The aphelia problem requires that a wide field of view scans a large field of regard multiple times a month. The aphelia problem also requires a modest PSF, a modest IFOV, and large pixels because rapid motion during perihelion smears a NEO image over several arcseconds during an exposure time.



(a)



(b)

FIGURE 4. Completeness versus time for (a) the *NEO Survey* infrared space telescope only, and (b) *NEO Survey* plus Pan-STARRS-1.

NEO SURVEY BOTH ENABLES AND RELIES UPON A LARGE SET OF GROUNDBASED ACTIVITIES

The actual *NEO Survey* in-space observatory, sometimes called the "flight segment" by NASA and ESA, is depicted in the green section in Figure 5. The rest of the *NEO Survey* science and data analysis is shown in the much larger blue section. *NEO Survey* is unusual because it relies on an extensive groundbased infrastructure to implement its mission. The groundbased infrastructure does most of the follow-up activities such as: detailed high-accuracy orbital-element refinement for threat assessment; possible selection for an in-situ spaceborne characterization mission; high-resolution spectral characterization as a precursor to mitigation missions; data-mining of orbital elements to identify non-Keplerian processes; and measuring the dynamic evolution of NEOs in general.

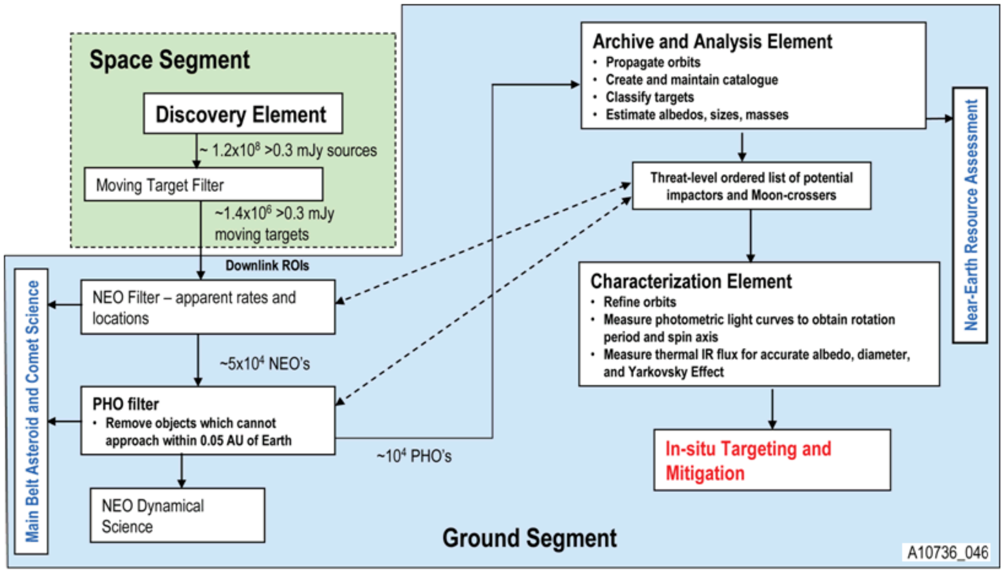


FIGURE 5. The *NEO Survey* flight segment is a small part of the overall mission. *NEO Survey* requires the use of an extensive groundbased infrastructure to process the data, calculate orbits, and enable follow-on activities.

NEO SURVEY USES A GREAT DEAL OF FLIGHT-HERITAGE ELEMENTS FROM PREVIOUS, HIGHLY SUCCESSFUL, DEEP-SPACE NASA MISSIONS

As depicted in Figure 6, *NEO Survey* is a fusion of elements from two very successful deep-space missions: the *Spitzer Space Telescope* and the *Kepler* mission. Thermal management aspects of *NEO Survey*, including solar-heating management, many cryogenic aspects, and aspects of the telescope, have direct design and fabrication heritage from *Spitzer*. Large amounts of *Kepler*'s spacecraft, architecture of the large pixel-count FPA, on-board data-processing, and especially a modified high-reliability variant of *Kepler*'s telecommunications system for operation at ~2 AU from the Earth, are included in this design. *NEO Survey*'s costs are tied to well-known numbers coming from actual, very relevant, flight programs. This is a mature system based on a pair of well-costed programs using actual as-built numbers.

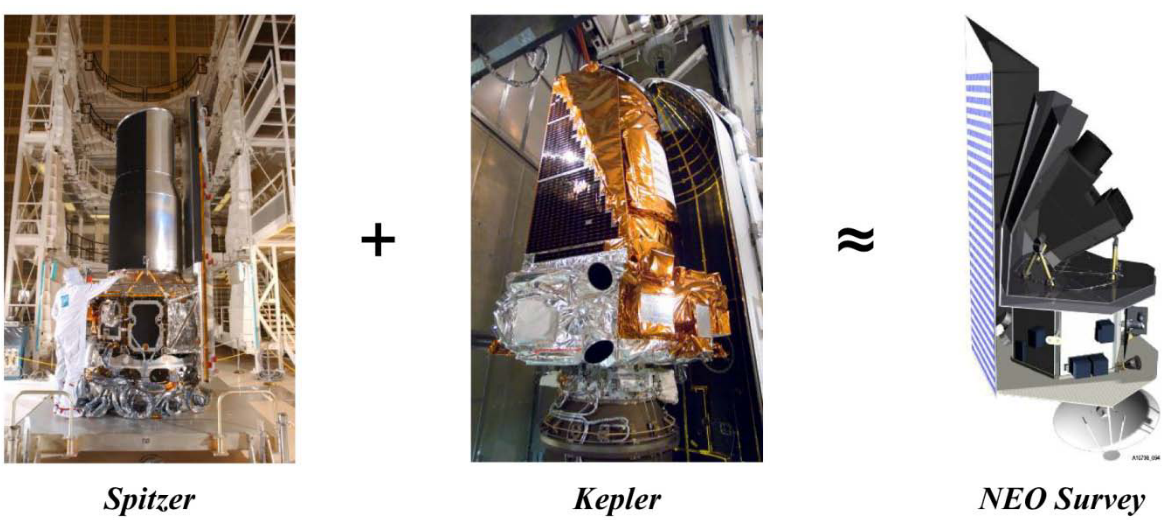
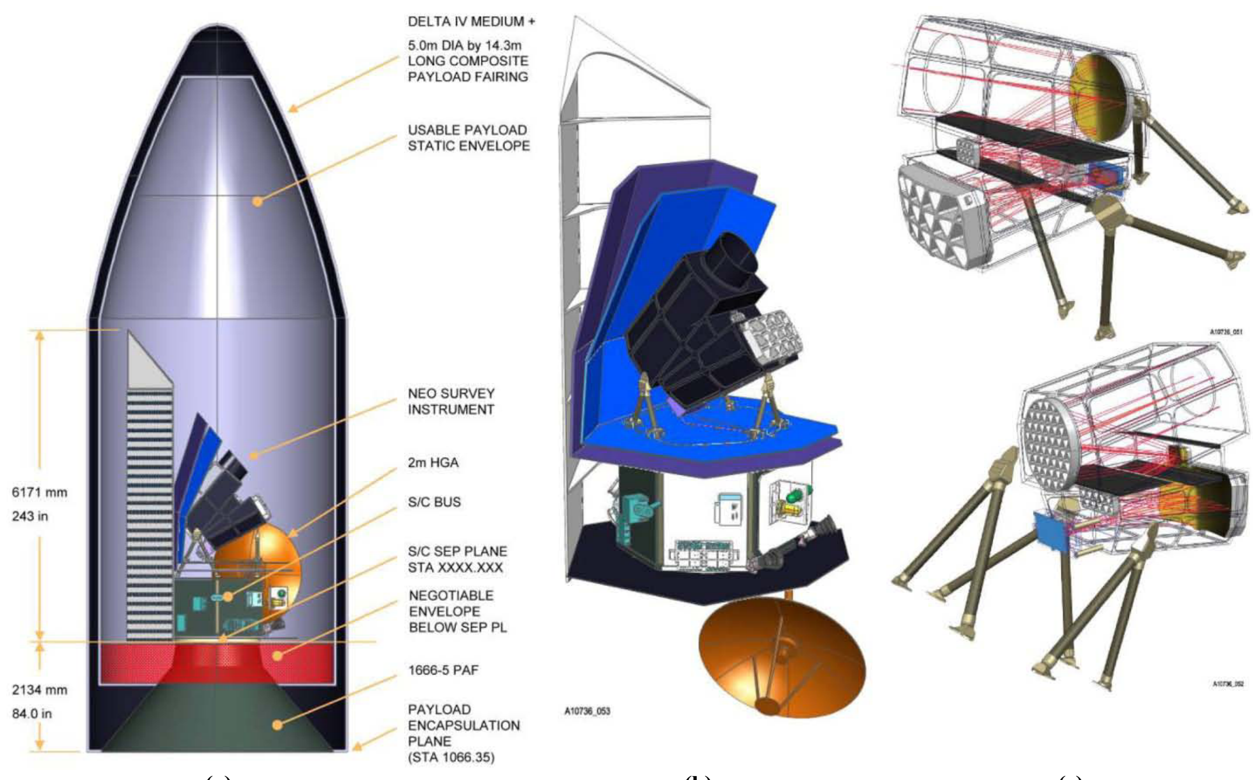


FIGURE 6. *NEO Survey* is a fusion of two successful deep-space missions now on-orbit, *Spitzer* and *Kepler*.

The relevant parts of the *Spitzer* system include the half-blackened cryostat main-shell, which validates NASA's ability to radiatively cool large IR instruments into the T= ~60K range, as well as make 50-cm-scale all-metal infrared telescopes. Barely seen just to the right of the CTA assembly, and seen edge-on, is the very sophisticated thermal shield that also carries *Spitzer*'s solar arrays, a concept directly applied to *NEO Survey*. The *NEO Survey* spacecraft is essentially a rebuild-to-print version of the *Kepler* spacecraft seen in the middle figure at the bottom of the photometer stack. A computer rendering of the *NEO Survey* concept is seen to the right and includes the spacecraft, the main thermal shield carrying the solar arrays, two passive thermal radiators, and the complete instrument. Seen below the spacecraft is the stowed 2-meter-diameter high-gain antenna (HGA).

Figure 7 consists of three panels. The left-most panel shows the entire *NEO Survey* observatory stowed inside the 5-meter fairing of an EELV-class launch vehicle, perhaps a Delta-IV-Heavy, with two strap-ons. The *NEO Survey* observatory is seen again in the middle panel. The tall, white structure at the back is the main thermal-shield that intercepts and then reradiates the ~26-kW of incident solar radiation (for the worst case of perihelion at 0.6 AU). The observatory's solar cells are mounted on the sun-facing side of this structure and have been designed to cope with the extremes of incident solar radiation, sun angle, and end-of-life degradation due to ionizing radiation. Much of the design for power management comes from the successful *Deep Impact* mission, another deep-space mission not shown here. The two angled inner-structures are intermediate-temperature thermal shields which passively reject any heat getting through the main thermal shield. The outermost shield runs at about 200K and the innermost runs at about 150K. The telescope's housing passively runs at about 60K, cold enough to operate the mission. Since the focal plane array (not seen here) is actively cooled to 40K, a high-reliability, closed-cycle cryocooler is needed. The cooler selected has an intermediate temperature heat-lift stage. One of these coolers is approaching 7.5 years of on-orbit operation on another mission. Eight of the 11 available watts from this intermediate stage are used to cool the entire instrument housing and telescope to 45K. Ray tracings of the 50-cm aperture, all-aluminum, unobscured telescope are shown in two views in the right-most panel. Since the telescope and its housing will be built from the same aluminum alloy, it is athermal by design, meaning it can be focused and aligned to meet the relatively large PSF at 300K and will remain aligned and focused at 45K. The instrument has no mechanisms.



(a) **(b)** **(c)**

FIGURE 7. Three views of the *NEO Survey* hardware. **(a)** The stowed observatory in a 5-meter-class EELV-like fairing, **(b)** the deployed observatory with the articulated HGA at the bottom pointing back to Earth and the instrument's aperture, and therefore line of sight, pointed up and to the right and **(c)** a pair of ray tracings showing the light paths in the four-mirror design.

SUMMARY

This paper reflects an unusual confluence of social, political, and technical elements combined with a new awareness of the threat régime posed by a class of NEOs previously thought of as benign, but which in fact are surprisingly lethal. These much smaller NEOs are relatively numerous and yet are hard to find using any presently-imaginable groundbased system operating over a span of decades. But these same NEOs are efficiently discovered and tracked using a dedicated, spacebased, infrared system operating in a Venus-like orbit. Such a system can be created by reflying the *Kepler* spacecraft supporting an infrared telescope that is smaller and warmer than the analogous system now flying on the *Spitzer Space Telescope*. Each incremental change to the *NEO Survey* mission, as compared to its flight counterparts in either *Kepler* or *Spitzer*, is a simplification in such areas as pixel count, aperture size, optical design and fabrication, and cryogenic cooling. Thus, each technical and programmatic aspect of the *NEO Survey* mission is well-grounded in technical heritage having the highest possible Technology Readiness Level (TRL). Also, each technical and programmatic aspect of this proposed mission is supported with cost projections based upon fully documented, and well understood, actual costs coming from the two heritage missions. For close to $600M, the *NEO Survey* mission can be built, launched, and operated long enough to complete its task. For the first time in history, and while acting alone in just over 7 years after first light, this system could deterministically answer the question— Will the Earth be hit by a worrisome NEO in the next 100 years? If supplemented by a groundbased observatory of an adequate design, such as the existing Pan-STARRS1 system, this question could be answered in ~5.5 years after first light. All of the technical and programmatic aspects of this problem have been addressed. What remains is the political will to fly it.

ACRONYMS

AU	-	Astronomical Unit
CONOPS	-	Concept of Operations
CTA	-	Cryogenic Telescope Assembly
EELV	-	Evolved Expendable Launch Vehicle
ESA	-	European Space Agency
FOR	-	Field of Regard
FOV	-	Field of View
FPA	-	Focal Plane Array
GEB	-	George E. Brown bill
HGA		High Gain Antenna
IR	-	Infrared
LAA	-	Low-Altitude Airburst
LOS	-	Line of Sight
LSST	-	Large Synoptic Survey Telescope
NEO	-	Near-Earth Objects
Pan-STARRS	-	Panoramic Survey Telescope And Rapid Response System
PSF	-	Point-spread-function
SDT	-	Science Definition Team1
TDI	-	Time-delayed-integration

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