

# ***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<sup>3</sup> (SDT) to study the threat posed by Near-Earth Objects (NEOs), to recommend solutions for efficiently detecting NEOs down to a much lower diameter than before, and to study techniques for mitigating an impending impact. Subsequently, the United States Congress directed NASA to investigate ways to implement many of the SDT's results. At this time Congress also 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, and is henceforth called the GEB requirement. The SDT concluded that: the thermal infrared ( $\sim 5$  to  $\sim 11$  microns) is the most efficient spectral regime for an efficient NEO search; that any IR aperture from about 50 to 100 centimeters is sufficient; and that locating a NEO-finding observatory in a Venus-like orbit (approximately a 0.7 AU semimajor axis) is ideal. The SDT had to make assumptions about future advancements in detector technology and deep-space compatible processing power, and assumed that diffraction-limited optical systems with no chromatic aberrations were doable within the constraints of a flight mission. Since then, NASA and its industrial partners, of which Ball Aerospace is one of many, have flown several deep-space missions, two of which are very relevant here—the infrared *Spitzer Space Telescope* (SST), and the recently launched *Kepler* mission, as discussed later. In this paper we present a high reliability, credibly costed, high-heritage design that meets the GEB requirements for about \$600M (USD). For no additional cost, this design will detect about 85% of all >100 meter diameter NEOs, about 70% of all >60 meter diameter NEOs, and about 50% of all >50 meter diameter NEOs. These smaller NEOs constitute a newly recognized threat regime that cannot be efficiently detected from the ground.

## **CONCEPT OF OPERATIONS (CONOPS)**

Fig. 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 our nominal Venus-like orbit having a semimajor axis of 0.7 AU with an orbital period of  $\sim 206$  days and a synodic period of  $\sim 514$  days (vital for discovering dangerous NEOs in roughly Earth-like orbits, as discussed below.) 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, our 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, one-time flyby of Venus as opposed to a series of complex orbital-insertion burns. Our results are not sensitive to the orbit's final details as long as the final orbital elements fall roughly within the boundaries of 0.8 AU by 0.6 AU.

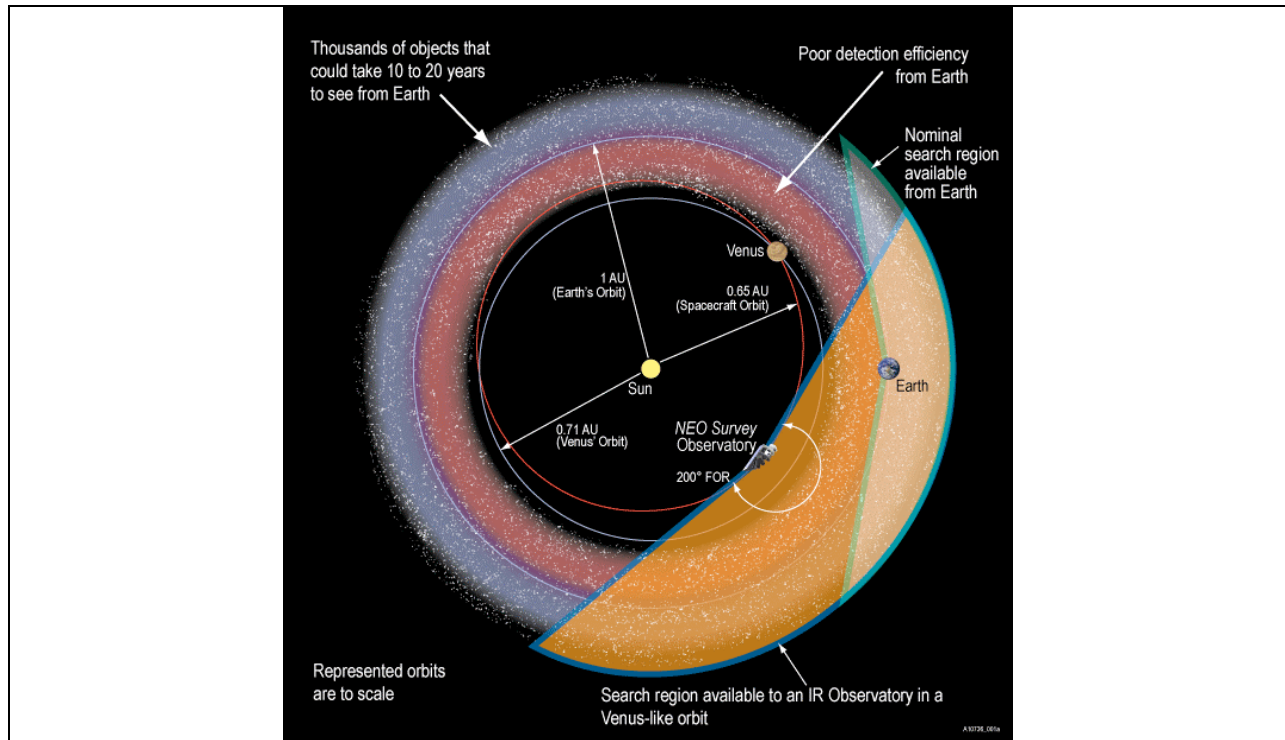


Fig. 1 Illustrates the *NEO Survey* field of regard and the advantages of a Venus-like orbit.

Fig. 1. shows *NEO Survey*'s 200 degree full-opening-angle Field of Regard (FOR), slightly more than the entire anti-Sun hemisphere. We chose a 24-day observing cycle 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 "GEB" mission in 7.5 years, or 5.5 years with the addition of one 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.

Fig. 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.

## OVERVIEW: Why This Mission? Why Now?

Groundbased searches at visible wavelengths are nearing 90% completeness for NEOs of diameter >1km. Extending the effort down to diameters of 140 meters, and smaller, is challenging from the ground due to: visible albedos of ~20% or less; unfavorable phase functions in reflected light; and difficulties observing near the Sun. Using a dedicated mid-IR telescope in a Venus-like orbit greatly improves the search efficiency for several reasons including: NEOs in small orbits can be seen at larger solar elongation angles; most of the energy radiated by NEOs is in the thermal IR; and the phase function of thermal emission is more favorable than for reflection. Also, *NEO Survey* accesses a greatly expanded near-Earth region in its field of regard (FOR). Additionally, NEOs in roughly Earth-like orbits have Earth-like periods and usually reside in the daytime sky. For example, a NEO within 5% of an Earth-like orbit closely approaches the Earth every 20 years. Such a NEO resides in the daytime sky and is hard to find from the ground. From a Venus-like orbit all such objects are easily detectable on the scale of ~520 days.

Recent work by Dr. Mark Boslough<sup>4</sup> shows that the impact physics of NEOs in the 30-100 meter range has been misunderstood due to a process he calls a Low-Altitude Airburst (LAA), which is a newly recognized threat regime that has been previously underestimated. In an LAA event the main body of the NEO comes apart at high altitudes (~80 km to ~10 km), but the object's mass and kinetic energy are conserved as a fast moving, loosely aggregated, collection of particles which entrain a column of air reaching the ground in what might be termed an "air hammer." Dr. Boslough's work shows that the "air hammer" from NEOs as small as 30 meters inflicts significant damage, as was seen in the 30-meter-class Tunguska event. Dr. 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's fireball settled onto parts of Egypt and Libya for about a minute with temperatures approaching 5,000K. It's hypersonic blast wave extended radially for about 100 kilometers. Dr. Boslough has also shown that the interaction of the LAA with the ocean's surface is much different from a large object's strike, and that any ensuing tsunami is not yet well modeled. Therefore any survey instrument capable of searching well below 140 meters is quite valuable.

Derating the estimate of the Tunguska object's size from ~60 meters to today's ~30 meters greatly decreases the impact interval from ~1,000 years to ~200 years. Given that Tunguska happened 101 years ago, the expected time until the next impact is ~100 years. The *NEO Survey* mission will capture about half of the 50 meter-class NEOs in its 7 year mission, and the detection rate increases rapidly with increasing size. And it's the smaller end of the size distribution curve that drives the urgency to fly a mission like *NEO Survey* sooner, rather than later. For example, 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 10 year period, a 50 meter NEO is discovered having an impact date in 50 years. What does this mean? It would take a year or two for groundbased assets to do detailed follow-up orbital refinements. Then, a roughly 10-year period 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. Then it would take about 10 more years to design, build, fly, and complete almost an mitigation mission. These timelines add 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, thus simplifying mitigation. For example, the difference between 10 years and 20 years of warning time could discriminate between a passive or nuclear mitigation technique.

### **THE BALL AEROSPACE & TECHNOLOGIES SYSTEM MODEL: What it is and How We Used It**

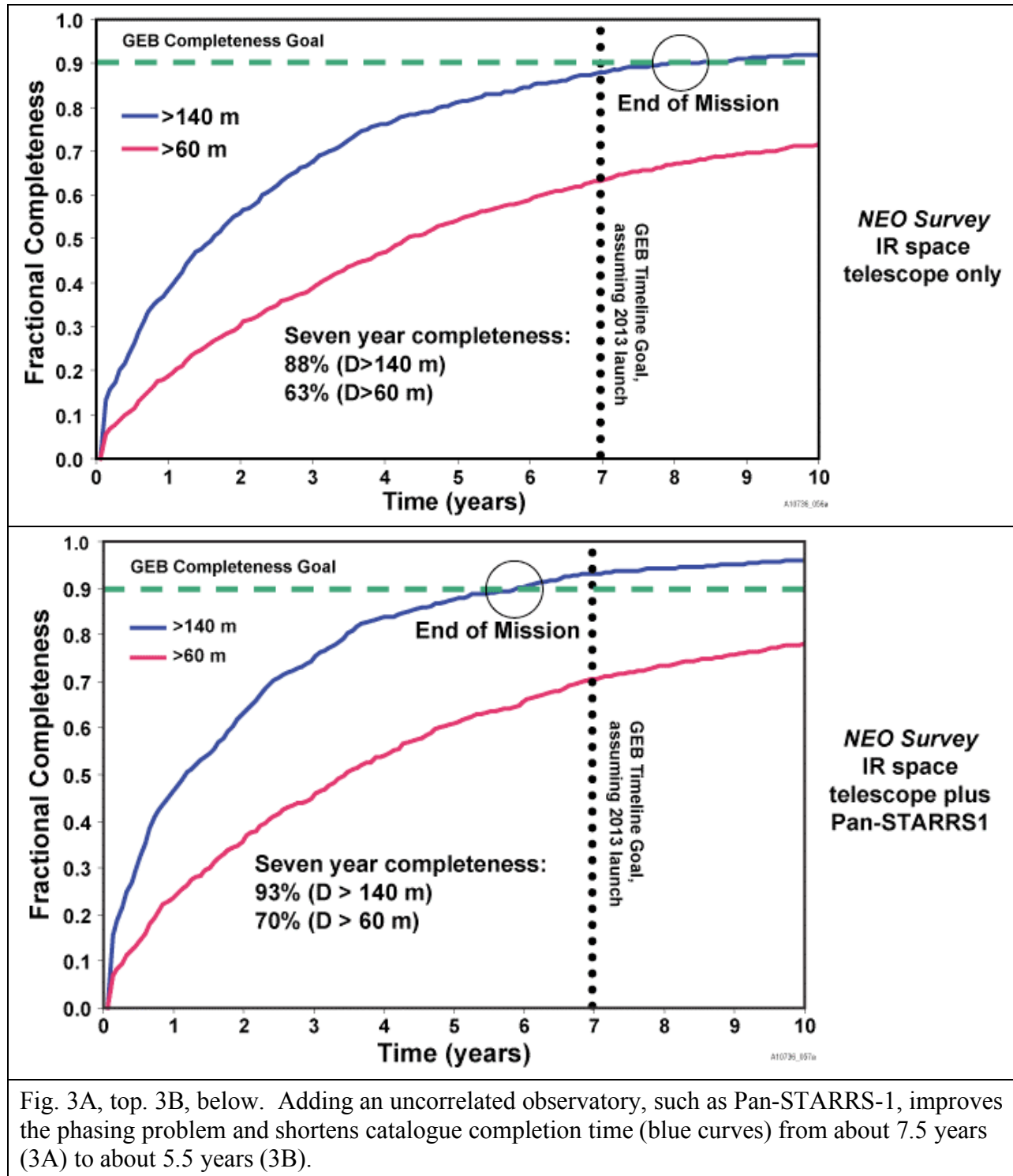
To guide the development of *NEO Survey*, Ball Aerospace developed a system model based on all the relevant physics: NEO orbital motion; zodiacal light; detector performance including dark current, read noise and quantum efficiency; sky brightness as a function of observatory location and pointing direction; the observing cadence; the signal-to-noise ratio (set at 6); the FOV and the FOR. Our model uses the 1,280 objects developed by Bottke<sup>5</sup> et. al. This simulation of realistic NEOs includes orbital elements and sizes. We used Delbo's<sup>6</sup> thermal inertia data and Morbedelli's<sup>7</sup> bimodal visible-albedo distribution where 78% of our simulated NEOs have an albedo of 20%, and the rest have 6%.

Initially, we used our model to investigate, and eventually discard, a wide variety of Schmidt-based variants of *Kepler's* photometer before looking at variants of the all-reflective *Spitzer Space Telescope's* Cryogenic Telescope Assembly (CTA).

Our telescope design has a 50 cm diameter clear aperture with a 2 degree by 5.5 degree field of view and a diffraction-limited point spread function at 6 microns. Our model helped us choose a cut-off wavelength of 10.5 microns due to dark current. And 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 and flying in deep space. We used our model to set the upper limit of the telescope's on-orbit temperature to 65K and to set the focal plane array's operating temperature at 40K, which we achieve with a flight-proven high-reliability 2-stage Stirling-cycle cryocooler.

### **ORBITAL PHASING: The Critical Factor**

Perhaps the most surprising result our model revealed was that after some modest aperture is reached (50-cm in the thermal IR) the Keplerian motion of the NEOs dominates the cataloging rate. Typical NEOs have orbital periods of from 2 to 6 years, and aphelia distances ranging from 2 to 5 AU. Thus, for most of the time, most NEOs are too far from the Sun to be seen by any technique. Also, Kepler's laws result in most NEOs spending about 10% of their orbital period close enough to be seen, meaning that many NEOs will come in, swing around the Sun and disappear before any observatory's orbital phasing lets them be seen. Thus, the addition of an uncorrelated "eyeball" anywhere else in the inner solar system greatly enhances the detection rate, something we call the Orbital Phasing Problem. Figs. 3A and 3B show the cumulative detection rate as a function of time for two size-classes of NEOs. They also show the usefulness of adding a single, uncorrelated, groundbased observatory to the system.



### **NEO SURVEY BOTH ENABLES AND RELIES UPON A LARGE SET OF GROUND BASED ACTIVITIES**

The *NEO Survey* observatory is depicted in the green section in Fig. 4. The rest of the *NEO Survey* science and data analysis activity is shown in the blue section. *NEO Survey* is unusual for its

reliance on an extensive groundbased infrastructure to complete much of its basic mission such as: high-accuracy orbital-element refinement for threat assessment; possible selection for an in-situ spaceborne characterization mission; high-resolution spectral characterization prior to mitigation; and measuring the dynamic evolution of NEOs in general.

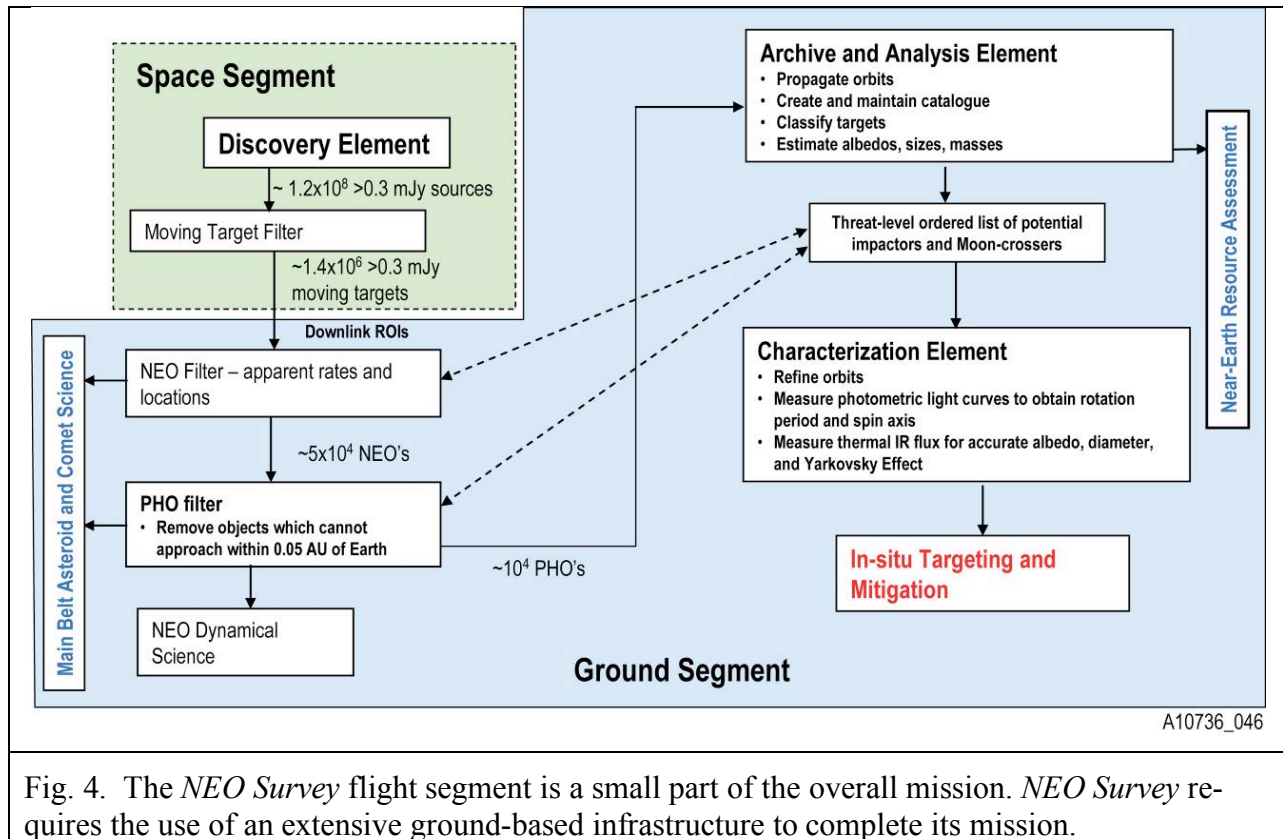
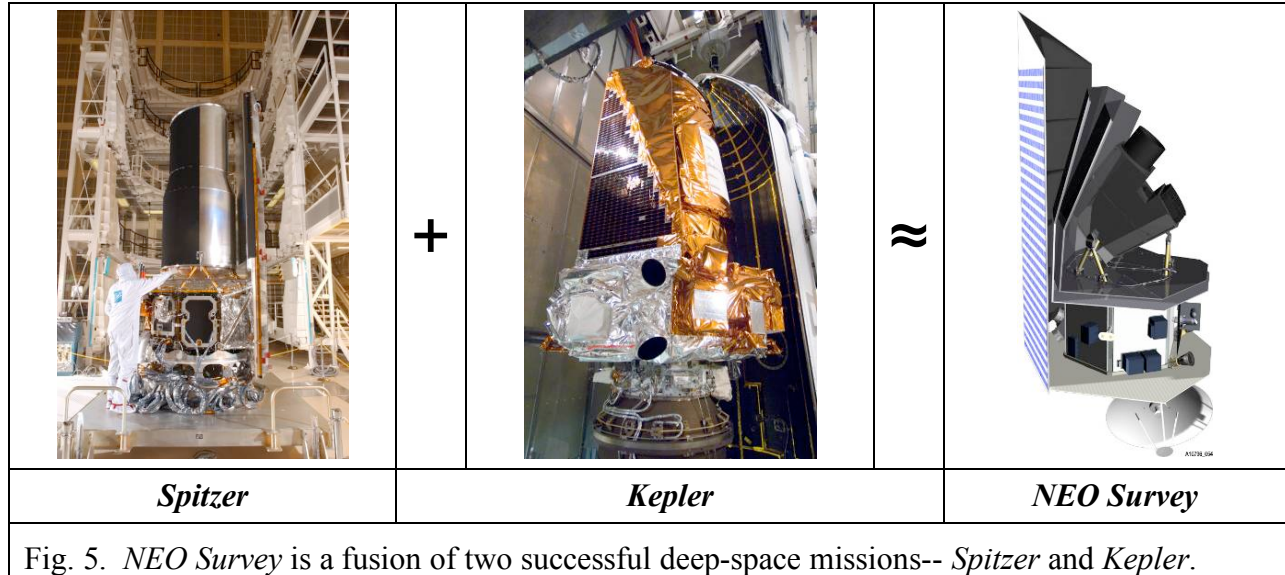


Fig. 4. The *NEO Survey* flight segment is a small part of the overall mission. *NEO Survey* requires the use of an extensive ground-based infrastructure to complete its mission.

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

As depicted in Fig. 5, *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 operating at  $\sim 2$  AU from the Earth, are included. *NEO Survey's* costs are tied to well-known numbers from actual, very relevant, flight programs.



The relevant parts of the *Spitzer* system include the half-blackened cryostat main-shell, which validates our ability to radiatively cool large IR instruments to the  $T \sim 50\text{K}$  range, as well as produce 50-cm-scale all-metal telescopes. The very sophisticated thermal shield that also carries *Spitzer*'s solar array is directly applicable to *NEO Survey*. The *NEO Survey* spacecraft is essentially a rebuild of the *Kepler* spacecraft.

The left-most panel of Fig. 5 shows the *NEO Survey* observatory 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 shown again in the middle panel. The tall white structure at the back is the main thermal-shield which intercepts and reradiates the  $\sim 26\text{ KW}$  of incident solar radiation (worst case at  $\sim 0.6\text{ AU}$ .) The observatory's solar cells are mounted on the sun-facing side of this structure and are engineered to for the mission's boundary conditions. Much of the power management system comes from *Deep Impact*, which is not shown. The purple and blue structures are intermediate-temperature shields that passively reject any heat getting through the main thermal shield. The purple shield runs at  $\sim 200\text{K}$  and the blue shield runs at  $\sim 150\text{K}$ . The telescope's housing passively runs at  $\sim 60\text{K}$ . Active cooling the focal plane array (not seen here) to  $40\text{K}$  requires a high-reliability, closed-cycle cryocooler of a type that is approaching 7 years of on-orbit operation for another mission. The cooler has an intermediate temperature stage from which we use 8 of the available 11 watts to cool the FPA to  $40\text{K}$  and the instrument's housing and telescope to  $45\text{K}$ . Ray tracings of our 50-cm aperture, all-aluminum, unobscured telescope are shown in the right-most panel. The telescope and its housing are of the same aluminum alloy. It is athermal and will be focused and aligned at room temperature and will remain so at  $45\text{K}$ . The instrument has no mechanisms.



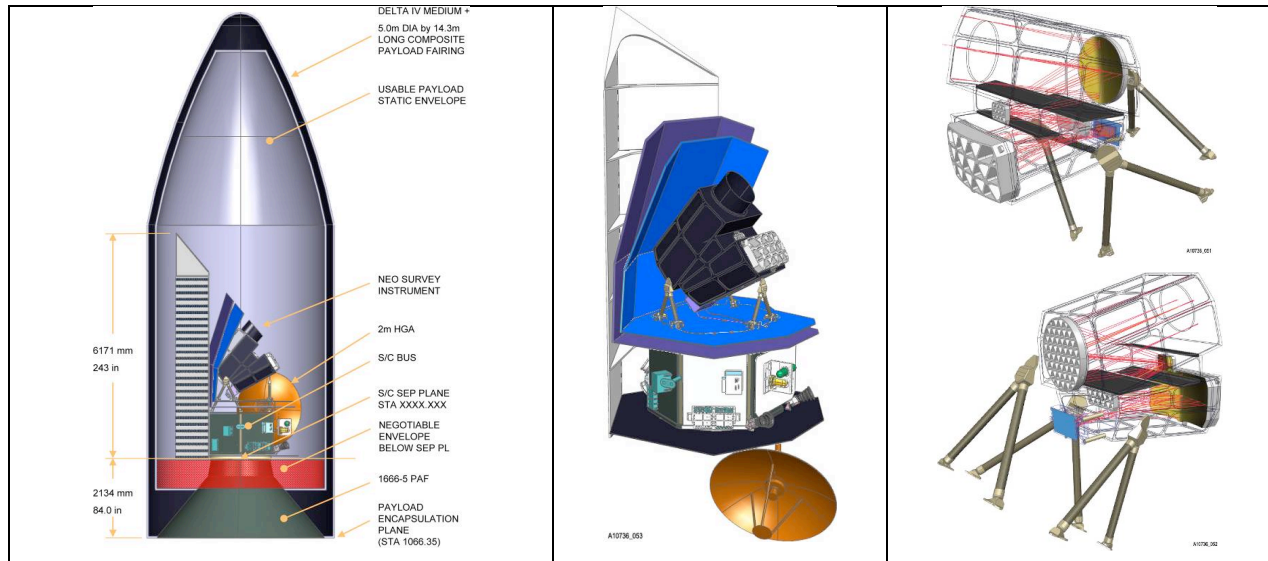


Fig. 6. Three views of the *NEO Survey* hardware. To the left is the stowed observatory in a 5 meter-class EELV-like fairing. In the middle is the deployed observatory with the articulated high-gain antenna at the bottom pointing back to Earth, and the instrument's aperture, and therefore line of sight, pointed up and to the right. To the right are a pair of ray tracings showing the light paths in our four-mirror design.

## REFERENCES

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