Testimony to the U.S. Senate Committee on Commerce, Science and Transportation

Hearing on Assessing the Risks, Impacts, and Solutions for Space Threats – March 20, 2013

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My name is Ed Lu, and I am the CEO of the B612 Foundation. Thank you for the opportunity to testify before the Senate Science and Space Subcommittee to describe the B612 Foundation Sentinel Space Telescope project. The B612 Foundation is a nonprofit 501(c) 3 organization dedicated to opening up the frontier of space exploration and protecting humanity from asteroid impacts. On June 28, 2012, the Foundation announced its plans to carry out the first privately funded, launched, and operated interplanetary mission – an infrared space telescope to be placed in orbit around the Sun to discover, map, and track threatening asteroids whose orbits approach Earth. Our name was inspired by the famed children's book by Antoine de Saint-Exupéry. B612 is the asteroid home of The Little Prince.

As the asteroid impact near Cheylabinsk Russia on February 15, 2013 vividly reminded us, our planet is occasionally struck by asteroids capable of causing significant damage. This was the largest asteroid impact since June 30, 1908, when an asteroid flattened 1000 square miles of forest in Tunguska, Siberia. The Earth orbits the Sun among a swarm of asteroids whose orbits cross Earth's orbit. These are *not* the asteroids that make up the asteroid belt between Mars and Jupiter, but rather the Near Earth Asteroids whose orbits take them much closer to the Sun, and who regularly cross the orbit of Earth. These asteroids are remnants of the formation of our solar system, and range in size from pebbles to many miles across.

More than a million of these Near Earth Asteroids are larger than the asteroid that struck Tunguska in 1908 with an energy more than 500 times greater than the atomic bomb dropped on Hiroshima. That asteroid was only about 40 meters across (about the size of a 3 story office building), yet destroyed an area roughly the size of metropolitan Washington DC. Unfortunately, less than 1% of the over one million asteroids greater than 40 meters have been identified to date. We therefore do not know when the next major asteroid impact will happen.

Currently there is no comprehensive dynamic map of our inner solar system showing the positions and trajectories of these asteroids that might threaten Earth. We citizens of Earth are essentially flying around the Solar System with our eyes closed. Asteroids have struck Earth before, and they will again – unless we do something about it. The probability of a 100 Megaton asteroid impact somewhere on Earth this century is about 1%. The odds of another Tunguska 5 Megaton event this century are much higher, about 30%. What if I told you there is a 30 percent chance of a random 5 megaton nuclear explosion somewhere on Earth this century? What would we do to prevent it?

But in the case of asteroids, we as a civilization have the capability to change the odds, and it is the mission of the B612 Foundation to ensure that such impacts do not happen again. Deflecting asteroids is technologically feasible, IF we have adequate early warning. If we know decades in advance of an impact, we can predict and actually prevent an impact using existing technology (kinetic impactors, gravity tractors, and if required, even standoff nuclear explosions) to nudge the asteroid and subtly change its course to miss Earth. Conversely, we can do nothing about an asteroid that we have not yet found and tracked. Thus, the first task we must undertake if we hope to protect ourselves from asteroid impacts is to conduct an astronomical survey of asteroids whose orbits approach Earth.

The B612 Foundation therefore decided to build, launch and operate a solar orbiting infrared space telescope called Sentinel to find and track asteroids which could impact Earth. Sentinel will be launched in July 2018, and during the first 6.5 years of operation will discover and track the orbits of over 90 percent of the population of Near Earth Objects (NEOs) larger than 140 meters, and the majority of those bigger than the asteroid that struck Tunguska (~40 meters). Sentinel will discover *100 times* more asteroids than have been found by all other telescopes combined.

Sentinel is novel amongst deep space missions in that it is being carried out by a private organization, the nonprofit B612 Foundation, and also because it is being managed using commercial practices under a milestone based, fixed price contract with the prime contractor Ball Aerospace and Technologies Corp. (BATC).

Sentinel Mission Overview

In 2005, the U.S. Congress recognized the need to extend the existing Spaceguard Survey for 1 km and larger NEOs down to smaller but still dangerous asteroids. The George E. Brown Act[1] authorized NASA to complete (>90%) a survey for NEOs down to a size of 140 meters, a size which while not threatening to human civilization is still capable of causing great damage (having an impact energy of roughly 100 Megatons of TNT). However, this future enhanced survey has not been funded by Congress, and the goal remains unfulfilled. Currently ~90% of

NEOs larger than 1km have been discovered and tracked; while only about 5% larger than 140 meters, and only about 0.2% of those larger than 45 meters[2,3] have been tracked.

With this situation as a backdrop, the B612 Foundation decided in 2011 to undertake such a survey itself, and publicly announced the Sentinel Mission on June 28, 2012. Because asteroid deflection requires relatively small change in asteroid velocity when done many years to decades in advance of the impending impact[4], the goal of this survey is to find and track asteroids with enough orbital accuracy to know if a serious threat exists and to give sufficient warning time to enable a successful deflection if necessary. We have chosen to adopt the 140 meter 90% completeness goal as our driving requirement, knowing that in addition in to generating a largely complete catalog at the 140 meter size level, many smaller yet still potentially dangerous asteroids will also be cataloged. The Sentinel mission is designed to give humanity sufficient warning time to be able to prevent threatening asteroid impacts.

Novel Private Funding and Commercial Program Management

One of the novel aspects of this mission is the way in which it is being funded. The B612 Foundation is a nonprofit charitable organization which is raising funds through philanthropic donations. Interestingly, large ground based telescopes (such as Lick, Palomar, Keck and Yerkes) have historically been largely funded through philanthropy[5]. In some sense Sentinel will be like these large observatories, with the exception that Sentinel will be in solar orbit rather than on a mountain-top. The B612 Foundation will in turn contract the spacecraft out to BATC, with B612 functioning in the role of program/contract manager and carrying out independent assessment of program progress. The total cost of the mission is currently under negotiation. The B612 Foundation expects to raise about $450M over the next 12 years to fund all aspects of this mission including development, integration and test, launch, operations, and program expenses.

The Sentinel mission is also taking an innovative approach to building and operating this interplanetary space mission. While previous missions that have departed from Earth orbit have been scientific investigations that have been developed with oversight by NASA or other governments (e.g. ESA), Sentinel will be managed by B612 Foundation by adopting commercial practices for procurement and operations. Currently, communications and remote sensing imaging satellites (such as Digital Globe’s WorldView series) are routinely procured under fixed-price contracts using commercial terms and conditions. These successful missions are compatible with such an approach because their performance requirements are very carefully specified in the contract and both parties are very familiar with the risks involved in the contract. In contrast, science missions typically push technology and performance margins in pursuit of innovative objectives. Furthermore, mission risks and possibly even the detailed design, are often not well understood at the time of contract signing. In these cases, NASA and contractors prefer a performance-based cost-reimbursable contract to limit the risk to the manufacturer.

B612 has a very well-defined and stable requirement as articulated above. Thus, one of the prerequisites for commercial contracting is met.

One of the advantages B612 Foundation has as a private organization is that it is not bound by federal procurement regulations. This allows B612 to make decisions and move quickly without the cumbersome regulations designed to prevent favoritism in federal contracts, but which can add great overhead and slow decisions in cases where there is a clear best approach and contractor. BATC has carefully explored the implementation of the Sentinel mission and has identified high-heritage existing hardware system implementations (The Kepler and Spitzer spacecraft) that enable BATC to quantify the risk of manufacture and operation of Sentinel. Thus, we have been able to choose BATC as our contractor, and to make rapid progress towards a commercial contracting approach. This gives us the opportunity to enter into a fixed-price contract, an important feature for B612 since we must have a definite fund-raising target and do not have the ability to cover open-ended liabilities and cost-growth that might result from programmatic uncertainties. Crucially, the management of costs is the responsibility of BATC, which frees them from expensive accounting and compliance requirements associated with cost-reimbursable contracts.

A key feature of a successful implementation of this commercial contracting approach is frequent and detailed communications between B612 and BATC. While BATC is responsible for meeting performance requirements, B612 remains aware of programmatic risks and mitigations and approves the progress of the work. This is facilitated by the identification of milestones within the contract that detail various development achievements at which point the progress of the overall contract can be assessed. These assessments provide opportunities for dialog on programmatic and mission risks and mitigations. This arrangement is relatively hands off compared to typical large space missions, and works both because B612 has a small but highly experienced technical team, and because of the high heritage of the BATC design. B612 has also enlisted an independent panel of experts known as the Sentinel Special Review Team[6] to provide advice on technical and programmatic risk to B612. In addition, B612 will have permanent on-site technical and management personnel to enhance our visibility into progress on the contract. This approach has been implemented with great success on numerous other commercial space missions.

Another key aspect of the mission is support from NASA. B612 Foundation and NASA have signed a Space Act Agreement[7] in which NASA will provide use of the Deep Space Network (DSN) for telemetry and tracking, as well as allowing NASA personnel to participate on the independent technical advisory team known as the Sentinel Special Review Team. NASA and the scientific community benefit because B612 will make the data available to the community through the standard process for reporting NEO observations (see Detection Scheme below).

Sentinel Mission Overview

The Sentinel mission places an infrared imaging telescope in a Venus-like orbit to identify and catalog NEOs over a 6.5-year mission life. Figure 1 shows Sentinel's viewing geometry. The "Venus-like" orbit at ~0.7 AU provides up to a 200 degree, anti-sun viewing field that the observatory methodically scans to detect the infrared light coming from any moving object in the field. By making observations from ~0.7 AU, Sentinel views a much larger portion of the sky relevant to finding NEOs than can be seen from the Earth, either from ground-based or space-based observatories. A space-based survey is also not compromised by the atmosphere, or by the presence of the moon, or by the requirement to look for NEOs low in the sky during twilight. Locating Sentinel in space near 0.7 AU from the Sun has the additional benefit of being interior to most NEOs, thereby observing them when they are closest to the Sun and at their brightest. This, or a similar orbit, is essential for detecting those long-synodic-period (low relative velocity with respect to Earth) NEOs that are the most dangerous and valuable to future exploration missions.

Sentinel will be launched from Earth on a Falcon 9 rocket. The cruise to the final heliocentric orbit at ~0.7AU uses a Venus gravity assist to minimize fuel requirements. Communications through the DSN with Sentinel consists of two kinds of interactions. Infrequent command uplinks occur through low speed command link, while mission data uses a high speed downlink. The total downlink data volume is ~4 gigabits a week, and the DSN link-time is approximately 4 hours per week. Flight data from the DSN is first processed at a ground station at the Laboratory for Atmospheric and Space Physics at the University of Colorado.

The Sentinel uses proven designs successfully flown on the Kepler and Spitzer missions to demonstrate feasibility and low development risk, and to provide a firm cost basis. Figure 2 shows the notional Sentinel Observatory. The tall structure on left is the thermal shield, which also carries the body-fixed solar array, a system based on *Spitzer*[8].

The central region shows the two intermediate-temperature thermal shields, rendered in brown. To the right of the intermediate temperature shields is the 50-cm-aperture mid-wave infrared (MWIR) telescope. The telescope is cooled to 45K by a combination of radiative and active cooling. The instrument's HgCdTe focal plane is actively cooled to 40K. The detection band from 5 to 10.4 microns is optimized for detecting T=250K objects, a characteristic temperature for NEOs near 1AU. The telescope is mounted on a *Kepler*-derived spacecraft, and reuses *Kepler's* avionics and structure.

Detection Scheme

To detect a NEO, we require two pairs of observations of the anti-Sun hemisphere in 24 days. The basic detection scheme's timeline is presented in Figure 3. There are 4 separate observations made of every part of the anti-Sun hemisphere every 24 days (and 4 pairs on most sections in 26 days.) The images are taken in correlated pairs that reveal the motion of any NEO in the 1-hour span between images. All the data for each pair of images is first stored, and then later compared on-board, and NEOs are detected by their motion during the one hour interval between the two images.

We greatly reduce the amount of telemetry data by retaining only those portions of the imaged field that contain pixels determined by the dedicated on-board Payload Computer to contain moving objects. Additionally, for each tile we include roughly 100 well-known infrared stars used to establish an astrometric grid.

At the ground station, these observations are converted into detection-fragments called “tracklets.” Tracklets are then sent to the IAU Minor Planet Center (MPC) in Cambridge, Massachusetts. The MPC maintains the world’s NEO database, and will convert tracklets into orbits. These MPC orbits then go to the Near-Earth Object Program Office at JPL which refines the initial MPC orbits, calculates the likelihoods of any impacts and globally distributes its findings.

Survey Performance

In 6.5 years of operation, Sentinel will detect and track the great majority (>90%) of all NEOs larger than 140m. In addition, Sentinel will detect and track 50% of all NEOs greater than 50m. Figure 4 presents Sentinel’s NEO cataloguing rate. These results were generated using an integrated-systems model which includes a modeled NEO population in combination with spacecraft telescope and detector performance models as well as the preliminary observing cadence described in figure 3. We iteratively used the model to guide our design through the phase-space of options until we hit the 90% level for 140 meter objects on this plot. Among the parameters considered in these trade studies were aperture, field of view, detector wavelength cutoffs, final spacecraft orbital parameters, focal plane array operating temperature, detection thresholds, pixel size, integration time, etc. Over 75 such trade studies have been carried out thus far.

Summary

Sentinel is important on a number of levels. First, the B612 Foundation is pioneering a new model for carrying out large space missions in which Sentinel is philanthropically financed and privately managed, but with a crucial government partnership. Second, the primary goal of the mission is not scientific. While it is true that Sentinel will be a groundbreaking new astronomical instrument, the primary requirement for the mission stems from a planetary defense (i.e. public safety) goal. Once Sentinel is in operation, it will generate a flood of new NEO discoveries, far in excess of all other observatories combined. After 6.5 years of operation it will discover and track approximately 1,000,000 NEOs, as compared to the currently known total of about 10 thousand. Not only will this catalog provide a list of potential targets for robotic and human exploration, but should any of these NEOs be on a collision course this information can allow us to successfully mount a deflection campaign and prevent a catastrophe. Our future may depend on it.

References

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Figure 1 - Sentinel's mission architecture enables it to detect and track NEOs within a much larger search volume than is available from the ground, and without the constraints of weather and lunar cycles.

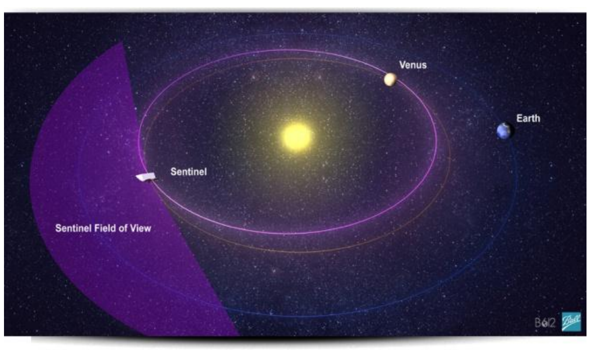
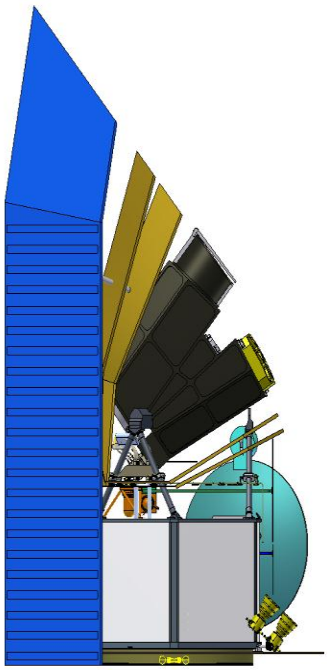


Figure 2 shows the Sentinel Observatory. It consists of a rebuild of the *Kepler* spacecraft (modified for the Venus-like orbit) and an infrared telescope.



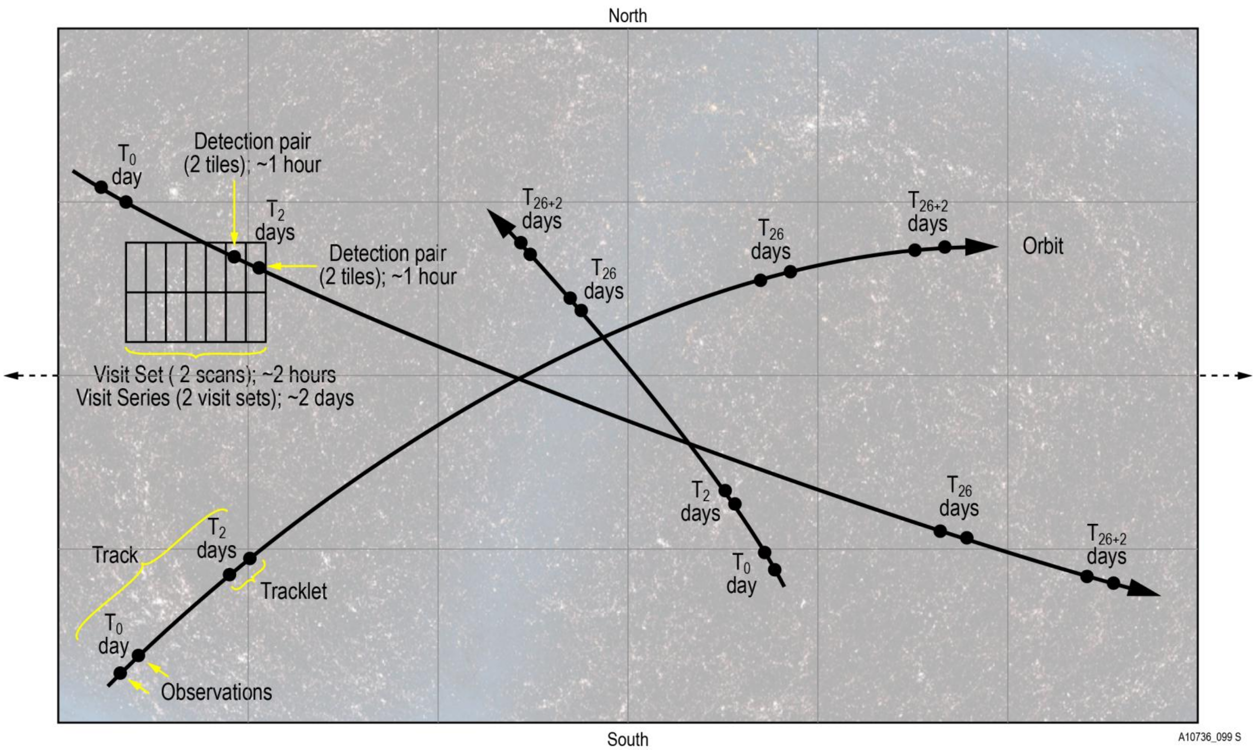


Figure 3. The basic viewing scheme uses one-hour pairs on two-day and then 26-day centers to locate moving NEOs.

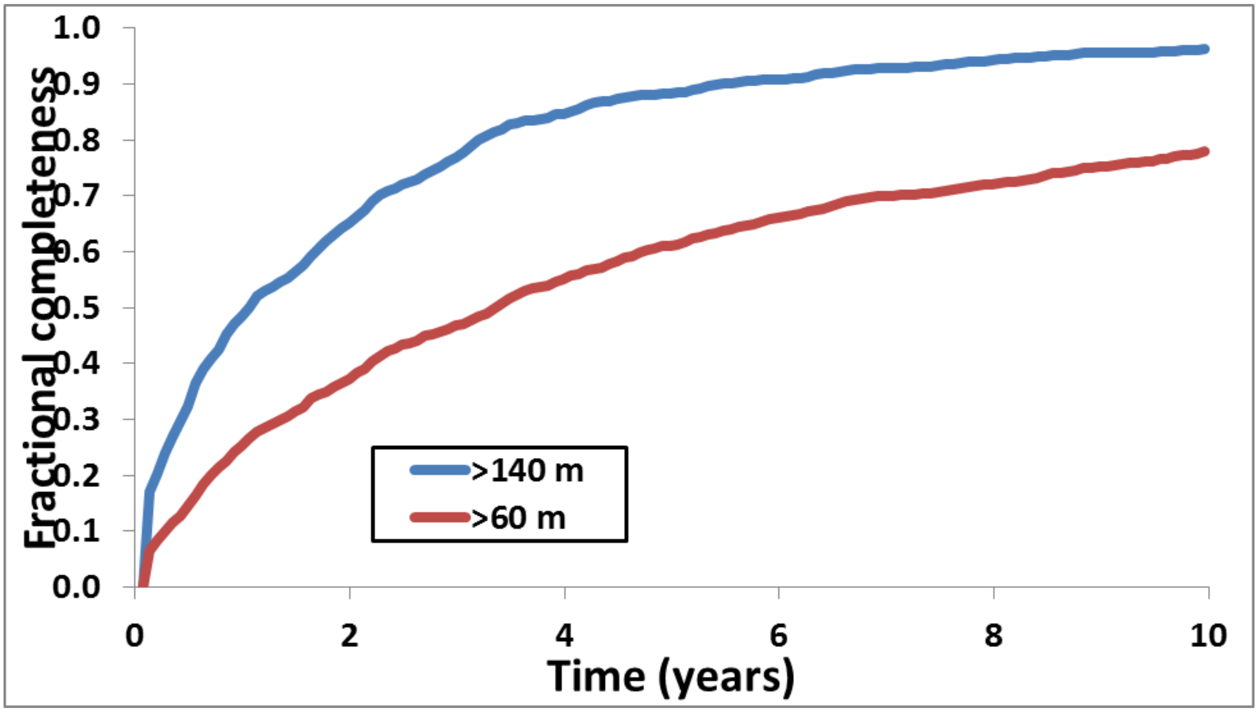


Figure 4. Survey completeness for all NEOs > 140-meter and 60-meter diameter vs. time for Sentinel, assuming simultaneous operation of ground based Pan-STARRS1