The B612 Foundation Sentinel Space Telescope

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ABSTRACT

The B612 Foundation is building, launching, and operating a solar orbiting infrared space telescope called Sentinel to find and track asteroids that could impact Earth. Sentinel will be launched in 2018, and during the first 6.5 years of operation, it will discover and track the orbits of more than 90 percent of the population of near-Earth objects (NEOs) larger than 140 m, and a large fraction of those bigger than the asteroid that struck Tunguska (~45 m). Sentinel is novel among deep space missions because it is being carried out by a private organization, the nonprofit B612 Foundation, and also because it is being managed using commercial terms under a milestone-based, fixed-price contract with the prime contractor Ball Aerospace and Technologies Corp (BATC).

INTRODUCTION

In 2005, the U.S. Congress recognized the need to extend the existing Spaceguard Survey for 1 km and larger near-Earth objects (NEOs) down to smaller but still dangerous asteroids. The George E. Brown Act[1] authorized NASA to complete (>90%) a survey of NEOs down to a size of 140 m, a size that, 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, scientists have discovered and tracked ~90% of NEOs larger than 1 km, about 5% larger than 140 m, and only about 0.2% of those larger than 45 m.[2] (Personal communication with Alan W. Harris).

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 accomplished many years to decades in advance of the impending impact,[3] the goal of this survey is to find and track asteroids with enough orbital accuracy to determine if a serious threat exists and to provide sufficient warning time to enable a successful deflection if necessary. The foundation has chosen to adopt the 140-meter, 90%-completeness goal as our driving requirement, knowing that in addition to generating a largely complete catalog at the 140-m 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 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 that is raising funds through philanthropic donations. Interestingly, large ground-based telescopes (such as Lick, Palomar, Keck, and Yerkes) have historically been mainly funded through philanthropy.[4] In some sense, Sentinel will be like these large observatories, with the exception that Sentinel will be in solar orbit rather than on a mountaintop. The B612 Foundation will, in turn, contract the spacecraft out to Ball Aerospace and Technologies Corp (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.

This interplanetary space mission takes an innovative approach to building and operating the Sentinel. While previous missions that have departed from Earth orbit have been scientific investigations developed with oversight by NASA or other governments (e.g., European Space Agency), 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 familiar with the contractual risks involved. 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 can add great overhead and slow decisions in cases where there is clearly a best approach and contractor. BATC has carefully explored the implementation of the Sentinel mission and has identified high-heritage existing hardware system implementations that

DOI: 10.1089/space.2013.1500

enable BATC to quantify the risk of manufacture and operation of Sentinel. Thus, we have been able to choose BATC as our contractor and make rapid progress toward 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 will be responsible for meeting performance requirements, B612 must remain aware of programmatic risks and mitigations and approve the progress of the work. This is facilitated by the identification of milestones within the contract that detail various developmental 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 it works because B612 has a small but highly experienced technical team and the BATC design is derived from such high heritage. B612 has also enlisted an independent panel of experts, known as the Sentinel Special Review Team (SSRT),[5] to provide advice on technical and programmatic risks to B612. In addition, B612 will have permanent onsite technical and management personnel to enhance our visibility while progressing with 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[6] in which NASA will allow use of the Deep Space Network (DSN) for telemetry and tracking as well as allowing NASA personnel to participate on the independent SSRT. NASA and the scientific community benefit because B612 will make the data available to the community through the standard process of reporting NEO observations (see Detection Scheme section 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 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

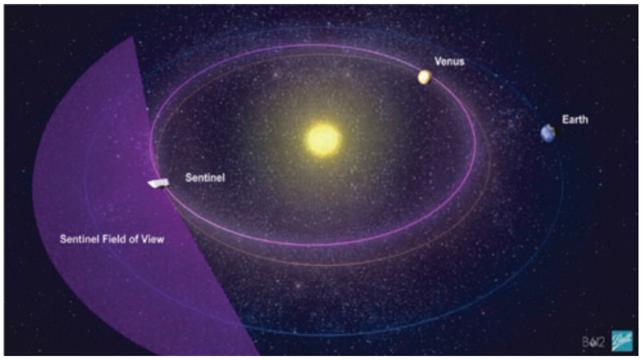

Fig. 1. Sentinel's mission architecture enables it to detect and track near-Earth objects (NEOs) within a much larger search volume than is available from the ground, and without the constraints of weather and lunar cycles.

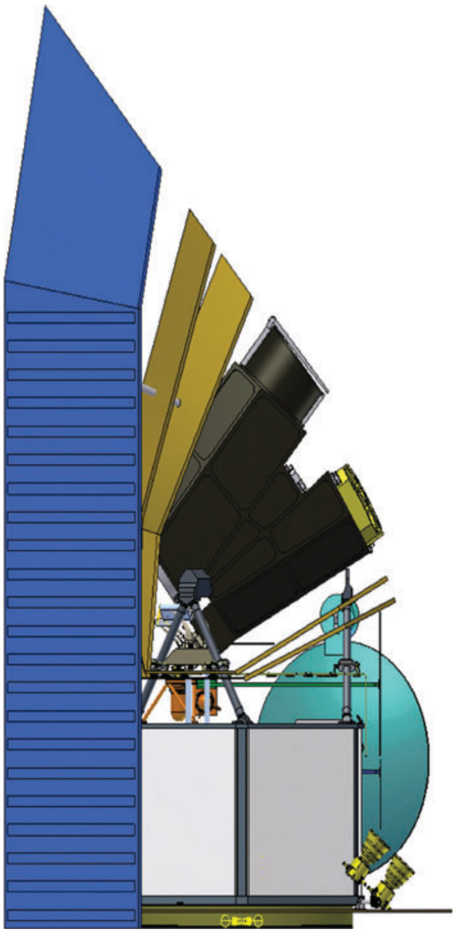

Fig. 2. This is an illustration of the Sentinel Observatory. It consists of a rebuild of the *Kepler* spacecraft (modified for the Venus-like orbit) and an infrared telescope.

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 valuable to future exploration missions.

Sentinel will be launched from Earth on a Falcon 9 rocket. The cruise to the final heliocentric orbit at ∼0.7 AU uses a Venus gravity assist to minimize fuel requirements. Communications with Sentinel through the DSN 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 that were successfully flown on the Kepler and Spitzer missions to demonstrate feasibility and low development risk and to provide a firm cost basis.[7,8] The notional Sentinel Observatory is illustrated in *Figure 2*. The tall structure on the left is the thermal shield, which also carries the body-fixed solar array, a system based on Spitzer. 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 with a combination of radiative and active cooling. The instrument's mercury cadmium telluride 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 1 AU. The telescope is mounted on a Kepler-derived spacecraft and reuses Kepler's avionics and structure.

DETECTION SCHEME

To detect an 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 four 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 onboard, and NEOs are detected by their motion during the 1-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 onboard 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 the Jet Propulsion Laboratory (JPL), which refines the initial MPC orbits, calculates the likelihoods of any impacts, and globally distributes its findings.

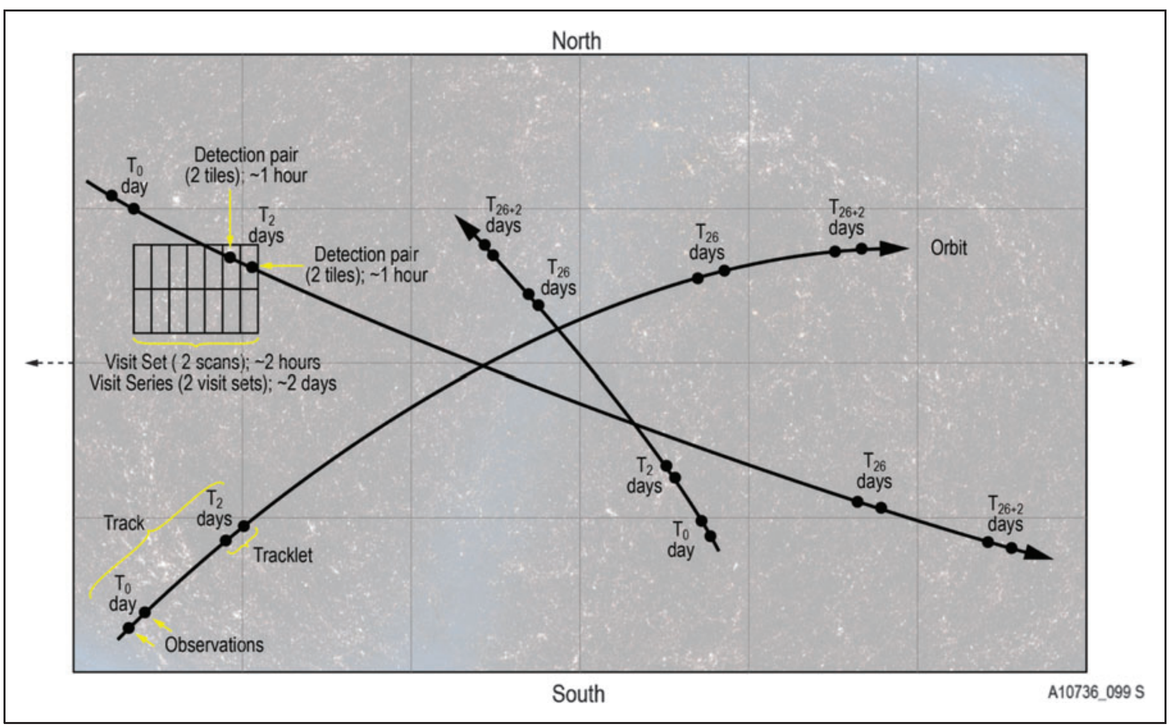

Fig. 3. The basic viewing scheme uses 1-hour pairs on 2-day and 26-day centers to locate moving NEOs.

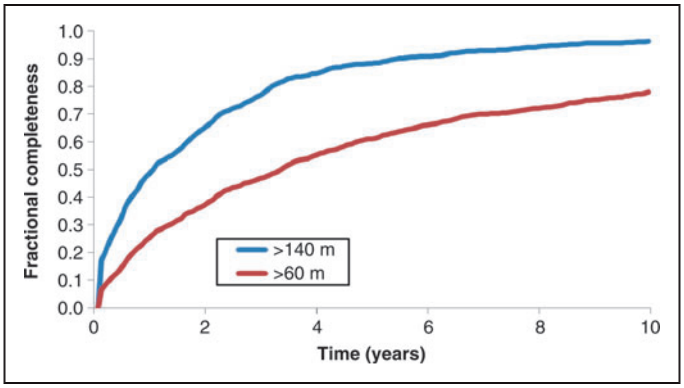

Fig. 4. Survey completeness for all NEOs greater than 140-m and 60-m diameter versus time for Sentinel, assuming continued operation of current ground-based telescopic surveys.

SURVEY PERFORMANCE

In 6.5 years of operation, Sentinel will detect and track the great majority (>90%) of all NEOs larger than 140 m. In addition, Sentinel will detect and track 50% of all NEOs greater than 50 m. *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-m 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, and more. More than 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 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 500,000 NEOs as compared to the currently known total of about 10,000. 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.

AUTHOR DISCLOSURE STATEMENT

No competing financial interests exist.

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