Asteroid Detection Results Using the Space Surveillance Telescope

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ABSTRACT

From 1998-2013, MIT Lincoln Laboratory operated a highly successful near-Earth asteroid search program using two 1-m optical telescopes located at the MIT Lincoln Laboratory Experimental Test Site (ETS) in Socorro, N.M. In 2014, the Lincoln Near-Earth Asteroid Research (LINEAR) program successfully transitioned operations from the two 1-m telescopes to the 3.5-m Space Surveillance Telescope (SST) located at Atom Site on White Sands Missile Range, N.M. This paper provides a summary of first-year performance and results for the LINEAR program with SST and provides an update on recent improvements to the moving-object pipeline architecture that increase utility of SST data for NEO discovery and improve sensitivity to fast-moving objects. Ruprecht et al. (2014) made predictions for SST NEO search productivity as a function of population model. This paper assesses the NEO search performance of SST in the first 1.5 years of operation and compares results to model predictions.

1. INTRODUCTION

The problem of NEO search and discovery has been of national interest to the United States Congress since the 1990s. Since 1998, Congress has issued a series of directives to the National Air and Space Administration (NASA), setting Near-Earth Asteroid (NEA) search and discovery targets in order to protect the Earth and its inhabitants from the threat of asteroid impact. The focus of the original 1998 Congressional mandate was to catalog 90% of NEOs larger than 1 km ($H<18$) in diameter, i.e. those large enough to cause a global extinction event. A subsequent 2005 Congressional directive seeks to extend the catalog down to objects as small as 140 m ($H\sim21.5$) by 2020, with the goal of protecting against smaller but still dangerous impacts that have the potential to cause significant regional damage.

The Lincoln Near-Earth Asteroid Research (LINEAR) program is an asteroid search program that has been contributing to NEO search and discovery since the first Congressional mandate expressing interest in providing asteroid impact warning for Earth. The LINEAR program was operated from 1998 to 2013 using two 1-m telescopes at MIT Lincoln Laboratory's Experimental Test Site (ETS) in Socorro, NM [2]. In 2013, increasing interest in cataloging the asteroid population to smaller sizes (140 m) and the availability of the 3.5-m Space Surveillance Telescope (SST) motivated a transition in LINEAR operations to the SST [3].

2. ASTEROID SEARCH WITH THE SPACE SURVEILLANCE TELESCOPE

2.1 The Space Surveillance Telescope

The SST is a 3.5-m telescope with a three-mirror Mersenne-Schmidt optical design located at Atom Site on White Sands Missile Range in NM at an altitude of 8,000 feet [4]. The telescope was developed by MIT Lincoln Laboratory for the Defense Advanced Research Projects Agency (DARPA), designed to search for and detect satellites and space debris in geosynchronous orbit. Utilizing custom, curved focal plane technology developed at MIT Lincoln Laboratory that matches CCD curvature to the focal surface of the optics, SST achieves a wide, 6 square degree field-of-view (FOV) with very fast f/1.0 optics. The CCD mosaic is comprised of 12 back-illuminated MITLL CCDs, each with 2048x4096 pixels and is typically operated in a 2x2 binned mode. In order to maximize sensitivity, the system operates without a standard filter in an open pass-band that is closely approximated by the Sloan r'-magnitude.

Because the SST's mission is space surveillance of artificial Earth satellites, it was designed as an Alt-Az mounted telescope without a field rotator. The lack of a field rotator poses a challenge in asteroid search mode because relative rotation due to the changing parallactic angle occurs between revisits and causes CCD defects to move relative to the right ascension and declination in a way that can confuse moving object detection algorithms. The image processing addresses this rotation by utilizing astrometric star subtraction techniques as opposed to a signal-based background subtraction, described more fully in [9].

2.2 **Image Processing for Asteroid Detection**

In 2013 test observations focused along the ecliptic were conducted with SST. These test data were used to develop an initial processing pipeline for asteroid detection with SST data. In January 2014, the LINEAR program began operational asteroid search with SST and efforts were focused on the rapid development of an end-to-end image processing and observation submission pipeline to submit asteroid observations to the Minor Planet Center (MPC). The MPC is the international clearing house for minor planet observations recognized by the International Astronomical Union (IAU) and is responsible for the identification, designation, and catalog maintenance of known objects. Initial end-to-end processing of SST data for the LINEAR program was supported by extensive use of third-party astronomical software tools including Astrometry.net [5], Source Extractor [6], SCAMP [7], and Montage [8]. The initial LINEAR processing pipeline developed for SST is described in detail in [9] and was designed to emulate legacy LINEAR processing, compensating for complexities introduced by the lack of a field rotator on SST. Early pipeline development efforts were made possible utilizing the LLGrid [10], the MIT Lincoln Laboratory supercomputer, in order to cope with the large data volume generated nightly at SST.

In 2015, pipeline development efforts have focused on developing a significantly faster, near real-time image processing and moving object detection pipeline. A new, streamlined processing pipeline that allows for simultaneous data collection and image processing and same-day observation submission to the MPC came online for operational processing in May and operates on a 40-core Dell R910 server (4 Intel Xeon E7-4870 CPUs with 10 cores each at 2.40 GHz with 256 GB RAM) at the SST site in N.M.

In order to achieve these performance improvements, several steps in the LINEAR processing pipeline were eliminated, including the use of both Astrometry.Net and Montage [9]. These improvements were achieved by moving the bulk of the LINEAR processing from image space to detection space, eliminating the need for time-consuming image re-projection and re-processing. The new processing pipeline is an important step in improving the efficiency of SST for NEO search and discovery, as it provides a sufficiently short window between data collection and observation reporting to allow for follow up of potential NEOs by the broader astronomical community.

2.3 **Evolving Asteroid Search Strategy**

Initial asteroid search efforts with SST were modelled on the legacy LINEAR 1-m observing strategy. This strategy focused on a wide-area search covering nearly 9,000 square degrees each lunation divided into two different search areas, with a cadence that allowed each region to be revisited 5 times each night with 15 minutes between revisits. Simulations were performed modelling SST performance using this legacy LINEAR observing strategy against a simulated population of large (>140 m) NEAs and simulation results were used to select a 2s integration time for SST in asteroid search mode [1][9], see Section 4.1. In 2014 the LINEAR program received 4-6 nights per month dedicated to asteroid search operations with SST.

In 2015, time allocation on SST increased with an average of ~8 nights per month allocated to the LINEAR program for asteroid search, amounting to 5-6 nights of good weather data. In addition to the increase in allocated time, the revisit cadence was decreased from 15 minutes to 7 minutes in order to better match typical asteroid angular rates to the pixel scale of the SST focal plane and thereby increase sensitivity to fast-moving NEOs. The cumulative sky coverage map for LINEAR observing since January 2014 is shown in Fig. 1.

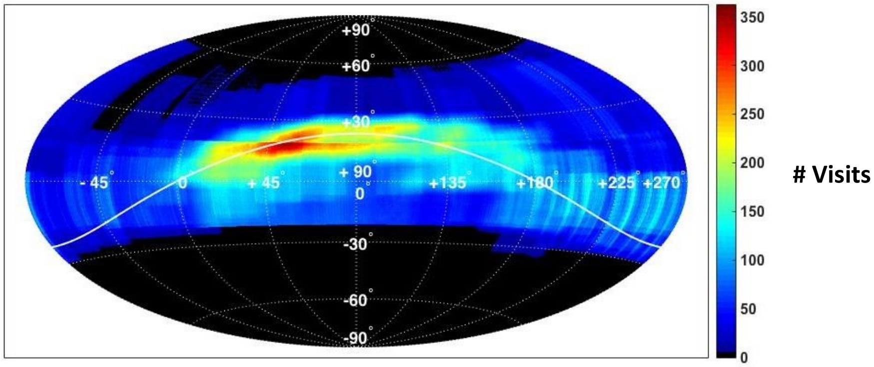

Fig 1. SST LINEAR sky coverage since January 2014. Colors indicate total number of visits to each region of the sky.

3. SUMMARY OF SST ASTEROID SEARCH PERFORMANCE

In 2014 the LINEAR program began submitting asteroid observations to the MPC and between January 2014 and July 2015 has had a total of 5,732,567 observations accepted by the MPC, of which more than half were generated in the first half of 2015. A detailed analysis of 2014 LINEAR asteroid search performance is presented in [9], and a summary of the number of observations accepted by year for all large survey programs is plotted in Fig. 2. These results indicate that since the LINEAR program became operational on SST in 2014, it has become a strong contributor to the international asteroid search and discovery effort, providing the second largest number of accepted observations on minor planets to the MPC in 2014 and the largest number to-date in 2015.

3.1 <u>Realized LINEAR pipeline performance</u>

Of interest is realized sensitivity of the end-to-end LINEAR processing pipeline compared to model predictions. The predicted sensitivity assumed in simulation for SST at the 2s exposure used for LINEAR observing was $m_{SST} = 21.1$, see Section 4.1. In order to assess the realized sensitivity of the LINEAR pipeline, a dataset comprised of observations on minor planets accepted by the MPC, is considered and the result shown in Fig. 3. In each case, we take the magnitude halfway between the median and max of the accepted magnitude distribution to be a proxy for the realized sensitivity of the end-to-end pipeline and plot error bars to indicate distance between median and maximum detection magnitude.

As can be seen in Fig. 3, the initial LINEAR development pipeline achieved an average nightly performance centered at $m_{SST} \sim 19.5$, with mean sensitivities of up to $m_{SST} = 20.5$ on nights with excellent conditions. In summer of 2014, an updated LINEAR pipeline with improved sensitivity was implemented and the realized performance increased by roughly a magnitude. As a result of these improvements, the median nightly sensitivity to moving objects achieved in the second half of 2014 and 2015 was $m_{SST} = 20.5$, with the predicted nightly sensitivity, $m_{SST} = 21.1$, achieved on nights with good weather and sky conditions.

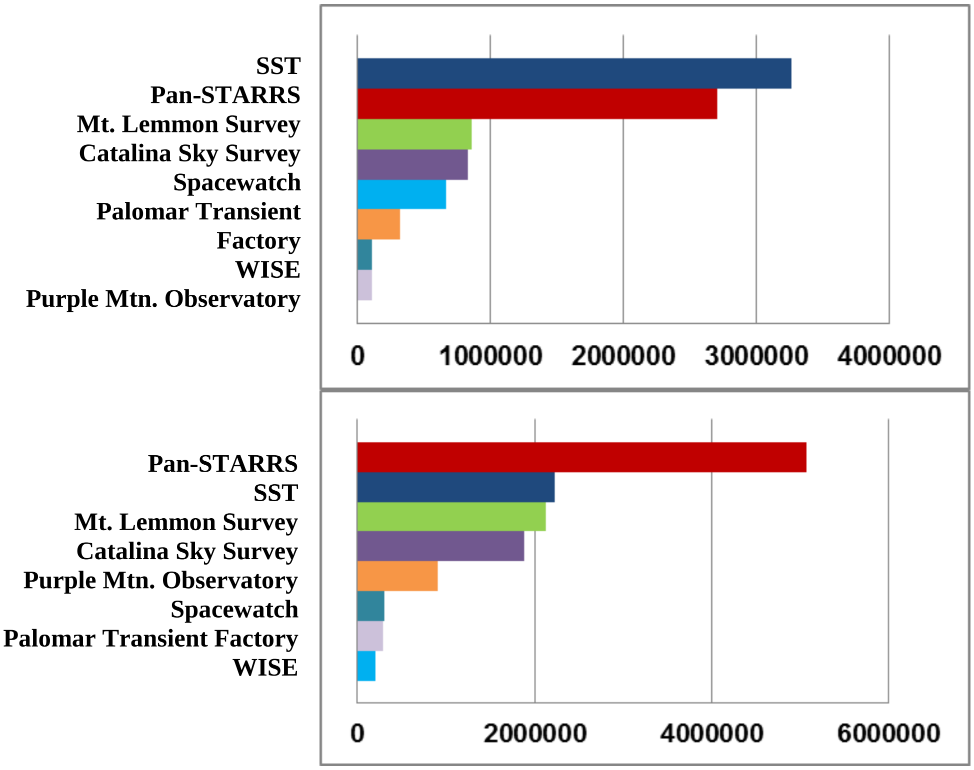

Fig. 2. Number of observations accepted by the MPC for the most productive asteroid surveys by observatory in 2014 (bottom) and 2015 through mid-June (top).

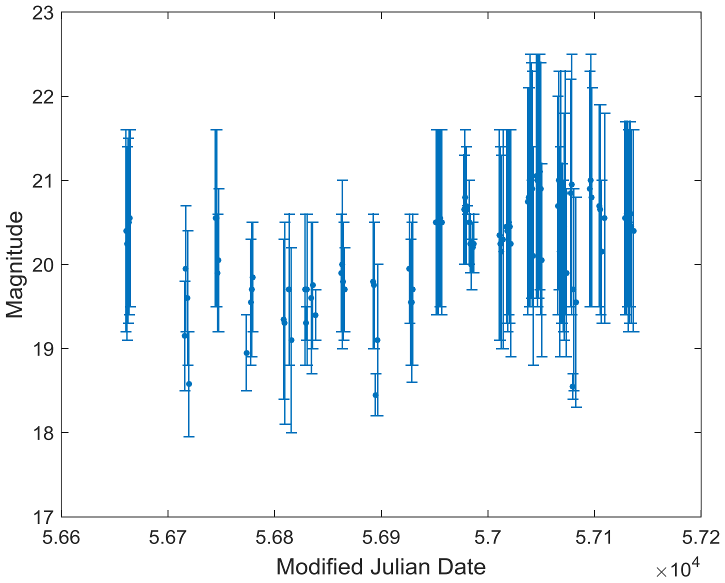

Fig. 3. Realized end-to-end LINEAR pipeline performance for moving objects derived from MPC accepted observations. The jump in sensitivity in mid-2014 is the result of improvements to the LINEAR image processing pipeline. Note that realized performance achieves an average sensitivity of ~20.5, not 21.1 as was assumed in initial simulations. Error bars indicate distance between the median brightness and faintest accepted observation.

3.2 Summary of NEO search performance

LINEAR performance with regard to NEO observations is of particular interest, since it is the NEO population that poses an impact hazard to Earth. Fig. 5 provides a comparison of average nightly SST NEO search productivity compared to other leading asteroid surveys for the six month period from October 2014 to March 2015. In order to better compare SST performance with limited time allocation to the performance of full-time surveys, only nights between the first and last nights of SST observing each lunation were included in the dataset across all observatories. From Fig. 5 it is clear that SST's nightly NEO search productivity lies between that of the Catalina Sky Survey and Pan-STARRS search results. Pan-STARRS excels at asteroid search due to its longer integration times and smaller pixels. The field rotation due to a lack of a field rotator at SST (discussed in Section 2.1) limits the maximum useful exposure that can be obtained in asteroid search mode to no more than 2-3 seconds, due to streaking of objects toward the edges of the FOV and prevents SST from searching as deeply as the PanSTARRS survey.

It is expected that the recent transition to near real-time processing will improve LINEAR NEO search performance in future lunations. Timely observation submission will allow likely NEO candidates from the LINEAR data to be made available to the broader asteroid search community for follow up observations via the MPC's NEO confirmation page (NEOCP). In previous months, long timelines between data collection and observation submission meant that new objects discovered in LINEAR data were likely to be lost before follow up observations could be obtained.

4. DIFFERENCES BETWEEN PREDICTED PERFORMANCE AND NEO SEARCH RESULTS

4.1 Predicted NEO Search Performance vs. Size

In 2014 simulations of NEO search performance with SST were conducted assuming an observing strategy similar to that of the legacy, 1-m LINEAR program [1]. These simulations assumed SST would operate with 1s exposures, 5 revisits separated by 20 minutes, and would cover an area of 6,000 square degrees per night with 20% losses due to weather.

Predictions were made for SST search productivity for both small (7-10 m) NASA Asteroid Redirect Robotic Mission (ARRM) targets, as well as large (>140 m) NEOs. The simulated large asteroid population was generated from the orbit distribution of known large NEAs using the methodology of [12] to generate a population of 100,000 synthetic large asteroids with sizes $14<H<22$ on randomized orbits matching the orbital element distribution of known large NEOs. These orbits were then propagated over a simulation time of two years using the OrbFit code [10] and the resulting asteroid ephemeris was observed in simulation using the parameters for SST described above. The resulting detections were normalized to several different size-frequency distribution models for the NEO population, described in [12], [13], and [14].The result of this initial simulation work, updated to reflect the 2s exposures used in the operational SST cadence were discussed in [9] and the results are shown in Fig. 4, assuming 3 nights/month allocated to asteroid search with SST.

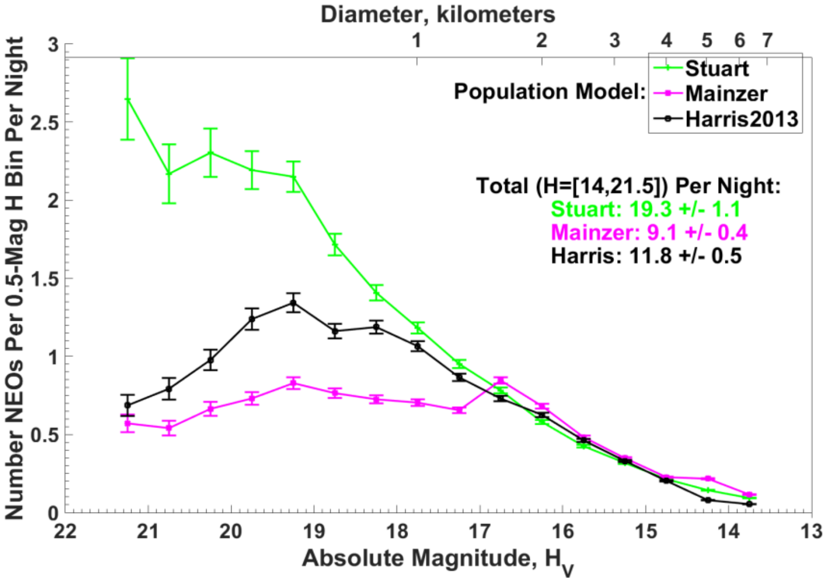

Fig. 4. Large (>140 m) NEO detection rates predicted for a 2s exposure, accounting for losses due to field rotation. Assumes a 3 night/month telescope allocation with a limiting magnitude of $m_{SST} = 21.1$.

4.2 Realized NEO Search Performance vs. Size

Fig. 5 provides an overview of NEO search productivity vs. H-magnitude for each of the major asteroid surveys down to the ~140 m sizes relevant to the 2005 Congressional directive. The cumulative number of objects detected per night by SST with an H-mag between 14 and 21.5 is, on average, 13.4 unique objects. It is tempting to compare these results to the predictions made in simulation, depicted in Fig. 4, which yield expected nightly observing rates of 19 ± 1 with model [13], 9 ± 1 with model [14], and 12 ± 1 asteroids per month with model [12]; however, due to significant discrepancies between the operational observing strategy in use at SST during winter 2014-2015 and the assumed cadence described in [1] and [9], we caution against making this comparison.

4.3 Differences between simulations and observations

In the simulation work described in Section 4.1, it was assumed that the SST would operate with a 2s exposure, achieving a limiting magnitude of $m_{SST} = 21.1$ and would cover a large 6,000 square degree search area each night. With more than a year of SST data collection and processing, it is now possible to examine the achieved sensitivity of the LINEAR processing pipeline in in 2014 and the first half of 2015, as well as to look at the search rate achieved at SST.

The nightly search area available to SST varies seasonally with the length of the night. With a requirement of five revisits to each observed region per night, the SST is capable of observing between 4,000 and 6,000 square degrees per night in summer and winter respectively. Additional factors such as weather have seasonal impacts, with the monsoon pattern in NM causing significantly increased impacts due to weather during the summer months. An analysis of weather impacts to LINEAR observing in 2014 indicate that out of 76 nights attempted, 10 nights were completely weathered out and an additional 19 nights experienced significant (>50%) losses in observing time due to weather. The cumulative impact due to weather on SST observing is therefore higher than predicted, with nearly 38% of attempted nights experiencing significant or total losses due to weather.

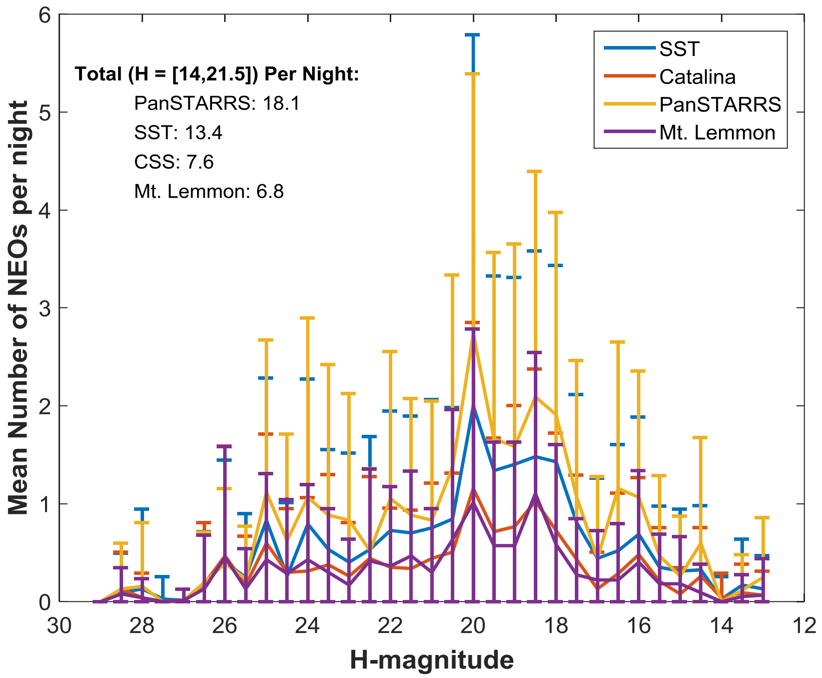

Fig 5. Cumulative number of NEOs vs. size (H-magnitude) for the leading asteroid surveys from October 2014 to March 2015. Mean and standard deviation of number per H-mag bin across all nights are plotted. The large error bars are a result of the significant night-to-night variation in NEO search productivity as a function of size. Note that in computing totals, H-magnitudes have been clipped to reflect only sizes considered in previous NEA simulation work (Fig. 4).

The discrepancies between the initial simulation work described in [1] and [9] and the operational cadence include differences in sensitivity, weather loss, and to a lesser extent sky coverage. Additionally, differences in telescope time allocation and observing strategy make any comparison between the initial simulation results and the observed number per month indicated in Fig. 4 difficult. Namely, in winter 2014-2015 SST received higher-than-average time allocation per month with ~12 nights each lunation devoted to asteroid search, this rate is significantly higher than the 3 night per month allocation assumed in initial asteroid survey simulations. We have attempted to compensate for this discrepancy by considering the average number of NEOs detected per night in Figs. 4 and 5.

The increased time allocation is confounded by decreased area coverage, as the LINEAR program with SST was funded for a series of experimental data collections in winter 2014-2015 in an effort to provide a data-driven constraint on the Earth’s temporarily captured object (TCO), or “minimoon” population. In order to maximize observability of TCOs [15], SSTs asteroid search time was focused primarily on the ecliptic, instead of utilizing a wider-area “all-sky” survey strategy, as was assumed in initial simulations. These factors make it inadvisable to compare the initial asteroid survey simulation results to the NEO search results discussed here.

5. FUTURE WORK

Given the large differences in expected number of observed NEOs vs size as a function of size-frequency distribution derived from initial simulation work (Fig. 4), SST observations are expected to provide leverage over the size-frequency distribution of the NEO population at small sizes. However, due to differences between initial simulation assumptions and operational observing cadences, a direct comparison between simulated performance and observations is not currently possible.

In order to make a direct comparison between SST results and predicted observation rates, it is necessary to build a high-fidelity asteroid search simulation based on historical observing data. With more than a year of operational LINEAR observing to date, it is possible to utilize historical telescope pointing and observing data in order to reconstruct a model of SST performance on a frame-by-frame basis. Such a simulation can be used to model observations of simulated NEO populations, sampling a known orbital element distribution across a variety of size frequency distributions. Statistical comparison of these simulation results to actual SST asteroid search performance are expected to yield strong constraints on the size frequency distribution of the NEO population at small sizes.

Additionally, development efforts to improve the LINEAR observing strategy and data processing pipeline to improve NEO detection and discovery rates are ongoing. Efforts to improve sensitivity to fast-moving NEOs and TCOs are underway, as well as on-sky testing of observing strategy improvements to increase NEO search productivity. Long-term goals also include the development of a strategy for the utilization of data collected in other operational modes for asteroid search, which would increase the number of nights per lunation available for asteroid search with SST.

6. CONCLUSIONS

The results of the first year and half of LINEAR observing with the 3.5 m Space Surveillance Telescope are summarized and particular attention is paid to SST performance with regard to NEOs. In 2014 SST provided the second largest number of observations accepted by the MPC of all asteroid surveys and as of mid-June 2015, SST has submitted the largest number of accepted observations for 2015.

SST's NEO search performance is comparable with other leading surveys such as the Catalina Sky Survey and Mt. Lemmon observatories; however, there is opportunity for improvement in SST performance and efforts to improve SST NEO search and discovery productivity are ongoing. Recently SST has transitioned to a near real-time pipeline which allows same-day observation submission to the MPC and dramatically shortens the data processing timelines described in [9]. This transition increases the utility of SST observing to the broader astronomical community as it provides timely observations to the MPC and allows for follow-up by other observatories.

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