ASTEROID DETECTION WITH THE SPACE SURVEILLANCE TELESCOPE

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ABSTRACT

The Space Surveillance Telescope (SST) is a 3.5 m wide field-of-view system developed for the Defense Advanced Research Projects Agency (DARPA) by MIT Lincoln Laboratory to advance the nation's capabilities in space situational awareness. In addition to the national interest in identifying and cataloging man-made space objects, there is a growing concern for near-Earth asteroid identification and tracking. MITLL is developing a program to detect near-Earth asteroids, as an extension of the Lincoln Near-Earth Asteroid Research (LINEAR) survey, to identify potentially hazardous near-Earth objects and to extend the catalog of known asteroids to smaller sizes (< 140 m). MITLL believes SST's capability to detect asteroids on size scales as small as 5-10 m is well suited to provide NASA with a sample of small asteroids of interest. The Keck Institute for Space Studies[1] studied the feasibility of asteroid capture into lunar orbit as a destination for additional investigation; potentially including a proposed NASA mission to send astronauts to near-Earth asteroids as a stepping-stone to further manned exploration of the Solar System. A major requirement of such an effort is the development of a sample of suitable asteroids, a job that SST is uniquely able to achieve by means of its capacity for search rate and sensitivity.

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1. INTRODUCTION

MIT Lincoln Laboratory (MITLL) has a long history of developing electro-optical space surveillance technology for man-made satellite search, detection, orbit determination, and catalog maintenance. The Lincoln Near-Earth Asteroid Research (LINEAR) program developed from that history of space surveillance [1]. MITLL designed telescopes and detector technology for the Air Force Geosynchronous Deep Space Surveillance (GEODSS) system. Later, MITLL developed CCD detectors to upgrade GEODSS primarily to enable large area surveys. In February 2011, MITLL brought to first light the 3.5 m Space Surveillance Telescope (SST). SST was developed under the sponsorship of the Defense Advanced Research Projects Agency (DARPA) to enhance the nation's deep space and small object surveillance capabilities. As part of its evolving mission, the SST will contribute to asteroid discovery for the LINEAR program.

The LINEAR program is designed to support NASA's strategic vision for the identification and tracking of Solar System objects, which may pose a hazard to humans primarily by planetary impact. This component of NASA's broader Solar System exploration mission is driven in part by the 1998 Congressional directive to NASA to protect the Earth and its inhabitants from the threat of asteroid impact. The focus of this mandate is to catalog 90% of near-Earth objects (NEOs) larger than 1 km ($H<18$)[1] in diameter. The 2005 Congressional directive seeks to extend the catalog down to objects as small as 140 m ($H\sim21.5$). Fig. 1 shows the absolute magnitude distribution of near-Earth asteroids previously discovered (by all sources) as a function of the year of discovery. There is a trend toward the discovery of fainter objects in more recent years. This trend can be attributed both to advances in technology that enable observations of fainter objects and to the fact that the larger objects have historically been easier to detect.

The LINEAR survey continues to be a key component in the search for large NEOs. We are working to extend the LINEAR program to improve sensitivity to objects smaller than 1 km and potentially achieve the 140 m goal. Three major advancements will enable LINEAR to improve its sensitivity to <1 km objects: developments to the existing LINEAR image processing chain; incorporating discoveries from the 3.5 m Space Surveillance Telescope (SST); and changing the survey methodology of the legacy LINEAR system to take advantage of opportunities for new search strategies made possible by sharing the sky coverage with the SST. The enhancements that are currently in development will produce a better understanding of the near-Earth asteroid population.

In this paper we describe the role of the SST in the LINEAR program (Section 2), and the observing strategy and sky coverage (Section 2.1). We also discuss the results of a recent study to assess the performance of the SST in detecting small asteroids appropriate for visitation or capture by a proposed NASA mission (Section 3). Section 4 contains the conclusion.

[1] We follow the absolute magnitude, H, versus physical-size convention of described by Bowell [2]. An asteroid's absolute magnitude is what an observer would measure if it were at a distance of 1 AU away, 1 AU from the Sun, at phase angle zero, and albedo from 0.05 to 0.25. We report sizes in the middle of this albedo range for simplicity.

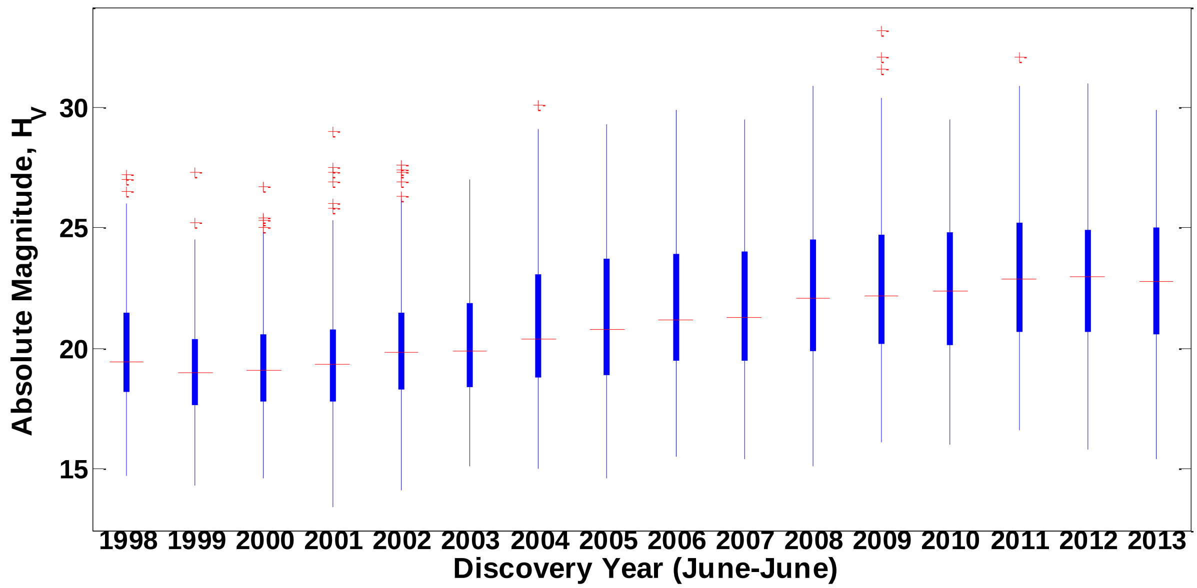

Fig. 1: Absolute magnitude distribution of known near-Earth asteroids as a function of discovery year (data from the Minor Planet Center webpage for the Amors, Atens, and Apollos [3]).

2. ROLE OF THE SPACE SURVEILLANCE TELESCOPE

The Space Surveillance Telescope will significantly augment the LINEAR program's efforts at NEO detection and tracking. The SST combines a 3.5 m primary and a wide field-of-view using an unconventional Mersenne-Schmidt design with a highly agile mount on a high and dry site. SST provides satellite and debris surveillance, particularly at the geosynchronous region located at approximately 36,000 km from the Earth's surface. Combined with a custom, curved focal surface CCD mosaic, SST provides a uniform 6 square degree field-of-view. The mosaic has 12 CCD devices across the uniformly illuminated Mersenne-Schmidt focal surface. Each CCD has 2048 by 4086 15 µm pixels. The advanced CCD technology enables wide area sky surveys for asteroid detection [4].

The Space Surveillance Telescope is located on Atom Site on the White Sands Missile Range, approximately 30 km from the present LINEAR site, but with substantially better sky conditions at 8000 feet. We will use the SST as a new object discovery tool, particularly for smaller (hence, fainter) asteroids. The legacy LINEAR system will provide complimentary coverage and act as a follow-up system for new SST detections. The legacy LINEAR system comprised two telescope systems working in tandem to cover as much sky as possible. The telescopes are both 1.0 m class GEODSS-type, with nearly identical cameras and data processing systems. The GEODSS telescopes have 1 m primary mirrors in a folded prime focus configuration.

SST will improve LINEAR NEO search in two general ways. First, with greater than 8 times the effective collecting area over the legacy system, SST will be able to detect faint NEOs during routine searches. This will allow us to generate detection lists for follow-up observations with the legacy LINEAR system using cued observing. Second, by reducing the search regions around the geosynchronous belt, SST allows the legacy LINEAR system to dwell longer on the remaining critical asteroid search regions. By employing frame stacking and velocity matched filtering methods on this imagery; the legacy system may also achieve detections of NEOs as small as 140

m. Fig. 2 illustrates the performance of different telescope systems against an asteroid of a given limiting magnitude at opposition; the SST will assist in resolving a critical knowledge gap around 140 m class objects and smaller.

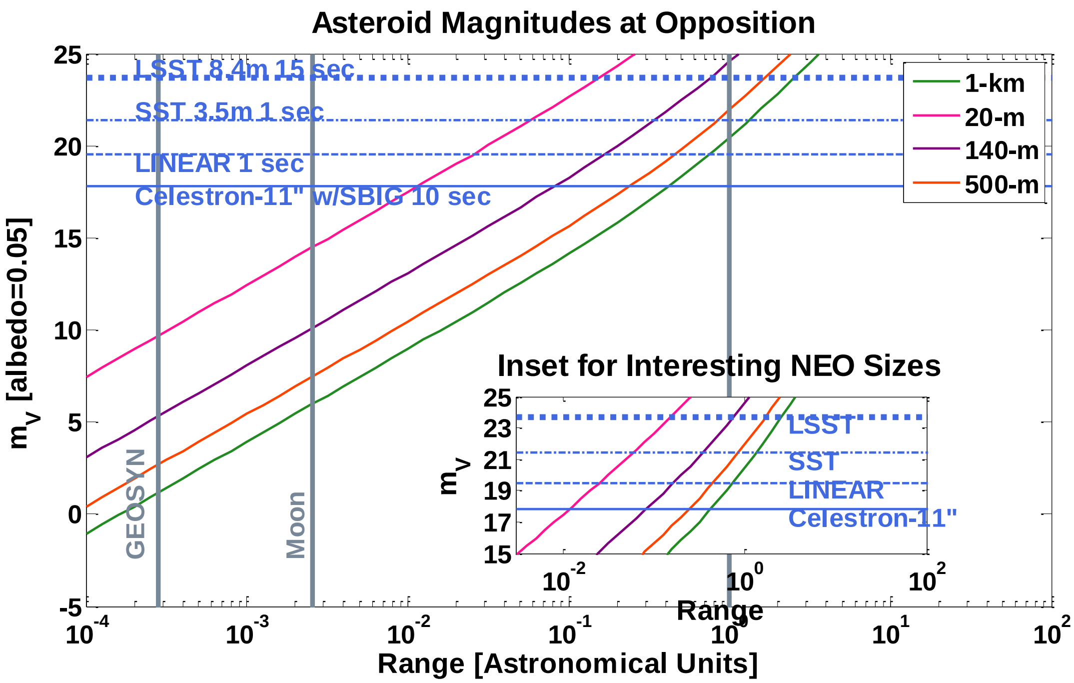

Fig. 2: SST will assist in resolving a critical knowledge gap. Using 1 m class telescopes limit our ability to see the full population of smaller asteroids. Larger apertures make detection easier, but conventional designs limit field-of-view, thus lowering search efficiency.

2.1. SKY COVERAGE

The observing strategy for running in asteroid search mode on the SST is designed to maximize areal coverage at a revisit rate that is optimal for object association and tracking. Studies show that the main belt asteroids have an apparent motion of approximately 0.01 arcsec/s, while the fast moving objects – the more interesting case of near-earth asteroids – have an apparent motion that may extend beyond 1 arcsec/s [5]. The SST asteroid search cadence is therefore designed to detect objects moving at such rates. The cadence when in asteroid search mode will be roughly 20 minutes between revisits. With an SST camera pixel size of 1.7 arcsec/pixel (binned), we expect asteroids to move up to 700 pixels in 20 min for the case of 1 arcsec/s motion.

An asteroid identification will require detection in 3 out of 5 frames, where the search cadence dictates a time spacing of approximately 20 minutes between frames. Simulations show that the 3/5 rule optimizes the detection rate and offers a buffer from the effects of bad pixels and gaps between adjacent CCD devices, while minimizing the rate of false positives.

In comparison, the depth of search for the legacy LINEAR system is about 19^{th} magnitude, using integration times that range from 5 seconds on short summer nights up to 15 seconds on long winter nights. The limiting magnitude is calculated for each field every night. Fig. 3 shows the sky coverage for the legacy LINEAR system for one dark period in October 2010 (upper panel) and for the multi-year period from 1999-2012 (lower panel). In each case, the estimated limiting magnitude is converted to the integration time necessary to achieve that limiting magnitude under good weather conditions. The good weather equivalent integration times for all the visits to each field are summed, and then converted back to a limiting magnitude to give an impression of how the cumulative depth of search varies over the sky

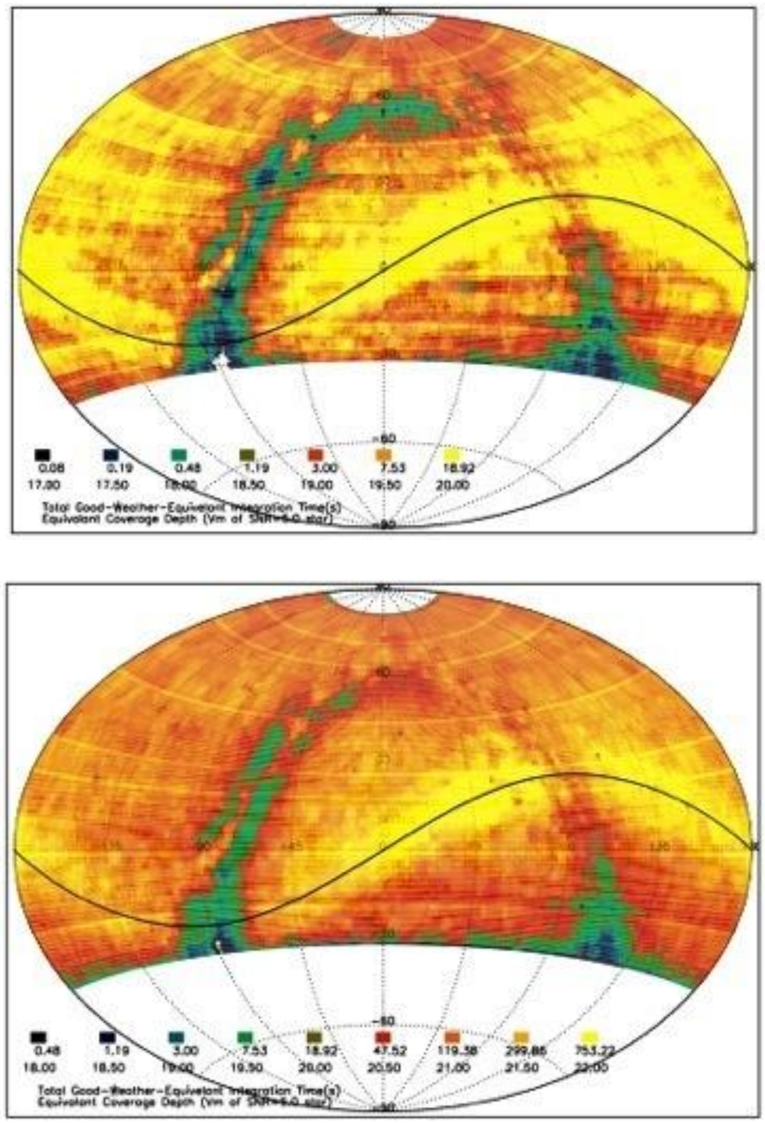

Fig. 3: The upper panel shows the search depth for 2011; the lower panel shows 1998-2012. The search rates are for the legacy LINEAR program using the 1.0 m GEODDS telescopes.

3. SIMULATED PERFORMANCE AGAINST SMALL ASTEROIDS FOR CAPTURE MISSION

MITLL undertook a study for NASA on the performance of the SST in detecting small asteroids that would be suitable candidates for future space flight missions. NASA is exploring a range of options for sending astronauts to near-Earth asteroids as a stepping-stone to further manned exploration of the Solar System. Asteroid destinations for human spaceflight would be chosen to maximize the opportunity it provides astronauts to explore distant entities in the Solar System, while maintaining a high level of safety. One possibility is to use an unmanned spacecraft to modify the orbit of a very small near-Earth asteroid so that it becomes captured into orbit in the Earth-Moon system. Those captured asteroids could be maintained in orbits in the cislunar[2] ($R_{GEO} \leq R \leq R_{Moon}$) regime providing generations of astronauts training; resource exploitation for both earthbound and space-based use; a proving ground for future technologies that can explore and retrieve materials from throughout the Solar System; and a compelling venue for international cooperation.

The Keck Institute for Space Studies [6] produced an expansive study of the feasibility of asteroid capture into lunar orbit. A major requirement of such an effort is the development of a census of suitable asteroids. In order to provide targeting for spacecraft, the detection and characterization of asteroids must include sufficient orbital accuracy. This requires a combination of a sufficient number of detections of candidate objects, primarily in the optical; rapid enough follow-up with high quality characterization sensors potentially including planetary RADAR; and an orbit-dynamics model of an appropriate fidelity that includes solar-system gravitational effects and significant non-gravitational perturbations.

Using the Keck study results as a basis, we investigated the time critical discovery and orbit characterization of small Near Earth Asteroids (NEAs). The Keck study concludes that in order to be discovered and captured into lunar orbit within a proposed technology timeframe of 2025, candidate asteroids should be around 7 meters in diameter and be in energetically favorable orbits that naturally bring them very near to the Earth. The small size of these objects produces considerable challenges for a telescope survey. We combine our understanding of ground-based optical sensors with population predictions to assess the ability to detect, track, and target potential asteroids for retrieval candidates, using the SST as the survey telescope. The input sample of asteroid orbits and sizes against which we measure the discovery rates are provided by collaboration with Univ of Hawaii (R. Jedicke, private communications) based on the Greenstreet orbital distribution model [7].

The population of natural satellites named Temporarily Captured Objects (TCOs) are also of interest for their potential availability for visitation by human spaceflight or for material resource extraction [8, 9]. Studies suggest that a transient population of small such objects that are captured by the Earth-Moon system is present at any given time, although difficult to detect [10]. Note that the TCOs are not part of the input sample of asteroid orbits used in our current investigation; the combination of orbital elements that would result in a capture is statistically unlikely to be part of the representative sampling of parameters that make up the input sample for our investigation. Consideration of TCOs as asteroid candidates for a future NASA mission is a subject of future work.

[2] R_{GEO} = Geosynchronous orbital radius for Earth-orbiting satellites = 42,164 km. R_{Moon} = Mean Earth-Moon distance = 384,400 km

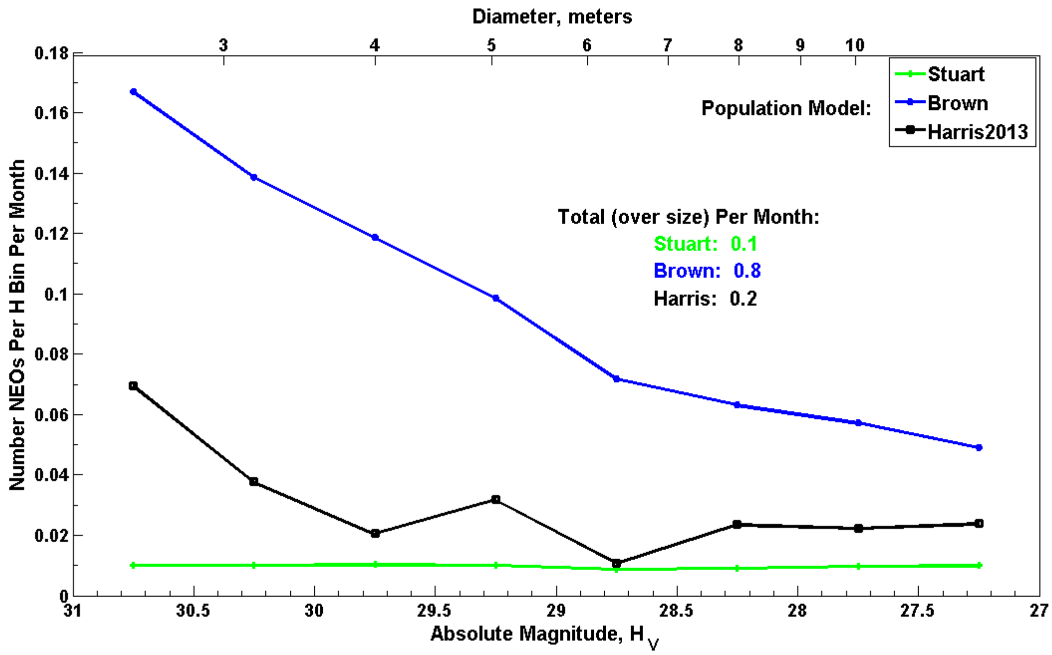

Fig. 4: Plot shows projected number of discoveries per (calendar) month of SST observations based on simulation results scaled by various population models. The uncertainty in the number of NEAs at 1-10m sizes dominates number of potential candidates for retrieval mission. The population models by which the sample of asteroids is scaled are described in Refs. 11, 12, 13.

The results of the first round of study are shown in Fig. 4, which has the projected number of discoveries per month as a function of asteroid absolute magnitude (i.e. size). Note that there are almost 2 orders of magnitude in variation of candidate population, depending on asteroid size model; thus the population model statistics dominate the uncertainty in the discovery rate. The performance predictions include the following assumptions: each night, cover those RA/DECs that are above 20° elevation cutoff at local midnight; use limiting magnitude appropriate for 1s integration time; apply simple weather loss where 20% of nights randomly lost; apply simple CCD device gap loss where 3% of detections randomly lost.

Each asteroid discovered in the simulation was followed for the discovery apparition and the number of days brighter than V=22 were counted, and then averaged in bins of 0.5 H magnitudes. Fig. 5 shows the time frame for follow-up of the simulated detections.

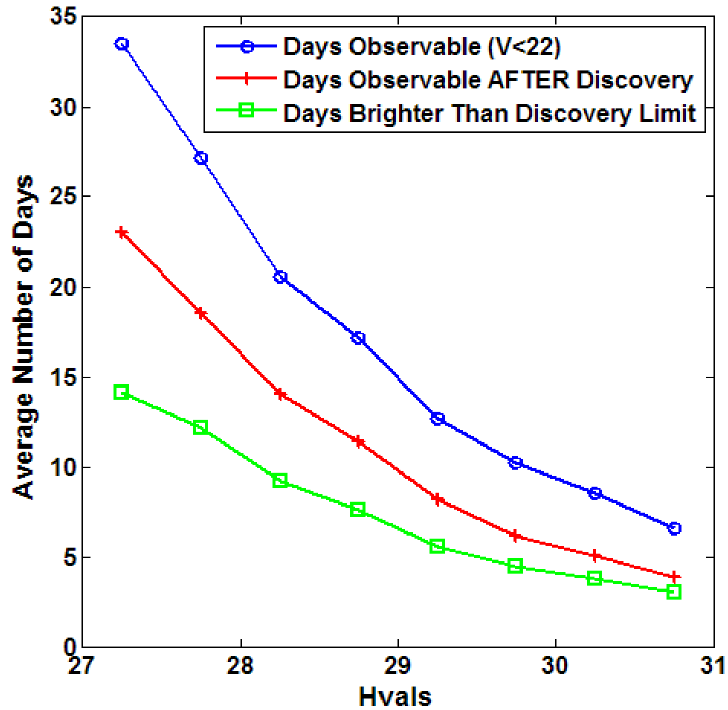

Fig. 5: Days asteroids are observable (above a minimum brightness). The red line shows the approximate amount of time available for follow-up observations after the discovery. The green line approximates the number of days available for the discovery to happen, and gives an indication of how rapidly the sky must be covered so as not to miss objects.

4. CONCLUSION

The LINEAR program is expected to realize a substantial improvement in the detection frequency of small NEOs through the use of the 3.5 m SST data for asteroid detection. The combination of legacy LINEAR and SST observations would provide a wider area coverage. The legacy LINEAR system will survey with longer integration times, thus achieving a lower limiting magnitude and projected NEO size. The result of the combined legacy LINEAR system and the SST asteroid detection pipeline will help bring us closer to the vitally important goals set out by the 1998 and 2005 Congressional directives.

The LINEAR program with the SST is expected to provide capability for cataloging of <1 km class (H>18) NEOs and achieves detections of 140 m class objects (H~21.5). Using common software tools for astrometry, target extraction, image combination, and photometric calibration, the SST asteroid data collection effort run by MIT Lincoln Laboratory would bring the resources of the nation's most advanced space surveillance telescope to the problem of near-Earth asteroid detection and orbit determination.

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