RAPID PRE-DISCOVERY OF NEAR-EARTH OBJECTS Tam Nguyen[1], [1]University of Maryland, College Park, MD 20742 USA; tamz@umd.edu

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Background and Motivation:
The Vera Rubin Observatory Legacy Survey of Space and Time (LSST) will provide an unprecedented number of potential Near-Earth Object (NEO) discoveries [1]. Many of these new NEO candidates will require additional detections for confirmation and orbit refinement. While follow-up strategies have been actively developed, it is expected to take a significant dedicated amount of time and resources to follow up on all potential LSST detections [2].

Pre-discovery provides a complementary and alternative method to traditional follow-up by locating potential NEO detections in archival image data, using sky positions derived from back-propagated initial orbit estimates. Unlike conventional follow-ups, pre-discovery approach can rapidly reduce orbit uncertainty for new NEO candidates without significant additional time and resources, as illustrated in Figure 1. Challenges remain with NEO pre-discovery due to the potential large search space caused by high initial orbit uncertainty as well as limited sensitivity of existing sensors compared to LSST capabilities.

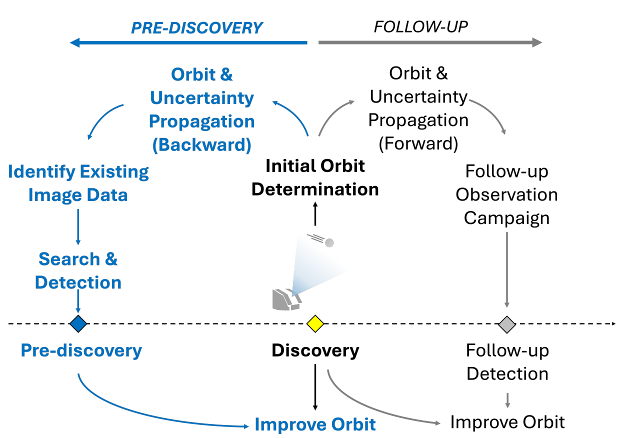

Figure 1: Pre-discovery and follow-up approaches to improving orbit of new NEO discovery

To address challenges of NEO pre-discovery, we have developed an efficient synthetic tracking pipeline capable of detecting NEOs beyond the single-frame sensitivity limit across a wide search space. Traditional synthetic tracking methods often consists of shift-stacking images along many trajectory hypotheses to increase the signal-to-noise ratio (SNR) of faint objects. In cases where the search space is large, such as in the case of high-uncertainty orbit estimates, traditional synthetic tracking methods can become highly computationally intensive. Our approach addresses this issue by implementing a dynamic-programming, divide-and-conquer algorithm to rapidly search a large trajectory hypothesis space to generate detections of faint objects. This technique has been previously demonstrated to provide significant computational speedup to synthetic tracking, providing detections of solar system objects orders of magnitude fainter than the single-frame detection limit with limited a priori state knowledge [3].

In this work, we introduce a proof-of-concept pre-discovery pipeline and present early results, demonstrating the feasibility of NEO pre-discovery using image data from the Transiting Exoplanet Survey Satellite (TESS) mission. This work demonstrates NEOs pre-discovery capabilities beyond the traditional sensitivity limit of existing sensors and without relying on high-precision orbit estimates, enabling more efficient NEO confirmation in the LSST era.

Pre-discovery Pipeline for faint NEOs:
The proof-of-concept pre-discovery pipeline for faint NEOs is illustrated in Figure 2. Archival images from existing surveys are queried for the relevant pre-discovery time frame using back-propagated ephemeris. To enhance detectability, a background and star subtraction process is applied to suppress static stellar sources and background noise, with additional masking to remove residuals from bright stars. The pipeline then employs a synthetic tracking method based on the Fast X-ray Transform (FaXT) to efficiently search for linear trajectories traversing the image stack. The FaXT algorithm speeds up traditional synthetic tracking method by employing dynamic programming and divide-and-conquer techniques, as described in detail in Nguyen et al. 2024 [3]. The algorithm outputs a 4D data structure, which stores the integrated pixel intensities along hypothesized linear trajectories, parametrized by initial positions and velocities in the image frame coordinates. Potential NEO detections are extracted from this data structure through spatial filtering, segmentation, and thresholding. Detections with sufficiently high signal-to-noise ratio indicates potential pre-discovery of the NEO of interest.

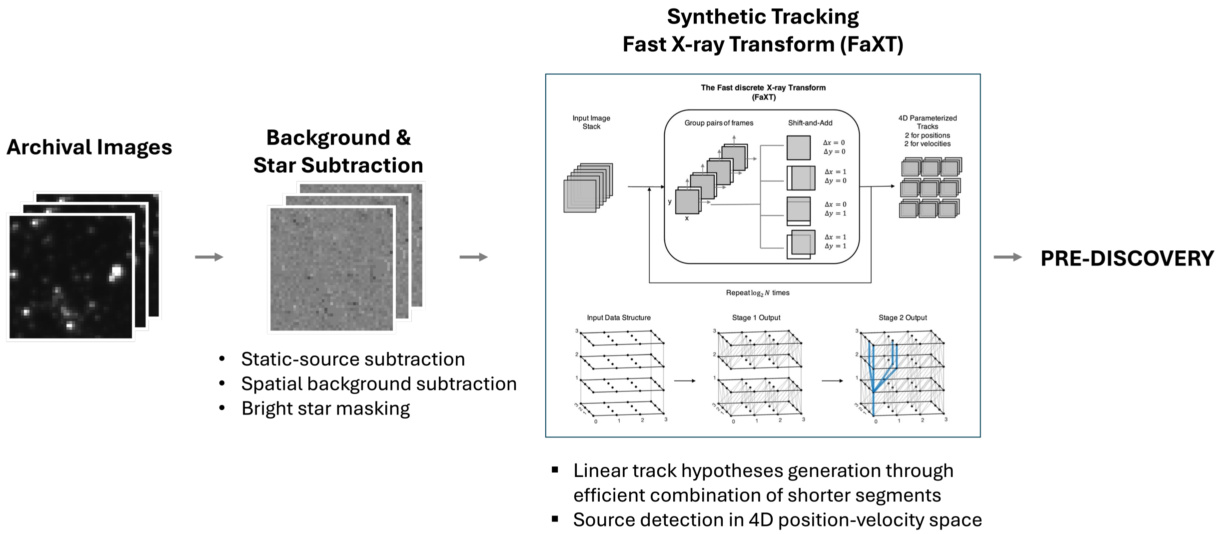

Figure 2: Faint moving object search and detection pipeline to enable rapid NEO pre-discovery

Proof-of-concept Demonstration:

To demonstrate the capability of the pre-discovery pipeline, we selected NEO 2019 AH11 as a test target for pre-discovery. 2019 AH11 was first discovered on Jan 11, 2019 by Pan-STARRS and subsequently followed-up by several observatories to refine its orbital parameters. Our analysis showed that 2019 AH11 was in the field-of-view (FOV) of the Transiting Exoplanet Survey Satellite (TESS) instrument in Sector 6, which spanned from Dec 11, 2018 to Jan 07, 2019 – a month leading up to initial discovery. TESS is a space telescope launched in 2018 with four wide-field cameras, each with $24^\circ \times 24^\circ$ FOV [4]. While the mission's primary goal is exoplanet detection, TESS has been shown to be a valuable asset for solar system object detection [3, 5, 6, 7]. It is noted that the apparent visual magnitude of 2019 AH11 during TESS Sector 6 was V≈21.5–21.9, much fainter than TESS single-frame sensitivity limit at V≈19 [7].

We present the successful pre-discovery of NEO 2019 AH11 in TESS data using a dynamic-programming synthetic tracking pipeline. The detection was made by processing the first 512 frames (each with a 30-minute exposure) from TESS Sector 6 - Camera 2 - CCD 3. During this 10.7-day period, the apparent visual magnitude of 2019 AH11 is V≈21.8 on average. The search volume for this proof-of-concept is 35 arcminutes in initial position and 0.14 arcseconds/minute in velocity with a total of 100 million track hypotheses [1]. The total computational search time is less than 10 seconds with a standard consumer-grade laptop. The pipeline returned a single detection, shown in Figure 3 at an SNR of 14.0. Through comparison with ground truth from the Minor Planet Center (MPC), it can be confirmed that this detection is within 1 pixel (21") of the expected sky position of 2019 AH11 at this time [2]. No other detections were made with the pipeline within the search space defined. It is worth noting that the astrometric precision of this detection is limited by TESS's relatively large pixels.

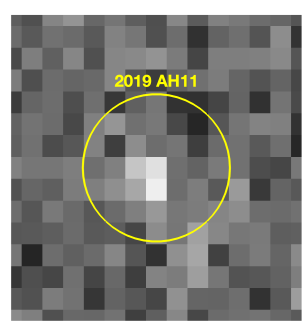

Figure 3: Pre-discovery detection of 2019 AH11 in TESS data from Dec 2018

[1] Future search regions will be defined by propagated orbit uncertainty.

[2] Precise ephemeris was not used as input to the pre-discovery pipeline to demonstrate search capability.

To assess the impact of pre-discovery on orbit determination, the Find_Orb software package [8] was used to compute orbit estimates and associated uncertainties based on available observational data. This analysis incorporated observations of 2019 AH11 in the first 5 days after discovery as reported to the MPC and newly generated pre-discovery observation from TESS data in the prior month. The TESS-based detection was reported as 2 separate observations at frame 128 and frame 256. Figure 4 shows the uncertainty in orbital period estimate of 2019 AH11 from observations available incrementally in the first 5 days after discovery– with and without the inclusion of pre-discovery data [3]. The results indicate a substantial reduction in orbit uncertainty: the uncertainty in orbital period drops from nearly 800 days to 40 days immediately after discovery and subsequently to about 2 days with early follow-up observations. Importantly, we found that the relatively low astrometric precision of the TESS detection had minimal impact on the overall orbit refinement performance.

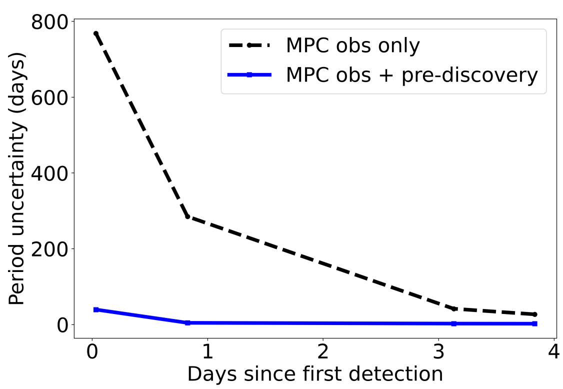

Figure 4: Orbital period uncertainty as a function of time since first discovery, with and without pre-discovery

Conclusion: We present a successful early proof-of-concept demonstration of a NEO pre-discovery pipeline that utilizes dynamic-programming synthetic tracking to generate detections of faint objects in archival image data over large search space. Our results include the pre-discovery of NEO 2019 AH11 in TESS mission data, captured approximately one month prior to its initial discovery by Pan-STARRS—at a time when the object was about 2.5 magnitudes fainter than TESS's nominal sensitivity limit. Despite the relatively low astrometric precision, the pre-discovery significantly reduced orbital uncertainty within the first few days following discovery. This methodology has the potential to rapidly reduce orbit uncertainties of new NEO candidates generated by LSST to relieve follow-up bottlenecks.

[3] Orbital period uncertainty is used here as a simplified proxy for the full orbital uncertainty.

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