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THOR: An Algorithm for Cadence-Independent Asteroid Discovery

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Abstract

We present "Tracklet-less Heliocentric Orbit Recovery", THOR, an algorithm for cadence- and observer-independent asteroid discovery. We test its effectiveness on two weeks of alerts from the Zwicky Transient Facility (ZTF) [1, 2, 3]. We show that by sparsely covering regions of interest in the phase space with "test orbits", transforming nearby observations over a few nights into the co-rotating frame of the test orbit at each epoch, and then performing a generalized Hough transform on the transformed detections, objects with orbits similar to the test orbit can be recovered at reasonable computational cost and at little to no constraints on cadence. Our present software implementation allows us to search out the majority of the Main Belt and the outer Solar System with a relatively small number of test orbits. Extensions and future optimization are planned to target NEOs.

1. Introduction

Discovering Solar System small bodies involves linking the detections of moving objects over many different nights into orbits. Typically, the same field is revisited multiple times a night to create "tracklets": sky-plane vectors composed of at least two detections that constrain the position and velocity of a moving object. The need for a specialized tracklet-building cadence has the downside of making surveys that don't follow it, including archival datasets, unsuitable for asteroid searches. An algorithm which can discover moving objects without the cadence restrictions imposed by building tracklets could allow surveys such as the LSST [7] to observe more of the night sky in a single night or re-optimize their cadence to accommodate different science goals with greater ease – we present such an algorithm.

2. Algorithm

THOR selects a series of test orbits from regions of interest in 6D orbital phase space. A key development in permitting the gridding of orbital phase space is the increase in computational performance enabled by linking from the heliocentric frame of reference. Holman et al. 2018 [4] showed that a robust and novel approach to discovering minor planets is to shift the observer's frame to that of the Sun. The THOR algorithm can be seen as an extension of the HelioLinC algorithm in the limit where tracklets do not exist to constrain the velocities of moving objects:

1. **Create a Test Orbit** An orbit with heliocentric position vector, r, and heliocentric velocity vector, v, is placed in a survey that contains the detections of moving objects.

2. **Propagate the Test Orbit and Gather Detections** The test orbit is propagated to all possible epochs at which a detection of the test orbit could have occurred. At each location of a potential detection nearby detections within some area measured on the sky-plane are gathered.

3. **Transformation into the Co-rotating Frame of the Test Orbit** The gathered detections are transformed to the heliocentric frame assuming the same heliocentric distance as the test orbit. Once transformed, the detections are projected into frame of reference centered on the test orbit's motion.

4. **Hough Transform** In the frame centered on the motion of the orbit, the transformed detections belonging to objects on similar orbits will appear as lines or clusters. These lines and clusters can be extracted using the equivalent of a generalized Hough transform.

Steps 1-4 are repeated as necessary for each test orbit selected from the regions of interest in orbital phase space. The majority of discoveries LSST will contribute are Main Belt asteroids, so we initially focus the selection of test orbits to tackle the Main Belt population.

3. Zwicky Transient Facility Data

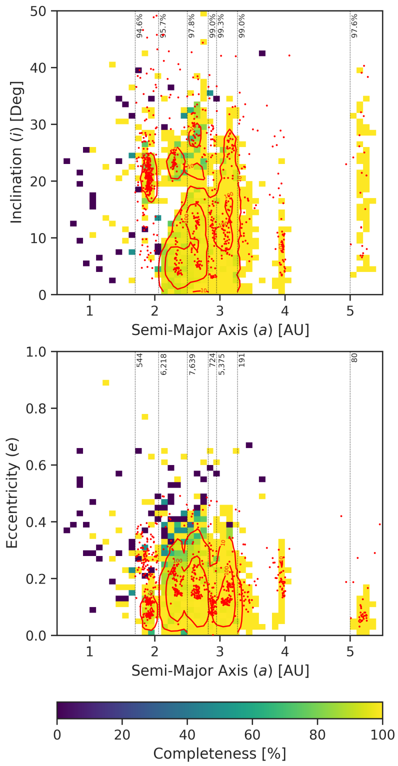

Figure 1: In the top panel is plotted percent completeness in bins of semi-major axis (a) and inclination (i). Number density contours are drawn as red lines to show the number of objects findable (five or more detections through out the two weeks of ZTF alerts). The 821 test orbits used are plotted as red points. The vertical dashed lines indicate the five semi-major axis bin edges, with the overall percentage completeness per bin written at the top. In the bottom panel is plotted percent completeness in bins of semi-major axis (a) and eccentricity (e), contours and test orbits are plotted in the same style as the top panel. Instead of percent completeness in each of the five bins we now explicitly state the number of objects found.

The Zwicky Transient Facility (ZTF) is a robotic time-domain survey of the northern sky capable of scanning more than 3700 square degrees per hour. We downloaded 15 nights worth of ZTF alerts and filtered out static and bogus sources yielding a final count of 252,836 (30.6%) known object observations and 574,790 (69.4%) unassociated observations.

We consider any known object with at least five detections through the 15 nights of alerts to be findable resulting in a total of 21,401 such objects. Assuming a classical Moving Object Processing System (MOPS) [5, 6, 7] approach we find that only 9,373 (43.8%) of the known objects would be findable. With ZTF's Moving Object Discovery Engine (ZMODE) algorithm [3] we find 14,200 (66.4%) would be findable.

Using our tracklet-less approach, we found 20,840 (97.4%) of the known objects of the 21,401 findable with the assumed discovery parameters. This represents a potential factor of two discovery increase over the traditional MOPS method, and a factor of ~ 1.5 increase over ZMODE.

The current software implementation of THOR recovers 98% of objects beyond 2.5 AU (see Figure 1). Extensions and future work are planned to attain both higher completeness for Main Belt populations inward of 2.5 AU and to tackle the populations of NEOs.

References

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