THOR: An Algorithm for Cadence-Independent Asteroid Discovery

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Tracklet-less Heliocentric Orbit Recovery

We present Tracklet-less Heliocentric Orbit Recovery (THOR), a prototype algorithm for asteroid discovery that is cadence and observer independent. THOR can be seen as an extension of the novel HelioLinC algorithm (Holman et al. 2018) in the limit where tracklets do not exist to constrain the velocities of moving objects. The THOR algorithm works in 4 main stages, below we briefly summarize these four stages.

1. Create a test orbit

Place a test particle at a position within the survey at a heliocentric distance, r, and with a velocity v. See **Figure 1**.

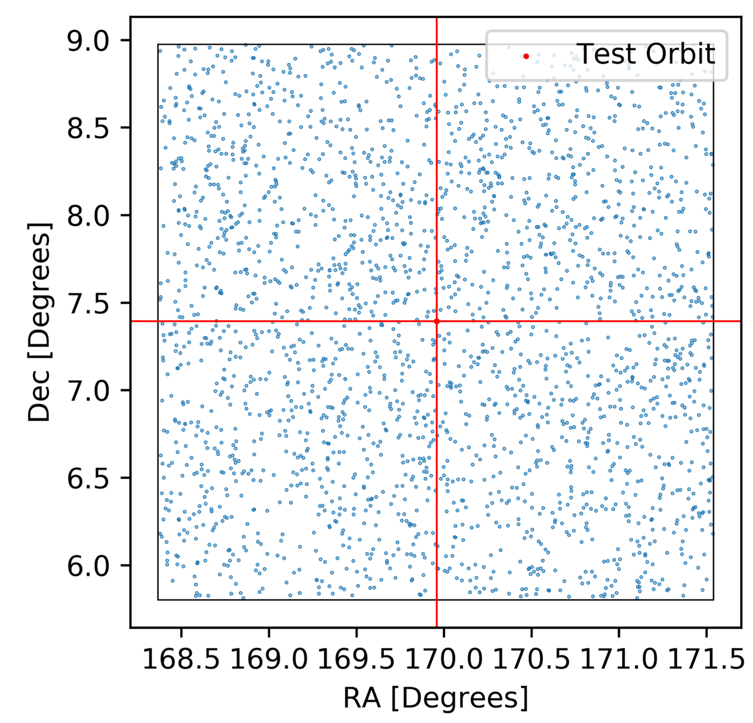

Figure 1: Plotted in blue are one night's worth of simulated detections in one of the 16 fields in the survey. The red dot and crosshair indicate the location of the average test orbit for this field.

2. Propagate the test orbit

Propagate the orbit to the different exposure times in the survey. Identify all detections within some radius, R, around the location of the test orbit.

3. Transform and project

Transform all the detections to the heliocentric frame and then project them into the frame of the orbit. In the projected frame, an object that has the same or a similar orbit to the test orbit will appear as a cluster. Any other objects on orbits near to the test orbit will appear as lines. See **Figure 2** and **Figure 3.**

Observer Independent ✓

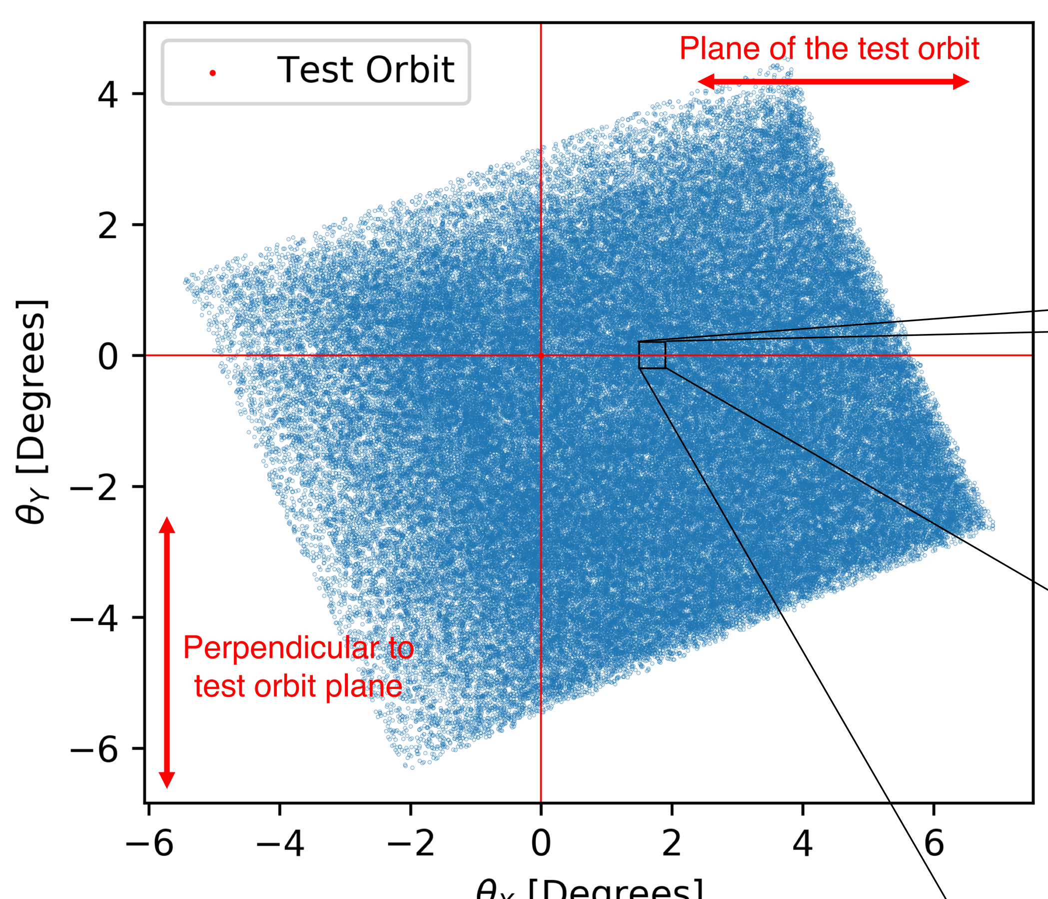

Figure 2: Plotted in blue are seven night's worth of simulated detections near the test orbit which have been transformed to the heliocentric frame and then projected into the frame of the orbit. Here the x-axis is aligned with the plane of the test orbit, while the y-axis is aligned perpendicularly to the plane of the test orbit. As before, the red dot and crosshair indicate the location of the test orbit, which in its own frame is located at (0, 0).

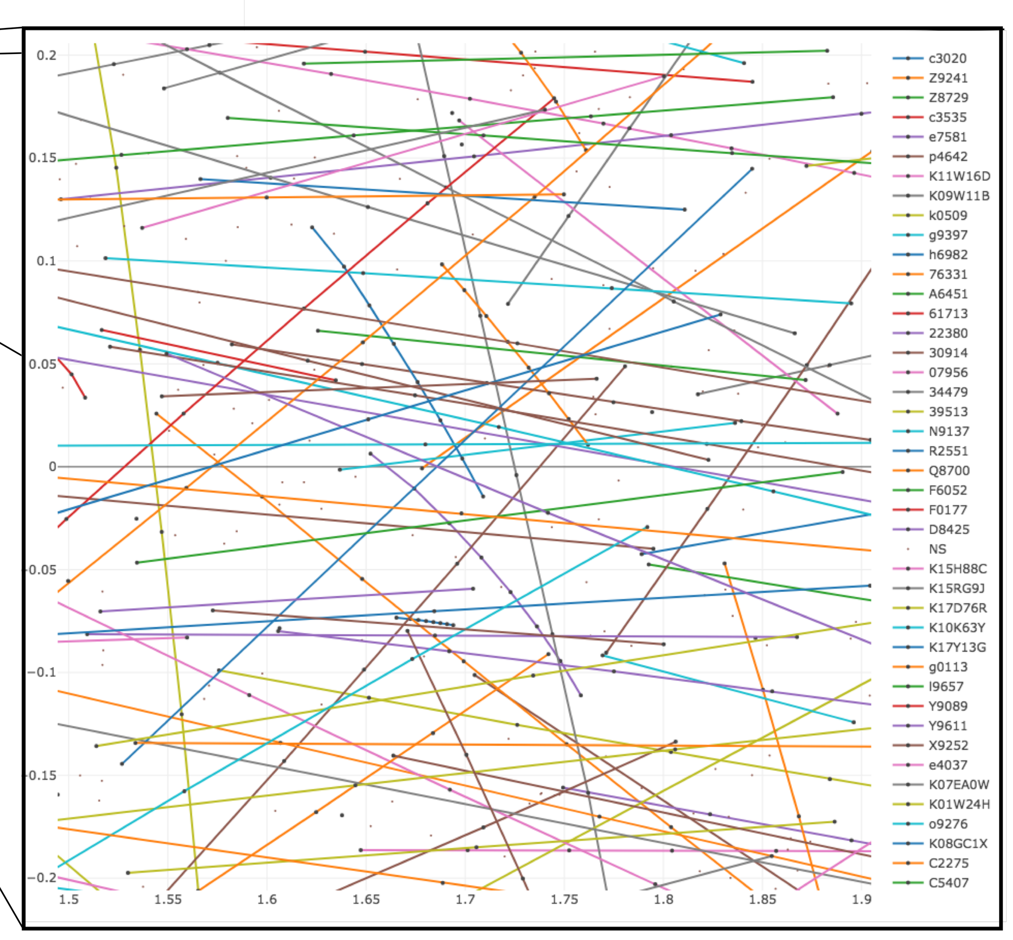

Figure 3: In the projected space, objects on similar orbits to the test orbit will appear as clusters or small lines (there are a few in the cutout above). Objects on nearby orbits (either closer or further away from the Sun) will appear as lines. Searching for these clusters and lines allows one test orbit to discover many other objects.

4. Hough transform

Lines and clusters in the projected space can be found using a Hough transform. By binning different velocities in the reference frame of the orbit and shifting the detections accordingly, lines in the projected space can be made into clusters. These clusters can be found using any out-of-the-box clustering algorithm. By binning velocities, **cadence constraints are also removed.** All that is necessary is for the test orbit to be propagated to where detections could have occurred. The Hough transform component of the THOR algorithm is the "inner-loop" and it is the component where performance optimization will be focused. See **Figure 4**.

Cadence Independent ✓

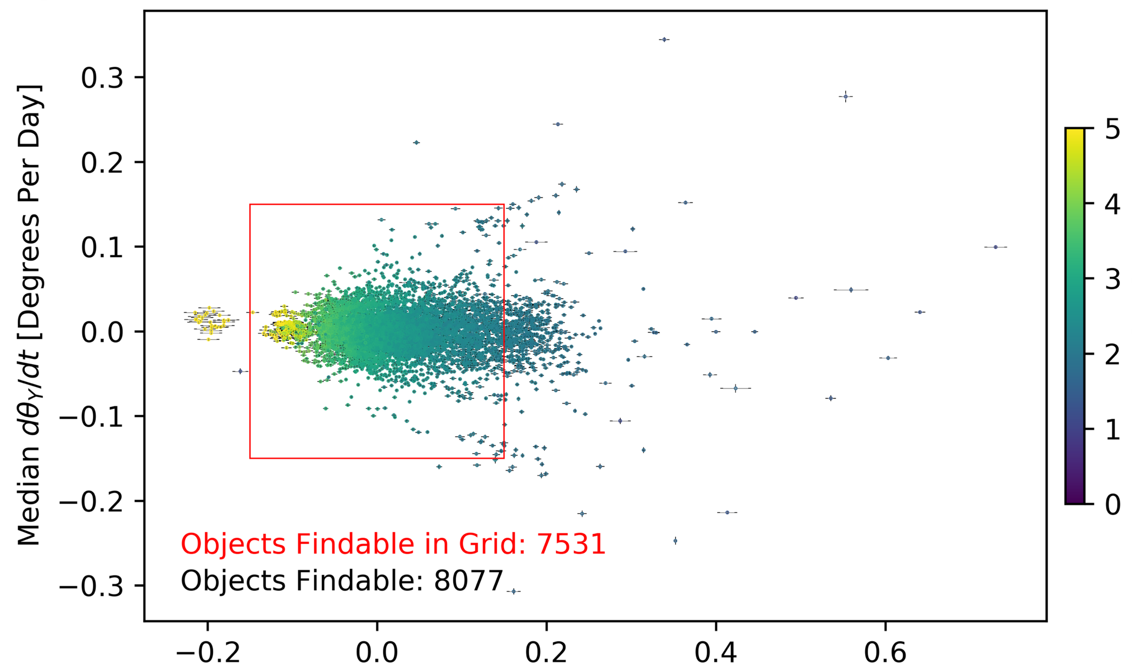

Figure 4: Plotted are the true median velocities in the projected frame of all the findable objects in the test orbit's projected space. The points are color-coded by heliocentric distance. The error bars represent the standard deviation of their median velocities. The red box indicates the default clustering grid where both x and y are divided into bins of 300 such that 90000 velocities are tested per orbit. Note the clear color gradient: all objects with negative velocities relative to the test orbit are moving slower and therefore are further out in the Solar System than the test orbit. All objects with positive velocities are moving faster than the test orbit and are more interior in the Solar System than the test orbit. In effect, setting the clustering grid allows you to sweep out different heliocentric distances.

94.55% simulated completeness

17 test orbits yielding 18000+ simulated discoveries

observer and cadence independent

The Problem

To enable the discovery of Solar System small bodies, surveys such as the LSST will rely on building "tracklets": sky-plane vectors composed of at least two detections that constrain the position and velocity of an object. Tracklets are then linked into multi-night "tracks" and from there the feasibility of the resulting orbit can be determined. From the tracklet stage, the linking problem is pretty straight forward (Kubica et al. 2007, Jones et al. 2018). However, using tracklets poses two problems:

1) **Cadence Constraints**: Making a tracklet requires the same field to be revisited within the same night to make the linking problem computationally feasible. This reduces the efficiency of the survey, especially for non-Solar System science cases.
2) **Observer Dependent**: Tracklets when linked into multi-night tracks will exhibit high frequency on-sky non-linear motion in part due to the observers motion complicating the linking problem.

What if Solar System small bodies such as asteroids could be discovered without the need for a "tracklet"?

Simulations

We created a simplified ZTF-like simulated survey consisting of 16 square fields with each field ten square degrees in size. The 16 fields are visited once per night every other night over a 14 day period resulting in seven unique visits per field. The survey footprint is centered roughly on the ecliptic in order to maximize detection density. To create the survey, we downloaded the Minor Planet Center's orbit catalogue and propagated the orbits of the entire catalogue to create simulated detections at each exposure time. To simulate the effects of difference image artefacts, 100 false detections were added per square degree. Studying how well THOR works at different noise densities and with astrometric error is subject to future work and development.

Findable: We consider any object with at least five detections throughout the simulated survey to be a findable object.

Found: Clusters were set to have a minimum of five detections. Any object that is linked in a pure cluster, a cluster that contains only detections from a single object, is considered to be a found object. Additionally, if a cluster had at least 5 detections from a single object but then also had several detections belonging to other objects or noise, we anticipate that Initial Orbit Determination (IOD) would filter these detections out and such a contaminated cluster can be cleaned. The contamination tolerance was set to 20%. For example, a ten detection cluster, as long as eight detections belonged to the same object, would then be considered a cleanable cluster and the constituent object is found.

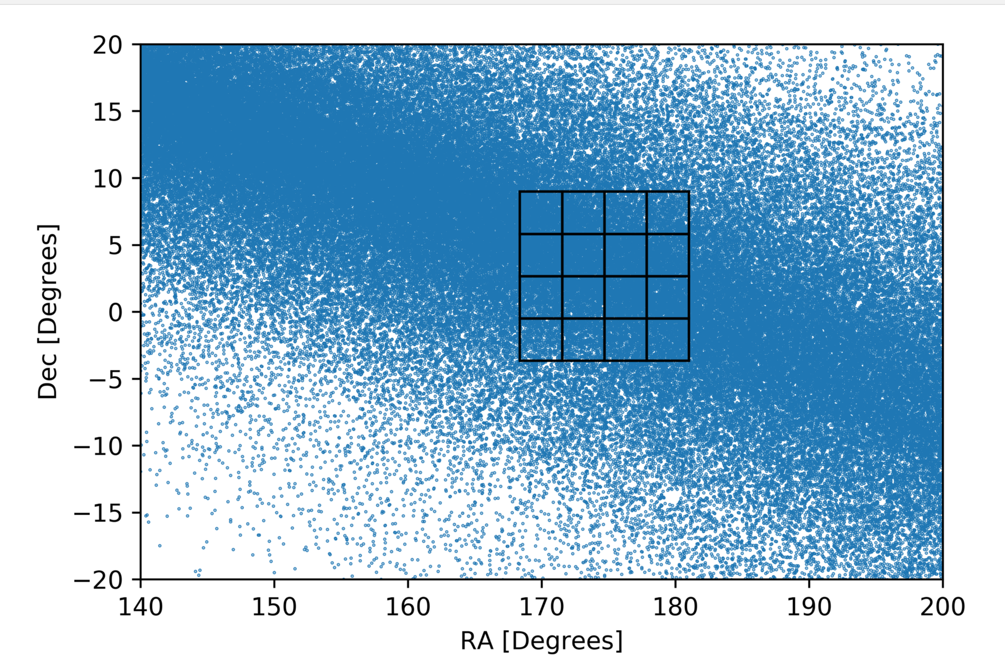

Figure 6: In blue is plotted the underlying orbital catalog for the first night of of the survey. The 16 rectangular patches are the 16 unique fields where we simulated seven visits over 14 nights.

Results

For each field of the 16 fields we selected an average orbit from all the objects which had detections that occurred during the first night. This resulted in 16 test orbits. We ran the THOR algorithm in two passes: first with moderate clustering parameters where each test orbit was run in series. Any clusters that were pure or could be cleaned (see **Simulations**) were then removed from the pool of observations. After the first pass was completed, 86% completeness was achieved. Since the 16 test orbits were all similar, the first orbit tested was the most productive orbit. It discovered 6016 objects. We then ran a second clustering pass with a wider grid, driving completeness to 90%. Due to the self-similarity of the 16 test orbits, we added a 17[th] orbit and ran it on a single field in the middle of the footprint. The goal of this orbit was to target some of the missing objects in the low inclination population at less than 2.3 AU (see **Figure 7**). This single test orbit drove completeness to 94.55%.

The work to optimize the selection of test orbits to maximize detection efficiency and minimize selection biases is ongoing, with encouraging preliminary results. We anticipate that this algorithm, in combination with a calculated selection of test orbits, could sweep out the majority of the Main Belt with few (~100s) of test orbits. Assuming the algorithm can be extended to the discovery of NEOs it may offer a more efficient alternative for future large-scale surveys such as the LSST.

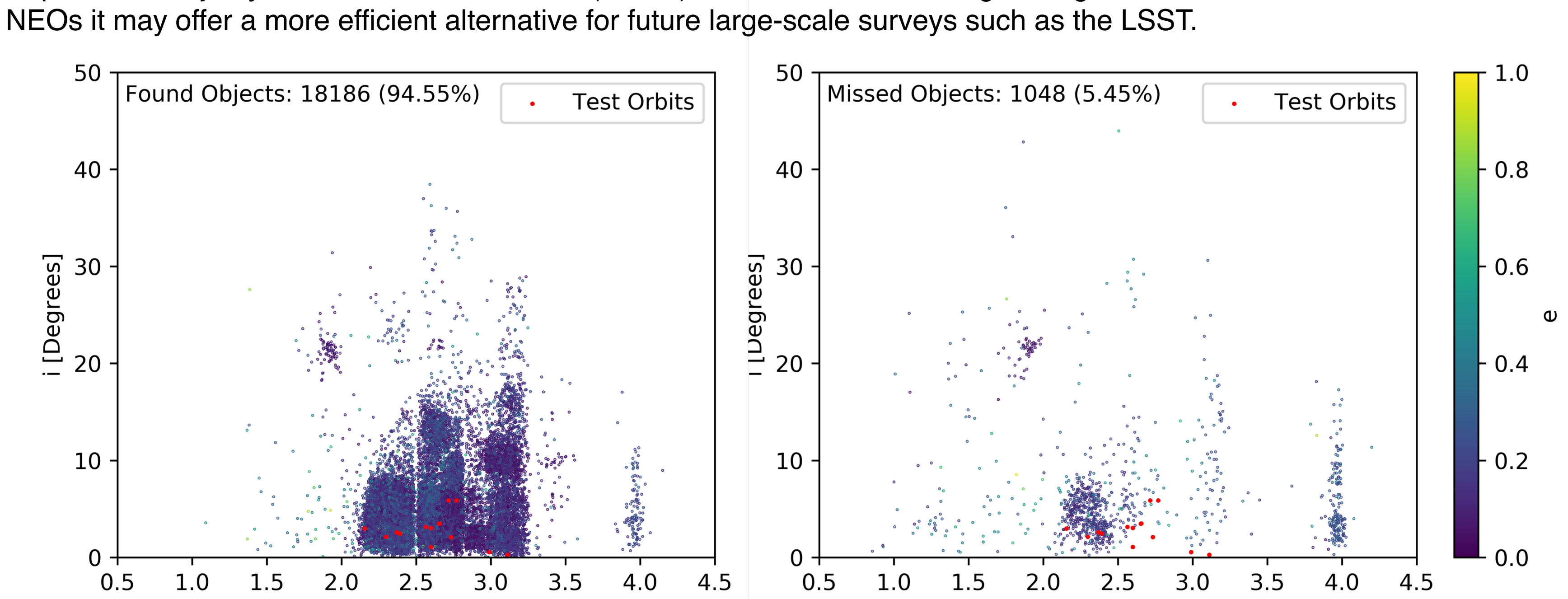

Figure 7: In both subplots, the red points indicate the test orbits used. The left subplot plots the a-e-i distribution of the found orbits. The right subplot shows the same distribution for the missed orbits.

References

Holman, M. J., Payne, M. J., Blankley P., et al. 2018, Astronomical Journal, 156, 3

Jones, R. L., Slater, C. T., Moeyens, J., et al. 2018, Icarus, 303, 181

Kubica, J., Denneau, L., Grav, T., et al. 2007, Icarus, 189, 151