MODE: a new Moving Object Discovery Engine

Frank Masci[1], Xiang (Cate) Liu[1], John Dailey[1], Joseph Masiero[2], Roc M. Cutri[1]

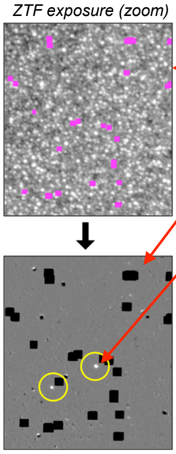
[1]*IPAC, California Institute of Technology*
[2]*Jet Propulsion Laboratory, California Institute of Technology*
fmasci@caltech.edu

Overview

- The Zwicky Transient Facility (ZTF) is a ground-based time-domain survey currently in operation on the Palomar 48 inch Telescope.
- ZTF is currently involved in the discovery of near-Earth objects (NEOs) and is extending our understanding of poorly-studied subsets of NEOs.
- We have developed an efficient, industrial-strength discovery pipeline for use on ZTF: the "Moving Object Discovery Engine" (MODE).
- MODE was initially developed and deployed for the Palomar Transient Factory (PTF; 2009-2016), which served as a test-bed for ZTF.
- MODE is also being adapted to support the discovery of potentially hazardous asteroids (PHAs) using the future NEOCam space mission.
- MODE utilizes transient candidates extracted from difference images from the realtime pipeline at IPAC (*Masci et al. 2019, PASP, vol. 131*).
- The use of difference-image extractions gives us an enormous advantage: the suppression of static (inertial) sources that would otherwise confuse the source-linking process used to discover moving objects.
- This is unlike existing NEO surveys that attempt to remove stationary sources using prior catalog matching across image epochs. This can be expensive and ambiguous, leading to missed tracklets.
- Image differencing has huge returns in the galactic plane and regions with complex backgrounds (see example below).
- MODE is optimized to discover *non-streaking* objects in single exposures, i.e., that move slower than the typical FWHM in a single exposure; for ZTF, this speed is <~ 2.5 deg. / day. This is because transient candidates from image-subtractions are detected and characterized using PSF-fitting.
- The ZTF pipeline also includes streak-detector to find "fast" moving objects on a per-exposure basis. Streak detection is not part of the MODE design.
- MODE can deliver moving-object *candidates* within ~ 2hr from a run that combines 3-nights of ZTF data, consisting of ~ 2.5 million input transients.
- MODE includes orbit-fitting for use in automated vetting of tracklets.
- For ZTF, MODE is executed on a single machine with 40 x 2.4 GHz Intel® Xeon® processor cores.

MODE Processing Flow for ZTF

ZTF exposure (zoom)

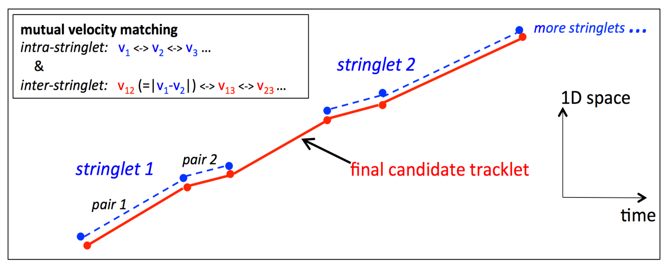


Difference Image

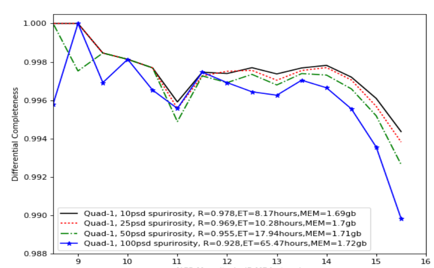
- **Realtime processing pipeline:** instrumental calibration of single-exposure images with astrometric & photometric solutions
- Image differencing & point-source-transient extraction with machine-learned vetting (available within ~ 20 min of observation)
- Retrieve transient candidates from database with reliability filtering
- **Execute MODE: Moving Object Discovery Engine:** generate moving object tracklets with metadata & QA metrics
- Perform orbit-fitting on each tracklet using *find_orb* software
- Threshold orbit-fit quality metrics to retain likely real moving objects worthy for human scanning
- Cross-match tracklet list against databases of known-moving objects
- Generate preliminary reports for Minor Planet Center; image cutouts on all detections; *digest2* report with probable orbit classes; additional QA metrics
- Human vetting, deliver reports to Minor Planet Center and issue alerts to follow-up potential new objects

Tracklet Finding Algorithm and Implementation

- A challenging computer science problem that makes using of tree-search algorithms: *kd-trees* and *quad-tree* partitioning on the sky.
- Implemented exclusively in Perl, utilizing methods from the object-oriented Perl Data Language (PDL) library with functions implemented in C/C++.
- PDL library provides a high level of parallelism for computations: multi-threaded vector/matrix methods optimized for multi-core architectures.
- Use a two step process to find tracklet candidates:
  1. *Link triplets of detections ("stringlets") within a min/max velocity cone centered on every detections by matching relative velocities & fluxes.*
  2. *Bin the stringlet velocity vectors and merge all stringlets that potentially belonging to same object to build final tracklets.*
  3. *Includes optional iterative removal of MBAs to mitigate contamination.*
- For details, see *Masci et al. 2019, PASP, vol. 131*



Performance using NEOCam simulations

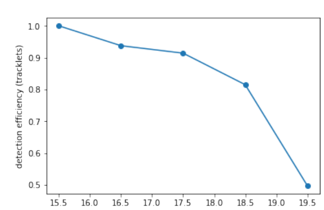


* Used synthetic detections from a population model of NEOs and MBAs covering a 12day period & one NEOCam survey-quad footprint.
* Simulated detections include astrometric error & spurious sources (< 100 per sq. deg.)
* MODE achieves >99% completeness and >~ 95% reliability

Performance for ZTF

- We explored the recovery fraction (completeness) and reliability of MODE-detected tracklets from data spanning three nights of ZTF observations.
- Truth set is from predicted occurrences of known asteroids in ZTF exposures
- In total, 3437 tracklets with ≥ 4 detections each were found to R_{ZTF} ~ 19.5.

R_{ZTF} mag limit	Completeness %	Reliability %
16.0	96	100
17.0	93	100
18.0	88	100
18.5	82	100
19.0	68	99.8
19.5	50	97.7



ZTF (*https://www.ztf.caltech.edu*)

The authors acknowledge funding from the Planetary Defense Coordination Office -- NASA, and the National Science Foundation under grant no. AST—1440341.