# EFTE-Rocks, a framework to discriminate fast optical transient phenomena from orbital debris

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## ABSTRACT

Wide-field telescopes like the Evryscope enable all-sky searches for fast optical transient events such as kilonovae, optical counterparts to fast-radio-bursts and other exotic events. To further understand these phenomena, we need infrastructure with the capability to monitor and quickly analyze these events. The Evryscopes are an all-sky system with a total field of view of 16,512 sq. deg. that, coupled with the Evryscope Fast Transient Engine (EFTE), can catalogue fast optical transients down to g=16. In the past two years, EFTE has seen millions of transients across the sky including hundreds of flaring events from cool stars and a population of millisecond glints produced by Earth-orbiting objects that appear morphologically similar to transient astrophysical phenomena. In order to further characterize these events, the Evryscope and other all-sky optical surveys, such as the upcoming Argus Pathfinder and Argus Optical Array, require a framework to discriminate between this fog of imposter transients and real astrophysics. EFTE-Rocks is an automated orbit determination pipeline that takes short-duration transients from EFTE and associates them into tracklets based on an initial trajectory. Here we present a framework to characterize which orbital debris produce glints seen by fast, wide-field telescopes; lessons learned; and future software improvements. We also discuss its applications to upcoming surveys that are capable of probing for fainter objects at faster cadences.

**Keywords:** Fast-transients, database design, framework design, optical transients, wide-field surveys, methods

## 1. INTRODUCTION

Moderate resolution wide-angle surveys that look for transient phenomena often optimize for events evolving on day-to-month timescales. Recent all-sky surveys also observe ultra-fast (minutes-to-hours timescales) transients that can increase in observed magnitude by several factors and the physical processes that drive these energetic events produce radiation with wavelengths spanning the entire electromagnetic spectrum. Thus multi-wavelength coverage of such events is vital to further understand the myriad of physical processes that produce exotic transients like prompt emission from gamma-ray bursts (GRBs), fast radio burst (FRB) counterparts, and violent flares occurring on late-type exoplanet-hosting stars. Facilities that survey for these events on either side of the optical spectrum have had near full-sky coverage for some time. Optical surveys with nightly sky coverage and observing cadences sensitive to short time optical transients are either scarce or only recently coming online. Examples of these include the Evryscopes,[1,2] the Mobile Astronomical System of Telescope-Robots (MASTER),[3] the Asteroid Terrestrial-impact Last Alert System (ATLAS),[4] the All-Sky Automated Survey for Supernovae (ASAS-SN),[5] the Zwicky Transient Facility (ZTF)[6] and the Multi-site All-Sky CAmeRA[7] (MASCARA).

As a monolithic array of 22 61mm wide FoV telescopes, the Evryscope observes the entire sky down to an airmass of two with a 13" pixel scale. There is one Evryscope in each hemisphere, and both are equipped with a custom transient detection pipeline, the Evryscope Fast-Transient Engine (EFTE).[8] EFTE monitors the entire Evryscope FoV for all transient phenomena brighter than g'=16 and evolving on timescales as short as two minutes.

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In addition to detecting astrophysical transients, like early-time flares from ultra-cool dwarfs (UCDs),[9–12] EFTE also picks up on sub-second-duration satellite glints. These flashes are the products of reflections between solar rays and reflective surfaces from geocentric satellites and debris. Previous work from multiple surveys have placed event rates on these orbital glints; the occurrence rate measured by Evryscope is $1800^{+600}_{-280}$ sky$^{-1}$ hour$^{-1}$ that peaks at g'=6.8.[8] However due to phase smearing, as a result of the ratio between glint duration and exposure time being $\ll 1$, the observed magnitude peaks at g'=13.9. These imposter transients are PSF-like in two-minute integrations, making them indistinguishable from astrophysical phenomena evolving over similar timescales. Current and upcoming ultra-wide-field surveys that produce transient event streams for rapid optical followup of events, like highly energetic flares and potential FRB optical counterparts, will need a framework to separate these events from their imposters. EFTE-Rocks is a pipeline which groups EFTE-detected candidates into tracklets and fits orbits to their trajectories.

In this paper, we describe the EFTE-Rocks Framework (Section 2), early results from our tracklet and orbit measuring analysis (Section 3), and summarize our work (Section 4).

## 2. FRAMEWORK DESIGN

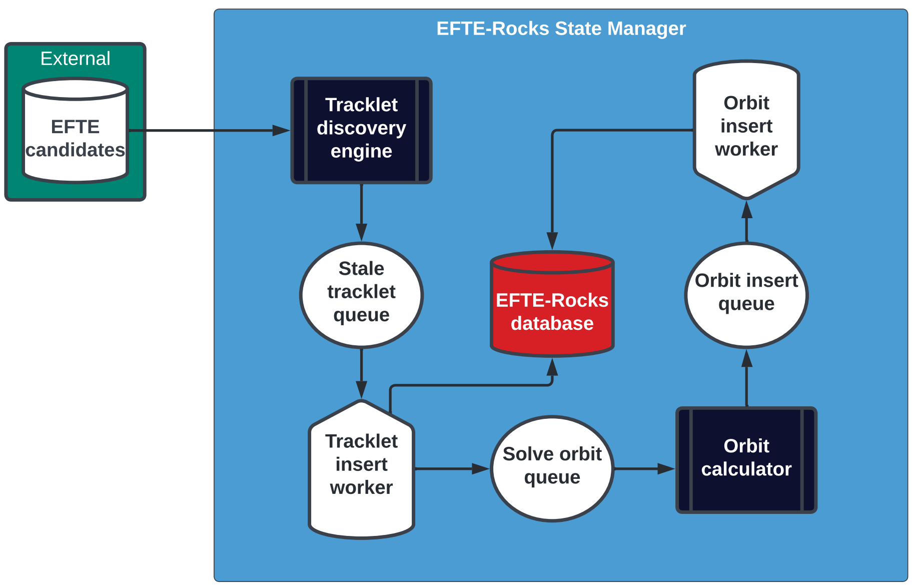


Figure 1. A flowchart of the EFTE-Rocks data flow and database communications.

The EFTE-Rocks pipeline is built from concurrent daemons that handle different aspects of the processing (Figure 1). These daemons include a tracklet discovery engine, an orbit solver, database handlers and a context manager. Each component of this framework operates as an independent process that enables us to associate sub-second-duration transients into tracklets in real time.

The goals of the EFTE-Rocks pipeline are:

- Tracklet association in EFTE alert streams producing $O(10^3)$ candidates from each 29 MPix Evryscope image.
- Orbit measurements within one two-hour Evryscope ratchet for tracklets that pass our vetting criteria described in Section 2.2.

This analysis pipeline and its results will be explored in more detail in Vasquez Soto et al. 2023 (in prep).

## 2.1 Tracklet Discovery

EFTE produces a stream of PSF-like detections called candidates. A candidate must have a signal-to-noise ratio $\geq 3$ and is detected using simplified image subtraction between pairs of images that are usually 10 minutes apart.[8] We obtain magnitude, position and a timestamp on each candidate after they are inserted into the EFTE database. EFTE-Rocks uses these candidates and attempts to associate them into tracklets. We define a tracklet as a set of candidates that form continuous trails across the Evryscope FoV. We make tracklets by starting with the first epoch in a night that contains candidates; here each candidate is treated as a distinct tracklet. EFTE-Rocks then uses large initial separation conditions to comb through each ensuing set of candidates, in chronological order, to associate them into already existing tracklets with unused candidates becoming new tracklets. We observe tracklets with as few as 3 and up to 48 candidates. Tracklets are monitored in the cache until no new candidates have been added after 30 minutes. Stale tracklets are pushed to a first-in-first-out (FIFO) queue that one of our database handlers consumes. All stale tracklets with a minimum of three candidates are stored in the EFTE-Rocks database for potential further analysis.

## 2.2 Orbit Solver

We calculate and store classical orbital elements determined in the geocentric reference frame for all tracklets in our data set that pass our orbit determination criteria. With this data we can then attempt to correlate our sets of orbital elements with those maintained by organizations such as North American Aerospace Defense Command (NORAD).

To determine what tracklets are considered real detections of an object in orbit, we developed a tracklet-length based criteria where any tracklet having at least N candidates is assumed to be real and has its orbit measured. We performed a bootstrap analysis, with $100,000$ draws and resampling, randomly selecting tracklets made with simulated EFTE candidates to calculate a false-alarm probability (FAP) based on tracklet length. For $N \geq 6$, the probability of a tracklet being produced by random alignments of candidates falls to 0.325%. This is the criteria for orbit determination on all tracklets discovered by EFTE-Rocks.

We leveraged the Evryscope's ultra-wide FoV to track objects over the whole sky and developed our own circular orbit solver to directly measure classical orbital elements. Below we describe how each orbital element is measured:

1. $t_0$: Reference epoch for orbital elements, measured as the epoch of the first candidate in a tracklet.
2. $e$: Eccentricity. We assume circular orbits thus it is always 0.
3. $\nu$ (or $M_0$): True anomaly or mean anomaly. The angular position of the orbiting body at $t_0$. This is the local azimuth of the first candidate in a tracklet.
4. $a$: Semi-major axis. This is measured from the average mean motion based on candidate positions.
5. $i$, $\omega$, $\Omega$: Inclination, argument of perigee and longitude of the ascending node are the three Euler angles defining the orientation of the orbital plane w.r.t. the geocentric frame. To calculate these angles we take pairs of candidates in 3D cartesian coordinates to determine the three unit vectors that define the orbital coordinate frame. From there we find $i$, $\omega$ and $\Omega$ by calculating the angle between the respective axes from the geocentric and orbital frame. We used a Monte-Carlo approach to determine the uncertainties on these orbital parameters.

The orbit solver daemon polls a FIFO queue that is populated with tracklet IDs that passed the orbit calculation criteria. With the tracklet ID, we can determine the candidate IDs associated with a particular tracklet and thus obtain all required information to measure the classical orbital elements. Once an orbit is solved it is saved in our database via the orbit-insert database handler.

### 2.3 Database Design

We implemented a database to maintain information related to tracklet discovery and orbit results. We use PostgreSQL 11.5, hosted locally on the analysis server. A database is the most intuitive way to interact with the candidates belonging to a tracklet when trying to correlate optical transients and satellites with them. This can be useful when developing localization maps for multi-wavelength followup and to establish tracklets produced by the same object over multiple nights however, this functionality is in the early stages of development.

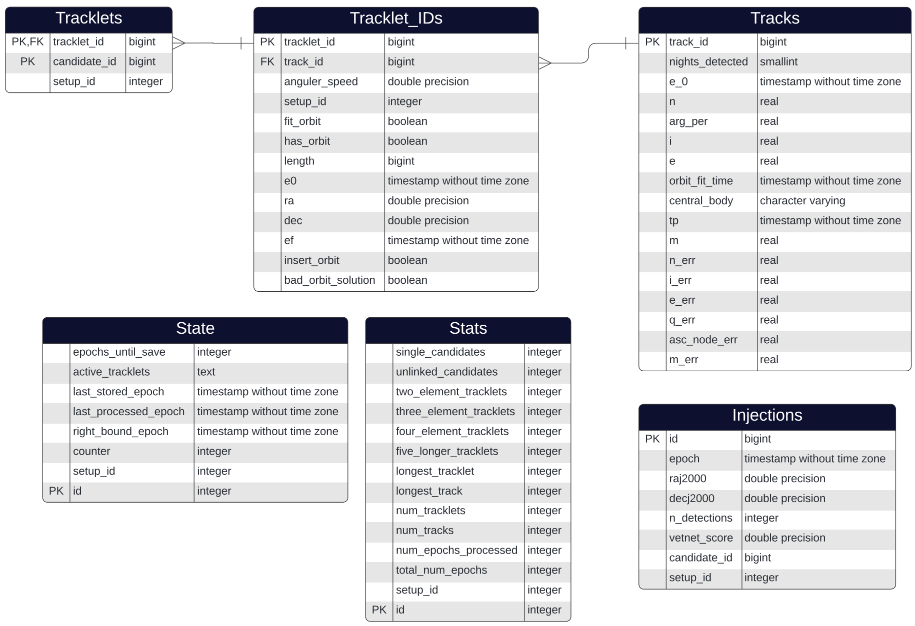


Figure 2. A summary of the EFTE-Rocks database with the primary key for each table. We maintain metadata about tracklets and their associated orbits as well as state information. The Injections table mimics the candidates table in the EFTE database and was used during our tracklet-length based bootstrap analysis described in Section 2.2.

### 2.4 Database Handlers

In addition to the analysis daemons described in Sections 2.1 and 2.2, we also developed two daemons that handle database insertion. These two daemons are the tracklet insert and orbit insert daemons.

The tracklet insert daemon is responsible for inserting stale tracklets into our database described in Figure 2. References to candidates from the EFTE database are stored in the Tracklets table and metadata associated with a tracklet are recorded in the Tracklet_IDs table. This handler consumes tracklets in the FIFO queue that is populated by the tracklet discovery engine. It also pushes tracklet IDs for those tracklets that pass our length cut into the solve orbit FIFO queue. This queue is consumed by the orbit solver daemon which in turn pushes tracklet IDs with calculated orbits into the orbit insert FIFO queue.

The orbit insert daemon consumes the orbit insert queue described above. This is the end point for the EFTE-Rocks analysis, once a tracklet has an orbit ready for database upload we call it a track as it has a set of tracklets and corresponding orbital elements. The orbital information is loaded into the Tracks table.

### 2.5 Context Manager

It is important to minimize downtime and enable quick recovery from unexpected failures, such as power loss, to avoid repeated analysis of the same data. We address this via a context manager that oversees the worker daemons described in Sections 2.1-2.4. The context manager maintains the state of previously analyzed epochs and epochs with candidates that are actively being consumed by our pipeline, along with tracklet length statistics in the State and Stats table. This design means that on rare instances of a complete restart, we at most reanalyze the previously completed epoch as opposed to restarting our analysis at the beginning of the night.

The context manager also handles all 3 FIFO queues necessary for inter-daemon communications, these are the tracklet insert, solve orbit and insert orbit queues. As EFTE-Rocks consumes epochs that contain candidates from the EFTE database, the context manager updates the current state with relevant metadata for EFTE-Rocks quick recovery (Figure 2).

## 3. EARLY RESULTS

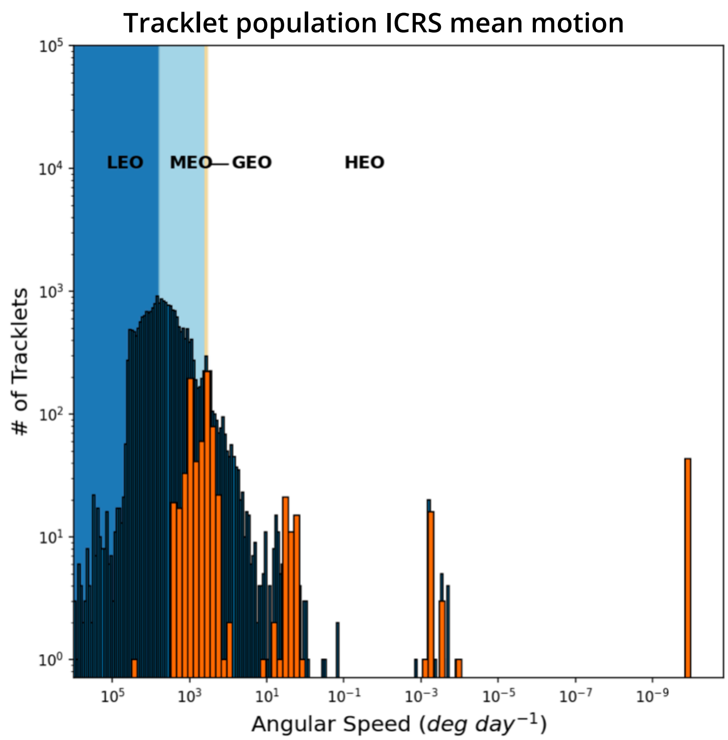


Figure 3. Mean motion calculated with EFTE candidates for every tracklet we associated with EFTE-Rocks. In blue are mean motions calculated from positions on-sky, for every tracklet having at least 3 detections. In orange are mean motions for every tracklet that had at least 6 detections. The mean motions in orange are derived from our MC orbit calculations for all tracklets passing our length cut.

Figure 3 describes two populations of tracklets sorted into bins based on their mean daily motion. In blue are the angular speeds for the whole population of tracklets found by EFTE-Rocks throughout the first six months of EFTE being online. We highlight different orbital regions of interest to show that the majority of objects that are producing long tracks, that we would consider real, are not occupying low Earth orbits (LEO). Instead we find the majority of objects producing cohesive tracks being in medium Earth orbit (MEO) as well as in the geostationary belt (GEO).

This is due to a combination of effects such as the duration of a flash, which as mentioned in[8] can be milliseconds in duration, and the exposure time of our survey. In a two minute integration an object in LEO will traverse $\sim 50 - 105$ degrees, producing somewhere between two and three candidates that are then vetted by EFTE. In order to map the LEO region for satellites and debris that produce short-duration PSF-like transients seen by all-sky surveys like the Evryscope and upcoming surveys like the Argus Optical Array and its mid-scale prototype Argus Pathfinder, we need to survey this fog of imposter transients at higher cadence and sky resolution. This capability will be possible with the Argus high-cadence mode being developed for Argus

Pathfinder and the full Argus Optical Array.[13,14] This will in turn reduce the false-positive rate of optical counterparts in future ultra-short duration transient surveys.

## 4. SUMMARY

Moderate resolution wide-angle surveys that look for ultra-short duration transients are currently dominated by the rate of foreground glints produced by orbital debris and satellites. Modern surveys with full-sky coverage and short exposure times are capable of characterizing the orbital distribution that this population of glints currently encompasses.

EFTE-Rocks is the orbital modeling extension to EFTE that leverages the all-sky FoV capability of the Evryscopes to systematically characterize the spatial distribution of optical glints from Earth-orbiting objects like satellites and debris. EFTE-Rocks forms tracklets that describe the path a single object would form as it moves across the sky, producing PSF-like glints that we observe in two minute Evryscope exposures. Here we described the EFTE-Rocks tracklet discovery and orbit modeling framework as a method of maintaining a library of tracklets and directly measuring their orbital parameters by using an all-sky array telescope. Further, this framework is extendable to other all-sky surveys that produce event streams similar to EFTE. With current all-sky FoV and moderate resolution surveys, it remains a challenge to provide good enough constraints on this population to the level of being able to associate these orbits with known satellites. Upcoming all-sky surveys like the Argus Optical Array, with arcsecond-resolution and a high-cadence mode, will enable advances in this work.

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