Real-time Small Body Precovery Searches in Any Astronomical Dataset

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Highlights

- Automated precovery searches of risk list objects in a growing list of catalogs of observations from astronomical surveys
- Hosted on a cloud platform capable of scaling to meet the computational needs
- Final human vetting of precovery candidates before submission
- 37 observations of 19 risk list objects have been identified in data from three datasets so far: NOIRLab Source Catalog, Zwicky Transient Facility, and SkyMapper Southern Survey

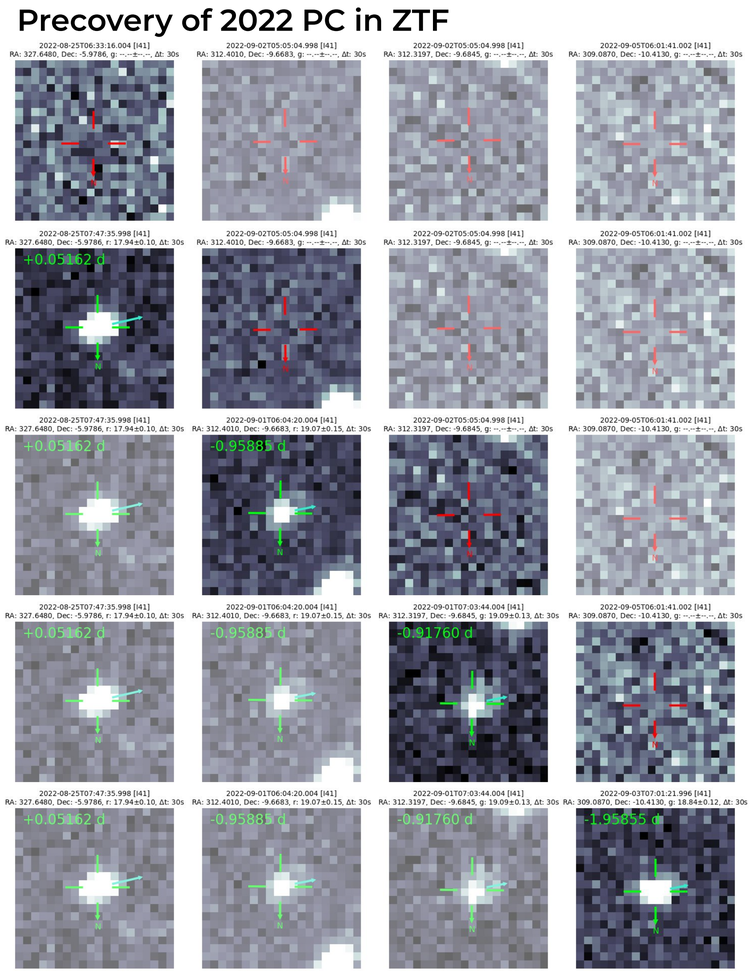
What is precovery?

Small bodies, such as asteroids or comets, are typically discovered with short observation arcs spanning only a few days. Finding more observations of small bodies that extend their arc of observation helps reduce the uncertainty of their best-fit orbits. Finding pre-existing yet unidentified observations of a small body after its initial discovery is called "**precovery**".

Precovery observations are particularly important for objects on the *risk list* — Near-Earth Objects (NEOs) that have a chance to impact Earth. Finding new observations of these objects will help decrease the uncertainty of their orbits and improve impact probability calculations. In the best case scenario, finding additional observations may de-risk these objects altogether.

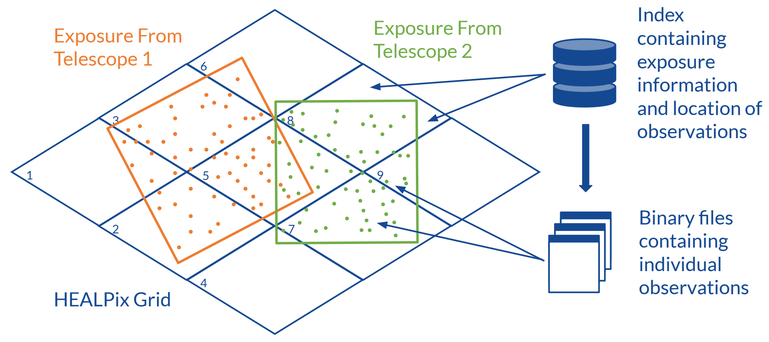
The Asteroid Institute developed an open-source software package called **precovery** [1] that searches for observations of small bodies in large catalogs of observations. This tool is deployed at scale as a service on the Asteroid Discovery, Analysis, and Mapping Platform (ADAM). ADAM is a cloud-based, scalable astrodynamics platform designed to enable compute-intensive research in planetary science and planetary defense.

Precovery of 2022 PC in ZTF



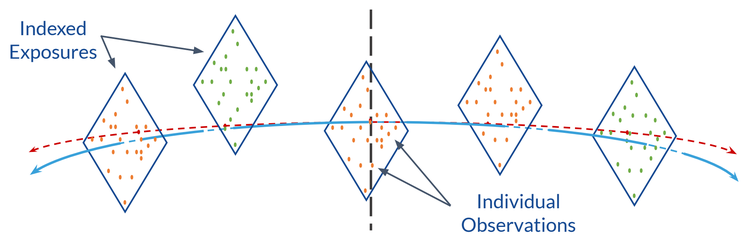
A mosaic of "postage stamps". In each column are images of the same area of the sky. The highlighted diagonal of pairs of images track the motion of 2022 PC. Images with green crosshairs occurred at the times and locations where 2022 PC is expected to appear, ie, at the locations of the candidate precovery observations. Images with red crosshairs show the same area of the sky as the precovery observations but at times where 2022 PC should not be in frame.

Creating a Unified Data Format

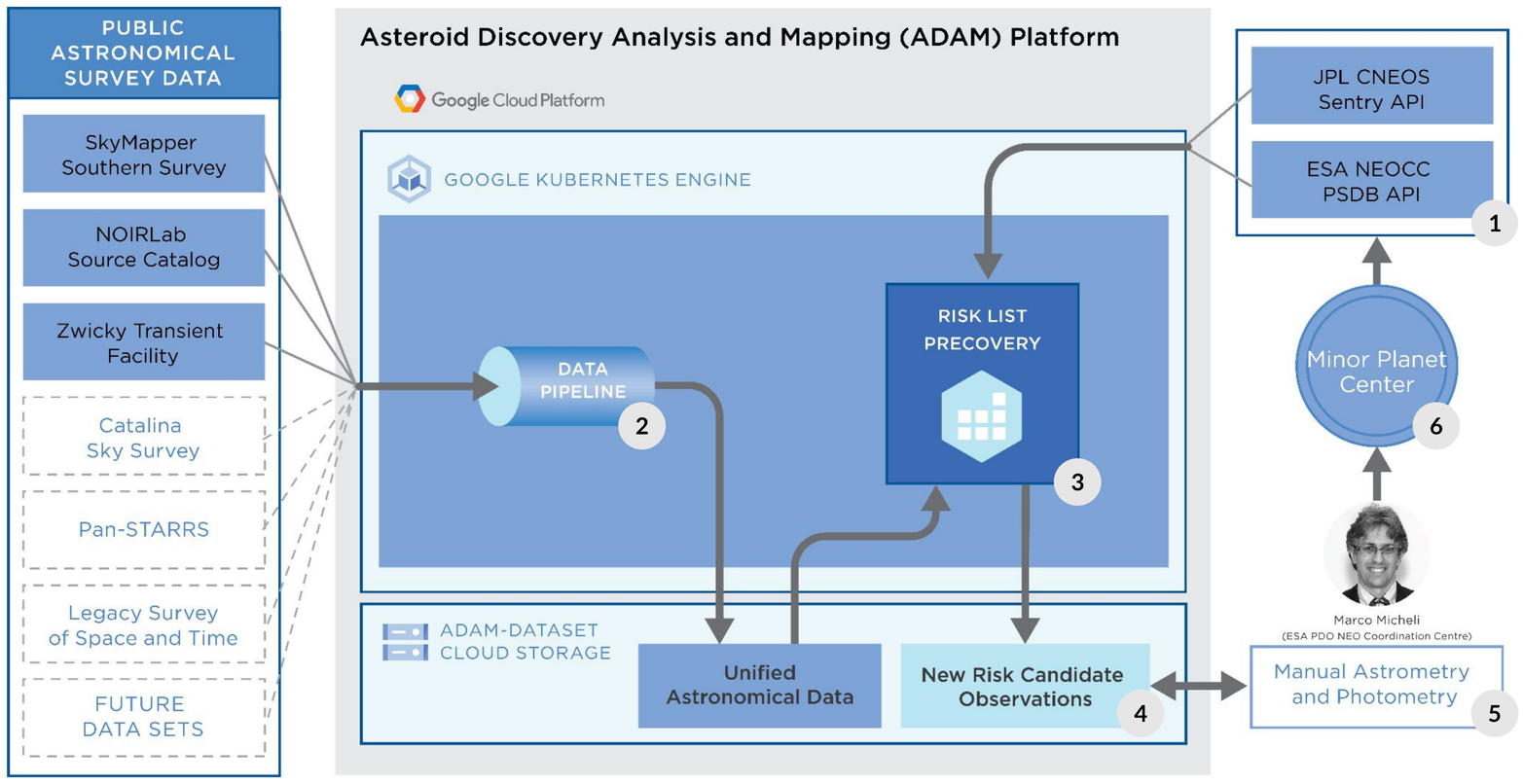


Precovery stores catalogs of observations from different data sources into a standardized and search-efficient format. Each unique exposure in catalogs of observations are mapped to a HEALPix grid [3] with the individual observations stored in binary files and an index into those files maintained in a SQLite database. We call this process "indexing".

Finding Candidate Precovery Observations



1. An input orbit is propagated with N-body dynamics to each window midpoint (each window is 7 days of "indexed" exposures from multiple datasets)
2. From each midpoint, the orbit is propagated with fast 2-body dynamics to identify any intersecting HEALPix-mapped exposures within each window
3. Once intersecting exposures have been identified the orbit is then propagated from the window midpoint to each exposure using N-body dynamics
4. The angular distances between the predicted position of the orbit and the observations are then calculated. If any observations lie within a user-defined angular tolerance those observations are identified as possible precovery candidates.



Precovery Search I. Automation

1. **Every night the ESA and JPL risk lists are automatically scanned** for any changes and are combined into a single list with duplicates removed. If any new objects have been added to either list, or any existing object's orbit has been updated this triggers a precovery search.
2. If new observations have been made available from an ongoing survey (such as ZTF), these **observations are automatically ingested into ADAM's unified astronomical data storage format** and are made available for precovery searches. Any new observations regardless of changes to the risk list will trigger a precover search of the risk list.
3. Precovery searches are performed by ADAM::precovery, which will **output a list of candidate precovery observations** and exposures where an observation could have occurred but no point-source was found.

Precovery Search II. Human Vetting

4. Each candidate observation is then processed using a cutouts generation code [2] which **produces a mosaic of images for human validation.** An example mosaic is included for risk list object, 2022 PC.
5. Viable candidates are selected by our team and sent for final validation to Dr. Marco Micheli at the ESA PDO NEO Coordination Centre. There, Dr. Micheli, **performs precise astrometry to re-measure the sources from images to take into account effects such as trailing** which are typically not accounted for in point-source catalogs.
6. After successful astrometric and photometric measurements are extracted, observations are **submitted to the Minor Planet Center**.

Unified Astronomical Data in ADAM

Observatory Code	Date Range	Observations	Percent of Total	Data Source
W84: DECam at CTIO	Sep 2012 - Nov 2019	2.371 billion	73.97%	NOIRLab Source Catalog (DR2) [4]
Q55: SkyMapper at SSO	Mar 2013 - Mar 2018	563 million	17.57%	SkyMapper Southern Survey (DR2) [5]
695: KPNO	Jan 2016 - Aug 2017	186 million	5.81%	NOIRLab Source Catalog (DR2) [4]
V00: Bok Telescope at KPNO	Nov 2015 - Feb 2019	43 million	1.34%	NOIRLab Source Catalog (DR2) [4]
I41: ZTF at Palomar	Jun 2018 - Feb 2023	41* million	1.31%	Zwicky Transient Facility Alert Stream [6-9]

Note: Surveys such as ZTF perform difference imaging which removes static and non-variable sources. In cases where difference imaging is not available, we remove static sources as best as possible via filtering in our data pipeline. *Ongoing survey: observations are ingested as they are made.

Results and Future Work

The Asteroid Institute has launched a new precovery service named ADAM::precovery that scans for changes to the ESA and JPL risk lists nightly. If any changes are detected or new observations have been made by ongoing surveys, ADAM's data assets which currently include the NOIRLab Source Catalog [4], SkyMapper Southern Survey [5], and the Zwicky Transient Facility [6-9], are searched for candidate precovery observations. All observations are vetted by our team before submission to the MPC.

ADAM::precovery thus far has found 37 observations of 19 risk list objects in these data.

Running a full-scale precovery search on all >1600 risk list objects across >840 000 exposures containing 3.2 billion observations takes ~3 hours on a Google Cloud VM with 30 cores.

ADAM's data assets will include Pan-STARRS, Catalina Sky Survey, and the upcoming Vera C. Rubin Observatory's Legacy Survey of Space and Time (LSST).

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