



**Background:** Meerkat is ESA's imminent impactor warning service [1]. It operates **autonomously 24/7**, processing tracklets from the NEOCP to deliver warnings for potential impactors. Newly-discovered objects often have **short observational arcs**, leading to errors with traditional orbit determination methods. To overcome this, Meerkat employs the method of **systematic ranging (SR)** [2] [3], whereby the object **attributable  $\mathcal{A}$**  ( $RA$ ,  $Dec$ ,  $RA$  rate,  $Dec$  rate at time  $t_0$ ) is fitted to a **grid of topocentric range and range rates ( $\rho$ ,  $\dot{\rho}$ )**. From the fit error and prior probability distribution we derive a **posterior distribution** - a statistical description of the orbital and physical characteristics.

## Meerkat Processing

Meerkat runs continually in a loop, following the process outlined in Fig 1. Issued alerts will include Figs. 2-4, with Fig. 5 included if impacting Monte Carlo solutions are drawn. Meerkat delivered timely alerts for the **past 7 imminent impactors**, as highlighted in Table 1.

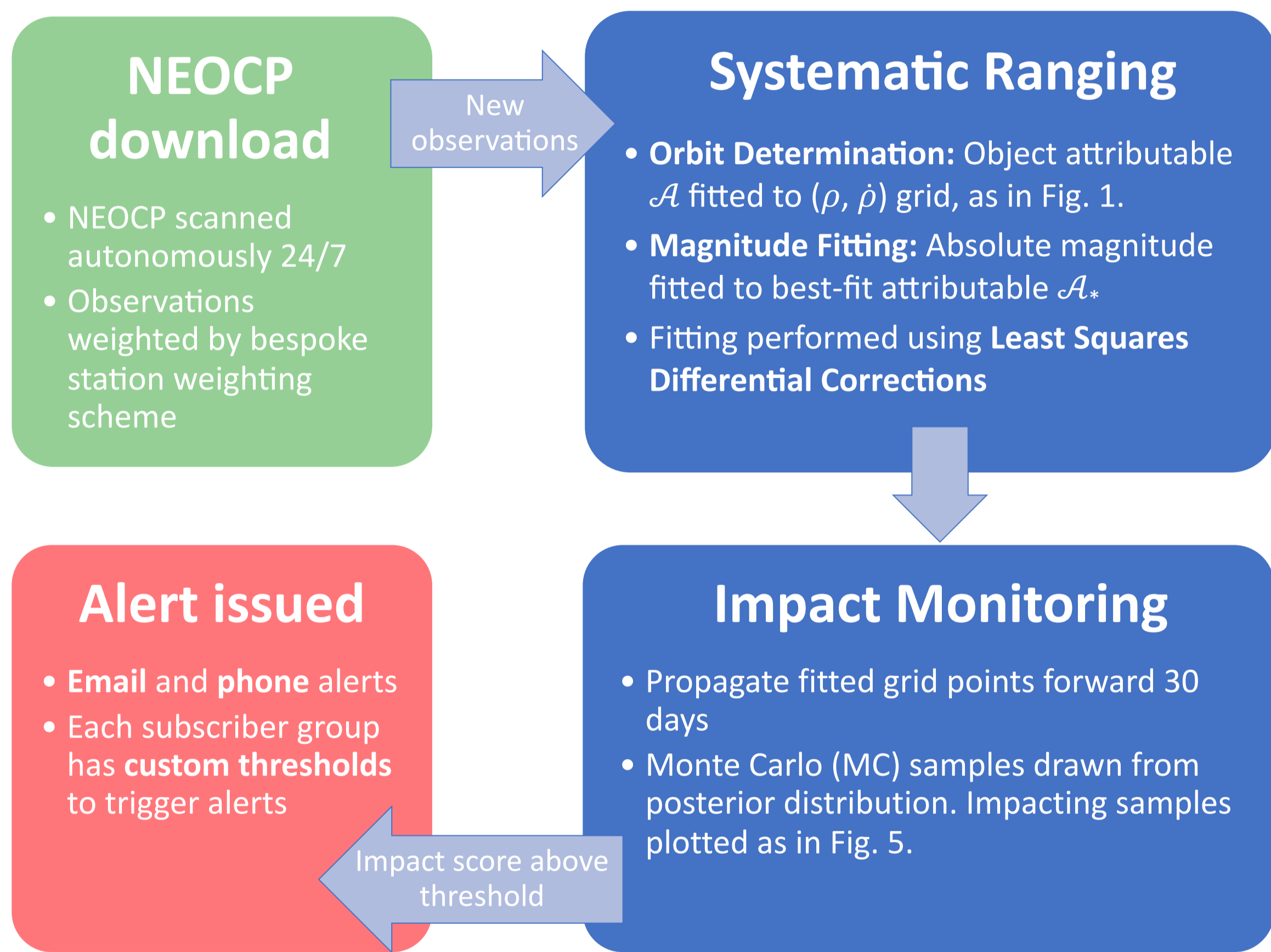


Fig 1. Flow chart showing stages of Meerkat processing

Asteroid	Time between detection and impact (hrs)
2022 EB5	1
2022 WJ1	3
2023 CX1	7
2024 BX1	3
2024 RW1	11
2024 XA1	10

Table 1. List of impacting asteroids with successful Meerkat alerts issued. It is worth noting that 2024 UQ would also have had a successful alert, had the observations been submitted before the impact event.

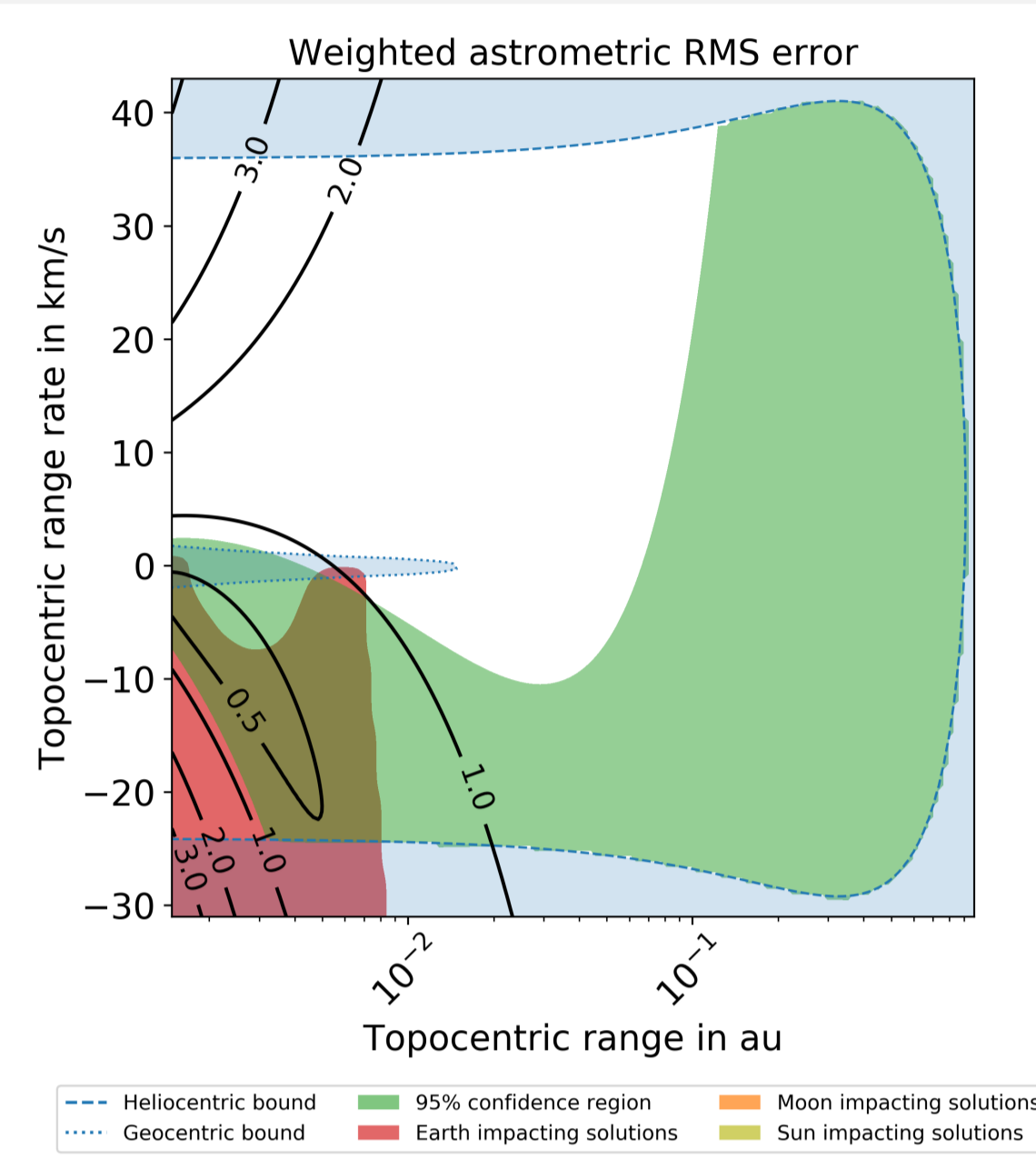


Fig. 2 Ranging plot for object CAQTDL2 ( $N_{obs} = 4$ ). The contours show the weighted RMSE from the orbit determination. All points outside the heliocentric bound are given a posterior probability of zero.

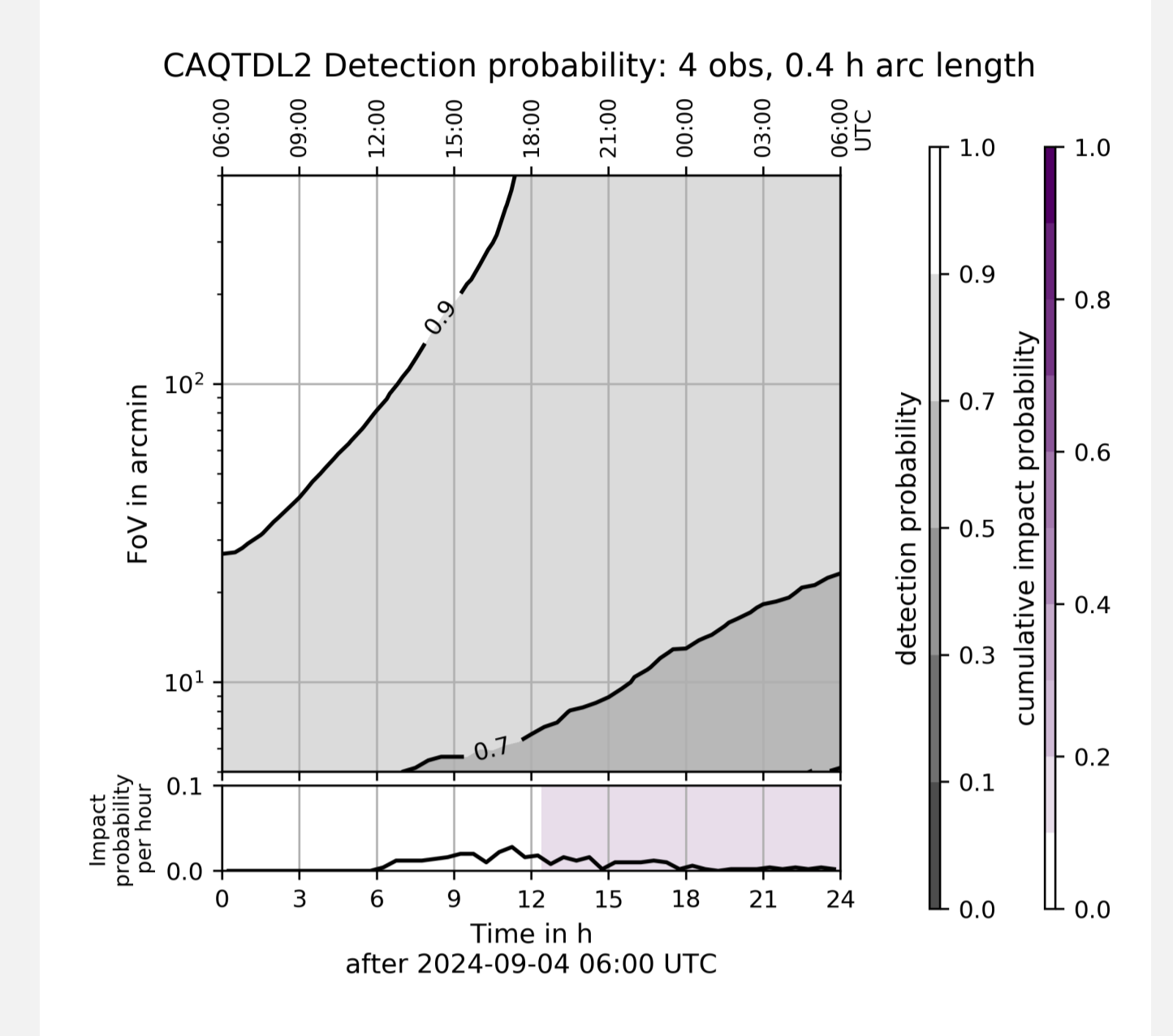


Fig. 3 Basic station selector plot for object CAQTDL2 ( $N_{obs} = 4$ ). The detection probability from the geocenter as a function of instrument FoV and observation time is plotted in the top panel. The bottom panel indicates the impact probability per hour with cumulative impact probability shaded behind.

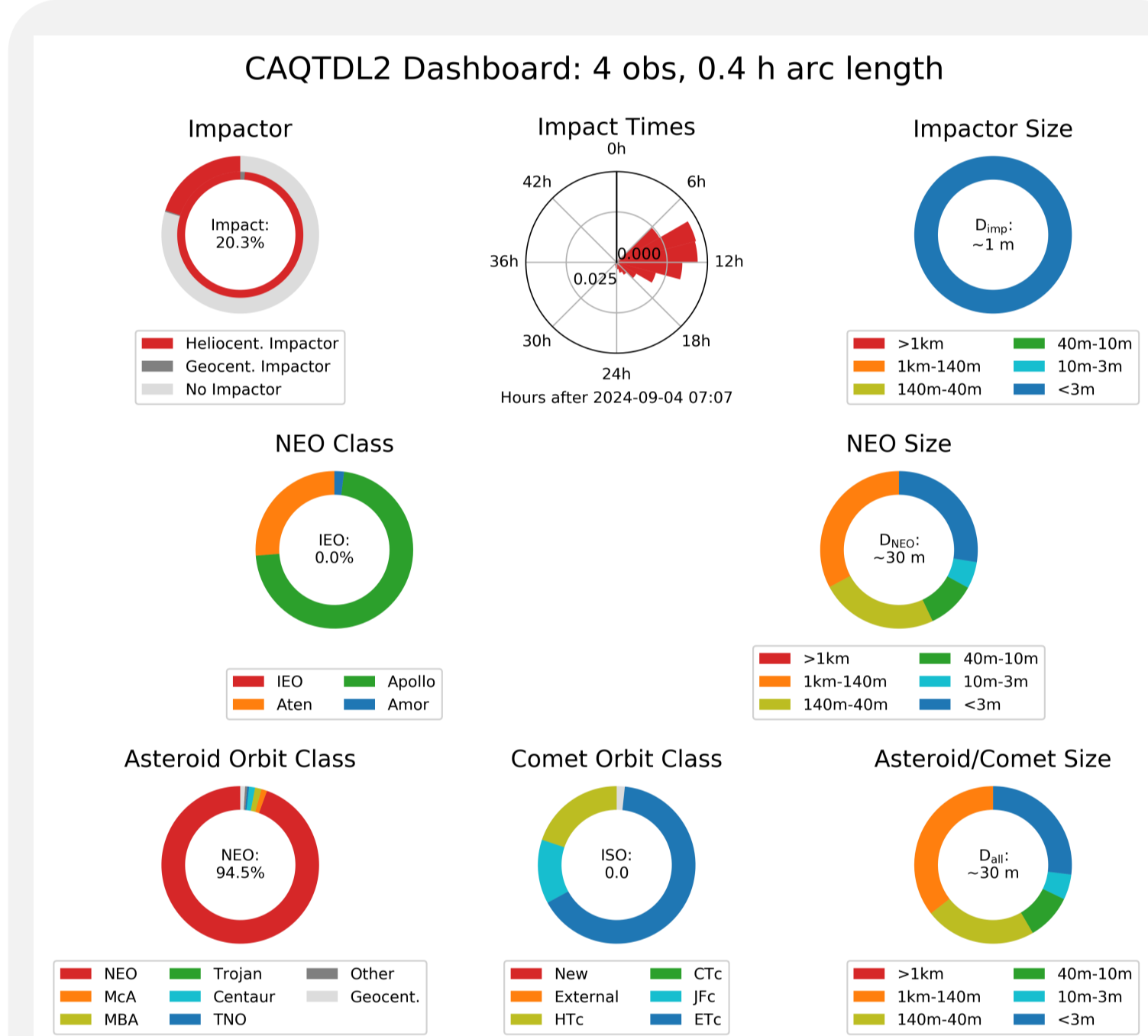


Fig. 4 Dashboard plot for object CAQTDL2 ( $N_{obs} = 4$ ). The rows indicate scores for impacting solutions, NEO solutions and all solutions respectively.

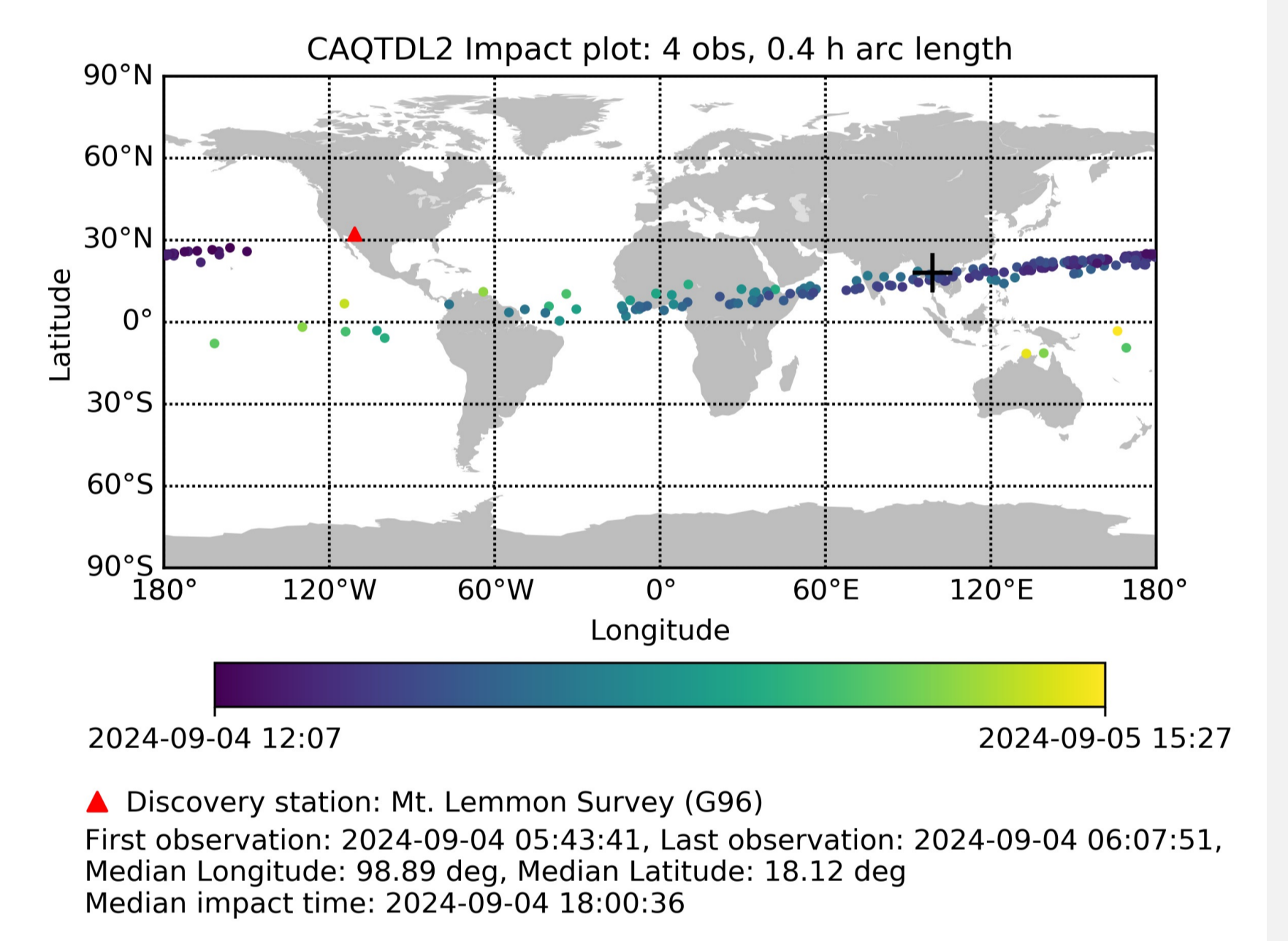


Fig. 5 Impact plot for object CAQTDL2 ( $N_{obs} = 4$ ). Impacting Monte Carlo samples drawn from the grid posterior distribution are plotted with an indicated impact time. The median impact location is plotted as a cross.

## False positive alerts

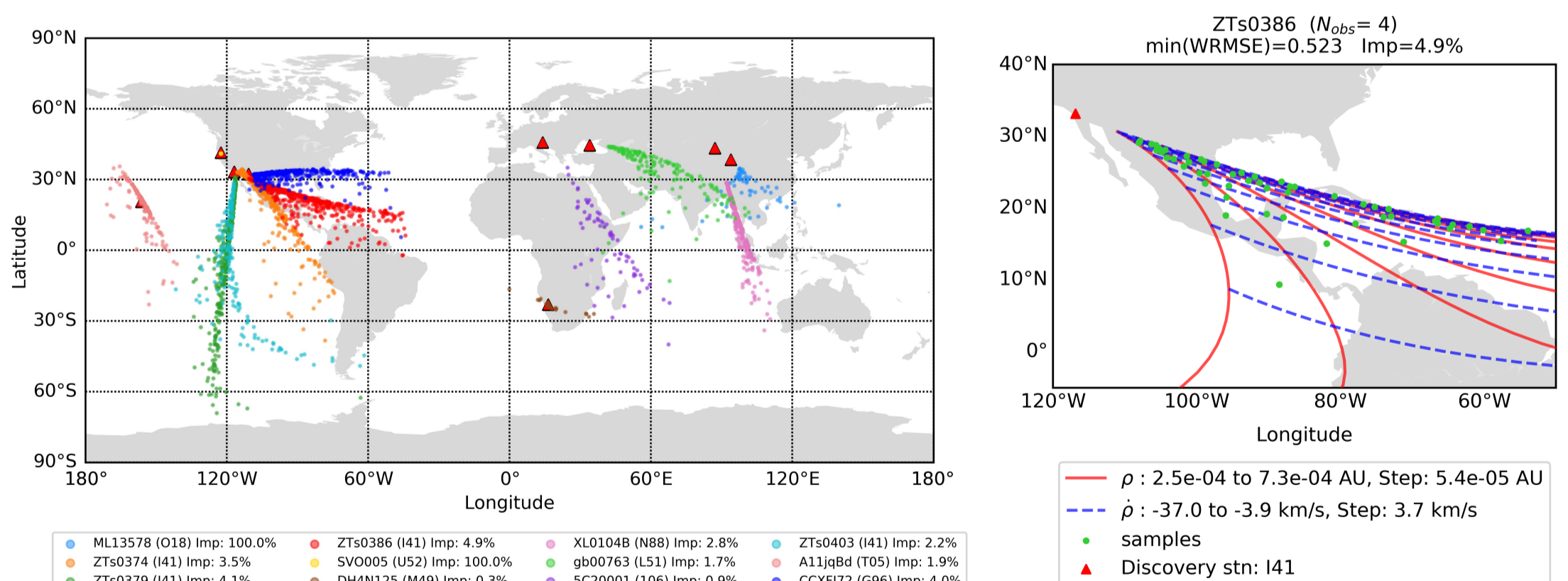


Fig. 6. Left panel: 500 heliocentric impacting MC samples for specific false positive alert objects. The discovery stations and impact scores are indicated. Right panel: The impact region of ZTS0386 in  $(\rho, \dot{\rho})$ -space is mapped into longitude-latitude space, highlighting the correlation of sample impact location with range-rate.

Between May 2024 and Apr 2025, Meerkat issued  $\sim 15$  discovery alerts ( $N_{obs} \leq 5$ ) where the MC impact locations appeared to point towards the discovery station, as shown in Fig. 6. The mechanism behind this is hypothesised as:

- Poor observations **inject artificial curvature** to the observation arc
- Consequently, all fitted orbits within admissible region **equally likely**
- Monte Carlo samples are **drawn from a uniform distribution**;  $s \sim \mathcal{U}(\rho, \dot{\rho})$
- Impact locations **cluster correlating to range-rate**.

The clustering is thought to be due to the natural dispersion that occurs with changing velocity. This effect is worsened by slower range rate samples having more time to be perturbed by Earth's gravity, and typically being fitted with less eccentric orbits. It is envisaged to devise a metric based on the flatness of the posterior distribution to indicate when this false positive will occur.

## Error rate

Of the 1045 objects and 4626 SR runs between 6<sup>th</sup> Jan and 7<sup>th</sup> Mar 2025:

- 10.7%** of all SR runs failed
- 27.5%** of objects had  $\geq 1$  failed SR runs
- 2.2%** of objects had only failed SR runs

Of the errors, two causes were most prominent:

- Propagator reaches max number of steps (13% of total errors):**
  - Occurs most frequently for very close approaches, who experience a deep dynamical encounter with Earth
  - Proposed solution:** Zero-weighting of grid points exceeding  $1e7$  max propagator steps threshold

**Posterior probability zero everywhere (82.5% of total errors):**

- Orbit fitting yields high residuals at every grid point
- This can occur when the solution in  $(\rho, \dot{\rho})$ -space is so converged that the confidence region is small enough to be missed by the grid step size.
- More frequently, occurs due to poor observations

- Proposed solution:** apply observation outlier identification and rejection upon failed grid fitting

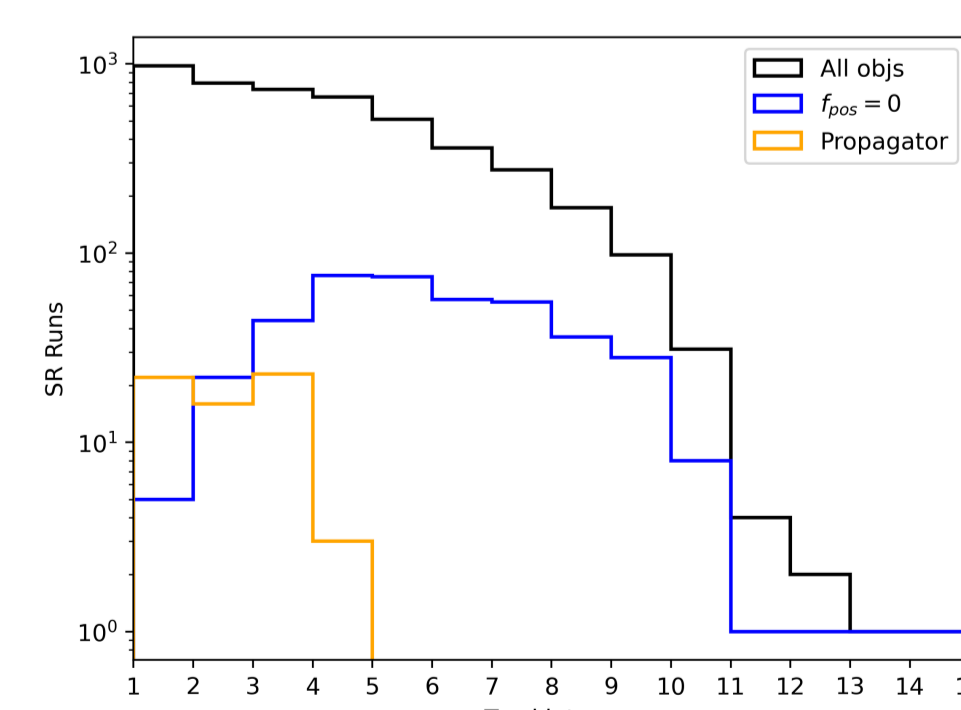


Fig. 7. The distribution of all SR runs over tracklet number compared to those with errors.

## New development features

Meerkat v2.0 is being developed in Python 3 with ESA's astrodynamics library **GODOT**. This package is highly **flexible**, allowing users to develop custom solutions to virtually any flight dynamics problem.



Meerkat v2.0 will be live in September. There are several exciting features in development for this release:

- Data handling:**
  - Integration of MPC PostgreSQL database for reading NEOCP observations, allowing 80 col + observer submitted observation error
  - Ability to read any of 80-col, ADES v2022 and ADES v2017
- Error reduction:**
  - Re-computation of failed objects in Meerkat downtime, with option to use batch SRIF orbit determination method
  - Observation outlier identification and rejection upon failed grid fitting
  - Recall of last used grid limits for each object, reducing computation time and allowing more highly converged solutions at high  $N_{obs}$  to be reached.
  - Refined propagator error handling using zero-weighting scheme
- Impactor analysis:**
  - Prioritisation queue for high-risk objects
  - Estimated entry angle, impact velocity and time until object enters Earth's shadow

## References:



- F. Gianotto, J. Cano, L. Conversi, L. Faggioli, M. Fenucci, D. Föhring, M. Frühauf, D. Koschny, R. Kresken, M. Micheli, et al., *Meerkat Asteroid Guard - ESA's Imminent Impactor Warning Service*, in: 2nd NEO and Debris Detection Conference, p. 49.
- S. Chesley, *Very short arc orbit determination: the case of asteroid 2004 FU162*, Proceedings of the International Astronomical Union 2004 (2004) 255-258.
- D. Farnocchia, S. Chesley, M. Micheli, *Systematic ranging and late warning asteroid impacts*, Icarus 258 (2015) 18-27

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