

On the uncertainties of astrometric observations



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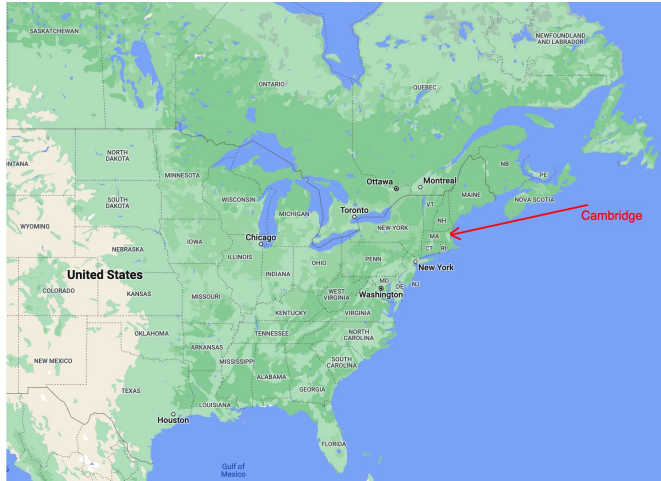
CENTER FOR **ASTROPHYSICS**
HARVARD & SMITHSONIAN



EU-ESA Workshop on Astrometric and Radar Observations of NEOs
October 6, 2025

Credit: NASA
Planetary Defenders Documentary

The Minor Planet Center



The MPC is the single worldwide location for receipt and distribution of positional measurements of minor planets, comets and outer irregular natural satellites of the major planets.

The MPC is responsible for the identification, designation and orbit computation of all of these objects.

The MPC was set up in 1947 at the University of Cincinnati under the direction of Paul Hegert.



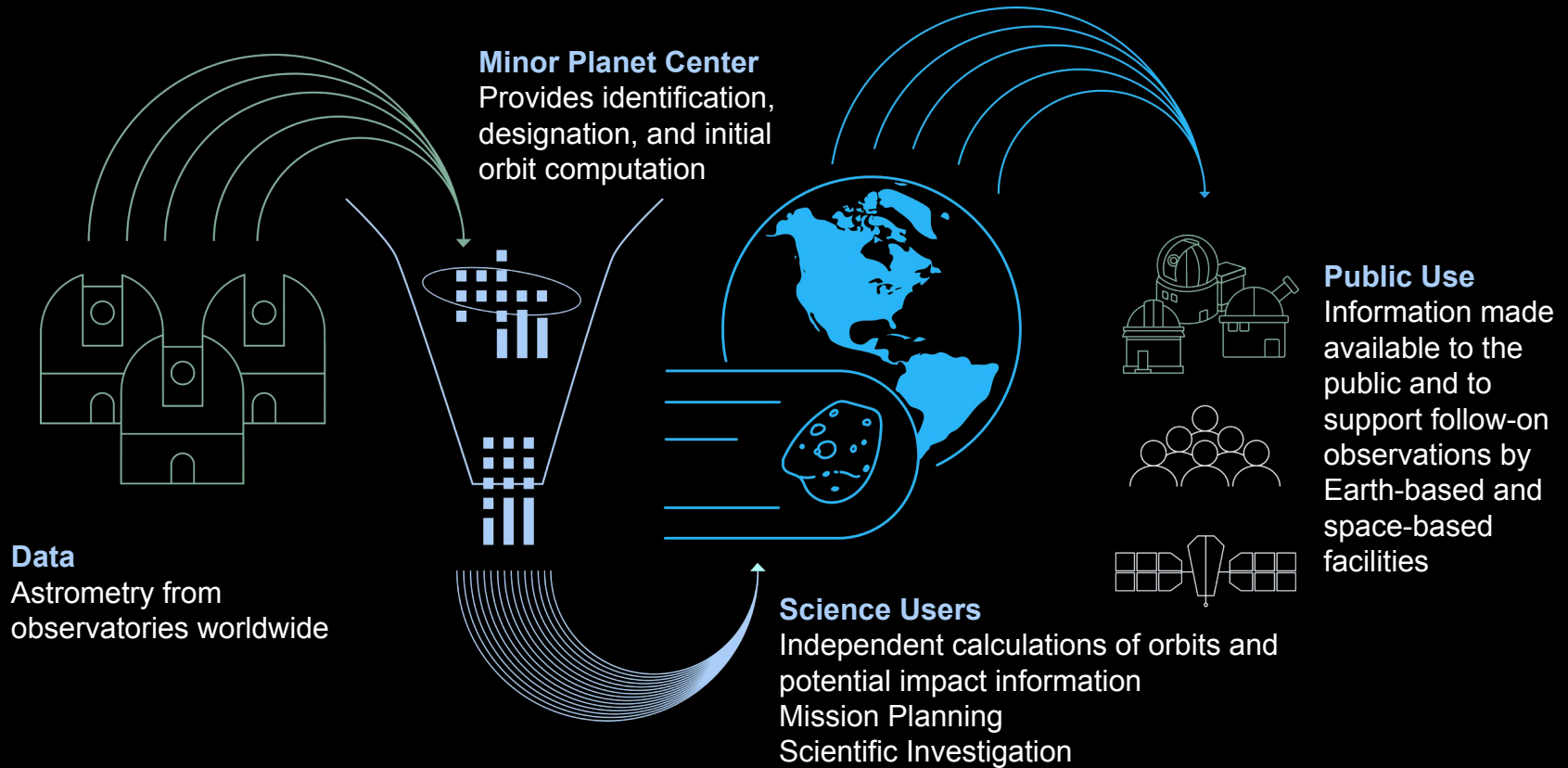
We are **physically located in Cambridge** (MA) as part of the Center for Astrophysics (Harvard & Smithsonian), **but we serve the small body community worldwide** under the auspices of the IAU (Division F).

The MPC has been in Cambridge since 1978.

MPC Data Flow



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Data volume

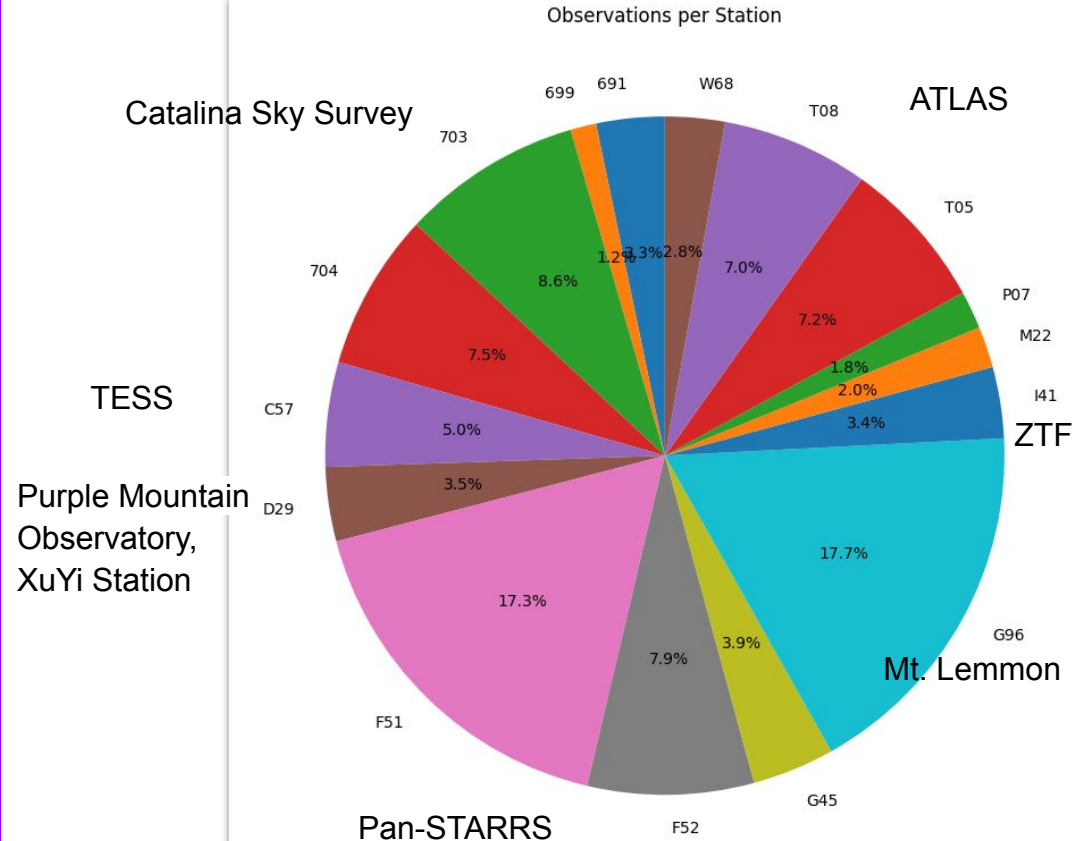
- The MPC currently receives between 40 - 50 million observations per year
 - With an average of 125k observations per night
- The observations pattern is not smooth, it depends on lunar cycles, weather, etc.
- With Rubin, the MPC is expected to receive 2x the amount of observations
 - 100 - 110 million observations per year
 - 300k observations per night
- Single large submissions, e.g.
 - Gaia observations of small bodies from DR4



Catalog: observations



- **Observations catalog contains almost 500 million observations**
 - 1.5 million are comet observations
- The majority of the observations are submitted from large surveys or large telescopes
 - Mostly funded in the United States by NASA
 - But also Chinese stations are now submitting large batches of observations
- **The orbit catalog contains almost 1.5 million objects**
 - 39,000 objects are Near-Earth asteroids
 - 4,595 are comets

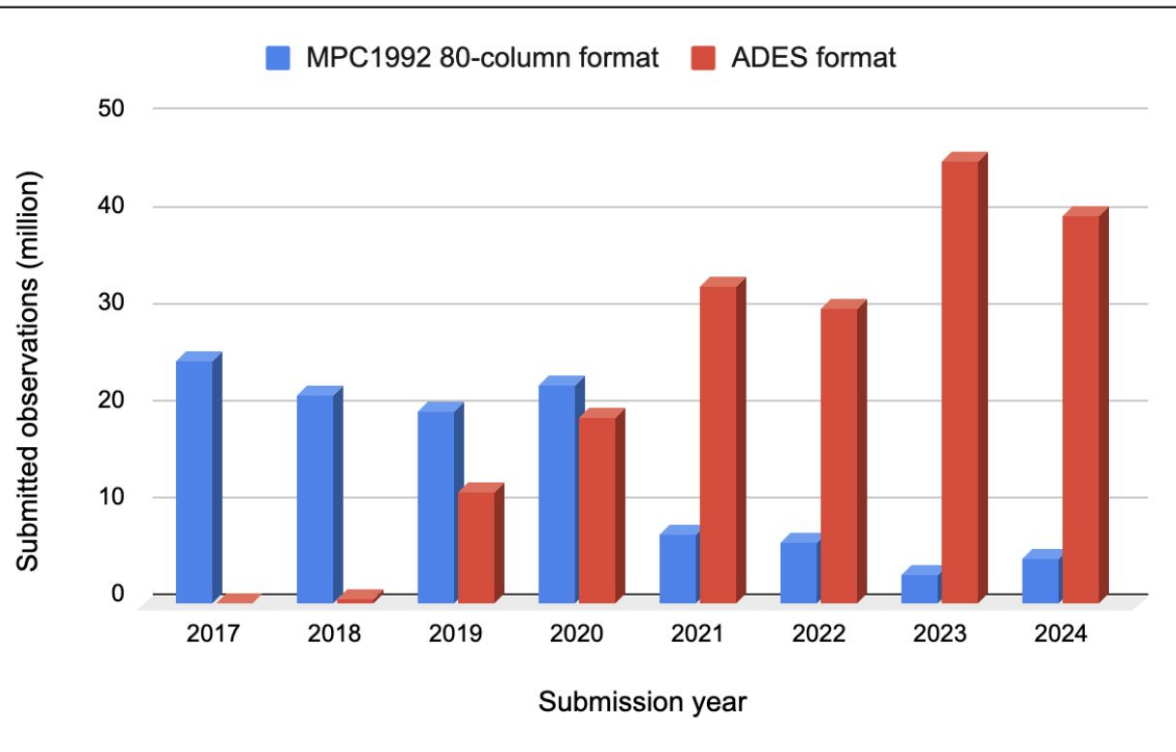


Data exchange standards

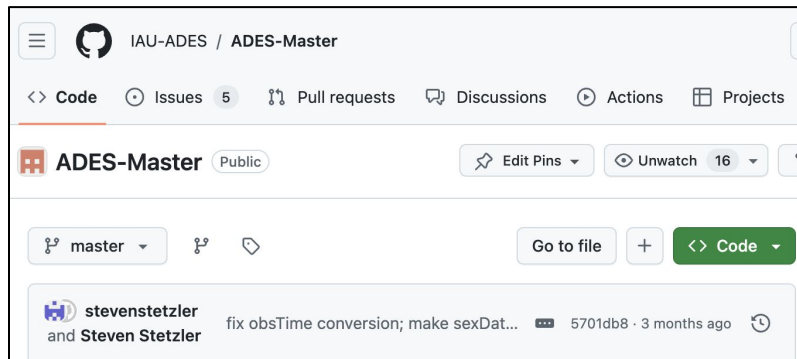


Legacy format: MPC-1992 80-column format

0003I	C2025 05 21.94461519 03 40.745-18 41 56.13	20.08cWE0020M01
0003I	C2025 05 22.37361119 03 19.698-18 41 58.91	20.49gUE0020I41
0003I	C2025 05 22.39681719 03 18.499-18 41 59.34	20.10rUE0020I41
0003I	C2025 05 27.37706018 58 53.951-18 42 35.00	20.29rUE0020I41
0003I	C2025 06 04.36164318 50 26.891-18 43 58.31	19.90rUE0020I41
0003I	C2025 06 08.34092618 45 32.947-18 44 39.84	UE0020I41
0003I	C2025 06 08.39967618 45 28.265-18 44 41.72	19.72gUE0020I41
0003I	C2025 06 10.34203718 42 54.201-18 44 58.54	19.31rUE0020I41
0003I	C2025 06 14.25203718 37 22.004-18 45 26.49	19.58gUE0020I41
0003I	C2025 06 18.35880818 31 01.100-18 45 35.06	18.65rUE0020I41
0003I	C2025 06 18.43649318 30 53.499-18 45 36.09	19.15gUE0020I41
0003I	C2025 06 21.23222218 26 14.460-18 45 24.35	20.21gUE0020I41



- **The more recent ADES format was adopted by the IAU in August 2015.**
- It was introduced with the goal of standardizing the exchange and storage of astrometric data (observations and uncertainties) and their associated data descriptions between observers and orbit computing centers.
- Since its stable (2017) version was released, ADES has become the format most commonly used for submissions



In Phase 1 we will add the new `obsBlockLarge` that can contain up to 500k optical-only observations. And there can only be a solo `obsBlockLarge` in a given `ades` element. So nothing besides the lone `obsBlockLarge`.

Once all of the high volume contributors have switched to this for submissions then we will implement limitations on the number and size of `obsBlock` s in a Phase 2.

I'll go ahead and implement Phase 1 in the draft PR [#76](#). Maybe even this week...

ADES is the preferred submission format

And the preferred format for internal MPC processing

The GitHub repository containing the ADES code is ***continuously updated*** if fixes or improvement are needed:

- Co-maintained by JPL & MPC
- Available for public download
- Available for public *discussion* of issues and improvements



[URL & QR-Code](https://github.com/IAU-ADES/ADES-Master)

<https://github.com/IAU-ADES/ADES-Master>

XML format

```
<obsData>
  <optical>
    <permID>1234567</permID>
    <provID>2018 AA1234</provID>
    <trkSub>a1b2c3d4</trkSub>
    <mode>CCD</mode>
    <stn>568a</stn>
    <prog>31</prog>
    <obsTime>2016-08-29T12:32:34.12Z</obsTime>
    <ra>215.6560501</ra>
    <dec>-13.5478723</dec>
    <rmsRA>0.015</rmsRA>
    <rmsDec>0.013</rmsDec>
    <rmsCorr>-0.215</rmsCorr>
    <astCat>2MASS</astCat>
    <mag>21.91</mag>
    <rmsMag>0.25</rmsMag>
    <band>w</band>
    <photCat>PPMXL</photCat>
    <photAp>13.3</photAp>
    <logSNR>0.78</logSNR>
    <seeing>0.8</seeing>
    <exp>1200</exp>
    <notes>klmnp</notes>
    <remarks>High winds affected tracking</remarks>
  </optical>
</obsData>
```

Equivalent PSV format

```
permID |provID      |trkSub  |mode|stn |prog|obsTime      |...
1234567|2018 AA1234|a1b2c3d4| CCD|568a| 31|2016-08-29T12:32:34.12Z|...
```

(The following lines are broken only for display in this document. In the actual PSV file, the lines continue beyond the ellipses.)

```
ra      |dec      |rmsRA|rmsDec|rmsCorr|astCat  |mag  |rmsMag|band|...
215.6560501|-13.5478723|0.015|0.013|-0.215| 2MASS|21.91|0.25| w|...

photCat |photAp|logSNR|seeing|exp |notes|remarks
PPMXL|13.3 |0.78 |0.8  |1200|klmnp|High winds affected tracking
```



- **Nonlinear weighted least squares fit**
- 6 orbital parameters
- Up to 4 additional parameters for non-gravitational perturbations
- Masses can also be added
- Dynamical model includes all the planets (JPL DE ephemerides) + most massive asteroids in the belt
- General relativity included as well (EIH)
- **Outlier rejection**
- Observations with $\chi^2 > 9.21$ are discarded where:

$$\chi_i^2 = \xi_i \gamma_{\xi_i}^{-1} \xi_i$$

Target function

$$Q(\xi) = \frac{1}{2m} \xi^T \mathbf{W} \xi$$

- ξ : residuals
- m : number of observations
- $\mathbf{W} = \Gamma^{-1}$: weight matrix

$$\Gamma = \begin{bmatrix} \sigma_{\alpha_1}^2 & \text{cov}(\alpha_1, \delta_1) & 0 & \dots & 0 \\ \text{cov}(\alpha_1, \delta_1) & \sigma_{\delta_1}^2 & 0 & \dots & 0 \\ \vdots & \vdots & \ddots & & \\ 0 & 0 & \dots & \sigma_{\alpha_m}^2 & \text{cov}(\alpha_m, \delta_m) \\ 0 & 0 & \dots & \text{cov}(\alpha_m, \delta_m) & \sigma_{\delta_m}^2 \end{bmatrix}$$

- **Normal equations**

$$\mathbf{C} = \mathbf{B}^T \mathbf{W} \mathbf{B}; \quad \mathbf{D} = -\mathbf{B}^T \mathbf{W} \xi \quad \left(\mathbf{B} = \frac{\partial \xi}{\partial \mathbf{x}} \right)$$

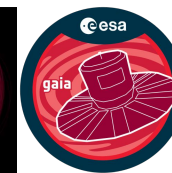
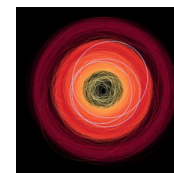
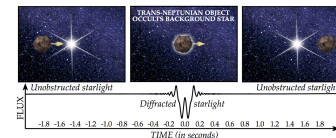
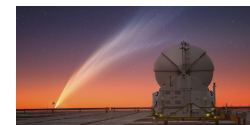
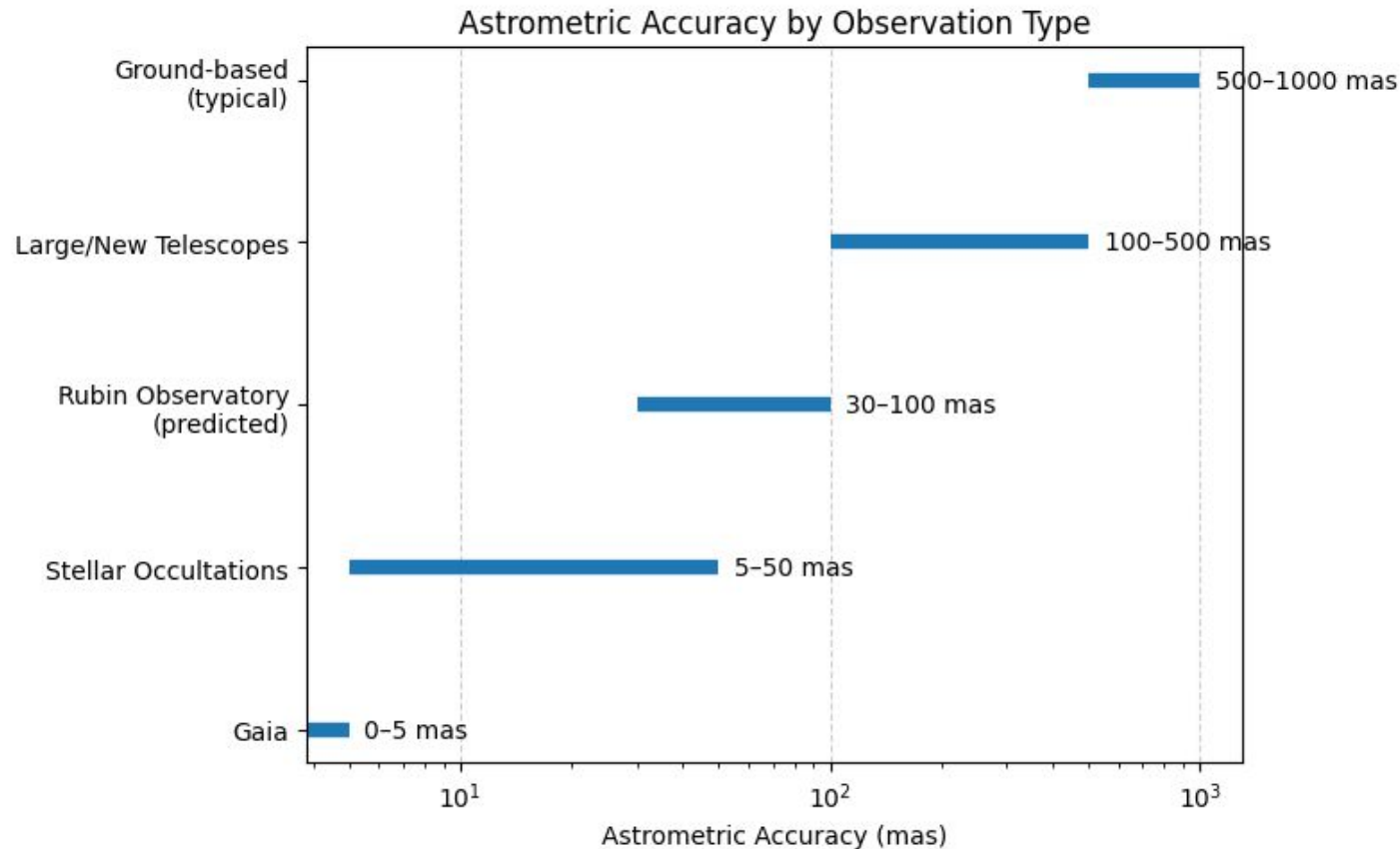
- **Differential correction**

$$\text{Correction} = \mathbf{C}^{-1} \mathbf{D}$$

Observations accuracies



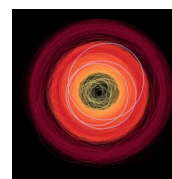
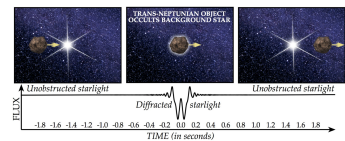
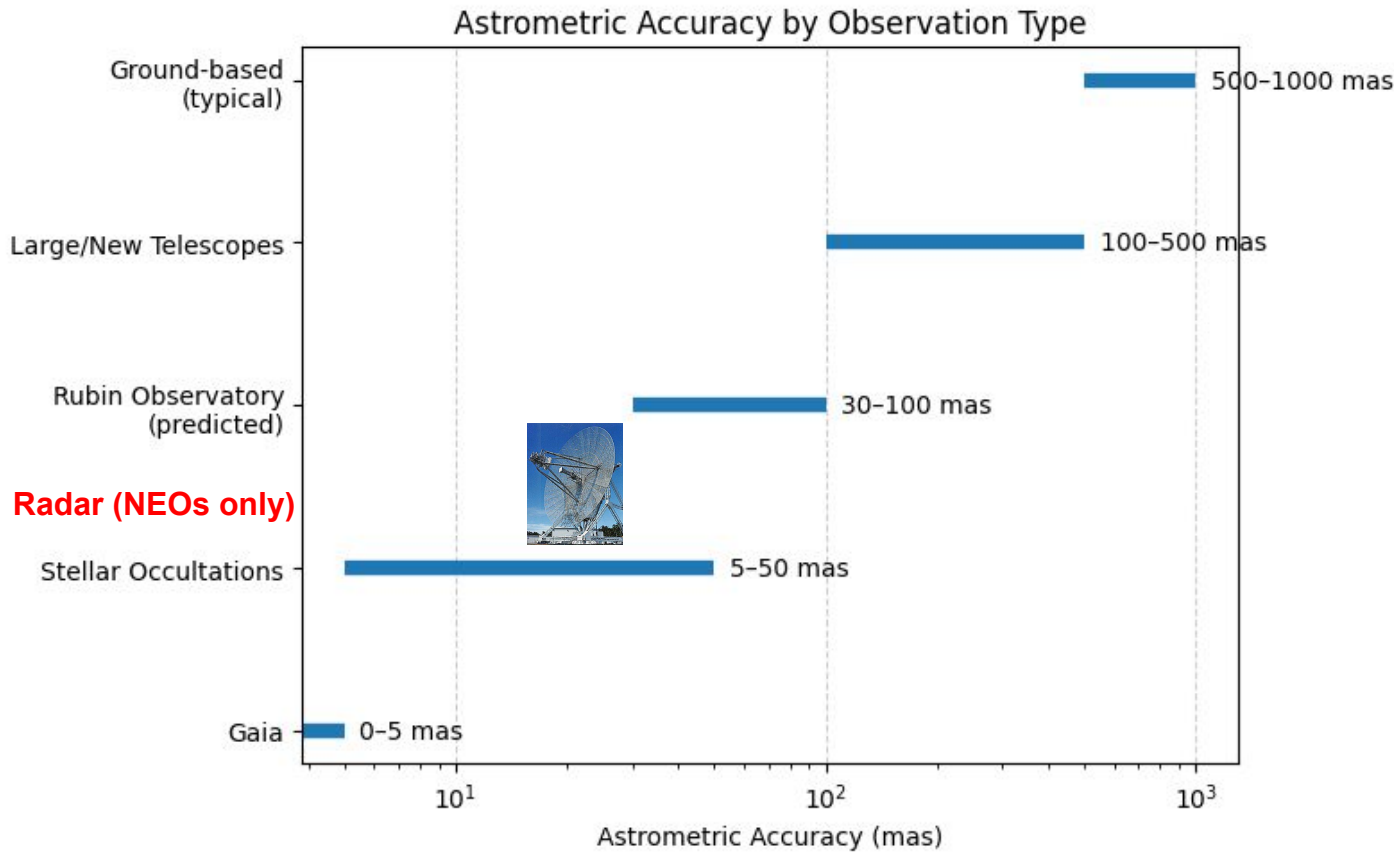
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Observations accuracies

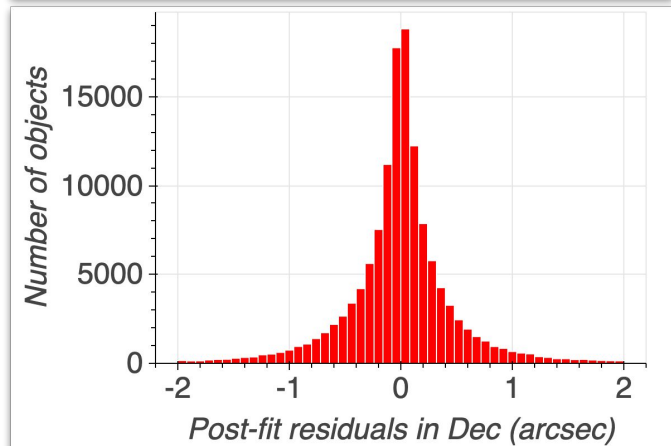
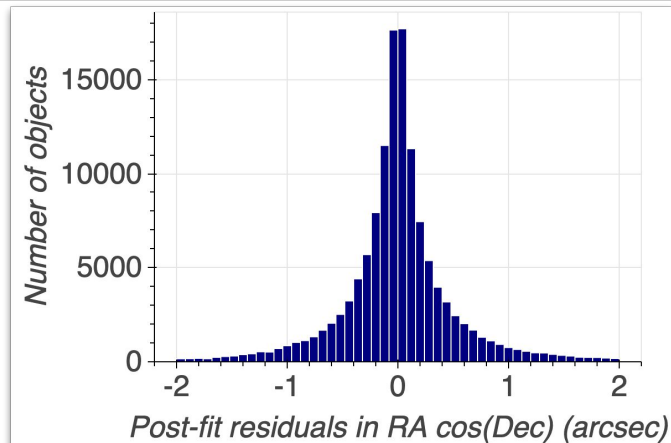
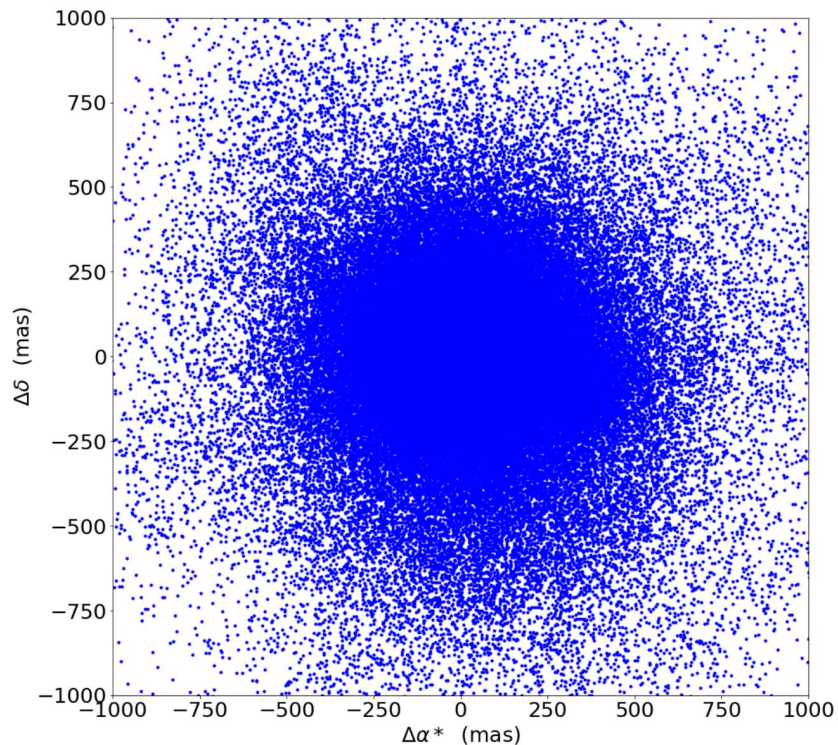


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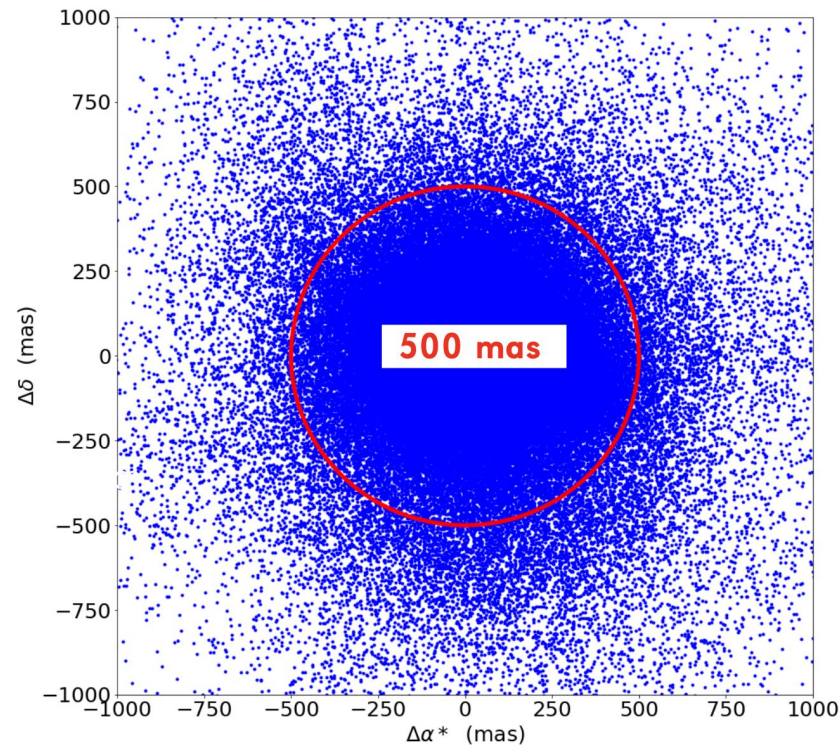
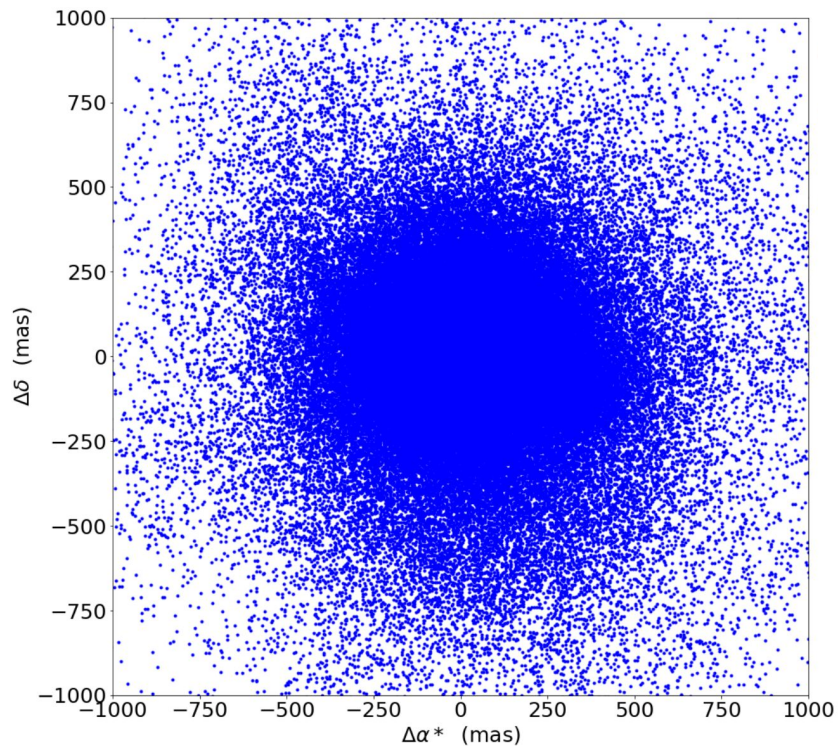
Observations accuracies

Post-fit residuals for a subset of
ground-based observations



Observations accuracies

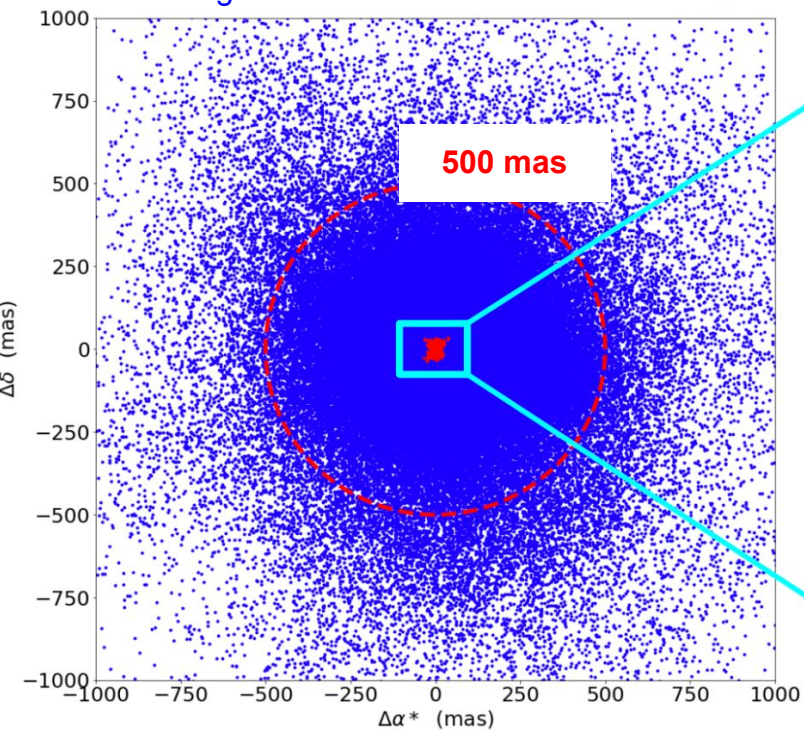
Post-fit residuals for a subset of
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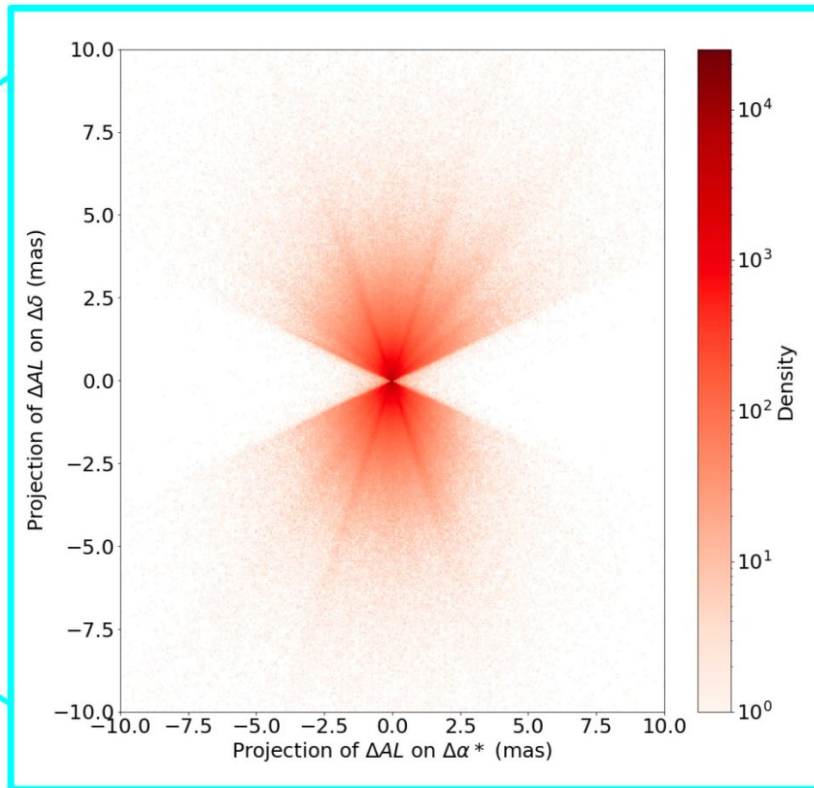
Asteroid population



Post-fit residuals for a subset of ground-based observations



Gaia small body observations from DR3



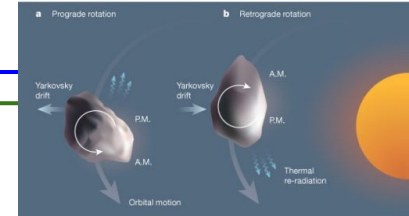
What does influence the accuracy?



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- **The epoch of the observations**

- Older observations have lower accuracies, but they are extremely useful to detect small perturbation, such as the Yarkovsky effect

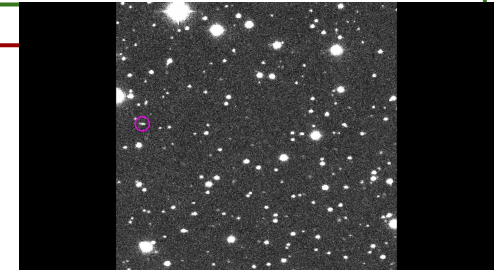


- **The stellar catalog**

- The catalog used to measure the positions of the object

- **Other factors**

- The rate of motion of the object (fast movers are more difficult)
- The object type
 - Comet observations are more difficult to measure
 - Faint and/or fast Near-Earth Asteroids
- The observed magnitude of the object
- The observer



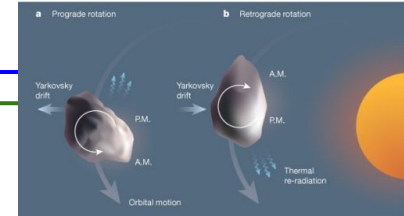
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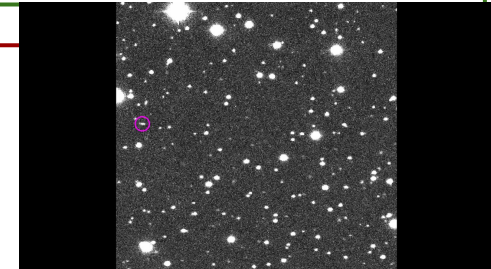


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Collective effort from multiple centers (e.g. MPC, JPL) to collect all the post-fit residuals for more than 300M observations and analyze their dependencies on the different factors

Timing issues

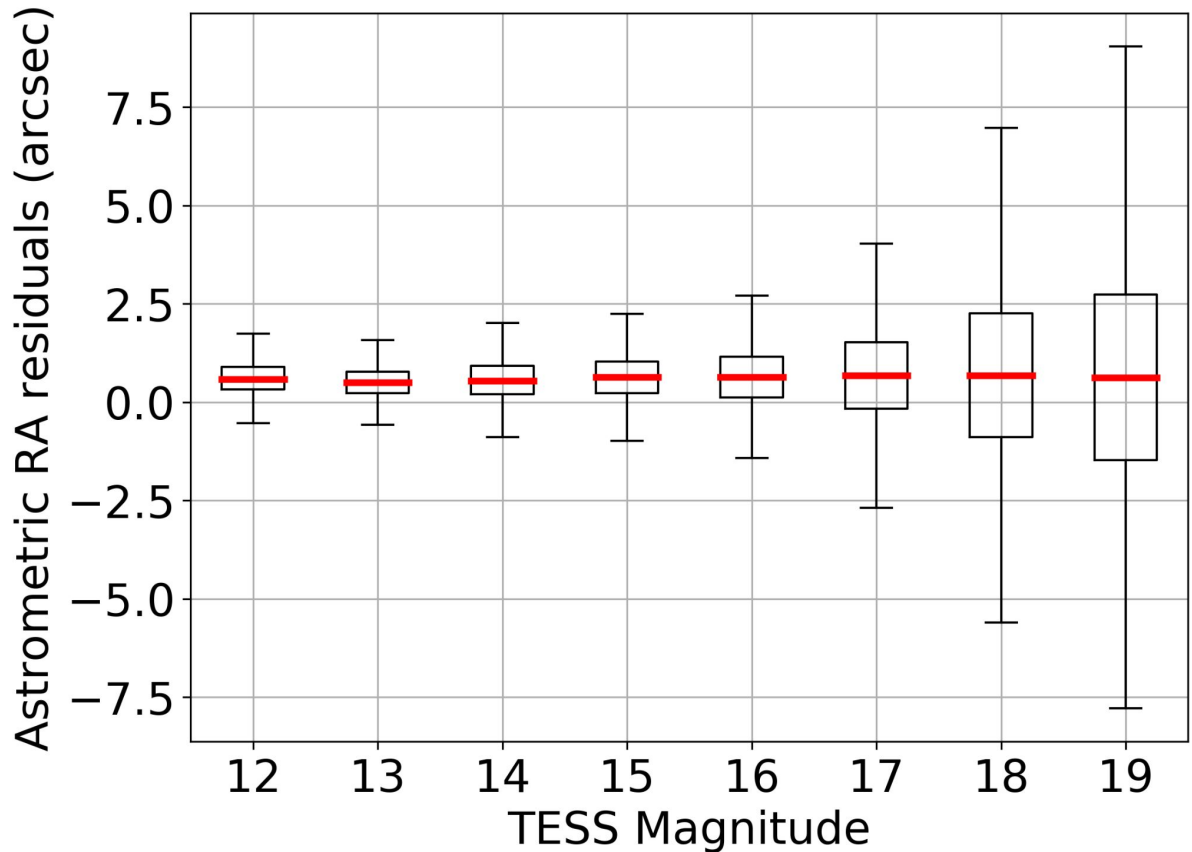


IAU

The International Astronomical Union

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- **Transiting Exoplanet Survey Satellite (TESS)** is a space telescope for NASA's Explorer program, designed to search for exoplanets using the transit method in an area 400 times larger than that covered by the Kepler mission.
- TESS serendipitously observes small bodies (low accuracy, but very interesting for light curves)
- The TESS team submitted more than 30M observations to the MPC
- A preliminary analysis of the post-fit residuals shows a clear bias in right ascension
- **The bias was due to a bug in time conversion**

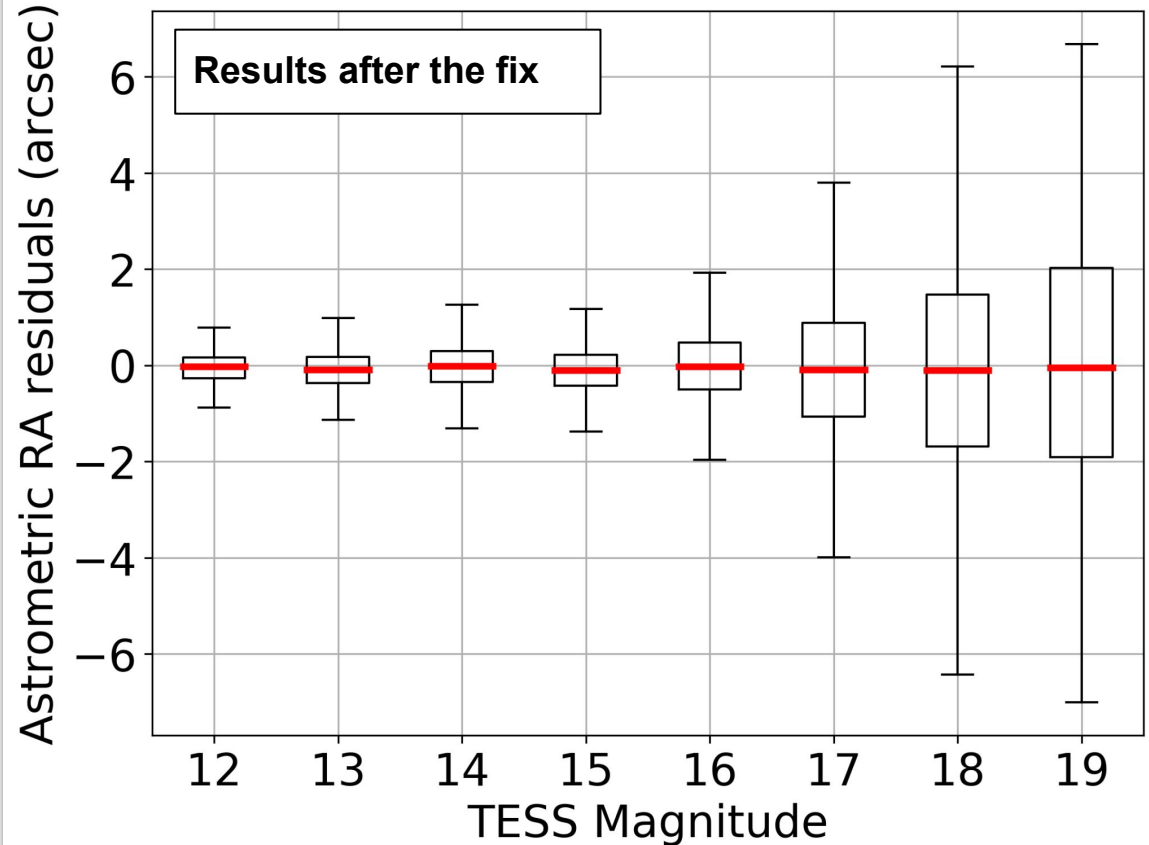


Timing issues



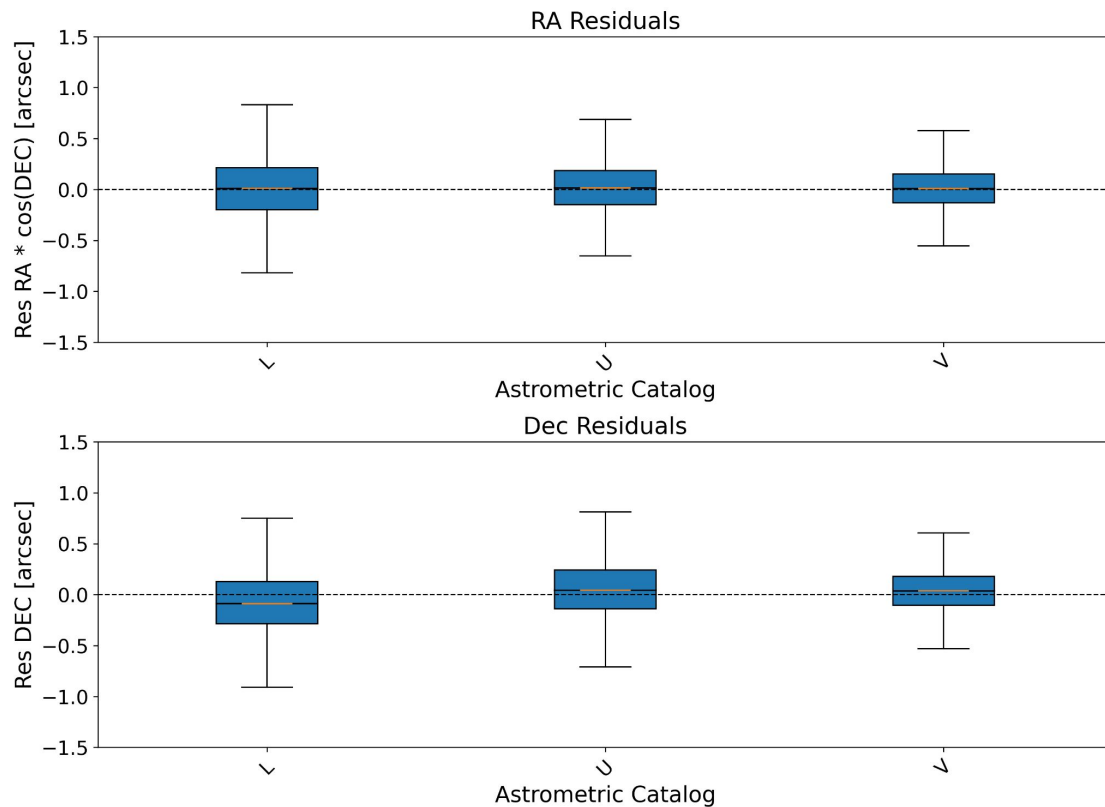
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Stellar catalogs

Box Plots of RA and Dec Residuals by Astrometric Catalog for T08 observatory



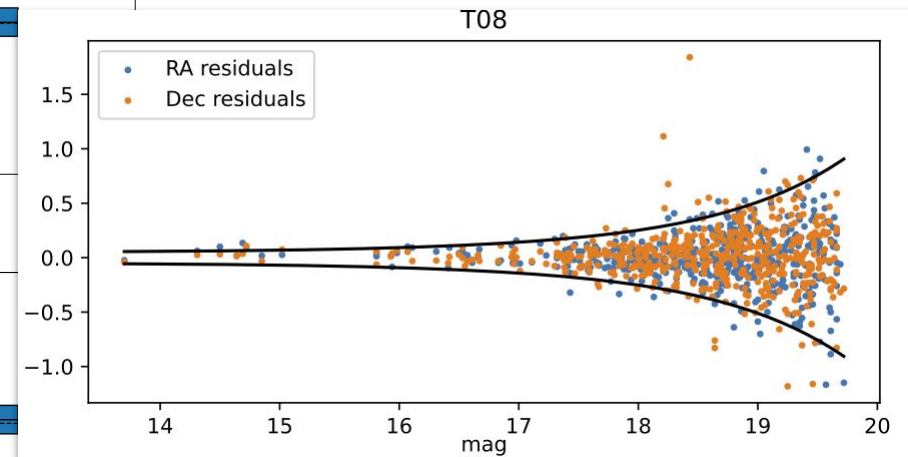
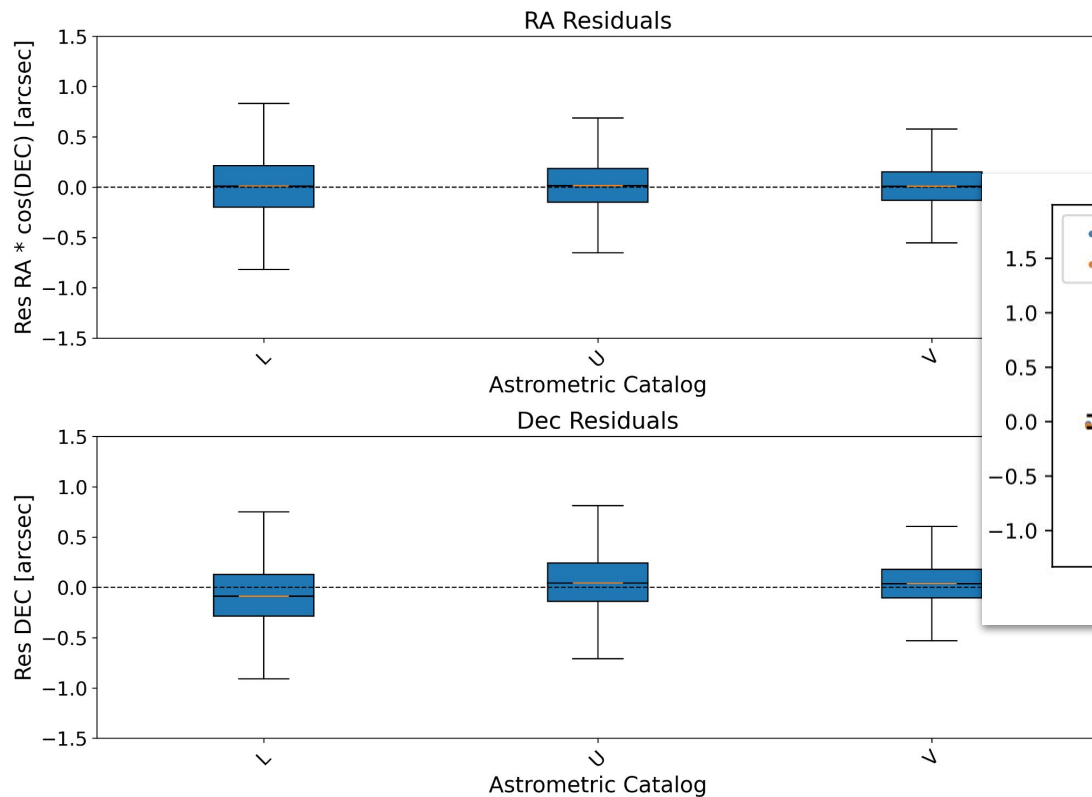
- **Astrometric post-fit residuals for one of the ATLAS telescopes**

- L = 2MASS
- U = Gaia DR1
- V = Gaia DR2

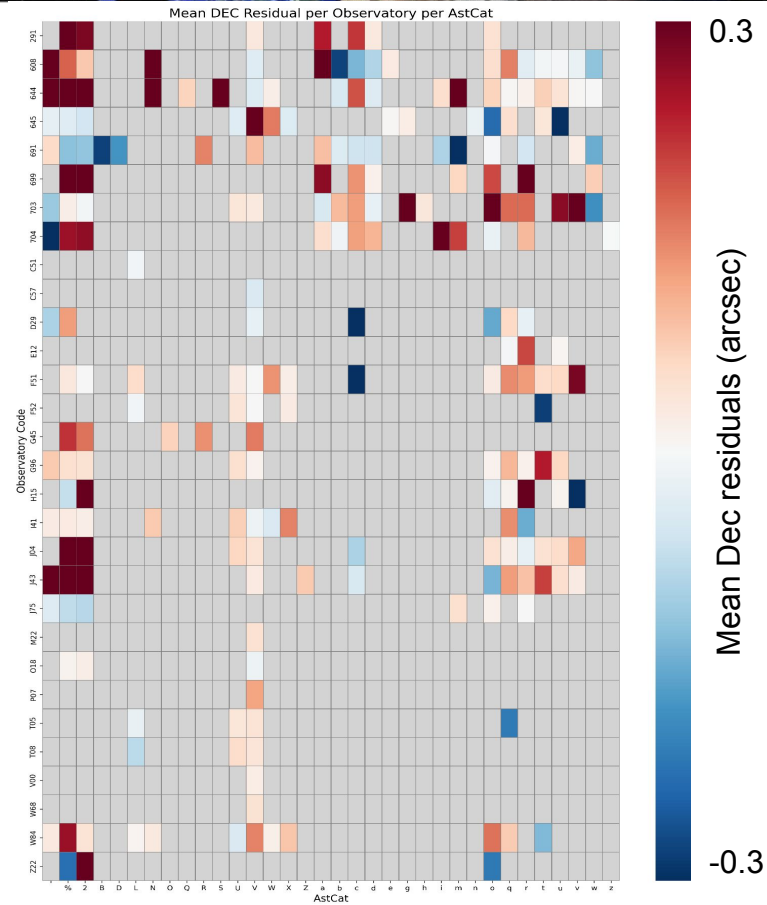
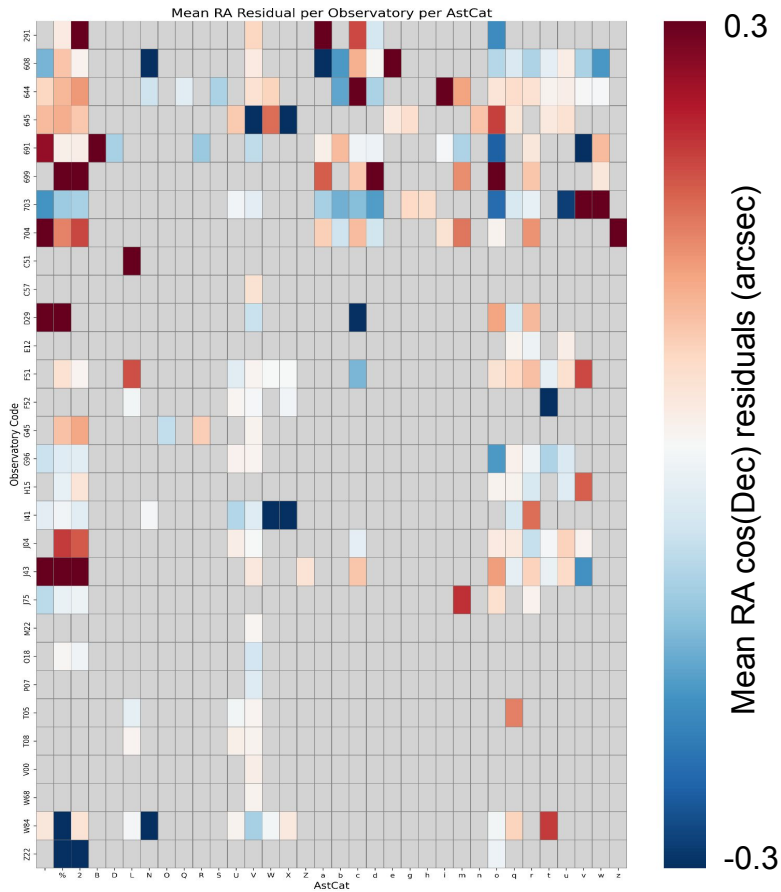
Stellar catalogs



Box Plots of RA and Dec Residuals by Astrometric Catalog for T08 observatory



Stellar catalogs



- **At the IAU General Assembly in Rome in 2027, the MPC would like to present the adoption of a new standard for the exchange of the orbits**
- The goal is the same: standardizing the exchange and storage of orbit data and their associated data descriptions between observers and orbit computing centers.

```
{  
  "version": "0.5",  
  "title": "Best Fit Orbit Data for Single Solar System Object",  
  "description": "Standardized MPC JSON format for the exchange of orbit-fit data. Designed to communicate the best-fit orbit for a single minor planet or  
  "type": "object",  
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    "non_grav_booleans",  
    "magnitude_data",  
    "epoch_data",  
    "moid_data",  
    "categorization",  
    "software_data",  
    "system_data"  
  ],  
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  ],  
}
```

Thank you for your attention!