Asteroid Astrometry by Stellar Occultations: Accuracy of existing sample from orbital fitting

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Aims

- Here we explore for the first time the performance on orbit accuracy brought by reducing occultations by stellar positions given in Gaia DR2 and EDR3 (Gaia level accuracy for occultations), exploited jointly to the new occultation error model.

- We compare the quality of orbital fits by using only occultation data vs using all available information for the same objects, to validate occultation's Gaia-level performance;

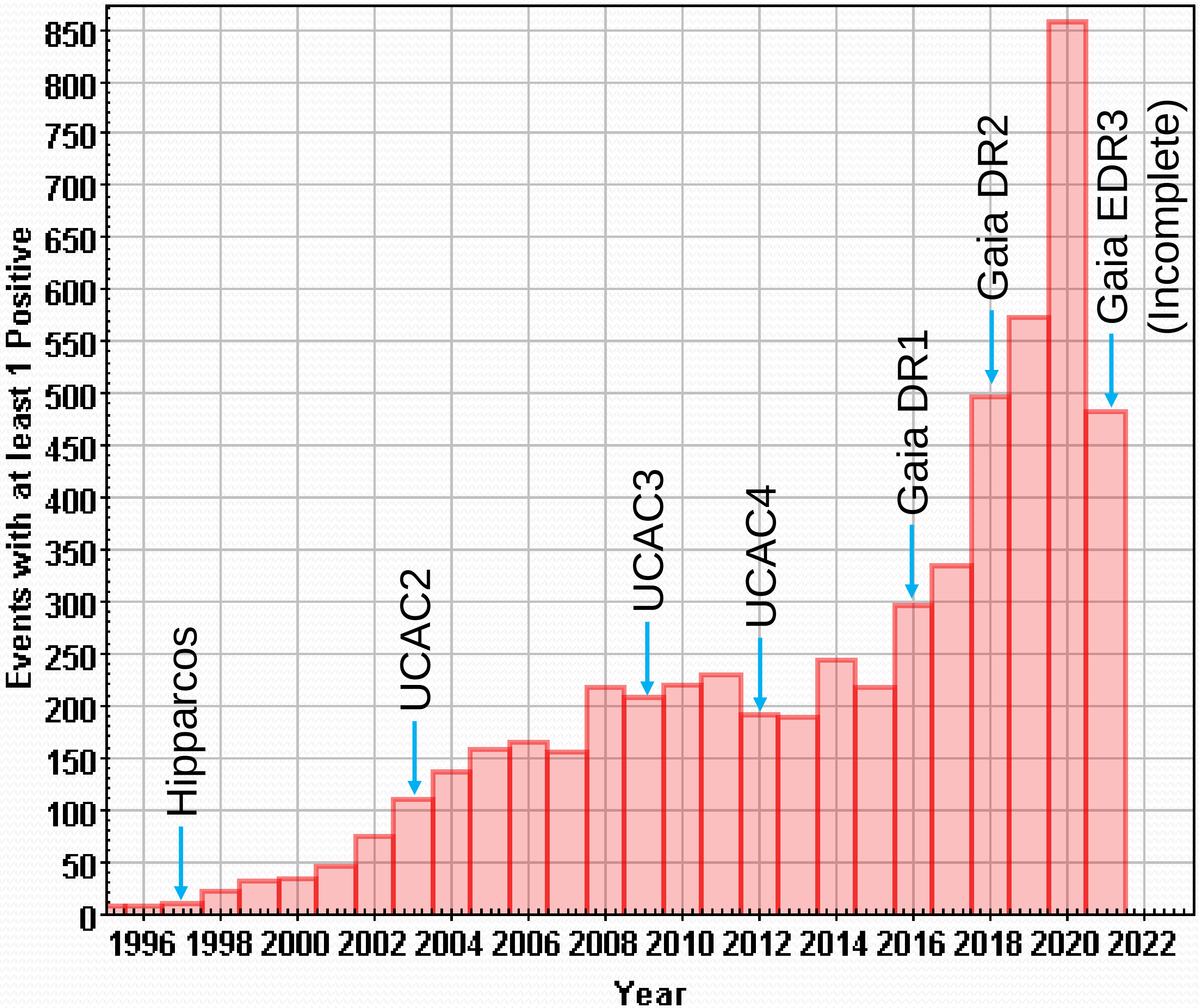
- We also want to compare the post-fit residuals to the error model.

Context: Census of Occultations

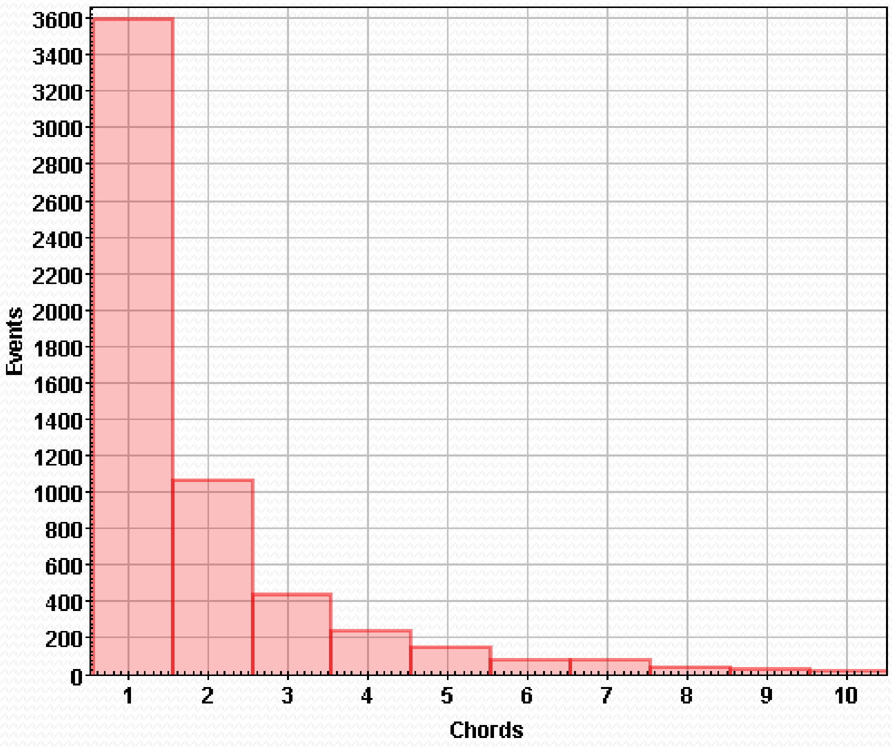
- Almost 6 000 stellar occultations performed to asteroids (planets and satellites excluded):
    - 1961-2021 (August 18^{th});
    - Over 1 600 asteroids involved;
    - Good historical average astrometry (~20 mas) compared to other ground-based methods (~400 mas for CCD imaging);

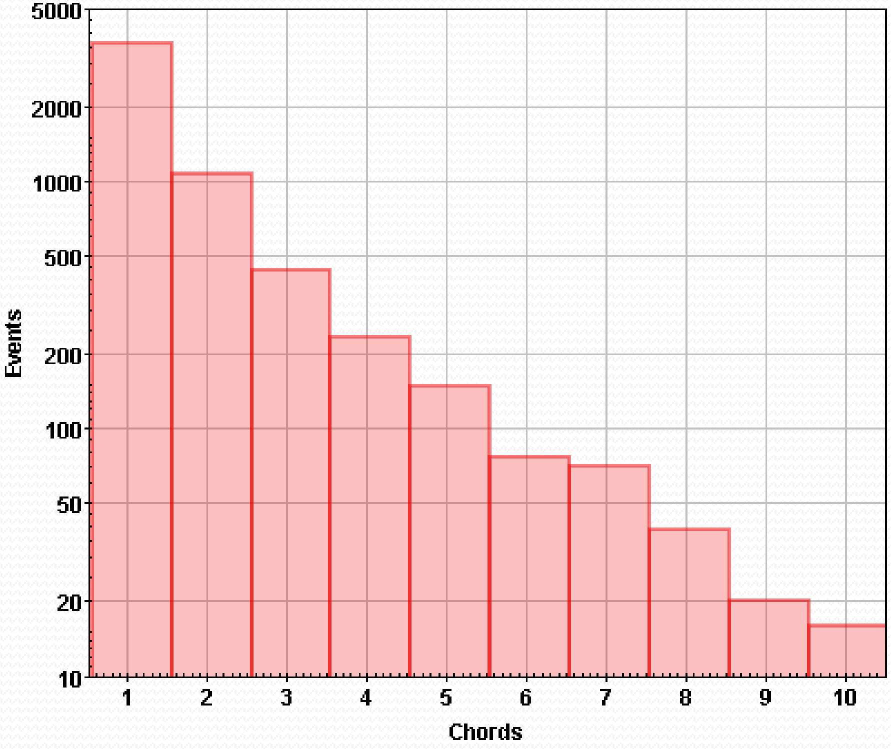
- Big growth in last few years, thanks to more reliable catalogues (e.g. Tycho, UCAC, Gaia) and larger community.

Census of Occultations



Census of Occultations



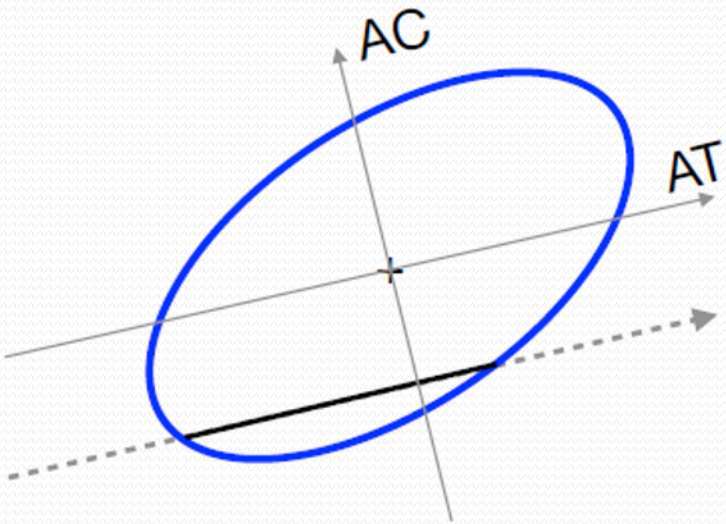


Mostly single chords (62% of events).
Multi-chord events tend to have smaller uncertainties.

Occultation Uncertainties (Herald et al., 2020)

- Occultation uncertainties depend on multiple factors, most notably:
  - Number of chords: single chords are less reliable than several chords for same event;
  - Chord distribution across object's 2D projection: 2/3 chords that are almost superposed provide less coverage to object's shape than the same number chords in near opposite sides.
  - Individual observer's timing uncertainties: precision of individual chords affects overall result;
  - Object's size and apparent velocity: uncertainties are relative to these factors;
  - Occulted star's astrometric precision (depends on catalogue).

Occultation Uncertainties

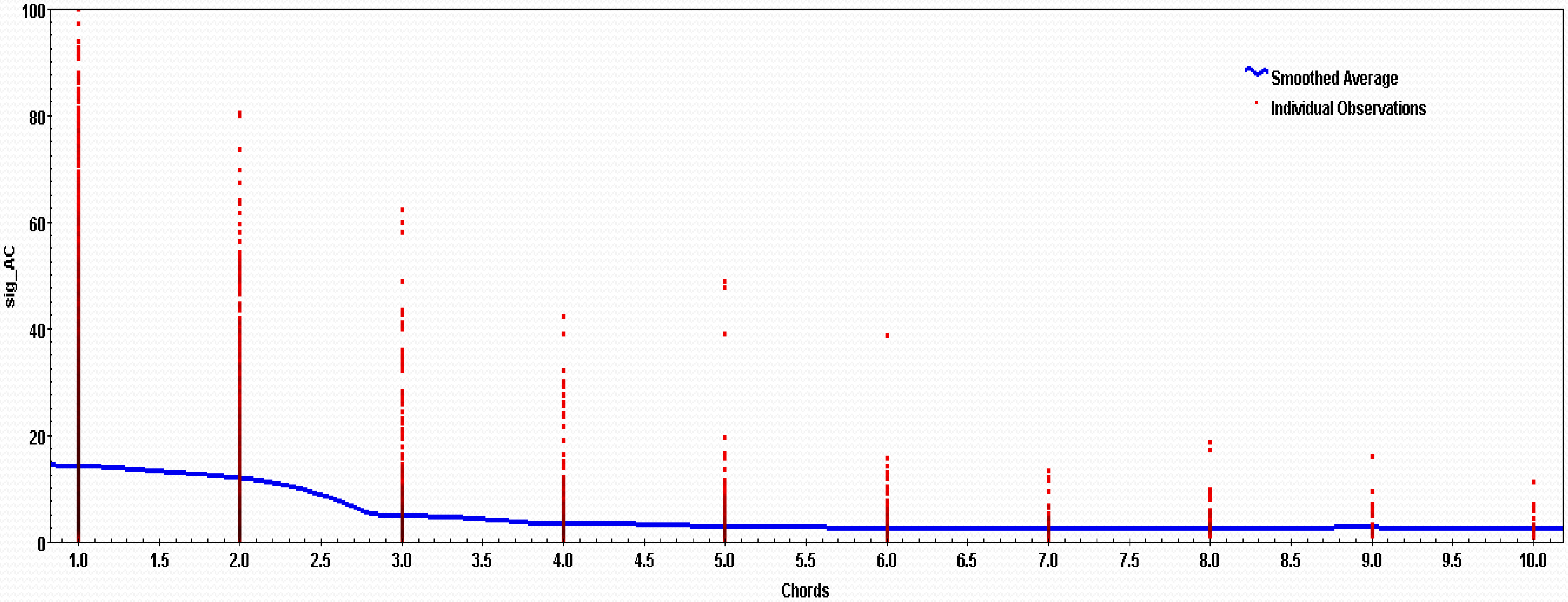


- AT: Along Track: direction of asteroid's motion during occultation. Uncertainty depends mostly on timing;

- AC: Across Track: direction orthogonal to AT. Uncertainty depends mostly on chord fitting.

Occultation Uncertainties (Herald et al., 2020)

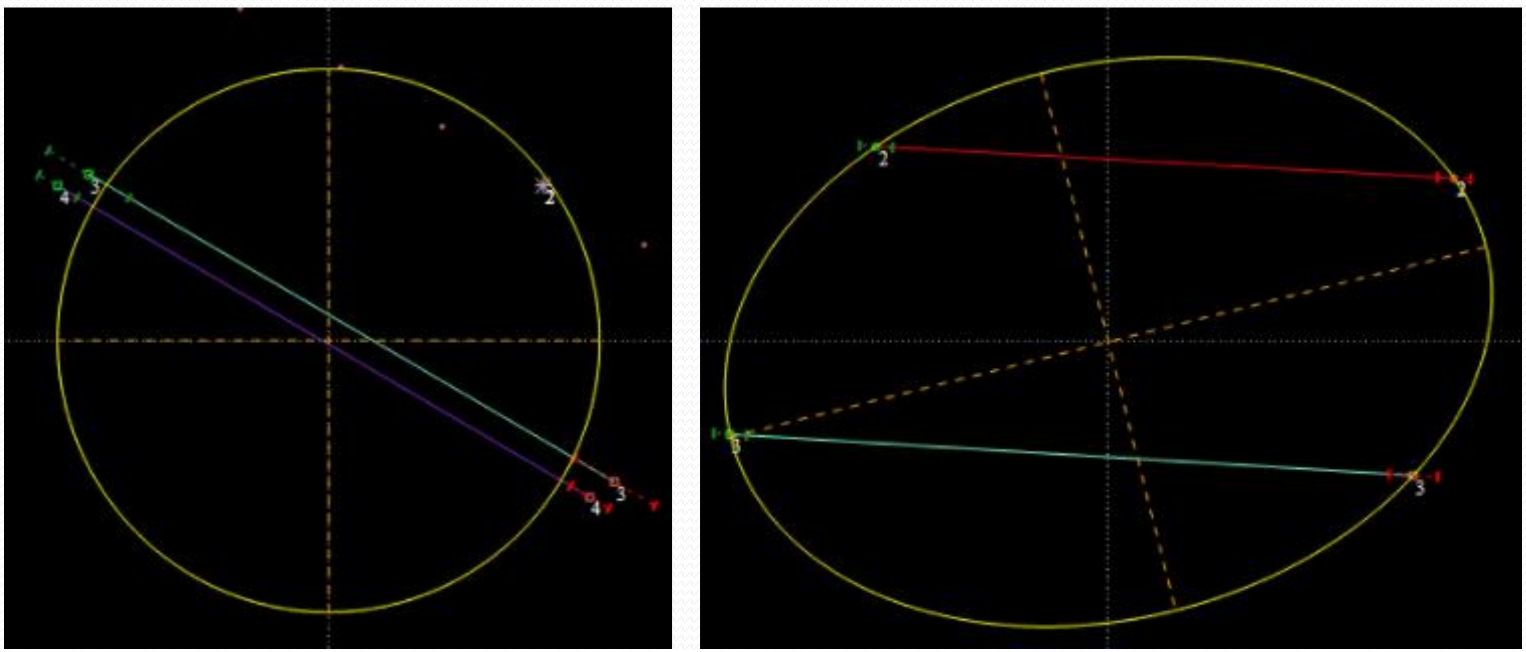
- Number of chords: single chords are less reliable than several chords for same event.



Across Track (AC) Uncertainty average as a function of number of chords.

Occultation Uncertainties (Herald et al., 2020)

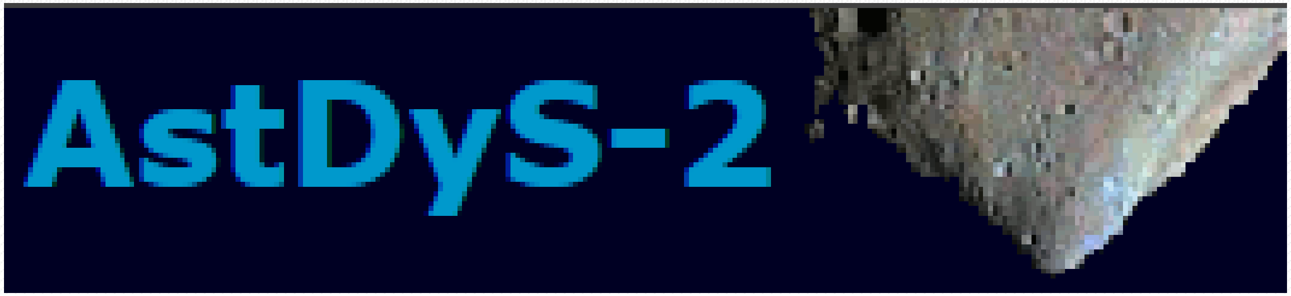
- Chord distribution across object's 2D projection: 2/3 chords that are almost superposed provide less coverage to object's shape than the same number chords in near opposite sides.



Despite the same number of chords, these events don't constrict the possible solutions in the same way.

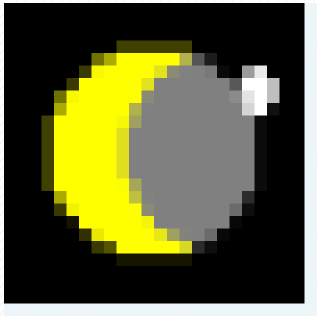
Software Used

- Tool used for orbital fitting: OrbFit, used by MPC;
- Initial parameters for orbital parameters: AstDyS-2.



Occultation Data

- Available in MPC format, but not very detailed;
- Provided by Dave Herald in ".psv" format, with more precise date, position, and with uncertainties provided;
- Complementary information, like number of chords, extracted from Occult's "Derived Asteroid Positions" archive and "Asteroid~Observations.xml".



Other Asteroid Data

- Gaia observations extracted from Gaia's DR2 "Solar System Observations" archive for all Gaia targets that have been observed through occultations (".gaia" format);

- Radar observations extracted from NASA's JPL website (".rad" format);

- Other sources extracted from MPC's database (".obs" format).

A History of Occultations vs Other Methods

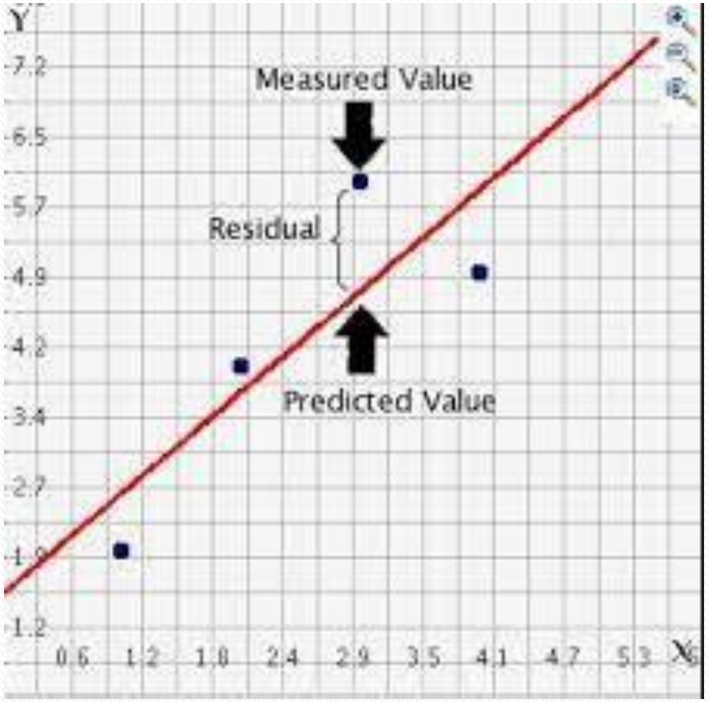
- What happens when you fit an asteroid's orbit using all of its observations (hundreds/thousands)? And what happens when you use occultations only (a few, most is 26)? Can the orbital quality be similar?

- The goal of this analysis is NOT to say "occultations > everything else". Rather, it is to strengthen the point that occultations are reliable and that, along with Gaia, can provide a catalogue of highly accurate observations that massively improves the knowledge of asteroid orbits with a long term focus;

- What happens if we use different catalogues for the stellar positions of each occultation event?

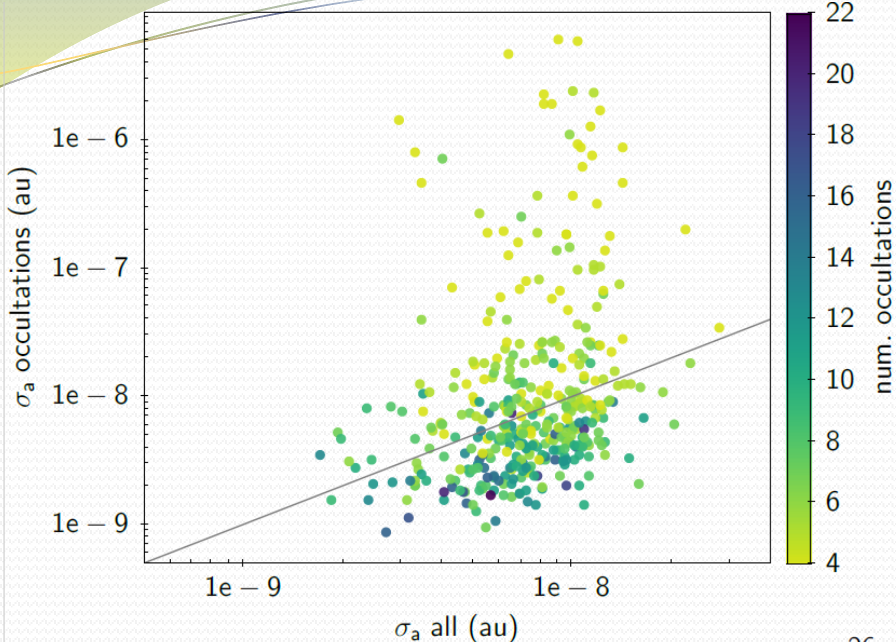
How to measure the quality of occultations?

- Two methods adopted:
  - Comparing the uncertainty on the orbit's semi-major axis (σ_a), vital for the uncertainties in occultation event predictions;
  - Checking the post-fit residuals for each occultation.

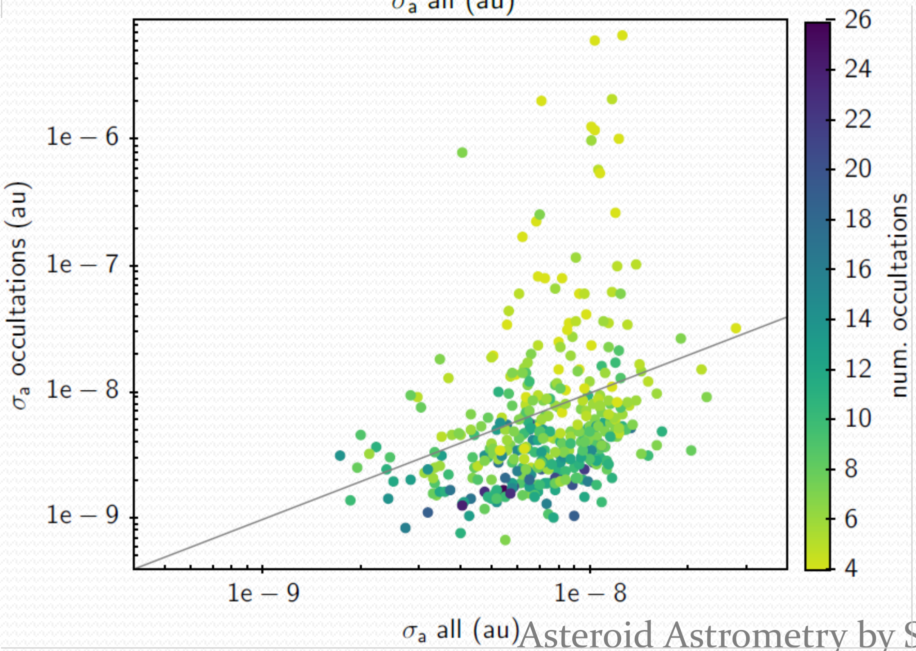


A residual is how far a measured value is from its expected value according to the fit.

Our work: DR2 vs EDR3

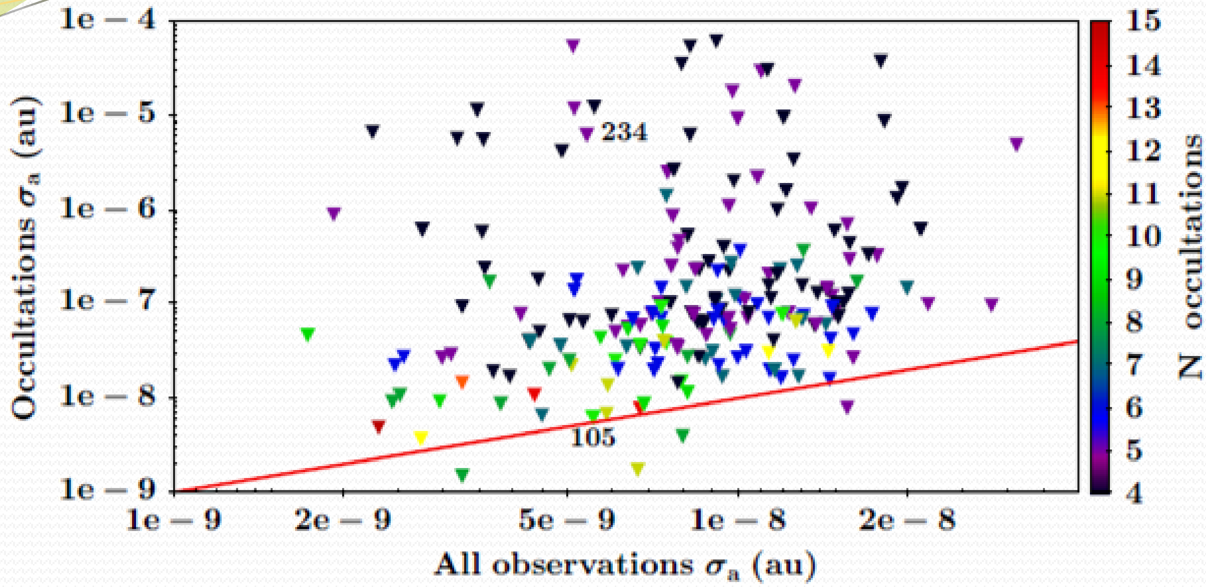


Our analysis, with DR2.
A minimum number of 4 occultation events was used to make an orbital fit.
Almost half of the objects have a smaller computed semi-major axis uncertainty with just occultations than with all methods.

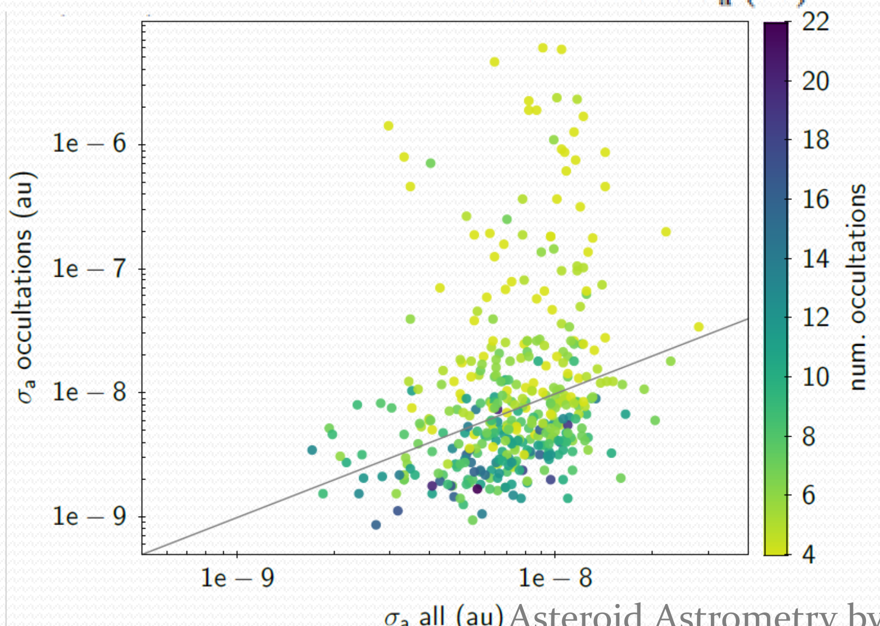


Our analysis, with EDR3.
Smaller increment compared to DR1 vs DR2, but now over half of the sample is better determined with only occultations!

Prior Work vs Ours: DR1 vs DR2

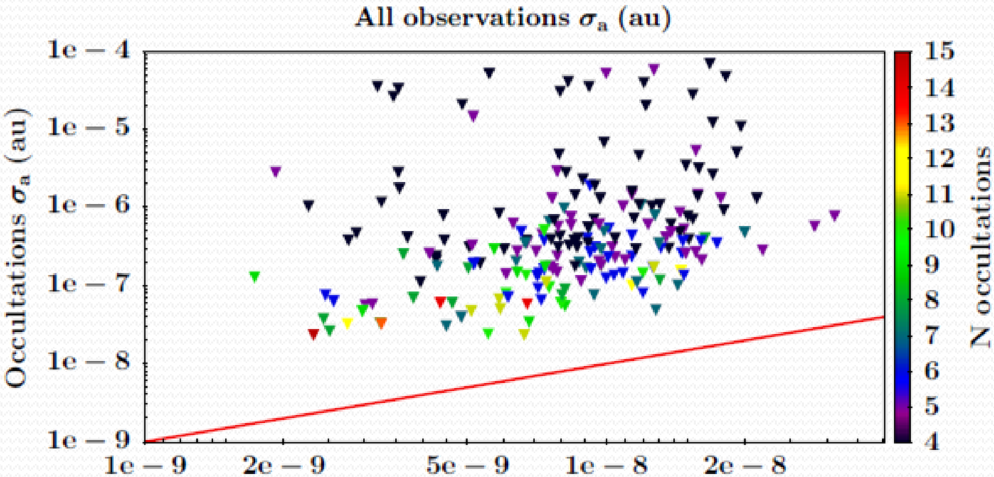


Spoto et al. (2017), with the same procedure, but Gaia DR1 for occulted stars.
Only 4 events better with only occultations, but many are already comparable.

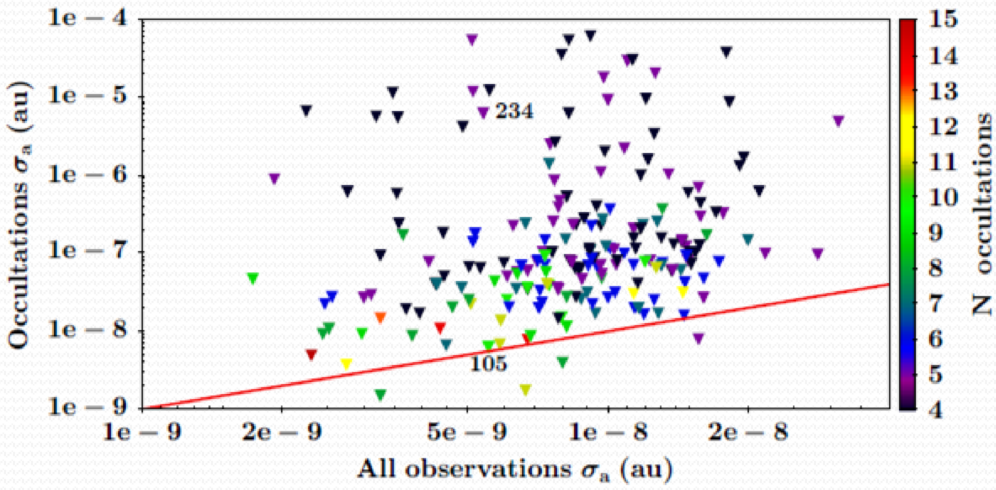


Our analysis, with DR2 for occulted stars.
Occultations now better in almost half of the cases! DR2 made occultations far more reliable, thanks to the proper motion accuracy, which helps with positional propagation.

Previous works: Pre-Gaia vs DR1



Spoto et al. (2017), using pre-Gaia data for stars in occultation events.
Occultations not yet at level of other observations (but close in select few cases).



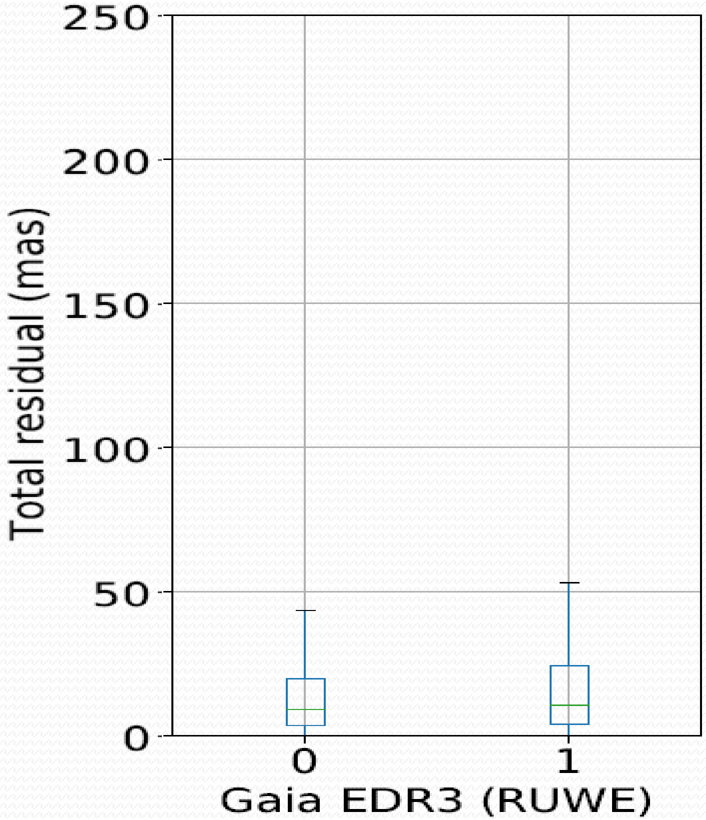
Spoto et al. (2017), DR1.

Can occultations be as precise as Gaia?

- Orbit quality isn't the only factor that can be used to analyse whether occultations provide solid data. Their residuals upon making an orbital fit also give insight to what influences results the most;

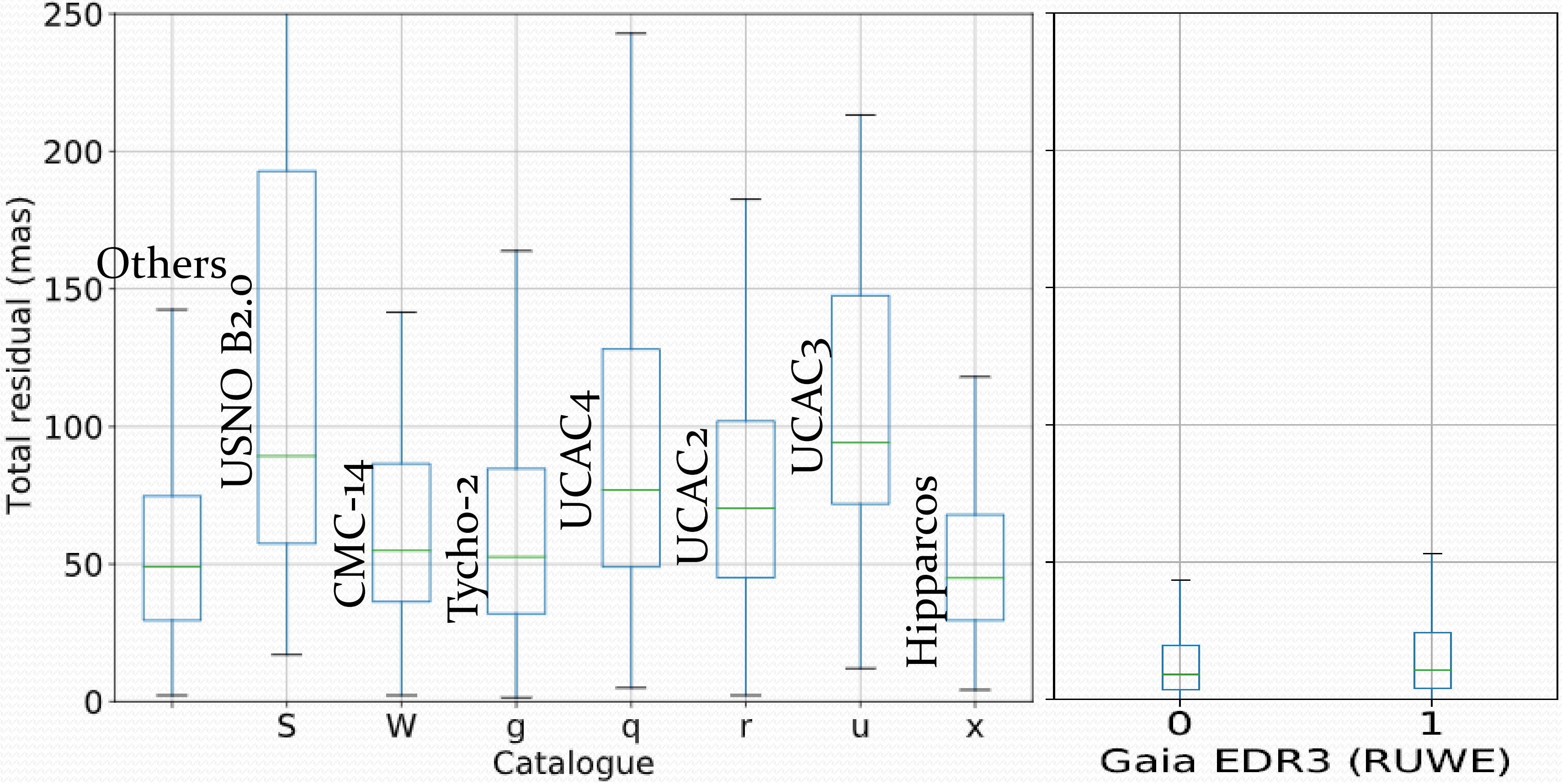
- Analysis was made to:
  - Number of chords for event;
  - Gaia's RUWE value for star (indicating quality of data in DR2/EDR3);
  - Year of observation;
  - Gaia's EDR3 vs Other Catalogues.

RUWE has small effect

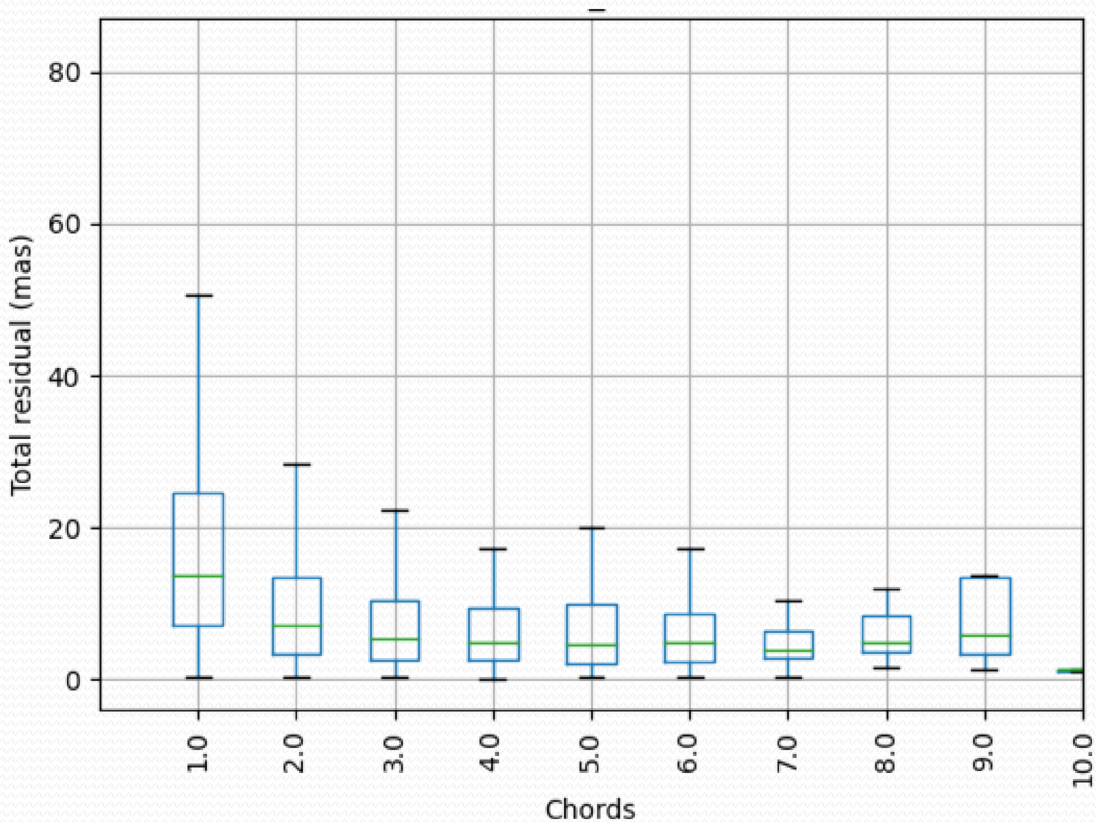


RUWE: Renormalized Unit Weight Error. Recommended to be below 1.4 (0) by the Gaia team. If RUWE > 1.4 (1), then Astrometric data might not be reliable.

Gaia is much safer than other sources

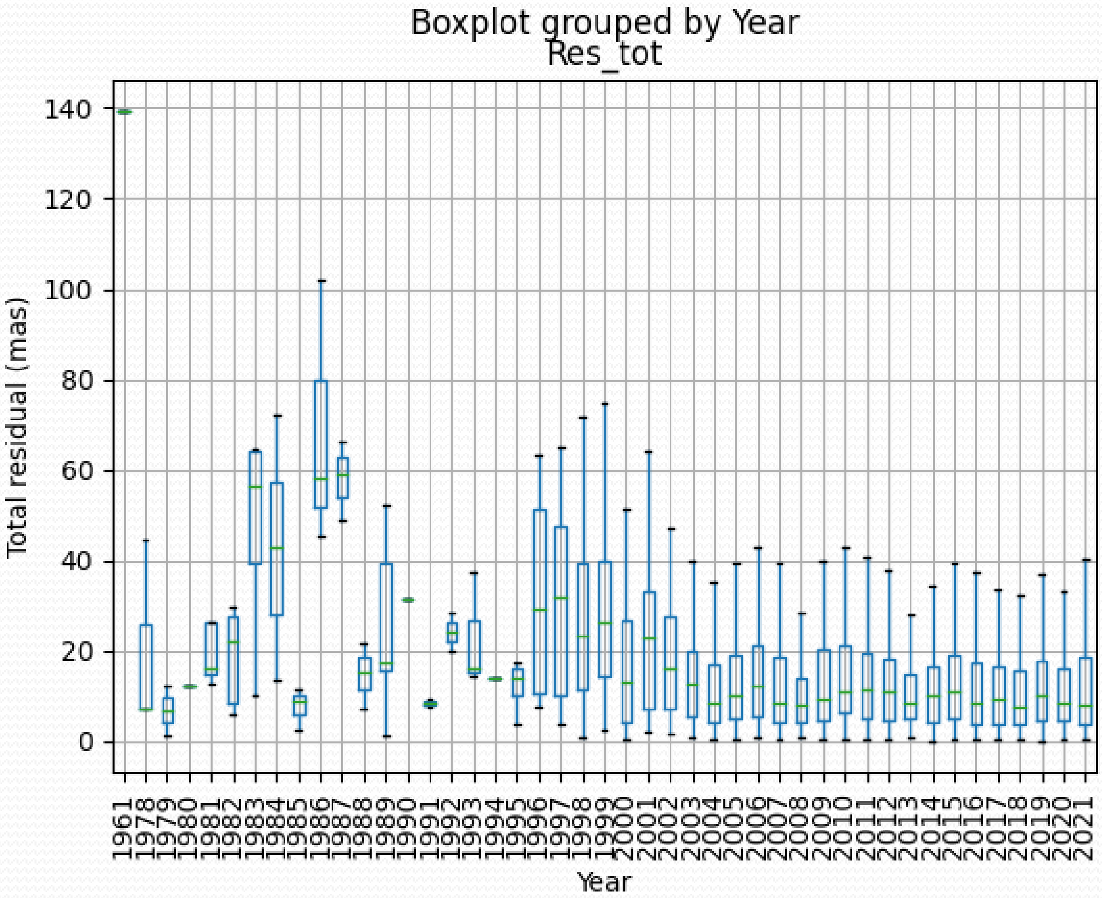


Chords have a BIG effect



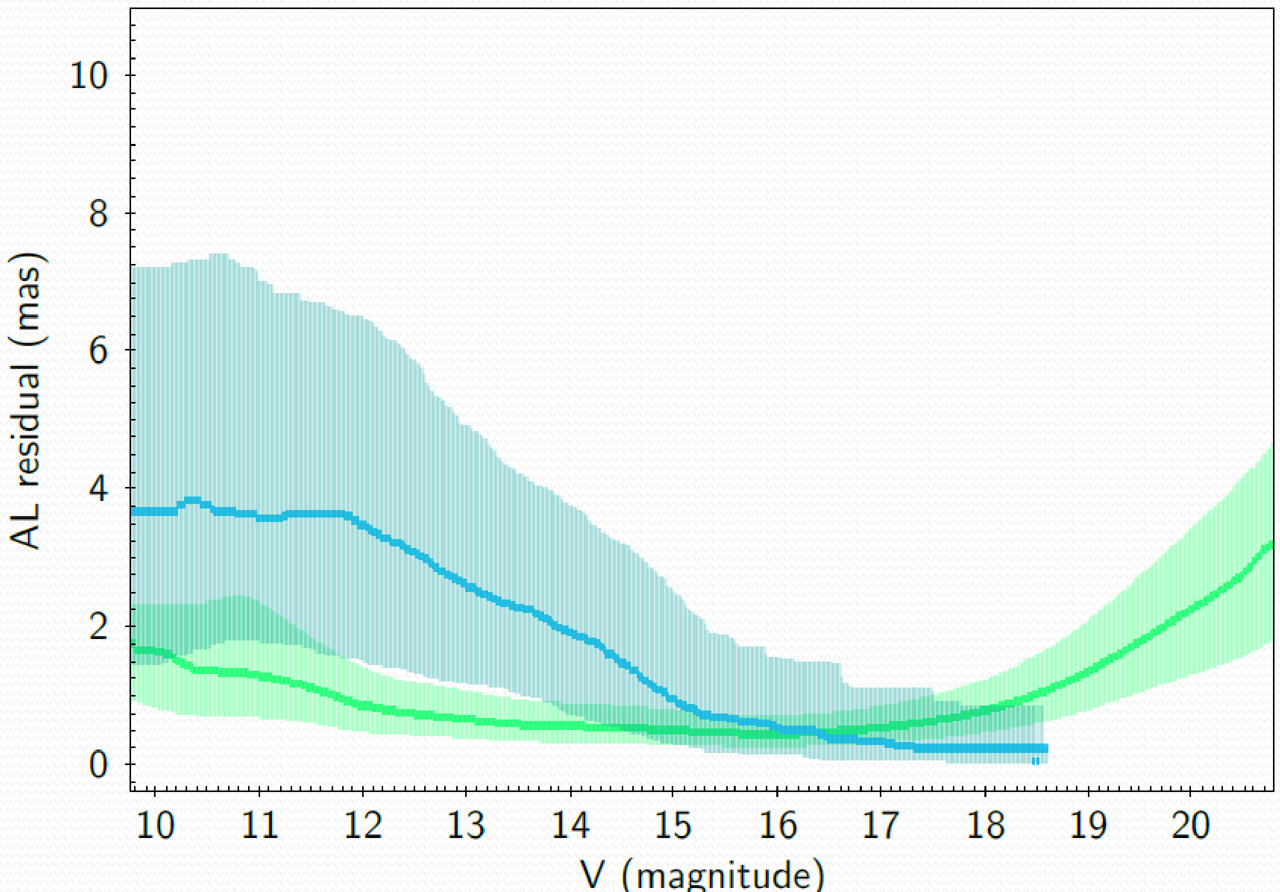
It pays off to make campaign for interesting objects!

Stabilization of residuals in the last decades



Methods of observation have stabilised, meaning the year of observation only has big impact for older data.

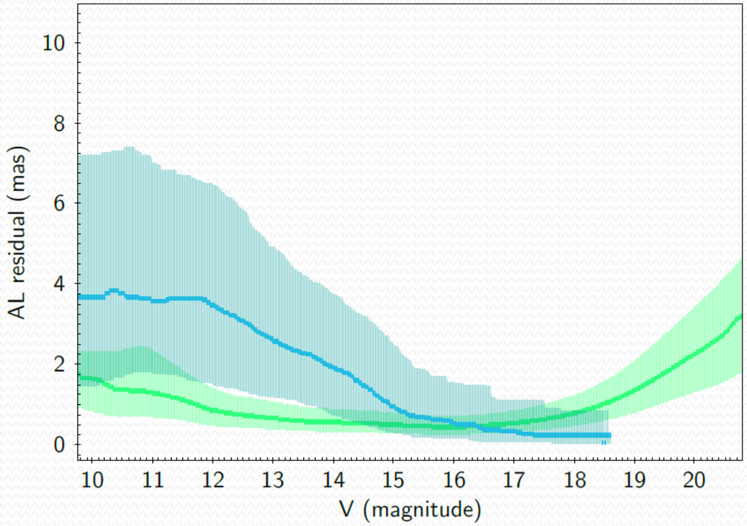
Can occultations be as precise as Gaia?



Gaia data (green) deteriorates with Asteroid Magnitude. Occultation data (blue) improves with it. This was extracted from the "occultations only" fits.

Occultations, then, provide a good complement to Gaia, even beyond its mission end.

WHY can occultations be better than Gaia?



- Occultations can have uncertainties as good as stars used for events;
- The measurements for these stars are averaged over many observations;
- Asteroids, on the other hand, have fewer observations to draw results from;
- Slight increase for low magnitudes happens due to the non-point shape of the asteroid, something which Gaia doesn't handle as well.

How do residuals behave?

- Orbit quality isn't the only factor that can be used to analyse whether occultations provide solid data. Their residuals upon making an orbital fit also give insight to what influences results the most;

- Analysis was made to:
  - Number of chords for event;
  - Gaia's RUWE value for star (indicating quality of data in DR2/EDR3);
  - Year of observation;
  - Gaia's EDR3 vs Other Catalogues.

Conclusions

- Gaia has brought a new level of reliability to occultations, including older ones with the star's Gaia solution propagated;
- Gaia and occultations complement each other well in terms of magnitude ranges for the objects, and occultations can provide Gaia-level measurements beyond the mission's end;
- Focus on interesting objects (NEA, TNO) can bring increased knowledge on those groups at a quicker pace than other methods;
- Results from this work written into paper, which is currently under revisions.

Watch out for Gaia's full DR3!

Third release: Gaia EDR3 and Gaia DR3

The third release is composed of Gaia Early Data Release 3 (Gaia EDR3), released in 2020 and the full Gaia Data Release 3 (Gaia DR3), expected in 2022.

Gaia EDR3: 3 December 2020

Gaia EDR3 contents

Gaia EDR3 overview page

Gaia DR3: expected first half 2022

The full **Gaia DR3** catalogue will be consisting of:

- Gaia EDR3 contents (see above)
- Object classification and astrophysical parameters, together with BP/RP spectra and/or RVS spectra they are based on, for spectroscopically and (spectro-)photometrically well-behaved objects.
- Mean radial velocities for stars with available atmospheric-parameter estimates.
- Variable-star classifications together with the epoch photometry used for the stars.
- Solar-system results with preliminary orbital solutions and individual epoch observations.
- Non-single stars.
- Quasars and Extended Objects results
- An additional data set, called the Gaia Andromeda Photometric Survey (GAPS), consisting of the photometric time series for *all* sources located in a 5.5 degree radius field centred on the Andromeda galaxy.

- Expected in first half of next year;
- The "DR2" of asteroids in terms of improvement.

Watch out for Gaia’s full DR3!

- Will contain massive upgrade of asteroid data, from ~14 000 to ~150 000 objects, and with a span of 34 months instead of 22;

- Major impact to knowledge on asteroid orbits, and thus to occultation prediction and target strategies;

- Further Data Releases will build upon this data, ending with 10 years of observations to ~350 000 asteroids. DR4 and beyond don’t yet have planned release dates.

Thank you!