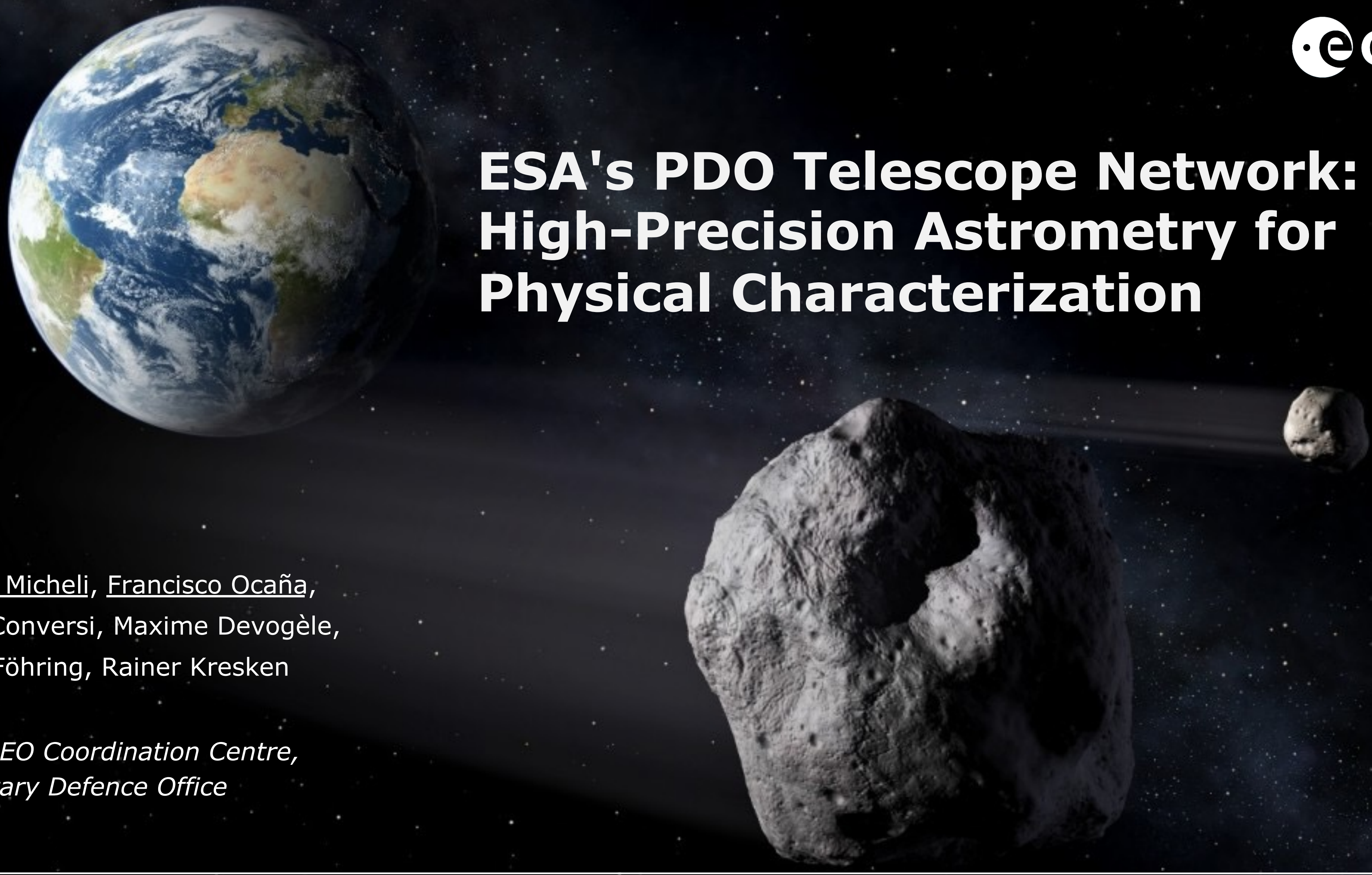

ESA's PDO Telescope Network: High-Precision Astrometry for Physical Characterization

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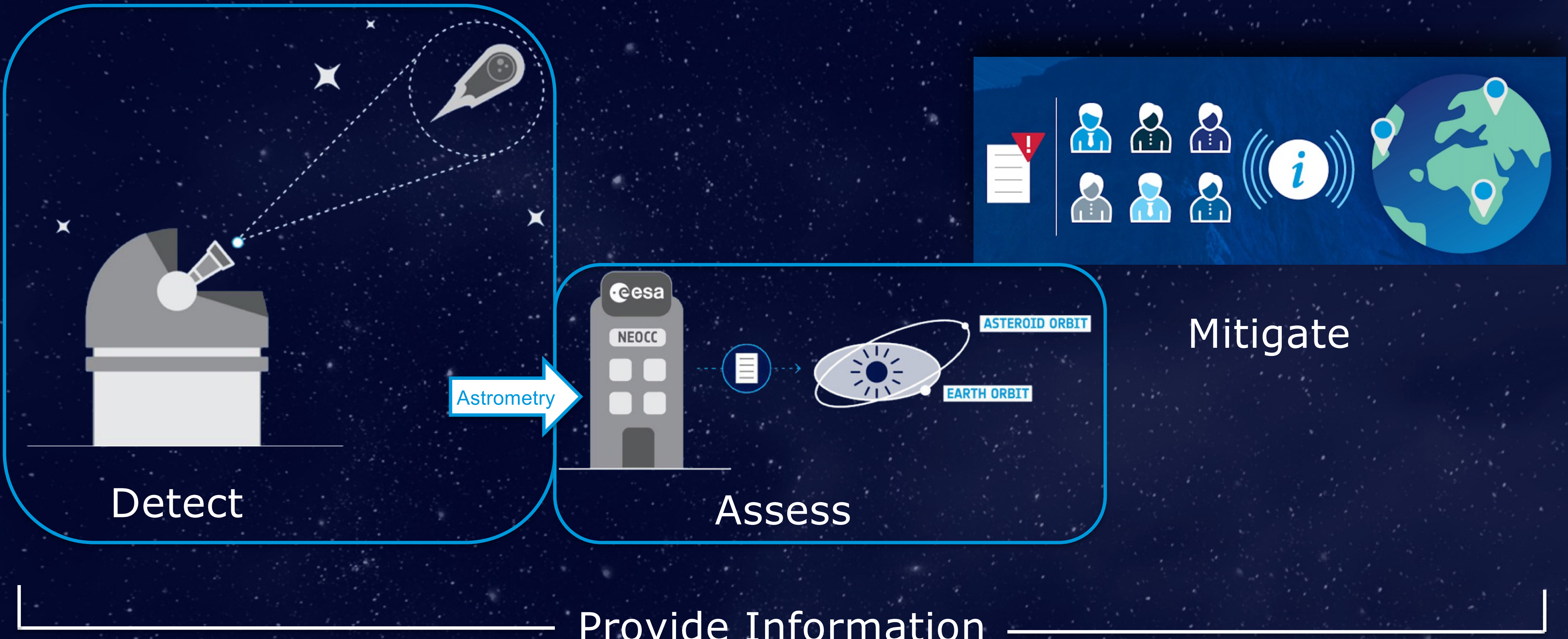
ESA NEO Coordination Centre,
Planetary Defence Office

→ THE EUROPEAN SPACE AGENCY

The Three Pillars Of ESA Planetary Defence



A wide telescope network

Dedicated survey telescopes typically don’t provide follow-up (unless incidentally).

Other telescopes must react and get additional data. Quickly, often in < 24 h.

It is therefore essential to use small telescopes all over the world.

We often prioritize sp and procedures!

Speed challenges

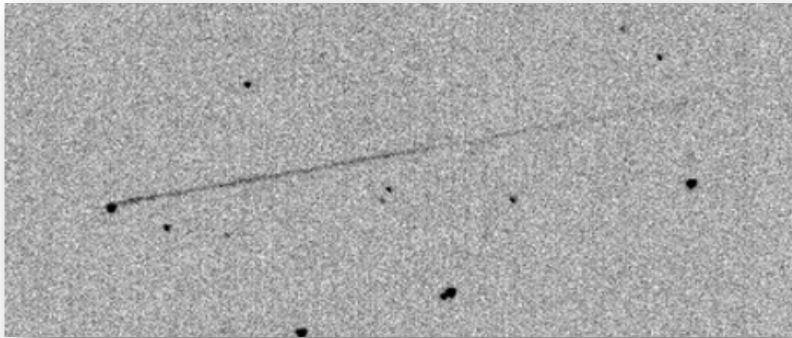
NEO follow-up observations are often fast.

We need to react fast:

ESA PDO

- We often need to react within minutes.
- With whatever instrument is available.
- The data is analyzed within minutes too.

The objects themselves are fast:



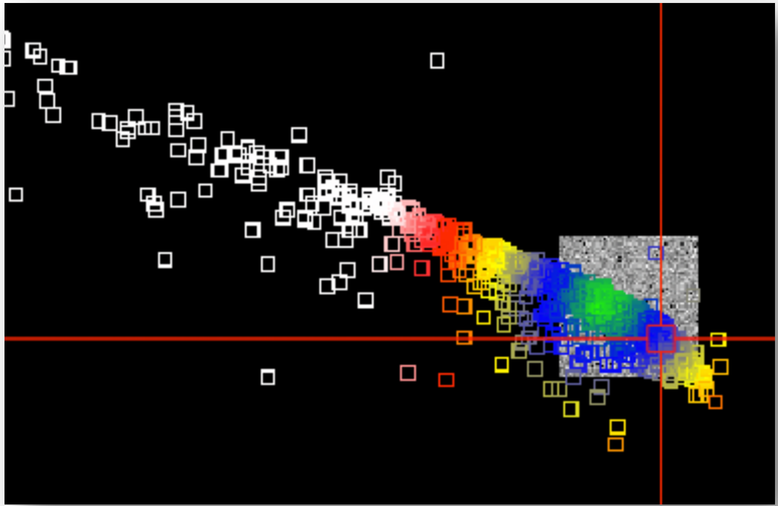
L. Buzzi, G. V. Schiaparelli Observatory

- Sky motions up to degrees per minute.
- We need to time them to <0.1 s.
- Intrinsically challenging conditions.

Localization challenges

Finding the object itself can be challenging.

The ephemeris is often poorly known:



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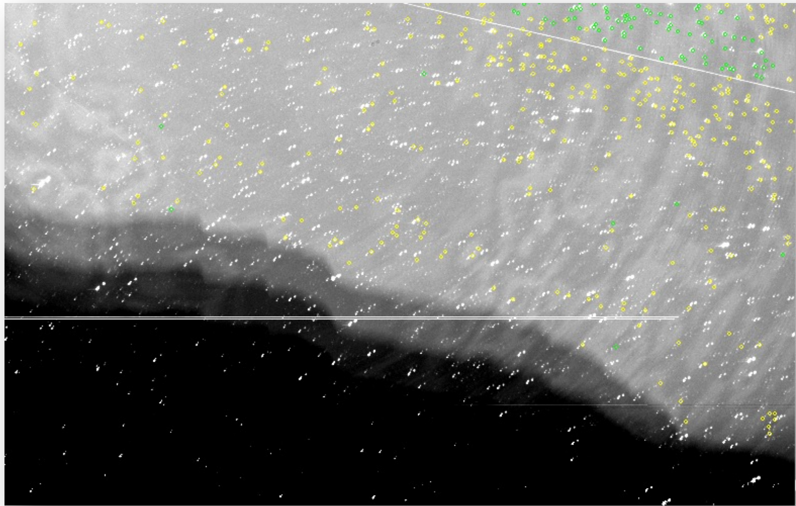
- The uncertainty can grow fast.
- The object may not even be in the FoV.

The location can be intrinsically challenging:



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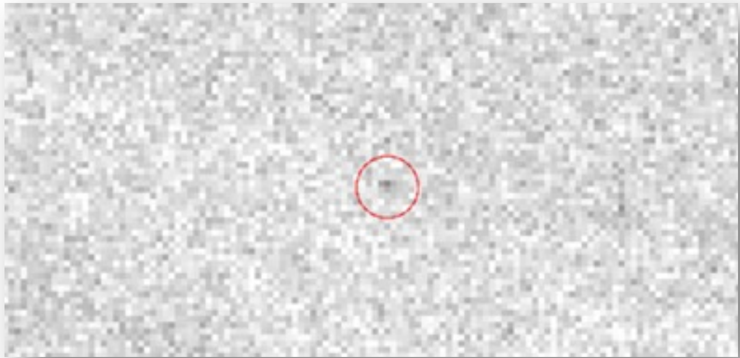
- We often observe at very low altitude.
- We may need to observe in full moon.

Signal challenges

On the other hand, we just need to see the object, we don't need to see it well.

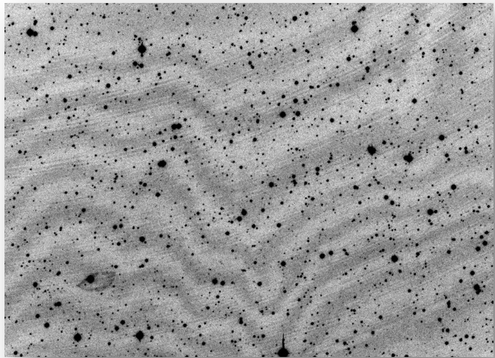
We optimize our exposures for SNR~3 to 7:



O. Hainaut / ESO / ESA PDO

- The goal is to locate the object within a much larger astrometric uncertainty.
- A SNR~3 detection may be sufficient to improve an orbit by orders of magnitude.

We almost always observe unfiltered:



Calar Alto Observatory / ESA PDO

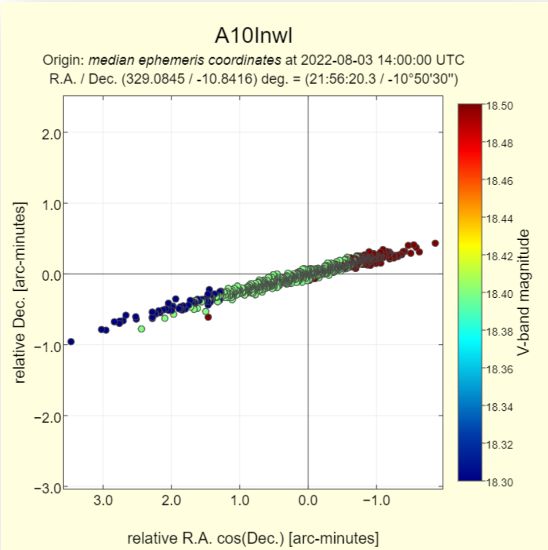
- Unfiltered imaging allows us to reduce the exposure time to get the object.
- In turn, we can do more objects and improve more orbits (our final goal).

A few reasons why astrometry is important

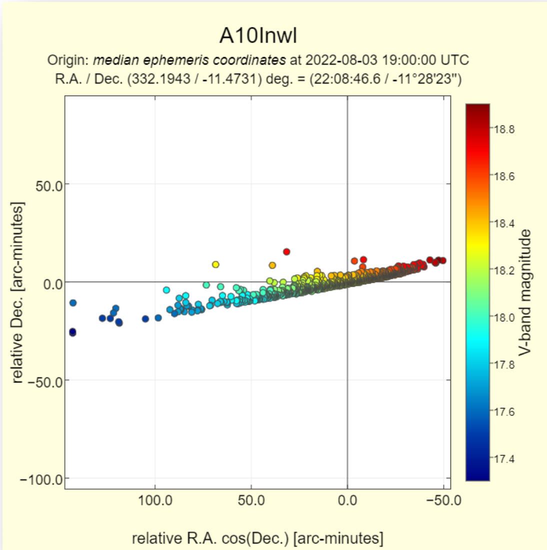
1. It enables the discovery and follow-up of a new object. Without proper astrometry, most small bodies will be lost within hours or days after their discovery.

An example: <u>how the uncertainty grows after discovery</u>

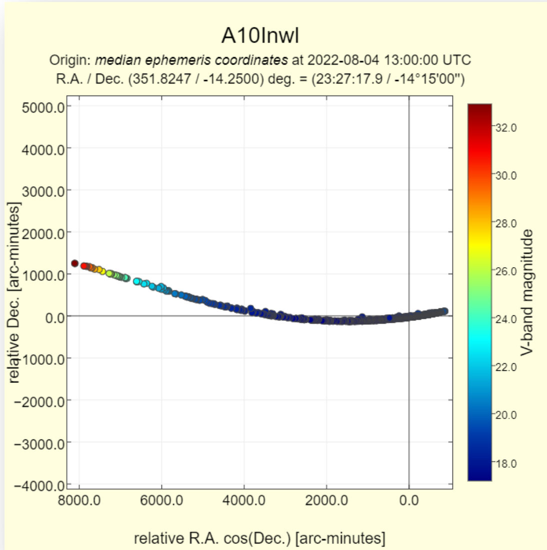
1 hour



6 hours



24 hours



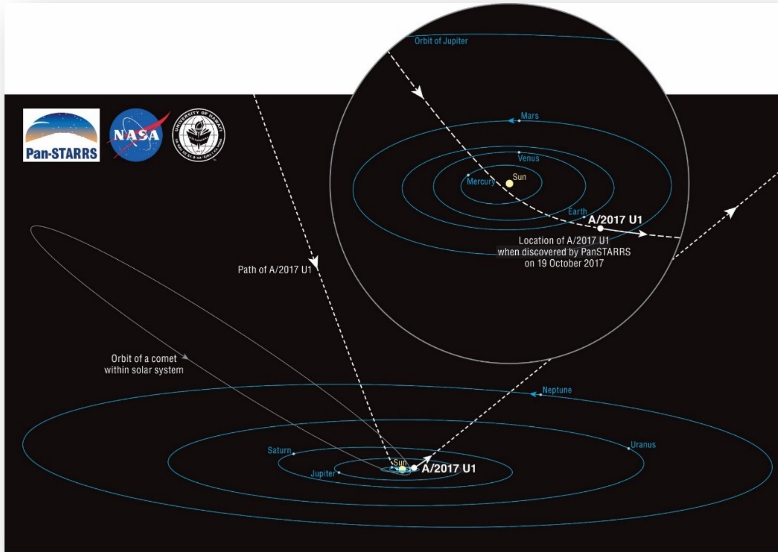
JPL Scout

A few reasons why astrometry is important

2. It allows us to determine the object’s orbit, and its peculiarities, separating peculiar or unique targets from routine objects, and studying their dynamics.

An example: <u>the discovery of 1I/‘Oumuamua</u>

```
 Perihelion 2017 Sep 9.660726 +/- 0.546 TT = 15:51:26 (JD 2458006.160726)
Epoch 2017 Sep  9.0 TT = JDT 2458005.5   Earth MOID: 0.1004   Me: 0.0269
q   0.26321883 +/- 0.0249           Ma: 0.0592                Micheli
H   22.1  G 0.15                    Peri.  243.12644 +/- 4.2
                                    Node    24.56580 +/- 0.10
e   1.2211552 +/- 0.0745            Incl.  123.41875 +/- 2.0
14 observations 2017 Oct. 18-19 (35.3 hr); mean residual 0".42
```



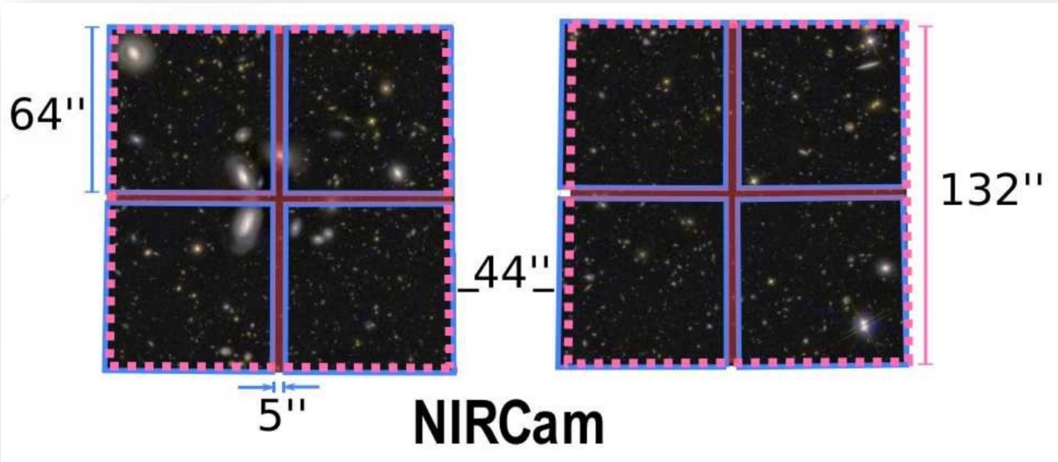
UH / IfA

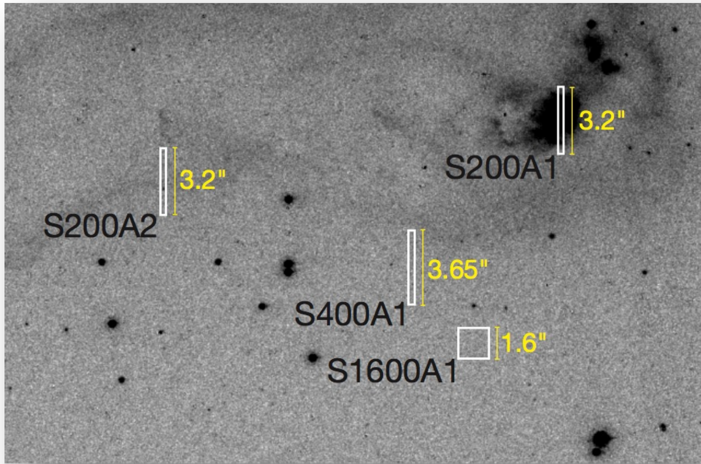
The first interstellar object was found by an NEO survey (Pan-STARRS), and immediately assumed to be a normal Solar System object. Only accurate and rapid astrometry allowed for a quick determination of its unique nature.

A few reasons why astrometry is important

3. It allows the determination of a precise ephemeris for each object, which in turns allows the use of other techniques.

An example: spectroscopy slits, AO instruments, sub-mm or space-based telescopes



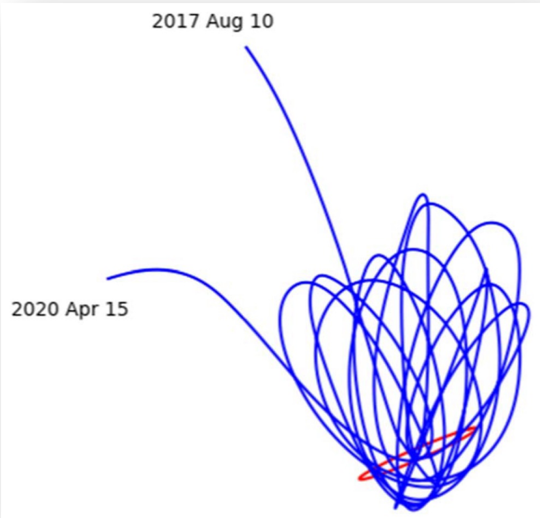


JWST/ STScI

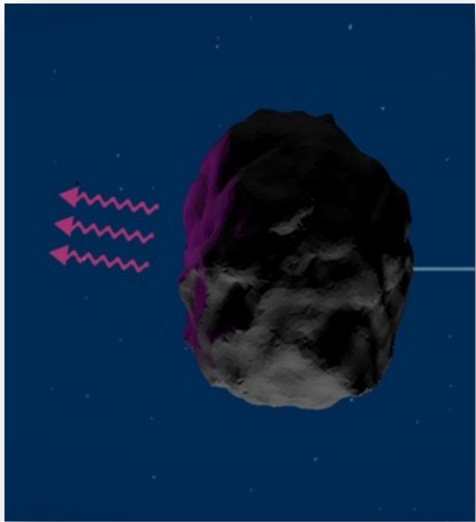
A few reasons why astrometry is important

4. When a long observed arc is available, it directly enables scientific measurements that provide physical information on the object itself.

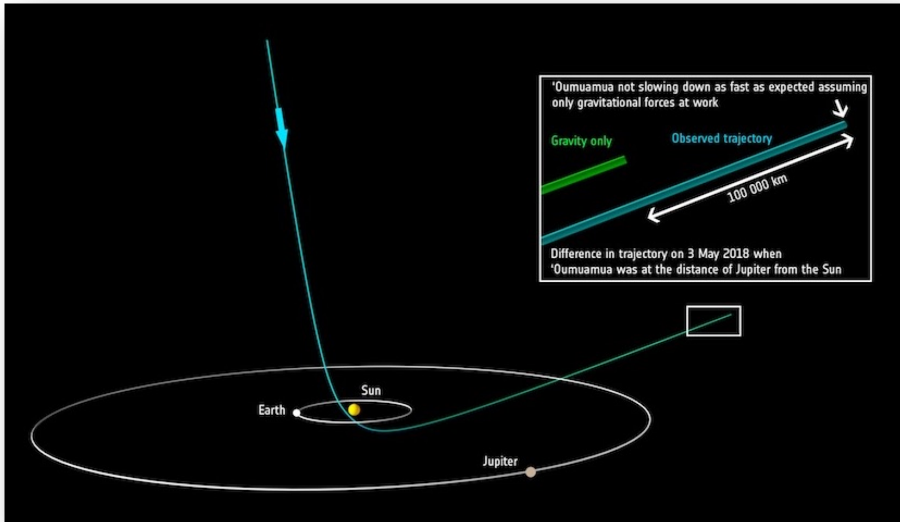
An example: <u>non-gravitational forces (solar radiation pressure, Yarkovsky, outgassing)</u>



S. P. Naidu et al.



NASA / GSFC

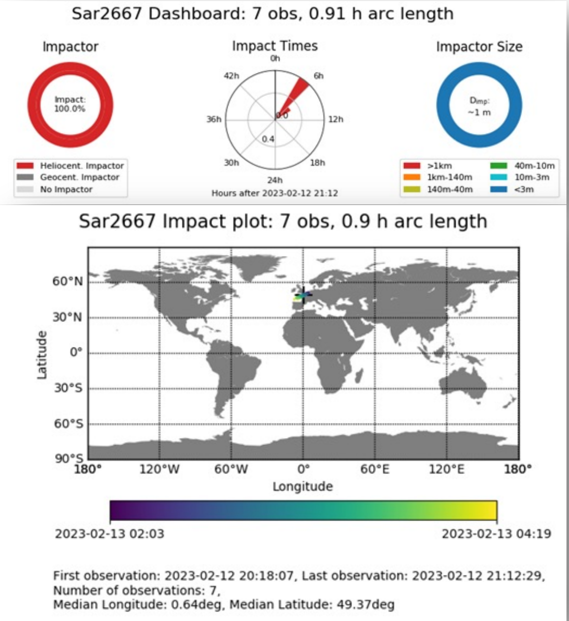


ESA

A few reasons why astrometry is important

5. For near-Earth asteroids, it provides the starting point for planetary defense activities, and enables the prediction of fireballs and the recovery of fresh asteroidal samples.

An example: impact alerts



ESA PDO

Gijs de Reijke

FRIPON / Vigie-Ciel

Astrometry for Planetary Defense

The examples above show that the way astrometrists choose and observe asteroids may look unusual to asteroid scientists with other goals.

- Currently, the average NEO discovery magnitude is 21-22, and 80% of the discovered NEOs have H>23.

- NEOs of our interest are rarely brighter than magnitude 15 (maybe impactors, or nearby close-approachers). Otherwise, most of our targets are observed in range of magnitude 20 to 24.

- Some high-profile targets are observed down to magnitude ~27 (VLT, space).

Astrometry for Planetary Defense (2)

- Our targets move fast, usually 1 to 10 "/min, and sometimes up to >200"/s. We require high timing accuracy, we are usually able to determine (and correct for) time biases down to ~30 ms.

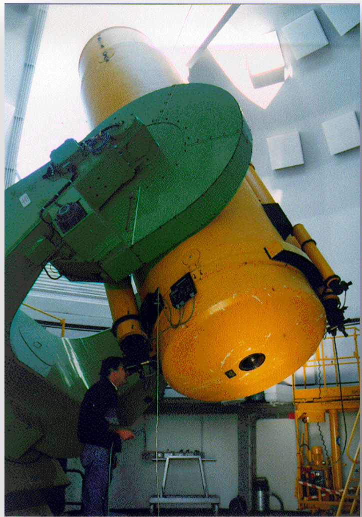
- Astrometric accuracy does not require excessive sampling (FWHM ~ 2 pixel). Our images may sometimes appear undersampled for other science cases.

- Default astrometric errors are often assumed to be ±0.5", but in reality, they can cover a wide range (from a few arcsec to tens of mas).

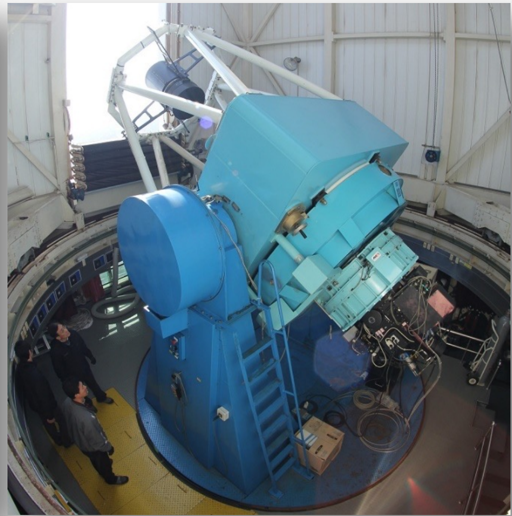
Typical assets for astrometric follow-up

There are 4 major classes of telescope “players” in the field of asteroid astrometry:

Pan-STARRS



Calar Alto Observatory



KASI

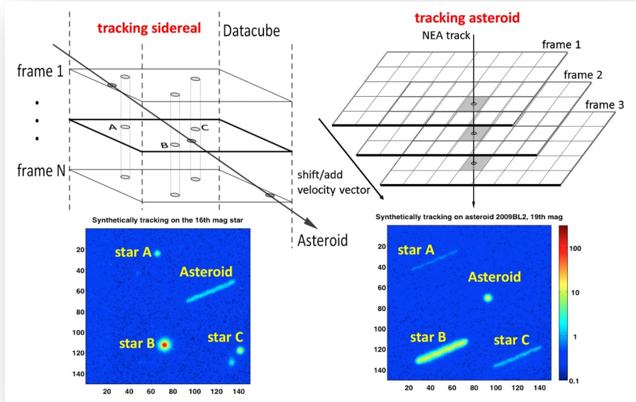
ESO / G. Hüdepohl

Surveys	Immediate follow-up	Extended follow-up	Deep follow-up
0.5 m – 2 m	< 1 m	1 m – 4 m	4 m – 10 m (+ Space)
Realtime	<1 day	~days to weeks	~months to years

Apertures and timescales: (the aperture and timescale rows of the table above)

Stacking & Synthetic tracking

We need long exposure times for the fainter targets. We stack several images to achieve the required SNR, while avoiding trailing losses.

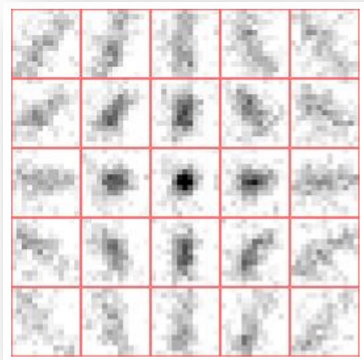


C. Zhai, M. Shao et al.

With synthetic tracking, the same telescope takes dozens of consecutive images.

The object is NOT visible in individual frames, but only after stacking them.

Since the motion can be unknown, a large number of stacking rates must be tested, until a point-like source appears.



D. Parrott

CMOSs help us reduce image-download overheads, which sometimes represent >50% of the total time for fast objects.

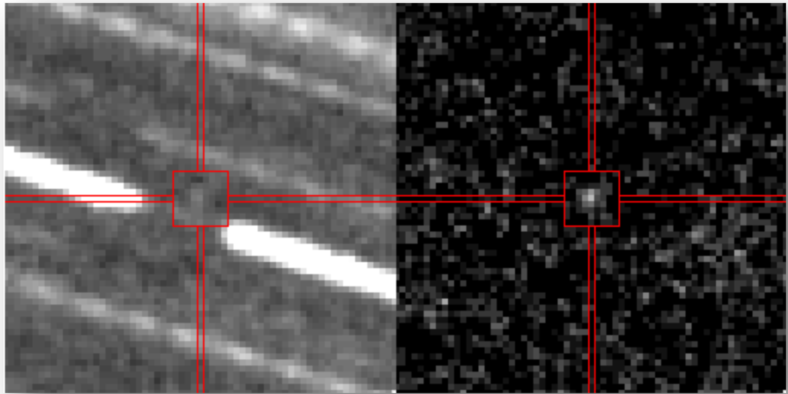
Even small telescopes can go very faint…

Astrometry can be done at very low SNR levels.

Even small telescopes can get useful observations of very faint targets.

An example: a magnitude >24 object with an 80 cm telescope

- Using an 80 cm telescope
- We could detect a V~24.2 asteroid.
- Obtained with 5 hours of exposure time.
- Stacking at variable rates is needed.



Calar Alto Observatory / ESA PDO

These detection strategies are often incompatible with good photometric measurements.

Our typical dataset

Thus, astrometric datasets are often challenging to use for characterization purposes.

- A few tens of images per target (usually >10 and <250).
- Large size (> 2k × 2k) and large FoV (usually ~10' to ~150').
- Images are aggressively binned (sampling ratio FWHM ~ 2 pixel).
- No calibration frames (we may self-flatten the images, no biases).
- Target is not always in the center and is usually invisible in individual exposures, often barely detectable when images are stacked. We sometimes obtain trailed detections.
- Twilight observations, or very high airmasses, are common.

Our archive (>1M images @ https://neo.ssa.esa.int/image-database) - searchable with SSOIS (CADC)

Conclusions / Open discussion topics

- Data for astrometry is often unfiltered, with low SNR and beyond all photometric requirements (high airmass, bad transparency...)
- However, one can assess the quality of the photometry of these measurements and correct the biases (talks by P. Vereš, T. Hoffmann and M. Fenucci in the next session).

AND

- Images taken for characterisation are also useful for astrometric purposes. Check if the object is in the expected coordinates, if not there, measure it properly (submit in ADES format, report uncertainties!). OR send us your images.
- On-going discussion on how to report photometry in ADES format.

neocc@esa.int