Executive summary: occultation astrometry for NEA study and risk mitigation

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1. Introduction

This project, renamed ACROSS (Asteroid Collaborative Research by Occultation Systematic Survey), aimed at considerably improving the predictability of stellar occultations by small and difficult targets such as the Near Earth Asteroids (NEAs).

In particular, it focused on the binary asteroid 65803 Didymos, target of the DART (NASA) and Hera (ESA) missions, and other NEAs: either secondary targets of Hera, or NEAs whose orbit is accurate enough.

Stellar occultations are an unbeatable approach to:

- Obtain new measurements with extremely high astrometric accuracy. As at the epoch of the occultation the position of the asteroid coincides with the star, if the star position is known precisely, the same precision can be obtained on the asteroid.
- Get high resolution information on the shape and size of the targeted asteroids, by combining observations of a same event obtained by multiple sites.

The observation consists in measuring the exact timing of the star disappearance, which lasts for ~seconds for a Main Belt asteroid, or fractions of it for a NEA. As only the star must be visible in telescopes, and it can be much brighter than the asteroid, small instruments can be used, at the reach of most amateur astronomers.

Stellar occultations, for this reason, offer a citizen science opportunity of outstanding impact.

2. Challenges

Occultations presents specific challenges:

- The prediction of the event consists in an Earth map of the “occultation path”, the strip of Earth surface swept by the star shadow while the asteroid is moving, where the observers should place their telescopes. The ultra-accurate Gaia astrometry has strongly improved the accuracy of predictions, pushing the limits of predictability into the domain of small asteroids such as NEAs.
- The smallest is the occulting asteroid, the narrower the occultation path. For a star overhead at zenith, the path width equals exactly the asteroid diameter (a projection factor enlarges it when the star is at lower elevations). The narrower the path, the more precise predictions need to be. An appropriate indicator of the prediction accuracy is the ratio between the width of the uncertainty at 1-sigma, and the width of the nominal path. Prediction challenge is maximum for NEAs, the smallest targets.
- For the same reasons, at the level of objects smaller than ~1 km, the Earth topography must be considered, as the projected path is affected.
- The faster is the motion of the asteroid, the sorter the duration of the occultation event. For NEAs, that are relatively close to Earth, this can be 0.1-0.2 s or less. The consequence is that one cannot use too small telescopes, as fast acquisition times are required.

- Very accurate timing is the clue for success. Nowadays, appropriate cameras and devices based on the PPS (pulse per second) signal of GPSs, allow to reach absolute accuracies at better than 1 ms.

At the beginning of the ACROSS project, 65803 Didymos and nearly all the other targets had an ephemeris accuracy that strongly exceeded their size. This lack of accuracy made the prediction an academic exercise without serious possibility of success by the observations.

3. Methods

ACOSS has put in place the following actions:

- A thorough exploration of the performance of software tools needed to reach the required accuracy, in particular:
    - Astrometric reduction of CCD images, with verification of the role of differential refraction
    - Orbit computation: an enormous amount of test required, to verify, in particular, the role of different weighting schemes and to look for subtle biases hidden in the measurement.
    - Occultation prediction: verification of the role of orbit propagation and comparison between different tools (Occult 4, SORA) not providing equivalent results.
- A campaign of dedicated astrometric measurements to improve the orbits of our targets, with accurate reduction of the CCD images. Telescopes ranging from the 1 m. to the 8 m class (VLT) have been used.
- The promotion of the activity to the network of amateur and professional observers, by exploiting web platforms such as Occult Watcher Cloud.
- The organization of field campaigns with dedicated telescopes in the field.

4. Results

While we write this note, the dedicated campaigns have not yet successfully detected an occultation by Didymos. In order to cover the 1-sigma cross-track width, a minimum of 10 observing stations spaced by ~500 m (cross-track) is required, provided that no systematic errors remain uncorrected in the determination of the occultation path. Any failure of one or more of the observing stations translates into a strongly diminished probability of detection.

The lack of positive detections up to now, can be ascribed in part to bad weather conditions or technical problems, and in part to the remaining presence of systematic errors in the astrometry. The contribution of these errors has been understood thanks to the most recent measurement, by the end of the project.

We are thus confident that it is only matter of a short time, and an event by Didymos will be detected on the base of the most recent orbit obtained. In any case, it must be stressed that we are already exploiting *negative* detections, as they put strict constraints on places where the occultation path was *not* passing. This information is fundamental to in/validate certain orbit solutions.

Moreover, ACROSS was very successful in:

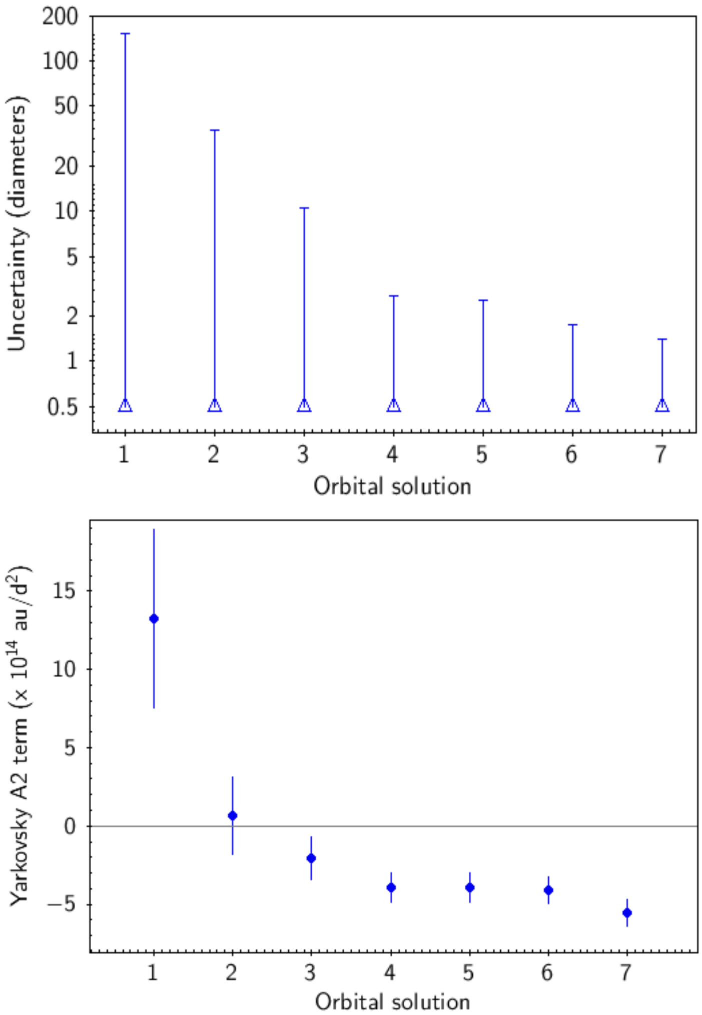

Fig. 1 - Improvement in the quality of the orbit of Dydimos by the ACROSS project. As a function of different orbital solution of increasing accuracy, the top panel shows the uncertainty on the position of Dydimos for current dates (expressed in diameters of Didymos, taken as 800 m). The bottom panel gives the value of the Yarkovsky acceleration and its error. Note the sign switch due to bad initial determinations, and the following convergence. Orbits 1 and 2 represent the situations before ACROSS (astrometric data from 1996 to 2015 and 2019 respectively. Numbers 3 to 5 add high quality data sets until 2021, July 2022, Sept. 2022. 6 and 7 are the same as 4 and 5 with different data weighting choices.

- Establishing a clear, appropriate methodology to exploit the suite of tools for astrometry reduction, orbit fitting, predictions, and diffusion of results.
- Setting up a durable link with the international community (amateur citizen scientists and professionals) by reaching many observers and creating a brand for our high challenging occultation campaigns.
- Effectively proving that the synergy of these actions brings difficult NEA occultations into the domain of detectable events.

The proof of this is provided by a measurable quantity: the improvement on the orbit uncertainty for Dydimos (Fig. 1) and all our selected targets, following the use of the new astrometry that we obtained, and the appropriate tools for its exploitation.

The positive detection of the occultation by the NEA 1994 AW1, is the most solid validation of the process (Fig. 2).
Also, the detection of the Yarkovsky (thermal) acceleration acting on Didymos is another indicator of the increased orbit accuracy (Fig. 1)

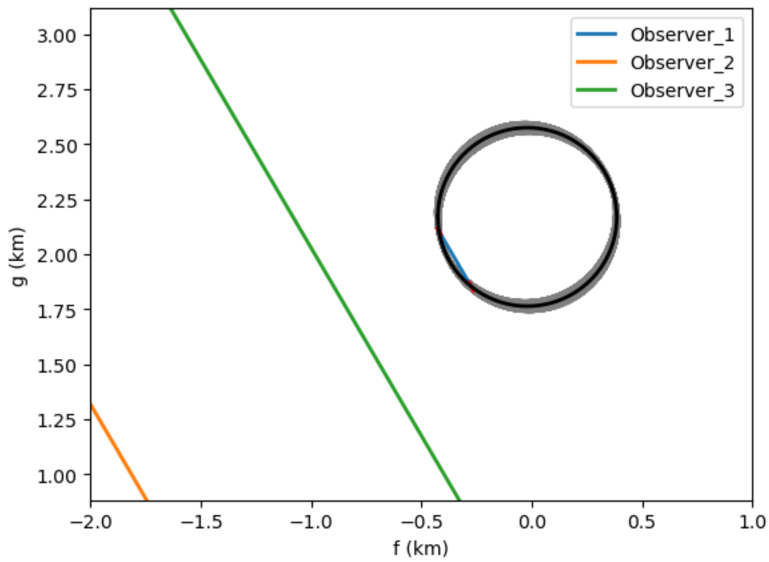

Fig. 2 – Astrometric reduction of the occultation by the NEA 1994 AW1. The plane of the plot is perpendicular to the line joining the center of the Earth to the asteroid. In this frame, the asteroid is not moving, and the the target star as seen by 3 different observers moves along the colored lines. One of the lines is shown as the short occultation chord in the circle that represents the asteroid. Its length and position are determined from the occultation timing. The asteroid diameter is very close to Didymos (811 m) and its silhouette is fitted to the occultation chord to obtain the accurate position of the center.

5. Conclusions and heritage of ACROSS

ACROSS has moved the limits usually accepted for stellar occultations and has proved that accuracies of 1-2 km (corresponding to Gaia-level epoch measurements) can be obtained on the final ephemeris of the most optimized NEA orbits. This is currently the limit that we think it is reasonable to assume for this challenge, implying that a correct deployment of observers can ensure occultation detection for objects in the range 0.3 to 1 km.

We will support and exploit the ACROSS brand, the tools and approaches implemented over the 12 months of support by ESA, to continue collecting the fruits of our efforts. ACROSS continues to actively collaborate with an international community of citizen scientists (Fig. 3), both within and beyond the European Union. We expect to detect positive occultations by 65803 Didymos soon and will continue to update its orbit when new measurements are available.

From the optical navigation data obtained by DART close to the impact, and radar observations immediately before, we have derived a very accurate orbital solution that can be used as a reference to detect the heliocentric deviation due to the impact in coming years.

A season of occultations by the secondary targets of Hera is also opening soon and provide many observation opportunities.

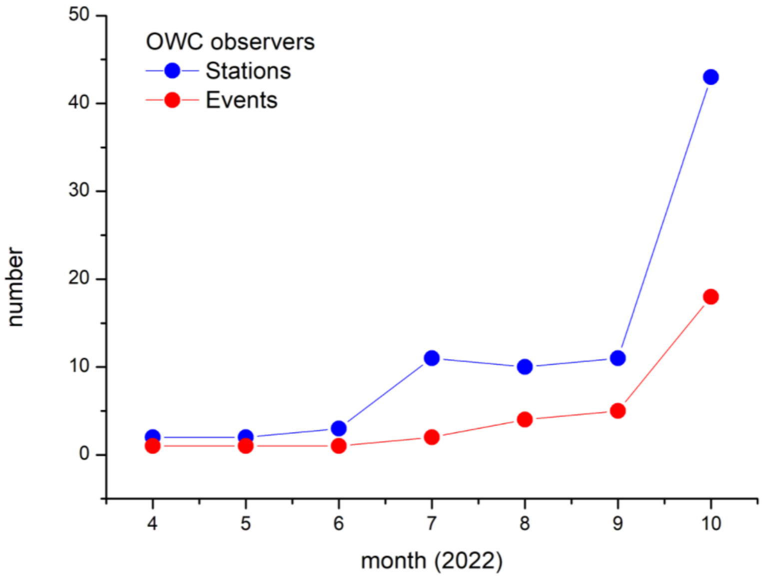

Fig. 3 – The increasing attractivity of ACROSS is shown by the growth rate of the number of stations that pre-registered on the OWC portal to observe or were in touch with the team to coordinate campaigns (in blue). The red line corresponds to the number of events that have been targeted. The activity of ACROSS is clearly expanding in visibility and impact.