SF2A 2024
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PROJECT OLED - LUNAR OCCULTATIONS OF DOUBLE STARS

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Abstract. The activities of the OLED project, a group of amateur observers dedicated to the observation of lunar occultations of binary stars, are presented. These events allow for the accurate determination of the relative astrometry, with a precision which is superior to that of interferometric techniques used by amateurs. The overall uncertainty of the project is currently below 20 milliarseconds, which allows us to access rather close pairs with short periods. We believe these activities may significantly contribute with useful data to the estimation or refinement of binary star orbits. Also, efforts are devoted to duplicity searches in stars thus far catalogued as single, and to confirming duplicity of stars in the Gaia DR3 nonsingle star tables.

Keywords: lunar occultations, double stars, binary stars

1 Introduction

Lunar occultation of stars is a powerful method for high-resolution astrometry *. When applied to binary stars, it allows for the relative astrometry of a pair (angular separation and position angle at a given time) with a precision of a few milliarcseconds (mas), enabling the observation of extremely close pairs using equipment accessible to amateur astronomers. However, it requires at least two observations of the same pair from significantly different locations along the lunar limb. For this, collective work, involving a team of observers spread over a large area and spanning at least several hundred kilometers, is essential.

The technique has been used since the 70s of the last century to detect new star duplicities, its use declining steadily in the last decade. However, the recent advances in the lunar limb profile and in amateur equipment now allows for time accuracies of ~ 1 millisecond (ms), and analysis of the observations results in final astrometric precisions of $\sim$ a few tens of mas. This opens up new avenues for amateur work and access to close binary stars of short period, a topic restricted so far to professional work.

A few members of the SAF Double Star Commission committed to this type of observations in 2021, while a network of observers was also being established in Spain. Today, the two teams form a unified network, pooling their results within the same OLED project (Occultations Lunaires d'Étoiles Doubles or Ocultaciones Lunares de Estrellas Dobles). The aim of the present article is to briefly introduce the principles of this technique and the organization set up within the OLED project, and to present some of the initial results. A full account of the latter can be found in Velasco & Laurent (2023) and Velasco & Laurent (2024).

2 Principles of the Lunar Occultation Method

An occultation is caused by the Moon's motion in the sky, Fig. 1 (top-left panel). The apparent lunar motion relative to the sky averages $0.4''$ per second of time at mid latitudes; this is sufficiently slow to allow for accurate translation of a time measurement to an angle in the sky, but fast enough to generate a high rate of occultations. These are systematically observed on the dark limb of the Moon. In the case of a single star, a sudden drop in brightness is observed. For a double star, two distinct drops are seen, corresponding to the successive occultation of the two components, Fig. 1 (bottom-left panel). The observation method relies on capturing a video of the occultation at a high frame rate, and the creation of a light curve of the event. An example is given in Fig. 1 (right panels). The two contact times of the events can be extracted from the light curve.

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*See e.g. White (1987) for a general (albeit old) introduction to lunar occultations.

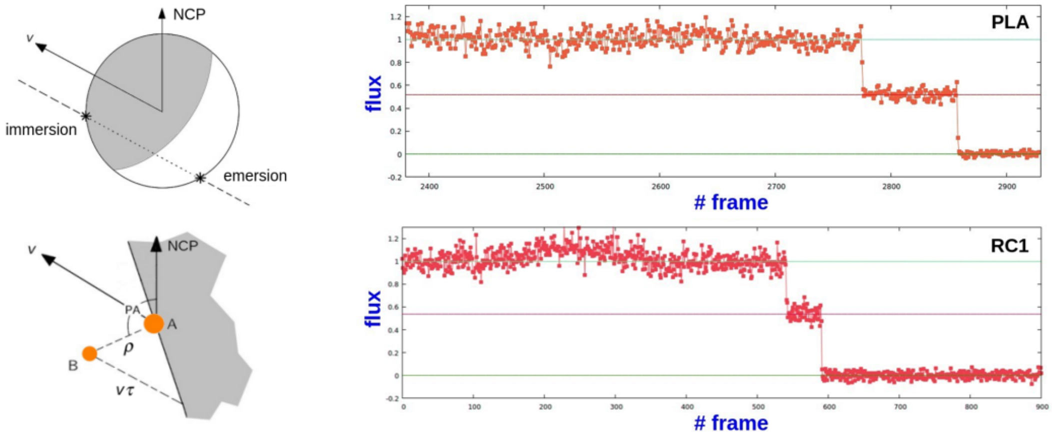

Fig. 1. Top-left: Geometry of a lunar occultation. The Moon moves with apparent velocity v, and occults a star at the eastern limb (immersion), which then reappears at the western limb (emersion). Useful events occur at the dark limb. **Bottom-left**: A binary star, with components A (primary) and B (secondary), is occulted at the dark limb, resulting in two consecutive contacts. The angle travelled by the Moon between the two events is $v\tau$, where τ is the time interval between the two contacts. From this, a lower limit for the pair separation ρ can be inferred, but not the real values of ρ and PA (position angle of the binary star). Note that, if the two stars are close, the lunar limb can be approximated by a straight line. **Right**: An example of two light curves obtained by two observers of the OLED project in the case of the physical binary star WDS J07128+2713 STF 1037 AB, occulted by the Moon on 23 March 2023. Note the flux at an intermediate level, indicating the presence of two components.

Reduction of the observations requires precise knowledge of the observer's position, the positions of the Earth and the Moon, as well as an accurate representation of the roughness of the lunar surface at the point of the occultation. This roughness is now known with high accuracy thanks to lunar orbiter missions such as LRO or Selene. The lunar limb profile at a given moment is currently known to within 5 mas. The reduction process leads to a lunar limb projected on the sky at the time of each event and for a particular observer.

When only a single observation of a double star is available, it is not possible to fully determine the astrometry of the binary star. Instead, we are left with a *one-dimensional solution*, that can be represented by a straight lunar limb in most cases. This solution defines the possible locations where the secondary component could be located at the epoch of the event, see Fig. 2, relative to the primary. A second observation from a different position on the lunar limb allows for the precise relative location of the two stars, as the intersections of the limbs obtained for each component from different stations lead to the absolute position of the two stars. From these the relative astrometry of the pair, ρ and PA, can be calculated using spherical trigonometry. Additional observations can further increase the accuracy of the results. The two observations can be made by different observers during the same occultation or during occultations of the same pair in different lunations (by the same or another observer). In this case, the two observation times will be averaged, so the observations should be made as close in time as possible, ideally within a few lunations.

It is essential to have precise timestamping for each frame (with an accuracy of a few ms) to produce useful data, which can achieved with a camera coupled to a GPS system (either built-in or external to the camera). A solution using software to synchronize the acquisition PC's clock to reference time servers using the internet is also a possibility. The requirements in terms of time accuracy are nowadays at the reach of the average amateur.

3 The OLED Project

The OLED project coordinates a group of 25 observers in Spain and France, and is included as a Gemini ProAm project and also in the Spanish SEA-FAAE ProAm group. A database of each observed occultation has been compiled, including exploratory observations conducted in 2021. As of the end of September 2024, the database contains almost 400 contacts, corresponding to 240 stars, 140 of which are listed in the WDS catalogue maintained by the USNO, with the remainder being single stars. A report has been published in the *Étoiles Doubles* journal Velasco & Laurent (2024) to ensure the publication in WDS of all data collected from 2021 to

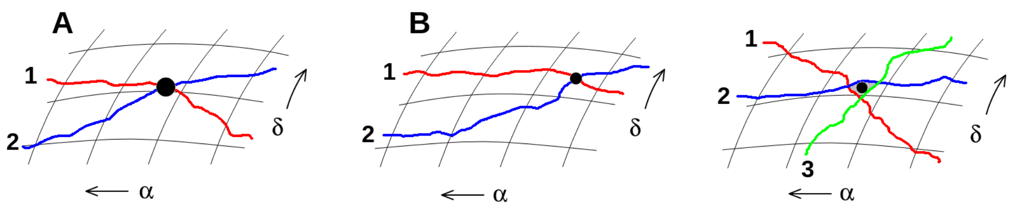

Fig. 2. Limb crossing technique. The sky-projected lunar limb at the measured contact time onto the celestial grid of meridians and parallels defines the loci of the possible positions of the star (the so-called *one-dimensional solution*). The intersection of two projections from two observers provides the absolute position of the star (*two-dimensional solution*). **Left**: Schematics of the technique applied to component A. **Middle**: Same as before, but for component B. The relative astrometry ρ and PA can be obtained from the positions of A and B. **Right**: With more than two observations the positions can be optimised in the least-square sense. α, δ stand for right ascension and declination, respectively.

March 2024. The OLED project's website † provides general information, predictions, and observational data, along with analysis of relevant stars.

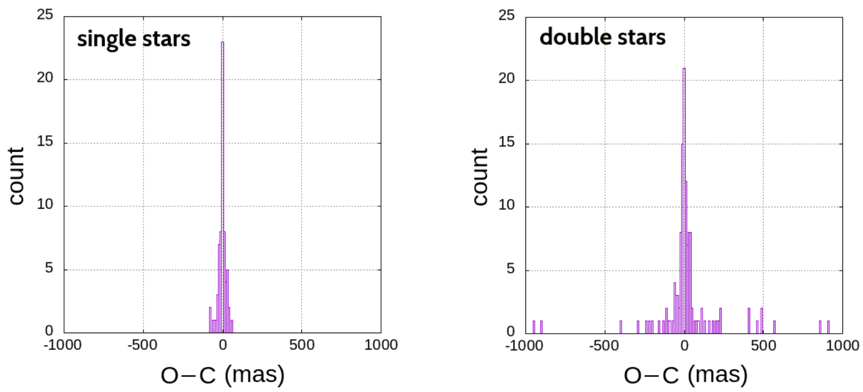

Fig. 3. Histograms of O−C (difference in radial distances, measured from the apparent centre of the Moon, between the contact point and the calculated star position at the time of occultation) for different sets of observations. **Left**: Set of 62 single stars taken from the PPM catalogue. **Right**: Set of 128 double stars of the WDS catalogue.

4 Some results

Each contact is extracted from the light curve, allowing for the calculation of an O-C (observed - calculated), which quantifies the distance between the measured position of the star and the predicted position at the time of the occultation. As a benchmark, Fig. 3 (left panel), presents a histogram of the O-C values obtained for 62 recorded contacts of single stars which are supposed to move linearly in space and for whom catalogue positions and proper motions are well determined. For these stars, and in the absence of any bias originating in the lunar motion and/or lunar limb, and with an accurate timebase, the value of O-C should vanish. The histogram shows that the average O-C is close to zero, which is reassuring as it indicates the absence of any bias in the reduction or measurement stages. The standard deviation is $\sigma = 19$ mas, which can be considered the reference collective uncertainty for the OLED project. Various effects account for this uncertainty, notably the uncertainty in the UTC timebase and in contact times extracted from possibly noisy light curves. The same analysis for 128 double or multiple stars is presented in Fig. 3 (right panel). The O-C graph also shows results centred about zero, but with greater spread. This is expected, as double stars exhibit anomalous motion relative to their catalogue positions. It is precisely these offsets that is used to extract the relative astrometry of double stars.

† `https://sites.google.com/aam.org.es/oled`

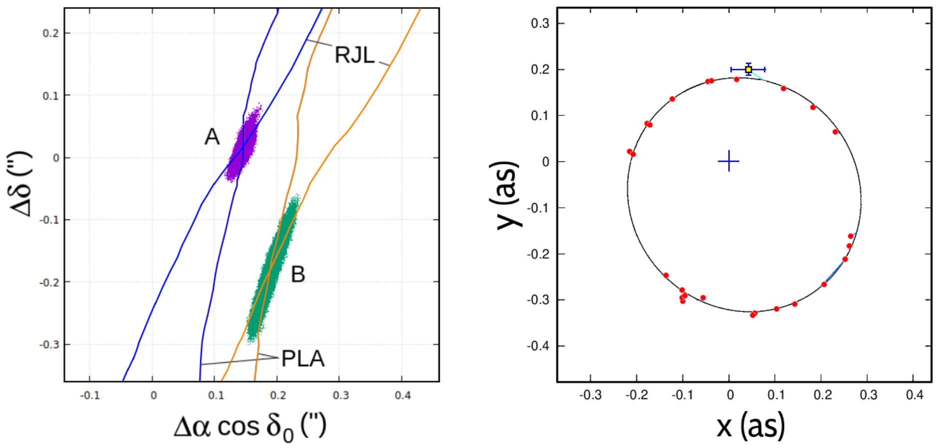

Fig. 4. Left: Projected limbs for the two components A and B of WDS J05017+2640 A1844AB, in the occultation occurred on J2024.0559, as derived from the measurements of two observers (RJL and PLA). Intersection points give the position of each star relative to the catalogue position of the primary (α_0, δ_0), i.e. $\Delta\alpha = \alpha - \alpha_0$ and $\Delta\delta = \delta - \delta_0$. Coloured areas in the neighbourhood of each position are results from a Monte Carlo sampling to evaluate uncertainties. **Right**: New astrometric position for the epoch of observation (square symbol), with uncertainties. Previous speckle interferometric measurements are indicated with red filled circles. A new orbit by the authors is also shown (unpublished).

As an example, Fig. 4 illustrates the result of an occultation observed in January 2024 by both a Spanish and a French observer, involving the pair WDS J05017+2640 A1844AB. The relative astrometry derived from these observations, at epoch J2024.0559, is $\rho = 0.205'' \pm 0.034''$, $\theta = 168.2° \pm 6.1°$. The very small angular separation of this binary ($\sim 0.2''$) makes it completely out of reach for other techniques that can be used by amateurs, including speckle interferometry. This result demonstrates the power of the method, as well as the value of working with observers spread over a wide geographic area. We note the amplitude of the uncertainty intervals in directions aligned with the lunar limbs, which have a small angle between them. Observing from more distant stations would have allowed for larger angles, improving the accuracy of the measurement.

5 Conclusions

Lunar occultations have clearly proven their effectiveness through the observations made so far by the OLED network, with final astrometric accuracies just over 20 mas. The method is valuable for very close pairs that are inaccessible to other techniques, and it complements other methods, as an occultation only requires a short time commitment from the observer (about 30 minutes). It is important to continue to expand the network of observers to maximize opportunities for obtaining the complete astrometry of a pair. Nevertheless, unpaired astrometric solutions made by a single station are also valuable for orbit estimation, and we are currently working on methods to estimate or improve orbits using these solutions.

Investigations are underway using the Gaia DR3 non-single stars catalogue Halbwachs & al. (2023). The lunar occultation method could help confirm duplicity or even provide the first measurements for some of these pairs. The Gaia NSS catalogue contains over 800,000 entries, many of them amenable to lunar-occultation analysis, which will certainly provide plenty of work for the observers of the OLED network!

We acknowledge the invaluable contributions of all the observers involved in the project to the field of double-star astronomy.

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