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PREDICTION OF STELLAR OCCULTATIONS BY DISTANT SOLAR SYSTEM OBJECTS WITH GAIA

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Abstract. Predictions of stellar occultations by outer Solar System objects require accurate positions of stars and accurate orbits. In the recent years, Gaia catalogues allow a huge improvement thanks to stellar positions accurate to less than 1 milliarcsec (mas). On the contrary, the orbits of outer Solar System objects are not so precise because these objects are distant and were observed only during a short period of their orbit. In this document, we present several techniques to improve the orbits of distant Solar System objects for the occultation purpose, in particular thanks to : 1) the astrometry deduced from previous occultations, 2) a new reduction of astrometric position using Gaia catalogues and 3) the direct observations of the objects by Gaia.

Keywords: astrometry, celestial mechanics, ephemerides, occultations, Kuiper belt objects

1 Introduction

Stellar occultation is the only technique to obtain, from ground-based observations, an accurate estimation of physical parameters of distant objects or to probe their atmosphere and surroundings. For example, size and shape can be determined to kilometric precision, atmospheric pressure can be measured down to nanobar levels, and ring system around the body can be characterised (Braga-Ribas et al. 2014; Ortiz et al. 2017; Meza et al. 2019, for instance).

The first step of these works is the prediction of stellar occultations to know where and when the event could be observed. Predictions require an accurate position of the star and an accurate ephemeris of the object. Thanks to Gaia catalogues (Gaia Collaboration et al. 2016, 2018a), the position of the stars is now known at the tenth of mas level accuracy. Ephemerides of these objects are less precise since they depend on the quality of the astrometry used to determine their orbit. For distant Solar System objects (DSSO), the precision is usually around several dozens of mas. Due to their distance, a small angular error corresponds to large error on the path at the surface of the Earth, making the occultation quite uncertain to observe. For example, 10 mas corresponds to 35 km at the Jupiter distance (5.2 AU), 100 km at Chariklo distance (15 AU), 200 km at Neptune distance (30 AU) and 700 km at Eris distance (97 AU).

Desmars et al. (2015) propose the NIMA method in order to refine predictions thanks to a better orbit determination. This method uses all the astrometric positions available on Minor Planet Center and additional observations from Observatório Pico dos Dias and Granada (from our astrometric survey). This method also allows to use astrometry of previous occultations.

In this document, we present how Gaia is also helping to improve the ephemerides of DSSO, in particular thanks to 1) the astrometry deduced from previous occultations, 2) a new reduction of astrometric position using Gaia catalogues, and 3) the direct observations of the objects by Gaia.

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2 Predictions with previous occultations

As of August 2019, about 168 occultations have been successfully observed for 63 differents DSSO[*]. These occultations not only help to determine the body shape, size, etc, they also provide an accurate astrometric position of the body's center at the time of the occultation. The full technique is detailed in Desmars et al. (2019).

This position only depends on the position of the occulted star (about 0.1 mas) and the global analysis of the occultation (about few km representing few mas). Finally, the precision of the deduced position from the occultation generally reach 2 mas for multi-chord occultations to 10-20 mas for single-chord occultations. For comparison, astrometric positions deduced from CCD have a precision from 50 mas (in the best case) to 300 mas in the general case. These positions are then used in the orbit determination process (for example NIMA) in order to refine the orbit and the future predictions of occultations.

This method was, for instance, used with Pluto thanks to 19 occultations observed between 1988 and 2016 allowing an orbit with a precision of few mas instead of hundred mas with other ephemerides (Desmars et al. 2019). Predictions of Pluto's occultations in the near future now reach a precision of 60-80km on the path of the shadow, allowing to observe the central flash in an area around 50 km along the centrality (Meza et al. 2019). The same method was used for Chariklo for which we observed 15 occultations from 2013 to 2017 (Bérard et al. 2017; Leiva et al. 2017; Desmars et al. 2018) and is applied to refine the orbits as soon as positive occultations are detected.

3 Predictions with astrometry reduced with Gaia catalogues

Occultations remain usually rare events and hard to observed for DSSO. Most of the DSSO were not observed yet by occultations and the previous method can not be used to refine orbit and future predictions. In such case, the only option is to use the classic astrometry using the Gaia catalogues.

Before Gaia catalogues, the most precise stellar catalogues reach an astrometric precision of 50 to 70 mas, as for example UCAC4 (Zacharias et al. 2013) with additional zonal errors. The first release of Gaia catalogue (Gaia Collaboration et al. 2016) provides stellar positions with a precision of 1-20 mas but no proper motions of the stars. The second release of Gaia catalogue (Gaia Collaboration et al. 2018a) provides stellar positions, proper motions and parallaxes. The global precision of the star now reaches 0.1-0.2 mas. Moreover, there is no more zonal errors in Gaia catalogues as it was the case with former catalogues. Classical astrometry can be improved by using Gaia catalogues for the astrometric reduction.

In order to study the benefit of the use of Gaia catalogues, we took the example of an occultation by Triton on 5th October 2017. For this occultation, we specifically observed Triton during 8 nights before the occultation in order to refine its position. For these observations, we first made an astrometric reduction with Gaia DR1 and obtained a mean offset for the 8 nights: $\Delta\alpha \times \cos\delta = -5.3 \pm 8.0$mas and $\Delta\delta = -4.8 \pm 5.7$ mas. Then we used Gaia DR2 for astrometric reduction leading to a mean offset of : $\Delta\alpha \times \cos\delta = +7.8 \pm 5.4$ mas and $\Delta\delta = -17.6 \pm 2.6$ mas. The residuals in right ascension and declination per night are represented on Fig.1. The residuals are better and more precise with the reduction with Gaia DR2. They are also constant over the nights, which is less the case with the Gaia DR1 reduction. At the end, the offset deduced from the Gaia DR2 reduction was used for the prediction.

Finally, the occultation was successfully observed over Europe and preliminary results show that the offset between prediction and the occultation was around 2 mas in declination which represents a shift of only 40 km on the path (Marques Oliveira et al. 2018). Astrometric reduction with Gaia catalogues provide more accurate astrometric reduction and particularly less affected by zonal errors coming, for example, from unknown proper motions.

4 Predictions with Gaia DR2 astrometry

Gaia DR2 catalogue provide astrometric positions for more than 14000 Solar System objects (Gaia Collaboration et al. 2018b). Unfortunately, only 2 DSSO are included in the catalogue. To analyse the improvement of Gaia DR2 positions for occultations, we deal with Trojans objects as the biggest are included in Gaia DR2.

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[*] `http://occultations.ct.utfpr.edu.br/results/`

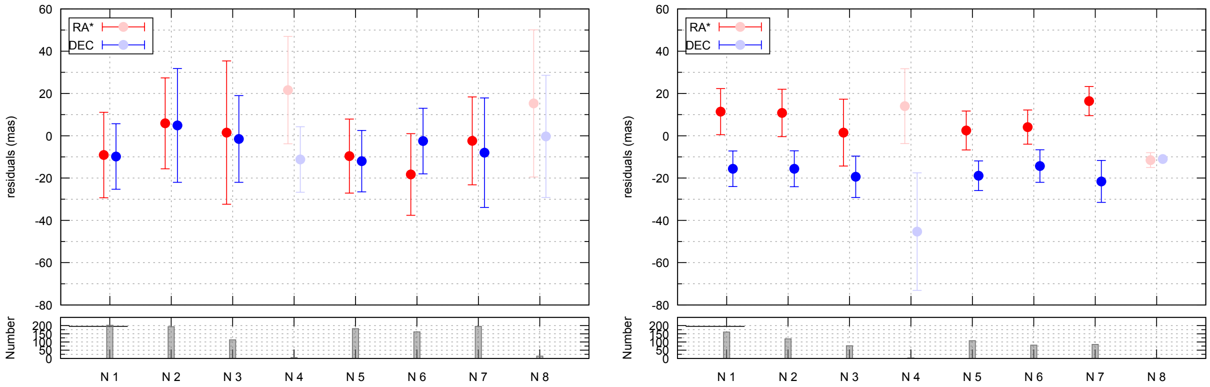

Fig. 1. Astrometric residuals in right ascension and declination for 8 nights of Triton observations using Gaia DR1 (**Left**) and Gaia DR2 (**Right**) catalogues for the reduction. Histograms also give the number of observations per night. Data in light colors were not used in the mean offset determination.

Due to the scanning process of the Gaia spacecraft, the astrometric positions in right ascension and in declination are highly correlated with a precision of about few mas in the along-scan direction whereas it is hundreds of mas (like classical CCD astrometry) in the across-scan direction (Gaia Collaboration et al. 2018b). Correlations have to be taken into account in the orbit determination process.

Gaia DR2 astrometric positions were used to predict an occultation by Deikoon on 23 February 2019. Figure 2 shows the predictions of this occultation with two different ephemerides : NIMAv2 by using only astrometric positions from Minor Planet Center (between 1988 and 2019) and NIMAv3 using in addition the Gaia DR2 positions (between 2014 and 2016). The uncertainty of the path is also represented with red dotted lines showing that the prediction with NIMAv3 is more precise.

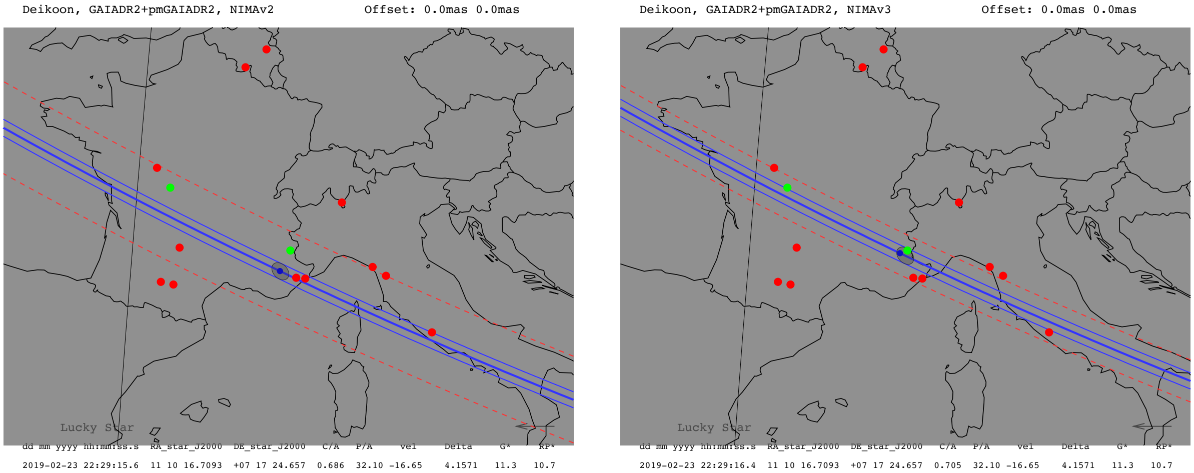

Fig. 2. Prediction of the occultation by Deikoon on 23 February 2019 using NIMAV2 with only the MPC astrometry (**Left**) and NIMAv3 using the MPC + Gaia DR2 astrometry (**Right**). Red dotted lines give the 1-σ uncertainty on the body limits. Green dots indicate stations that report a positive occultation, red dots are for stations reporting a negative observation. The dark disc represent the shadow of Deikoon at the mid-time reported by the eastern green station.

Finally, the occultation was detected in two stations in France. The shadow of Deikoon at the mid-time of the occultation reported by the Eastern station (in green) is also represented on the figures. Other stations (in red) also reported a negative observation still useful to provide constraints on the size of the object. The preliminary analysis of the light curve and timing show that the prediction using the Gaia DR2 positions was very accurate both for the path (impact parameter *i.e.* the closest distant between the center of the shadow and the station on the fundamental plane) and the timing (Table. 1).

ephem	Δt		$\Delta\rho$
	s	mas	mas
NIMAv2	1.0	5.5	21
NIMAv3	0.2	1.1	2

Table 1. Residuals in timing and impact parameter for Deikoon occultation in on 23 February 2019 using NIMAv2 (with only MPC positions) and NIMAv3 (with MPC and GaiaDR2 positions).

In 2019, we have also detected positive occultations for other Trojans with less promising results, *i.e.*the prediction was not necessarily better by using Gaia DR2 astrometry. As these occultations were single chord occultation (observed by only one station), systematic errors such as timing issue are possible and careful analysis will be done in the future. The Trojans are a good test as future Gaia releases will provide astrometric positions of most of the Solar System objects during the mission period.

5 Conclusions

Predictions of stellar occultations by distant Solar System objects were greatly improved thanks to Gaia. The star positions now reach less than 1 mas whereas orbits of DSSO can also be improved with the help of Gaia: with astrometric position deduced from previous occultations, with astrometry of CCD reduced with Gaia catalogues or with direct astrometric positions from Gaia itself. For some specific objects (Pluto, Chariklo, etc), the prediction of stellar occultations now reaches the mas level accuracy representing only few tens of km, which ten to hundred times better than what we had only five years ago.

Future Gaia releases as well as the Large Synoptic Survey Telescope (Hsieh et al. 2019) will provide astrometric positions for most of the Solar System objects allowing to greatly improve the orbits and the future predictions of stellar occultations. Accurate predictions allow to gather and place precisely observing stations on the Earth surface to observe for example a grazing occultation to study the structure of a ring system or the topographic features at the surface of the object, or to observe a central flash in order to probe the atmosphere of some objects (Pluto, Triton).

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