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Prediction of stellar occultations by distant solar system bodies in the Gaia era

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Abstract. Stellar occultations are a unique technique to access physical characteristics of distant solar system objects from the ground. They allow the measure of the size and the shape at kilometric level, the detection of tenuous atmospheres (few nanobars), and the investigation of close vicinity (satellites, rings) of Transneptunian objects and Centaurs. This technique is made successful thanks to accurate predictions of occultations. Accuracy of the predictions depends on the uncertainty in the position of the occulted star and the object's orbit. The Gaia stellar catalogue (Gaia Collaboration (2017)) now allows to get accurate astrometric stellar positions (to the mas level). The main uncertainty remains on the orbit. In this context, we now take advantage of the NIMA method (Desmars *et al.*(2015)) for the orbit determination and of the Gaia DR1 catalogue for the astrometry. In this document, we show how the orbit determination is improved by reducing current and some past observations with Gaia DR1. Moreover, we also use more than 45 past positive occultations observed in the 2009-2017 period to derive very accurate astrometric positions only depending on the position of the occulted stars (about few mas with Gaia DR1). We use the case of (10199) Chariklo as an illustration. The main limitation lies in the imprecision of the proper motions which is going to be solved by the Gaia DR2 release.

Keywords. Kuiper Belt, catalogs, astrometry, ephemerides, occultations.

1. Introduction

Stellar occultations are a unique technique to access physical characteristics of distant solar system objects from the ground: size and shape at the kilometric level, tenuous atmospheres at few nanobars, and investigation of close vicinity (satellites, rings). This technique is successful thanks to accurate predictions of occultations depending on the precision of star's position and the object's orbit.

Predictions of occultations by distant bodies is a difficult challenge. Indeed, good predictions require both accurate positions of the star and the body. As the objects are distant (from 15 to 90 au) and small in size (100-2000 km), the apparent size of the body is about 10 to 50 mas. A precision to the same level or less is required for good predictions. In comparison, 30 mas is equivalent to a coin of 1 euro seen at 200 km.

The uncertainty of the prediction comes from the uncertainty on the star and the object positions. For the star position, the source of uncertainties are the zonal errors in stellar catalogs (which is not the case anymore since Gaia DR1) and uncertainty in the proper motion. For the object's position, the source of uncertainty comes from the astrometric positions used for orbit determination. Since the Gaia DR1 (Gaia Collaboration (2017)), the main source of uncertainty in the predictions now comes from the ephemeris.

2. Methods of predictions

Assafin *et al.*(2012) and Camargo *et al.*(2014) propose method of prediction based on the JPL ephemeris and an offset deduced from observations. The method was successfull when the observations were made only few days before the occultation. Since mid-2013, we use the NIMA method for the predictions (Desmars *et al.*(2015)) using our own ephemeris NIMA. The main advantage is that we can used more observations (from the Minor Planet Center, from the Rio team and unpublished observations) and we have the control of the weighting process. Also, we can use astrometric positions derived from positive occultations.

3. Astrometry from previous occultations with Gaia

During an occultation, the star and the object have the same direction, meaning that at the time of the occultation, an astrometric position of the body can be derived from the position of the star. In particular, since the publication of the Gaia DR1, the accuracy of the star's positions is about 1-10 mas which is much more accurate than a classical astrometric position reduced from a CCD frame (about 300 mas). On the 2009-2017 period, 45 predicted occultations for 18 TNOs/Centaurs (Chariklo, Makemake, Eris, ...) have been successfully detected. We are able to derive an astrometric position for all of them. In particular, for Chariklo, we have observed 13 occultations. We used these positions derived from the Gaia DR1 catalog to refine the orbit. Figure 1 shows the difference between NIMA and JPL ephemerides in right ascension (left) and declination (right) by using observations reduced with UCAC4 in blue points (top) and by using also astrometric positions from occultations derived with the Gaia DR1 catalog in red points (bottom). The gray area around the line represents the 1-σ precision of the NIMA ephemeris. The orbit is clearly improved with the use of the Gaia DR1 catalog and the astrometric positions. With the previous version of the ephemeris, we have a precision of 30-40 mas in declination whereas with the new version the precision is less than 10 mas. The apparent size of Chariklo (25 mas) and its rings (80 mas) are represented for comparison in Fig. 1. In particular, now the precision is smaller than the apparent size of Chariklo. Thanks to the Gaia DR1 catalog and the refinement of the orbit, we are able to predict occultations to 10-mas level allowing to gather the observing stations on the ground.

4. Proper motion issue

Despite accurate astrometric positions, Gaia DR1 does not provide proper motions for all the stars (only stars in TGAS). Since the beginning of 2017, several publications provide proper motions for fainter stars.

Altmann *et al.*(2017) propose HSOY, a stellar catalog with proper motion for 583 million stars. Proper motions are derived from the Gaia DR1 and the PPMXL catalogs. More recently, Zacharias *et al.*(2017) derive proper motions from the Gaia DR1 and a

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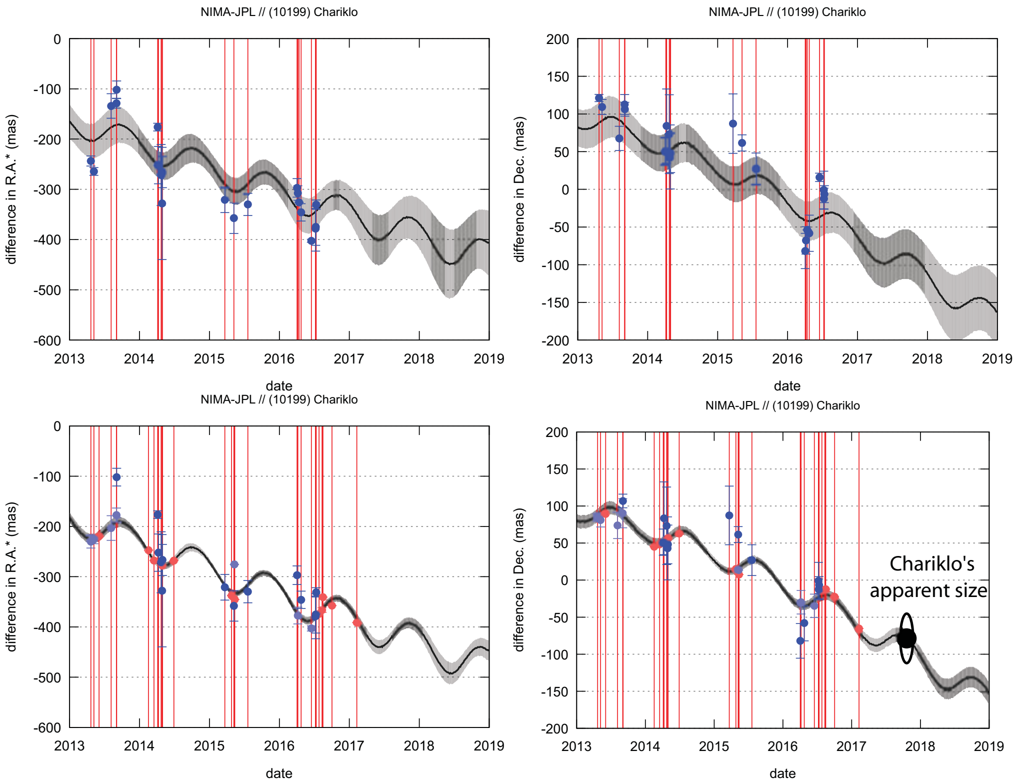

Figure 1. Difference between NIMA and JPL ephemerides for Chariklo in right ascension (left) and declination (right) by using only astrometric observations reduced with UCAC4 (top) and by using also astrometric positions from occultations (bottom). The blue points represent the observations reduced with UCAC4 and red points represent positions from occultations. The gray area represents the 1-σ precision of the NIMA ephemeris.

new reduction of US Naval Observatory CCD Astrograph Catalog. The UCAC5 catalog contains proper motions for 107 million stars. Finally, Tian *et al.*(2017) also propose the Gaia-PS1-SDSS (GPS1) proper motion catalog based on a combination of Gaia DR1, PS1, SDSS and 2MASS astrometry for 350 million sources.

Before the publication of these catalogs, we used a method from Dave Herald (personal communication) to derive proper motions from the Gaia DR1 and the UCAC4 catalogs. Basically, this method can be summarized as:

- Derive from UCAC4 positions and proper motion, the UCAC4 position at UCAC4 epoch E_U: (α_U, δ_U)
- Gaia position at Gaia epoch E_G : (α_G, δ_G)
- Proper motions computed as:

$$\mu_\alpha = \frac{\alpha_U - \alpha_G}{E_U - E_G}; \mu_\delta = \frac{\delta_U - \delta_G}{E_U - E_G}$$

In order to test the different sources, we compare proper motions for the 14 stars that have been occulted by Chariklo in the last few years. Fig. 2 shows the proper motion in declination for three different sources: HSOY, UCAC5 and Herald's method. Proper motions in UCAC5 and Herald's method are usually in a good agreement, which is expected as the Herald's method uses stars from UCAC. Nevertheless, proper motion for some stars still remains different. HSOY provides a different proper motion for most

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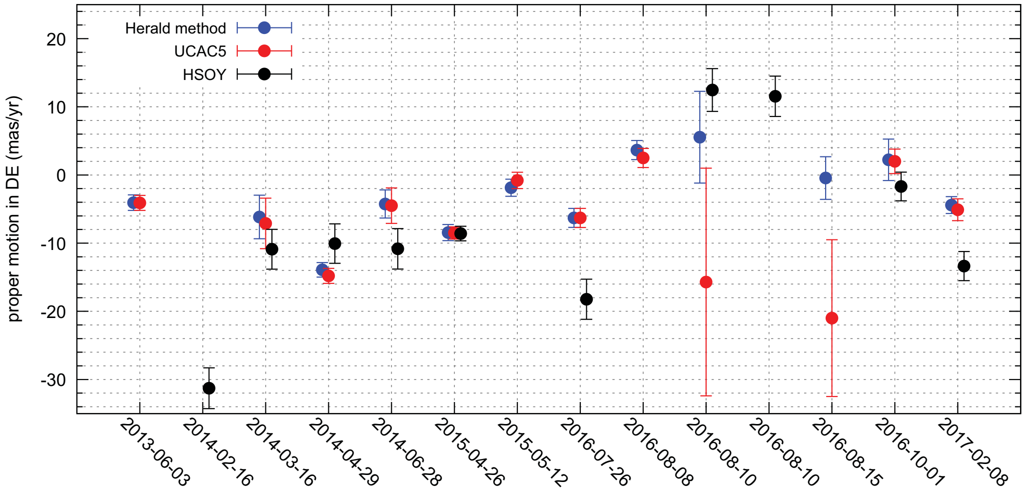

Figure 2. Comparison of proper motion in declination between Herald's method, HSOY and UCAC5 catalogs for the stars involved in Chariklo's occultations (dates of occultations are indicated in abscissa).

stars. Until the publication of the Gaia Data Release 2, the proper motion will remain an issue for accurate predictions of occultations.

5. Conclusion

Gaia-DR1 greatly improves the predictions of occultations. Before Gaia, the precision of prediction was about 30-40 mas whereas after Gaia DR1, the precision is about 10 mas. With the Gaia DR2, we expect to have a precision smaller than 1 mas. Moreover, accurate astrometric positions from positive occultations help to refine orbits without direct observations of the body with Gaia. A precision of few mas is now reachable for some objects (Chariklo, Pluto) leading to accurately predict grazing occultations or central flash and allowing to gather observers on the shadow's path. Nevertheless, until the publication of Gaia DR2, the proper motions will remain the main source of uncertainty for the predictions. The Gaia DR2 will also provide direct observations of some TNOs/Centaurs and help to greatly refine their orbit. Finally, we also plan to make use of surveys (LSST, Dark Energy Survey, ...) to derive astrometric positions.

This work has made use of data from the European Space Agency (ESA) mission *Gaia* (https://www.cosmos.esa.int/gaia), processed by the *Gaia* Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement.

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