Occultation Predictions of Irregular Satellites

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Introduction

Irregular satellites revolve around giant planets at large distances in eccentric, highly inclined and frequently retrograde orbits. Because of these peculiar orbits, it is largely accepted that these objects did not form by accretion around their planet, but were captured in the early Solar System (Sheppard, 2005).

There is no consensus for a single model explaining where the irregular satellites were formed. Ćuk & Burns (2004) showed that the progenitor of the Himalia group may have originated in heliocentric orbits similar to the Hilda asteroid group. Sheppard (2005) stated that the irregular satellites may be some of the objects that were formed within the giant planets region.

Grav et al. (2003) and Grav & Bauer (2007) showed that the irregular satellites from the giant planets have their colors and spectral slopes similar to C-, D- and P-type asteroids, Centaurs and trans-neptunian objects (TNOs). This suggests that they may have come from different locations in the early solar system.

Sheppard (2005) and Jewitt & Haghighipour (2007) also explored the possibility that the irregular satellites originated as comets or TNOs. TNOs are highly interesting objects that, due to their large heliocentric distances, may be highly preserved with physical properties similar to those they had when they were formed (Barucci et al., 2008). This is even more true for the smaller objects, since in principle larger sizes favour physical differentiation processes in the body and vice-versa. However, due to the distance, the smaller TNOs from this region are more difficult to observe. Thus, if irregular satellites - or at least a few of them - do share a common origin with small TNOs, and since these objects are situated at much closer heliocentric distances now, this gives a unique chance of observing and studying representatives of this specific TNO population in much greater detail than could ever be possible by direct observation of this population in the Kuiper Belt.

Phoebe is the most studied irregular satellite. Clark et al. (2005) suggest that its surface is probably covered by material of cometary origin. It was also stated by Johnson & Lunine (2005) that if the porosity of Phoebe is 15%, Phoebe would have an uncompressed density similar to those of Pluto and Triton.

Size, shape, albedo and composition would help a lot to trace back their true origin, but these physical parameters are yet poorly known for irregular satellites. The observation of stellar occultations would allow for the determination of such parameters. Indeed Jupiter will cross the galactic plane in 2019-2020 and Saturn in 2018, improving a lot the chances of observing such events in the near future.

For this, we made new numerical integration of the orbits of the 8 major irregular satellites of Jupiter (Himalia, Elara, Pasiphae, Lysithea, Carme, Ananke, Sinope and Leda) using only the positions obtained by Gomes-Júnior et al. (2015). We aim to eliminate the systematic errors in the JPL ephemeris pointed out by these authors. For Phoebe, we updated the ephemeris of Desmars et al. (2013) using the observations of Gomes-Júnior et al. (2015), Peng et al. (2015), observations from Minor Planet Center and observations from Flagstaff. With this, we predicted stellar occultation for the 9 objects.

Using the derived ephemerides and the UCAC4 catalogue we managed to identify 5442 candidate stellar occultations between January 2016 and December 2020 for the 9 irregular satellites studied here.

Phoebe, being the most studied object with a good measured size, can be used to calibrate and evaluate the technique for similar objects. Up to date, no observation of

Table 1: Estimated diameter of the satellites and correspondent apparent diameter

Diameter of the satellites			
Satellite	mas[a]	km	Ref.
Ananke	8	29	1
Carme	13	46	1
Elara	24	86	1
Himalia	41	$(150 \times 120) \pm 20^b$	2
Leda	5	20	1
Lysithea	10	36	1
Pasiphae	17	62	1
Sinope	10	37	1
Phoebe	32	212 ± 1.4^b	3

References: (1) Rettig et al. (2001); (2) Porco et al. (2003); (3) Thomas (2010).
[a]Using a mean distance from Jupiter of 5 AU, from Saturn of 9 AU and from Neptune of 30 AU. [b]From Cassini observations.

a stellar occultation by an irregular satellite was published. Since their estimated sizes are very small (see Table 1), this may have discouraged earlier tries. But, in fact, given their relatively closer distances as compared to TNOs and Centaurs, and considering the precision of our ephemeris and of star positions, we can now reliably predict the exact location and instant where the shadow of the occultation will cross the Earth.

Orbit computations

Gomes-Júnior et al. (2015) published 6523 precise positions for 18 irregular satellites from observations made at the Observatório do Pico dos Dias (OPD), Observatoire Haute-Provence (OHP) and European Southern Observatory (ESO) between 1992 and 2014.

Here we compute new orbits based on the observations published in Gomes-Júnior et al. (2015). First, because the reduction was made with a consistent and precise stellar catalogue and with a robust astrometry (PRAIA, Assafin et al., 2011). Second, besides recent observations, this consistent set of numerous and precise positions covers many orbital periods at many distinct orbital plane sights, so that the orbital inclinations along with all other orbital elements could be satisfactorily derived without the need of further position sets. For these reasons, only this set of positions was used for the satellites of Jupiter.

Due to the context of this work regarding to stellar occultations, the orbit fitting procedures used aimed primarily to derive precise ephemerides for the near future. The procedures allow for the improvement of orbits as new observations are added.

Special tailored Ephemerides (STE) for Jupiter irregular satellites

The last observations used to develop JPL current ephemeris of the irregular satellites of Jupiter were obtained in 2012 (Jacobson et al., 2012). As a result, the errors in the JPL ephemeris for the current epoch are large enough to prevent accurate predictions of stellar occultations without any corrections.

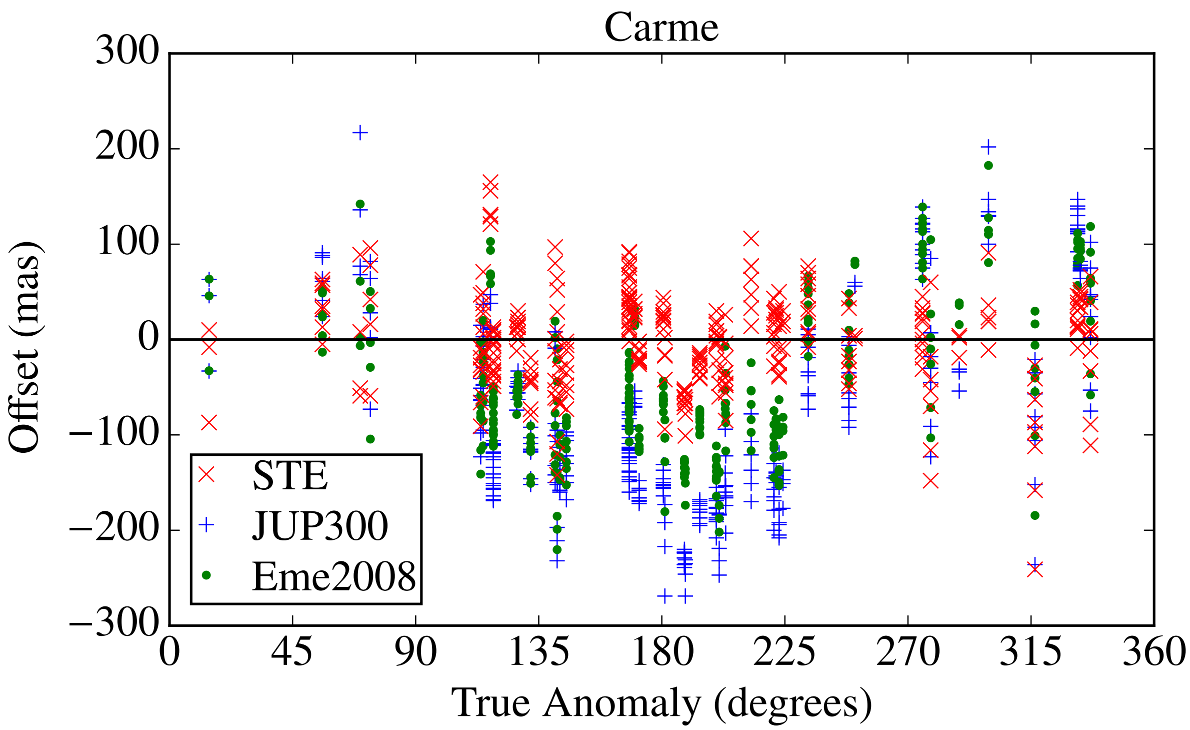

Figure 1: Offsets in declination of the positions published by Gomes-Júnior et al. (2015) for Carme. The red "x" relative to the special-tailored ephemeris, the blue "+" relative to the JUP300 JPL ephemeris and the green dot relative to Emel'yanov & Arlot (2008). As expected, the ephemeris systematic errors pointed out by Gomes-Júnior et al. (2015) are reduced with the STE ephemeris.

All the orbits determined for the satellites show satisfying residuals. The residuals are smaller than those obtained with JPL ephemeris, which was expected because the accuracy of an ephemeris decreases when we get further from the time of observations. The main risk of divergence over time comes from the possible absence of long-term effects when fitting to a short timespan of observations. If that were the case, our ephemeris would diverge too quickly to be of any use. JPL ephemerides are fitted over all the available observations. As a result, they will diverge less quickly than our own. Though they are no longer precise enough for our use, they remain a precious reference to identify whether our own model presents a quick divergence.

We compared our ephemeris to the JPL for all the Jupiter satellites we fitted, until 2018. For instance, the divergence between 2015 and 2018 is at most 98 mas in $\Delta\alpha\cos\delta$ and 58 mas in $\Delta\delta$ for Himalia and 181 mas in $\Delta\alpha\cos\delta$ and 152 mas in $\Delta\delta$ for Carme.

Fig. 1 displays the offsets of the positions published by Gomes-Júnior et al. (2015) for the satellite Carme in declination relative to our ephemeris, to Jacobson et al. (2012) JUP300 JPL ephemeris and Emel'yanov & Arlot (2008) ephemeris.We see that the systematic JPL ephemeris offsets pointed out by Gomes-Júnior et al. (2015) are reduced with our ephemeris, as expected.

The obtained ephemeris is hereafter refered as STE, for special-tailored ephemeris.

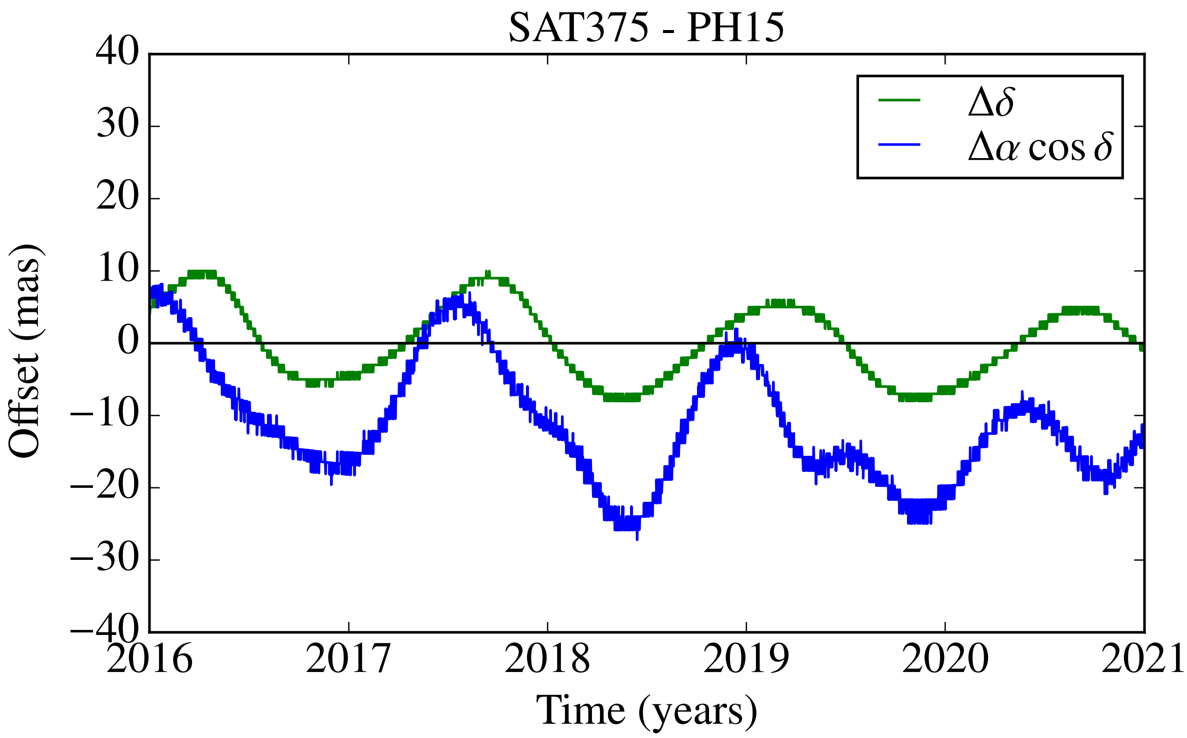

Figure 2: Comparison between the PH15, SAT375 JPL and Planet & Observations (Eme) ephemeris for the satellite Phoebe.

Phoebe's ephemeris

For the specific case of Phoebe, the ninth satellite of Saturn, we have updated the ephemeris published in Desmars et al. (2013). The new ephemeris (PH15) used the same dynamical model, including the perturbations of the Sun and the eight planets, the eight major satellites of Saturn and the J_2 parameter. The observations used to fit the model are identical to Desmars et al. (2013) (including 223 Cassini observations) with additional observations from Gomes-Júnior et al. (2015), Peng et al. (2015), observations from Minor Planet Circulars between 2012 and 2014 (available on the Natural Satellite Data Center[1]), and observations from Flagstaff (U.S.N.O, 2015) between 2012 and 2014. It represents a total number of 5886 observations from 1898 to 2014. In contrast, in Desmars et al. (2013) was used 3367 observations from 1898 to 2012. It represents an increase of almost 75% in the number of observations.

In Fig. 2 we compare our ephemeris (PH15) with the SAT375 JPL[2] ephemeris. The difference between them is smaller than 30 mas ($<$ 10 mas in Declination). This difference is smaller than the apparent diameter of Phoebe (see Table 1)

[1] `http://lnfm1.sai.msu.ru/neb/nss/bsapoouf.htm`

[2] Jacobson, R.A. 2015-Feb-27. "Satellite Ephemeris: SAT375", JPL Satellite Ephemeris File Release, `ftp://ssd.jpl.nasa.gov/pub/eph/satellites/nio/LINUX_PC/sat375l.txt`

Prediction of stellar occultations

Candidate events

The prediction of the occultations was made by crossing the stellar coordinates and proper motions of the UCAC4 catalogue (Zacharias et al., 2013) with the ephemeris presented in the previous section. The search for stellar candidates follows the same procedure as presented by Assafin et al. (2010, 2012) and Camargo et al. (2014).

We predicted occultations for the 8 major irregular satellites of Jupiter, Ananke, Carme, Elara, Himalia, Leda, Lysithea, Pasiphae and Sinope, and for Phoebe of Saturn.

A total of 5442 events were identified between January 2016 and December 2020. In Table 2 we present the number of stellar occultations predicted by year for each satellite. It is possible to see an increase in the number of events found for Phoebe in 2018 and for the satellites of Jupiter in 2019-2020. This is because at that periods these satellites will cross the apparent galactic plane. We call attention that about 10% of the events will involve stars brighter than magR=14 (and almost 25% brighter than magR=15), which helps the attempt of amateur observers.

Table 2: Number of stellar occultations for each satellite from January, 2016 up to December, 2020.

Satellite	2016	2017	2018	2019	2020	Total
Ananke	12	16	49	359	187	623
Carme	20	14	30	369	220	653
Elara	14	16	33	305	193	561
Himalia	15	12	54	257	230	568
Leda	8	24	38	362	208	640
Lysithea	16	11	35	330	212	604
Pasiphae	20	19	44	362	206	651
Sinope	15	21	34	356	256	682
Phoebe	32	98	238	79	13	460

In Fig. 3 we show an example of an occultation map. This is an occultation by Elara that will happen in February 21, 2017. This event can be observed from Australia and it is one of the best opportunities for this object due to the slow velocity of the event and it involves a bright star (MagR*=12.4).

Robustness of predictions

In contrast to TNOs, the irregular satellites have much better ephemeris because the orbits of their host planets are better known, their observational time span is much wider and covers many orbital periods. Moreover, the irregular satellites are much closer to Earth which implies in a much smaller shadow path error in kilometers. These advantages may be somewhat balanced by the smaller sizes estimated for the irregular satellites. Thus, in comparison, the chances for a successful observation of an stellar occultation by an irregular satellite should be considered at least also as good as those by TNOs.

To check the availability of observing an occultations we tested the robustness of a prediction for a large target. The test design consisted in observing the object and star to

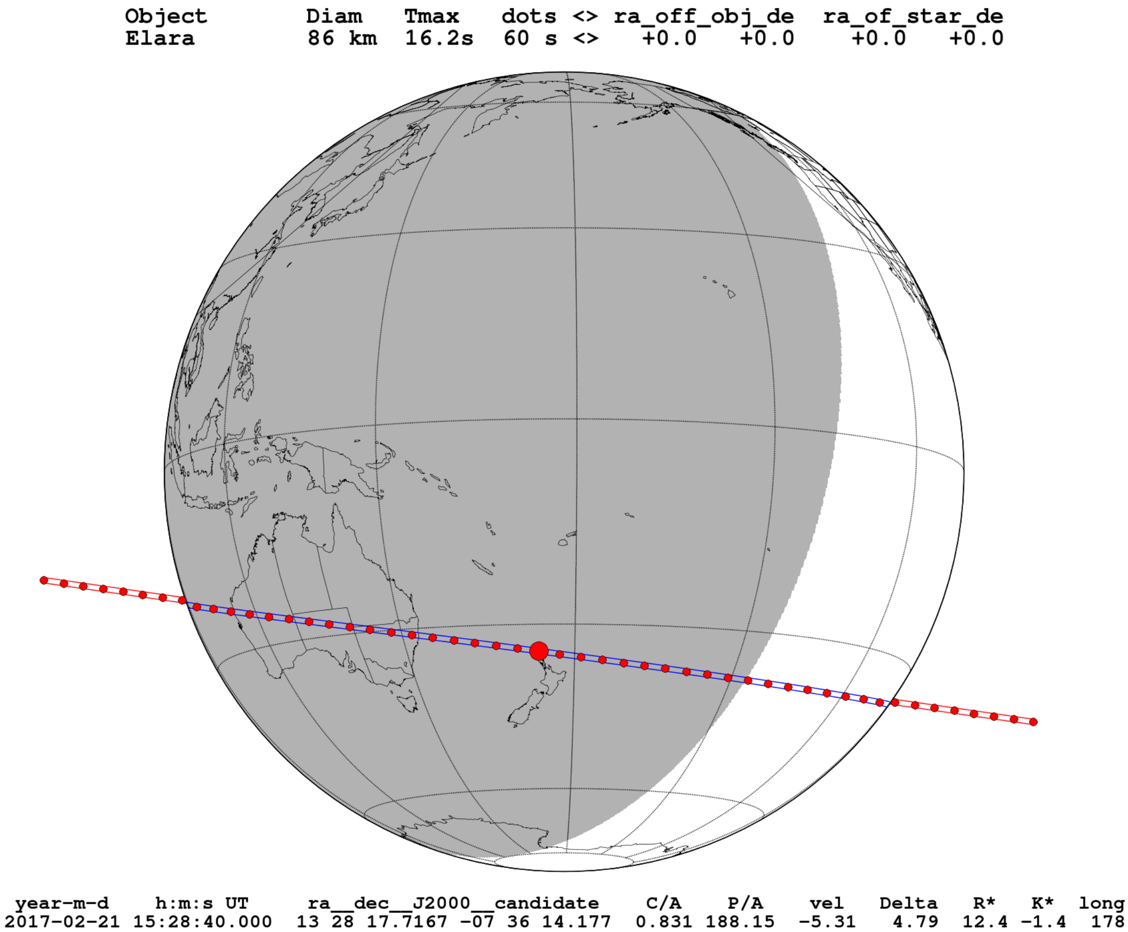

Figure 3: Occultation map for Elara. The central red dot show the geocentric closest approach of the shadow. The small ones shows the center of the shadow separated by 60s. The lines show the path of the shadow over the Earth. The shadow moves from right to left. **Labels:** Diam: Diameter of the object; Tmax: Maximum duration of the event for a central observation; C/A: the geocentric closest approach, in arcseconds; P/A: the satellite position angle with respect to the occulted star at C/A, in degrees; vel: velocity of event in km/s; Delta: Geocentric distance to the occulting object in AU; R^{*}: normalized magnitude to a common shadow velocity of 20 km s^{-1}; long: east longitude of subplanet point in degrees, positive towards east.

be occulted near the date of the event predicted when the two objects were present in the same field of view (FOV), close to each other. Thus, the relative positions between the two objects had minimal influence of the errors of the reference catalogue of stars used and possible field distortions The relative positions of the star and satellite were used to check the original prediction. Notice that in the test we did not attempt to observe any actual occultation. The test could be performed at any site, regardless of the Earth location where the occultation would in fact be visible.

We tested the occultation by Himalia predicted to occur on March 3, 2015. The shadow would cross the northern part of South America. For the event, four situations were considered:

1. Our nominal, published prediction with the STE ephemeris, and the nominal UCAC4 position of the star;

2. Prediction with the JPL ephemeris and the nominal UCAC4 position of the star;

3. From star and satellite offsets calculated from observations made a few days before the occultation when the objects were very separated (different FOVs);

4. Same as 3 but with the star and the satellite close in the same FOV.

Table 3 shows the differences between the predictions in the four situations. For situation 3 we observed the objects on February 22 with the Zeiss telescope (diameter = 0.6m; FOV = $12\overset{\prime}{.}6$; pixel scale = $0\overset{\prime\prime}{.}37/pixel$) at the Observatório do Pico dos Dias, Brazil (OPD, IAU code 874, 45°34′57″W, 22°32′04″S, 1864m). On that day, Himalia and the star were observed in separate FOVs as they were still far apart. On the night of the event, March 3, the objects were observed with Perkin-Elmer telescope (diameter = 1.6m; FOV = $5\overset{\prime}{.}8$; pixel scale = $0\overset{\prime\prime}{.}17/pixel$) at OPD just over an hour after the time scheduled for the event. Satellite and star were separated by about 16 arcsec, so very close to each other (situation 4). From the calculated offsets, the center of the shadow was obtained. Notice that the shadow path was not predicted to cross the OPD (which was located at almost 2000 km south from the shadow path). This was not necessary for testing the prediction.

The critical parameter in the comparisons is the C/A, which here is related to latitudes. The apparent radius of Himalia is about 20 mas (see Table 1). In the context of the test, for a 0 mas offset in C/A we would have 100% probability of observing the occultation, and 0% in the case of a C/A offset equal to or larger than 20 mas, the radius of Himalia. From Table 5, we have nearly 0% probability of success in situation 3, for which the offset in C/A was -20 mas, but when the relative astrometry was poor, 10 days prior to the event. Once at the day of the event in situation 4, the C/A offset dropped to -9 mas only, corresponding to a 55% probability of success. Comparison with the prediction using the JPL ephemeris (situation 2) gives a +11 mas C/A offset, or a compatibility of 45% between the ephemerides. All this suggests that there was a good probability of observing the event. The largest differences between the shadows of the four situations were 36s in time along the shadow path and 101km (31 mas) in the direction perpendicular to the shadows, suggesting that observers should be spread in narrow latitude ranges 100 km wide.

Table 3: Comparison between the predictions of the Himalia occultation at March 03, 2015.

Differences with respect to the STE prediction			
Method	Instant of C/A	C/A	Sit.
STE	00:39:51 UTC	0″.703	i
JPL	-26s	+11mas (36km)	ii
Feb. 22 Obs.	-14s	-20mas (65km)	iii
Mar. 03 Obs.	-36s	-09mas (29km)	iv

C/A: geocentric closest approach; Sit: Situation test considered.

Discussion

We performed new numerical integration for improving the orbits of some of the larger irregular satellites. Consequently, with more precise ephemeris, we, then, predicted stellar occultations aiming to access fundamental parameters like size, shape, albedo, ultimately aiming to track the formation origin of these bodies.

For the irregular satellites of Jupiter (Ananke, Carme, Elara, Himalia, Leda, Lysithea, Pasiphae and Sinope), we produced ephemeris using only the observations of Gomes-Júnior et al. (2015). The systematic errors found in the JPL ephemeris (Jacobson et al., 2012) and Emel'yanov & Arlot (2008) were corrected. This new ephemeris was denominated Special Tailored Ephemeris.

We also updated the ephemeris of Phoebe (Desmars et al., 2013) using the observations of Gomes-Júnior et al. (2015), Peng et al. (2015) observations from MPC and from Flagstaff. A total of 5886 observations between 1989 and 2014 were used in the process. This represents and increase of about 75% in the number used to generate the orbits of Phoebe by Desmars et al. (2013).

We predict stellar occultations for the period of 2016-2020 for eight irregular satellites of Jupiter: Ananke, Carme, Elara, Himalia, Leda, Lysithea, Pasiphae, and Sinope; and one satellite of Saturn: Phoebe. The procedure used was the same as that for the prediction of stellar occultations by Pluto and its satellites in Assafin et al. (2010) and by Centaurs and TNOs in Assafin et al. (2012) and Camargo et al. (2014).The candidate stars were searched in the UCAC4 catalogue. The occasional passage of Jupiter by the galactic plane in 2019-2020 and Saturn in 2018 creates the best opportunity of observing stellar occultations in the near future due to the great density of stars in the region. Indeed, a total of 5442 events are foreseen.

In a broader, general sense, the probability of successfully observing an occultation is roughly the ratio of the satellite's radius by the budget error (2 sigma for a 95% confidence level) of ephemeris and star position. Thus, UCAC4 errors ranging between 20 mas - 50 mas (1 sigma) combined with a mean error (1 sigma) in the JPL ephemeris of 30 mas for Himalia and 150 mas for Leda published in Table 2 of Jacobson et al. (2012) would give 28%-17% probability of observing such an event by Himalia and $\approx$ 2% for Leda, the smallest irregular satellite in the sample. Observations a few days before the date of occultation predicted may improve the combined errors to 40-80 mas, depending on the magnitude of the objects.

The test made with an occultation expected to happen in March 03, 2015 for Himalia showed that this event would probably have been observed successfully in case there were observers available in the shadow area. The results show satisfying small offsets with respect to the local of the prediction.

Gomes-Júnior et al. (2015) also observed Sycorax (satellite of Uranus) and Nereid (satellite of Neptune). Sycorax had a few observations on 9 nights in two years which did not cover one orbital period. For Nereid, the observations covered many orbital periods, but due to Nereid's large orbital eccentricity there are no observations near the pericenter.

Uranus and Neptune are crossing a very low dense region of stars. This results in almost no stellar occultation by these objects up to 2020. In fact, using JPL ephemeris, we identified only 2 events for each satellite in this period, but these are events with bad conditions (shadow far from observatories; faint stars).

Continuous observations of the satellites are recommended and fitting of our dynamical model to those observations are expected to reduce the respective STE ephemeris errors. The first version of the GAIA catalogue is to be released up to the end of 2016 and will improve the position error of the stars to the 1-5 mas level. Re-reduction of older positions, and reduction of new positions of irregular satellites with GAIA will improve new orbit determinations. It will also allow for the discovery of ocultations by more stars not present in the UCAC4 catalogue. The release of the GAIA catalogue should have a positive impact on both the astrometric precision of occulted stars and the reduction of new astrometric positions of the satellites. As a result, prediction of stellar occultations by irregular satellites shall increase in number as well as in success.

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