Deliverable 3.2

H2020 COMPET-05-2015 project
"Small Bodies: Near And Far (SBNAF)"

Topic: COMPET-05-2015 - Scientific exploitation of astrophysics, comets, and planetary data
Project Title: Small Bodies Near and Far (SBNAF)
Proposal No: 687378 - SBNAF - RIA
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WP	**WP 3 Lightcurve inversion technique**
Del.No	**D3.2**
Title	**Predictions of shape orientations**
Lead Beneficiary	UAM
Nature	Demonstrator
Dissemination Level	Public
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WP3 Lightcurve Inversion techniques
Objectives: WP3 has the main objective to join various types of data for full physical models of benchmark asteroids and to develop the web service with a database in order to provide the models to the community.
Deliverable 3.2: Predictions of shape orientations [month: 12].
Objectives: Predictions of shape orientations for forecast occultation events, ISAM (Interactive Service for Asteroid Models) service upgrade.

Description of deliverable

1 Scaling 3D shape models of asteroids

Asteroid shapes, although viewed as point-like sources in most of the telescopes, can be reconstructed using advanced lightcurve inversion methods. As they rotate, these bodies reflect sunlight with different parts of their surface, causing their brightness to decrease or increase with time (shown in a plot called lightcurve – Figure 1). The pattern of such light variations depends on viewing and illumination geometry, and in the case of main belt asteroids it can notably change from year to year. But e.g. for near-Earth asteroids (NEAs), the change can be on much shorter timescales, during weeks. From these changes, the spin axis position in space can be determined, and computer 3D shape models can be constructed (examples are given in the figures in Table 1 at the end of this document).

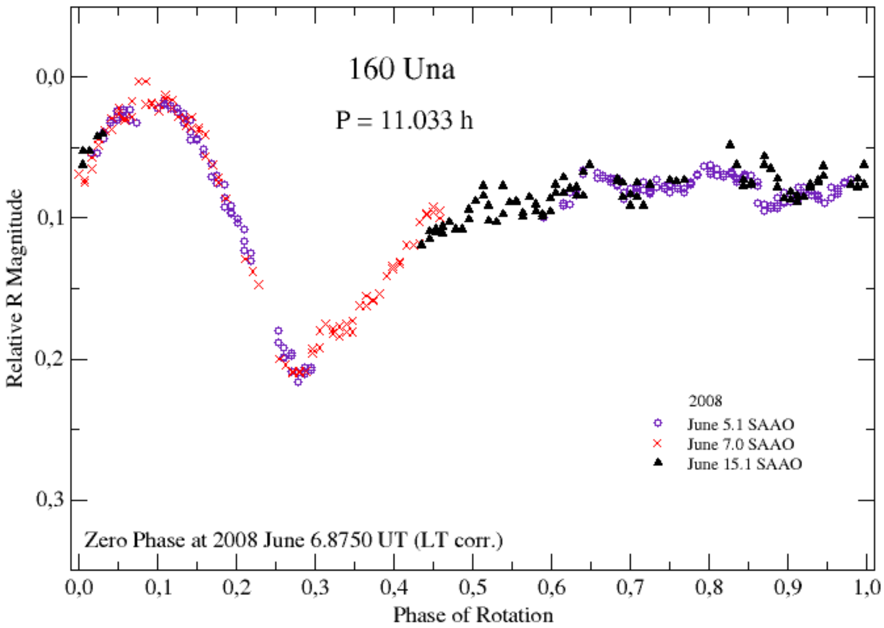


Figure 1: Example of an asteroid lightcurve. The vertical axis shows the brightness (in magnitudes), and the horizontal axis the time (in rotational phase folded with a period of 11.033 hours). Many asteroids display highly irregular and asymmetric lightcurves, because of their complex shapes (after: Marciniak et al. 2009)

However such shape models are scale-free, because the size of the studied asteroid cannot be inferred from lightcurves alone. The object could be large with low albedo or much smaller in case of a high albedo (albedo determines what amount of light is reflected by a surface). For realistic albedo ranges between 0.03 and about 0.5, the size can differ by a factor roughly between 3 and 5. See the example of Hayabusa-2 mission target named 162173 Ryugu (Figure 2).

Also, there are usually two solutions for the spin axis position, spaced in longitude by around 180^o and it is not possible to tell which one is correct. But there are other complementary techniques to study asteroids - stellar occultation is one of them (see the description of this technique in other SBNAF deliverables: D5.1 and D6.1). In short, an asteroid on its way over the sky can sometimes occult a star, casting a shadow on the Earth surface. This shadow has the exact size and shape of the asteroid (more precisely: projected 2D-shape at the given moment). These events can be predicted in advance (see SBNAF

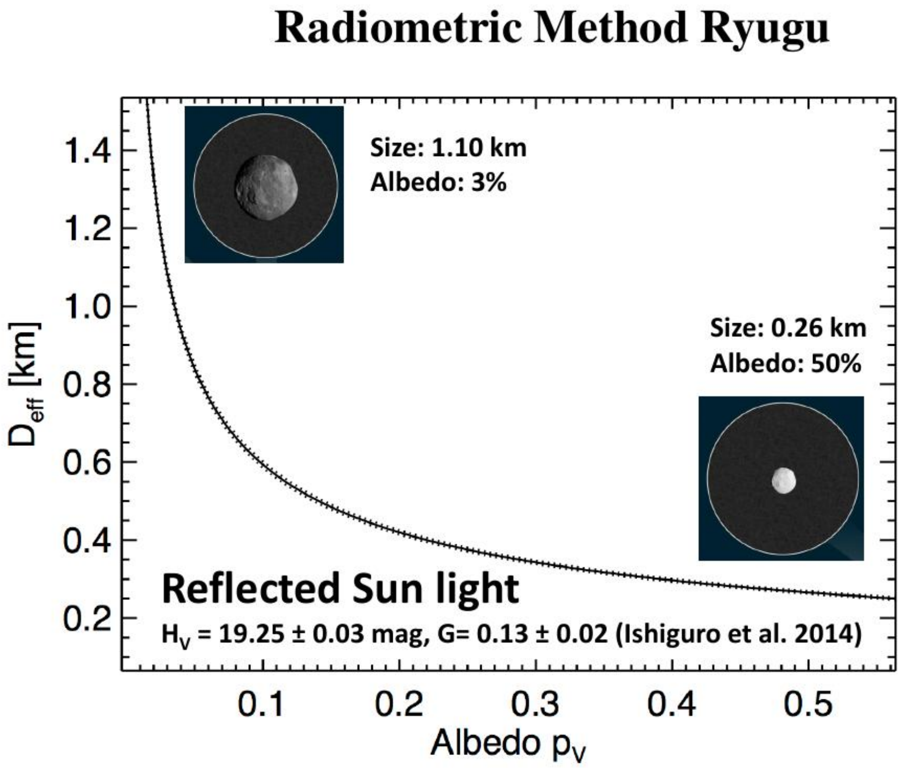


Figure 2: Relation between possible size and albedo for asteroid Ryugu. Observations made in infrared range can help to determine the size accurately. D_{eff} is volume equivalent diameter from radiometry.

deliverable D 5.2 for the list for year 2017, and the webpage[1]) and observers simply need to measure times of the star disappearence and reappearance. From such shadow chords a contour of an asteroid can be constructed, and it can serve to scale previously obtained shape models based on lightcurves, additionally confirming topographic features, and often enabling to reject one of the possible spin solutions (results can be found in e.g. webpage[2] and papers by: Kissling et al., 1991; Dunham et al. 1990; George et al. 2011; and Ďurech et al.2011).

2 Shape model orientations in ISAM service

Asteroid models created with lightcurve inversion by various authors are provided to the community through services like DAMIT[3] (Database for Asteroid Models from Inversion Techniques, Ďurech et al. 2010), PDS[4], and ISAM[5] (Interactive Service for Asteroid Models, Marciniak et al. 2012). When such models are used for further research, there should be a

[1] http://www.asteroidoccultation.com/
[2] http://www.asteroidoccultation.com/observations/NA/
[3] http://astro.troja.mff.cuni.cz/projects/asteroids3D
[4] https://pds.nasa.gov/
[5] http://isam.astro.amu.edu.pl

proper credit given to the actual authors of given models (information available under the link “source” in ISAM, and “Detail” in DAMIT).

ISAM service is our web-based tool that allows to display available shape models of asteroids in the plane of sky in a requested moment, both in the future and in the past. It also allows to generate lightcurves by rotating the shape models in any chosen time and geometry, in a form of plots and animations, with various 3D effects. For applications like stellar occultation fitting, the whole silhouette of the occulting body needs to be seen. The view can be rotated forward in time to show the asteroid as it would appear to a nearby observer, which would be needed for observations from visiting spacecrafts. Otherwise, an Earth-based observer is assumed.

All this is possible in the ISAM service.

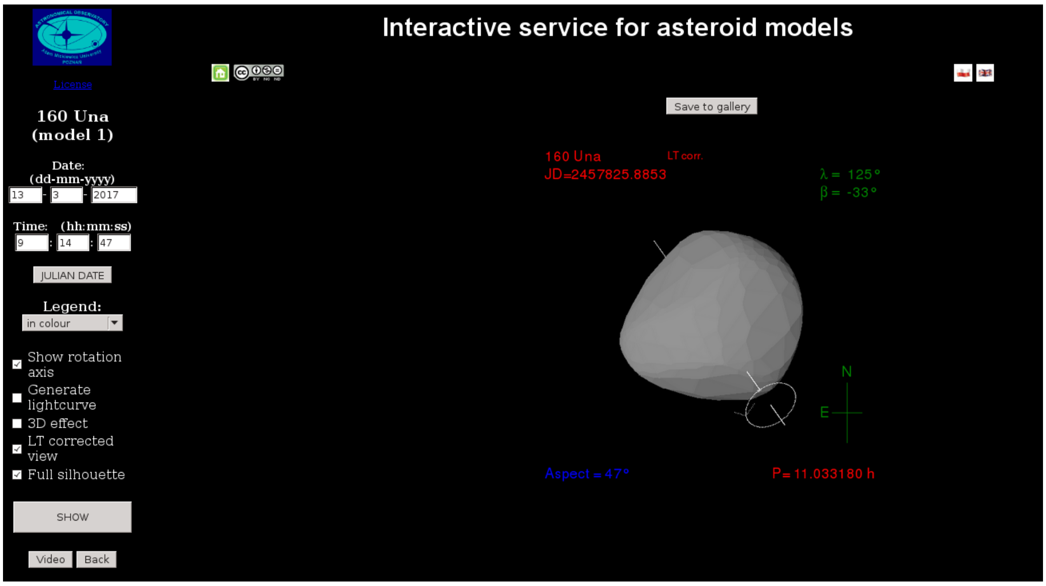


Figure 3: Example view of the “orientation” mode of the ISAM service. One of our earlier models is displayed (source: Marciniak et al. 2009).

3 ISAM usage

In order to start working with ISAM service one needs to **select an asteroid** from the list of all bodies with available models - the set is largely identical with the one in the DAMIT service and is being regularly updated. For the purposes of occultation fitting, an **“Orientation” mode** needs to be chosen.

At the webpage a short description is provided of how to use the “orientation” mode. This is the place where one can generate the model plane-of-sky views for any **requested date and time** (restricted to the calendar years 1700 - 3000). Both Julian and Gregorian date formats are possible. A display of a legend can be adjusted and additional options can be chosen. If parameters remain unchanged, choosing the **“SHOW” button** generates the model orientation for the present moment of time. To generate the lightcurve that the model would produce at a given orientation, one needs to choose the “Generate lightcurve” option. The plotted lightcurve takes a few seconds to be generated and can be downloaded, both as a plot or in the form of data file.

In Figure 3, the outcome of the "orientation" mode is shown. The displayed model is described by the Julian date, coordinates of the north pole, an aspect angle (angle between the north pole of an asteroid and the direction to the observer), and the period of rotation connected to a specific model solution. The north and east directions in the plane-of-sky are also shown. Images with their legends can be displayed in black and white and downloaded for the use in publication, provided that a proper reference is given.

The rotation axis is marked with a straight line piercing the poles and has a length that depends on the viewing angle. To help one to visualise the axis in space, a small circle is shown over the north pole, which changes its shape with changing viewing angle. It also shows the sense of rotation and moves when the animation mode is used. For some applications, like in-situ observations a view corrected for Light-Travel time is available. It rotates the asteroid forward in time, not changing the JD epochs, to generate phases which become visible only after the light reflected from the asteroid surface actually reaches the Earth.

For the stellar occultation fitting, it is important to mark the options **"full silhouette"** (then **"SHOW" button** to refresh the image). By default, only the illuminated parts of the asteroid models visible from the Earth are shown against a black background. However during a stellar occultation, the chords are related to the whole body of the asteroid regardless of whether they are illuminated or not (as in our example in Figure 3). Using **"full silhouette"** option shows the asteroid shape fully illuminated.

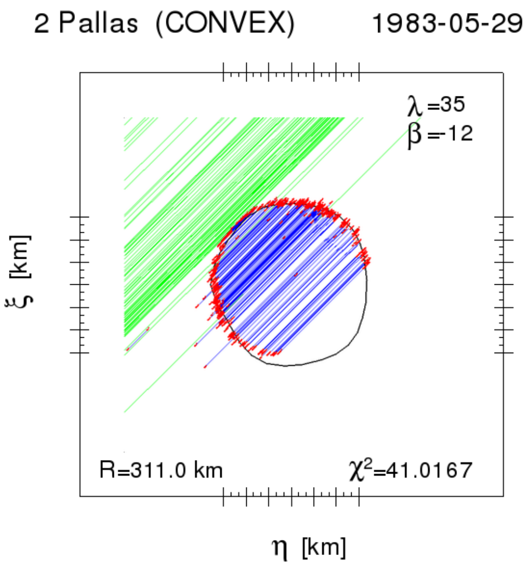


Figure 4: Unusual stellar occultation by asteroid 2 Pallas on 29 May 1983 (from: Dunham et al., 1990) with over 100 of chords fitted to convex inversion model of this target based on lightcurves (from: Torppa et al., 2003). The radius of largest dimension of the model is given in the bottom left.

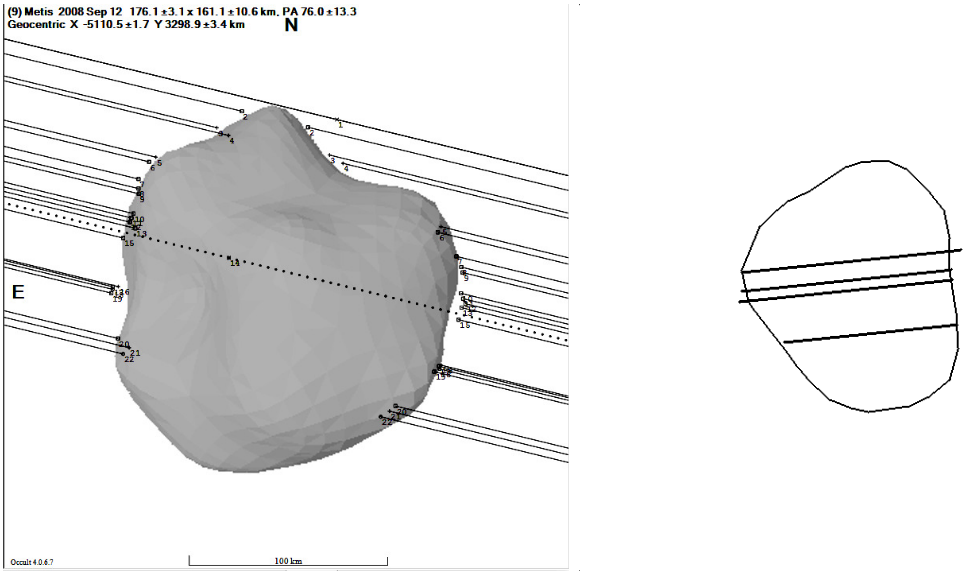


Figure 5: Left: stellar occultation by asteroid 9 Metis on 12 September 2008, fitted to initial SAGE model of this target based on lightcurves. Right: Recent stellar occultation by 21 Lutetia on 10 February 2017, preliminarily fitted to its KOALA model contour (Carry et al. 2012)

4 Succesful past events

There have been many stellar occultations whereby previously obtained shape models have been scaled and confirmed. Examples are shown in Figures 4 and 5, which include SBNAF targets 2 Pallas, 9 Metis, and 21 Lutetia. Here we show the fit to occultation contours of their previous models. We are going to refine their shape models with the improved SAGE algorithm (the status of this work is reported in deliverable D6.5).

5 Orientation predictions

Below we present shape orientations of ten of SBNAF targets for stellar occultations predicted for the year 2017 over Spain and Argentina (see deliverable D 5.2). In some cases even the initial data reduction fitting an ellipsoid to the occultation chords will already allow us to reject one of the pole solutions (e.g. 7 Iris or 20 Massalia in Table 1). Later the occultation timings will be incorporated into an algorithm that fits the shape silhouette to the occultation chords to minimise the deviations and scale the model in kilometers. If the asteroid has the mass estimate available, knowing its precise volume, we will be able to compute its density, and thus find out about its internal structure and composition (Carry 2012). These values can provide valuable constraints on Solar System formation models (e.g., Morbidelli et al. 2005, Levison et al. 2009, Walsh et al. 2011).

The possiblility to predict shape model orientations is also very useful for cases where the radiometric technique (where the thermal infrared radiation emitted by the model is studied) results in very different size values for data from different epochs. An example can be seen for the case of 9 Metis in Figure 6: the radiometry from two datasets gave very different values for the spherical equivalent diameters: $D_1 = 196 \pm 40$ km and $D_2 = 160 \pm 20$ km, but with the help of ISAM we could show that the object's cross section is indeed very different for these two epochs and that this discrepancy is not entirely related to the simplifying assumptions of the thermal model (non-rotating sphere with an idealised non-conductive surface).

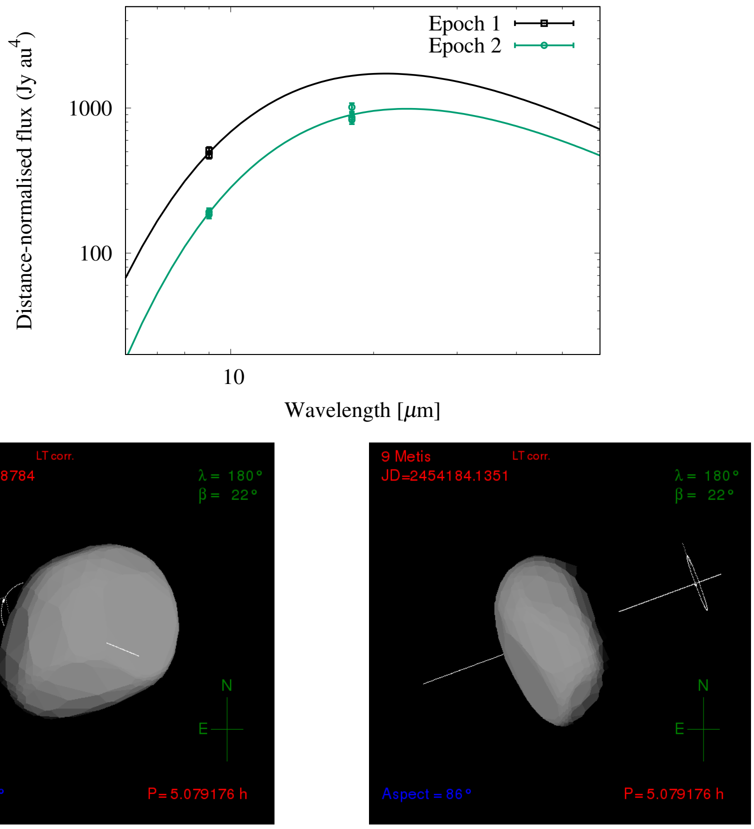
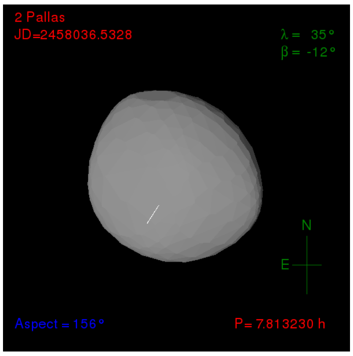
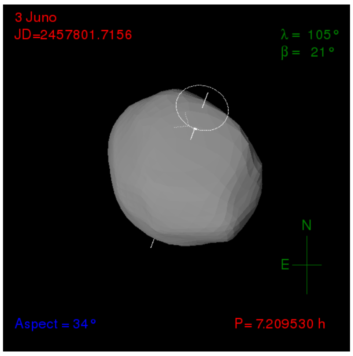
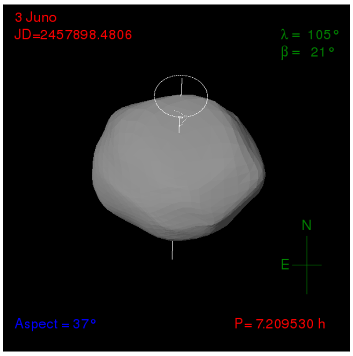
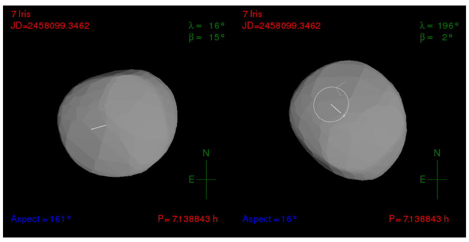


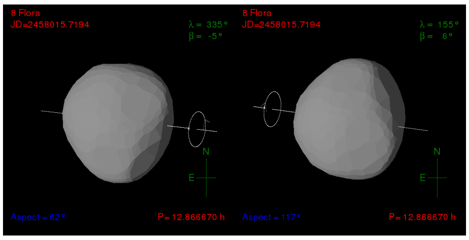
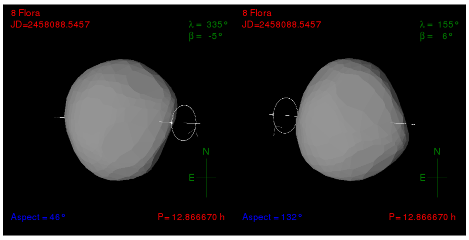
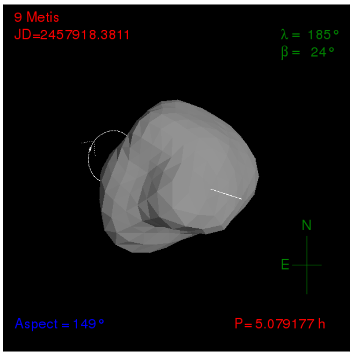
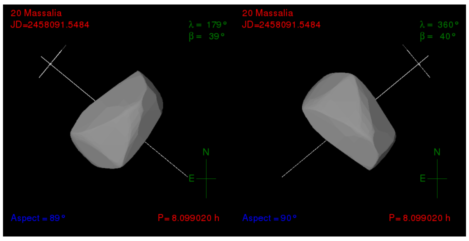
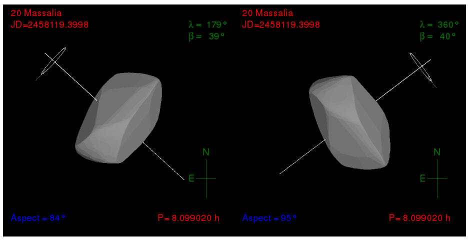
Figure 6: Top: Infrared fluxes of asteroid 9 Metis observed at two diffrent epochs (points), and the corresponding spherical model fits (lines). The fluxes and the model have been normalised to a geometry of observation of 1 au, so that the differences in the fluxes are only related to the different projected areas observed at those epochs (the observing geometries were very similar). Bottom left: Earth-based observer's view of the object in epoch 1; bottom right: *idem* for epoch 2.

6 Outlook

We are planning to especially draw occultation observers' attention to events where asteroids with ambiguous spin state solutions or uncertain shape models are involved (here asteroids number: 7, 8, 20, and 37).

Scaling of shape models, if not possible by occultation evens due to lack or too uncertain chords, can also be done by means of adaptive optics imaging on large telescopes and/or via radiometric techniques.

Name/Date	Algorithm	Shape Orientation
2 Pallas 2017-10-10	convex inversion (Ďurech et al. 2011)	
3 Juno 2017-02-17	ADAM (Viikinkoski et al. 2015)	
2017-05-24	ADAM (Viikinkoski et al. 2015)	
7 Iris 2017-12-11	convex inversion (two solutions) (Hanuš et al. 2013b)	

8 Flora 2017-09-19	convex inversion (two solutions) (Hanuš et al. 2013b)	
2017-12-01	convex inversion (two solutions) (Hanuš et al. 2013b)	
9 Metis 2017-06-13	KOALA (Hanuš et al. 2013b)	
20 Massalia 2017-12-04	convex inversion (two solutions) (Kaasalainen et al. 2002a)	
2017-12-31	convex inversion (two solutions) (Kaasalainen et al. 2002a)	

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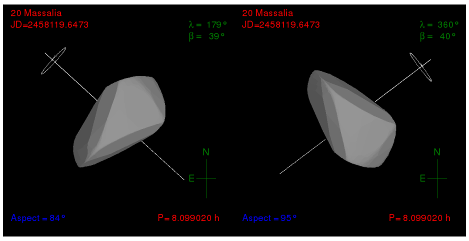
<td>
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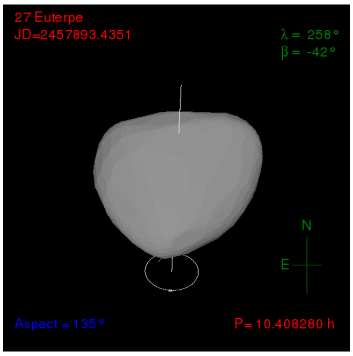
<td>27 Euterpe
2017-05-19</td>
<td>convex inversion (Stephens et al. 2012)</td>
<td>
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2017-03-10</td>
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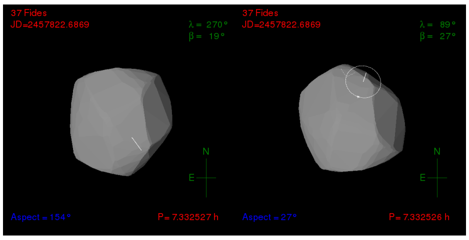
<td>
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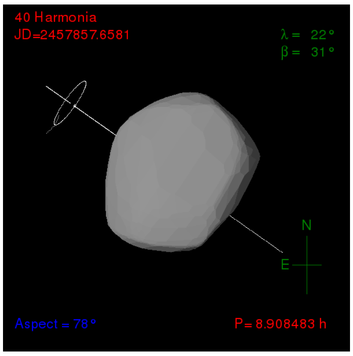
<td>40 Harmonia
2017-04-14</td>
<td>convex inversion (Hanuš et al. 2013b)</td>
<td>
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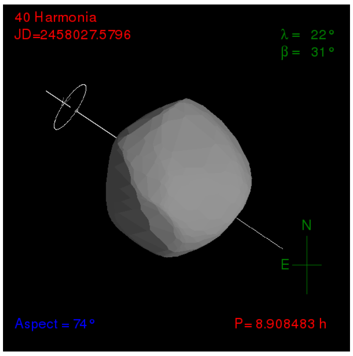
<tr><td>2017-10-01</td><td>convex inversion (Hanuš et al. 2013b)</td><td>
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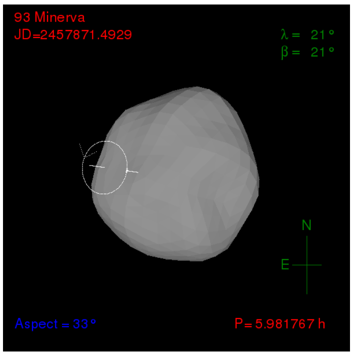
<tr><td>93 Minerva
2017-04-27</td><td>KOALA (Marchis et al. 2013)</td><td>
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Table 1: Predictions of asteroid shape models orientations for the moments of stellar occultations expected in the year 2017. Model views generated using ISAM (`http://isam.astro.amu.edu.pl`).

7 Bibliography

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- Torppa et al. 2003, Icarus 164, 346 "Shapes and rotational properties of thirty asteroids from photometric data"
- Viikinkoski et al. 2015, Astronomy Astrophys. 581, L3 "VLT/SPHERE- and ALMA-based shape reconstruction of asteroid (3) Juno"