AO Images of Asteroids, Inverting their Lightcurves, and SSA

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ABSTRACT

In a program to study asteroids with large telescopes, we have recently obtained images of Main-Belt asteroids with adaptive optics (AO) on the Keck-II 10 meter telescope, the world's largest. Although generally featureless as expected, these images show irregular asteroid outlines, and by following the changing size and orientation we have been able to deduce their full triaxial ellipsoid dimensions and spin axis direction in less than one night. Even before the first such AO images, Kaasalainen [1,2] and his colleagues made attempts to deduce the shape of asteroids from their lightcurves. We compare our AO images to these lightcurve inversion (LCI) models, and show the excellent agreement. Similar techniques can be applied to satellite lightcurves.

1. INTRODUCTION

As astronomy as been revolutionized by adaptive optics (AO), so has the field of asteroid lightcurve work with new methods of lightcurve inversions. While asteroid shapes (usually in the form of triaxial ellipsoid axes ratios) and rotational pole locations have been obtained from lightcurves (the variation of brightness as the asteroid rotates in several hours) of these unresolved targets over decades as they move around the sky, only in the last several years have these data been turned into (unscaled) three dimensional models by Kassalainen and his colleagues [1,2]. By making the simple assumptions that the particular light scattering model is unimportant and the asteroid surface is convex everywhere, they have succeeded in inverting lightcurves to construct LCI (LightCurve Inversion) models that deviate from the simple smooth triaxial ellipsoids used in previous lightcurve work, and AO [3,4] as well.

Recalling that no more than a handful of asteroids have ever been visited by spacecraft, and that all asteroids are smaller than the seeing disk (< 1 second of arc) from Earth, the best images of asteroids have been otherwise obtained with AO on 8-10 m telescopes from the ground, the largest being the twin 10 m Keck telescopes on Mauna Kea. In this paper we compare the models of Kassalainen to images obtained at Keck, and show both the validity of the models and the utility of treating the AO images as projections of our canonical smooth, featureless triaxial ellipsoids.

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2. KECK AO OBSERVATIONS

We competed for heavily oversubscribed time on Keck-II, and were granted one night in August 2006 to image a few asteroids as they rotated during the evening. Using AO behind the 10 m telescope at a wavelength of 2.1 μm, we were able to derive the pole and triaxial ellipsoid dimensions of four asteroids, as reported in Tables 1-3, from images obtained in this single night. Performing a simple deconvolution, dividing the objects by the Lorentzian PSFs obtained in the fitting process, we can compare either convolved or deconvolved images to Kassalainen models. Figure 1 shows the 10 m telescope images of the asteroids and of check stars, and Fig 2 shows their Fast Fourier Transforms (FFT).

Table 1. Asteroid Ellipsoid Parameter Results

Name	a (km)	b (km)	c (km)	$\theta(^\circ)$	$N(^\circ)$	ψ_0 (UT)
2 Pallas	548 ± 3	504 ± 3	459 ± 15	$+42 \pm 6$	2 ± 1	8.71 ± 0.06
129 Antigone	163 ± 4	133 ± 2	90 ± 28	$+46 \pm 10$	231 ± 3	10.25 ± 0.06
409 Aspasia	198 ± 5	172 ± 3	172 ± 3	-34 ± 3	293 ± 5	10.01 ± 0.12
704 Interamnia	349 ± 4	339 ± 3	274 ± 22	-26 ± 16	275 ± 1	6.62 ± 0.19

Table 2. Asteroid Ellipsoid Poles

	Eq		Pole	Ecl	
Name	RA($^\circ$)	Dec($^\circ$)	Err Rad ($^\circ$)	$\lambda(^\circ)$	$\beta(^\circ)$
2 Pallas	41	−13	3	34	−27
129 Antigone	222	+39	5	202	+52
409 Aspasia	58	+65	4	72	+43
704 Interamnia	343	+73	3	47	+66

Table 3. Volumes and Mean Diameters

Name	Volume (km^3)	$\bar{d}$ (km)	IRAS [5] d (km)
2 Pallas	$6.64(\pm 0.22) \times 10^7$	502 ± 5	498 ± 19
129 Antigone	$1.02(\pm 0.32) \times 10^6$	125 ± 13	124†
409 Aspasia	$3.05(\pm 0.11) \times 10^6$	180 ± 2	162 ± 7
704 Interamnia	$1.70(\pm 0.14) \times 10^7$	319 ± 9	317 ± 5

† Not observed by IRAS; diameter is from the IMPS ground-based catalog [5].

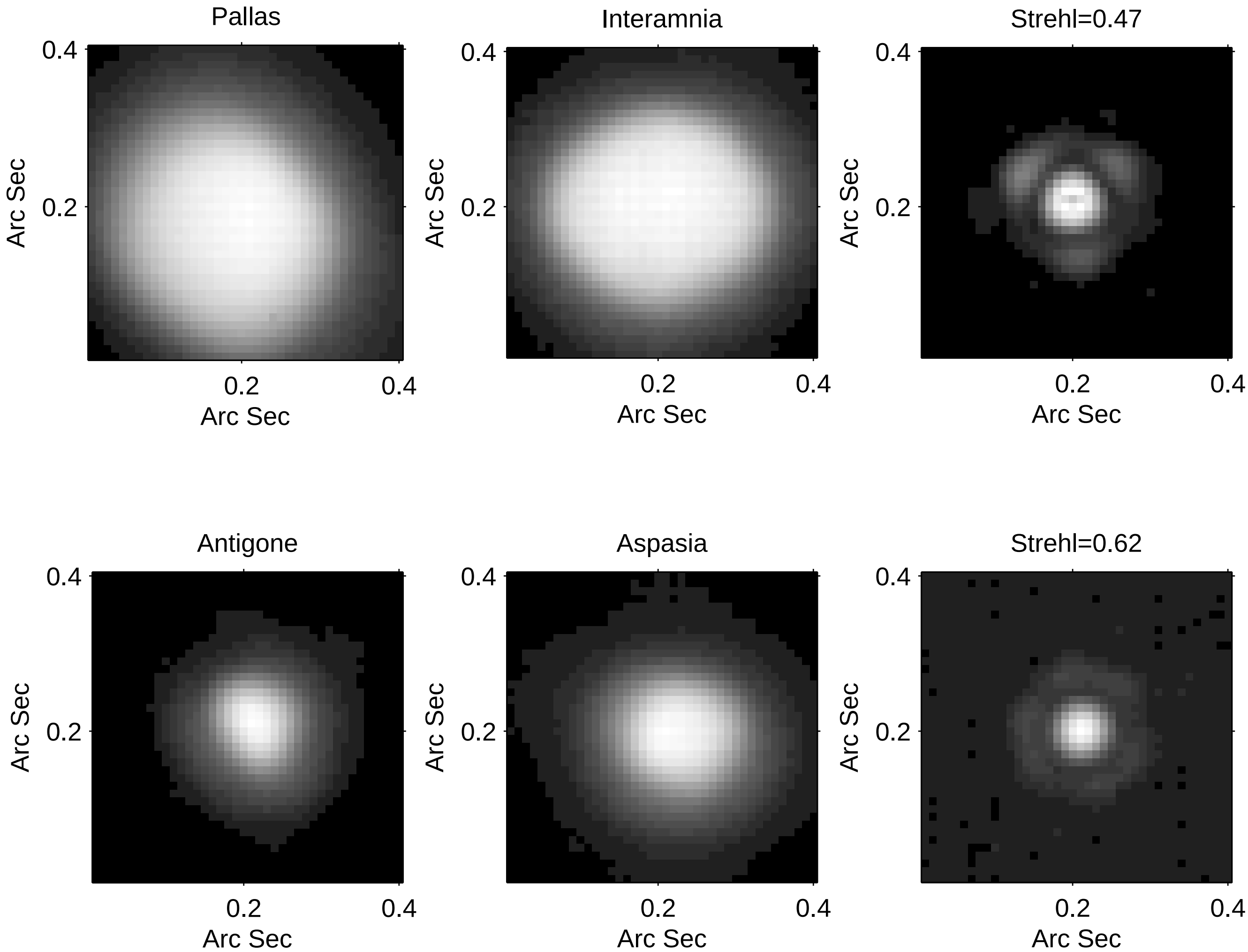

Figure 1. Images of four asteroids and two stars. The star at upper right has a Strehl of 0.47, and at lower right 0.62. Unlike the images of asteroids to follow, these images are displayed on a square root scale to show the faint structure around the stars.

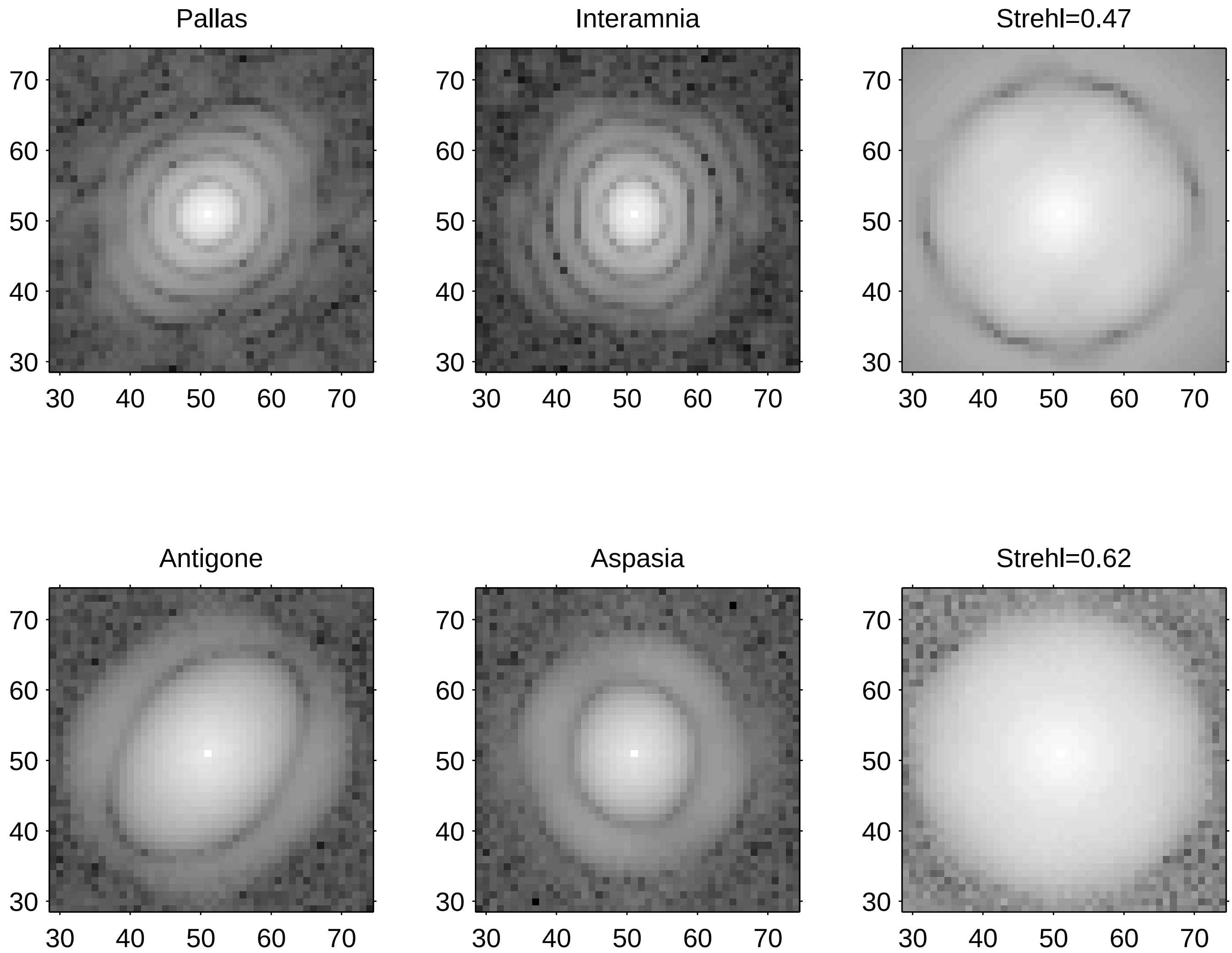

Figure 2. Amplitudes of FFT's of images in Fig 3. To show subtle but important detail, these FFT's are displayed on a log scale. Notice how the high frequency cutoffs are well demarcated in all of the FFT's, outside of which appears only noise. Also notice how the large asteroids Pallas and Interamnia show several ripples or minima while the smaller asteroids show only one or two.

3. LIGHTCURVE INVERSION MODELS

Kassalainen and colleagues make their models available on a web site* and in Figs 3 and 4, we compare deconvolved images of 2 Pallas and 129 Antigone to the models. As expected, the images show no albedo features (asteroids have been painted gray by collisions), but deviations from elliptical outlines are apparent, and are well-captured by Kassalainen's models, although some differences between the LCI models and our images are evident.

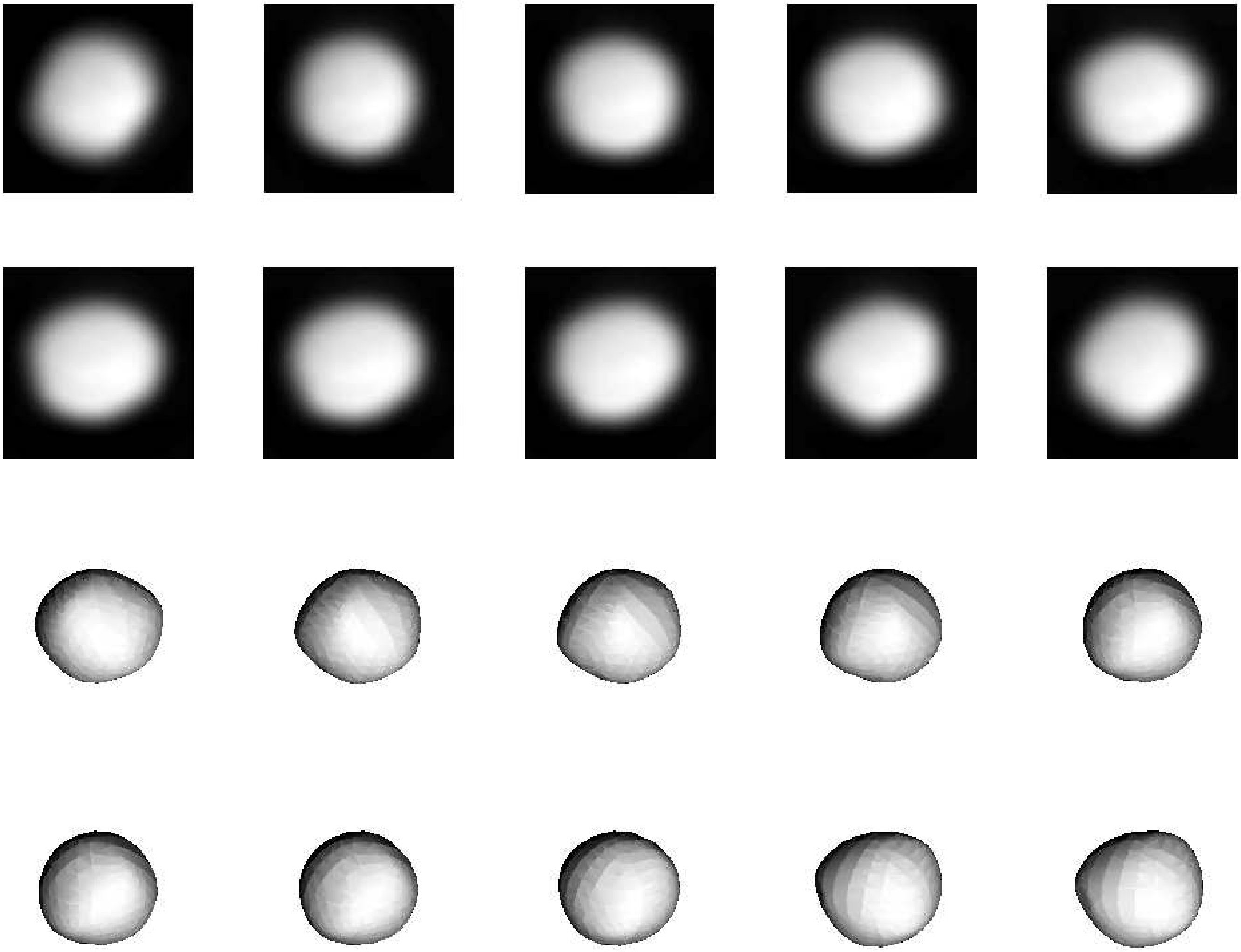

Figure 3. Deconvolved images of 2 Pallas and models from lightcurve inversions.

*http://astro.troja.mff.cuni.cz/ projects/asteroids3D/web.php

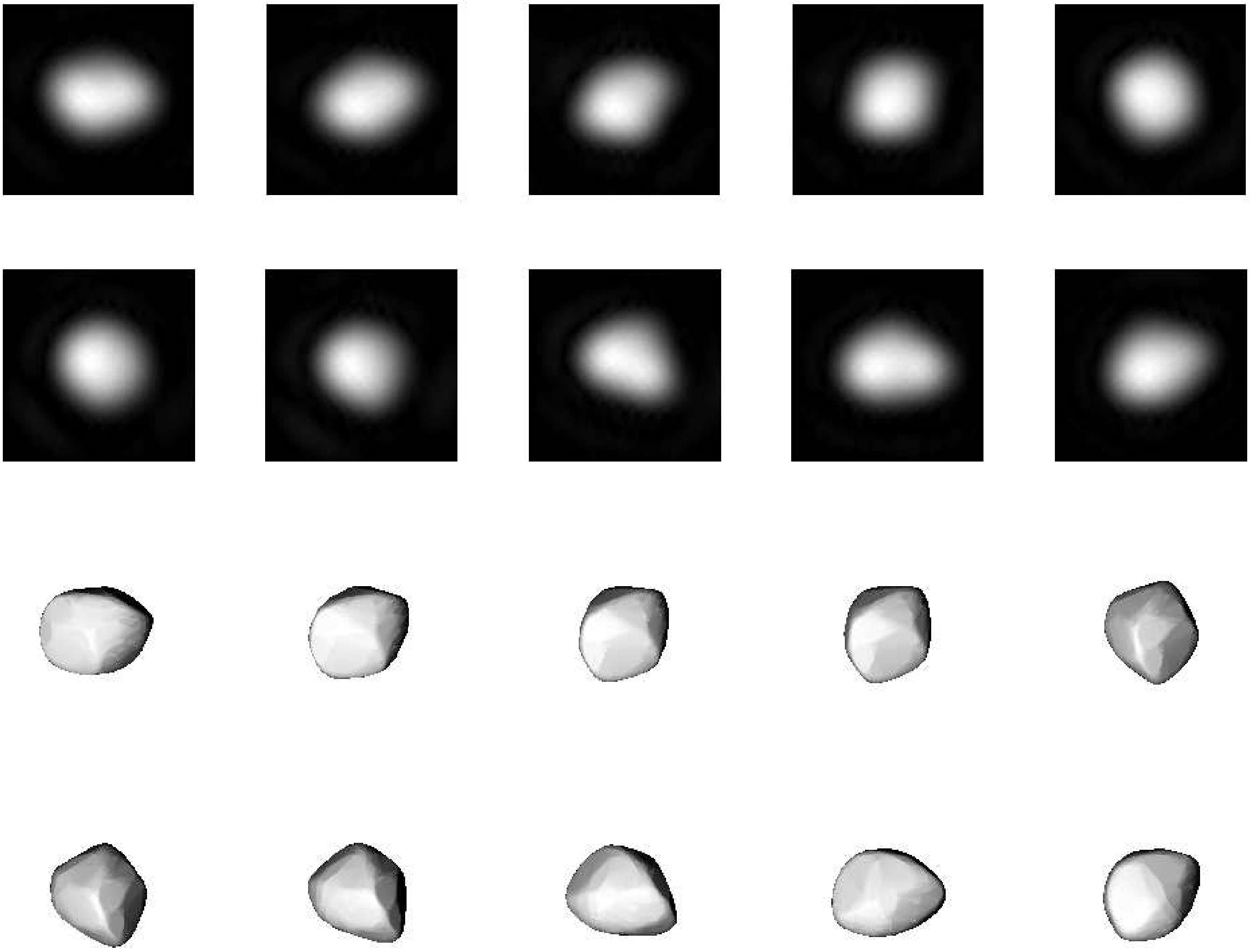

Figure 4. Deconvolved images of 129 Antigone and models from lightcurve inversions.

4. EDGE RECONSTRUCTION

With featureless asteroids, image reconstruction techniques are most productive in finding the edges or outlines of objects. We have developed a method to produce the same kind of LCI 3-D models from the contours of a series of reconstructed images of asteroids. Since asteroids are so hard-edged, any unsophisticated algorithm can be used to produce a one-contour outline, and we use the standard MATLAB contour function on images produced by our simple deconvolution. For each image, we know the asteroid's sub-Earth longitude and latitude from our triaxial ellipsoid model and pole. We then construct the coordinates of the contours for each image produced by MATLAB, keeping in mind that edges are defined not by points located 90° from the direction of the observer, but by points where the surface normal is pointing 90° from the observer. The surface normals for ellipsoids are easily and exactly calculated for every point on the surface. Combining these longitudes and latitudes with the apparent distances from the center to the contour points then gives radius vectors in asteroid coordinates for the contours of a single image. By combining several such contours at various rotational phases (Fig 5), a 3-D model can be built up. Our 3-D model of Antigone from 10 Keck images in one night is shown in Fig 6.

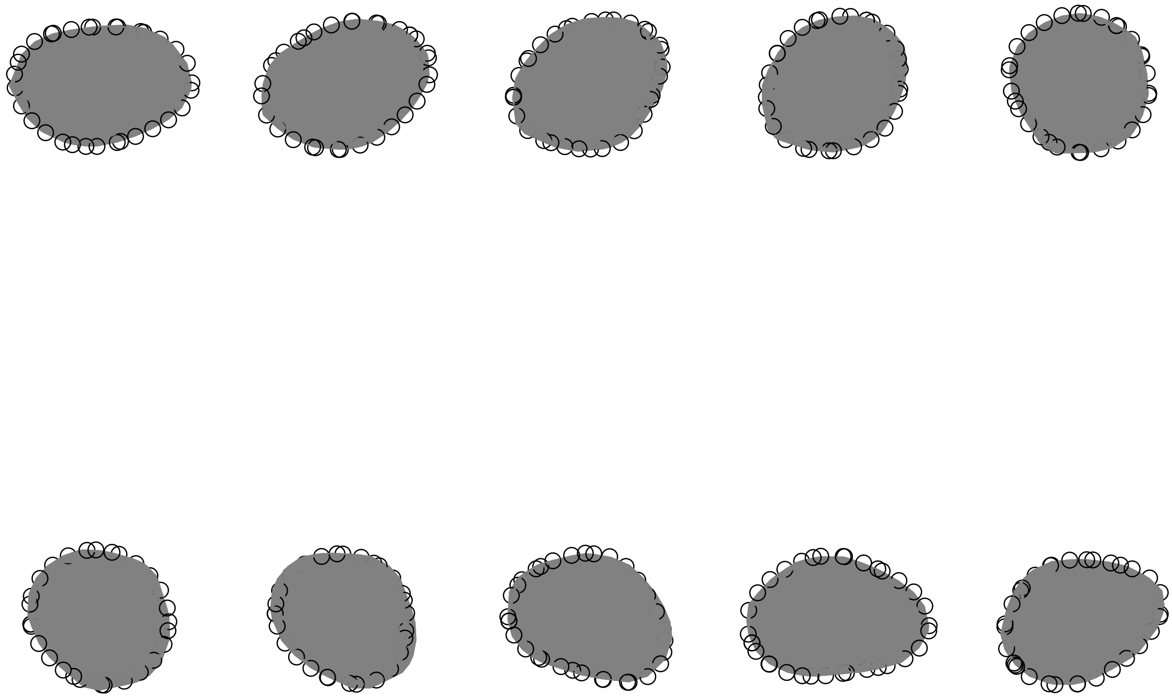

Figure 5. Contours on the projected 3-D model of 129 Antigone reconstructed from edges.

Because only limited views of an asteroid can be obtained in one night, much of the surface, and many outlines, are not visible, leaving large gaps in the 3-D model. We can fill in these radius vectors by using the ones from the triaxial ellipsoid model we obtain from fitting the images. Turning over these radius vectors to MATLAB's *convhulln.m* program then produces a set of tetrahedrons, where one face of each contributes to covering the entire surface of an asteroid. This combination ellipsoid and edge model is also shown in Fig 6.

Figure 7 shows four 3-D models viewed from three orthogonal directions. It is apparent that extrapolating to unseen regions can result in losing the true shape, but this can easily be remedied by performing the same analysis at another opposition, when the asteroid has moved significantly, providing a different viewing aspect.

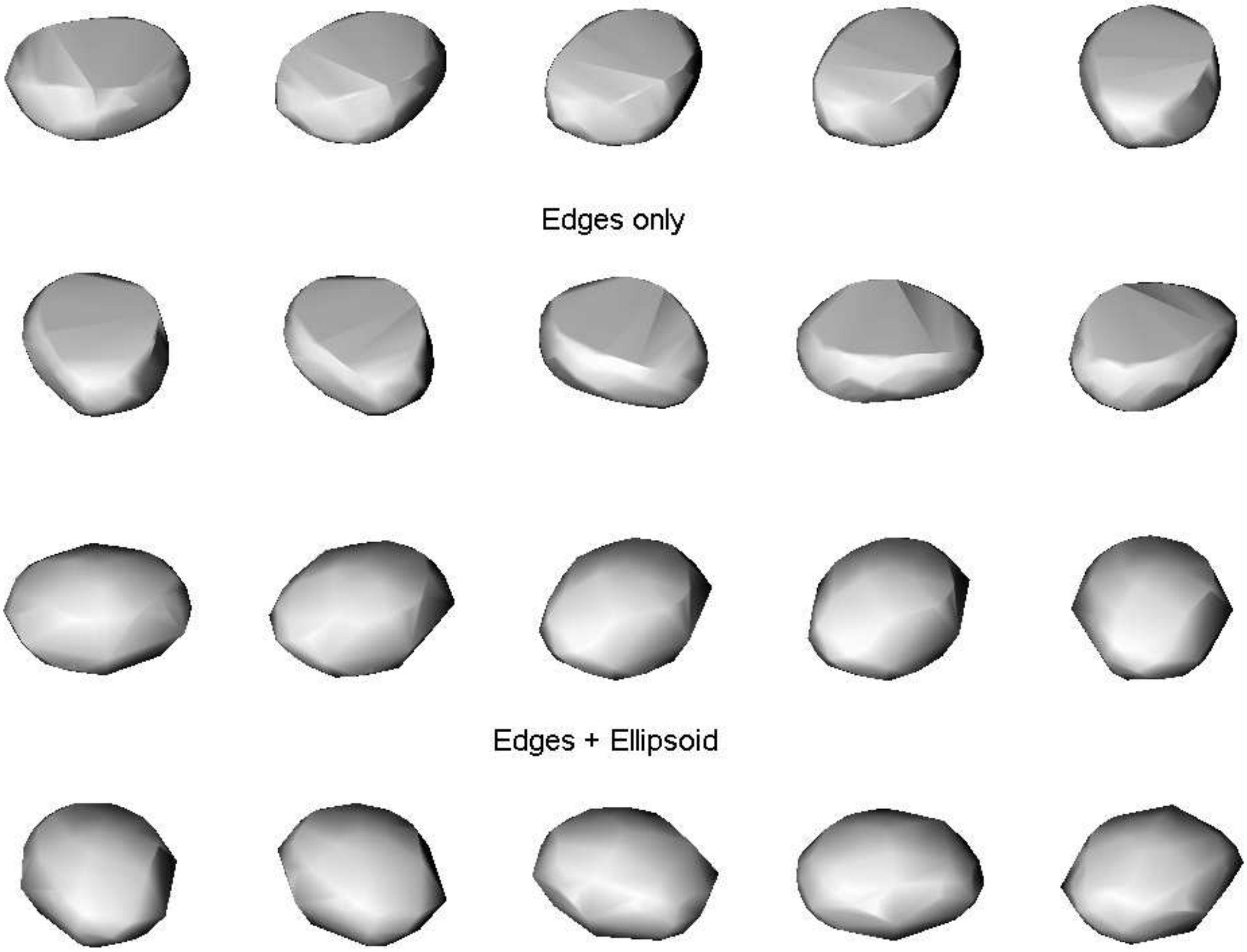

Figure 6. 3-D models of Antigone made from 10 deconvolved images using edges only (top ten) and edges supplemented with ellipsoid solution radius vectors (bottom ten).

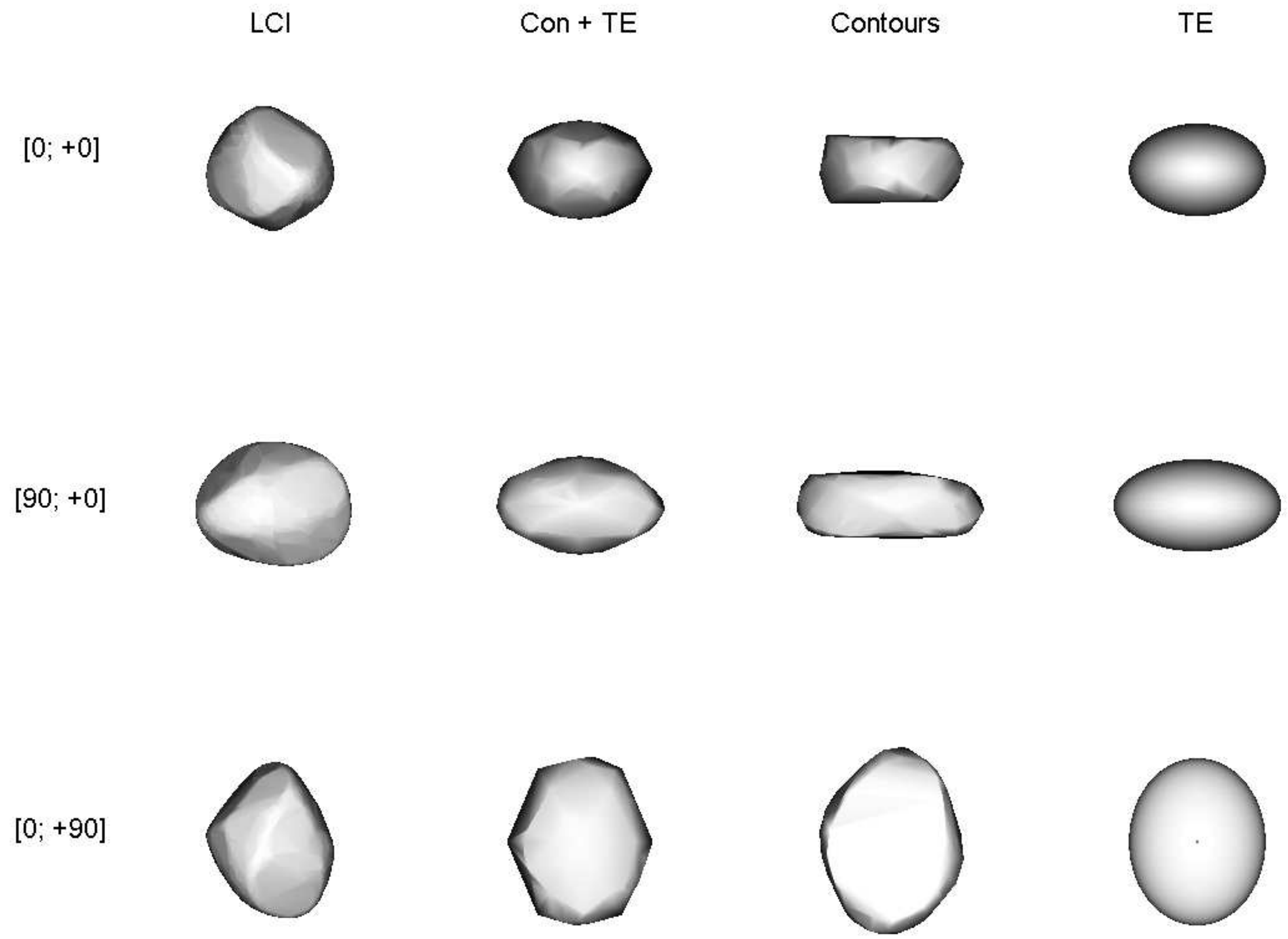

Figure 7. Four 3-D models of Antigone, all normalized to the same volume. Each is shown at the same sub-Earth longitude and latitude as listed on the left.

5. SSA

The techniques developed by Kaasalainen and colleagues are based on unresolved photometric measurements of asteroids observed over decades. Low-earth satellites can go through the same geometry in one pass. Edge reconstruction can be applied to a series of two-dimensional deconvolved AO images, again available on one pass. Application of these two techniques could be profitable in the study of satellites, both LEOs and GEOs, although for the edge reconstruction technique the latter would require observations with 8-10 m telescopes. A satellite pass makes the problem easier in that the observations can be obtained quickly, but the overall problem is much harder because the basic assumptions used for asteroids do not necessarily apply to satellites. Satellites are not smooth featureless triaxial ellipsoids, they may have strong concavities, and scattering laws are important (specular, diffuse, Lambertian, etc.). However, with a different set of simplifying assumptions, the techniques used on asteroids can be a tool for studying barely resolved or unresolved satellites.

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