IMPROVING THE DECONVOLUTION METHOD FOR ASTEROID IMAGES: OBSERVING 511 DAVIDA, 52 EUROPA, AND 12 VICTORIA

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ABSTRACT

Deconvolution of astronomical images is a process whereby images are modified in an attempt to remove the blurring effects of our turbulent atmosphere and the inherent systematic errors that result from use of an Adaptive Optics (AO) system. We have used an image deconvolution program called MISTRAL[1] to deconvolve AO images of three asteroids taken with Keck II's NIRC2 camera: 511 Davida, 52 Europa, and 12 Victoria. We were looking for geologic surface features on the asteroids, as well as asteroid size and pole position for rotation. By understanding more of the structure and composition of these asteroids, we can learn more about how the solar system formed and evolved. Along with having used MISTRAL on these asteroid images, we also tested and evaluated the use of the software, in order to learn to use it to its best ability. Here we describe an effective way to use MISTRAL. An improved method of deconvolution will be beneficial to all astronomical AO imagery, which could improve scientific astronomical measurements.

INTRODUCTION

No telescope image is a perfect representation of an astronomical object, even with the best Adaptive Optics and cameras. Images are affected by everything in between the object emitting light and the computer screens on which they are eventually displayed, i.e., images are spatially convolved and noisy. MISTRAL (for Myopic Iterative Step-preserving Restoration Algorithm) is an image restoration method written in Interactive Data Language (IDL) which can deconvolve images, based on prior assumptions about the objects being viewed, a noise and convolution model, and a point-spread-function (PSF).

We have used MISTRAL to deconvolve images of three large, main belt asteroids, 511 Davida, 52 Europa, and 12 Victoria, as part of the Resolved Asteroid Project (RAP). These images were taken with the Keck II telescope with the Adaptive Optics assisted NIRC2 camera. 511 Davida was observed December 27, 2002, 52 Europa was observed January 20, 2005, and 12 Victoria was observed June 11, 2003.

Previously, these asteroids have only been seen as unresolved point sources. Some properties of the asteroids, such as mass, period of rotation, and rotation vector have been measured or estimated with photometric light curves. Now, with the use of a large telescope, AO, and deconvolution, we can more precisely determine the sizes, rotation vectors, and albedos of these asteroids, and have begun to create improved 3D models of them. With these improved models, we also hope to enable ourselves and other researchers to better constrain the physical geology and impact history of asteroids, which when understood, will provide clues to understanding the processes that govern planet formation.

To use MISTRAL, one can simply supply it with an image, PSF, and two numeric parameters, but for the best results, specific pre-deconvolution processing should be applied to the image and PSF, as well as a careful selection of the parameter settings. We have explored several ways to prepare images for MISTRAL, and recommend what worked best for us.

DECONVOLUTION

The deconvolution process attempts to un-blur images by modeling the way in which light from the object being imaged spreads out. To model this spread, the deconvolution routine MISTRAL uses an image of a point source (star) nearby the object to act as a point-spread-function (PSF), which is a measurement of the spread of light in an image (Figure 1). This is classical mode. Alternatively, MISTRAL can work without a known PSF in myopic mode. The MISTRAL deconvolution routine has been validated by modeling and use on some planetary objects (Mugnier, 2004).

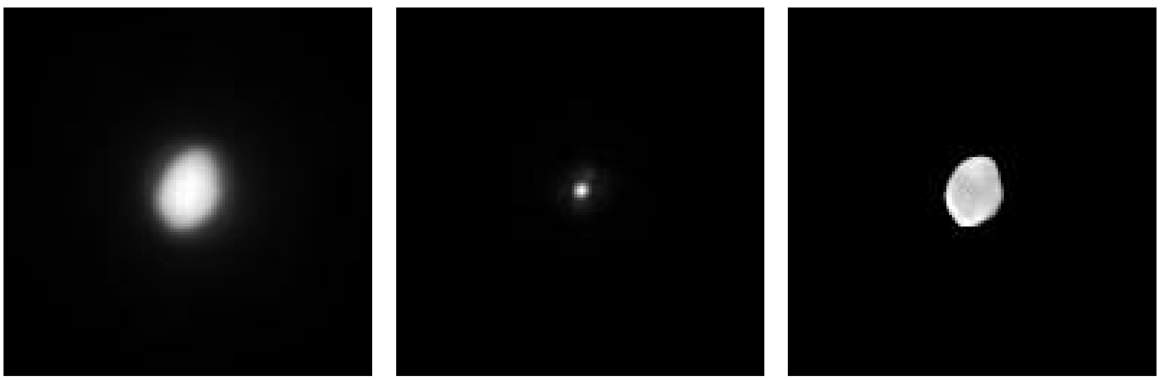


Figure 1: These images show (a) asteroid 52 Europa, reduced, (b) a PSF for deconvolution, and (c) the same image of 52 Europa, deconvolved.

The three main components of the deconvolution method are a fine noise model, a PSF estimation capability, and an object regularization term. The object regularization term (object prior) is a way to include prior knowledge of the observed object into the deconvolution method. MISTRAL uses a prior that is suited to astronomical objects that have a mix of sharp edges and smooth areas. (For pointlike objects, an alternative prior can be used.)

The convolution model used by MISTRAL is: <u>**i** = (**h*****o**)+**n**</u>, where **i** is the image, **o** is the object, **h** is the PSF, * is the convolution operator, and +**n** is the (not necessarily additive) noise. To use MISTRAL on a raw image **i**, it must be preprocessed, which should involve the correction of the background and flat field, the camera's bad pixels and correlated noise, the scaling of the image in photons, and the recentering and addition of images. The PSF **h** is usually found by recording the corrected image of a nearby, unresolved star.

In classical mode, deconvolution involves a noise model and an object prior, and works by finding the minimization of a criterion, which MISTRAL does by following a Bayesian probabilistic or penalized-likelihood method. The noise model is designed to account for photon noise, following Poisson statistics, as well as detector noise, following Gaussian statistics. The object prior that is used is quadratic-linear, or L_2-L_1, which means that it tries to use the best aspects of both quadratic and linear priors. This prior has two hyper-parameters; the global factor μ (regobj) and the threshold δ (thresh).

The global factor μ determines whether the object prior tends toward linear or quadratic regression, while the threshold δ determines the threshold in the model at which deconvolution will tend to switch between quadratic and linear regression. In MISTRAL, these must be set as parameters in the call to the MISTRAL function. A recommended set of hyper-parameters is to take μ as about 1, and δ to be on the order of the image gradient's norm (Mugnier, 2004).

In myopic mode, the PSF and the object are jointly estimated in the same probabilistic framework. This mode should be used when the observed PSF is not available. The minimization of the probabilistic criterion is started with an estimate of the object for a fixed PSF, and stopped when the object and PSF no longer evolve.

PRE-DECONVOLUTION

Prior to deconvolution, the NIRC2 asteroid images had to be reduced as usual, which included flat field division, background sky subtraction, removing hot/dead pixels, cropping the image to the asteroid, and coaddition of frames.

Since there were no images taken for use exclusively as sky frames, sky frames had to be created from the asteroid images. There were two methods tested for this: one of them involves median filtering and the other involves averaging over quadrants of the images which do not have asteroids in them. The only difference in the resulting deconvolutions between these methods that was apparent was the number of iteration times that MISTRAL used before it decided upon convergence. It was decided that either sky frame creation method works equally well.

On the other hand, MISTRAL is very sensitive to coaddition. Image coaddition is a process whereby successive images of the same object or PSF are aligned with one another and added together, in order to produce an image which has a higher signal to noise (s/n) ratio than the individual images had. Statistical calculation tells us that when N images are added together or averaged, the resulting s/n ratio increases by sqrt(N). Since higher s/n ratios indicate less noisy images, image and PSF coaddition is an important part of the pre-deconvolution data reduction process.

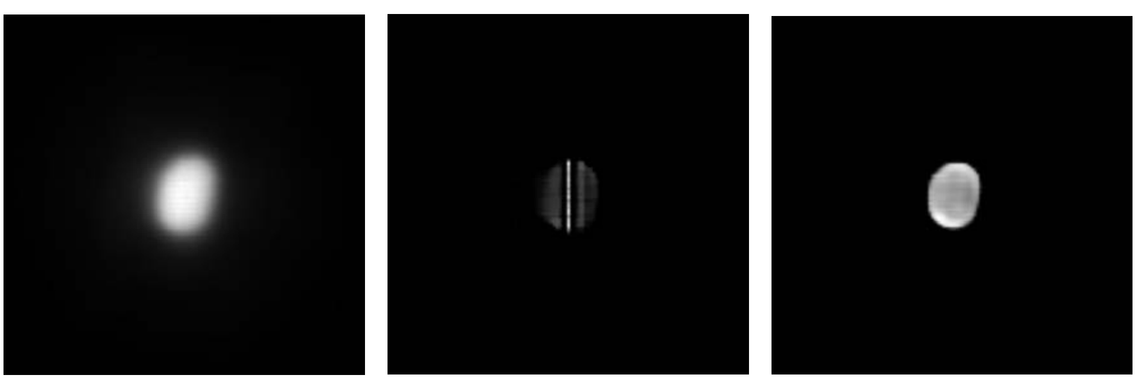


Figure 2: The image on the left is a reduced and (improperly) coadded image of 52 Europa, and the image in the center is its deconvolution. Notice that even though the coaddition

looks good to the eye, MISTRAL shows us that the image was not well coadded. The right image is the deconvolution after the coaddition was fixed.

There were 3 coaddition methods investigated. The first one, aligning images by the brightest pixel within a region, turned out to be problematic for both image and PSF addition, producing blurry images and PSFs. This is evident in our early attempts at deconvolution, which showed artificial checkerboard or striped patterns (Figure 2). The second method, aligning images by use of the IDL Astronomy Use Library's image correlation routine, correl_optimize, appears to be effective for images but not for PSFs. The third method involves the user clicking on the center of the PSF then calling IDL's gauss2dfit routine and aligning the Gaussian fits. Coadding the images with correl_optimize and the PSFs with gauss2dfit produces the best deconvolved images.

SETTING THE PARAMETERS

To deconvolve images, MISTRAL requires that the user supply two numeric parameters: regobj and thresh. It is not obvious what numbers should be used for these in order to come up with the best results. One method recommended by other MISTRAL users is to simply try various parameter settings in the program and see which ones give the best results. In order to determine the best parameter settings, we developed an IDL procedure to deconvolve an image with a PSF over a range of parameter settings, and give back an HTML table of the resulting images. The best parameter settings can now be selected from the table.

As of yet, there is no definitive quantitative method to determine which deconvolution is the best. Deconvolved images have so far been compared by how many iterations MISTRAL needs to deconvolve an image, and by qualitative evaluation of the sharpness of the asteroid image edges and the amount of ringing visible within the asteroid images. One way that an image might be better than another could be a less prominent ringing effect in the images. Another indicator of a better image would be the appearance of asteroid surface features in the deconvolved images.

In deconvolving images of these 3 asteroids, it was noticed that the parameters had to be set differently for each asteroid. In the case of 12 Victoria, which had the highest change in luminosity between frames, different parameter settings were used on different frames.

ASTEROID RESULTS

The immediate benefit to using MISTRAL on asteroid images is that the edge of the asteroid becomes very apparent, and so the asteroid's size and shape can be immediately determined. This size measurement puts upper limits on the sizes of the asteroids. From these improved size measurements, the albedos of the asteroids can be calculated.

Prior to deconvolution, we had coadded images of 511 Davida at 11 timesteps spanning its full 5.13h period with 7 PSFs, 7 timesteps of 52 Europa spanning most of its 5.63h period with 2 PSFs, and 6 timesteps of 12 Victoria spanning 5.55h of its 8.66h period with 1 PSF. Images of 511 Davida and 12 Victoria were all taken in the near infrared K' filter, while images of 52 Europa are in each of the K' and H filters. Table 1 gives the UTC and phase angle of each timestep for Europa and Victoria.

Using IDL three-dimensional object graphics, Conrad et. al. showed using a rotating triaxial ellipsoid that the size of 511 Davida is near the lower bounds of the size estimate given by Drummond and Hege. Using a similar technique, we compared the relative sizes and rotation vectors given by Michalowski et. al. for 52 Europa and those given by Torppa et. al. for 12 Victoria, to the apparent sizes and rotations seen in our resolved, deconvolved images.

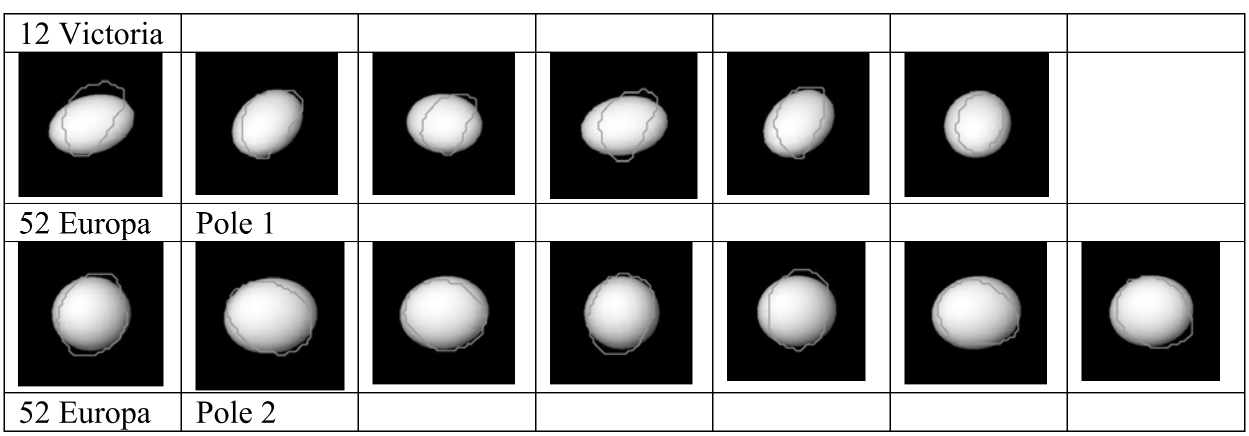
To analyze the shapes, sizes, and rotation vectors of 52 Europa and 12 Victoria, we first found their edges in the deconvolved images using a luminosity threshold of 1/3*max. We then used IDL to plot 3-D ellipsoids at the pole orientations and shapes predicted for the asteroids. For 52 Europa, the axial ratios are given as a/b = 1.21 and b/c = 1.04. There are two possible rotation vectors given in ecliptical longitude and latitude as 262°, +46°, and 67°, +25° (Michalowski, 2004). For 12

12 Victoria		period:	8:40		**52 Europa**		period:	5:38	
Phase	**UT**	**UT_{REL}**	**θ_{REL}**	**$\Delta\theta$**	**Phase**	**UT**	**UT_{REL}**	**θ_{REL}**	**$\Delta\theta$**
1	6:20		0.00		1	10:40		0.00	
2	7:34	1:14	51.23	51.23	2	11:27	0:47	50.06	50.06
3	9:25	3:05	128.08	76.85	3	12:03	1:23	88.40	38.34
4	10:18	3:58	164.77	36.69	4	13:03	2:23	152.31	63.91
5	11:53	5:33	230.54	65.77	5	13:46	3:06	198.11	45.80
6	12:45	6:25	266.54	36.00	6	14:17	3:37	231.12	33.02
					7	15:04	4:24	281.18	50.06

Table 1: Times and rotation angles for the epochs of the 52 Europa and 12 Victoria observations. UT_{REL} gives the elapsed time from the first epoch; θ_{REL} gives the rotation angle since the first epoch in degrees; and $\Delta\theta$ gives the rotation angle between epochs in degrees.

Victoria, the axial ratios are given as a/b = 1.3 and b/c = 1.3. The rotation vector is 137°, +55° (Torppa, 1993). The edge outlines were then laid over the ellipsoids, and the predicted shapes were compared with the observed ones (Table 2).

As can be seen in Table 2, neither 12 Victoria nor 52 Europa are as ellipsoidal as 511 Davida appeared to be (Conrad, 2006). For these two asteroids, the elliptical triaxial ratios seem to be nearly correct, but the rotation axes seem to be wrong.



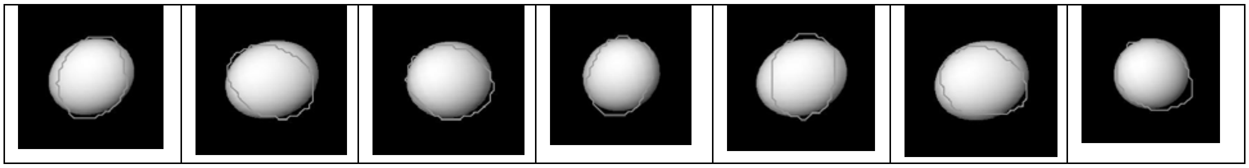


Table 2: The model ellipsoids with the deconvolved asteroid image outlines.

MISTRAL PERFORMANCE RESULTS

MISTRAL has been tested with various parameter settings on images of 511 Davida, 52 Europa, and 12 Victoria. In the pre-deconvolution data reduction, there were two methods of creating sky frames tested, and both worked equally well. It seems that deconvolution is not dependant on how sky frames are made. The coaddition method used to stack images is important in deconvolution. Of the 3 coaddition methods tested, image correlation worked best for asteroid images, while elliptical Gaussian fit correlation worked best for PSFs.

The MISTRAL parameters regobj and thresh can be selected by choosing them from a table of deconvolved images. The luminosity of the image to be deconvolved seems to have a strong affect on the best choice of parameters. The method for choosing the best deconvolution is qualitative: the best images have sharp edges, little ringing, and possibly surface features.

Half of the images of 52 Europa were taken with the K' filter and the rest were with the H filter. Images taken in the H band are noticeably noisier than those taken in the K' band. This is apparent in the reduced data as well as in the deconvolved images, which showed the size of the asteroid as slightly larger in the H color than in K'.

CONCLUSION

With the successful use of deconvolution, the edges of the asteroids became sharp in the resolved images. This enabled a comparison to be done between the apparent edges of the asteroids and the triaxial ratios and rotation models of the asteroids. The next steps in analyzing these asteroids will be measuring their sizes and albedos, and constructing better rotation models using ellipsoids. This modeling will be much more effective with many more frames over the course of one asteroid rotation. Six or seven frames gives only a small snapshot compared to the nearly continuous photometric measurements that have been done. With more frames available per cycle, shape and rotation modeling will be much more effective and accurate.

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