Extraction of Black Hole Shadows Using Ridge Filtering and the Circular Hough Transform

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Abstract
Using data from the Event Horizon Telescope, new imaging techniques will soon be able to provide us with accurate images of nearby black holes. To test our understanding of these black holes and their formation, it is important to find techniques to extract features from these images. One such feature, the black hole shadow, encodes information about the size and spin of the black hole. Here, we present a new technique that can extract the black hole shadow radius at finer accuracies than past methods.

Background
Our extraction technique was tested on simulated images of the black hole in M87 and compared with past techniques. One past technique attempted to detect circles in the raw (unfiltered) image, while another used a gradient filter. Our new technique uses a ridge filter before searching for circles in the image. Two types of images, ground truth and reconstructed, were used. In the figure to the left, the radii of the detected shadows are graphed as a function of the size of the Gaussian beam with which the images were convolved. With larger convolving beams, the detected radii in past techniques deviate from the true black hole radius (the gray horizontal line), while our technique gives relatively consistent and accurate results, even at lower resolutions.

Methods
The ridge filtering process is shown to the right. A ridge detection function highlights the sections of the image that are local maxima in at least one direction. These ridge features are thinned to prevent ambiguity and then clustered into groups with similar features. Finally, double thresholding is applied to banish weak or unrelated features. After the filter is applied, a circular Hough transform is then used to detect circular features in the image and thus yield a value for the black hole shadow radius. This transform tests how much the features of the image contribute to circles of various radii. The radius of the circle with the highest contribution is then assumed to be the radius of the black hole shadow. Due to computational costs, the transform was applied on lower resolution images.

Results
Sample results are shown in the graphs below. The leftmost graph below displays images for both the ground truth and reconstructed images for jet and disk models of M87. The unfiltered images are shown in the leftmost column. Then, for raw, gradient-filtered, and ridge-filtered versions of these images, a circular Hough transform was applied, and the best fit circle was graphed on top of the corresponding filtered image. The rightmost figure below is a graph of the Hough profiles for each of the three methods. The Hough profile is a measure of the strength of circular features in the image as a function of the circle radius. Each Hough profile was normalized by its maximum value, and the radius at which the peak occurs is the radius of the detected black hole shadow. The vertical black line represents the true value of the black hole shadow radius with the dotted lines indicating 10% uncertainty.

Conclusions
Using these simulated images of M87, we have been able to develop a new technique for detecting the size of the black hole shadow. This new method is more robust than past techniques, and appears to give more consistent and more accurate results. Using a reconstructed jet-model image, ridge detection was able to extract the size of the black hole shadow with an accuracy of better than 10% (bottom right image), while other methods had much higher errors. Detecting the shadow radius using a gradient filter tends to find the inner or outer edge of the image, so in reconstructed images there can be a large bias. Detection using the raw image tends to be more accurate, but the radius values at high resolution for ground truth and reconstructed images tend to diverge, making it hard to extrapolate a value for the ground truth shadow radius from a reconstructed image. The results from the ridge filtering technique tend to give more consistent values, and these values tend to be very close to the real value. These results seem to be a good indication that we will be able to accurately extract the size of the black hole shadow from real images and reduce our uncertainty in the mass of the black hole within M87.

Sources: Kuramochi et al., 2017; Psaltis et al., 2015; Hough et al., 1972