AUTOMATION OF SIZE ESTIMATION OF NEAR-EARTH ASTEROIDS FROM LOW SNR ARECIBO RADAR IMAGING. C. E. Champagne[1,2], E. G. Rivera-Valentín[3], B. Aponte-Hernández[1], P. A. Taylor[4]; [1]Lunar and Planetary Institute (USRA), Houston, TX 77058, [2]University of Louisiana at Lafayette, Lafayette, LA 70504, [3]Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, [4]National Radio Astronomy Observatory & Green Bank Observatory, Charlottesville, VA 22903.

Introduction: The S-band (2380 MHz, 12.6 cm) planetary radar at the Arecibo Observatory in Puerto Rico provided detailed observations of over 1000 asteroids. During a typical observing run, Arecibo would first transmit a monochromatic, continuous wave and measure the Doppler broadening due to the object's rotation along the line of sight. Such experiments would allow for refined astrometric measurements, estimates of the rotation period, detection of a satellite (if present), and estimate of the surface scattering properties over the illuminated area. For objects with sufficient signal-to-noise ratio (SNR), delay-Doppler experiments, where Arecibo would transmit a modulated signal, would produce radar images. These are 2-dimensional maps of backscattered power with delay along the vertical axis and Doppler along the horizontal axis.

With sufficient radar observations over multiple nights and apparitions, and observations in other wavelengths, a fully 3-dimensional shape model of an asteroid can be developed [e.g., 3 & 4]; however, not all objects have been observed sufficiently to produce shape models. In those cases, visual inspection of delay-Doppler images is used to estimate the radius. Although estimating the leading edge of the echo can be easy, the trailing edge can be difficult because as the radar incidence angle increases the backscatter power decreases [2]. It is important to obtain an accurate estimate of the size of near-Earth asteroids (NEAs) in the event that they are potentially hazardous. An accurate size allows for determination of the effects of an impact and provides information for planetary defense strategies.

Here we develop, validate, and test statistical techniques to measure the size of an object in a radar image in a consistent and quantitative manner. We then apply the developed algorithm to a training data set of objects to provide new preliminary size measurements for comparison with other observations.

Method: Delay-Doppler images are in the form of z-score normalized power relative to the signal noise. Z-score normalization results in noise-only pixels having a mean value of zero and a standard deviation of one. As a first step, to automate identification of the general location of the object, we used the DBSCAN (Density-Based Spatial Clustering of Applications with Noise) algorithm with radar images as inputs. DBSCAN finds statistically significant clusters of signal within spatial-based data sets [5] and allows for automation of the first guess as to the location of the object. The radar image is then collapsed to produce power spectra as functions of delay, from which our algorithm can identify the leading and trailing edge of the signal, and Doppler, from which the algorithm can identify the approaching and receding side of the asteroid.

In this next step, two measurements of the observable extent of the asteroid are made: using the standard deviation of the z-scores as a function of delay, and using the maximum z-score as a function of delay. The average and standard deviation of noise-only locations is then taken to characterize the typical fluctuation. Our developed algorithm then determines the extent of the object by finding where the signal is greater than one and two standard deviations above the noise. A weighted average of the two extent measurements are then taken as the estimated visible extent of the asteroid with the uncertainty as the weighted standard deviation.

Validation Studies: The developed algorithm was validated using synthetic radar images and real Arecibo radar observations.

Synthetic Data: To create synthetic radar images, we began by defining shape parameters (e.g., sphere with a Bennu-like ridge) and applied standard radar-scattering parameters. We then used the SHAPE software to run the forward problem in order to produce the radar image of the chosen shape as a function of sub-radar latitude. Two shapes were tested, spherical and "diamond-like" shapes (i.e., asteroids with equatorial ridges such as Bennu). Synthetic delay-Doppler images were produced as a function of the subradar latitude ranging from 0° (i.e., where the object's spin pole is perfectly perpendicular to the line of sight) to 80° (i.e., where the object's spin pole is nearly parallel to the line of sight) in increments of 10°. Noise following a chi-square distribution was then randomly generated and added to the image. To study the effect of SNR, we varied the maximum signal within each image from 10-σ to 200-σ in steps of 10-σ. To ensure noise statistics were adequately captured, we used Monte Carlo methods to randomly generate noise 100 times to estimate the radius and corresponding uncertainty. The average over the 100 realizations was taken as the radius measurement for the considered maximum SNR. In Figure 1, we show a plot of the ratio between the estimated radius and the actual radius for the sphere case. We find that the accuracy of the developed algorithm is primarily a function of SNR. There is little variation with algorithm efficacy as a function of subradar latitude, as expected for a sphere.

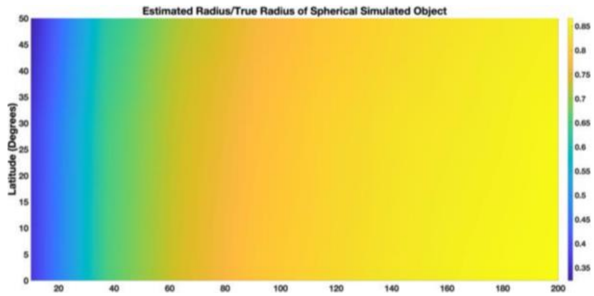

Figure 1: Plot of the ratio of estimated radius to actual radius as a function of maximum SNR and subradar latitude of a synthetically produced observation of a perfect sphere.

Test Objects: After the synthetic data study, we selected several spherical-like NEAs with varying maximum SNRs that have radius estimates from either the NEOWISE mission, radar shape models, or estimates from optical observations. The NEOWISE mission, which used a space telescope to discover and characterize asteroids, has used infrared observations to estimate the size of NEAs through thermal modeling [6]. These measurements have been shown to be well-supported by radar observations [7]. Additionally, using the observed absolute magnitude (H_{mag}) of an asteroid and making assumptions of its geometric albedo (p_v), the diameter (twice the radius) can be estimated following [8]:

$$D = \frac{1329}{\sqrt{p_v}} 10^{-H/5}$$

In Figure 2, we show the estimated radius using our newly developed method for each asteroid compared to their radius from NEOWISE, H_{mag}, or radar shape model.

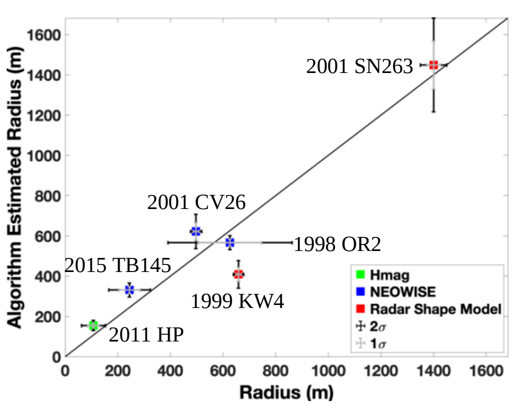

Figure 2: Algorithm-based radius estimates as a function of either estimates from H_{mag} (green), NEOWISE (blue), or radar shape model (red). The solid black line is the one-to-one correspondence.

As seen in Figure 2, generally within at least 2-σ error, the algorithm-based estimates agree with other radius estimates. The only exception is 66391 Moshup, which is discussed in the next section.

Case Study: Asteroid 66391 Moshup (1999 KW4) is the only object within our test study whose size is under approximated by our developed algorithm. The radar-based shape model of Moshup finds a radius of 658.5 ± 20 m [9], while our algorithm suggests 410 ± 70 m. The shape model of Moshup shows a flattened pole and a diamond shape. Peculiarities in the shape and/or viewing geometry may result in difficulties with discerning the full radar echo in an image (e.g, see Fig. 4) that are difficult to even discern with the algorithm.

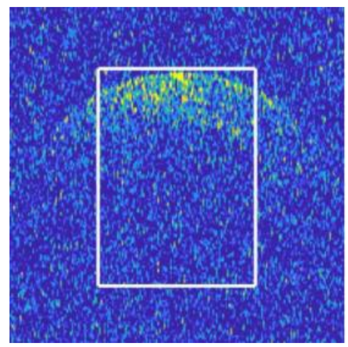

Figure 3: Delay-Doppler image of 66391 Moshup (1999 KW4). The white box encompasses the actual radius (~660 m).

Conclusions: In the field of planetary defense, it is important to know the size of near-Earth asteroids; however, current methods of determining asteroid size can require a lot of data and processing time. Here, we developed an algorithm to automate size estimation from low-SNR radar images. Our preliminary results show the algorithm performs well for most of the test objects. Further work is required to understand why some irregular shapes are not fit well by the algorithm.

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