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Undergraduate Thesis:

Shape Modeling and Boulder Mapping of Asteroid 1992 UY4

By

Nicholas Dat Tien Duong

University of Louisville

Department of Physics & Astronomy

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A Thesis Submitted to the Honors Department
at the University of Louisville in Partial Fulfillment of the
Requirements for Graduation Summa or Magna Cum Laude

Thesis approved on

Date

by the following Thesis Committee:

Gerard Williger (U of L, Physics & Astronomy), Supervisor and Committee Member

David Schultz (U of L, Biology), Senior Honors Thesis Committee Member

Michael Busch (SETI Institute, Planetary Sciences), Committee Member

Joshua Emery (UT Knoxville, Earth and Planetary Sciences), Committee Member

Thomas Riedel (U of L, Mathematics), Committee Member

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Terminology

au (astronomical unit) - mean Earth-Sun distance (1.496×10^8 km)

astrometry - precise measurements of the positions and movements of celestial bodies

chi-square - a measure of the difference between the synthetic and real data to see how well the model matches the observations (χ^2)

contact binary - small Solar System body with two components in contact

ecliptic - the plane defined by Earth's orbit (Earth orbits counter-clockwise as viewed from the north)

ecliptic longitude - angle measured from vernal equinox in ecliptic coordinates (λ)

ecliptic latitude - angle measured from the ecliptic plane in ecliptic coordinates (β)

facet - a plane described by three vertices in the SHAPE models

orbital resonance - a stable relation between two bodies in orbits, where their periods are a simple integer ratio of each other and the bodies return to the same relative position periodically

point spread function (PSF) - the two dimensional “footprint” of the radar image of the asteroid, here based on telescope aperture and optics, wavelength, angle observed from the zenith and the curvature of the asteroid surface; in practice, this can be an ellipse on the plane of the sky and a more complex egg-shape on the surface of the asteroid

principal axis - primary axis that a small Solar System body rotates on

prograde - in the same sense as Earth orbiting the sun

retrograde - opposite of prograde

rotation phase - the longitude on a body toward a line of sight

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ABSTRACT

In August 2005, the near-Earth Asteroid 1992 UY4 made a close flyby, coming within 0.04 au of our planet. Between the dates of 1-10 August 2005, it was observed via delay-Doppler radar imaging by the Arecibo Observatory (2380 MHz, 13 cm) and the DSS-14 antenna at the Goldstone Deep Space Communications Complex (8560 MHz, 3.5 cm). The images achieve a resolution as fine as 7.5 m/pixel and reveal a lumpy and modestly asymmetric object. The images also revealed the presence of numerous large boulders/blocks on the surface of 1992 UY4. By using the modeling software SHAPE, which is standard in the field of asteroid radar imaging, and by using a visual examination of the models vs. radar images and the χ^2 statistic as a relative (but not absolute) probability metric, I found two potential pole directions: one at $\lambda = 285^\circ \pm 10^\circ$, $\beta = -80^\circ \pm 10^\circ$, and one at $\lambda = 110^\circ \pm 10^\circ$, $\beta = 75^\circ \pm 10^\circ$, the mirror direction. They represent a north-south ambiguity: 1992 UY4 may rotate either prograde or retrograde. I find that the models for the first pole direction better match the observations and I conclude that 1992 UY4 is most likely a retrograde rotator.

I identified 18 boulder candidates on 1992 UY4's surface based on inde-

pendent visual inspection of the images by Dr. Michael Busch, myself, and standard astronomical image statistics. Their distribution is concentrated in those longitudes that were seen in multiple observations from Arecibo. There are few boulders on the edges of Arecibo's field of view, but this is likely observing bias. With the available data and without more complex modeling and statistical techniques, I cannot determine if boulders are uniformly distributed across the surface of 1992 UY4 or not. Further observations would be needed to map the rest of the asteroid. Unfortunately, there are no upcoming opportunities for future ground-based radar observations, since 1992 UY4 will not pass as near to Earth as it did in 2005 for the next several hundred years. However, thanks to my study of 1992 UY4, in addition to details about the asteroid itself, I have enabled the improvement of its trajectory.

1. INTRODUCTION

Asteroids are small rocky bodies that are remnants of the formation of our Solar System 4.5 billion years ago. There are hundreds of thousands known out of the millions that exist. Most lie between the orbits of Mars and Jupiter in a zone called the main asteroid belt. Out of the various families of asteroids, we are interested in Near-Earth Asteroids (NEAs) - bodies with a perihelion distance less than 1.3 au (Fig. 1.1).

Figure 1.1: A diagram depicting the orbits of NEAs and PHAs (Potentially Hazardous Asteroids) by NASA (https://www.nasa.gov/mission_pages/WISE/news/wise20120516.html).

NEAs can range in size from 1 m up to roughly 32 km in size and also vary in spectral type, which can sometimes correspond to an asteroid's composition. Three broad categories of asteroids (DeMeo et al. 2009) are:

- 1) C-type - Extremely dark and carbonaceous.
- 2) S-type - Has a silicate (stony) composition.
- 3) X-type - Asteroids with similar spectra but different compositions that fall into several sub-types, such as:
 - E-type - high albedo and they are thought to have enstatite achondrite (mineral-like) surfaces.
 - M-type - Intermediate albedo. Most show clear silicate features, with some having metallic compositions.
 - P-type - Has a low albedo, a featureless reddish spectrum, and are suggested to have a composition of organic rich silicates and carbonaceous compounds.

The study of NEAs contribute to understanding the exact process by which Earth and life on it formed. Early in its history, Earth's surface is thought to have been inhospitable to allow for the existence of the progenitors to life, due to volcanic activity, the late heavy bombardment, etc over 3.8 billion years ago. Such factors caused the planet to be far too hot to preserve its volatiles (given its orbital location, and the incoming solar flux, plus the heating of the surface via impacts), including water (Halliday 2013). The earliest known fossils on Earth date back to 3.5 billion years ago, with

evidence that biological activity could have started even earlier, perhaps 3.8-4.3 billion years ago (Dodd et al. 2017). Such fossils raised questions about how the building blocks for life arrived in a relatively small time frame.

It is thought that other Solar System bodies which formed under colder conditions than Earth may have been responsible, as lighter atoms could be gravitationally captured in the gas form, and organic molecules could survive intact given the lower ultraviolet solar flux in the outer solar system. Water ice and other organics are thought to be more common on asteroids and may be more widespread in asteroidal interiors than previously thought (Rivkin and Emery 2010). Comets are thought to have contributed as well. The comet rendezvous mission Rosetta monitored the evolution of comet 67P/Churyumov-Gerasimenko during its approach to the Sun and found numerous volatiles and complex organic compounds (Ehrenfreund 2016). We can infer that impacts by these bodies may have delivered the necessary materials that allowed life to form. As new NEAs are discovered and characterized, they give us a unique source of understanding into the history of our Solar System.

NEAs are also potential threats to our planet. Annually, an average of 30-50 NEAs ranging in size from one meter to tens of meters have close approaches of less than 1 lunar distance to Earth (JPL). Smaller asteroids generally burn up in the atmosphere before striking the Earth. For larger asteroids, atmospheric entry is not enough to significantly disintegrate the body and can result in strikes with energies many times higher than modern

nuclear weapons. Such an impact would cause mass damage to nearby cities and widespread death. If substantial enough, an asteroid impact could lead to an extinction event. Earth has been hit by NEAs many times, so eventually it is desirable to prepare necessary precautions against the next major impact.

NEAs harbor the potential for great destruction but can also grant us insight into our origins. Scientists work diligently to characterize these objects, to calculate future trajectories, and to plan for asteroid missions and long-term contingencies. Knowing an asteroid’s shape and spin-state for example can help plan for asteroid deflection, such as using a kinetic impactor, where having an accurate trajectory calculation is vital.

Not many NEAs have been well-characterized, because radar facilities have only been around for a few decades and asteroids of sufficient size with close flybys are rare. Important parameters which constrain their formation and evolution would include their size, shape, radar albedo (which relates to both the surface composition and the sizes of particles on the surface/in the regolith (broken up rocks which make “soil”, such as seen on the moon), and boulder distribution. In addition, radar observations give important constraints on their orbital parameters for future near-Earth encounters. Two relatively recent radar analyses on large NEA characteristics are on asteroids 1580 Betulia (Magri et al. 2007) and 1566 Icarus (Greenberg et al. 2017).

Betulia is a C-type NEA that approached within 0.238 au of Earth. Magri et al. estimated its shape and spin vector from this data and their study resulted in predictions of the asteroid’s close planetary encounters for over

four thousand years into the future. Icarus is an S-type NEA that made a close approach to Earth in June 2015 at 22 lunar distances. The research suggests a high-porosity surface, presumably related to Icarus' cratering, spin, and thermal histories.

Opportunities to do radar observations on NEAs are infrequent. NEAs larger than 1 km that have a close approach to Earth are uncommon (Fig. 1.2) so we must research these objects as they come. The data are challenging to work with due to inhomogeneities in the point spread function (the “footprint” of the radar on the asteroid) in space and time, variable signal-to-noise across the asteroid's surface, inhomogeneous rotation phase (longitude coverage) and the impossibility of repeating the observations. This project is to further characterize NEA 1992 UY4, because so few asteroids of this size pass close enough to Earth to make detailed radar observations. The science questions in this thesis are:

1. What is the spin axis of 1992 UY4? There are physical reasons why retrograde rotators are expected among NEAs.
2. How well can we characterize the boulder population? This requires a calculation of a model of the asteroid shape.

I performed a detailed analysis on 1992 UY4's overall shape to constrain its spin axis, and made a survey of boulders to study their surface distribution. This was conducted under the mentorship of Dr. Michael W. Busch during the SETI Institute's Research Experience for Undergraduates in the

summer of 2016. I continued my research in the following academic year with the additional counsel of my academic advisor, Dr. Gerard Williger.

Figure 1.2: The number of NEAs that have been discovered as of 2017 March 26 and their relative sizes. Chart made by Alan Chamberlin of NASA/JPL (<http://neo.jpl.nasa.gov/stats/>)

2. 1992 UY4

2.1 *Background*

1992 UY4 was discovered by Dr. Carolyn Shoemaker on 25 October 1992 using the 18-inch Schmidt camera at the Palomar Observatory in California (Shoemaker et al. 1992).

1992 UY4 is a P-type NEA. Farnocchia et al. (2013) found that retrograde rotators composed greater than 80% of their sample of 23 NEAs. Thus, 1992 UY4 is most likely to follow this trend and is a retrograde rotator. This is partly because of the Yarkovsky effect (Bottke et al. 2006 and Vokrouhlický et al. 2015), a force caused by the emission of thermal photons from the “afternoon” side of a rotating body being warmed by radiation from the Sun. This force opposes the orbital motion of retrograde rotators, causing a slow decrease in their semi-major axes. Thus, along with orbital resonances of main belt asteroids with Jupiter and Mars, we can infer that retrograde rotators in our Solar System may have also migrated inward from a larger orbit due to the Yarkovsky effect. Other properties of this asteroid, with references, can be found in Tab. 2.1.

I study the shape of 1992 UY4, along with the boulder distribution and

Absolute Magnitude	17.6 (JPL Horizons Ephemeris System)
Rotation Period	12.9060+-0.0008 h (Warner et al. 2006)
Lightcurve Amplitude	0.26+-0.02 mag (Warner et al. 2006)
Elongation	-1.1 (Benner et al. 2015)
Pole Direction	Unknown
Diameter	2 km (Benner et al. 2015)
Optical Albedo	0.04 (Benner et al. 2015)
Spectral Type	P (optically dark) (Volquardsen et al. 2007)
Semi-Major Axis	a=2.647 au
Eccentricity	e=0.625
Inclination	i=2.8 degrees
Perihelion	q=0.991 au
Aphelion	Q=4.301 au

Table 2.1: A list of currently known physical properties of NEA 1992 UY4.

clustering on this asteroid. Building up a large sample of NEAs and studying their distribution functions for the shape and boulder parameters can give clues to the evolution and structure of asteroids. Mission planning also arises from studying NEAs, such as the OSIRIS-REx sample return mission to asteroid 101955 Bennu. These are all a testament to how NEA research can give knowledge on the origin and evolution of these small Solar System bodies and give scientists more insight towards how life formed on Earth.

2.2 Radar Facilities

Radar is a very powerful technique for characterizing near-Earth and main-belt asteroids. This results from radar’s ability to spatially resolve objects that often cannot be resolved at comparable resolutions by other ground-based techniques. Radar has revealed binary and contact binary

objects, non-principal axis rotators, irregularly-shaped NEAs, objects with metallic compositions, and many more types (Benner et al. 2015). We can examine the radar scattering properties of the surface to get information on the surface composition and morphology. We can also improve predictions of the orbits of NEAs through radar astrometry.

With radar, there is a decrease as the fourth power of distance in signal-to-noise. This is due to the signal decreasing as the second power of distance during transmission (before bouncing back) and reception (after bouncing back). This requires that targets be relatively nearby to the Earth and limits when observations can be conducted. Standard radar imaging broadcasts a signal and awaits a reflection of it from the object. Delay-Doppler radar imaging is the primary technique used to take observations of NEAs because it accounts for the rotation of the asteroid. As an asteroid rotates, some areas of the surface are moving toward us and other areas are moving away from us. The signal will be Doppler-shifted depending on which side it hits. Scientists also account for Doppler shift caused by the movement of the asteroid with respect to the Earth. The detector on the radio dish will record the time and strength of the reflected signal at many different wavelengths. This provides two dimensional images that resolve target asteroids. Doppler resolution corresponds to the projected distance from the asteroid's spin axis, and is independent from delay resolution, which corresponds to line-of-sight distance (Harmon 2002)¹.

¹ Resolution can also be improved by exploiting the fact that the radio telescope moves over the course of the observation while Earth orbits the sun at about 100,000 km/hr.

Figure 2.1: Arecibo Observatory’s planetary radar operates at a frequency of 2380 MHz (13 cm) (left) and the Goldstone Solar System Radar on the DSS-14 antenna operates at 8560 MHz (3.5 cm) (right). Photos from NSF (https://www.nsf.gov/news/special_reports/astronomy/downloads.jsp) and NASA (<http://gssr.jpl.nasa.gov>).

The world’s most sensitive facilities for radar observations of asteroids are the Arecibo Observatory’s planetary radar and the Goldstone Solar System Radar (Fig. 2.1). Arecibo has a fixed dish and operates at a frequency of 2380 MHz (13 cm). The Goldstone Solar System Radar is located on the DSS-14 antenna at the NASA Goldstone Deep Space Communications Complex and operates at 8560 MHz (3.5 cm). The capabilities of both facilities complement each other. For the flyby of 1992 UY4, Arecibo and Goldstone have resolutions of 7.5 m and 3.75 m per pixel respectively. Arecibo is about 20 times more sensitive due to its larger collecting area and can detect objects twice as far, but Goldstone is steerable and thus can track objects for several times longer. For many targets, both observatories are utilized to maximize observing efficiency.

There are several challenges to using radar observations of NEAs and

shape-modeling software which significantly complicate any statistical analysis:

1. The point spread function (or “sensitivity footprint”) of a radio telescope under the best of conditions is a circle in the plane of the sky, and is the resolution element for an image. When making a delay-Doppler image, this point spread function is projected onto a rotating sphere, making the point spread function into a more complex egg or quasi-teardrop shape. The resolution furthermore depends on the asteroid’s physical distance in km. The result is that the resolution on the surface of the asteroid in physical units (meters) changes in time and by location on the asteroid’s surface. This is exacerbated by the fact that the asteroid and Earth are moving relative to each other in independent orbits.
2. Because the point spread function distributes photon flux over a changing number of pixels, the pixel values are correlated in a similar variable way over an image.
3. There is going to be inhomogeneous coverage in rotation phase (longitude on the asteroid) and latitude depending on when the asteroid is visible in the sky for any given radio telescope. This also means that the signal-to-noise ratio of the images will vary across the asteroid’s surface, and therefore the sensitivity to features will also change in a complex way across the surface of the asteroid.

4. NEAs usually do not pass by often enough to repeat observations in a regular way if at all.

The net result is that asteroid delay-Doppler images, like many data sets in astronomy, are inhomogeneous, incomplete, variable in resolution and signal-to-noise ratio, and cannot be repeated. Nevertheless, astronomers find ways to work within the statistical complexities of such data sets to place their results and conclusions within the general framework of the scientific method.

2.3 Observations

Benner et al. (2005) submitted a proposal to Arecibo for radar imaging of seven NEAs, one of which was 1992 UY4. The requested time covered its sky motion and a bit over 75% of its rotation phase, which are important for the three-dimensional shape and spin-vector estimation. Arecibo and Goldstone observed 1992 UY4 over 2005 August 1-10 using delay-Doppler radar imaging as the asteroid passed within 0.04 au of Earth, which is only about 16 times the distance from the Earth to the moon. The images revealed a lumpy and modestly asymmetric object resembling a “meatball” (Fig. 2.2) and also revealed the presence of numerous large boulders/blocks on its surface.

Figure 2.2: Delay-Doppler radar image of 1992 UY4 from August 2005. Resolution is 7.5 m/pixel and the echo signal gives a “view” from above its spin axis. The Arecibo Observatory is located about 2 million kilometers “above” this image, with time delay increasing from top to bottom and Doppler signal increasing from right to left. This will be the case for the rest of the observation images.

3. SHAPE SOFTWARE OVERVIEW

My primary tool for analysis of 1992 UY4 was modeling software called SHAPE, originally written by R. S. Hudson (1993). Since the early 2000s, Christopher Magri of the University of Maine, Farmington has maintained and progressively updated SHAPE. Magri et al. (2007) describes its usage on models for 1580 Betulia. That paper has 40 citations in the refereed literature up through March 2017 from the NASA Astrophysical Data Systems bibliographical search engine (similar to “PubMed” for life sciences), indicating that SHAPE is a standard in the field. We apply SHAPE to 1992 UY4 for analysis.

I start with an *observation* file for the asteroid being studied, which contains descriptions of the data and the names of the actual data files that are inputted into the software. SHAPE allows a number of representations for shape models, with different parameters contained in *model* files. The three most common representations are:

- An ellipsoid.
- A sum of spherical harmonics.

- A polyhedron with a number of vertices equal to a user-specified amount.

These models are realized as polyhedral shapes composed of triangular facets and each representation is described by a combination of different free and fixed parameters that range from three to hundreds or even thousands. They can describe the object's spin state, orbital components, physical dimensions, the vectors normal to each surface facet, etc. The time delay correction parameters are especially important for refining our knowledge on an asteroid's trajectory. Each type of model also carries a number of penalty functions. These functions discourage SHAPE from producing models that fit the data well but are physically implausible, and are one way of addressing a number of systematic (non-Poisson or non-random) errors. Penalty functions also enforce Occam's razor by discouraging complex models until a simpler model is unobtainable. Penalty functions are given numerical values to alter how each function is weighted during model runs. A positive penalty weight discourages the property being penalized. A negative penalty weight encourages that property. I am primarily concerned about 2 penalty functions, with the others being held at their default values.

- *nonsmooth* - discourages adjacent facets that are not coplanar.
- *concavity* - discourages facet-scale concavities.

I alter these penalties in the spherical harmonic model runs. Penalty functions are described in a series of parameter files. The primary parameter files used in this research are:

- *fpar* - performs the “fit” action to create synthetic models of the asteroid.
- *wpar* - performs the “write” action to display what the model actually looks like and gives information on how well the model predictions match the data.
- *mirrorpar* - performs the “mirror” action which replaces a model with its mirror-image version. This is needed to find the second of two pole directions for the asteroid because of a north-south ambiguity in rotation.

The modeling algorithm for SHAPE explores parameter space and computes a model by searching at each step for the best-fit value of one of these parameters while holding all of the others constant. “Best-fit” refers to driving the sum of the reduced χ^2 and one or more of the penalty functions toward a local minimum. A local minimum is described by a point where the model is a good fit to the real data. To find this minimum, SHAPE computes an objective function for each unchanged free parameter. Next, it adds a user-specified increment step to it and computes a new objective function for the changed parameter. After comparing the two objective function values, the software applies ever-larger steps in the “downhill” direction until finally the function starts to rise again. This lets the software bracket the local minimum. Using a version of the Brent-Dekker method, SHAPE will iterate in the bracket for the best local minimum and quickly converge

to it.

It must be emphasized that although SHAPE uses the χ^2 statistic of how well the models match the observations, it is a relative rather than an absolute measure. This is for two main reasons.

1. The resolution of the radar images is higher than that of any fit that SHAPE could produce in any reasonable computing time limit. Therefore, the software does not fit the asteroid shape down to the resolution limit of the data. The model of the shape is used to compare asteroids between each other, and also for boulder placement. The χ^2 p-value is therefore not an absolute indicator of how good a shape fit is for these two applications.
2. The p-value arises from a binary test: does the null hypothesis model fit the data acceptably within the errors? Here, the question is not a simple null hypothesis for a model to fit the data. The question is where 1992 UY4 fits into the existing small database of NEA observations with respect to shape and boulder distribution. Therefore, it is not applicable to use p-values with SHAPE statistical calculations.

The use of SHAPE as a relative determinant of asteroid shape and boulder distribution analysis tool has become standard in the field given these considerations. The software will go through several iterations, slowly decreasing the reduced χ^2 value. If the value does not change more than a user-specified amount over one iteration across all model parameters, the

software will stop running. SHAPE then outputs 4 primary types of model images:

1. observation images
2. fitted model images
3. residual images (the difference in echo power from the observed image of 1992 UY4 and my synthetic model)
4. plane-of-sky (POS) images (different than the delay-Doppler images - this shows how the target would look if it were in the sky right above us).

This output is used to study properties of the target asteroid. I use these general methods to analyze 1992 UY4.

4. SHAPE MODELS AND POLE DIRECTIONS

I explored the parameter space with SHAPE in several ways, working from simple models to more complex representations via ellipsoidal fits, spherical harmonics, and eventually vertex models.

Figure 4.1: A diagram depicting the ecliptic coordinate system. The system is defined by Earth's orbit around the Sun. The ecliptic is a plane nearly coplanar with the Earth's orbit, with the North and South Ecliptic poles perpendicular to this plane. The ecliptic itself is defined as the 0 for ecliptic latitude and the 0 for ecliptic longitude is defined by the direction to the Sun from Earth at the Vernal Equinox (about March 21). Notice also that the North Ecliptic Pole differs from Earth's north pole (which points toward Polaris) by about 23.5° . Diagram by Michael Richmond of RIT Observatory (<http://spiff.rit.edu/classes/phys301/lectures/coords/coords.html>).

4.1 Ellipsoid Models

Figure 4.2: POS image of my ellipsoid model. I exchange detail for quick run times to find the pole direction. Finding the pole at this step is important if I want the more complex representations to have a good starting parameter set.

I started with ellipsoid models, which have the least amount of detail but are the quickest to run, taking roughly 5 to 10 minutes for each fitting on a single processor. I perform a grid search to find the asteroid’s pole direction. Without the proper axis, the more complex models will not accurately capture 1992 UY4’s shape. The grid search spanned across all possible angle combinations of ecliptic longitude and latitude (λ and β respectively) in J2000 coordinates (Fig. 4.1).

The grid search required manual input, with λ ranging from 0° to 360° and β ranging from -90° to 90° . We used 10° increments for the grid search, resulting in an uncertainty of $\pm 10^\circ$. To determine if a pole direction was a good fit for the asteroid, I went through each of the outputted frames and evaluated them by eye. I compared the observation, fit, and residual images and sought differences in echo power, the relative intensity of the radar echo as a function of Doppler shift and radar time delay, and whether the real and

synthetic asteroid appeared across an identical range of pixels in the frame. If the bandwidth of the echoes does not match, the pole direction will be incorrect.

The shape of my synthetic 1992 UY4 appeared oblong (Fig. 4.2) as a consequence of the initial ellipsoid fit which does not match the asymmetric “meatball” appearance in the observations.

4.2 *Spherical Harmonics*

From Benner et al. (2006), the surface is characterized by gently undulating topography with many modest concavities. To fit this lumpy shape more effectively, I next turned to spherical harmonic models.

Spherical harmonics are the solutions to the angular portion of Laplace’s equation, $\nabla^2 f = 0$, in spherical coordinates using separation of variables. They are an infinite set of harmonic functions defined on the surface of a sphere and are an analog of a Fourier decomposition in three dimensions. They arise in many physical problems that range from the computation of atomic electron configurations to the representation of gravitational and magnetic fields of planetary bodies. I use them here as a rough representation for 1992 UY4.

These models better captured the bulges present on 1992 UY4’s surface. However, the structures seen are still highly unrealistic. I obtained a shape more likened to a sea urchin, with multiple bulges jutting out of the

Figure 4.3: POS image of my spherical harmonic model. This model did not represent an accurate physical fit for 1992 UY4 but it is a good first approximation for the spherical shape.

central body instead of sharp spikes. I began altering the penalty functions *nonsmooth* and *concavity* and came to a model better representative of the actual shape of 1992 UY4. It is not an accurate physical fit but it is an improved approximation for 1992 UY4 compared to the ellipsoid fit (Fig. 4.3).

4.3 Vertex Models

Once the penalty functions were sufficiently altered, I moved on to vertex models to capture the finer details of 1992 UY4's surface (Fig. 4.4 left). I settled on 500 vertices for the models as a compromise between speed and accuracy. These models achieved a resolution of about 140 m/pixel and also refined the bulges present in my spherical harmonic models while also better defining the concavities present on the asteroid. Note that this

Figure 4.4: POS images of my 500-vertex models for the first (left) and mirror (right) pole directions. There are two different pole directions due to a north-south ambiguity. It is unknown whether 1992 UY4 rotates prograde or retrograde.

model resolution is nearly 20 times larger than the image resolution in one dimension, or nearly 400 times larger than each image resolution in terms of area (if pixels were square, which is an over-simplification but a good illustration).

The radar images still presented a north-south ambiguity, which leaves both prograde or retrograde rotation as possibilities. I had to consider the pole direction given by an angle combination on the opposite side of our asteroid. Inputting the first pole direction into SHAPE software's *mirrorpar* function, I produced the mirror pole direction (Fig. 4.4 right).

4.4 Results

The two potential pole directions are located at $\lambda = 285^\circ \pm 10^\circ$, $\beta = -80^\circ \pm 10^\circ$, and at $\lambda = 110^\circ \pm 10^\circ$, $\beta = 75^\circ \pm 10^\circ$, the mirror direction.

Model	reduced χ^2	degrees of freedom
Ellipsoid Model	1.528	11,845,799
Spherical Harmonic Model	1.342	11,845,799
Vertex Model (First Pole)	1.245	4,397,543
Vertex Model (Mirror Pole)	1.299	6,242,220

Table 4.1: A list of the reduced χ^2 values for each type of model. Notice as I progress to more complex models, the reduced χ^2 gets closer to 1, which indicates a better fit. The number of degrees of freedom gives an indication of the number of pixels used in the fit over all frames, which is in the millions, minus the number of free parameters, which is in the thousands. Note that p-values are not applicable here, because the goal is not to fit a model of the asteroid surface down to an image resolution unit and then compare the model to the data for an absolute goodness-of-fit calculation. Rather, the goal of the ellipsoid and spherical harmonic models is to find the best starting values for vertex models, and the goal of the vertex models is to discriminate between various pole locations and rotation directions. Although the formal p-values for the above entries are less than 10^{-6} , the relative reduced χ^2 values are useful to determine a relative difference in fit between the models. In addition, with millions of degrees of freedom (pixels) and only a few thousand parameters, the p-value becomes a less sensitive statistical measure as systematic errors such as uncertainties in the time-dependent point spread function over an asteroid's surface will become important compared to statistical (photon counting) errors. The systematic errors are not likely to be distributed in the same random way as statistical errors, therefore the χ^2 statistic is useful more as a relative rather than an absolute measure of goodness-of-fit.

To resolve the ambiguity, I examine the χ^2 values and the higher order fit images for the vertex models.

Tab. 4.1 shows reduced χ^2 values for each type of model that I created using SHAPE. Note that the reduced χ^2 value is used as a relative discriminant between models rather than an absolute one to answer a binary question about the goodness-of-fit for any particular model to the data. See the table caption for details. As I progress to more complex models, the χ^2 gets closer to 1. This indicates a better fit. Note that the χ^2 value for the mirror pole

Figure 4.5: SHAPE output for the first pole direction with 500 vertices, located at $\lambda = 285^\circ \pm 10^\circ$, $\beta = -80^\circ \pm 10^\circ$.

Figure 4.6: SHAPE output for the mirror pole direction with 500 vertices, located at $\lambda = 110^\circ \pm 10^\circ$, $\beta = 75^\circ \pm 10^\circ$.

vertex model is worse than the first pole vertex model. This suggests that the first pole model is a better fit and 1992 UY4 is a retrograde rotator.

With the higher order models, I can also examine each frame as observed by Arecibo. The 500-vertex models for both the first pole direction and its mirror direction are shown in Fig. 4.5 and Fig. 4.6. I needed to determine whether or not certain features are captured by one set of fits over the other. There is a sharp ridge near the top of the observation image, which is from the first frame from Arecibo's August 6 observations. This feature is present in the first fit but not the mirror fit. These disparities are present in several of the other frames from other observation days as well. Based on this visual interpretation of the residual images, which is supported by the relative

reduced χ^2 values of the first fit compared to the mirror fit, we therefore determine that the first pole direction ($\lambda = 285^\circ \pm 10^\circ$, $\beta = -80^\circ \pm 10^\circ$) is relatively the best fit, though it is not realistic to give a strict percentage value for one fit over the other as all models under-fitted the image resolutions. Given these considerations, I conclude that 1992 UY4 is most likely a retrograde rotator.

5. BOULDER MAPPING AND CANDIDATE BOULDERS

5.1 *Mapping Method*

Figure 5.1: Example of an observation image of 1992 UY4 from the Goldstone dataset. These images were excluded from usage for boulder mapping due to insufficient echo signal.

To map boulders, I examined each of the observation frames of 1992 UY4 as seen from Arecibo. The Goldstone observations were excluded due to insufficient signal-to-noise (Fig. 5.1). This is done through two main steps:

1. I examined each frame and searched for relatively bright clumps of pixels present in the image. I measure the signal-to-noise ratio as follows. Each delay-Doppler pixel has a value determined by the sum of the

amount of radar echo power returned from the corresponding locations in space and random thermal noise from the telescope optics and radar receiver. At radio wavelengths, the energy per photon is low and the number of photons is large; so shot noise due to photons being quantized is not significant. Note that boulders are generally not resolved in the images, so they would cover at a minimum the number of pixels in the radio telescope point spread function, which is about 4 (a 2×2 array). For such a clump of at least 4 bright contiguous pixels, which I interpret to be a boulder, the individual pixel values should be at least 3 to 5 σ above the mean background signal. I calculate this first by adding up the data values in the bright pixels. I then calculate the background by the median of the pixel values in an annulus of width 2 pixels centered on the bright spot which has a radius of at least 2 to 3 pixels beyond the bright spot. For a 2×2 pixel boulder, this means an annulus of radius 4 to 6 or 5 to 7 pixels, giving about 63 to 75 pixels. I excluded background regions which had obvious boulders or other features. I then calculated the standard deviation of pixel values in the annulus to give a root mean square variation in the background. The significance of the feature is then the sum of the pixel values in the boulder region minus the mean background, divided by the (standard deviation in the annulus times the square root of the number of pixels in the boulder region) to give the signal-to-noise ratio of the boulder. Typical boulder pixel values are around 10 to 100. Typical background

values are 2 ± 2 (a standard deviation of 2). The signal-to-noise ratio per pixel in any boulder ranges from a minimum of 3 to 5, and goes as high as 50. The signal-to-noise ratio per boulder is multiplied by the square root of the number of pixels in the boulder, or roughly a factor of 2. The minimum significance of any boulder is therefore around 6 to 10σ above the mean.

2. I compared different frames in time to see whether the clumps were moving rotationally along each frame. For this, the clump must move across at least 3-4 frames to satisfy this criterion. By having a boulder appear on more than one frame, its significance in units of σ (normalized variation above the mean) is multiplied up again by the square root of the number of frames. Therefore, the significance of any particular boulder which appears on two frames ranges from a minimum of 8 to 14σ and up to as high as 70 to 100σ . However, as the pixels are correlated and systematic errors may dominate the standard deviation of the background pixels, these are only approximate σ values. Nevertheless, having a boulder appear in more than one frame adds weight to our interpretation of its validity. Dr. Michael Busch also inspected the frames visually in the same manner as other boulder analyses he has done, and verified boulder candidates.

If I noticed a clump of pixels that fulfilled the above criteria, I logged a boulder. I repeated this process as I cycled through each frame multiple

Figure 5.2: Boulders are indicated by relatively bright clumps of pixels moving rotationally along each frame. The different colored arrows follow two separate boulders. Collage by Dr. Lance A. M. Benner (JPL).

times, where I often examined the same series of images 10-20 times (Fig. 5.2).

I initially found roughly 30 candidate boulders by examining roughly 40 frames. This is probably an overestimate caused by misidentifications. I therefore looked to where each of the candidate boulders were mapped and eliminated boulders which corresponded to similar locations on the asteroid

to remove duplications. I also need to differentiate a boulder from other structures, such as a mound or crater on the surface of 1992 UY4. If the boulders and other structures were in the line-of-sight of Earth, they would all reflect the signal back. However, as the asteroid rotates, the structures such as mounds and craters disappear from our line-of-sight but the boulders still protrude from the surface and can reflect a signal back (Fig. 5.3).

Figure 5.3: A diagram showing reflected signals from the surface of an asteroid. Notice at position 1, the boulder and crater are reflecting a signal back at Earth. However, at position 2, the boulder is still reflecting but the crater is now shadowed and unable to reflect back. This is an example of how I can differentiate boulders from other surface structures.

Figure 5.4: Visualization of mapped boulders from along primary spin axis. The various colors represent the different days observed by Arecibo: orange for Aug. 6, red for Aug. 7, green for Aug. 8, blue for Aug. 9, and pink for Aug. 10.

5.2 Results

Out of the roughly 30 initially, I discovered 18 candidate boulders, with each boulder's significance ranging from about 8 to 10 σ to over 50 to 70 σ or even higher across the surface of 1992 UY4 (Tab. 5.1). I stress that the significance, in units of σ , is based on a combination of photon counting statistics (which dominate the pixel values for the boulders) and the repetition of a feature across several frames, but do not factor in systematic errors,

which would dominate the standard deviation of the background. These σ values are therefore approximate, but the measurements are done in a way which is established for astronomical image analysis (Schechter et al. 1993). To illustrate my boulder sample, I transferred the coordinates onto a model synthesized in a visualization tool named MayaVi, a Python package (Fig. 5.4).

Fig. 5.5 shows a view of 1992 UY4 from along the equatorial ridge. Notice the overabundance of boulders that appear compared to Fig. 5.4.

Figure 5.5: Visualization of mapped boulders from along equatorial ridge. Overabundance is due to the north-south ambiguity.

This is again due to the north-south ambiguity ingrained in the data. If not on the equatorial ridge of the asteroid, the software did not know which hemisphere a given boulder originated from, so it produced two sets of coordinates for one boulder (Tab. 5.2). This resulted in greater than 18 boulder locations.

The boulders' distribution in longitude appears non-uniform in the Arecibo data. The edges of Arecibo's field of view, indicated by the orange and pink shadings, show very few boulders. This is probably due to observing bias, as the mapping method assumes some false positives and false negatives.

As I manually identified which clumps of pixels were boulders, it is possible that I could have logged a false positive. Conversely, I could have also rejected a clump of pixels that I deemed as lacking a boulder - a false negative. The contrast between the number of boulders observed at various spots can be understood by examining the lower boulder densities at the edges of the observation ranges. The echo signal in those areas may not be as strong as the areas in line-of-sight from Earth. This darkens the observation images towards the edges of each frame, making it quite difficult to spot a boulder in those regions. The boulders were visually verified independently by Dr. Michael Busch.

I therefore cannot conclusively state whether or not the boulders are uniformly spread across the surface at this time. More observations would be required for 1992 UY4 in order to view the surfaces not seen during the August 2005 flyby. Unfortunately, 1992 UY4 will not pass so near to Earth

as it did until 2482, with other, more distant approaches occurring in the intermediate years.

Set	Boulder	Lat., Long.	Corresponding Facets
0	1*	55.5, -165.1	102-04
0	2*	58.0, -148.0	104-06
0	3*	70.8, -100.6	164, 209, 210, 211, 236-238
0	4*	52.0, -115.0	129, 161, 162, 208, 209, 235, 236, 274, 275
1	1*	-1.1, -151.5	373, 374, 440, 441, 507, 508-10, 574-76
1	2	62.0, -131.1	78, 106, 107, 139
1	3*	59.3, -65.6	142, 213-15
1	4*	53.9, -74.3	240, 278, 327, 388
1	5*	87.9, -85.9	55-57
1	6*	30.5, -110.8	325, 380-82
2	1*	76.1, -128.1	35, 36, 51, 52
2	2*	42.6, -137.5	138, 205, 206
2	3	84.8, -100.2	54, 55
2	4	80.9, -61.3	38
2	5	79.9, -115.5	36, 53
2	6	74.0, -121.5	52, 53, 78, 79
2	7	62.2, -135.1	77, 106, 107
2	8*	68.3, -122.7	78, 79, 107, 108
3	1*	40.0, 15.8	122, 177
3	2*	57.2, -49.9	114, 115, 143, 144, 167, 168
3	3	90.0, 90.4	21, 22
3	4	63.0, -110.8	109, 162, 163, 208, 209
4	1*	79.1, -9.4	2, 8, 23
4	2*	86.9, -159.8	0, 1, 6
4	3	60.0, -55.3	114, 143, 167
4	4*	75.5, -80.7	166, 212, 240
4	5	70.9, 62.1	66, 92
4	6*	86.4, 68.7	3, 12

Table 5.1: A list of all candidate boulders. The various set numbers correspond to the different sets of observation frames for each day Arecibo viewed 1992 UY4: Set 0 for Aug. 6, Set 1 for Aug. 7, Set 2 for Aug. 8, Set 3 for Aug. 9, and Set 4 for Aug. 10. Lat. and Long. in this case correspond to locations on the asteroid and do not follow the aforementioned ecliptic coordinate system. These coordinates are based on the coordinates in line-of-sight from Earth (given by SHAPE) and are assumed to be in degrees, with an uncertainty of $\pm 1^\circ$. This is true for later boulder tables as well. I initially find about 30 but narrow it down to 18 by examining relative locations on the surface of UY4 and eliminating duplicates. Asterisks indicate the 18 reliable boulder candidates which appear over multiple frames, are associated with adjacent facets and which are significant above the background as explained in the text.

Set	Boulder	Lat., Long.	Corresponding Facets
0	1	-48.6, -164.4	865, 866, 889, 890
0	2	-53.1, -144.9	833, 867, 890-92
0	3	-69.4, -105.8	794, 795, 837, 871
0	4	-51.2, -116.7	704-06, 754, 793, 836
1	1	-1.1, -151.5	373, 374, 440, 441, 507, 508-10, 574-76
1	3	-53.3, -70.5	712, 713, 758
1	4	-20.7, -76.9	455, 522-24, 588-90
1	5	-88.0, -87.1	896, 927, 928
1	6	-27.9, -116.1	581, 645, 646
2	1	-80.8, -101.9	894-96
2	2	-40.0, -128.6	702, 754, 792
2	8	-71.3, -107.2	837, 871, 872
3	1	-25.1, 9.5	663, 722, 723
3	2	-35.8, -45.9	716, 800
4	1	-50.3, -5.13	881, 882, 906
4	2	-63.2, -12.1	934, 954, 955
4	4	-55.0, -73.3	651, 712, 758
4	6	-60.0, 12.4	907, 908

Table 5.2: Similar to Table 5.1, this is the list of the 18 most reliable boulder candidates on the mirror side. Notice that Set 1, boulder 1 has the same coordinates as Tab. 5.1. This is because that boulder is located on the equatorial ridge of 1992 UY4, so there is not an ambiguity there. See Table 5.1 caption for details.

6. HIGHER RESOLUTION MODELS

Figure 6.1: SHAPE output for the first pole direction with 1000 vertices.

Figure 6.2: SHAPE output for the mirror pole direction with 1000 vertices.

Although 1992 UY4 is hundreds of years from passing nearby once again, I can refine the models to constrain the shape of 1992 UY4 further. I remotely accessed the 1992 UY4 data on SETI Institute's servers to run higher resolution vertex models, increasing the number of vertices from 500 to 1000 (Fig. 6.1 and Fig. 6.2). Tab. 6.1 shows the reduced χ^2 values for the 1000 vertex models. I am able to decrease the reduced χ^2 for the first pole vertex model

Model	reduced χ^2	degrees of freedom
Vertex Model (First Pole)	1.200	11,845,799
Vertex Model (Mirror Pole)	1.307	11,845,799

Table 6.1: Similar to Table 4.1, the reduced χ^2 values for the first pole and mirror pole 1000-vertex models. Note that reduced χ^2 has been decreased in both cases, compared to the 500 vertex models. The increased number of vertices resulted in a better fit. See the caption to Table 4.1 and the text for details about the use of the χ^2 statistic and the lack of applicability for the p-value.

to 1.200 and obtain a better fit for 1992 UY4 than for the mirror pole. This improves the resolution to about 100 m/pixel and resolves more structures on 1992 UY4's surface. In addition, I am able to better resolve the north-south ambiguity and the probability constraint on 1992 UY4's rotation angle.

The relative reduced χ^2 values for the two models suggest retrograde rotation, though a specific percentage probability for each case is difficult to assign for the same reasons described for the 500 vertex models. I also see that the sharp feature outlined at the top of the asteroid in the observation image is still in the $\lambda = 285^\circ \pm 10^\circ$, $\beta = -80^\circ \pm 10^\circ$ pole direction but not the mirror direction $\lambda = 110^\circ \pm 10^\circ$, $\beta = 75^\circ \pm 10^\circ$. Notice how the second ridge appears in the region between the arrows (Fig. 6.3).

In the 500 vertex models, this ridge was moderately visible in both fits. In contrast, for the 1000 vertex models, this ridge is much more pronounced in the best fit pole direction but is not present at all in the mirror pole direction (Fig. 6.4). I am led to conclude from the relative reduced χ^2 statistics that the spin axis corresponds to the pole direction given by $\lambda = 285^\circ \pm 10^\circ$, $\beta = -80^\circ \pm 10^\circ$ and 1992 UY4 is a retrograde rotator.

Figure 6.3: I check for the existence of the ridge in between the arrows in our 1000 vertex models for the two potential pole directions.

Figure 6.4: The ridge is present in the best pole direction model (left) but not in the mirror pole direction model (right). Also, the sharp pronounced feature at the top of the observation frame is more noticeable in the best pole model but not the mirror pole. Features like this can be seen throughout the multiple outputted frames. I can say that UY4 has a higher relative probability of being a retrograde rotator. An exact probability cannot be calculated in part because the errors per model point vary in a complex fashion because the pixel errors (due to the point spread function) vary in time and location across the asteroid, and the statistics do not necessarily reflect systematic errors well.

7. SUMMARY AND FURTHER WORK

7.1 *Discussion*

I came across two potential pole directions after modeling NEA 1992 UY4 with the SHAPE software. Through careful analysis of the two opposing models, I conclude that 1992 UY4 is most likely a retrograde rotator, with a pole direction at $\lambda = 285^\circ \pm 10^\circ$, $\beta = -80^\circ \pm 10^\circ$ and a reduced χ^2 value of 1.200. Although the models I obtained were not at the resolution of the observed data, they were sufficient to discriminate between the two rotation directions. I could decrease reduced χ^2 further but this requires significant run times of weeks or even months. I also counted 18 boulders on the surface of this NEA, which were first usually identified, then checked using accepted astronomical image significance criteria, and finally independently corroborated by Dr. Michael Busch, using standard methods in the field of NEA research. A visual inspection shows no obvious clumping, but a definitive statistical determination is yet to be done.

I compare characteristics of 1992 UY4 with selected recent NEA observations. Betulia (Magri et al. 2007) has a rotational period of about 6 hours and Icarus (Greenberg et al. 2017) has a rotational period of about 2 hours,

and both have a roughly flat spheroid shape. 1992 UY4 has a rotational period of about 12.9 hours and an asymmetric, spheroidal shape. Asteroid shape is not expected to be spherical for objects less than a few hundred km in diameter because gravity is not strong enough to pull them into that least-energy configuration. However, for small objects with relatively slow rotational periods, such as 1992 UY4, the rotation is not significant enough to cause major deviations from the spherical shape. With Betulia and Icarus, the fast rotation could have resulted in bulging or an accumulation of loose material (regolith, etc) along the equatorial ridge, leading to the flat spheroid shape. For example, a rocky asteroid with a density of 2000 kg/m^3 and a radius of 1 km would have an escape velocity of only about 1 m/s. Betulia and Icarus were also found to have pole directions of $\lambda = 136^\circ$, $\beta = 22^\circ$ and $\lambda = 270^\circ$, $\beta = -81^\circ$ respectively. This means that Betulia is a prograde rotator and Icarus is a retrograde rotator, like 1992 UY4. We note that Icarus and 1992 UY4 have similar pole directions, coming within about 10° of each other, though this could be a statistical fluke.

This research is also part of an effort by NASA's Frontier Development Lab (FDL) at the SETI Institute to create innovative ways to refine the shape modeling process, as well as consider possible solutions to any impact threats. The human eye is often more reliable for pattern recognition than numerical algorithms, but writing and executing such algorithms is complex, so at present, the time-consuming visual inspection of many images is still one of the standard methods of shape analysis and boulder identification.

Another challenge is the size of grid search performed to find the candidate pole directions. Unless known *a priori*, it is an arduous process to locate a candidate pole and even then, the search may not yield a unique solution. Using my research as a reference, NASA's FDL team managed to utilize an automated routine for SHAPE, which adjusted the various parameters for the shape models. This reduced the time and manpower required to model 1992 UY4. For example, my grid search for the pole direction took about a week but FDL found the same coordinates in roughly 3 days. This routine could reduce the time spent on similar projects by weeks.

In 2013, NASA issued the Asteroid Grand Challenge: a task focused on finding all asteroid threats to human populations and knowing what to do about them. Over the past decade, the number of discovered NEAs has grown rapidly and this trend will continue as new projects arise. As of February 2017, there have been more than 15000 NEAs discovered. A ground-based telescope that will be operational in the 2020s will be the Large Synoptic Survey Telescope (LSST)¹. LSST could yield vastly more NEA discoveries and allow for a dramatic increase in targets for observation. Its sensitivity could allow for the discovery of these objects months or even years before being detectable by radar.

LSST will make new optical surveys, but scientists can also refine existing surveys at other bands. The observational contributions of Arecibo

¹ The University of Louisville joined the LSST Cooperation in 2016 as the lead institution for a consortium of 8 Kentucky universities

could be improved if there were additional telescope time and an automation of the NEA observations. There are also challenges in funding these improvements. A number of different facilities, like Haystack Observatory and radio telescopes in Germany, Italy, and Latvia, could be utilized to observe NEAs. Although orders of magnitude less sensitive than the more advanced radars, these facilities could detect a modest number of these objects annually during very close flybys.

7.2 *Boulder Samples and Clustering*

Itokawa (Michikami et al. 2008) is an S-type NEA that was imaged by the Hayabusa spacecraft, which provides a high resolution imaging comparison to Earth-based radar data. Itokawa was intriguing because it contained areas of “smooth” and “rough” terrains, with the latter being riddled with boulders. The images revealed 373 boulders greater than 5 m in diameter across its surface, with a surface density of over 1000 per km². Their origins were examined quantitatively by using an impact cratering model and the research showed that the boulders could not have been solely caused by impact cratering but rather the catastrophic disruption of a parent body. Their results indicated that Itokawa was a “rubble-pile” body, which reformed after being shattered.

Toutatis (Jiang et al. 2015) is a S-type NEA that was visited by the Chang’e 2 spacecraft. Images helped identify more than 200 boulders across

the surveyed area. Its cumulative boulder size-frequency distribution (SFD) indicates a great degree of fragmentation. It is also thought to be a “rubble-pile” but the slope of its SFD compared with Itokawa’s implies a different preservation state or diverse formation scenarios. Although I did not find as many boulders as from these two space probe results, the boulder clustering for the large end of the size distribution can be compared with them, especially if more samples like that from 1992 UY4 can be obtained from radar observations.

With the higher resolution models, I plan to remap the surface of 1992 UY4 to characterize the clustered boulders. I will also check for the robustness of my results using standard statistical techniques, such as bootstrap resampling with correlation functions. These functions are generic mathematical tools for calculating the statistical correlation between different random variables and can be used in a wide range of applications. They are commonly used to correlate the angular locations of galaxies on the sky (Landy and Szalay 1993). I am looking forward to examining possible clustering on 1992 UY4 and have the goal that my research will contribute to the field of NEAs.

7.3 *Trajectory*

My research with 1992 UY4 helped refine trajectory predictions over the course of time (J. D. Giorgini, personal communication). Dr. Giorgini was

able to generate an updated trajectory solution for 1992 UY4 on 2016 August 22, incorporating measurements based on my shape models, along with all previous radar and optical astrometry. These measurements helped alter the information on 1992 UY4's previous close approaches, which is important for predicting future flybys. This is designated as orbit solution 91 and can be found through the JPL Horizons Ephemeris System.

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APPENDIX

The following pages contain a collage of SHAPE's output for the vertex models in the $\lambda = 285^\circ \pm 10^\circ$, $\beta = -80^\circ \pm 10^\circ$ pole direction. Each row of images represents a different view of the model of 1992 UY4 and correspond to each of the observations conducted by Arecibo and Goldstone. Each column represents the 4 different types of output SHAPE produces. From left to right:

1. observation images - Delay-Doppler radar images obtained by Arecibo and Goldstone.
2. fitted model images - My synthetic models of 1992 UY4, created using SHAPE.
3. residual images - The difference in echo power between the observation and fit images.
4. plane-of-sky (POS) images - The appearance of 1992 UY4 if it were in the sky right above us.

I display these to demonstrate the number of frames I went through (multiple times) when searching for candidate boulders. Again, the Goldstone images were excluded due to insufficient signal-to-noise, leaving roughly 40 sets of data to sift through.

Nicholas Dat Tien Duong

Curriculum Vitae

18514 Longview Park Lane
Louisville, KY 40245
Cell: +1(502)619-0222
Email: ntduon01@louisville.edu

Statement of Purpose: What lies out there for humanity to discover? There are a multitude of unanswered questions and I often find myself deep in thought about our place in the universe. I wish to indulge my curiosity and I believe that my strong foundation, experiences, and resolve to strive for greater heights will lead me to a successful career in my field. Astrophysics – grasping the knowledge of our universe – is my passion and offers the perfect segue into truly exploring the unknown.

Education

2012 – 2017 **University of Louisville (U of L), Louisville, Kentucky, B.S. in Physics** with a concentration in Astronomy/Astrophysics and B.A. in Mathematics.
GPA – 3.65, College of Arts and Sciences

Research Experience

January 2016 **Research Assistant, U OF L: EXOPLANET GROUP.**

– Present Dr. John Kielkopf at U of L is currently training me and a few others in utilizing the software necessary to work with KELT (Kilodegree Extremely Little Telescope) data. This includes, but is not limited to, AstroImageJ, SAOImage DS9, and IRAF. U of L is part of an international collaboration called the Shared Skies Partnership, giving me the chance to work with scientists around the world in my field. I will get to remotely access telescopes operated by Moore Observatory in Louisville, Mount Lemmon Observatory in Arizona, and Mount Kent Observatory in Australia. Current plans are to perform follow-up observations on exoplanet candidates. I will also get the opportunity to possibly work with data from TESS (Transiting Exoplanet Survey Satellite), once it is launched into space in 2018.

June 2016 – **REU Student, SETI INSTITUTE, Mountain View, CA.**

August 2016 Under the mentorship of Dr. Michael Busch at SETI (Search for Extra Terrestrial Intelligence) Institute, funded by the National Science Foundation's Research Experience for Undergraduates (REU) for the summer of 2016, I studied the Near-Earth asteroid 1992 UY4. Our aim was to model the shape of UY4 using the SHAPE software and then analyze the boulder distribution across the surface of the asteroid. During modeling runs, we came across two primary spin pole directions but ultimately ruled out one of them, concluding that UY4 was a retrograde rotator. We found 18 boulder candidates but due to observing biases and lack of more data, we cannot make a statement on the distribution at this time. I am currently doing remote runs from the University of Louisville for higher resolution models. I presented a poster on my research at the 229th American Astronomical Society (AAS) conference and I am currently writing my Senior Honors Thesis about my work from this REU.

June 2015 – **Research Assistant**, U OF L: ATMOSPHERIC SCIENCES GROUP.

May 2016 Dr. Jian Du-Caines at U of L hired me as a part-time research assistant for her Atmospheric Sciences research. My primary goal was to study the impact of ENSO (El-Niño Southern Oscillation) and QBO (Quasi-Biennial Oscillation) using MATLAB's analytical tools on data from the eCMAM (extended Canadian Middle Atmospheric Model).

Academic Honors and Scholarships/Awards

EVPRI Internal Research Grant, U of L, Spring 2017

The Executive Vice President of Research and Innovation (EVPRI) provides oversight of research, scholarship, and creative activity at the University of Louisville. This grant serves as funding for myself as I write my Senior Honors Thesis on my asteroid work from the SETI Institute's REU program.

Bullitt Scholarship in Astronomy, U of L: Department of Physics & Astronomy, Fall 2016

Through a generous donation from the William Marshall Bullitt family, this scholarship is awarded to one or more students pursuing an education in astronomy at the University of Louisville. It is based on the student's academic record (coursework and research), as well as interests and future goals pertaining to astronomy.

American Astronomical Society (AAS), Junior Member, August 2016 – Present

NSF Research Experience for Undergraduates (REU) appointment at SETI Institute, Summer 2016

Mortar Board National Senior Honorary, April 2016 – Present

Technical Skills and Experience

MATLAB, MAC/WINDOWS

Advanced.

PYTHON/JUPYTER, UNIX/LINUX, SHAPE (MODELING SOFTWARE)

Intermediate.

C++, L^AT_EX, ASTROIMAGEJ, SAOIMAGEDS9, IRAF

Basic.

Teaching Experience

January 2016 – Present **Undergraduate Teaching Assistant, Astronomy Learning Center (ALC), U of L.**

Responsibilities include conducting the ALC's drop-in tutoring service, new to U of L. Students come at predetermined times to receive tutoring for the introductory astronomy courses. My role is to foster the student's learning experience while also promoting independence and critical thinking on the part of the tutee.

August 2016 – December 2016 **Resources for Academic Achievement (REACH) Tutor, U of L.**

Responsibilities included planning small group sessions, mediating student interaction, facilitating student learning in the introductory astronomy course, assessing the progress of each individual student, and providing an end-of-course study session prior to finals.

August 2016 – December 2016 **Undergraduate Teaching Assistant, Introductory Astronomy Lab, U of L.**

Responsibilities included instruction and supervision during lab activities, as well as grading reports in a timely manner. Students were encouraged to go beyond the course and better understand the astronomical phenomena being demonstrated in the activities.

January 2016 – April 2016 **Undergraduate Teaching Assistant, College Algebra, U of L.**

Conducted weekly recitations in order to assist students with working through problems and examples. My goal is to provide the students with insight beyond that of their instructor and to use my knowledge to facilitate their learning of algebraic concepts. I proctored for quizzes/exams and was responsible for grading them in a timely manner.

Languages

English, C2

This is my first language.

French, A2 – B1

I am moderately fluent in conversations.

Vietnamese, A1

My heritage is Vietnamese.

Extracurricular Activities

Mortar Board Pallas Chapter, Academic Vice President and Member
(April 2016 – Present)

Society of Physics Students (SPS), Social Coordinator and Member
(August 2014 – Present)

Society of Women in Physics and Astronomy (SWiPA), Member
(August 2016 – Present)

Vietnamese Student Association (VSA), Member
(August 2015 – Present)

Kentucky Science Center, Part-Time Volunteer
August 2015 – December 2015

Hobbies/Interests

- I recently joined the Core Combat Sports Gym for Boxing.
- I am self-teaching myself how to play the Ukulele.
- Outdoor Activities: Hiking, Camping, Swimming

Future Goals

- I wish to earn a Fulbright Scholarship and research exoplanets from Australia.
- I would like to pursue a Masters in Mechanical Engineering in order to apply it to astronomical instrumentation.
- I would like to pursue a Ph.D. in Astrophysics.