Radar observations and a physical model of Asteroid 4660 Nereus, a prime space mission target

Marina Brozovic a,∗, Steven J. Ostro a, Lance A.M. Benner a, Jon D. Giorgini a, Raymond F. Jurgens a, Randy Rose a, Michael C. Nolan b, Alice A. Hine b, Christopher Magri c, Daniel J. Scheeres d, Jean-Luc Margot e

a Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109-8099, USA
b Aerospace Observatory, National Astronomy and Ionosphere Center, Box 956, Arecibo, PR 00613, USA
c University of Maine at Farmington, Preble Hall, 173 High St., Farmington, ME 04938, USA
d Aerospace Engineering Sciences, University of Colorado, Boulder, CO 80309-0429, USA
e Department of Astronomy, Cornell University, 304 Space Sciences Bldg., Ithaca, NY 14853, USA

Abstract
Near-Earth Asteroid 4660 Nereus has been identified as a potential spacecraft target since its 1982 discovery because of the low delta-V required for a spacecraft rendezvous. However, surprisingly little is known about its physical characteristics. Here we report Arecibo (S-band, 2380-MHz, 13-cm) radar observations of Nereus during its 2002 close approach. Analysis of an extensive dataset of delay–Doppler images and continuous wave (CW) spectra yields a model that resembles an ellipsoid with principal axis dimensions $X = 510 \pm 20$ m, $Y = 330 \pm 20$ m and $Z = 241 \pm 40$ m. The pole direction is approximately located at ecliptic pole longitude and latitude of $\lambda = +25^\circ$, $\beta = +80^\circ$ with the uncertainty radius of 10°. Our modeling yields a refined rotation period of 15.16 ± 0.04 h. Nereus has a circular polarization (SC/OC) ratio of 0.74 ± 0.08, which implies substantial near-surface centimeter-to-decimeter scale roughness. Dynamical analysis of our model suggests that YORP alteration of the rotation period may become evident within a few years. Nereus has two stable synchronous orbits where natural material may remain in orbit, while most asteroids observed to date do not have such stable synchronous orbits. We also find that spacecraft orbits about Nereus are feasible.

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1. Introduction

Nereus (1982 DB) was discovered on February 28, 1982, by Eleanor F. Helin at Palomar. Its orbit ($a = 1.49$ AU, $e = 0.36$, $i = 1.4^\circ$) marks it as a low-delta-V target for rendezvous and sample return missions (Helin et al., 1984). It is ranked among the top 3% of the most accessible near-Earth asteroids (http://echo.jpl.nasa.gov/~lance/). Nereus was an early target for the NASA Near-Earth Asteroid Rendezvous (NEAR) mission that visited asteroid Eros instead. It was also the original target for Japan’s Hayabusa spacecraft, which ultimately visited Asteroid Itokawa (Kawaguchi et al., 1996; Fujiwara et al., 2006). In addition, Nereus was considered as a potential candidate for several other missions that never advanced beyond the planning stages (Williamson, 2003; Qiao et al., 2006, 2007; NEAP mission: http://neo.jpl.nasa.gov/news/news001.html).

Table 1 summarizes pre-radar knowledge of physical properties. Nereus has been classified (Binzel et al., 2004a) in the Tholen taxonomy (Tholen, 1984) as an E-class object, character-

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Optical and thermal properties of Nereus.</th>
</tr>
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<tbody>
<tr>
<td>Spectral class</td>
<td>E II (Binzel et al., 2004a; Clark et al., 2004b; Gaffey and Kelley, 2004)</td>
</tr>
<tr>
<td>Absolute magnitude</td>
<td>R-band 18.22 ± 0.06 mag (Ishibashi et al., 2000a, 2000b)</td>
</tr>
<tr>
<td></td>
<td>V-band 18.3 mag (Bartokov, 1996)</td>
</tr>
<tr>
<td></td>
<td>V-band 18.2 ± 0.7 mag (JPL small-body database, <a href="http://ssd.jpl.nasa.gov/sbdb.cgi">http://ssd.jpl.nasa.gov/sbdb.cgi</a>)</td>
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<tr>
<td>Optical albedo</td>
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<tr>
<td>Diameter</td>
<td>0.33–1.3 km (Delbô et al., 2003)</td>
</tr>
<tr>
<td>Rotation period</td>
<td>15.1 ± 1.2 h (Ishibashi et al., 2000a, 2000b)</td>
</tr>
<tr>
<td>Lightcurve amplitude</td>
<td>0.58 ± 0.03 mag (Ishibashi et al., 2000a, 2000b)</td>
</tr>
<tr>
<td>Thermal flux</td>
<td>0.1–0.37 × 10−14 W m−2 μm−1 (Delbô et al., 2003)</td>
</tr>
</tbody>
</table>

Summary of the physical properties of Nereus based on pre-radar studies.

* Corresponding author. Fax: +1 818 393 7116.
E-mail address: marina.brozovic@jpl.nasa.gov (M. Brozovic).

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Based on their orbital and physical characteristics, the E-class NEAs Nereus, 1998 WT24 and 3103 Eger have been suggested as candidates for the source of aubrites on Earth (Gaffey et al., 1992; Binzel, 1995; Harris et al., 2007). However, recent analyses of the E-class (Clark et al., 2004a; Gaffey and Kelley, 2004; Fornasier et al., 2008) place Eger and Nereus in the E II subclass, which does not seem to have an equivalent in the current aubrite samples (Clark et al., 2004a; Nédélec et al., 2007). E II subclass spectra are characterized by a sharp 0.49 μm absorption band and occasionally much weaker 0.9–0.96 μm dip. This secondary feature does not seem to be present in the Nereus’ spectra (Binzel et al., 2004a). The 0.49 μm spectral band is usually attributed to the presence of olivine (CaS) and/or troilite (FeS) (Burbine et al., 1998, 2001; Oldhamite (CaS) and/or troilite (FeS) (Burbine et al., 1998, 2001; Oldhamite (CaS) and/or troilite (FeS) (Burbine et al., 1998, 2001). The 0.9–0.96 μm absorption band is thought to be an indicator of pyroxene-olivine compounds (Burbine et al., 1998).

The origin of Nereus is not clear, although it is likely the main belt. One of the previous studies (Binzel et al., 2004b) attempted to connect Nereus to an E-class rich Hugardia region in the main belt, similar to an idea about the origin of NEA 3103 Eger (Gaffey et al., 1992; Fornasier et al., 2007). However, it was difficult to explain the differences in the inclinations of 3103 Eger (Gaffey et al., 1992; Fornasier et al., 2007). The 0.49 μm spectral band is usually attributed to the presence of olivine (CaS) and/or troilite (FeS) (Burbine et al., 1998, 2001; Oldhamite (CaS) and/or troilite (FeS) (Burbine et al., 1998, 2001). These studies have suggested that Nereus is an elongated object with diameter between 1.1–1.3 km. It also appears that along the long axis, one end of Nereus is narrower and more angular than the other end. We obtained our first estimate of the long axis (∼500 m) and the intermediate axis (∼250–300 m) from the extent of visible range. The object’s rotation appears consistent with the period of 15.1 h as obtained from the lightcurves (Ishibashi et al., 2000a, 2000b). A very intriguing view of Nereus is along its angular edge (Figs. 1A–1D). The flat leading edge on Jan 11 implies a facet-like surface oriented orthogonal to the line of sight. Furthermore, panels E and F in Fig. 1 show that Nereus also has a more rounded appearance when viewed after ∼180° rotation. We do not see any obvious craters or bright spots as observed on 1998 WT24, another E-class NEA (Busch et al., 2008).

During our observations, the asteroid traversed more than 100° of sky position, but the echo bandwidth at any given rotation phase did not change substantially, indicating that the subradar latitudes were not far from equatorial. However, we did notice very distinct changes from early dates to later dates in the appearance of images at similar rotation phases, indicating changes in subradar latitude. Even some twenty degrees of subradar latitude change in a single hemisphere (provided we remain near the equator) would not be detectable in the bandwidth (e.g. cos(0°)/cos(−20°) ≈ 6% difference). One possibility suggested from inspection of the image sequence was that the subradar point moved from slightly southern latitudes to slightly northern latitudes.

3. Shape modeling

3.1. SHAPE software

Our SHAPE software, originated by Hudson (1993) and developed considerably since then by Magri et al. (2007), uses constrained, weighted least squares to estimate a 3D model from delay–Doppler images, CW spectra, optical lightcurves, and/or plane-of-sky images. The Supplementary material contains a table where we list the imaging and CW datasets used in our modeling study. The algorithm uses three progressively more refined levels of shape representation: an ellipsoid parameterized by a major axis length and two axis ratios, a spherical harmonics model parameterized by series coefficients for the object’s radius vector, and finally a vertex model parameterized by vertex locations. All three kinds of models are realized by vertex-model approximations defined by a surface of triangular facets. A set of adjustable parameters describes the radar scattering law, the optical scattering law, the spin state, the radar calibration, and corrections to the delay–Doppler prediction ephemerides. The algorithm cycles through a list of parameters and calculates when the minimum contribution to the total χ² for that particular variable occurs, guided by user choices for initial values, step sizes, and convergence criteria. A parameter search and model optimizations may also be guided by certain penalty weights that prevent unphysical characteristics and distortions by penalizing departures from such attributes as principal-axis rotation, uniform internal density, or convexity. SHAPE’s ability to find a global minimum
is affected by the chosen step sizes and complex correlations among the variables, so subjective judgment plays a significant role.

3.2. Results of shape modeling

3.2.1. Pole direction

The ellipsoid fit started from our best a priori estimates of the lengths of the three symmetry axes, the pole direction, and the rotation period. We continuously refined the shape model as we progressed from an ellipsoid to a spherical harmonics representation and finally to a vertex model. Our initial guess was that Nereus’ axis of rotation was close to being perpendicular to the radar line of sight in most of the delay–Doppler images. We used a grid search in $10^\circ$ increments over the entire ecliptic longitude ($\lambda$) and latitude ($\beta$) space in order to find the pole direction. The best solutions (visually, and in terms of goodness-of-fit statistics) have $\beta > +70^\circ$, and there does not seem to be a good equivalent for $\beta < -70^\circ$ (a retrograde pole). The high $\beta$ makes it difficult to pinpoint the direction of pole longitude: the closer to $+90^\circ$ we are, the more ambiguous $\lambda$ becomes. Our final pole direction is within $10^\circ$ radius of $\lambda = +25^\circ, \beta = +80^\circ$.

3.2.2. Size and shape

Delay–Doppler images of a sphere constitute a two-to-one mapping from surface coordinates to image coordinates (the “north-
For nonconvex objects, the mapping can be three or more to one (Ostro, 1989; Ostro et al., 2002). For image sequences obtained sufficiently far from the equator, the delay–Doppler trajectory of all visible surface points is unique, and this is why such images can be inverted to reconstruct the target’s shape if the rotation phase coverage is adequate. Of course, if the sequence is restricted to, say, very high northern latitudes, then only about half of the target is seen. Thus the ideal radar imaging sequence would sample rotation phase thoroughly over a wide range of latitudes.

Shape estimation from radar data restricted to equatorial orientation has been extensively explored by Ostro et al. (1996) and Hudson and Ostro (1999) in their study of 1620 Geographos. The modeling yielded the pole-on silhouette of the object, but the components of the shape parallel to the z-axis remained unconstrained. The north–south ambiguity may be resolved to some extent by imposing constraints on the object’s dynamics (e.g. moment of inertia about the z-axis has to exceed the moments about the two equatorial principal axes). It is also possible to manipulate the radar (and/or optical) scattering law in order to improve understanding of the object’s dimension and shape normal to the equatorial plane.

The OC spectra in Fig. 2 were used in the shape modeling to help calibrate a simple cosine function that was assumed for the radar scattering law:

\[
d\sigma/dA = R(C + 1)(\cos \alpha)^2C.
\]

Here, \(\sigma\) is a radar cross section, \(A\) is the target surface area, \(\alpha\) is the scattering angle, \(R\) is the Fresnel reflectivity and \(C\) is a measure of the specularity of the scattering (Mitchell et al., 1996).

With Nereus, we encountered a situation similar to that described for Geographos. Although our data set provided excellent rotation phase coverage, our views of Nereus did not depart from the equator by more than 19°, i.e. all subradar latitudes remained less than 19°. This resulted in a large number of acceptable models that have very similar pole-on silhouettes and a wide range of north–south sizes and structures. Our preferred model represents the best (statistical and visual) fit to the radar data. In order to express the uncertainty in the shape model, we also show an alternative model that statistically fits the data almost as well.

Table 3 summarizes physical parameters for the two vertex models along with standard errors assigned to the preferred model's parameters. Fig. 3 displays principal-axis views for each of the models. Yellow indicates areas that are not well constrained by the data because the radar scattering angle was always greater than 60°. Fig. 4A shows our longitude and latitude coverage for combined Goldstone and Arecibo observations according to the preferred model (pole at \(\lambda = +25^\circ, \beta = +80^\circ\)). The subradar latitude ranges from \(-19^\circ\) to \(+5^\circ\). A coverage plot for the alternative model is very similar (subradar latitude ranges from \(-17^\circ\) to \(+1^\circ\)) due to an almost identical pole direction. Fig. 4B shows Nereus’ sky motion during our observations.

Despite almost 100° degrees of sky motion, we still have only a small departure from an equatorial view that likely contributes to the north–south symmetry of our model. Nonetheless, we emphasize that no artifacts are introduced into reconstruction of Nereus’ pole-on silhouette, which remains consistent among various shape models.

The shape of Nereus does not stray too far from an ellipsoid. The two models in Fig. 3 have dimensions of 0.510 × 0.330 × 0.241 km and 0.494 × 0.320 × 0.317 km respectively. The larger volume alternative model has pronounced bumps around the north and south poles, which are not well constrained by the radar images, suggesting that the bumps are possibly a modeling artifact. Therefore, we used penalty terms to guide SHAPE toward more realistic, physically likely solutions. We prefer the “smaller volume” model of Nereus, with \(Y/Z\) ratio equal to 1.37.

The uncertainties in Table 3 are expressed in asymmetric fashion around the preferred model. It is unlikely that Nereus will be much smaller along the z-axis, so we chose the error on the lower bound to be small. However, the secondary model shows that the upper bound on the dimension along the z-axis is much less constrained. This asymmetry in the volume uncertainty propagates through all other correlated parameters.

Our equivalent diameter of Nereus is 0.33 ± 0.03 km, similar to the thermal model (NEATM) result, 0.33 ± 0.05 km (Harris, 1998; Delbœuf et al., 2003). The consistency between the radar and NEATM results is most likely an outcome of Nereus’ nearly convex shape. Moderate discrepancies between the size estimate in thermal mod-
eling and the radar modeling have been reported for the cases when an asteroid had prominent and exotic features that probably cause a complex and difficult-to-model thermal distribution on the surface (Magri et al., 2007). Nereus has a moderate elongation with $X/Y \approx 1.55 \pm 0.1$, a value slightly lower than suggested in Ishibashi et al. (2000a) lightcurve analysis ($X/Y > 1.7$). When compared to other NEA elongations that have been derived from the radar studies (http://echo.jpl.nasa.gov/~lance/nea_elongations.html) it sits close to the average value $1.53 \pm 0.47$ ($N = 29$).

### 3.2.3. Model fits to the delay–Doppler images

Figs. 5A and 5B show how well our two shape models of Nereus match the radar data. We show $\sim 30\%$ of the delay–Doppler images, and the rest may be found in Supplementary material. A radar view of the “sharp” edge of Nereus ($\varphi = 0^\circ$) was challenging to match in the model. Even more rounded views of Nereus ($\varphi = 200^\circ$ to $270^\circ$) have some discrepancies in the curvature of the delay–Doppler distribution. We increased the weights of certain images, but the improvements were marginal at best. We created various subsets of the images (Arecibo only, Goldstone only, selective combination of the two) and applied the SHAPE algorithm to those only. This again yielded no significant improvement. Most of the fitting mismatches are due to the high levels of noise in the data (especially the case for Goldstone images, see Supplementary material). We tried minimizing the noise levels by using special “masking” techniques to isolate the signal. The basic idea of masking is to identify a priori a small rectangular image region that contains the signal. Our alternative model was obtained with this method, but as stated before, that model fits the data as well as our preferred model but is not obviously better.

The rotation period obtained from the radar data is $15.16 \pm 0.04$ h, corresponding to a spin rate of $570 \pm 1$ deg day$^{-1}$. One-degree-per-day precision (or 0.2% of the period) was possible because of the nearly 40-day span of delay–Doppler images. Certain model radar images seem to be a little bit “fast” or “slow” in phase with respect to the data images, but this happens in an unpredictable manner. A period that is too slow or too fast would cause a systematic delay/accumulation in the phase that would become more and more apparent as we approach the later dates. A wrong estimate about the initial phase orientation of Nereus on Dec 20 (our first observation) would cause a constant offset in the phase.

### 3.2.4. Consistency with optical lightcurve data

The synthetic lightcurve, generated using our preferred model, shows consistency with a published lightcurve (Ishibashi et al., 2000b; Fig. 6A). Those authors suggested that a substantial magnitude change ($0.58 \pm 0.03$ mag) is a consequence of a large angle.
between Nereus’ pole orientation and the line of sight. Based on our pole estimation, the lightcurve was obtained when Nereus’ spin axis was perpendicular to the line of sight. Consequently, the lightcurves could not have improved our shape model for Nereus, because the area around the north pole that remains unconstrained in the radar data also made weak contribution to in the lightcurve data.

Fig. 6B shows a synthetic lightcurve computed from the preferred Nereus model for the same dates and times as the data obtained in August, 1997 by Ishibashi et al. Although the lightcurve provides a leverage of ~1600 rotations between the time they were taken (Aug 1997) and our observations (Jan 2002), we decided not to try to refine the period obtained with the radar data beyond 1 deg day$^{-1}$.

Our model allows us to estimate the visual geometric albedo for Nereus. The only previous value ($p_v = 0.55 \pm 0.17$) comes from the NEATM model (Delbó et al., 2003). We calculated the albedo using the standard expression (Russell, 1916; Fowler and Chillemi, 1992; Pravec and Harris, 2007),

$$f_v = \frac{1329}{D^2} \times 10^{-0.4H_v + 0.85} \times 0.95,$$

We assumed an average absolute visual magnitude of $H_v = 18.2$ and an effective diameter $D = 0.32 \pm 0.03$ km. The resulting optical albedo is high even for an E-class object although there exists at least one example, 2004 DC (Taylor et al., 2006) that seems to have an optical albedo close to unity. For comparison, 1998 WT24 has an albedo between 0.38 and 0.56 (Harris et al., 2007; Busch et al., 2008) while 3103 Eger has an albedo between 0.34 and 0.53 (Veeder et al., 1989; Benner et al., 1997). One explanation for the high albedo is that we are using a simplistic analytical expression for a poorly understood relationship between an asteroid’s size, albedo, absolute magnitude, and taxonomic class. It is also possible that the estimate of Nereus’ absolute visual magnitude is biased. As noted in Table 1, the magnitude was published in only two studies (Batrakov, 1996; Ishibashi et al., 2000b), and only the second one (R-band) states an uncertainty $H_R = 18.22 \pm 0.06$.

The JPL small-body database (http://ssd.jpl.nasa.gov/sbdb.cgi) gives an absolute visual magnitude for Nereus of $H_v = 18.2 \pm 0.7$, with the more conservative uncertainties based on photometry reported through 2004, calculated in the standard IAU $H$–$G$ system (Bowell et al., 1989).

The NEATM study (Delbó et al., 2003) used the absolute magnitude of 18.7 when they estimated Nereus’ albedo of $p_v = 0.55 \pm 0.17$. If we use this lower absolute magnitude, our result ($p_v = 0.54 \pm 0.03$) is consistent with the NEATM albedo. A new photometric study of Nereus would help to constrain its optical albedo, and more generally, to improve understanding of the absolute magnitudes of E-class asteroids.

4. Nereus orbit refinement

Our modeling yielded delay–Doppler values for each radar frame referenced directly to Nereus’ center of mass. Table 4 gives radar astrometric estimates for a representative frame on each date. The assigned uncertainties in delay and Doppler are based on the radar data resolution. For the Goldstone data, the uncertainties are roughly one pixel in size. For the Arecibo data, due to finer pixel size, we have estimated standard error about 2–3 pixels in size. Post-fit residuals indicate consistency of our model-based radar astrometry, the optical astrometry, and the JPL n-body dynamical model. During the time that this paper was under review, six new optical measurements were reported for Nereus. The last
measurement occurred on September 6, 2008, thus adding 1547.5 days or +19% to the data arc. The new optical astrometry requires a statistically insignificant correction of only 0.05±0.15σ to the initial SHAPE-based orbit solution (#53), even after a 4.2 year prediction (Nereus’ orbital period is 2.3 years). This is evidence the new radar astrometry being reported is not systematically biased.

Table 5 gives our model based radar-refined orbit solution (#53). Table 6 lists predictable past and future close planetary approaches. The listed encounters are constrained by the 3σ errors on the time and distance of the closest approach. The most interesting close approach in the foreseeable future will happen in 2060, when Nereus passes Earth at only 3.1 lunar distances.

5. Disk integrated properties

Table 7 lists disk-integrated properties for Nereus based on Arecibo CW observations. We do not include CW data from Goldstone because of calibration issues. However, it is worth noting that the circular polarization ratios obtained from the Goldstone data (transmitted both in RCP and LCP) are consistent among themselves and also with the Arecibo results.

Nereus has comparable signal power in both the SC and the OC channels (Fig. 2). Arecibo data give an average circular polarization (SC/OC) ratio of 0.74±0.08. This implies multiple scattering and/or reflections from surface structures with sizes comparable to the radar wavelength (centimeter and decimeter scales). The average SC/OC ratio for the NEA E-class is 0.89±0.08 (N = 6 objects; Benner et al., 2008) and the average ratio for two main belt objects is 0.67±0.23 (Shepard et al., 2008). For comparison, the average SC/OC ratio for the S-class NEAs is 0.27±0.08 (N = 70 objects; Benner et al., 2008).

Table 7 also lists the OC cross section, σOC. The accuracy of σOC depends on the accuracy of the system’s calibration as well as on the number of looks, which should be high enough to obtain Gaussian noise statistics (slightly low in our case except on January 9, when we had 60 looks). By combining the measurements of SC/OC ratio and σOC, we estimate the mean total-power SC+OC cross section, σ_{total} = (3.8±0.8) × 10^{-2} km^2.

The accuracy of the radar cross section computed from the model depends on how closely we estimated the object’s shape and radar scattering law. We have a reasonable agreement (within 15%) between the data and the model σOC considering that we have used a homogeneous cosine law (Eq. (1)) to approximate the radar scattering. The total SC+OC radar albedo may be calculated by dividing the model’s total cross section by the projected area. The total power (SC+OC) radar albedo based on the preferred model is η_{total} = 0.44±0.05, a value consistent with a recent estimate of another E-class NEA, 1998 WT24 (η_{total} = 0.42±0.04; Busch et al., 2008). We repeated the same albedo calculation for the alternative model from Fig. 3B and the best estimate was within the preferred model’s uncertainty range, η_{total} = 0.39±0.03.

6. Nereus’ gravitational/dynamical environment

6.1. The YORP effect

The spin states of moderately sized objects (<10 km) are known to be sensitive to processes associated with reflection and re-emission of solar radiation from an asteroid’s surface (Slivan, 2002; Vokrouhlicky et al., 2003, 2006; Lowry et al., 2007; Taylor et al., 2007; Kryszczynska et al., 2007). The theory of the YORP (Yarkovsky–O’Keefe–Radzievskii–Paddack) effect (Rubincam, 2000) describes how torques from radiation pressure and thermal re-emission can alter an asteroid’s spin rate and obliquity.

We have used the averaging methods derived in Scheeres (2007b) and Scheeres and Mirrahimi (2008) in order to find a set of YORP equations that describe the changes in Nereus’ rotation. We have assumed that the asteroid has homogeneous thermal surface properties and a uniform bulk density between 2 and 5 g cm^{-3}. We find that Nereus’ current obliquity of 10.6° indicates that its spin rate should be increasing at a rate of about 3.4 ± 10^{-17} to 1.4 ± 10^{-16} rad s^{-2}, so that the rotation period should halve in about 100,000 to 260,000 years depending on the density, similar to the halving time found for Asteroid (54509) YORP (Lowry et al., 2007; Taylor et al., 2007). A detectable change could occur in a few years, although we note that the YORP effect also depends on the density distribution within the asteroid (Scheeres and Gaskell, 2008), which cannot be constrained by radar observations. Considering that our radar observations date from 2002, the period changes may already be present. To constrain the past obliquity dynamics of Nereus it is necessary to determine its thermal inertia.

6.2. Nereus’ gravitational environment

The orbital dynamics summarized here is discussed more fully in Scheeres et al. (1996), Scheeres and Mazar (2002) and Scheeres (2004, 2007a). Close-orbit dynamical parameters of Nereus are summarized in Table 8. The escape speed ranges from 0.145 to 0.211 m s^{-1} for a density of 2 g cm^{-3} and from 0.239 to 0.334 m s^{-1} for 5 g cm^{-3}. This is a sufficient speed for the particle to escape the gravitational field of the object regardless of the launch geometry. Fig. 7 shows the distribution of gravitational slope, that is, the angle between the local acceleration vector and outward surface normal. The average gravitational slope is close to 11° for the entire range of densities, and the maximum value is between 28° and 29°. These values imply a reposed and relaxed surface.
Fig. 5. (A) Preferred model fits. The data (representing 30% of the available images) have been selected in order to show one complete rotation of Nereus. The phase starts at 0° orientation at the top-left corner of the figure and ends at ∼360° at the bottom-right corner. For each date, the first column contains the original delay-Doppler images that were used in the shape reconstruction, the second column shows the model fits and the third column features the plane-of-sky view of the asteroid. In an individual frame, delay increases from top to bottom, and Doppler frequency increases from left to right. The plane of sky view is contained in 0.7 × 0.7 km square with 201 × 201 pixels. The magenta arrow shows the orientation of the spin vector, while the red and green shafts denote the positive ends of the long and the intermediate principal axes. (B) Alternative model fits. The images contain the same data as in (A), except that the alternative model has slightly higher resolution. The plane of sky view has 251 × 251 pixels that cover 0.7 × 0.7 km area. All plane-of-sky images have the projected center of mass marked with a small black cross. Appearance of black frames around the radar data happens due to the masking technique that we used to isolate the signal from the noisy background.
The Nereus Hill sphere ranges from 27 to 36 km at perihelion, for densities of 2 and 5 g cm$^{-3}$, respectively. These distances place upper limits on where a small, natural satellite could be found about the body. At Arecibo, our regular 0.1 μs imaging setup covers ~980 km, which is far more than any near-Earth asteroid’s Hill sphere. The initial search did not reveal any satellite candidates around Nereus. If present, a satellite would have to be only a few tens of meters in diameter (or smaller).
and rotating much more rapidly than Nereus to escape our notice.

We performed our dynamical study under the assumption that Nereus is a pure principal axis (PA) rotator. In this case, Nereus has four possible synchronous satellite orbits that lie close to its equatorial plane (Fig. 8). These are special locations relative to the rotating body where a particle can stay exactly synchronous with Nereus if placed at these locations with an angular orbital rate equal to Nereus’ rotation rate. Two of these orbits are always unstable, meaning that a natural particle is not likely to be found there. Due to Nereus’ specific shape and rotation rate, the other two, which lie along the intermediate axis of the body, are stable for all plausible values of Nereus’ density. For most asteroids surveyed to date all of these points are unstable. This stability is only relevant for boulders and larger sized bodies, but it does imply that a natural companion could maintain such an orbital location.

An analysis of orbits of particles about Nereus strongly affected by solar radiation pressure has also been made, such as is the case for spacecraft orbits. Based on this analysis, previously described in Scheeres (2007a), we find that spacecraft orbits about Nereus are feasible, albeit are subject to strong constraints. These constraints are that the orbit lie near the terminator plane of the asteroid and have a semi-major axis between 1 and 2 km, assuming a spacecraft mass to area ratio of 35 kg·m⁻². These results are of interest, because Nereus is a strong candidate for a rendezvous mission. Should such a mission be investigated, the orbital analysis would have to be repeated with a specific model of the spacecraft.

7. Discussion

7.1. Nereus and other E-class objects

Comparison between Nereus and 1998 WT24, the only other E-class NEA whose shape and spin vector are available from radar

<table>
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<th>Table 4</th>
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<td>Nereus radar astrometry.</td>
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<td>16:50:00</td>
<td>G</td>
<td>36.76926589</td>
<td>±0.125</td>
<td>-0.047</td>
<td>-194945.298</td>
<td>±0.125</td>
</tr>
<tr>
<td>2002 01 27</td>
<td>16:50:00</td>
<td>G</td>
<td>33.28261095</td>
<td>±0.125</td>
<td>0.025</td>
<td>-235958.598</td>
<td>±0.125</td>
</tr>
<tr>
<td>2002 01 26</td>
<td>16:30:00</td>
<td>G</td>
<td>31.82881870</td>
<td>±0.125</td>
<td>0.075</td>
<td>-12752.950</td>
<td>±0.125</td>
</tr>
<tr>
<td>2002 01 25</td>
<td>17:50:00</td>
<td>G</td>
<td>30.70698246</td>
<td>±0.125</td>
<td>0.012</td>
<td>-104748.878</td>
<td>±0.125</td>
</tr>
<tr>
<td>2002 01 24</td>
<td>16:20:00</td>
<td>G</td>
<td>29.75254935</td>
<td>±0.125</td>
<td>0.060</td>
<td>-64888.574</td>
<td>±0.125</td>
</tr>
<tr>
<td>2002 01 23</td>
<td>17:50:00</td>
<td>G</td>
<td>29.20271248</td>
<td>±0.125</td>
<td>0.120</td>
<td>-39949.313</td>
<td>±0.125</td>
</tr>
<tr>
<td>2002 01 20</td>
<td>21:20:00</td>
<td>G</td>
<td>29.40332046</td>
<td>±0.125</td>
<td>-0.136</td>
<td>46520.417</td>
<td>±0.125</td>
</tr>
<tr>
<td>2002 01 19</td>
<td>20:00:00</td>
<td>G</td>
<td>30.18133016</td>
<td>±0.125</td>
<td>-0.103</td>
<td>90610.817</td>
<td>±0.125</td>
</tr>
<tr>
<td>2002 01 18</td>
<td>22:10:00</td>
<td>G</td>
<td>31.13942222</td>
<td>±0.125</td>
<td>0.014</td>
<td>107757.400</td>
<td>±0.250</td>
</tr>
<tr>
<td>2002 01 15</td>
<td>20:00:00</td>
<td>G</td>
<td>35.99485428</td>
<td>±0.125</td>
<td>0.077</td>
<td>197405.524</td>
<td>±0.250</td>
</tr>
<tr>
<td>2002 01 13</td>
<td>18:30:00</td>
<td>A</td>
<td>40.26155721</td>
<td>±0.200</td>
<td>-0.162</td>
<td>61739.104</td>
<td>±0.040</td>
</tr>
<tr>
<td>2002 01 12</td>
<td>19:28:00</td>
<td>A</td>
<td>42.44830876</td>
<td>±0.200</td>
<td>-0.118</td>
<td>63457.452</td>
<td>±0.040</td>
</tr>
<tr>
<td>2002 01 11</td>
<td>19:25:00</td>
<td>A</td>
<td>44.83500439</td>
<td>±0.200</td>
<td>-0.201</td>
<td>66627.953</td>
<td>±0.040</td>
</tr>
<tr>
<td>2002 01 10</td>
<td>19:43:00</td>
<td>A</td>
<td>47.27304672</td>
<td>±0.200</td>
<td>-0.206</td>
<td>68613.430</td>
<td>±0.040</td>
</tr>
<tr>
<td>2002 01 09</td>
<td>19:59:00</td>
<td>A</td>
<td>49.78466065</td>
<td>±0.200</td>
<td>-0.014</td>
<td>70245.997</td>
<td>±0.040</td>
</tr>
<tr>
<td>2001 12 20</td>
<td>22:54:00</td>
<td>A</td>
<td>103.24786672</td>
<td>±0.500</td>
<td>0.02</td>
<td>68384.732</td>
<td>±0.050</td>
</tr>
</tbody>
</table>

Nereus’ shape model gives estimates of the positions of the center of mass in round-trip delay and Doppler frequency (relative to a predicted ephemeris) at the listed time epochs at the telescope reference point. The reference point for Arecibo is the center of curvature of the telescope’s main reflector while for Goldstone it is the intersection of the elevation and azimuthal axes of the 70-m antenna (DSS-14). The post-fit residuals are with respect to JPL orbital solution #53.
Radar observations and a physical model of Asteroid 4660 Nereus

Table 6
Close approaches for Nereus based on the orbital solution #53.

<table>
<thead>
<tr>
<th>Date (coordinate time)</th>
<th>Body</th>
<th>CAdist (AU)</th>
<th>MNIdist (AU)</th>
<th>MAXdist (AU)</th>
<th>Vrel (km s⁻¹)</th>
<th>TCA35g (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.D. 1837 Dec 13.29016</td>
<td>Earth</td>
<td>0.019667</td>
<td>0.018987</td>
<td>0.020825</td>
<td>6.210</td>
<td>1542.1</td>
</tr>
<tr>
<td>A.D. 1869 Jan 12.85428</td>
<td>Earth</td>
<td>0.013158</td>
<td>0.013497</td>
<td>0.013966</td>
<td>5.368</td>
<td>783.3</td>
</tr>
<tr>
<td>A.D. 1879 Sep 03.44307</td>
<td>Mars</td>
<td>0.057770</td>
<td>0.057623</td>
<td>0.057925</td>
<td>10.958</td>
<td>29.4</td>
</tr>
<tr>
<td>A.D. 1940 Jan 29.76067</td>
<td>Earth</td>
<td>0.020792</td>
<td>0.020760</td>
<td>0.020825</td>
<td>5.545</td>
<td>37.5</td>
</tr>
<tr>
<td>A.D. 1920 Feb 20.29471</td>
<td>Earth</td>
<td>0.039835</td>
<td>0.039828</td>
<td>0.039843</td>
<td>7.363</td>
<td>1.7</td>
</tr>
<tr>
<td>A.D. 1937 Dec 26.85313</td>
<td>Mars</td>
<td>0.078510</td>
<td>0.078505</td>
<td>0.078514</td>
<td>9.776</td>
<td>0.2</td>
</tr>
<tr>
<td>A.D. 1951 Feb 24.08976</td>
<td>Earth</td>
<td>0.064932</td>
<td>0.064930</td>
<td>0.064933</td>
<td>8.168</td>
<td>0.3</td>
</tr>
<tr>
<td>A.D. 1961 Dec 10.90276</td>
<td>Earth</td>
<td>0.027894</td>
<td>0.027894</td>
<td>0.027903</td>
<td>6.671</td>
<td>2.0</td>
</tr>
<tr>
<td>A.D. 1980 Aug 06.20362</td>
<td>Mars</td>
<td>0.061940</td>
<td>0.061939</td>
<td>0.061940</td>
<td>11.528</td>
<td>0.0</td>
</tr>
<tr>
<td>A.D. 1982 Jan 23.84482</td>
<td>Earth</td>
<td>0.027712</td>
<td>0.027711</td>
<td>0.027712</td>
<td>5.408</td>
<td>1.0</td>
</tr>
<tr>
<td>A.D. 1996 Apr 14.07933</td>
<td>Mars</td>
<td>0.075456</td>
<td>0.075456</td>
<td>0.075456</td>
<td>11.550</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Listed are all planetary encounters closer than 0.1 AU for which the 3-σ time-of-encounter is less than 10 days and the encounter distance 3-σ uncertainty is less than 0.1 AU. These criteria are satisfied over the interval 1837–2166. Nominal close-approach dates are given in Coordinate Time. CAdist is the nominal close-approach distance at the nominal close-approach time, uncorrected for light travel time. MNIdist and MAXdist are the 3-σ distances at the nominal encounter time. Vrel is the nominal relative velocity. TCA35g is close approach 3-σ uncertainty in minutes. Integrations were performed using the DE-405 planetary ephemeris and include relativistic perturbations due to the Sun, planets, and Moon as well as asteroids Ceres, Pallas, and Vesta. The limits of predictability for objects having multiple planetary encounters over centuries will normally be affected by additional factors such as radiation pressure, Yarkovsky acceleration, planetary mass uncertainties, and asteroid perturbations. These factors are not included here, since the relevant physical models are imprecisely defined and key parameters are unmeasured.

Table 7
Disk integrated properties.

<table>
<thead>
<tr>
<th>Date (UT)</th>
<th>Time range</th>
<th>σOC × 10⁻² (km²)</th>
<th>SC/OC</th>
<th>σtotal × 10⁻² (km²)</th>
<th>#Looks</th>
<th>SNR/run</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.D. 2002 Jan 22.51582</td>
<td>Earth</td>
<td>0.029024</td>
<td>0.029024</td>
<td>0.029024</td>
<td>5.419</td>
<td>0.0</td>
</tr>
<tr>
<td>A.D. 2002 Dec 11.57088</td>
<td>Earth</td>
<td>0.026300</td>
<td>0.026299</td>
<td>0.026300</td>
<td>6.578</td>
<td>0.5</td>
</tr>
<tr>
<td>A.D. 2003 Apr 05.75360</td>
<td>Mars</td>
<td>0.054757</td>
<td>0.054756</td>
<td>0.054756</td>
<td>11.319</td>
<td>0.1</td>
</tr>
<tr>
<td>A.D. 2004 Jul 26.75893</td>
<td>Mars</td>
<td>0.060067</td>
<td>0.060067</td>
<td>0.060067</td>
<td>10.893</td>
<td>0.1</td>
</tr>
<tr>
<td>A.D. 2006 Feb 14.28903</td>
<td>Earth</td>
<td>0.008010</td>
<td>0.008008</td>
<td>0.008012</td>
<td>6.331</td>
<td>1.1</td>
</tr>
<tr>
<td>A.D. 2007 Feb 04.73972</td>
<td>Earth</td>
<td>0.014989</td>
<td>0.014928</td>
<td>0.015050</td>
<td>5.681</td>
<td>0.7</td>
</tr>
<tr>
<td>A.D. 2008 Sep 05.93268</td>
<td>Earth</td>
<td>0.038405</td>
<td>0.037810</td>
<td>0.039050</td>
<td>10.510</td>
<td>68.8</td>
</tr>
<tr>
<td>A.D. 2102 Feb 27.54401</td>
<td>Earth</td>
<td>0.075608</td>
<td>0.072525</td>
<td>0.078644</td>
<td>8.515</td>
<td>507.9</td>
</tr>
<tr>
<td>A.D. 2112 Dec 22.86071</td>
<td>Earth</td>
<td>0.017642</td>
<td>0.017445</td>
<td>0.017856</td>
<td>5.804</td>
<td>403.3</td>
</tr>
<tr>
<td>A.D. 2153 Aug 18.12511</td>
<td>Mars</td>
<td>0.067387</td>
<td>0.051773</td>
<td>0.084974</td>
<td>9.878</td>
<td>712.9</td>
</tr>
<tr>
<td>A.D. 2155 Feb 26.25157</td>
<td>Earth</td>
<td>0.061568</td>
<td>0.036526</td>
<td>0.084655</td>
<td>8.025</td>
<td>4600.9</td>
</tr>
<tr>
<td>A.D. 2166 Feb 08.75952</td>
<td>Earth</td>
<td>0.010393</td>
<td>0.005636</td>
<td>0.031052</td>
<td>5.843</td>
<td>14090.1</td>
</tr>
</tbody>
</table>

All radar observations (Busch et al., 2008), show that despite belonging to the same E-class, these two objects are very different. Nereus is slowly rotating (15.16 h) with the YORP effect accelerating the spin rate, while 1998 WT24 rotates much faster (3.70 h) and the YORP effect decelerates the spin rate. 1998 WT24 shows a complex surface dominated by large concavities and a prominent cluster of radar-bright pixels. Slightly smaller Nereus (equivalent diameter of 0.33 km vs. 0.41 km for 1998 WT24) has a uniform shape that departs from an ellipsoid only in its angular edge. The SC/OC ratio for 1998 WT24 is the highest in the NEA E-class (0.97 ± 0.10) while Nereus has a below-average SC/OC of 0.74 ± 0.08.

Nereus may also be compared to a main belt E II class Asteroid 2867 Steins. Steins’ spectral (Nedelcu et al., 2007; Fornasier et al., 2008; Weissman et al., 2008) characteristics resemble those of Nereus, but as a main belt object, it is much older (2 GY, Fornasier et al., 2007) and larger (4.8–6 km, Küppers et al., 2007; Schulz et al., 2008), and its rotation period (6 h, Küppers et al., 2007; Schulz et al., 2008) is more than two times faster than that of Nereus. The measurements from Rosetta’s recent (September, 2008) flyby of Steins will allow a closer comparison of E II objects in the main belt with the E II objects in the NEA population. The first Rosetta images (Schulz et al., 2008) show that Steins is...
densely cratered, consistent with a much older surface than that of Nereus.

### 7.2. Future Nereus observation opportunities and objectives

The next opportunity for optical observations occurs in late 2010, when Nereus will approach within 0.6 AU and reach 18th magnitude. Our pole estimate predicts that Nereus will again be close to the equatorial orientation. Lightcurve analyses might be able to detect the YORP effect and significantly improve spin acceleration estimates. Nereus’ proximity in 2010 would also be an opportunity to re-observe its spectrum. E II objects sometimes show 0.9–0.96 μm absorption lines that have not yet been seen in Nereus’ spectrum (Binzel et al., 2004a). Furthermore, the spectra of some E-class objects show the presence (3 μm absorption line) of hydrated minerals (Rivkin et al., 2002) which is very peculiar considering their initial exposure to high temperatures.

It would be interesting to compare new spectral information about Nereus with Rosetta data on Steins. At that point, both representatives of the E II class would have both their shapes and their spectral features well known. Comparison between the two could provide insight into how taxonomic class is related to surface characteristics (e.g. roughness) as recently discussed by Benner et al. (2008).

### Table 8

Dynamical quantities for Nereus.

<table>
<thead>
<tr>
<th>Assumed density (g cm(^{-3}))</th>
<th>2</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average gravitational slope (deg)</td>
<td>10.6</td>
<td>11.0</td>
</tr>
<tr>
<td>Maximum gravitational slope (deg)</td>
<td>28.0</td>
<td>28.6</td>
</tr>
<tr>
<td>Escape speeds range (m s(^{-1}))</td>
<td>0.145–0.211</td>
<td>0.239–0.334</td>
</tr>
<tr>
<td>Guaranteed return speeds range (m s(^{-1}))</td>
<td>0.109–0.144</td>
<td>0.195–0.247</td>
</tr>
<tr>
<td>Difference between speeds range (m s(^{-1}))</td>
<td>0.029–0.068</td>
<td>0.036–0.088</td>
</tr>
<tr>
<td>Total surface gravity range (\times 10^{-4}) (m s(^{-2}))</td>
<td>0.747–0.929</td>
<td>7.918–2.324</td>
</tr>
</tbody>
</table>

All computed quantities assume constant density. The facet-scale gravitational slope is defined as the angle between the local acceleration vector and inward surface normal. The table contains average and maximum gravitational slopes for each of the two densities (separate columns). Escape speed is a sufficient speed that a particle needs to achieve in order to permanently escape the body. Guaranteed return speed refers to the speed below which the ejecta must return to the surface. A speed greater than the guaranteed return speed is a necessary speed where at least some particles at some trajectories manage to escape the gravity. The total surface gravity refers to the combined gravitational and rotational acceleration.

The next opportunity to observe Nereus with radar will occur in December of 2021 when Nereus will approach within 0.026 AU. Signal to noise ratios for Goldstone and Arecibo will be \(\sim 1.5\) and \(\sim 3.2\) stronger than in 2002. Nereus’ orientation will reach subradar latitudes as high as \(\sim 50\) degrees right at the time of the closest approach (and the strongest radar signal). These favorable observing conditions will permit significant improvement in the shape model presented here.

### Acknowledgments

We thank the Arecibo and Goldstone technical and support staffs for help with the radar observations. The Arecibo Observatory is part of the National Astronomy and Ionosphere Center, which is operated by Cornell University under a cooperative agreement with the National Science Foundation (NSF) and, at the time of this experiment, also had support from the National Aeronau-
tics and Space Administration (NASA). We are very much in debt to the reviewers, Bob Gaskell and an anonymous reviewer whose comments significantly improved this paper. We would also like to thank Michael W. Busch for useful discussion on SHAPE modeling. Some of this work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA. This material is based in part upon work supported by NASA under the Science Mission Directorate Research and Analysis Programs.

Supplementary material

The online version of this article contains additional supplementary material. Please visit DOI: 10.1016/j.icarus.2008.12.029.

References


