RADAR CHARACTERIZATION OF NEAR-EARTH ASTEROIDS

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Radar Measurement Precision

	Range (meters)	Radial Velocity (meters/second)
Best radar resolution	10	0.0001
Asteroid "size"	1000	~0.01 to 1
Asteroid "location"	10000000000	10000

Optical predictions have pointing errors averaging ~300 times larger than predictions that include radar data.

Residuals for Past NEA Recoveries

Object	Recovery date	O	R	O/R
1989 PB (4769 Castalia)	May 1990	24″	0.4″	60
1991 AQ	Sep 1994	57″	0.1″	380
1986 DA (6178)	Oct 1994	56″	0.9″	60
1991 JX (6489 Golevka)	Mar 1995	3600″	4.6″	780
1989 JA (7335)	Oct 1996	196″	99.3″	2
1986 JK (14827 Hypnos)	Apr 2000	114″	0.1″	910
1998 ML14	Nov 2002	125″	0.5″	250
1990 OS	Jun 2003	50477″	3200″	16

[a] Here O represents the positional offset (the observed position at recovery minus the predicted position) for a pre-recovery orbit solution incorporating only optical astrometry. R represents the residual for a pre-recovery orbit solution using radar combined with optical. O/R is the ratio of residuals for the two cases and is a measure of the relative reduction in position error when radar astrometry is included in the orbit solution.

Radar detection of a PHA secures its orbit.

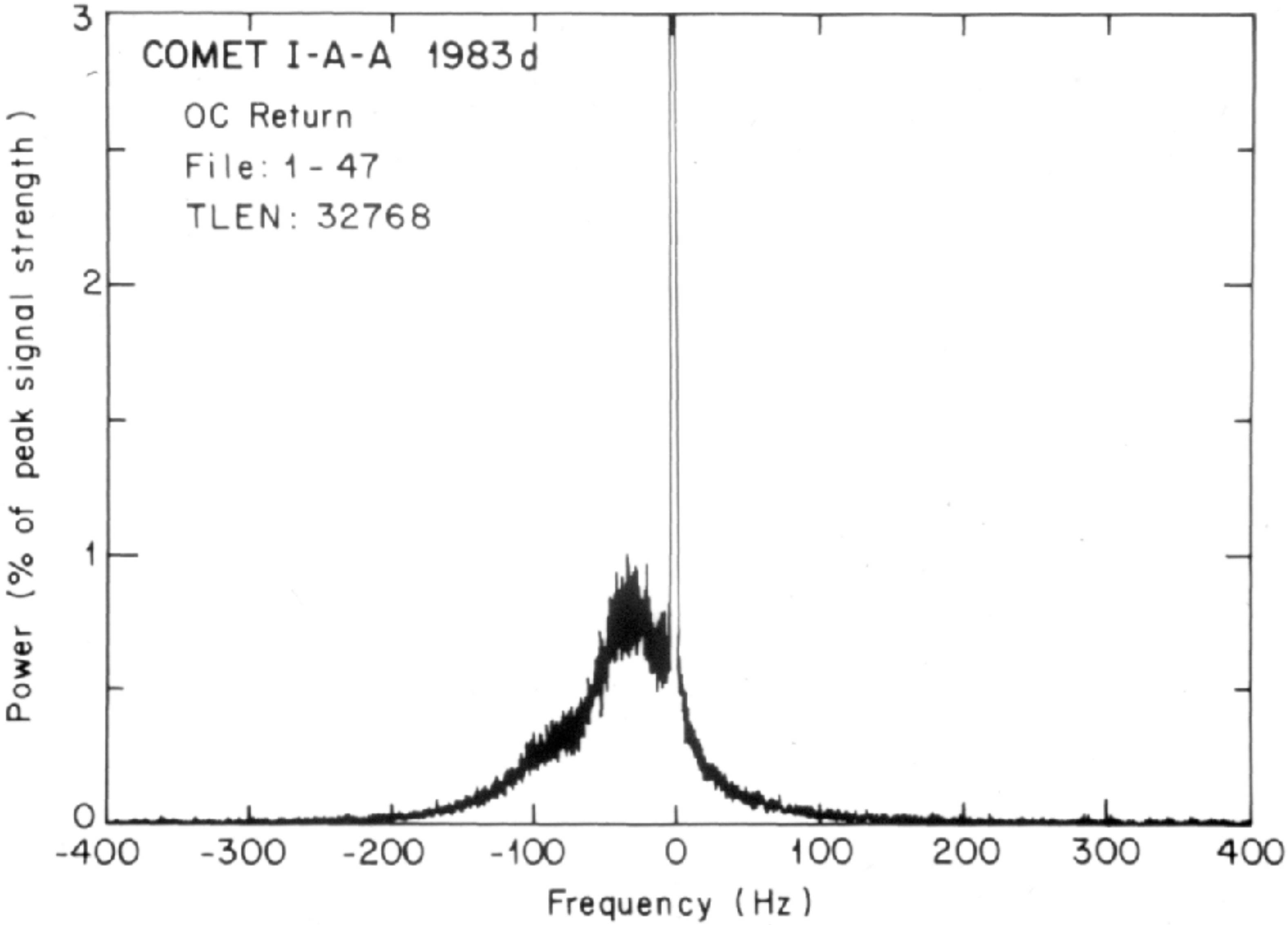
(Of the 842 identified PHAs, 236 are lost in the sense that the three-sigma uncertainty in the time of the next close-approach $\leq$ 0.1 AU exceeds $\pm$ 10 days, corresponding roughly to an angular uncertainty greater than 90°.)

For objects observed <u>only during their discovery apparition</u>, radar has added an average of more than three centuries to the window of accurate prediction of future close Earth approaches.

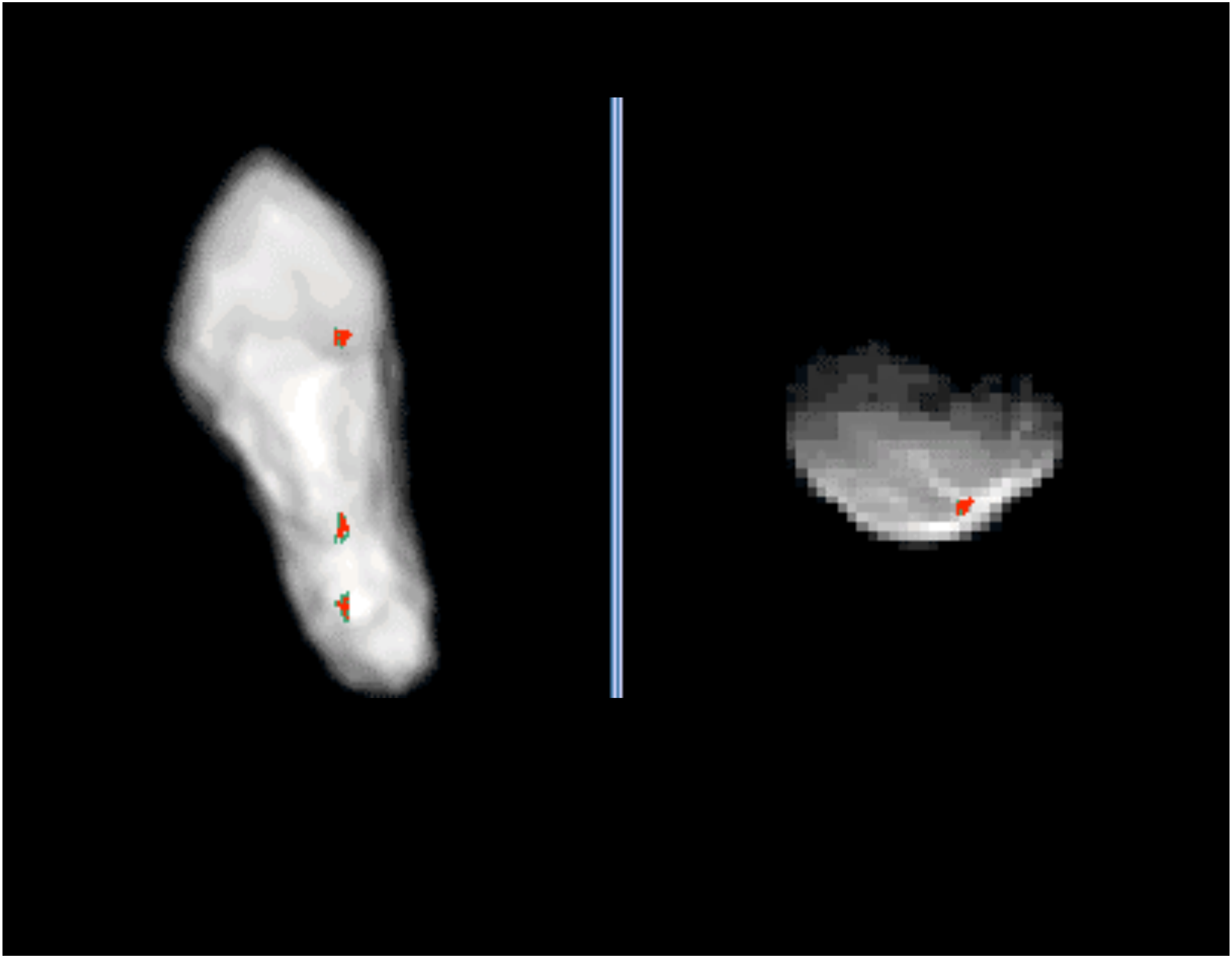
For multi-apparition objects, radar may not enlarge the window of accurate prediction of future close Earth approaches, but can dramatically improve the accuracy of orbits.

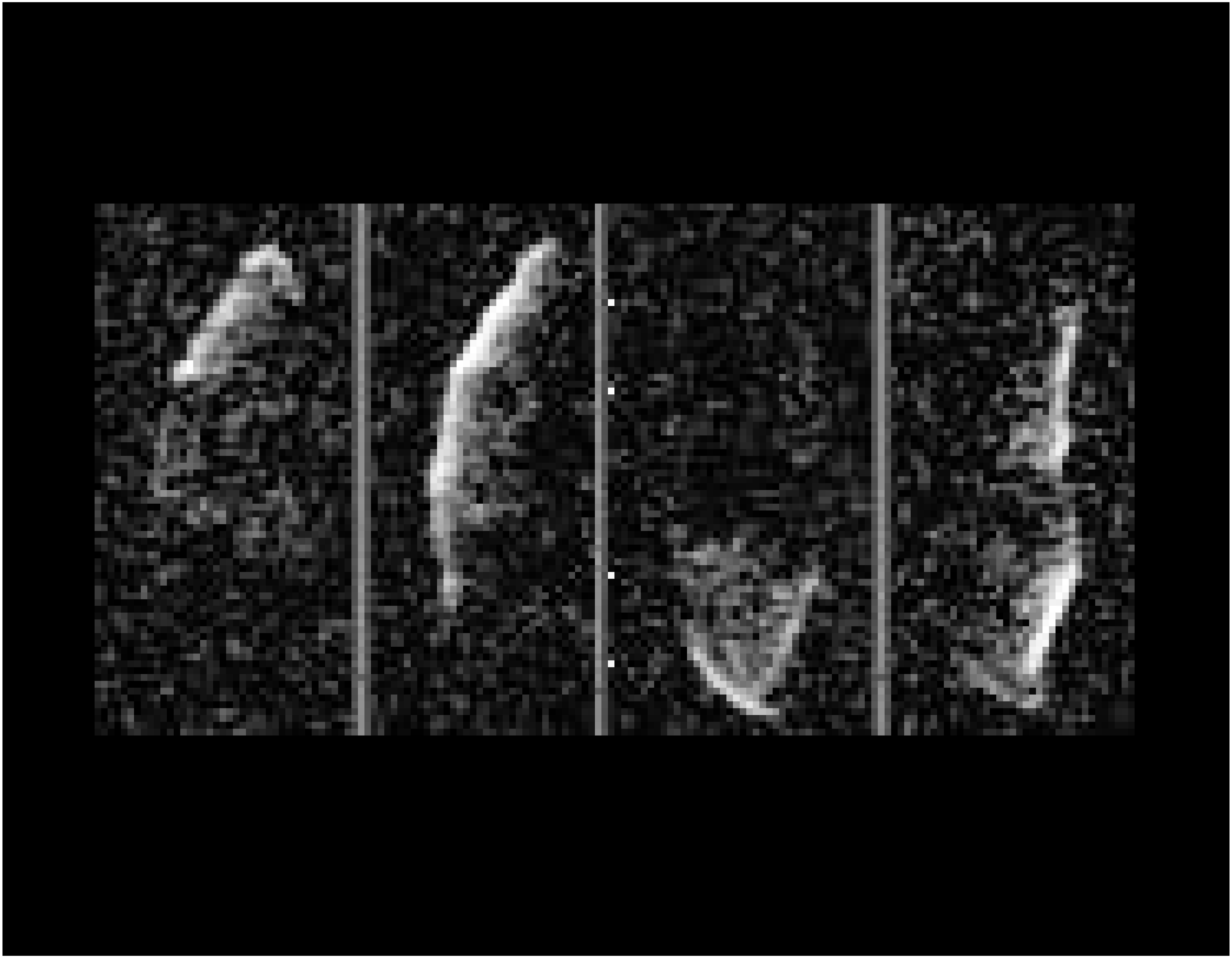
Apophis example: Collision probability in 2036:

Radar+Optical:	~1 / 45000
Optical only:	~1 / 13000

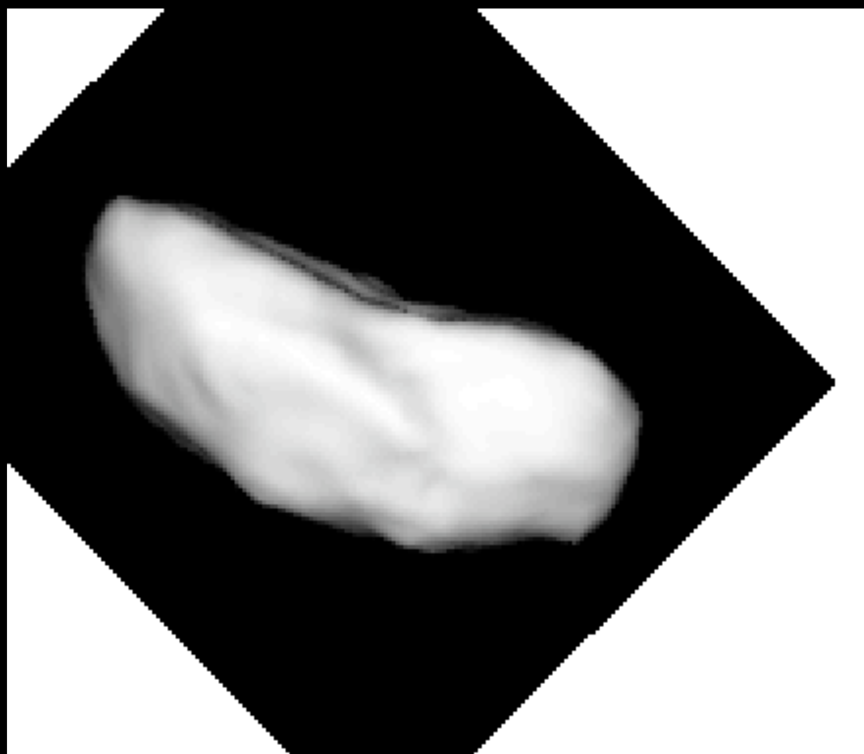


Harmon, J.K., et al. (1989). *Astrophys. J.* **338**, 1071–1093.





Itokawa



Radar model
from inferior data

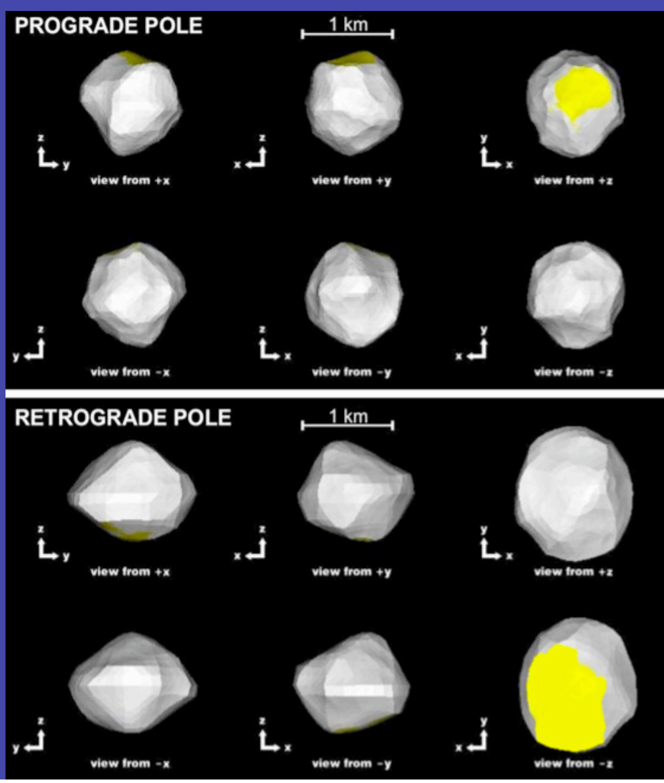
Hayabusa approach image

Asteroid 1950 DA's Encounter with Earth in 2880: Physical Limits of Collision Probability Prediction.

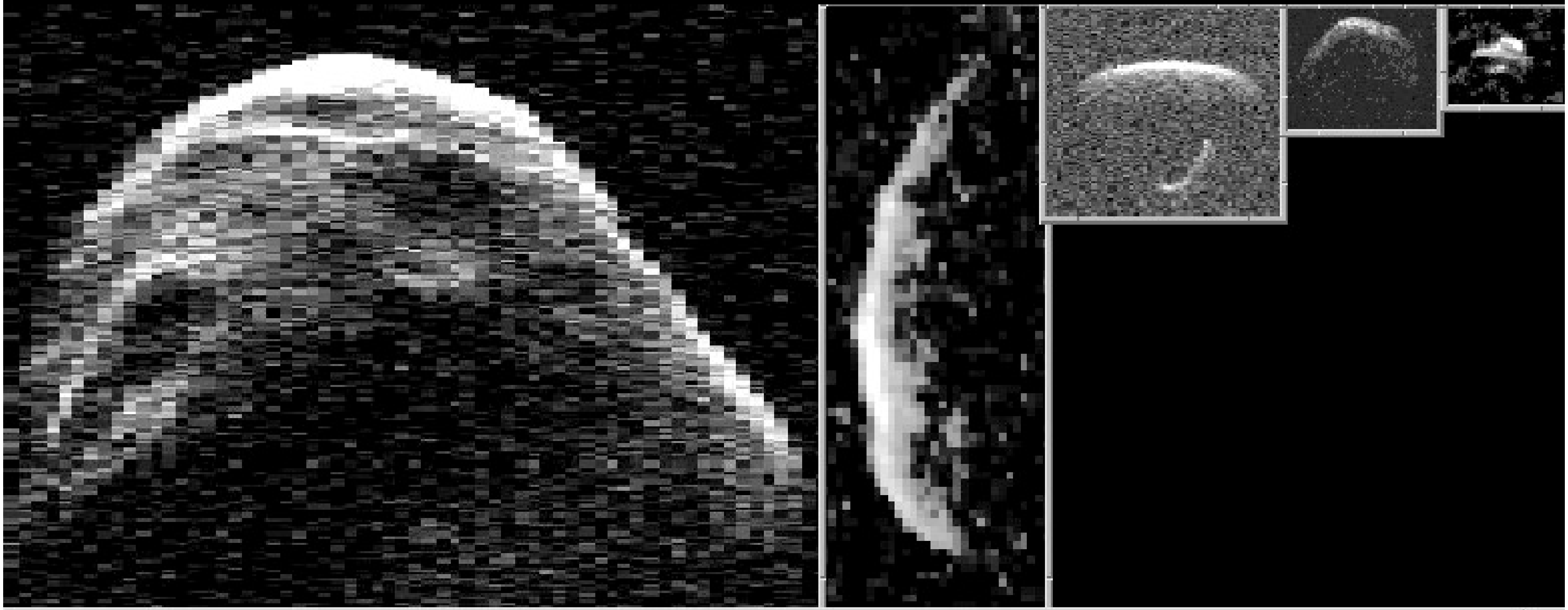
J. D. Giorgini et al. (2002, *Science* **296**, 132-136):

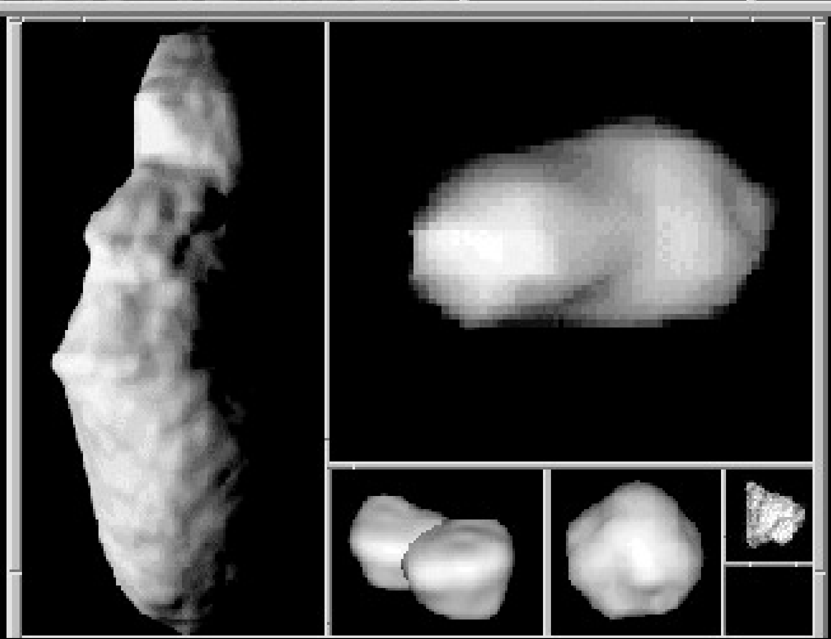
Earth collision probability in March 2880 could reach 1/300 if the rotation is prograde.

M. W. Busch et al. (submitted to *Icarus*):



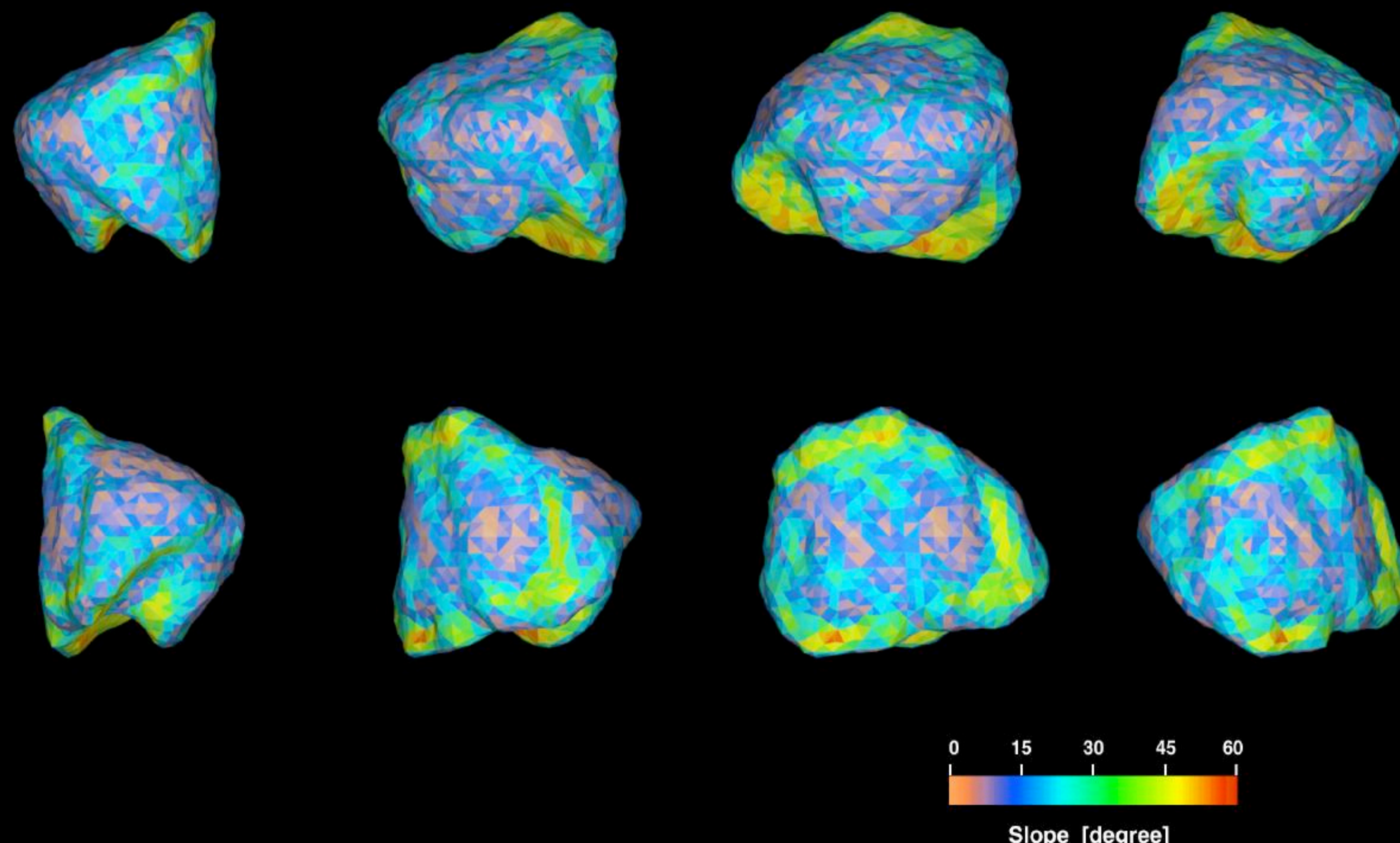
Existing radar data and optical lightcurves yield equally acceptable prograde and retrograde solutions, in each case suggesting a metallic composition.



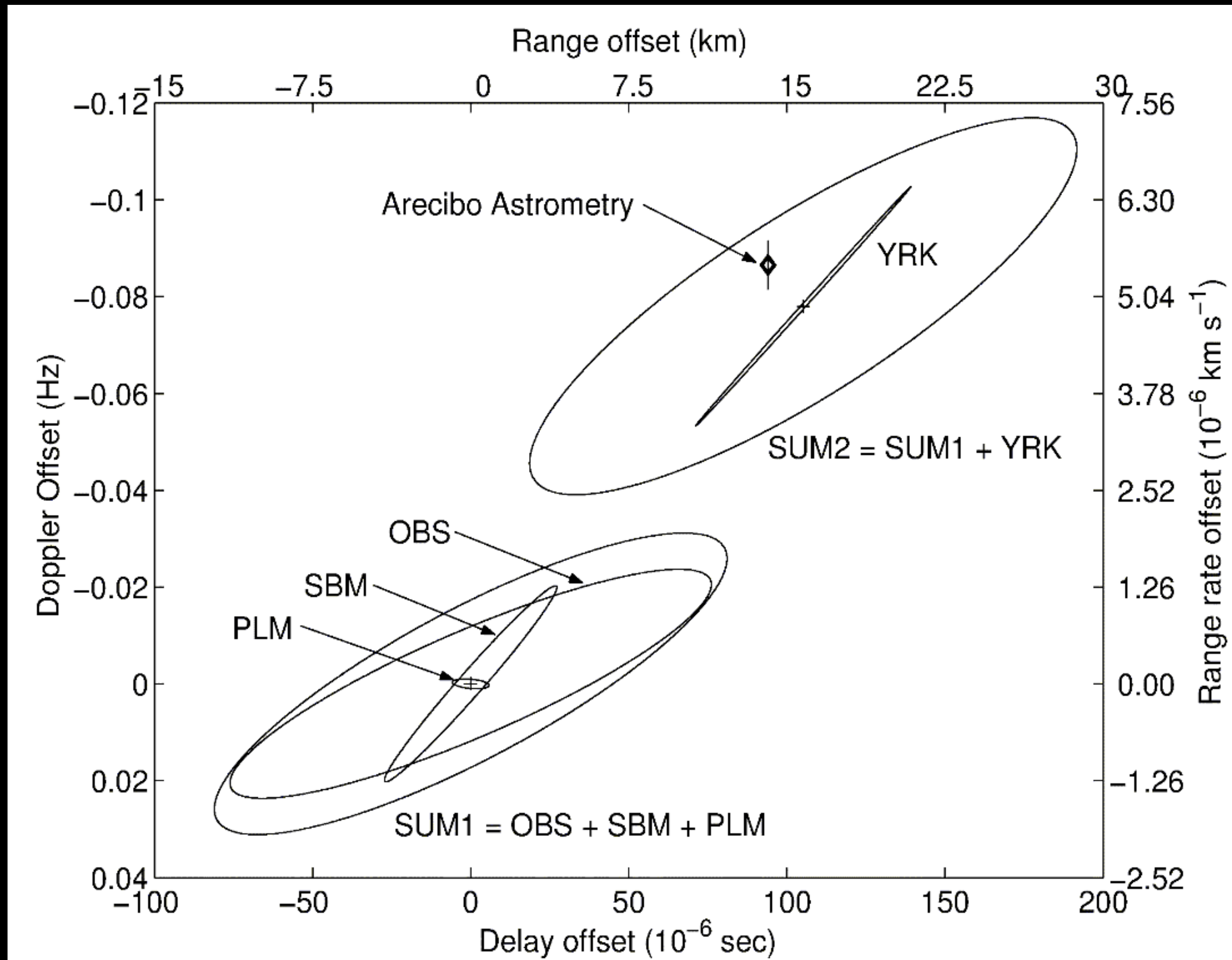


There is no such thing as a "typical" NEA.

Golevka gravitational slopes

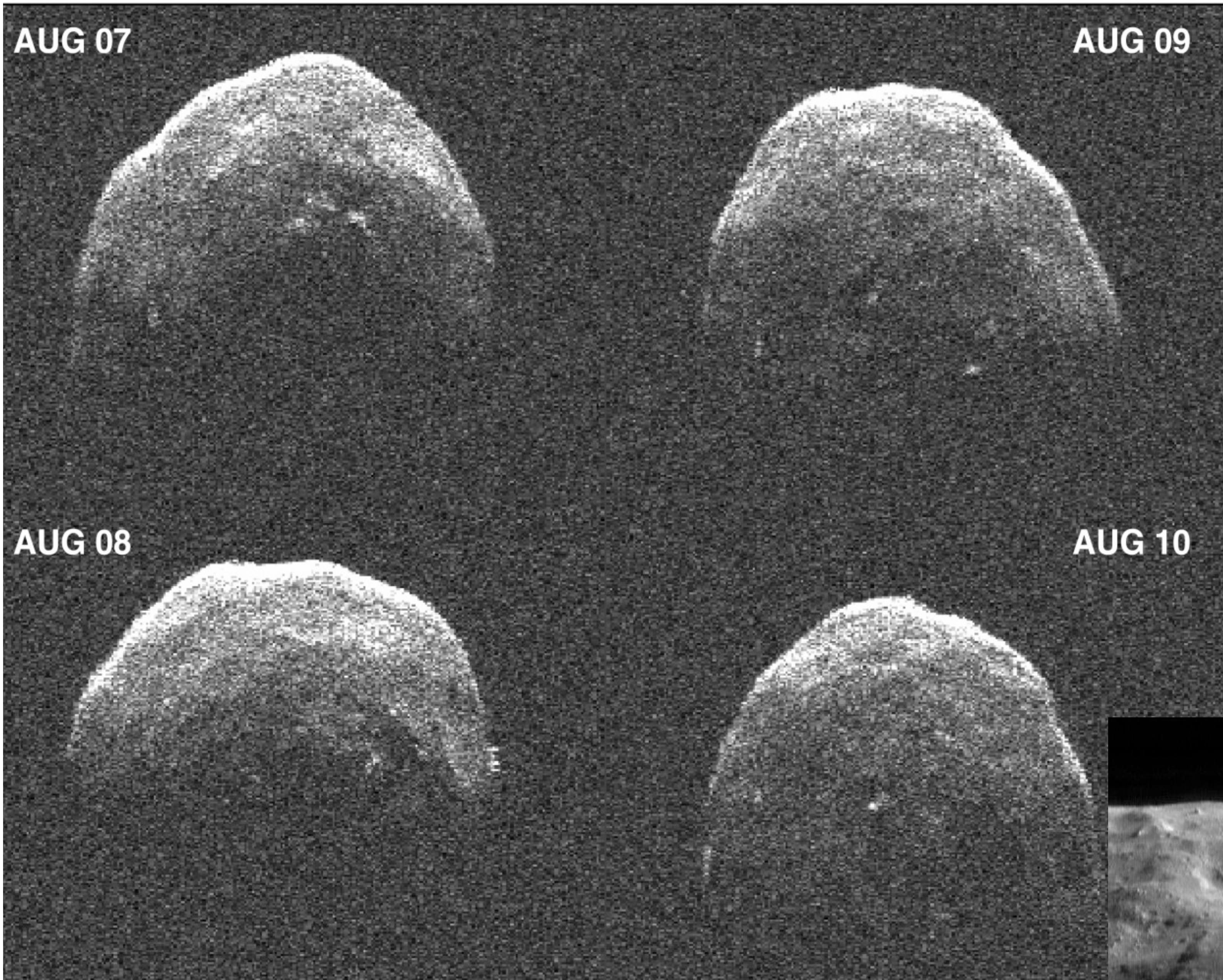


Direct Detection of the Yarkovsky Effect by Radar Ranging to Asteroid 6489 Golevka



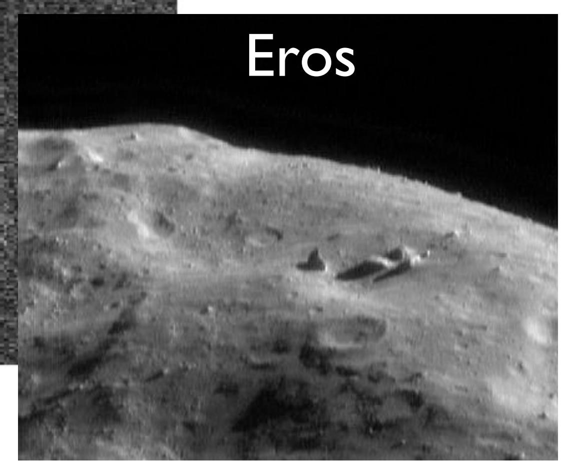
S. R. Chesley, S. J. Ostro, D. Vokrouhlicky, D. Capek, J. D. Giorgini, M. C. Nolan, J. L. Margot, A. A. Hine, L. A. M. Benner, and A. B. Chamberlin. *Science* **302**, 1739-1742 (2003).

1992 UY4: Arecibo, Aug. 2005, 7.5 m x 0.029 Hz



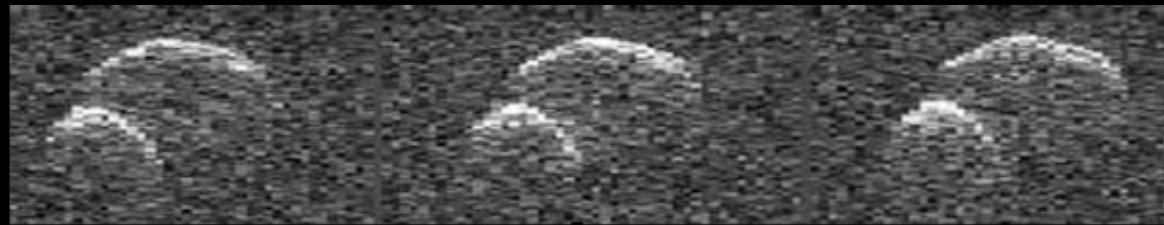
Benner et al., in preparation

Itokawa

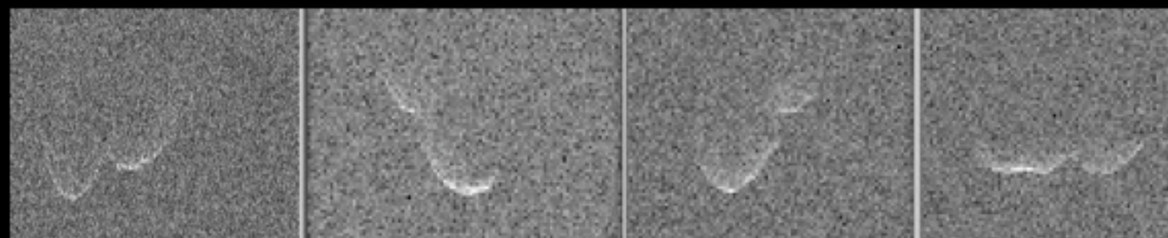


Contact-Binary Shapes

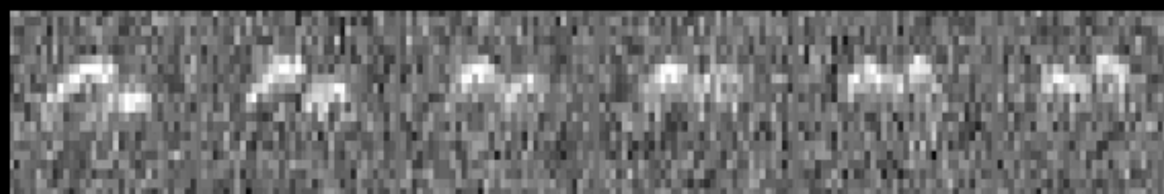
4486 Mithra



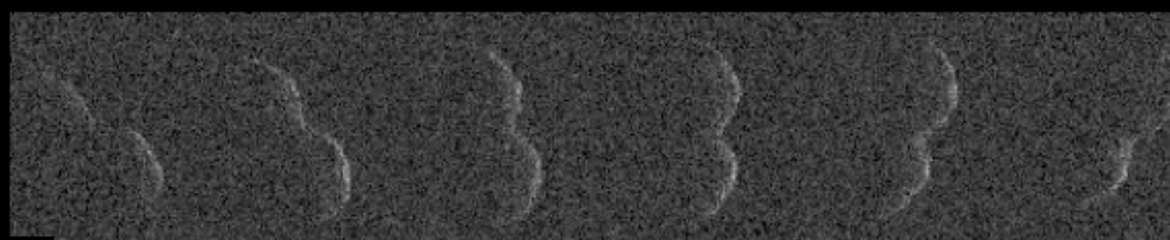
11066 Sigurd

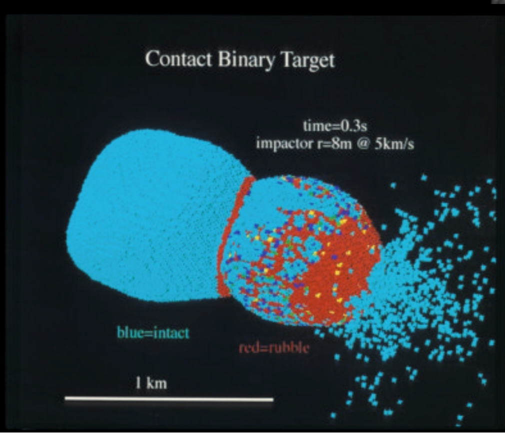


3908 Nyx



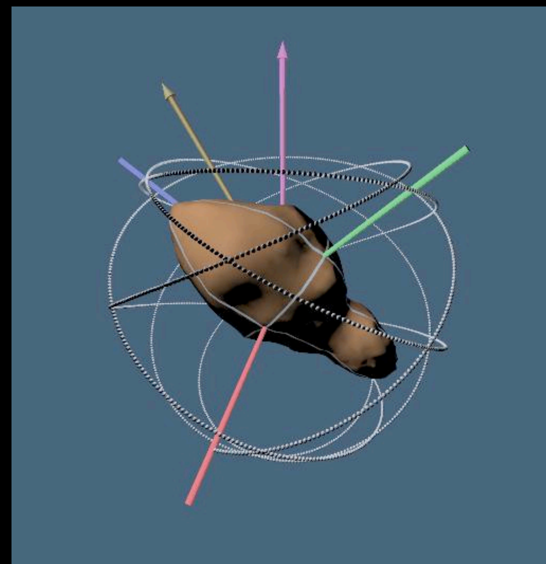
2005 CR37





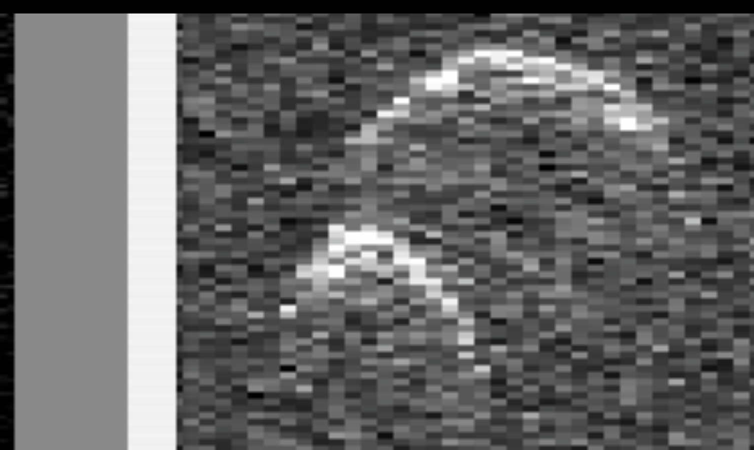
Asphaug et al. (1998), *Nature* **393**, 437-440.

Non-Principal-Axis Rotators:



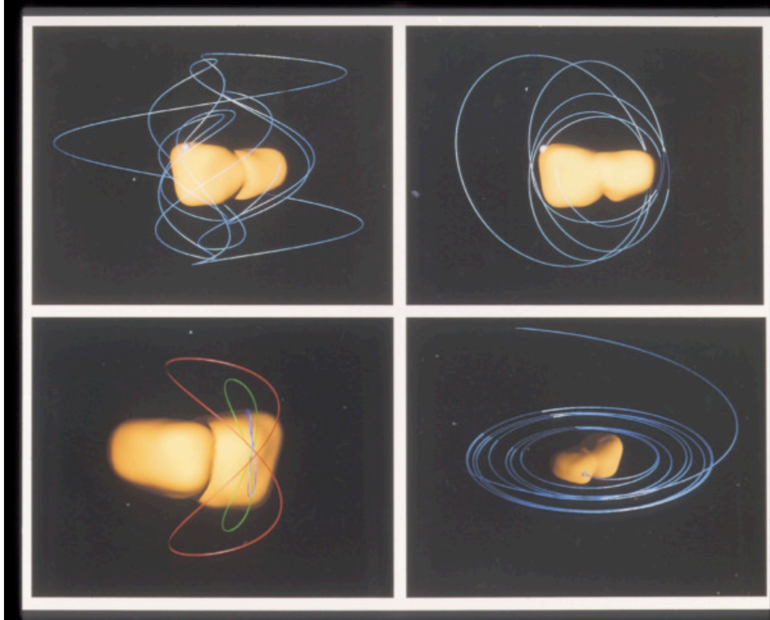
Toutatis

1999 JM8

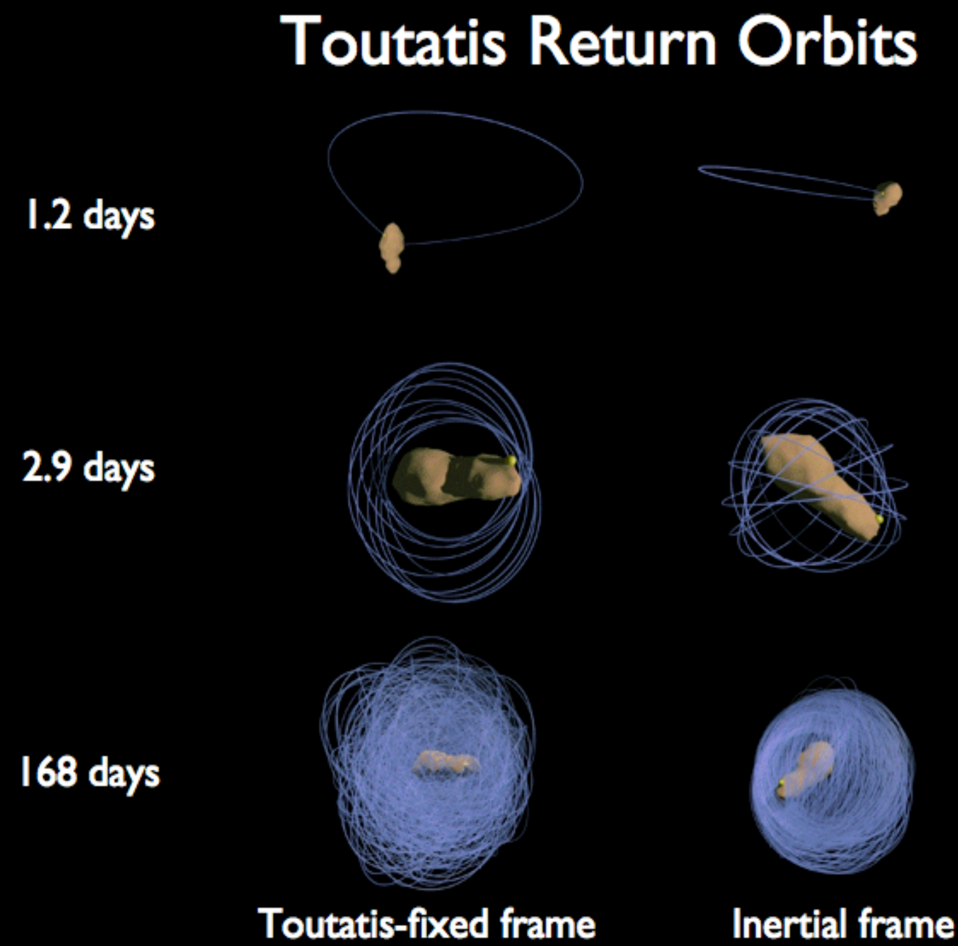


Mithra

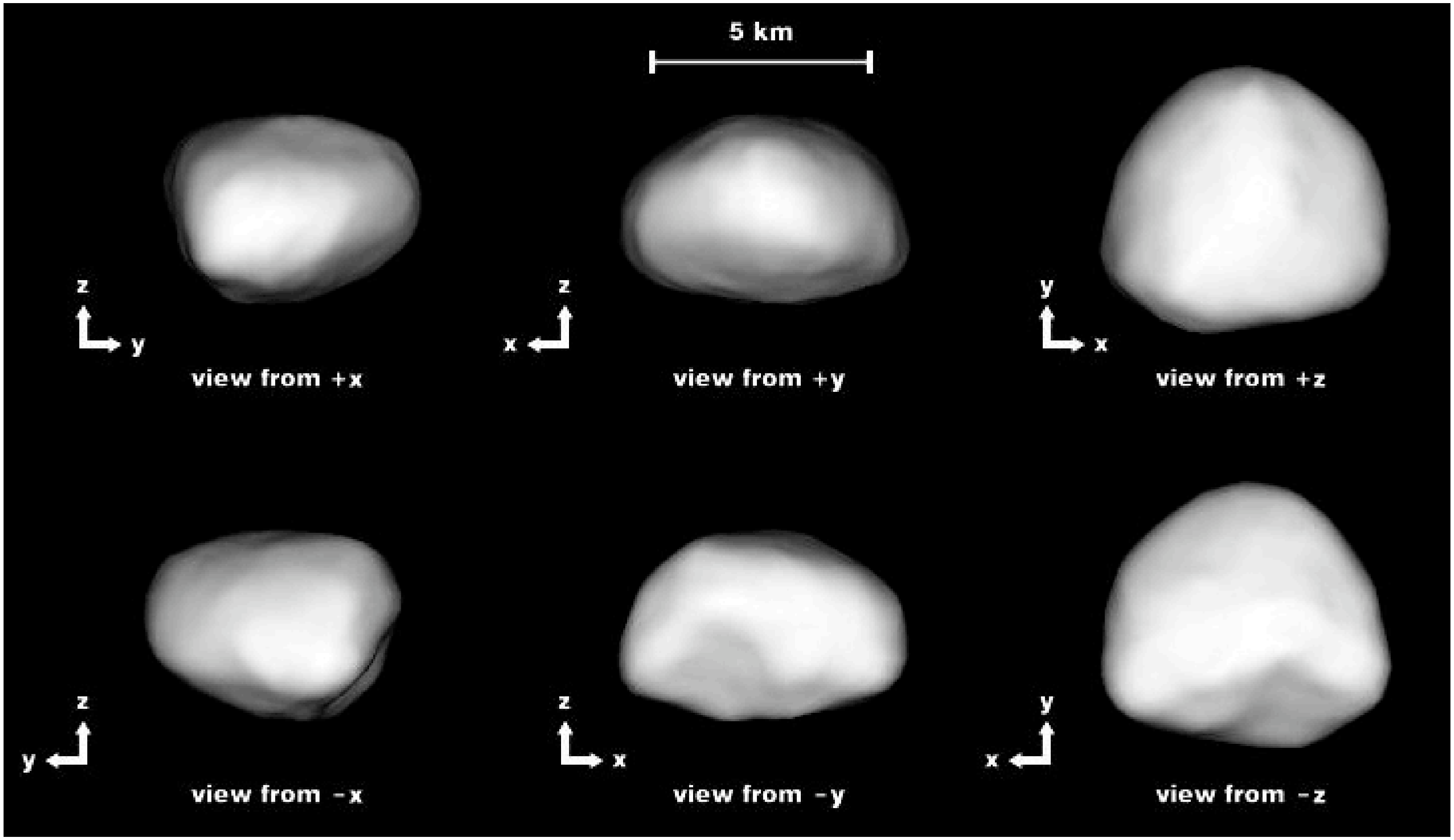
Spacecraft operations close to a small, irregularly shaped asteroid are extremely difficult due to the complexity of the gravitational environment, which depends on the asteroid's size, shape, spin state, and mass distribution.



Orbits Close to Castalia:
Scheeres et al. (1996), *Icarus* **121**, 67-87

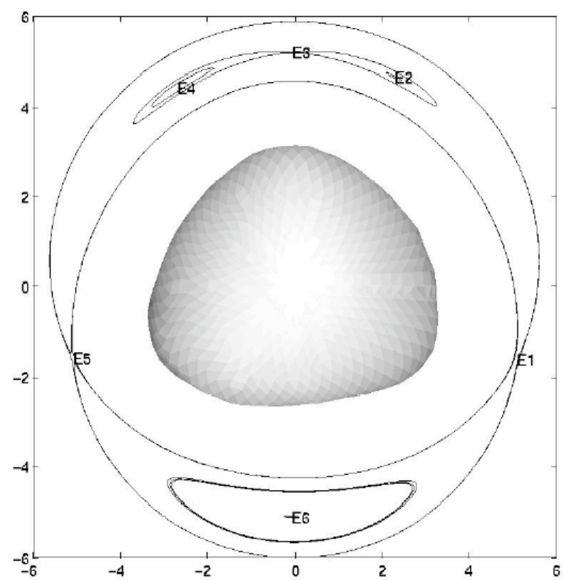


Scheeres et al. (1998), *Icarus* **132**, 53-79.

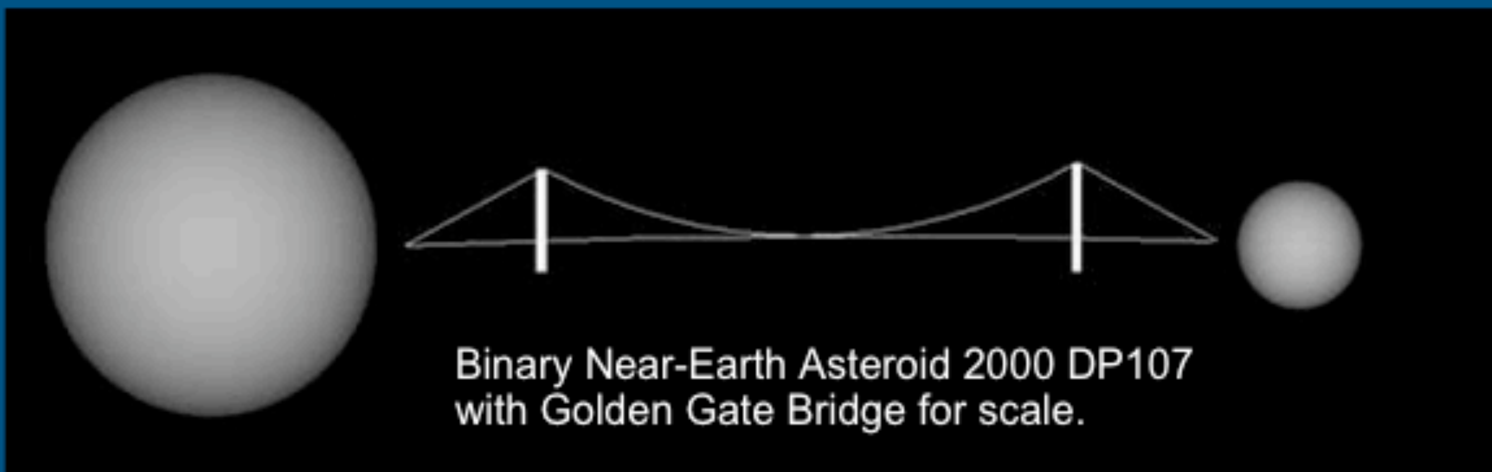


1580 Betulia

C. Magri et al. (2007), *Icarus* **186**, 152-177.



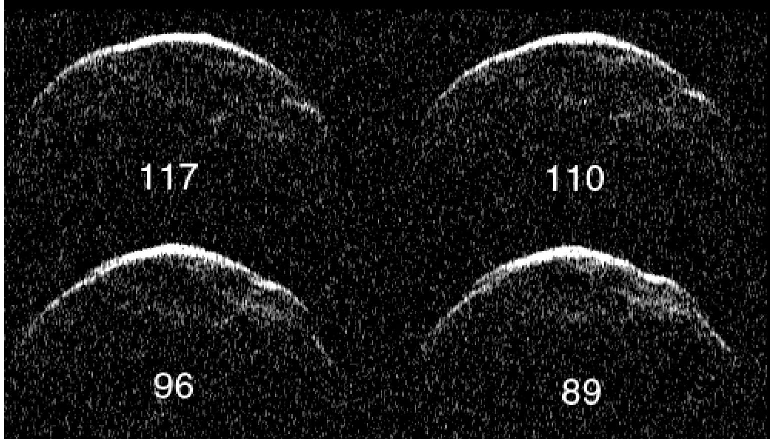
First images of a binary NEA: 2000 DP107

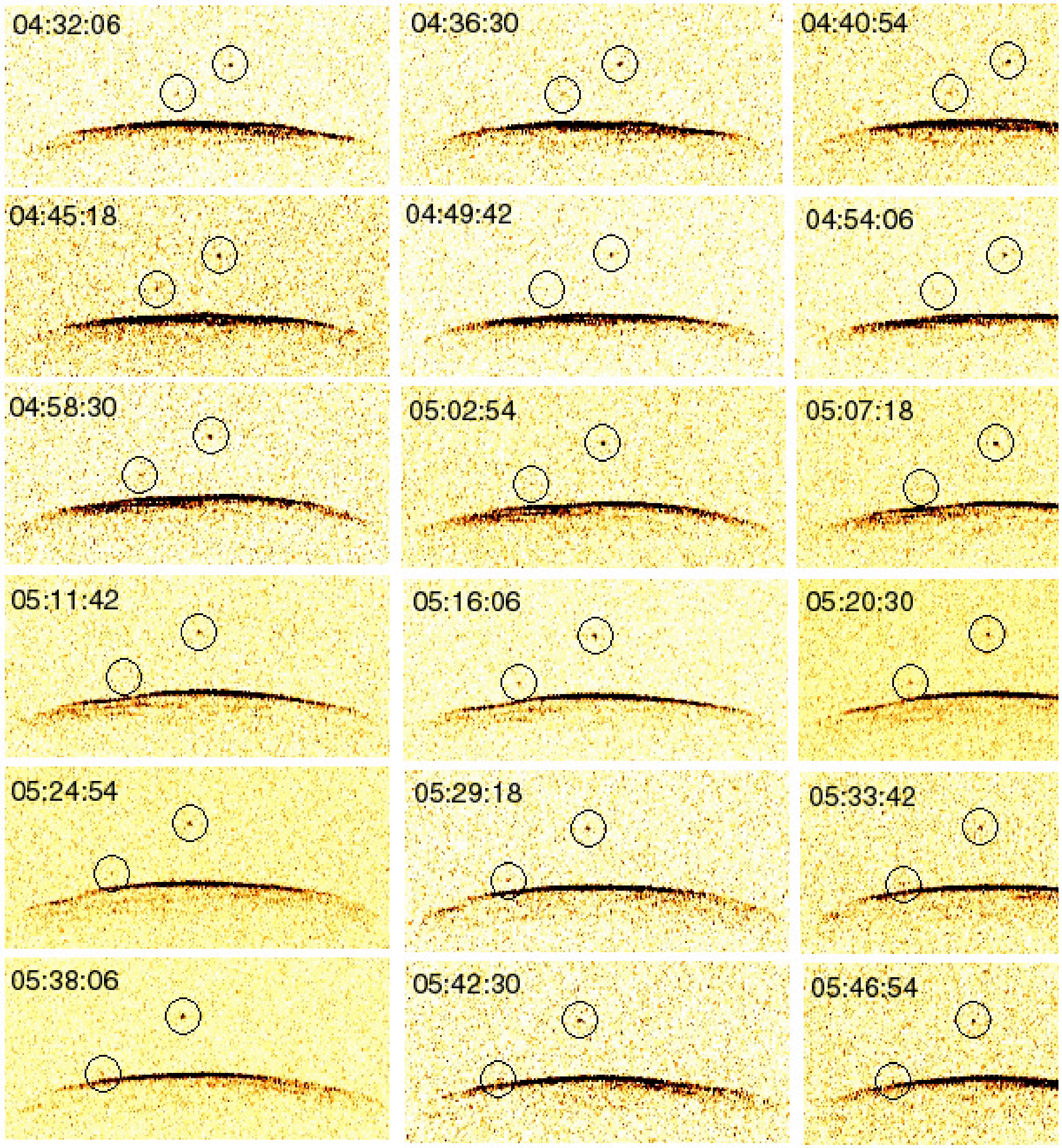


J.-L. Margot et al. (2002), *Science* **296**, 1445-1448.

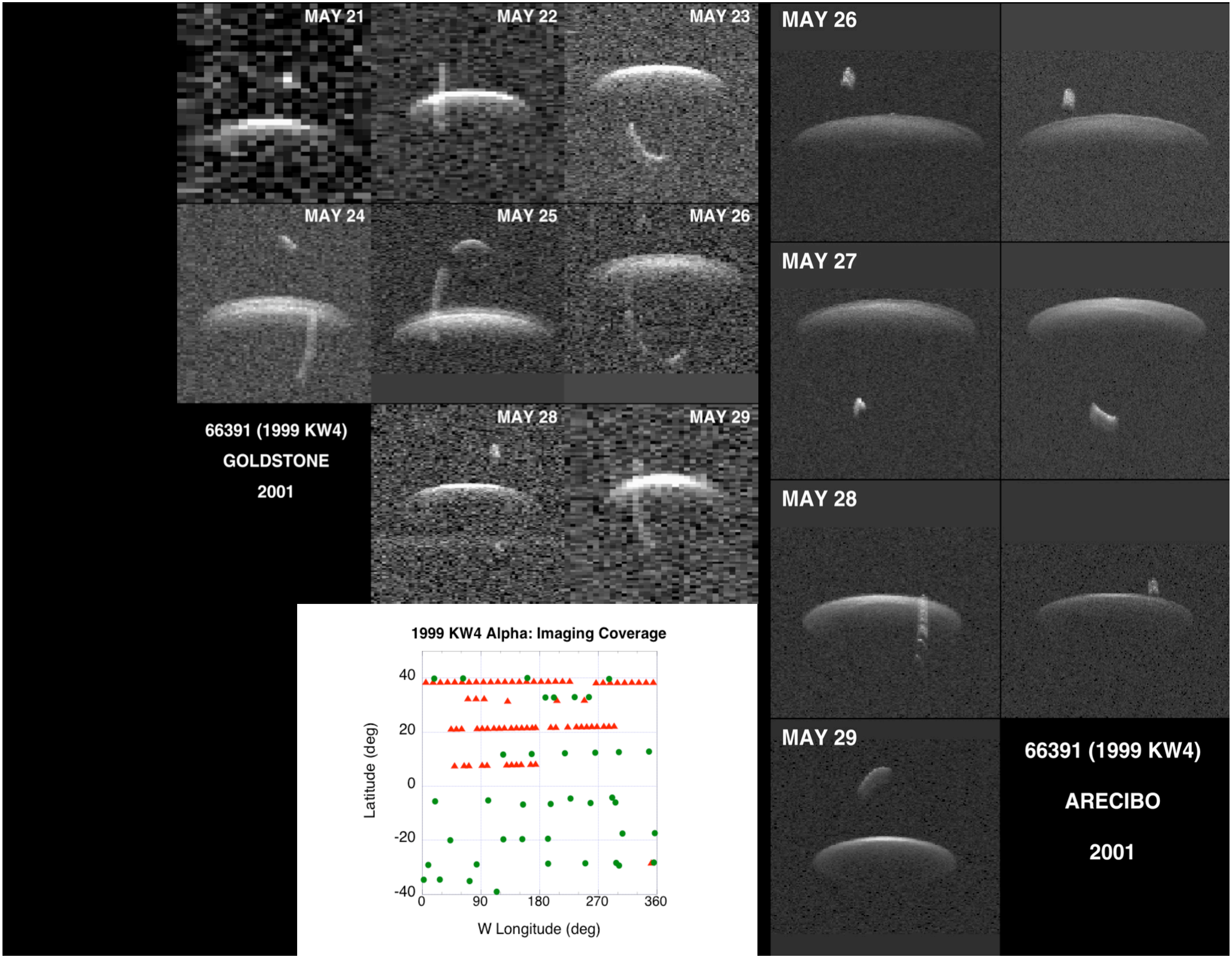
Radar, Optical, and Thermal Observations of Binary Near-Earth Asteroid 2002 CE26.

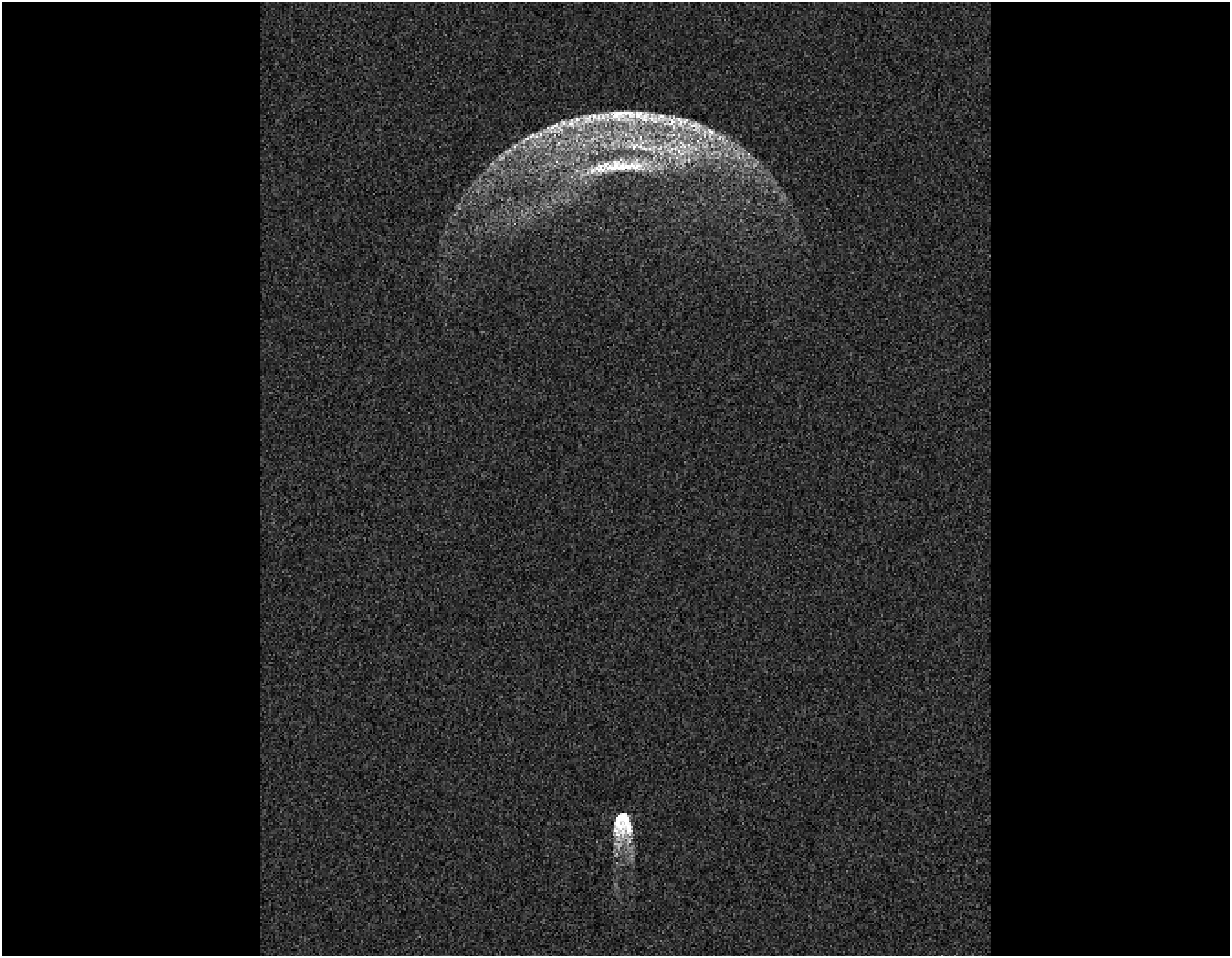
M. K. Shepard et al. (2006), *Icarus* 184, 198-210.



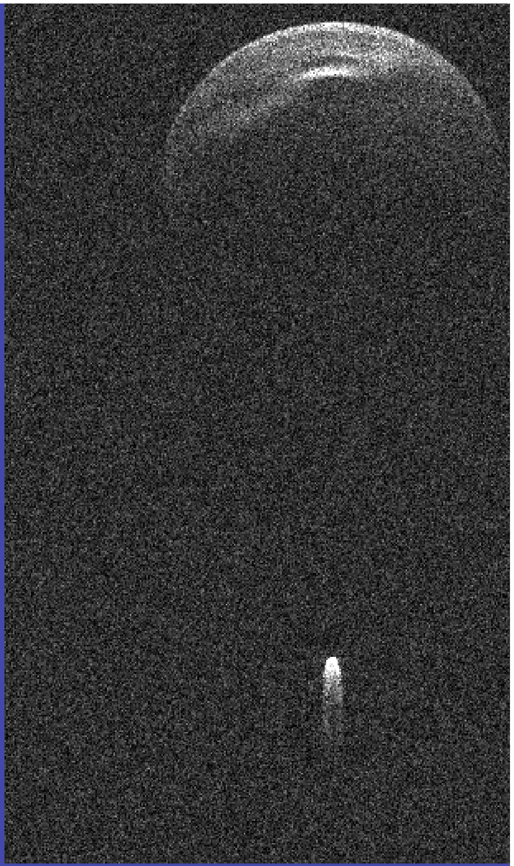


Composite of images on Aug 31 showing features consistent with a possible tertiary satellite.


MAY 21
MAY 22
MAY 23
MAY 24
MAY 25
MAY 26
MAY 28
MAY 29
66391 (1999 KW4)
GOLDSTONE
2001
1999 KW4 Alpha: Imaging Coverage
Latitude (deg)
40
20
0
-20
-40
0
90
180
270
360
W Longitude (deg)
MAY 26
MAY 27
MAY 28
MAY 29
66391 (1999 KW4)
ARECIBO
2001



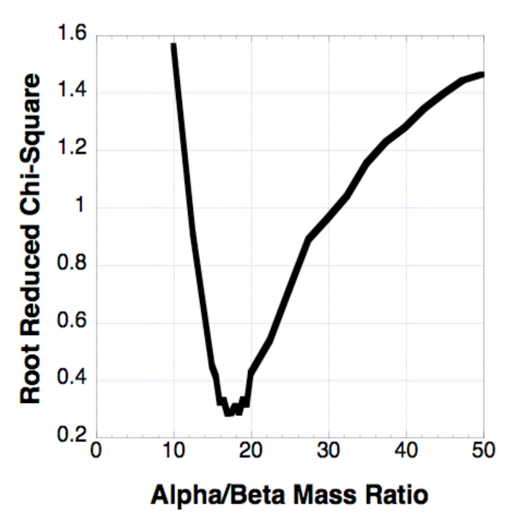
KW4 Analysis:

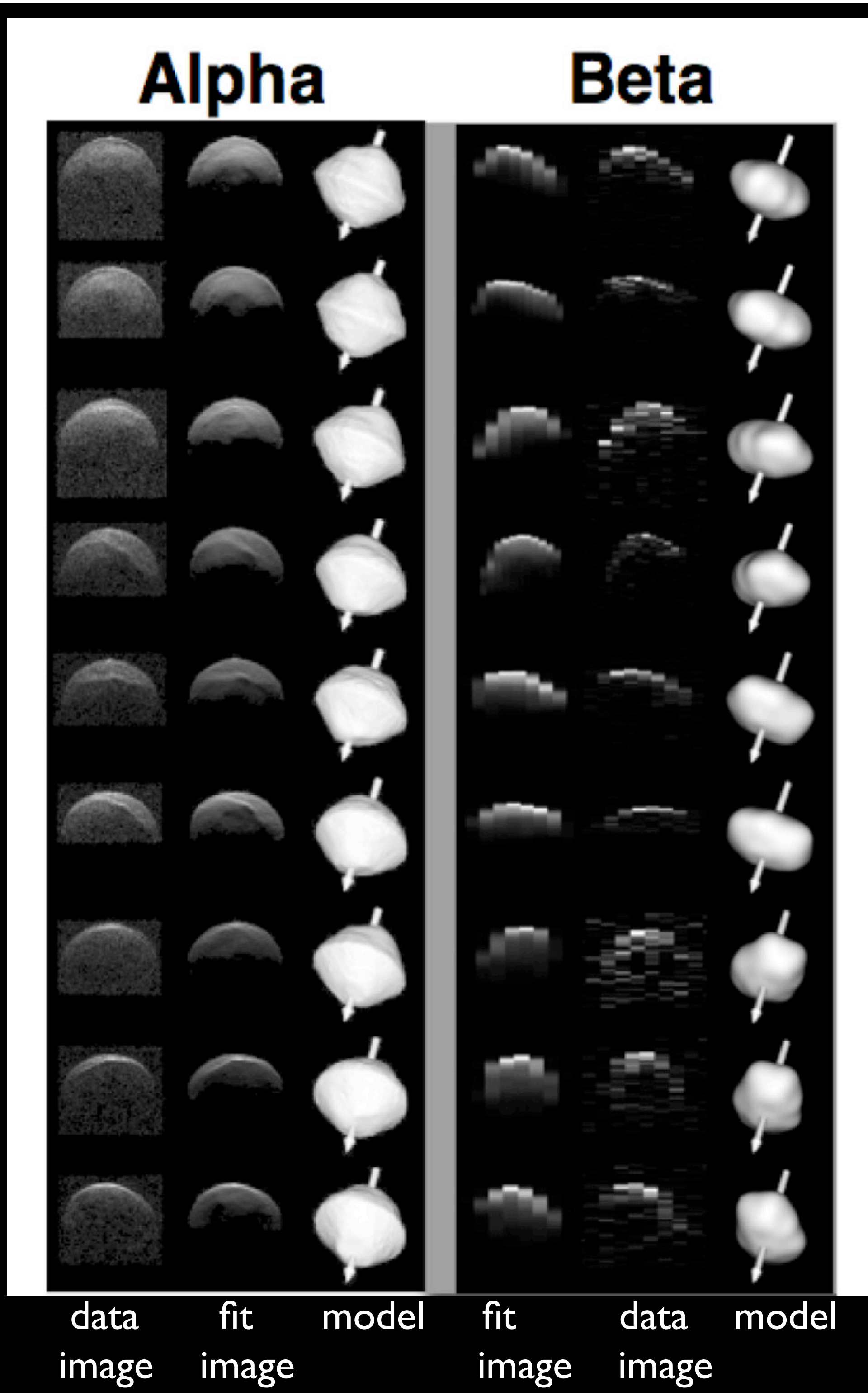


- Vignette images to form Alpha-only and Beta-only sets.
- Estimate each component's

  shape
  spin
  radar scattering properties
  COM location in each frame

- Use Beta-minus-Alpha differences in the components' COM delay-Doppler locations to estimate the (two-body, point-mass) relative orbit of Beta with respect to Alpha. (Gives system's total mass.)
- Estimate KW4's heliocentric orbit using radar and optical astrometry, evaluating chi-square as a function of the assumed mass ratio, which defines the location of the system's BARYCENTER along the Alpha-Beta line.



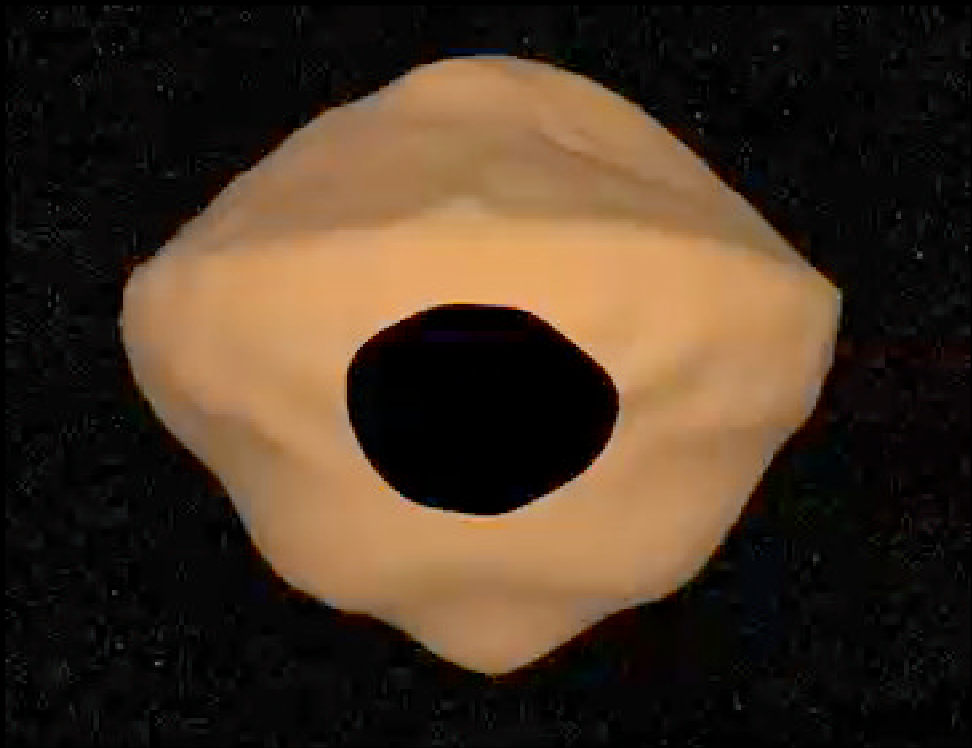

Alpha
Beta
data image
fit image
model
fit image
data image
model

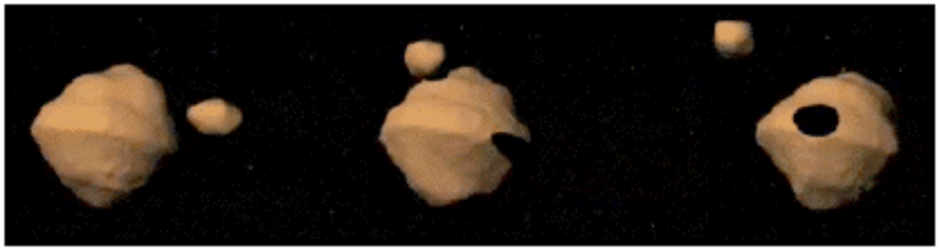
Average Relative Orbit

Period, P	17.4223 ± 0.036 hours
semimajor axis, a	2548 ± 15 meters
eccentricity	0.0004 ± 0.0019
epoch, MJD	2055.4132 ± 0.88
long asc node	105.4º ± 3º
Inclination	**156.1º ± 2º**
arg. peri.	319.7º ± 182º
total mass, $M = 4\pi^2 a^3 / G P^2$	(2.488 ± 0.054) e+12 kg

The Key to Understanding the KW4 System:

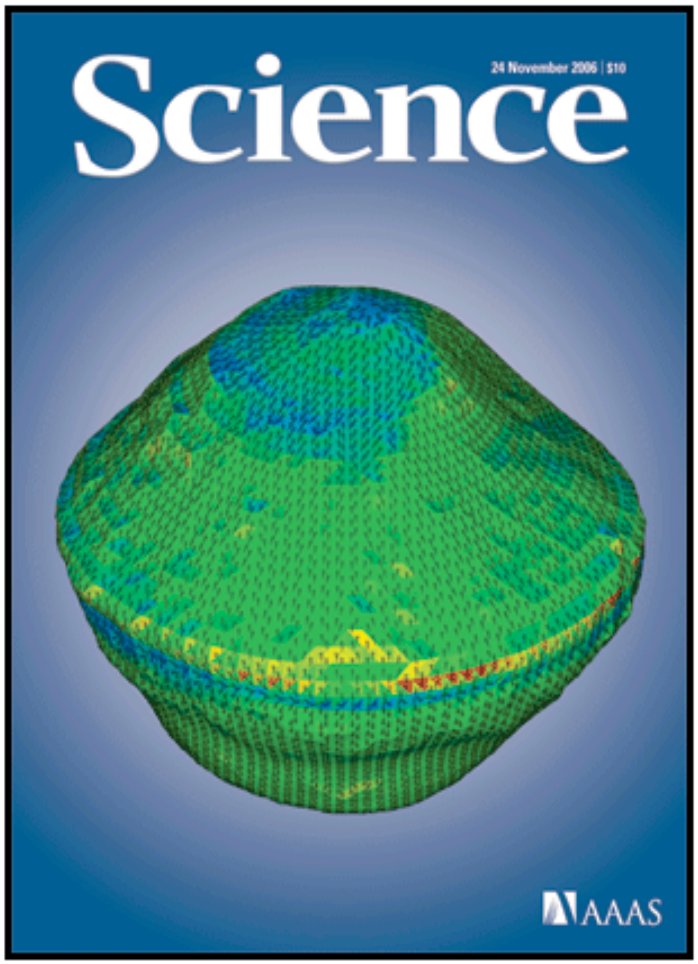
Simulations that take the model shapes, masses, and average rotations and orbit as initial conditions for integrations using the actual gravitational potentials produced by the shapes and the coupling between the components' motions.





http://echo.jpl.nasa.gov/~ostro/kw4

Asteroid (66391) 1999 KW4



This web page accompanies papers published online in *Science* Express on Oct. 12, 2006, and in the Nov. 24, 2006, issue of *Science* magazine:

Radar Imaging of Binary Near-Earth Asteroid (66391) 1999 KW4.
S. J. Ostro, J.-L. Margot, L. A. M. Benner, J. D. Giorgini, D. J. Scheeres, E. G. Fahnestock, S. B. Broschart, J. Bellerose, M. C. Nolan, C. Magri, P. Pravec, P. Scheirich, R. Rose, R. F. Jurgens, E. M. de Jong, and S. Suzuki.
Science **314**, 1276-1280 (2006) (DOI: 10.1126/science.1133622).
(paper)
(supplementary online material) (in cludes KW4's close Earth approaches)

and

Dynamical Configuration of Binary Near-Earth Asteroid (66391) 1999 KW4.
D. J. Scheeres, E. G. Fahnestock, S. J. Ostro, J.-L. Margot, L. A. M. Benner, S. B. Broschart, J. Bellerose, J. D. Giorgini, M. C. Nolan, C. Magri, P. Pravec, P. Scheirich, R. Rose, R. F. Jurgens, E. M. de Jong, and S. Suzuki.
Science **314**, 1280-1283 (2006) (DOI: 10.1126/science.1133599).
(paper)
(supplementary online material)

Equations of motion

- The general system has 12 DOF, only 3 of which are easily removed

$$\frac{M_1 M_2}{M_1 + M_2}\ddot{r}_i = U_{r_i}$$

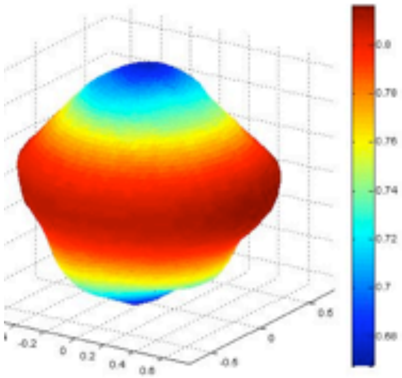
Translation

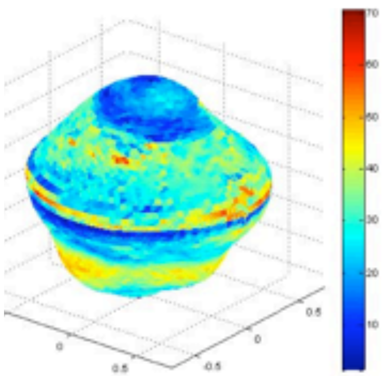
$$\dot{H}_i^I = -T_{ij}^I \epsilon_{jkl} T_{mk}^I U_{T_{ml}^I}$$
$$\Omega_i^I = (I_{ji}^I)^{-1} T_{kj}^I H_k^I$$
$$\dot{T}_{ij}^I = T_{ik}^I \Omega_l^I \epsilon_{klj}$$

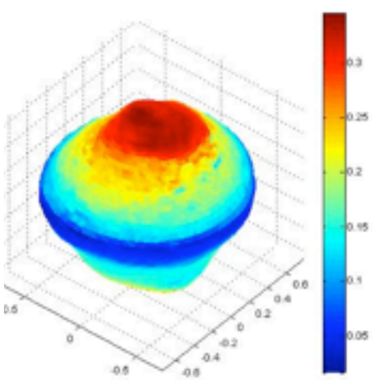
Rotation

$$i, j = 1, 2, 3$$
$$I = 1, 2$$
$$\epsilon_{123} = 1, \text{skew-symmetric}$$

$$U(r, T^1, T^2) = \mathcal{G} \int_{B^1} \int_{B^2} \frac{dm^1 dm^2}{|r + T^1\rho^1 - T^2\rho^2|}$$







Extreme Environment on Alpha

- Alpha spins just shy of/at its disruption rate
- The geopotential low on Alpha is at its equator
- Particles on its surface are just meters or less from being in orbit
- Any loose material spun off of Alpha will be trapped by Beta
  - Will eventually fall back on Alpha
  - Will transfer angular momentum to the orbit
  - Will regulate Alpha's spin at its maximum rate

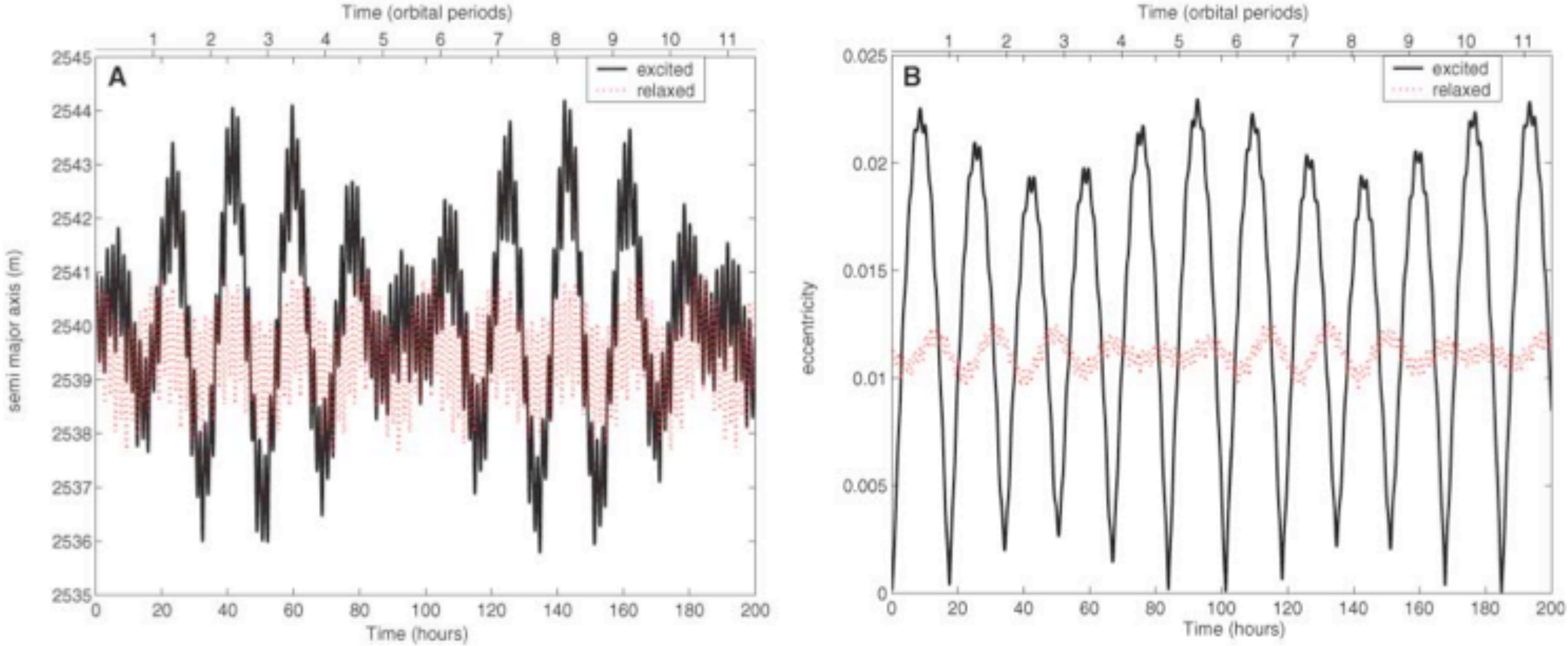


Fig. 1. Evolution of KW4's orbit (**A**) semimajor axis and (**B**) eccentricity over 200 hours, computed for the relaxed and excited system.

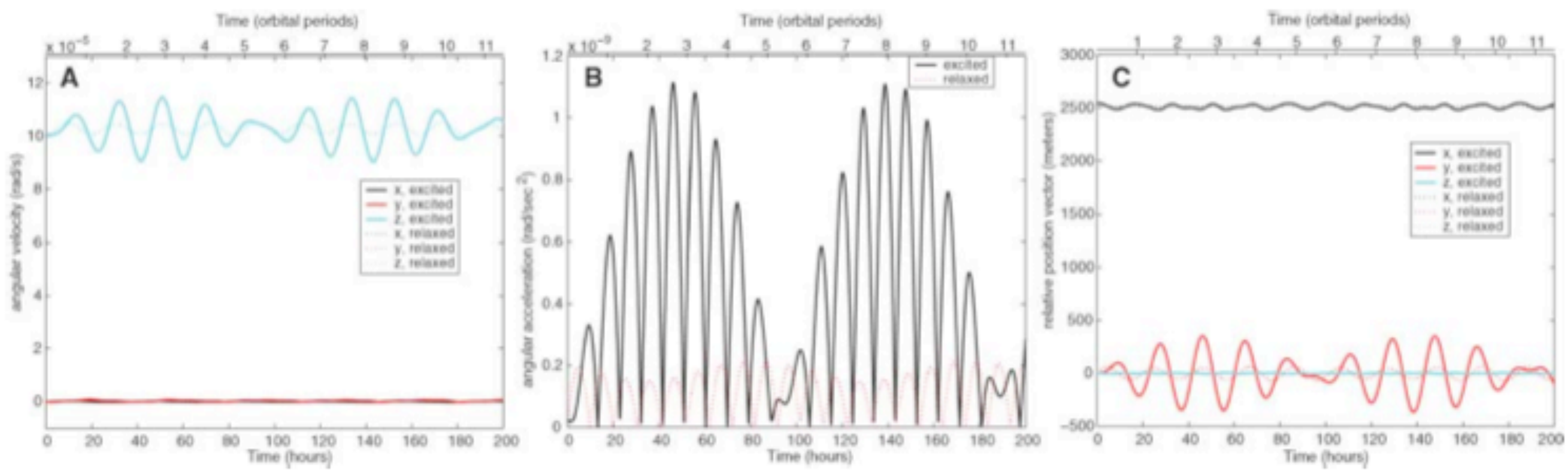


Fig. 2. (**A**) Rotational angular velocity and (**B**) total angular acceleration of Beta, shown in the Beta fixed frame, for the relaxed and excited cases. (**C**) Alpha's orbit in a Beta-fixed frame. The large *y* variations are due primarily to Beta's attitude libration about the Beta-Alpha line.

Radar Synergies

- NEO Tracking, Characterization, and Threat Mitigation

- Human Exploration

For any scenario with an object on course for Earth collision in this century, <u>what information</u> do we need at each stage of the scenario for mitigation to succeed?

<u>How, and at what cost, will we get this information?</u>

A. With optimal application of Arecibo/Goldstone radar capabilities?

B. Without radar?