



SPIN, SHAPE, AND INTERIOR OF NEAR-EARTH ASTEROID 4179 TOUTATIS

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With thanks to Lance Benner, Marina Brozovic, Jon Giorgini, Joseph Jao, Dan Scheeres, Yu Takahashi, and the Goldstone and VLA observing staff

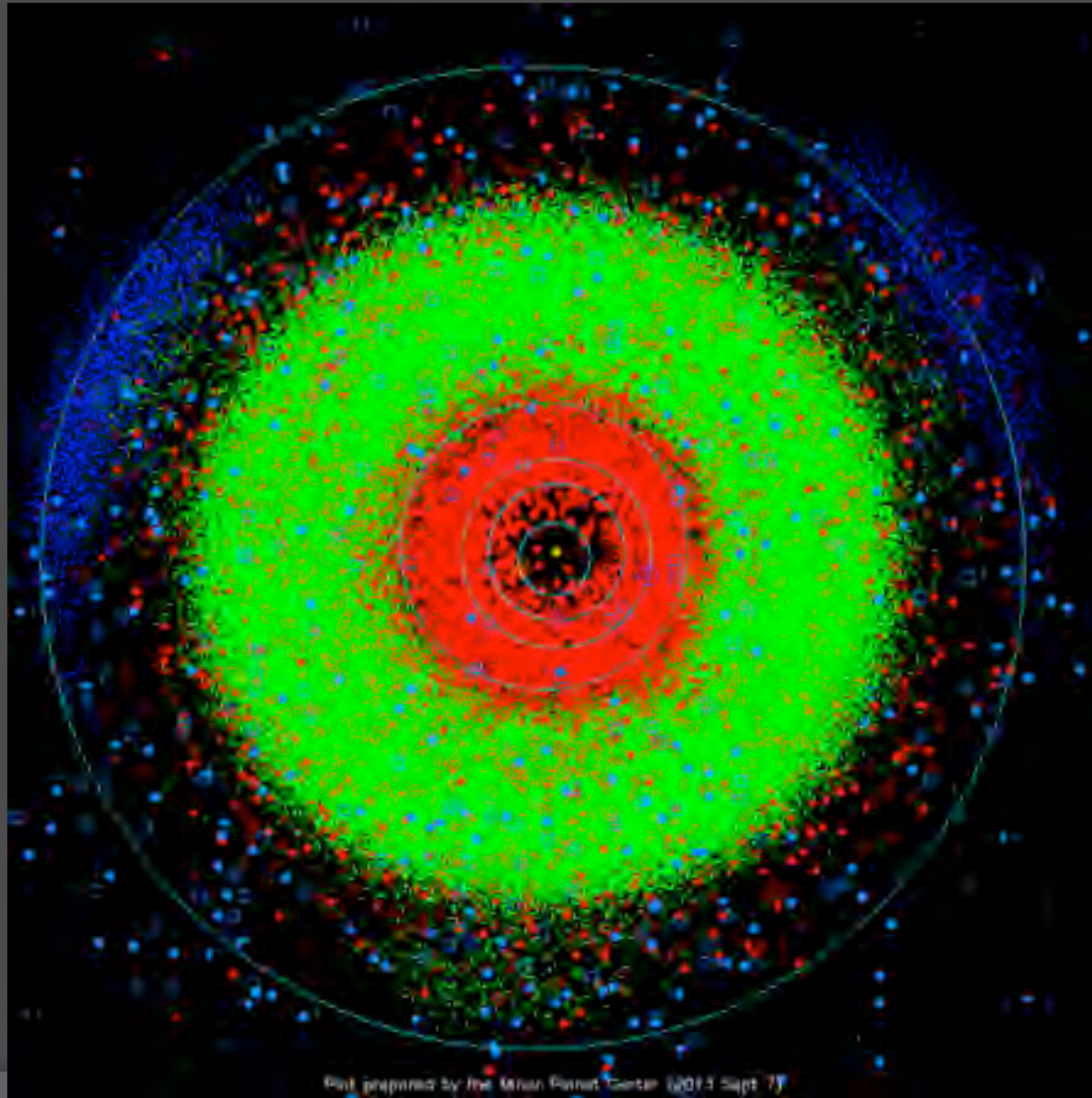
Where Are The Asteroids?

Green:
Main Belt Objects

Dark Blue:
Jupiter Trojans

Light Blue:
Comets

Red:
Near-Earth
Asteroids





Toutatis

Orbital elements: $a = 2.533$ AU, $e = 0.629$, $i = 0.445^\circ$ *Orbital Period: 4.03 years*

Passed within 0.1 AU of Earth in 1992, 1996, 2000, 2004, 2008, 2012

Radar Astronomy



Arecibo Observatory, Puerto Rico (305 m)

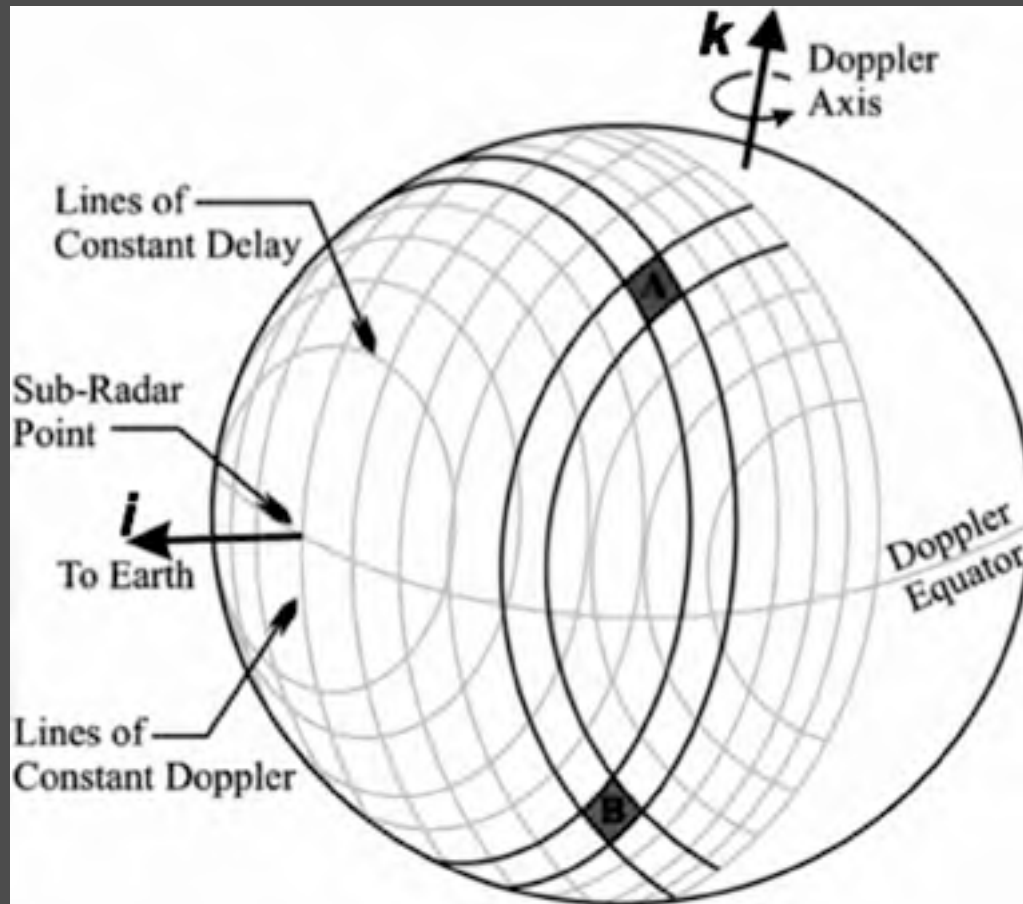


*Goldstone,
California (70 m)*

Radar Astronomy

- ⦿ Transmit coded signal, receive echo.
- ⦿ Echo strength and polarization determined by surface properties.
- ⦿ Resolve target in time delay and Doppler shift.
- ⦿ Resolution limit: 25 ns x ~0.01 Hz
3.75 m x 1 mm/s
50 μas (equivalent)
- ⦿ Requires: *large* antenna (70 – 300 m),
high transmit power (400 – 850 KW),
nearby targets (<0.05 AU for 3.75 m resolution).

Delay-Doppler Imaging

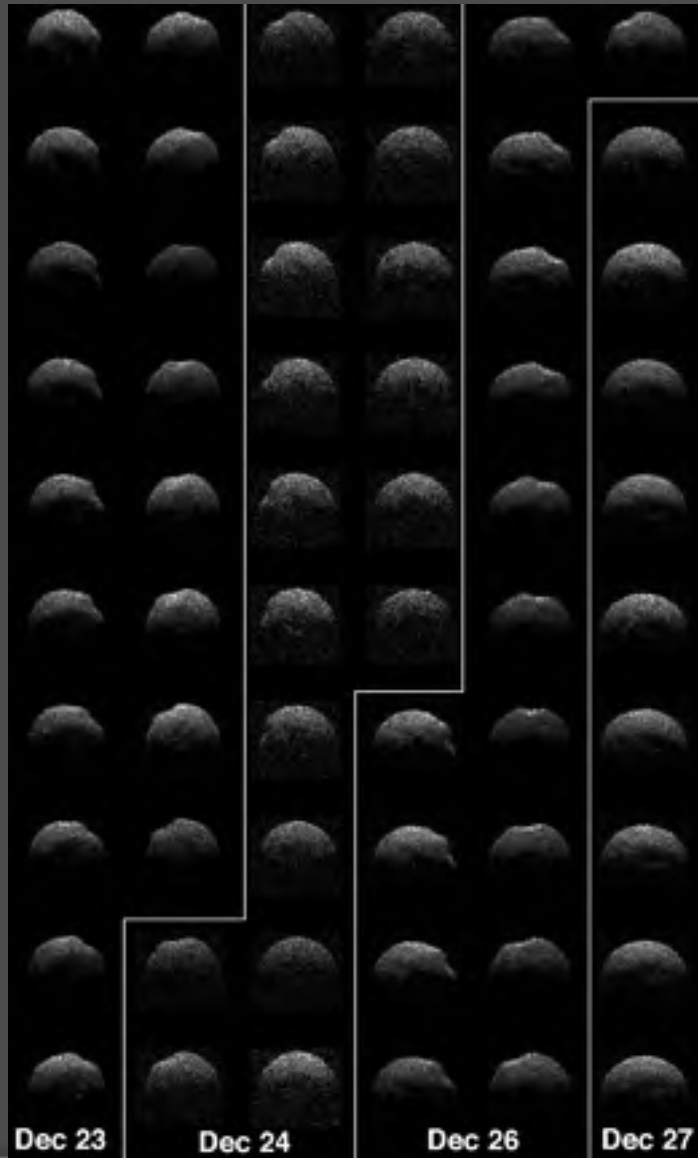


- Each point in a delay-Doppler image corresponds to at least two points on the target.
- Given a sufficient set of images, the object's shape, size, and spin state can be uniquely determined.



Arecibo Delay-Doppler Image of Venus

Example Delay-Doppler Asteroid Images

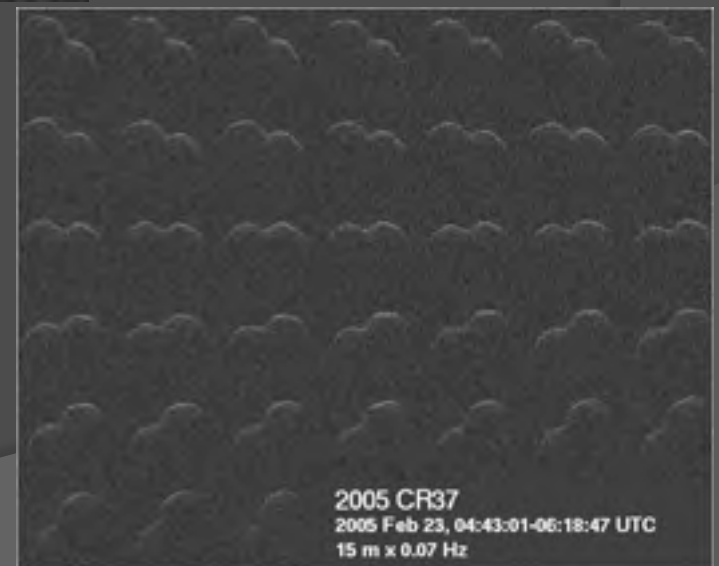


2008 EV5, Arecibo, images from 2008



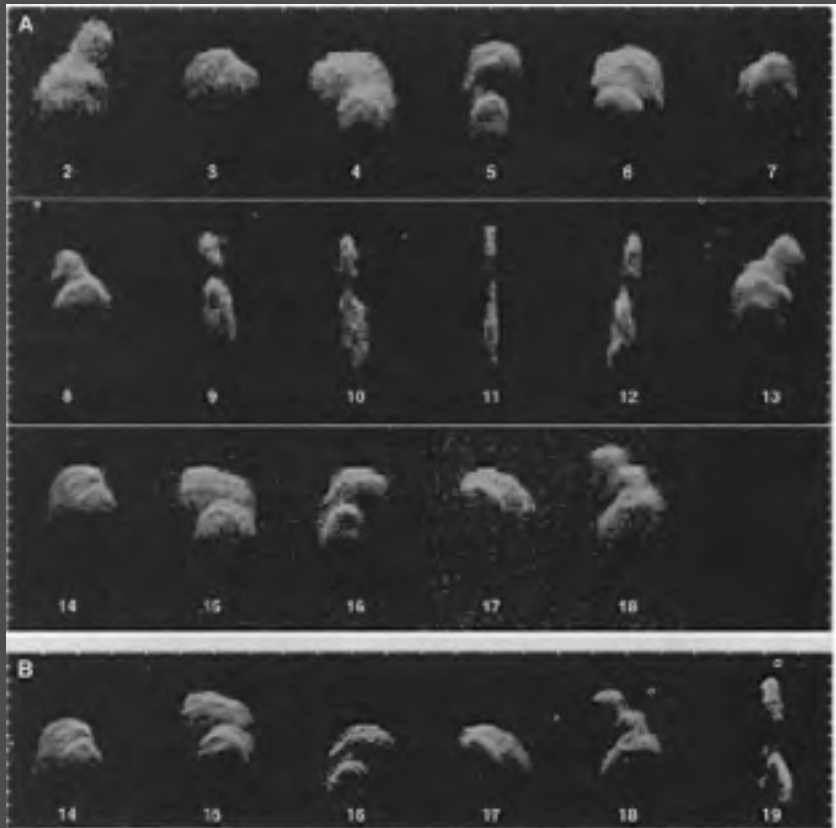
© Inverse problem: what plausible shape & spin state give the best fit to the delay-Doppler images?

© Least-squares optimization implemented in C software package – called **SHAPE**.

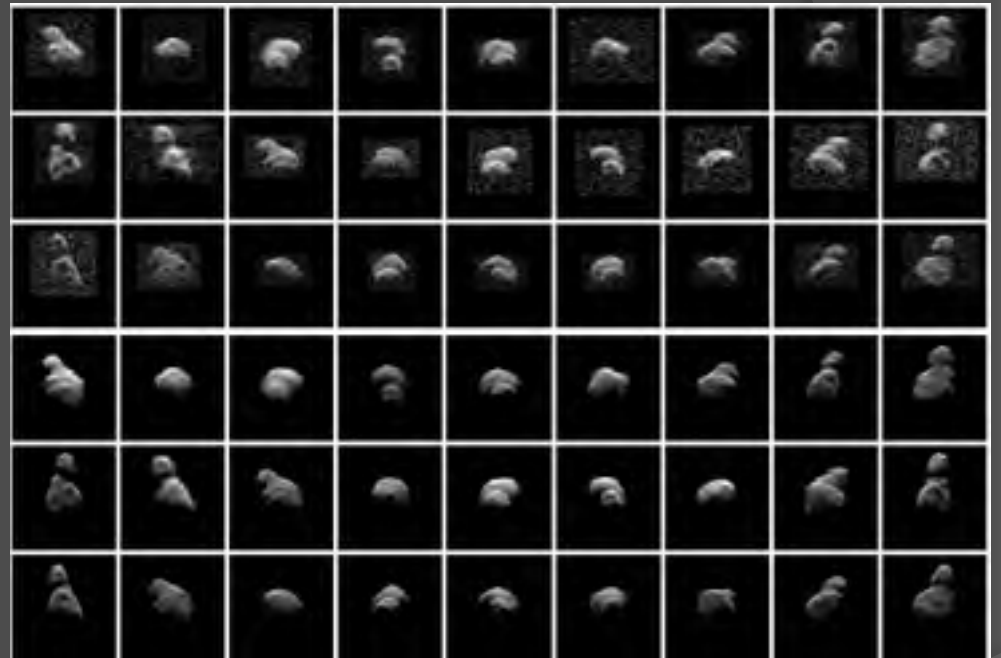


Toutatis in 1992-1996

Observations led by Steve Ostro, shape and spin state models led by Scott Hudson.



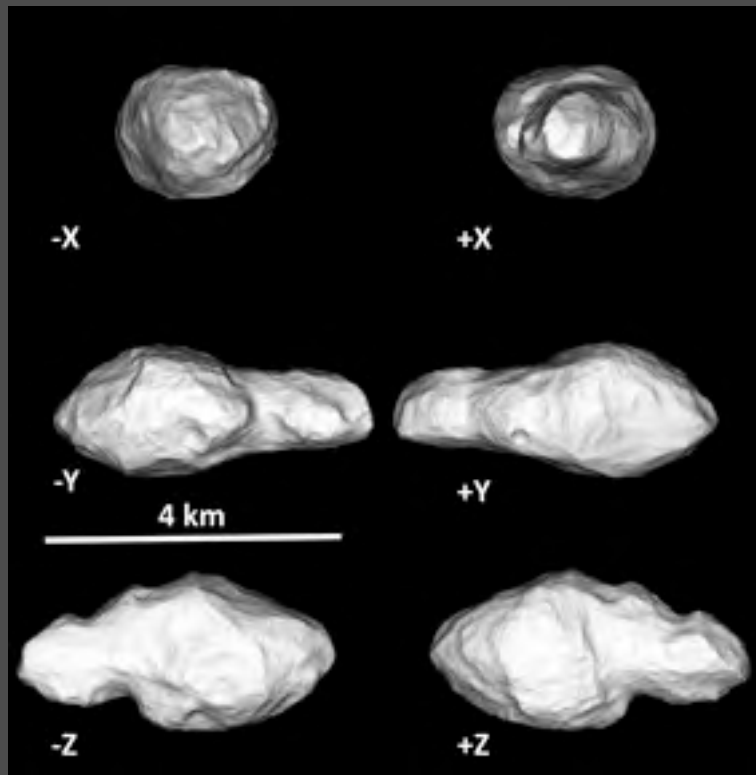
1992 Arecibo & Goldstone Radar Images



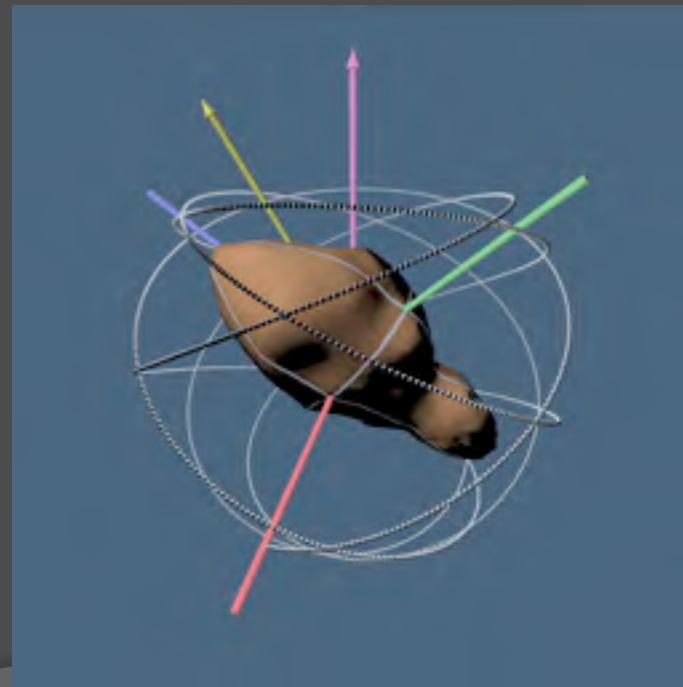
1996 Arecibo & Goldstone Radar Images

Toutatis in 1992-1996

1. Toutatis is bilobate, ~4.5 km long.
2. It has an aperiodic NPA spin state.
3. NPA spin depends on Toutatis' moments of inertia.

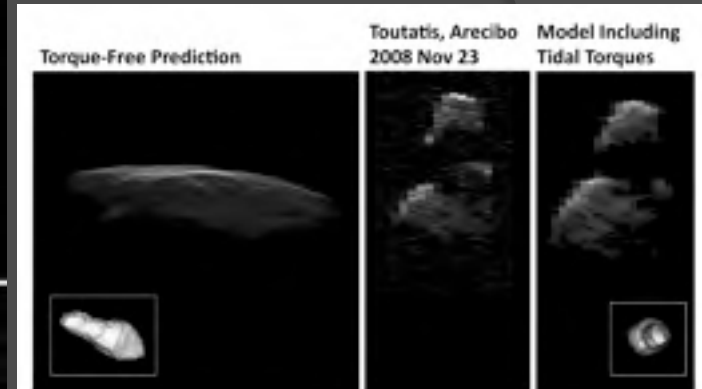
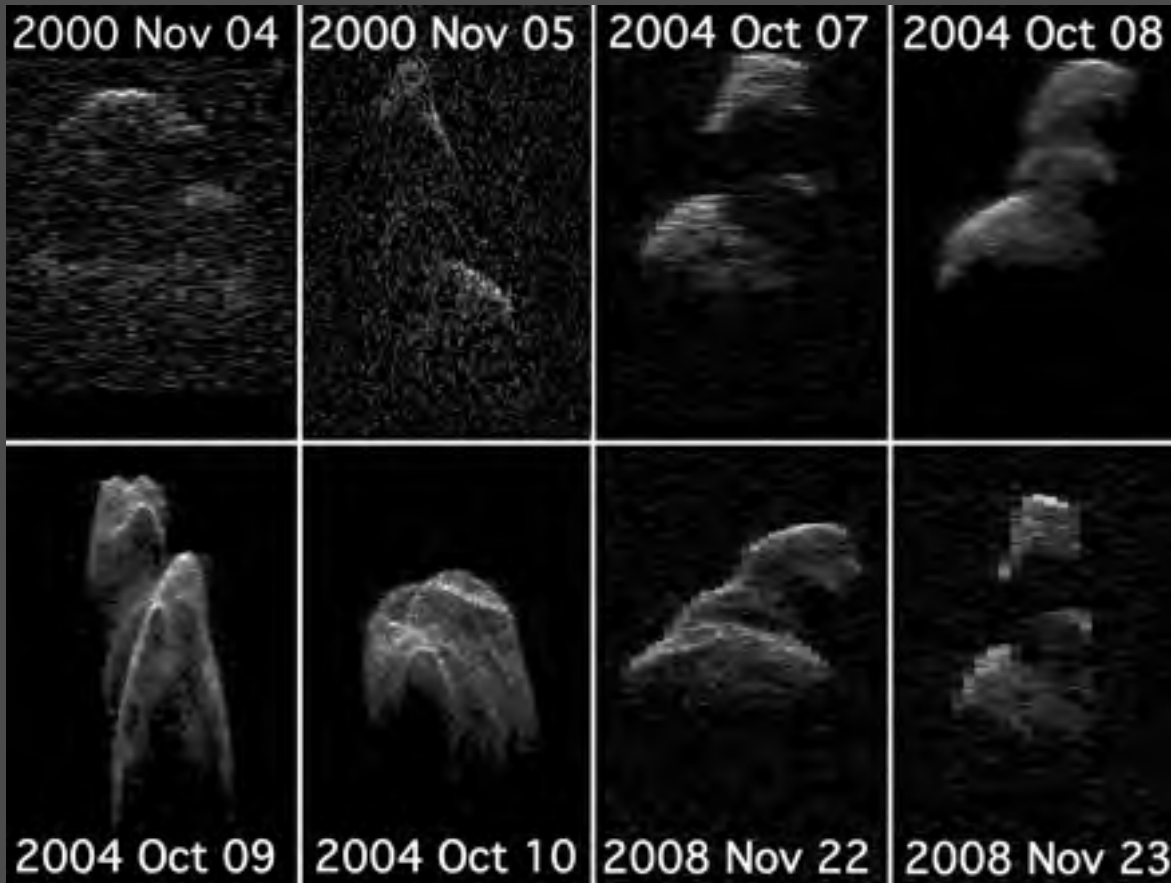


Old Radar-derived shape of Toutatis.



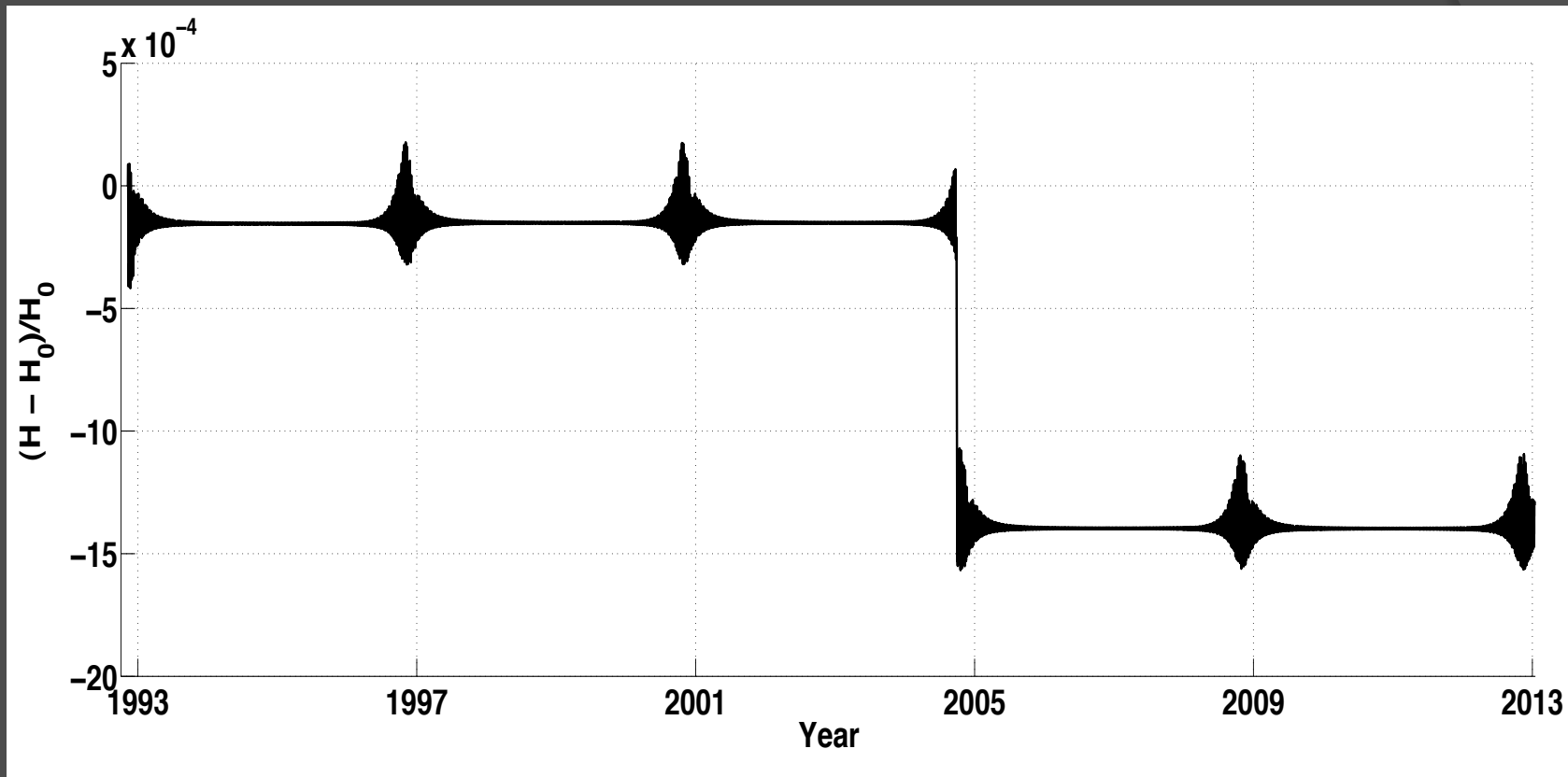
Toutatis' non-principal-axis (NPA) spin state

Toutatis in 2000-2008



- Radar images: Goldstone '00, Arecibo '04 & '08.
- Mismatch between '92-'96 spin state fit and later images.

Toutatis' Changing Spin State

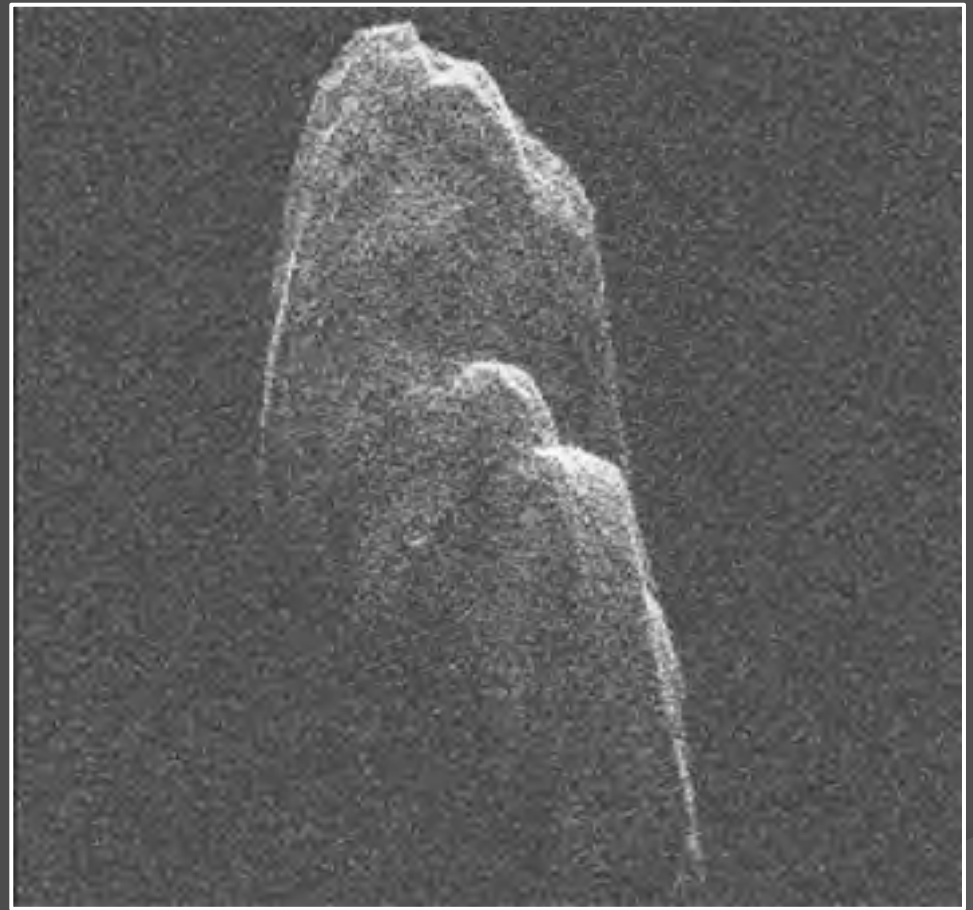


*Changes in Toutatis' angular momentum from Dec 1992 to Dec 2012.
Chart and fit from Yu Takahashi et al. 2013.*

- ⦿ Toutatis is torqued by tides from the Sun and Earth. The largest spin state change since 1992 was during the '04 flyby.
- ⦿ Moment of inertia ratios from '92-'08 spin state fit:
 $I_s/I_l = 3.23 \pm 0.01$ and $I_f/I_l = 3.087 \pm 0.005$

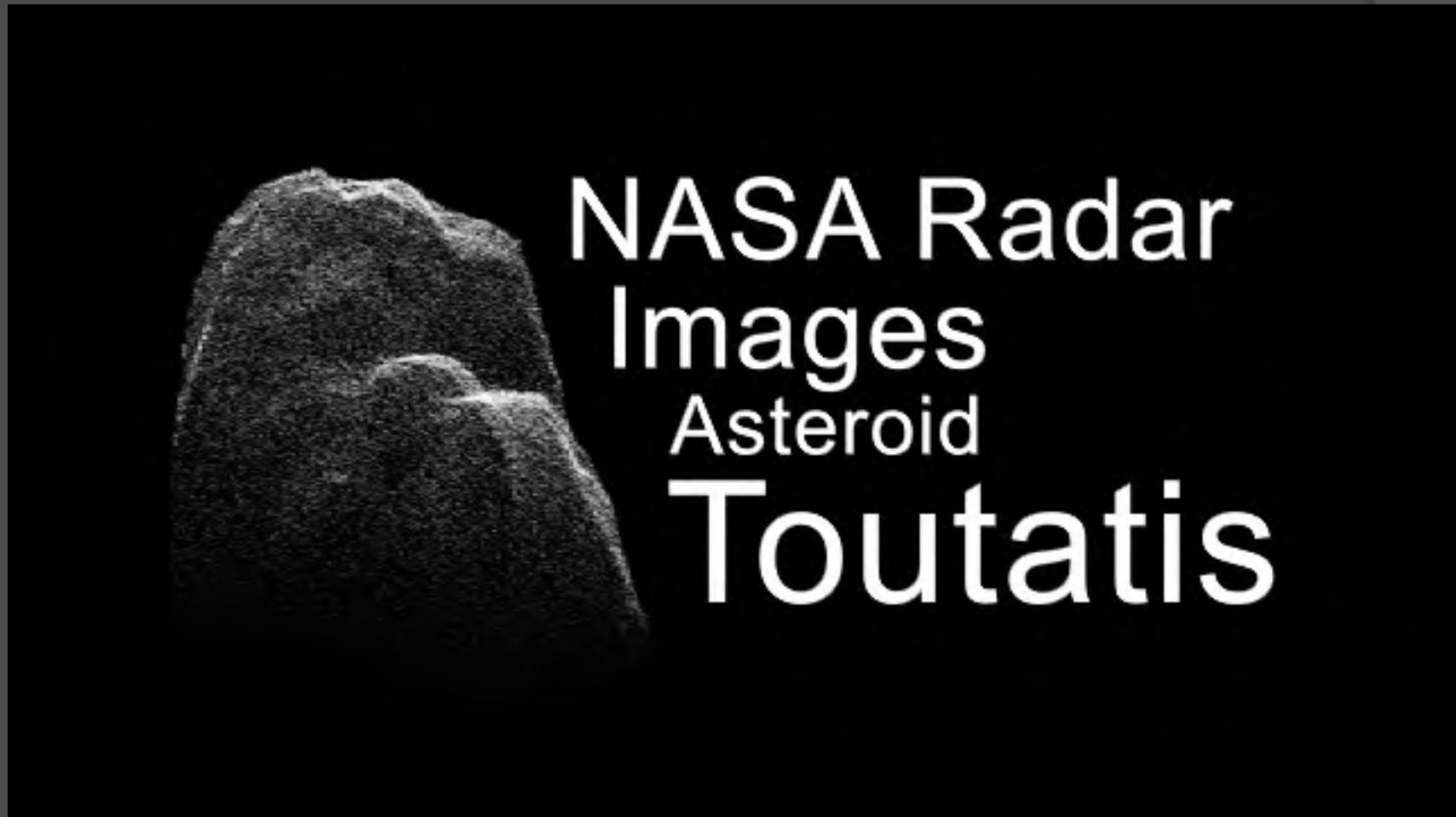
Data from 2012

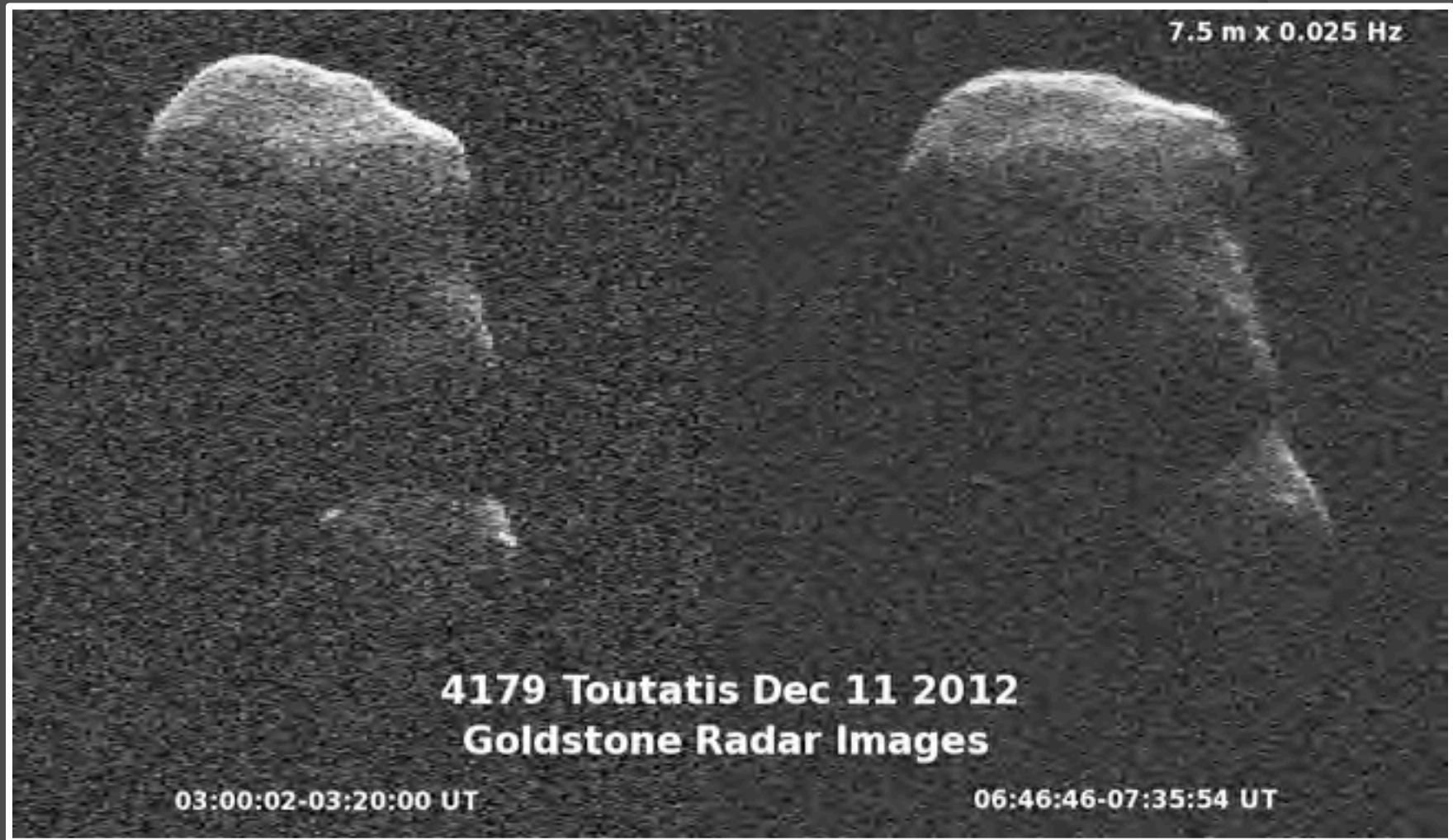
- Goldstone radar imaging on 16 days between 2012 Dec 4 and Dec 22.
 - Dec 13 images overlap CE2 flyby.
- Image resolution: 18.75 m to **3.75 m** per range pixel.
- Radar speckle tracking from Dec 18 to Dec 22.



Goldstone 2012 Dec 12 delay-Doppler radar image, 3.75 m/pixel in range

Images from 2012 Dec 12 & 13 UT





7.5 m/pixel and 3.75 m/pixel images of Toutatis show some 10-m-scale bright features. Boulders?

How Good Was The Shape Model?

Toutatis Image, 2012 Dec 4, 03:30 UT



Euler angles: $(63 \pm 8^\circ, 80 \pm 4^\circ, 244 \pm 5^\circ)$

Toutatis Nominal Prediction
($51.7^\circ, 76.4^\circ, 238.9^\circ$)

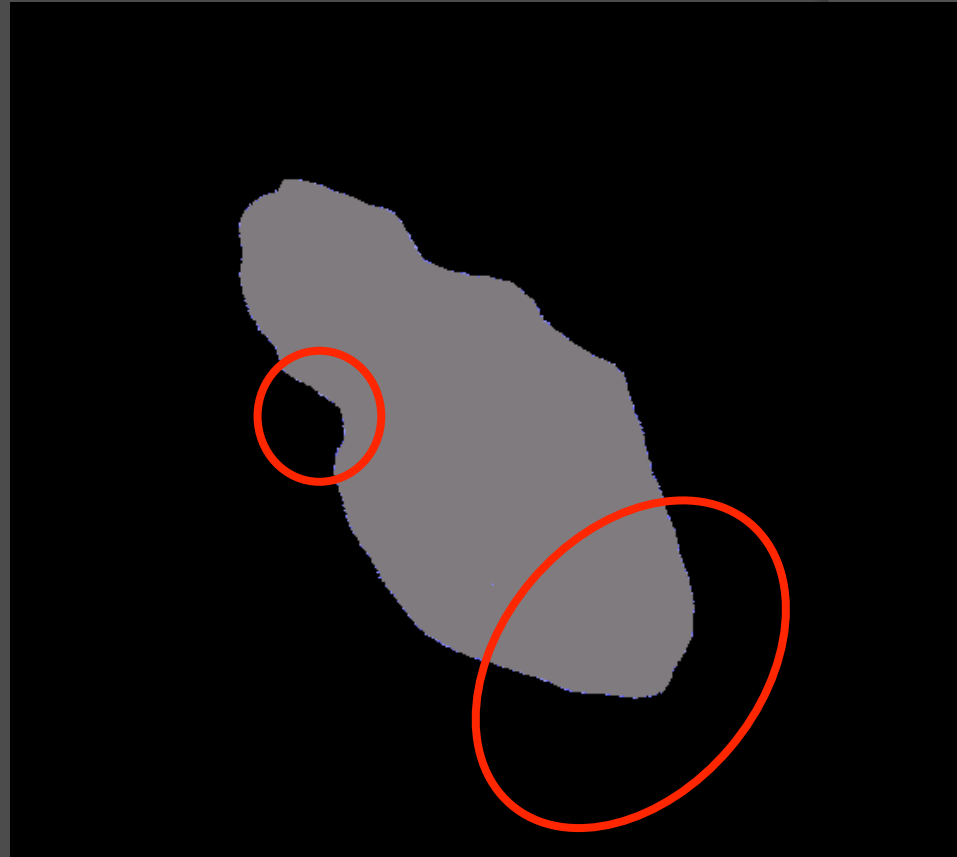


- Spin state predictions were quite good.
- Radar and Chang'e 2 images imply errors in the shape model of *perhaps 3% by volume*.
- Limitations of **SHAPE** software: initial ellipsoid model of the big end was preserved throughout later shape fits.

Comparison: CE2 and Old Radar Shape



Chang'e 2 85-km distance image



Silhouette of old (pre-2012) radar-derived Toutatis shape model, with largest errors highlighted. Does not include solar illumination.

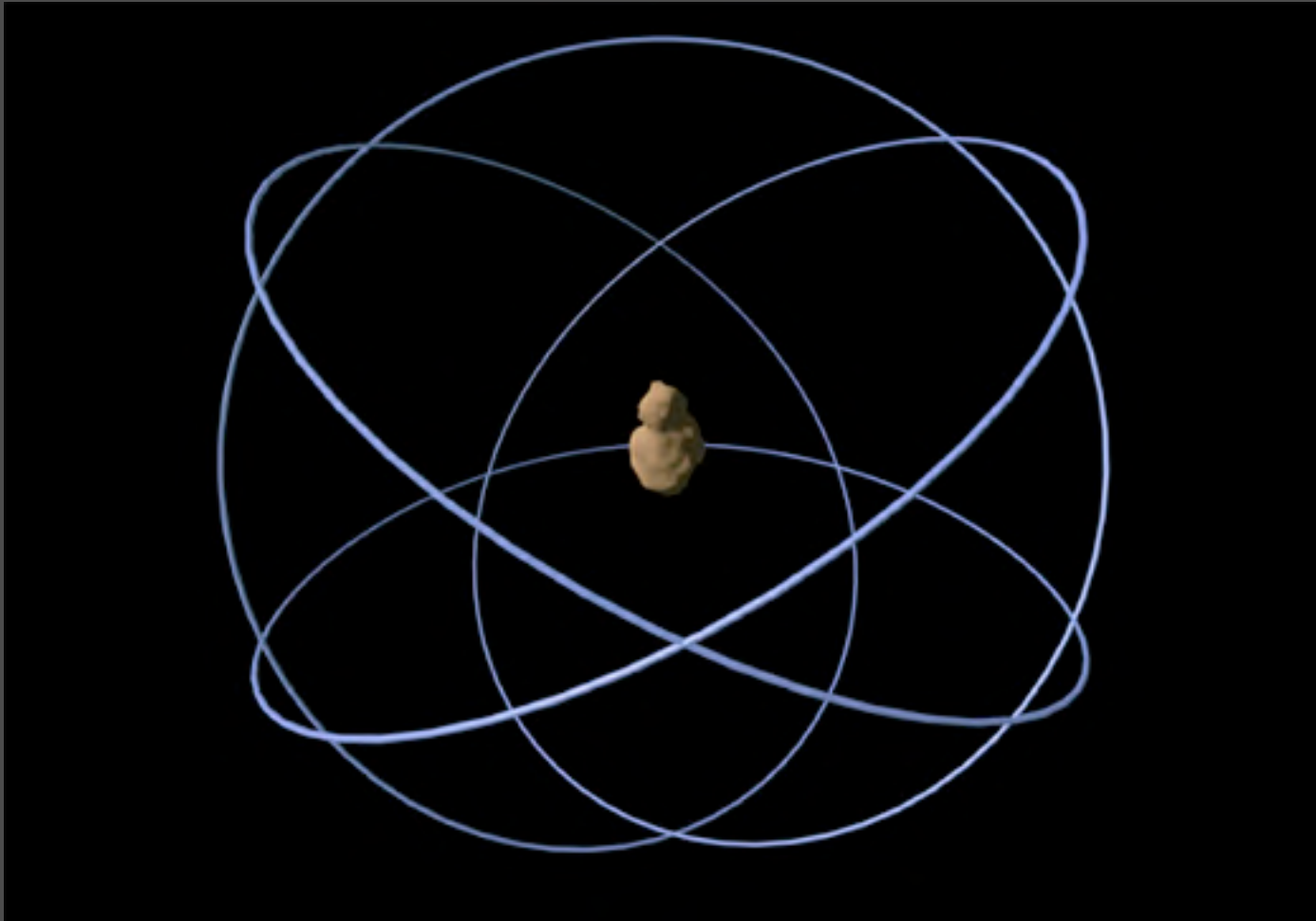
What Happens Next?

- Improve the spin state model with 2012 data.
- Correct the shape model:
 - Radar images from last year allow both higher resolution and correction of errors on the big end.
 - Potentially combine CE2 and radar data.
- Consider implications for internal structure.



Silhouette of old Toutatis shape model from $-z$ direction, with largest errors highlighted.

Thank You!



Repeating orbit in Toutatis-centered reference frame (Scheeres et al.)