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Determining asteroid spin states using radar speckles

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ABSTRACT

Knowing the shapes and spin states of near-Earth asteroids is essential to understanding their dynamical evolution because of the Yarkovsky and YORP effects. Delay-Doppler radar imaging is the most powerful ground-based technique for imaging near-Earth asteroids and can obtain spatial resolution of <10 m, but frequently produces ambiguous pole direction solutions. A radar echo from an asteroid consists of a pattern of speckles caused by the interference of reflections from different parts of the surface. It is possible to determine an asteroid's pole direction by tracking the motion of the radar speckle pattern. Speckle tracking can potentially measure the poles of at least several radar targets each year, rapidly increasing the available sample of NEA pole directions. We observed the near-Earth asteroid 2008 EV5 with the Arecibo planetary radar and the Very Long Baseline Array in December 2008. By tracking the speckles moving from the Pie Town to Los Alamos VLBA stations, we have shown that EV5 rotates retrograde. This is the first speckle detection of a near-Earth asteroid.

1. Introduction

Radar astronomy is a set of techniques for observing planets, comets, moons, and asteroids: transmitting from a ground station, receiving the echo, and resolving target objects in time delay (line-of-sight distance) and Doppler shift (line-of-sight velocity). Radar observations provide estimates of the near-surface bulk density and surface structure, precise trajectory predictions, and information on the target's shape, surface morphology, and rotation state comparable to that obtained by a close spacecraft flyby (Ostro et al., 2002).

The spin states of near-Earth asteroids (NEAs) are of particular interest. Asteroids' spin states are coupled to their orbits and shapes through the Yarkovsky and YORP effects. The Yarkovsky effect refers to the net effect of the radiation pressure produced by an object's thermal emission and is the largest single source of uncertainty in trajectory prediction of <2-km diameter asteroids that have been observed with radar (Ostro and Giorgini, 2004). The direction and magnitude of the Yarkovsky acceleration are determined by the object's surface temperature distribution, which is in turn determined by the orbit, pole direction, size, shape, albedo, and near-surface thermal inertia. Orbital integrations and direct measurements predict Yarkovsky-induced position offsets of millions of kilometers on timescales of decades to centuries when coupled with close planetary encounters (Giorgini et al., 2002, 2008; Chesley et al., 2003). Similarly, the YORP effect changes asteroid spin states on timescales of 10–100 kyr, with the radiation-pressure torque determined by the current orbit, shape, and spin state (Bottke et al., 2006). On timescales of >100 kyr, YORP can drive the fragmentation, orbital evolution, and coalescence of binary objects (Cuk and Burns, 2005; Scheeres, 2007; Walsh et al., 2008; Cuk and Nesvorny, 2010).

Shape reconstruction from delay-Doppler images has provided shape models and pole directions for about 30 asteroids (Benner, 2010). In many cases, the delay-Doppler data permit multiple shapes, often two solutions that are mirror images of each other but with opposite pole directions. This occurs because individual delay-Doppler images are ambiguous. For example, for a spherical object, each point in the northern hemisphere will have the same delay-Doppler position as one in the southern. Without extensive coverage in both sub-radar latitude and longitude (provided by significant sky motion and thorough rotation coverage), and high signal-to-noise ratio, ambiguous solutions result (e.g. Ostro et al., 2002; Busch et al., 2007; Brozovic et al., 2010). We have developed the technique of radar speckle tracking to overcome these ambiguities and provide another way to estimate pole directions.

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2. Radar speckles

On timescales of minutes, the radar echo flux received by an antenna is slowly varying and determined by the target object's size, shape, orientation, radar scattering properties, and distance from Earth. On short timescales (seconds or less), the echo oscillates randomly in brightness: a radar speckle pattern (Green, 1968; Kholin, 1988; Elachi and Van Zyl, 2006; Margot et al., 2007). Each point on the surface of the asteroid reflects the incident radar wave differently and acts as a radiator with random phase. Viewed from the Earth, the radiation from each pair of points will interfere to produce a sinusoidal pattern of bright and dark speckles, as seen in Young's classic double-slit experiment. The points with the largest projected separation will produce the smallest speckles, with angular scale λ/d, where d is the diameter of the target and λ is the radar wavelength. The speckles from all possible pairs of points add together randomly to produce the speckle pattern received at the Earth, where the smallest speckles have length:

$$L_{Speckle} = r\lambda/d \tag{1}$$

for a target a distance r away (Fig. 1).

The speckle pattern is determined by the object's radar scattering properties and shape on all spatial scales larger than a fraction of a wavelength. In principle, sampling the entire pattern would permit a full reconstruction of the shape (Kholin, 1988). That would require an implausibly large number of independent receiving stations (see Supplementary Material 2). In practice, we are limited to measuring the speckles received at a small number of locations, insufficient to do more than measure $L_{Speckle}$. However, there is information in how the speckles change with time. As the asteroid rotates, the distance from the radar to each point on the surface changes, changing their relative phases and rotating the speckles in the same direction as the surface. On longer timescales (typically minutes), the speckles change in pattern as the incidence angle, and hence the radar scattering, at each point on the asteroid's surface changes.

Stations with a separation projected normal to the line of sight (a baseline, Fig. 1) larger than $L_{Speckle}$ will receive series of speckles that are not, in general, correlated with each other (Kholin, 1988). This means that multiple receive stations for plane-of-sky interferometric imaging of radar targets, which several authors have proposed (Supplementary Material 2, Black et al., 2005; Busch et al., 2008), is not possible. However, if two stations are fortuitously aligned in the direction of speckle motion *or* spaced much closer together than the speckle scale, we can still determine the target's sense of rotation. Speckles from prograde-rotating asteroids will move from east to west, and those from retrograde rotators from west to east. Thus the motion of the speckle pattern indicates the sense of rotation.

We determine the direction of speckle motion by cross-correlating the echo power (*not* the complex-valued voltage functions used in interferometry) received at two stations, separated by a baseline of length B, to determine the relative time lag t_{lag} – the difference in arrival time of a speckle between the stations. The sign of t_{lag} indicates the asteroid's sense of rotation. The projected speckle speed $|B/t_{lag}|$ is determined by the asteroid's rotation period P, the latitude θ of the sub-Earth point on the asteroid, and the angle α between the asteroid's spin vector projected on the sky and the baseline (Green, 1968; Kholin, 1992; Margot et al., 2007). Typical speckle velocities for near-Earth asteroids with rotation periods shorter than tens of hours are >1000 km/s during radar tracks (Eq. (2)), so we may ignore the contributions from the Earth's rotation (<0.5 km/s) and the relative motion of the Earth and the target (always <90 km/s, usually <10 km/s):

$$|B/t_{lag}| \approx \frac{2\pi r\cos(\theta)}{P\sin(\alpha)} \tag{2}$$

For very close-approaching (low r) or slowly-rotating (high P) radar targets, Eq. (2) ceases to be a good approximation, and Earth's rotation and the relative motion must be subtracted from the observed velocity to obtain the true speckle speed. For example, 4179 Toutatis has P > 100 h (Hudson and Ostro, 1995), and will have speckle velocity ~130 km/s at r = 0.046 AU during its Earth approach in 2012, as compared to a contribution of 12 km/s from the asteroid–Earth velocity. Given optical lightcurves and/or a detailed series of delay-Doppler radar images and the asteroid's known orbit, P and r are known. The magnitude of t_{lag} therefore corresponds to one dimension of the asteroid's pole direction (the angle α).

Multiple baselines at appropriate separations, different angles, and different times give the asteroid's complete spin vector (Green, 1968), limited by the uncertainties in measuring the different t_{lag} values. The direction of the spin vector (the pole direction) is the direction that gives the appropriate values of α for all the baselines. Similarly, with multiple baselines, P can be estimated in the absence of lightcurve data (although when available, lightcurves can provide much more precise period measurements). At least three baselines are required for a unique measurement of the spin vector by speckle tracking alone. These baselines can be between either the same or different pairs of stations, but must be at different times so that the target has moved and the sub-Earth latitude and projected spin axis have changed.

The maximum cross-correlation amplitude between two stations is determined by the radar echo's strength and the collecting areas and system temperatures of the two receiving antennas, but most importantly by the baseline length projected along the direction of speckle motion. For $B\cos(\alpha) < L_{Speckle}$, where cross-correlation is possible, the relationship between the correlation amplitude and the projected baseline length is very roughly (Kholin, 1992):

$$C = e^{-2(B\cos(\alpha)/L_{Speckle})^2} \tag{3}$$

This very strong dependence on baseline length means that baselines much shorter than the speckle scale are required, unless α happens to be close to 90°.

The cross-correlation as a function of time lag is a continuously varying function, with peaks with width in time approximately equal to the speckle duration $(L_{Speckle})/|B/t_{lag}| = \lambda P/(2\pi d)$. Smaller changes in time lag only partially shift speckles into or out of correlation with each other. Fortunately, if the correlation amplitude is much larger than the noise on it, t_{lag} can be determined to much less than the peak width.The 1-σ uncertainty in t_{lag} is

$$\Delta t_{lag} = \frac{1}{\sqrt{cor\mathrm{SNR}}}\frac{\lambda P}{2\pi d} \tag{4}$$

where $cor\mathrm{SNR} = C\frac{P_{Eff}}{kT_{Eff}}b^{1/2}t_{Int}^{1/2}$

and $P_{Eff} = \frac{P_T G_T \sigma}{(4\pi)^2 r^4}\left(\frac{A_1 A_2}{A_1 + A_2}\right)$

The correlation signal-to-noise ratio (corSNR) is determined by the overall correlation amplitude, the effective echo power (P_{Eff}), the echo bandwidth (b), the integration time (t_{Int}), and the effective temperature of the receivers (here assumed to be the same for both stations). The effective echo power is the product-over-sum of the echo power received at the two stations, and is determined by the transmitter power (P_T) and gain (G_T), the distance to the target and its radar cross-section (σ), and the effective areas of the antennas (A_1 and A_2). The expression for P_{Eff} is the interferometric version of the well-known radar equation (e.g. Ostro et al., 2002).