Icarus 260 (2015) 1–6

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Goldstone radar imaging of near-Earth Asteroid 2003 MS2

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ARTICLE INFO

Article history:
Received 3 March 2015
Revised 30 May 2015
Accepted 2 June 2015
Available online 12 June 2015

Keywords:
Radar observations
Asteroids, rotation
Asteroids, surfaces

ABSTRACT

We report radar observations of near-Earth Asteroid (NEA) 2003 MS2 with Goldstone (8560 MHz, 3.5 cm) on June 28, 29, and July 4, 2003, shortly after the asteroid's discovery. Delay-Doppler images with resolutions as fine as 19 m/pixel reveal an unusually angular object with pronounced facets. The longest sequence of images was obtained on July 4 when the asteroid rotated ~140 deg in 2.7 h. During this interval, bandwidths varied by a factor of ~1.5 and indicate that 2003 MS2 is an elongated object. The rotation and bandwidth variations evident in the radar images are consistent with the 7 h rotation period and the 0.7 magnitude lightcurve amplitude reported by Muinonen et al. (Muinonen, K. et al. [2007]. Spins, shapes, and orbits for near-Earth objects by Nordic NEON. In: Milani, A., Valsecchi, G.B., Vokrouhlický, D. (Eds.), Near Earth Objects, our Celestial Neighbors: Opportunity and Risk. Cambridge University Press, Cambridge, pp. 309–320). If we adopt the 7 h period, then the maximum and minimum bandwidths place lower bounds on the pole-on dimensions of (0.33×0.19) km/cos δ, where δ is the unknown subradar latitude. The radar and photometric observations by Muinonen et al. constrain the pole directions to $(\lambda, \beta) = (20 \pm 20$ deg, 0 ± 40 deg) and $(200 \pm 20$ deg, 0 ± 40 deg). The circular polarization ratio of 0.31 ± 0.02 is comparable to that of 25143 Itokawa, suggesting a similar degree of near-surface roughness at decimeter spatial scales.

1. Introduction

Near-Earth Asteroid 2003 MS2 was discovered on June 25, 2003 at Lowell Observatory by the LONEOS program one week before the asteroid's close encounter at a distance of 0.025 au on July 2. Archive searches later identified two pre-discovery images from March 7 at Apache Point Observatory. The Minor Planet Center classified 2003 MS2 as a "potentially hazardous asteroid" with a semi-major axis of 1.04 au, an eccentricity of 0.13, an orbital inclination of 20.0 deg, and a perihelion of 0.91 au. Its absolute magnitude of 21.1 (MPEC 2003-M50) suggests a diameter within a factor of two of 0.2 km. Immediately after discovery, we identified 2003 MS2 as a strong radar target at Goldstone with an estimated signal-to-noise ratio (SNR) per day in excess of 500.

Muinonen et al. (2007) reported a rotation period of ~7 h using a 5.9 h lightcurve obtained on January 14, 2005 with the 2.56 m Nordic Optical Telescope at La Palma. They obtained a lightcurve amplitude of 0.7 mag that constrained the aspect ratio (intermediate/long axis) to a maximum of 0.67. To date, the spectral class of 2003 MS2 remains unknown.

2. Observations

The planetary radar system at Goldstone utilizes the 70 m DSS-14 antenna that is part of NASA's Deep Space Network. It is fully steerable and operates in the X band at a frequency of 8560 MHz ($\lambda = 3.5$ cm) (Ostro, 1993). Goldstone is equipped with a transmitter that nominally radiates 440 kW. At the time of the 2003 MS2 discovery announcement, Goldstone was already scheduled to observe near-Earth Asteroid (65909) 1998 FH12. Some of the time when both asteroids were visible was used to observe 2003 MS2 as a target of opportunity. Goldstone observations were obtained on June 28, 29, and July 4 and are summarized in Table 1.

In general, a radar experiment consists of transmit and receive cycles equal in duration to the round-trip-time (RTT) to the object. Each transmit-receive cycle is called a "run" and can be analyzed as a sum of some number of statistically independent measurements of the echo power distribution or "looks." We use two modes of radar observations during the course of our experiment: continuous wave (CW) observations and binary phase coded (BPC) ranging and imaging. During CW observations, we transmit a circularly

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http://dx.doi.org/10.1016/j.icarus.2015.06.001
0019-1035/

Table 1
Radar observations.

Date	Time UTC	Setup	Resolution µs	Resolution Hz	RA (deg)	DEC (deg)	Dist. (au)	OSOD	Runs
2003-June-28	10:15:59–10:33:48	CW	–	0.61	181.5	76.3	0.036	7	15
	10:36:39–10:42:01	CW	–	2.4				9	5
	10:54:25–11:04:25	Ranging	10	6.15				9	8
	11:07:48–11:12:18	Ranging	11	5.59				9	4
	11:14:44–11:20:33	Ranging	1	8.20				9	5
2003-June-29	17:55:58–17:59:33	CW	–	0.49	152.0	69.3	0.031	13	4
	18:03:49–18:21:29	Imaging	0.125	1.0				13	16
	18:24:51–18:55:18	Imaging	0.125	0.5				13	29
2003-July-4	18:05:10–18:17:39	CW	–	0.98	118.0	9.3	0.029	17	13
	18:35:06–18:39:45	Ranging	10	6.15				17	5
	18:53:05–18:57:49	Ranging	11	5.59				17	5
	19:04:17–19:20:46	CW	–	0.98				17	17
	19:26:13–19:35:41	CW	–	0.49				19	10
	19:57:54–22:40:02	Imaging	0.125	0.25				19	128

2003 Goldstone radar observations of 2003 MS2. Right ascension (RA), declination (DEC), and geocentric distance are given for each observational setup. OSOD refers to the JPL orbit solution number from the On-Site Orbit Determination software used to update the trajectory estimate. Runs are the number of transmit and receive cycles.

polarized electromagnetic wave of constant amplitude and frequency and receive its reflection from the asteroid in the same sense (SC) and opposite sense (OC) polarizations with respect to the outgoing wave.

The frequency of the reflected wave is dispersed in Doppler frequency due to the asteroid's rotation. The Doppler broadening or bandwidth of the echo is expressed by:

$$B = \frac{4\pi D}{\lambda P}\cos(\delta) \quad (1)$$

where B is the bandwidth of the echo, D is the object's maximum dimension in the plane of sky perpendicular to the radar line of sight, P is the rotational period, λ is the radar wavelength, and δ is the sub-radar latitude.

The BPC mode of observations uses a time-coded waveform that permits the measurement of echo power in both Doppler frequency and time delay. We use BPC waveforms for ranging measurements and for coarse- and high-resolution imaging. The highest resolution delay-Doppler images of 2003 MS2 were obtained with a 0.125 µs time delay setup, corresponding to a range resolution of 18.75 m.

3. Results

The first radar echoes were obtained on June 28, just 3 days after the asteroid's discovery. The initial orbital solution (JPL Horizons solution 7) was determined from 56 optical observations spanning June 25–27, 2003 and provided good pointing constraints (3-σ uncertainty of 1.9 arcsec) for the radar experiment. The initial 3σ Doppler uncertainty was ~4000 Hz, which is large but not unusual for a newly discovered object. The first echo detected indicated a correction to the pre-experiment orbit solution of only −12 Hz (0.009σ). A series of Doppler and ranging corrections to the ephemerides were made throughout the experiment and are summarized in Table 2.

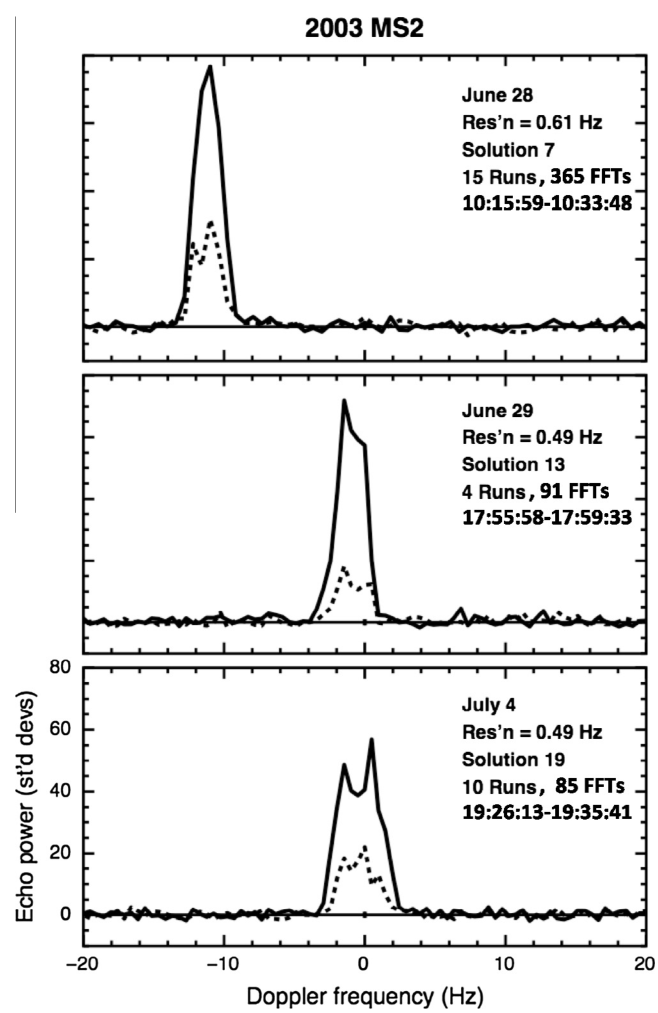

Fig. 1. Goldstone echo power spectra of 2003 MS2. Echo power in standard deviations of the background noise level is plotted as a function of Doppler frequency using the orbital solution indicated in the figure. The spectra are sums of 15, 4, and 10 runs, respectively. Corrections to the ephemerides were used to update the orbit and are listed in Table 2. Each plot is shown at the same scale.

Table 2
Radar astrometry.

Epoch	UTC	Measurement	Sigma	Correction	OSOD
2003-06-28	10:20:00	439594.875	2.0 Hz	−12 Hz	7
2003-06-28	11:00:00	35820178.3	10.0 µs	−162.5 µs	9
2003-06-28	11:20:00	35758682.2	1.0 µs	−161.5 µs	9
2003-06-29	18:00:00	360967.515	1.0 Hz	−1 Hz	13
2003-07-04	18:10:00	−298290.238	2.0 Hz	−10 Hz	17
2003-07-04	18:50:00	29129907.1	10.0 µs	+361.5 µs	17
2003-07-04	22:40:00	29650252.875	1.0 µs	+1.2 µs	19

Radar astrometry for 2003 MS2, which is also posted on the JPL Solar System Dynamics website (http://ssd.jpl.nasa.gov/?radar).