Observations of near-Earth asteroid 2011 UW158 using Quasar VLBI network

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We report results of intercontinental bistatic radar observations of near-Earth Asteroid 2011 UW158 during its close approach to the Earth in July 2015. High power continuous wave signal at a fixed 8.4 GHz frequency was transmitted to the asteroid from the 70 m antenna of the Goldstone Observatory (DSS-14) and then the echo reflected back from the target was received by the 32 m radio telescopes of Quasar VLBI network in Zelenchukskaya and Badary observatories. Analysis of the echo power spectra allowed us to estimate the size and spin period, which agrees with the photometric observations as well as obtain some information about asteroid's shape and near-surface roughness. We also reported 18 Doppler estimates and computed the heliocentric orbit of 2011 UW158.

Introduction

Today, radar astronomy is one of the most effective techniques for determining the physical properties of near-Earth asteroids (NEAs). The size, shape, spin period, surface properties, as well as more accurate orbital elements of NEAs can be obtained using radar observations. In this paper we present the bistatic radar observations and physical properties of near-Earth asteroid 2011 UW158. This asteroid was discovered on 2011 October 25 by Pan-STARRS 1 in Maui, USA. Its spin period was reported to be 0.61 h (Gary, 2016) and absolute magnitude of 20 mag, suggesting a diameter of roughly 450 m. This object made a close approach to the Earth at a distance of 0.0164 AU on 2015 July 19. Such absolute magnitude and approach distance yields sufficient signal-to-noise ratio (SNR) at the 32 m radio telescopes of Quasar VLBI network (Ipatov, 2014).

Intercontinental radar observations of 2011 UW158 were scheduled by the Institute of Applied Astronomy in cooperation with Goldstone Observatory using 70 m antenna (DSS-14) to transmit and 32 m radio telescopes (RT-32) of Quasar VLBI network in Zelenchukskaya and Badary observatories to receive the echoes. Such type of radar observations called bistatic, where the transmitter and receiver are located on different antennas (Zaitsev et al. 1997). Bistatic observations have a number of advantages. First of all, there is no need to switch the antenna between signal transmission and echo receiving. It is also possible to receive the echoes using several antennas in interferometric mode. Bistatic observations allow us to continuously observe rapidly rotating celestial bodies, and in case of interferometric mode to estimate the direction of rotation and to obtain more accurate positional observations.

Observations and data processing

We observed 2011 UW158 from 20:25 to 21:00 UT July 18. During this time the DSS-14 radar transmits a circularly polarized continuous wave (CW) signal at 8560 MHz (3.5 cm). RT-32 radio telescopes in Zelenchukskaya and Badary observatories receive the reflected signal. We used two separate channels to receive echoes in the same (SC) and opposite (OC) circular polarizations as that of the transmitted wave. The received echo was sampled by R1002M Data Acquisition System and recorded by Mark5B (Grenkov et al. 2010). R1002M system converted and sampled the received signal in 0.5 MHz bandwidth. After applying the fast Fourier transform to the echo time series, we obtained CW echo power spectra for one-second intervals with a frequency resolution of 1 Hz. Henceforth, we combined these spectra to choose the time intervals and their SNR taking into account the Doppler frequency as a function of time.

Analysis of spectra

Figures 1 and 2 show weighted sums of all CW spectra at Zelenchukskaya and Badary. These spectra give SNR of about 215 for the OC polarization. Echo power is plotted in standard deviations versus Doppler frequency relative to the estimated frequency of echoes from the asteroid's center of mass. Solid and dashed lines denote echo power in the OC and SC polarizations. Circular polarization of the signal is reversed after reflection from the plane surface and the maximum power of the reflected signal is expected in the OC polarization, though some of the signal, due to secondary reflections, is received with the same polarization. The ratio of SC to OC is a measure of near-surface wavelength-scale roughness (Benner et al., 2008). This circular polarization ratio is often denoted by μ_C. We obtain circular polarization ratios $\mu_C = 0.56 \pm 0.06$ and $\mu_C = 0.37 \pm 0.04$ for Zelenchukskaya and Badary observatories. This ratios are close to the known values $\mu_C = 0.34 \pm 0.25$ for the majority of NEAs, which implies that the near-surface roughness is average at centimeter-to-decimeter spatial scales.

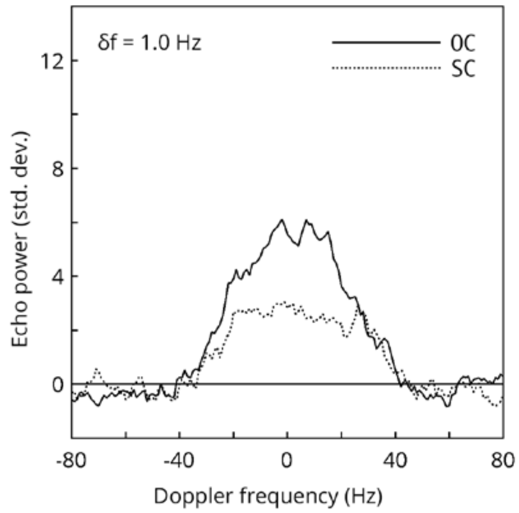

Fig. 1 Opposite- and same-circularization continuous wave echo power spectra obtained at Zelenchukskaya observatory.

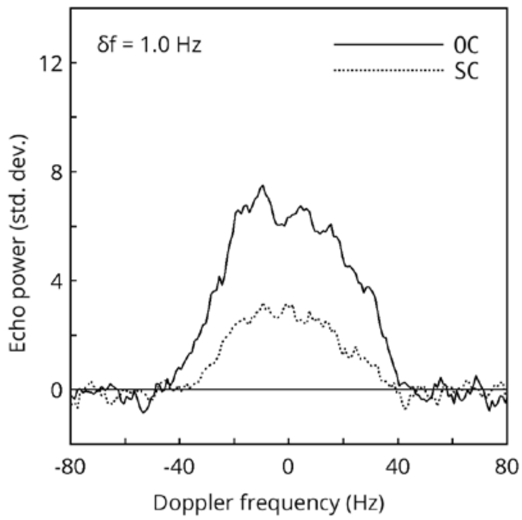

Fig. 2 Opposite- and same-circularization continuous wave echo power spectra obtained at Badary observatory.

Physical model

We obtain a two series of 9 CW echo power spectra for each observatory spanning 30° of rotation phase with the 200 sec integration time per spectrum with SNRs of about 70. These spectrums in both OC and SC polarization are shown in Fig. 5 and Fig. 6 for Badary (Series 1) and Zelenchukskaya (Series 2) observatories respectively. Series 1 and 2 spectra are plotted on identical linear scales of echo power versus Doppler frequency. The power spectrum bandwidth as function of

UTC for both series is given in Fig. 3. Values of bandwidth for Series 1 and 2 are indicated with black and white dots. Solid curve shows the best-fit average function to the bandwidth values indicates a spin period of 36±3 min, which is close to the reported lightcurve period (Gary, 2016).

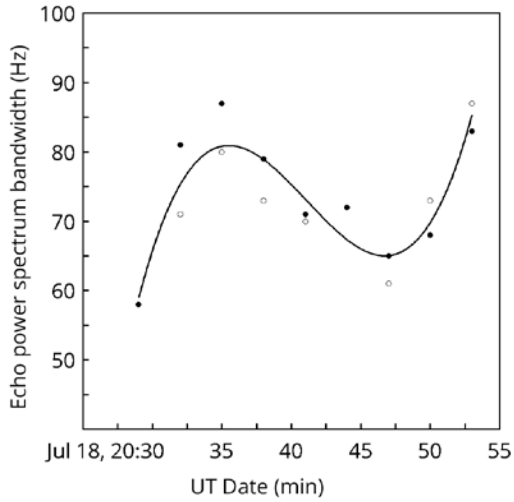

Fig. 3 Echo power spectrum bandwidth as function of UTC.

Taking the geometric relation between echo power spectrum and the shape of rotating asteroid (Ostro et al. 1990) into account, we estimate hull of 2011 UW158 polar silhouette. Knowing the obtained spin period and assuming that the spectrum bandwidth is a continuous vector function of rotation phase we use least squares to fit an 3-harmonic Fourier series to the data vector. The result is a two-dimensional convex hull which is a projection of the asteroid onto its equatorial plane. To convert Hz to meters we assumed that the asteroid-centered declination of the radar is equal to zero. We have considered solutions for each of the observatories separately and a joint solution for both observatories shown in Fig. 4. The solid profile represents the joint solution and the dotted profiles correspond to the observatories individually. The Earth is toward the bottom of the Fig. 4. and the hull rotates clockwise about its center of mass. The figure shows that the body has an elongated shape with dimensions varies from 350 to 520 meters, which is consistent with the radar observations of the Arecibo Observatory, Green Bank and Goldstone (Naidu et al. 2015).

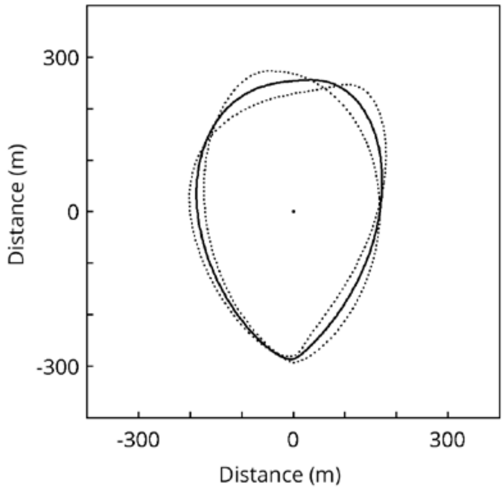

Fig. 4 Convex hull of 2011 UW158 polar silhouette.

Above each spectrum on Fig. 5 and Fig. 6 is a replica of the 2011 UW158 hull (the dotted profiles in Fig. 4), drawn at the same linear scale as the Doppler axis and at the corresponding rotation phase. The UTC midpoint of each rotation phase is indicated. It represents the relation between the orientation of the hull to the line of sight and the shape of the spectrum over time.

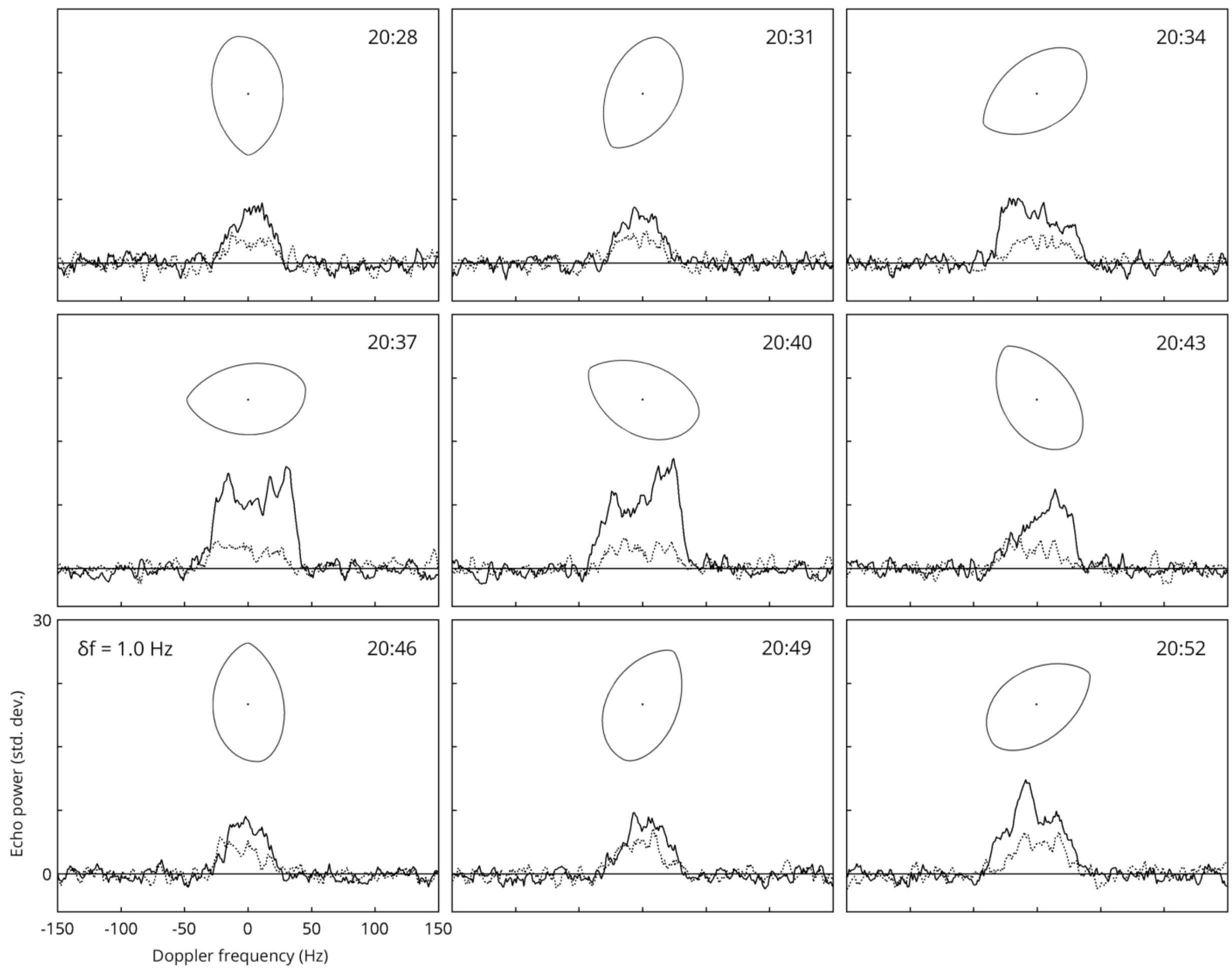

Fig. 5 2011 UW158 echo spectra and hull at 9 rotation phases obtained at Badary observatory.

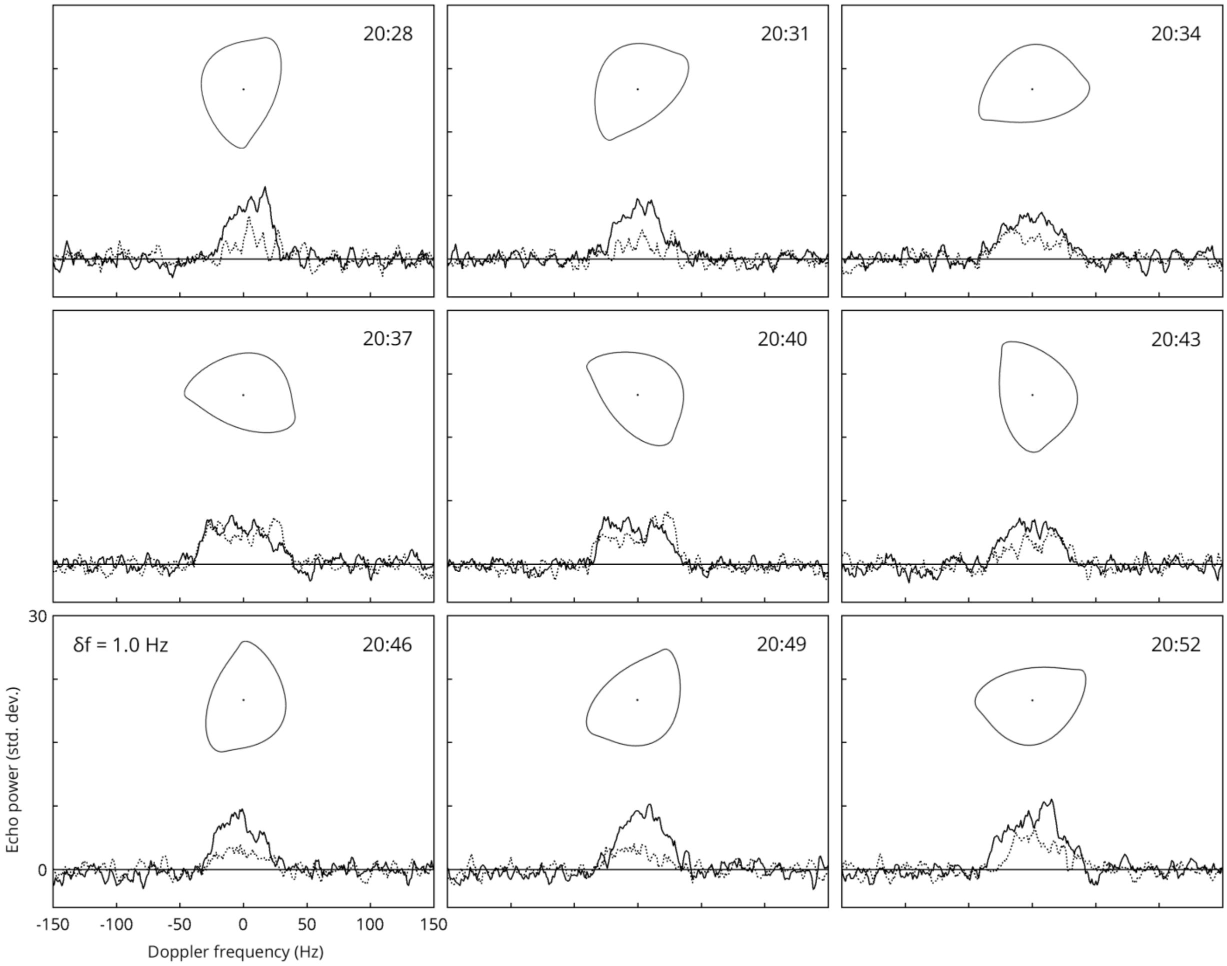

Fig. 6. 2011 UW158 echo spectra and hull at 9 rotation phases obtained at Zelenchukskaya observatory.

Astrometry and orbit

For each spectrum of Series 1 and Series 2 we obtain 18 Doppler frequency estimates in Table 2. To determine the uncertainties of Doppler measurements the orbit of 2011 UW158 was calculated using 921 optical observations, 8 range and 18 our Doppler observations (Bondarenko et al. 2014). The optical observations span October 2011 to November 2015. Table 1 lists the best fit orbital elements and their uncertainties. The Minimum Orbit Intersection Distance with respect to Earth is 0.0026126 AU, making 2011 UW158 a potentially hazardous asteroid.

Table 1 Heliocentric orbital elements of 2011 UW158 at Epoch 27 June 2015 (TDB).

Quantity	Value	1-σ Uncertainty
Mean anomaly (°)	349.644211875983300	2.3×10^{-7}
Argument of perihelion (°)	8.647209242351241	6.0×10^{-7}
Longitude of ascending node (°)	286.272925199741600	3.5×10^{-7}
Inclination (°)	4.649839784639325	1.3×10^{-7}
Eccentricity	0.3751308317245291	7.9×10^{-10}
Mean motion (°/day)	0.4792646070227142	7.6×10^{-10}

The O-C values for Doppler frequency observations listed in Table 2. The RMS error is equal to 4 Hz, which is close to the expected value, based on the accuracy of the described calculations.

Table 2 Doppler estimates of echo.

UTC epoch 2015-08-18	Zelenchukskaya		Badary	
	Doppler frequency (Hz)	O-C (Hz)	Doppler frequency (Hz)	O-C (Hz)
20:28	54903	-11	58479	-8
20:31	54727	-6	58367	-3
20:34	54550	-3	58246	-7
20:37	54373	1	58135	1
20:40	54190	-2	58016	1
20:43	54011	0	57905	9
20:46	53832	2	57783	7
20:49	53643	-6	57654	0
20:52	53463	-6	57525	-7

Summary

The radar echo of signal transmitted from the 70 m antenna of the Goldstone Observatory was successfully detected. Obtained results confirm the possibility and effectiveness of the bistatic radar observations of near-Earth Asteroids using 32 m radio telescopes of Quasar VLBI network as receiving part of a bistatic configuration. It was shown that receiving and processing of the continuous wave echo allows to estimate the value of the Doppler frequency with sufficient accuracy which can be used to obtain the spin period and size of Near-Earth Object as well as improve the accuracy of prediction ephemerides. Following this positive experience we plan to continue bistatic radar experiments for obtaining continuous wave spectra and range-Doppler images in the near future.

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