LATVIAN JOURNAL OF PHYSICS
AND TECHNICAL SCIENCES
2022, N 3

DOI: 10.2478/lpts-2022-0021

RADAR OBSERVATIONS OF OLD CENTAUR ROCKET FROM 1966

Yu. Bondarenko*, D. Marshalov

Institute of Applied Astronomy, Russian Academy of Sciences,
10 Kutuzova Embarkment, St.Petersburg, 191187, RUSSIA
*e-mail: bondarenko@iaaras.ru

We report the results of radar observations of a near-Earth object discovered on 17 September 2020, with the Pan-STARRS 1 telescope at the Haleakala Observatory in Hawaii. Initially, this object was considered an asteroid and even received the standard provisional designation 2020 SO by the Minor Planet Center. However, its Earth-like orbit and low relative velocity suggested that the object may be of artificial origin, being the Centaur rocket booster from the Surveyor 2 mission that was launched to the Moon on 20 September 1966. In the period from November 2020 to March 2021, this object approached the Earth twice within one lunar distance of the Earth. Radar observations were conducted on 30 November in bistatic mode with the 70-m Goldstone Solar System Radar DSS-14 and 32-m radio telescope RT-32 at the Svetloe Observatory, while the object was in the visibility window of two antennas at about 200 thousand km from the Earth. The main goal of the study was to determine the physical properties of this object using radar astronomy to clarify its origin.

Keywords: *Near-Earth objects, radar observations, spacecraft, space debris.*

1. INTRODUCTION

On 17 September 2020, one unusual near-Earth object was discovered by the Pan-STARRS 1 telescope at the Haleakala Observatory on the island of Maui. At first, it was assumed that this is an ordinary asteroid approaching the Earth, so the object received the standard designation 2020 SO by the Minor Planet Center [1]. On 8 November 2020, the object was temporarily captured by the Earth's gravity and made two large eccentric orbits around the Earth–Moon system, leaving Hill's sphere in March 2021. During this interval, the object twice approached the Earth on 1 December

2020 at 0.13 lunar distances (LD) and on 2 February 2021 at 0.58 LD. Figure 1 shows the temporary orbit of 2020 SO around the Earth from September 2020 to May 2021.

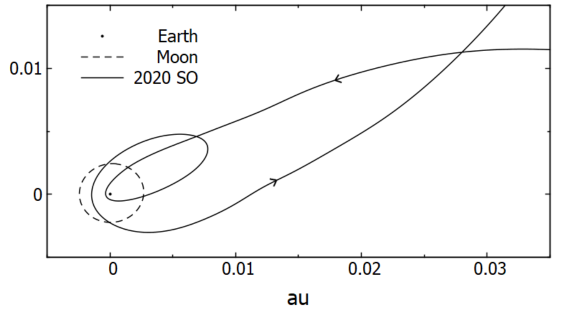

Fig. 1. The orbital trajectory of 2020 SO (solid line) relative to the Earth from September 2020 to May 2021 in projection onto the ecliptic plane. The arrows show the direction of motion, while the dashed line represents the orbit of the Moon.

However, the fact that 2020 SO had a low relative velocity of ~0.6 km/s, and its orbit around the Sun was very similar to that of the Earth, led to doubts that it was an ordinary asteroid. An analysis of additional observations showed a significant effect of solar radiation pressure on the 2020 SO trajectory, confirming its low-density nature, which was not typical of asteroids. The assumption that 2020 SO was a remnant of an old space mission was made by the director of the Center for Near-Earth Object Studies (CNEOS) at NASA's Jet Propulsion Laboratory Paul Chodas [2]. He found that this object came close enough to the Earth in late 1966, coinciding with the launch of the Surveyor 2 mission.

The Surveyor 2 lunar lander was launched from Cape Canaveral on 20 September 1966, on an Atlas-Centaur rocket. Immediately after the launch, Surveyor 2 separated from its Centaur upper-stage rocket booster, heading towards the Moon, and the spent upper-stage ended up into an unknown orbit around the Sun. Figure 2 shows Centaur upper-stage before being assembled with the Atlas rocket and during the launch of NASA's Surveyor 2 moon lander on top of the Atlas-Centaur rocket. It was made of stainless steel and had a cylindrical shape with a height of 9.6 meters and a diameter of 3.05 meters.

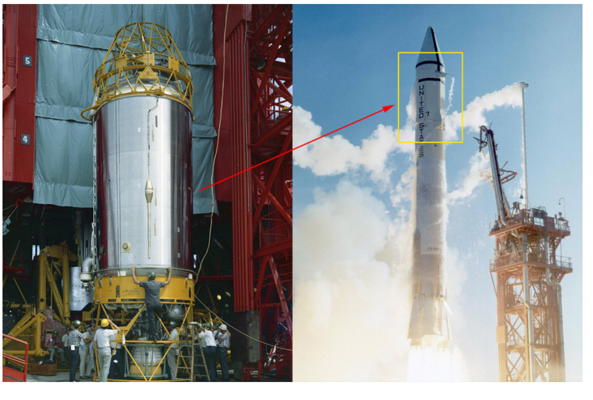

Fig. 2. Centaur upper-stage rocket booster (left) and launch of NASA's Surveyor 2 moon lander a top of Atlas-Centaur rocket (right). Credits: NASA.

Over the past 20 years, at least four human-made objects have received asteroid designations [3]–[6]. The ability to distinguish between natural and artificial objects is important, as countries continue to increase research in space, and more artificial objects are in orbit around the Sun. Today radar astronomy is one of the most precise methods to obtain information about the dynamic and physical properties of near-Earth objects. The size, shape, spin period and surface properties can be obtained with radar observations. The principal goal was to obtain the physical properties of near-Earth object 2020 SO using radar astronomy to understand whether it is a natural object or an old rocket body.

2. RADAR OBSERVATIONS

Radar observations were carried out in cooperation with the Asteroid Radar Research group from the Jet Propulsion Laboratory. Observations involved the 70-meter diameter antenna (DSS-14) of the Goldstone Deep Space Communications Complex and the 32-meter diameter radio telescope (RT-32) at the Svetloe observatory. The parameters of the radio telescopes used in the observations are provided in Table 1. Due to the close approach distances, the observations were carried out in bistatic mode with transmission at DSS-14 and reception at RT-32. We used this mode because the round-trip signal time (RTT) to the target and back was about 1.4 s, which was half the time it took to switch from transmitting to receiving at DSS-14.

Table 1. Radio Telescopes Used in the Observations

UT Date	DSS-14	Svetloe (RT-32)
Geographical coordinates	35.4258° N, 116.8895° W	60.5343° N, 29.7794° E
Diameter, m	70	32
Aperture efficiency	0.64	0.56
Transmitter frequency, MHz / cm	8560 / 3.5	NA
Transmitter power, kW	440	NA
System temperature, °K	18	52

We observed 2020 SO on 30 November, while the object was in the visibility window of two antennas at about 203 thousand km from the Earth near to its closest approach on 1 December. First DSS-14 transmitted 440 kW circularly polarized continuous wave (CW) at a carrier frequency of 8560 MHz (3.5 cm) and then modulated the transmitted carrier with a repeating pseudo-random code using binary phase coding (BPC). RT-32 antenna received echoes simultaneously in the same circular (SC) and opposite circular (OC) polarizations as transmitted, sampled them and recorded. Table 2 lists the observing start and stop times with the corresponding round-trip signal times, length of the pseudo-random code used, duration of each code element (or baud) and the range resolution of corresponding setup.

Table 2. Masterlog of Radar Observations of 2020 SO

UT Date	Start-Stop hh:mm:ss – hh:mm:ss	RTT s	Setup	Code	T_{baud} μs	δr m
30 Nov 2020	04:56:15–05:14:40	1.37	CW	–	–	–
	05:17:52–05:21:47	1.37	BPC	127	10	1500
	05:23:37–05:37:30	1.36	BPC	127	1	150
	05:37:39–05:50:52	1.35	BPC	127	0.125	19
	06:05:00–06:25:45	1.33	BPC	127	0.125	19

We used a monochromatic continuous wave to measure the total power of the echo, its frequency and Doppler broadening. The modulated carrier was used to resolve the target in two dimensions – time-delay (or range) and frequency (or Doppler shift) forming a range-Doppler radar image. The range resolution along the line-of-sight depends on the selected baud duration and the frequency resolution depends on the fast Fourier transform (FFT) length or integration time.

3. DATA PROCESSING RESULTS

We cross-correlated the PBC echo time series with a replica of the transmitted code and applied FFT in each range bin to obtain range-Doppler images (Fig. 3). A series of images in Fig. 3 are arranged in chronological order and correspond to one of four object rotational phases, repeating with a period of about 9.5 sec. The integration time of each image is a half second. Range (distance from the observer) increases down at 19 m per pixel and Doppler frequency increases to the right at 10 Hz per pixel.

The radar images show that the entire object fits within one range bin. This suggests that the selected modulation mode did not allow the object to be resolved in range, since the size of 2020 SO did not exceed 19 meters. However, the frequency resolution allowed us to accurately estimate the dimensions of this object.

If the transmitted signal is reflected from a rotating target, one part of which is approaching the observer, and the other recedes, then the signal is broadened due to the Doppler effect. From the obtained series of images, we estimated the Doppler broadening, which varied from 100±10 Hz to 400±10 Hz during the object's rotation phase. For a spherical object, the echo bandwidth B is given by:

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

where $D(\phi)$ is the diameter (breadth) of the object at rotation phase ϕ; λ is the transmitted wavelength; P is its rotation period, and δ is an angle between the observer line-of-sight and the object's apparent equator. Considering the rotation period of P=9.5 sec and assuming $\delta = 0°$ we obtained that the size of 2020 SO varied from 2.6±0.2 m to 10.6±0.2 m depending on the rotation phase. This indicates that the object has an elongated shape with the ratio of 4:1.

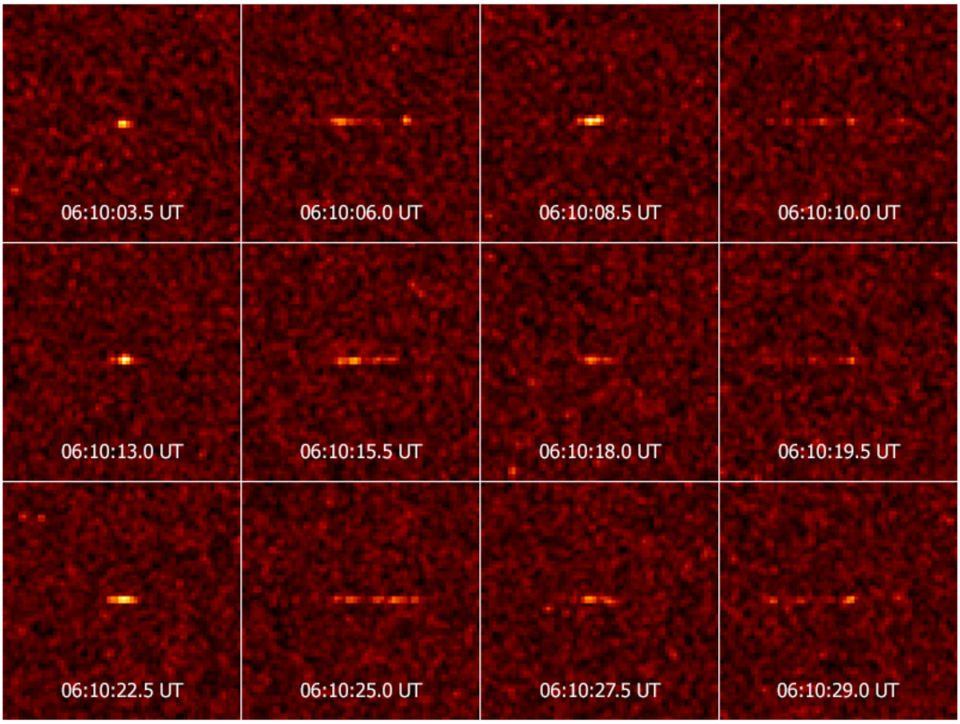

Fig. 3. A series of range-Doppler radar images of near-Earth object 2020 SO on 30 November 2020 showing three complete rotations.

Considering the Doppler frequency as a function of time, we applied FFT to the 10 second of CW echo time series to obtain echo power spectra of 2020 SO (Fig. 4). Echo power is plotted in standard deviations of the background noise versus Doppler frequency. The frequency resolution Δf is 10 Hz. Zero frequency in the figure corresponds to the frequency calculated for the object's center of mass. Solid and dashed lines show OC and SC spectra, respectively.

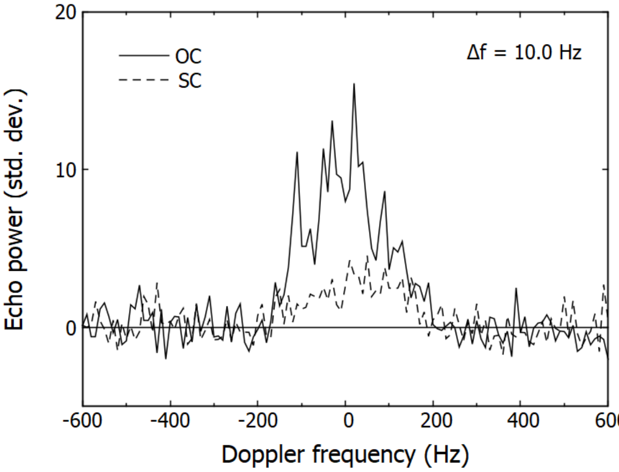

Fig. 4. Continuous wave echo power spectra of 2020 SO obtained on 30 November 2020, from 05:00:02 to 05:00:12 UT.

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 multiple reflections or scattering from a rougher surface is received in the SC polarization. Therefore, a higher SC/OC ratio indicates a greater degree of near-surface wavelength-scale roughness or multiple scattering. We estimated the circular polarization ratio of ~0.31, which suggested that the surface of 2020 SO had irregularities responsible for multiple signal reflections on a centimeter scale.

The signal-to-noise ratio (SNR) of the received echo can be estimated as the ratio of the received echo power P_{rx} to the standard deviation of the receiver noise ΔP_{noise} using the radar equation [7]:

$$SNR = \frac{P_{rx}}{\Delta P_{noise}} \sim \frac{P_{tx} G_{tx} A_{rx} \sigma}{T_{sys} R^4} \sqrt{\Delta\tau / B},$$

where P_{tx} is the transmitted power, G_{tx} is the transmitting antenna gain, A_{rx} is the receiving antenna effective aperture, T_{sys} is the receiver temperature, σ is the radar cross-section of the target, B and $\Delta\tau$ are the bandwidth and integration time of the echo signal.

By integrating the OC continuous wave echo power spectra in Fig. 4 and using data from Table 1, we obtained the radar cross-section of σ=17.6 m^2. The radar cross-section is given by $\sigma=\hat{\sigma}A$, where $\hat{\sigma}$ is the radar albedo and A is the projected area of the target. Albedo indicates the radar reflectivity of a surface compared to a perfectly reflective isotropic scatterer. If 2020 SO is a rotating cylinder that is 10 m long and 3 m in radius, then its OC radar albedo can be estimated at about 95 %, which indicates a high reflectivity of its surface in the radio range, typical of metals.

4. CONCLUSIONS

On 1 December, when 2020 SO made its closest approach to the Earth, several observatories reported the rotation period of the object from photometric observations to be 9.4 seconds [8], [9], and an amplitude of about 2.5 magnitude suggests a 10:1 ratio between the maximum and minimum dimensions of the object, which is in good agreement with radar results.

In late November, a team from the University of Arizona performed spectroscopy observations of 2020 SO using NASA's Infrared Telescope Facility (IRTF). They compared the obtained near-infrared spectrum with the spectra of another old Centaur D rocket, which had been in geostationary orbit from 1971. It turned out that obtained spectra are consistent with each other, thus finally concluding that 2020 SO is also a Centaur rocket booster [10].

As a result of radar observations, the rotation period of 2020 SO was determined to be only 9.5 seconds, which was too fast for known asteroids. Obtained range-Doppler radar images confirm that the object has an elongated shape with a length of about 10 meters and a width of about 3 meters, which corresponds to the size of Centaur upper-stage rocket booster. Obtained circular polarization ratio of ~0.31 can be explained by the presence of surface irregularities at centimeter scales. The radar albedo of 95 % confirms that the surface of 2020 SO has a high reflectivity in the radio range, typical of metals. Our results are consistent with observational data obtained in other ranges of the spectrum. We have demonstrated the ability of radar astronomy to distinguish between natural and artificial near-Earth objects.

2020 SO was finally removed from the Minor Planet Center database on 19 February 2021 due to its artificial origin [11].

ACKNOWLEDGEMENTS

We would like to thank Lance A. M. Benner and the technical staff at Goldstone and Svetloe for the help with the radar observations.

REFERENCES

1. MPEC 2020-S78: 2020 SO. (2020). *Minor Planet Electronic Circular*. Available at https://www.minorplanetcenter.net/mpec/K20/K20S78.html
2. JPL News. (2020). *Earth May Have Captured a 1960s-Era Rocket Booster*. Available at https://www.jpl.nasa.gov/news/earth-may-have-captured-a-1960s-era-rocket-booster
3. Jorgensen, K., Rivkin, A., Binzel, R., Whitely, R., Hergenrother, C., Chodas, P., … & Vilas, F. (2003). Observations of J002E3: Possible Discovery of an Apollo Rocket Body. *Bulletin of the American Astronomical Society*, *35*, 981.
4. MPEC 2007-V69: 2007 VN84. (2007). *Minor Planet Electronic Circular*. Available at https://www.minorplanetcenter.net/mpec/K07/K07V69.html
5. Miles, R. (2011). The Unusual Case of 'Asteroid' 2010 KQ: A Newly Discovered Artificial Object Orbiting the Sun. *Journal of the British Astronomical Association*, *121* (6), 350–354.
6. MPEC 2018-A63: 2018 AV2. (2018). *Minor Planet Electronic Circular*. Available at https://www.minorplanetcenter.net/mpec/K18/K18A63.html
7. Ostro, S.J. (1993). Planetary Radar Astronomy. *Reviews of Modern Physics*, *65*, 1235–1279.
8. Virtual Telescope Project. (2020). *Near-Earth Object 2020 SO: Rotation and Time-Lapse*. Available at https://www.virtualtelescope.eu/2020/12/02/near-earth-object-2020-so-rotation-and-time-lapse-01-dec-2020
9. Great Shefford Observatory. (2020). *Phased Plot: 2020 SO*. Available at https://birtwhistle.org.uk/images/2020_SO_20201201.06_PBirtwhistle.png
10. Reddy, V., Battle, A., Campbell, T., Chodas, P., Conrad, A., Engelhart, D., … Wainscoat, R. (2021). Challenges in Differentiating NEOs and Rocket Bodies: 2020 SO Study. In: *IAA Planetary Defense Conf.*, 26–30 April 2021, Vienna, Austria.
11. MPEC 2021-D62. (2021). *Minor Planet Electronic Circular*. Available at https://www.minorplanetcenter.net/mpec/K21/K21D62.html