RADAR OBSERVATIONS OF NEAR-EARTH ASTEROID 2019 OK. L. F Zambrano-Marin[1,2], E. S. Howell[4], M. Devogèle[1], S. E. Marshall[1], D. Hickson[1], A. K. Virkki[1], F. C. F. Venditti[1],, E. G. Rivera-Valentín[3], P. A. Taylor[3], V. Negron[1], I. Cabrera[1], J. Marrero[1]; [1]Arecibo Observatory, University of Central Florida, HC3 Box 53995, Arecibo, PR 00612, (luisafz@aosa.naic.edu), [2]Universidad de Granada, Escuela Internacional de Posgrado, Facultad de Ciencias, Tecnologías e Ingenierías, c/ Paz 18, 18071 Granada, Spain, [3]Lunar and Planetary Institute, USRA, 3600 Bay Area Blvd., Houston, TX 77058. [4]Lunar and Planetary Laboratory, University of Arizona, Arizona, USA, (ehowell@naic.edu).

Introduction: We report the analysis of radar observations obtained during the close flyby of near-Earth asteroid (NEA) 2019 OK on 2019 July 25. Right before its closest approach (0.00048 au, 0.186 LD) 2019 OK was discovered by citizen scientists Cristovao Jacques, Eduardo Pimentel, and Joao Ribeiro de Barros at Brazil's SONEAR Observatory, on 2019 July 24. Although during its close flyby 2019 OK was not categorized as a potential impactor, motivation for additional optical and radar observations included its short discovery time and extremely close and fast approach - testing the fast response of ground-based observatories.

Radar Observation Results

Continuous Wave. The first data typically collected during an Arecibo S-band (12.6 cm, 2380 MHz) radar observation are the continuous wave (CW) radar echo-power spectra, which are produced when Arecibo transmits a monochromatic, unmodulated circularly polarized wave and receives the echoes in both the opposite circular (OC) and same circular (SC) polarizations as transmitted. The OC radar cross section is the integrated surface reflectivity from direct backscattering [1], whereas the SC radar cross section is representative of the diffuse scattering that takes place due to reflections from rubble, craters, ridges, and other structures on the order of the radar wavelength [2,3]. The measured OC radar cross section of 2019 OK was 6.21 x 10^{-4} km^2 with a calibration uncertainty of 25%.

The ratio of the radar cross section in the SC polarization to that in the OC polarization is termed the circular polarization ratio (μ_C), and serves as an initial estimate of surface roughness [1,4,5]. For 2019 OK, μ_C was 0.339 for the average of each scan and 0.331 for the average of all scans, indicating that 2019 OK could be a C-class or S-class asteroid when compared to values published by [11] and [8].

For the calculation of the bandwidth, we followed the same process and analyzed the data in each individual CW scan (run), first summing over all scans obtaining a bandwidth of 39.3 Hz. Each scan measures the instantaneous bandwidth, and variation over time is expected for an irregular object; the weighted average of the sum of each scan's measurement yields a bandwidth of 38.0 Hz.

The bandwidth depends upon the object's rotation period, diameter and the sub-radar latitude.. For the above bandwidths and a diameter of no less than 150 m and no more than 200 m, we find the period to range from 0.10 hr (D = 150 meters) to 0.13 hr (D = 200 m). This is not surprising, as most objects with D < 300 m tend to rotate at rates above the spin barrier (2.2 hrs [6,7]). There is no indication of a companion body.

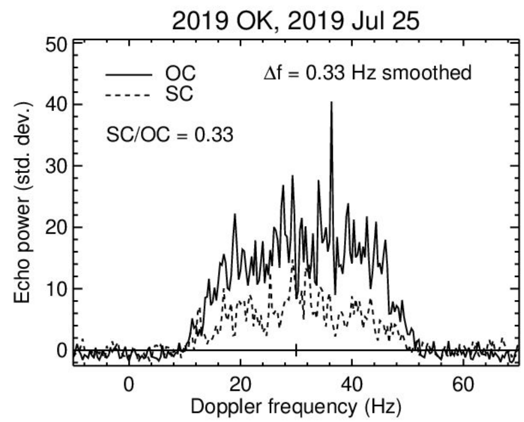

Figure 1: 2019 OK's echo power distribution over Doppler frequency measured on 2019 July 25 when the object was at 3.5 LD, and receding from Earth 16.38 hr after its perigee passage. The observed "spikiness" is due to the self-noise interference, and does not necessarily reflect any physical or shape variations.

Range-Doppler imaging. When the target signal-to-noise ratio (SNR) is high enough, we transmit a binary-coded waveform that is phase modulated; where the cycle of the code is changed pseudorandomly at a given interval of time (i.e., baud). By measuring the distribution of the echo power in time-delay/Doppler frequency space we can map a three dimensional object into a two dimensional image [1,8]. For this observation, phase modulation bandwidths used were 2.5 MHz for a 4 µs baud to 20 MHz for 0.05 µs baud.

For 2019 OK we obtained 21 scans with modulation at a baud of 4 µs at a resolution of 600 m/px in range and 15.27 Hz in Doppler. For 0.5 microseconds phase modulation we obtained 6 scans at a resolution of 75 meters per pixel in delay and 1.9 Hz in Doppler; all signals were contained within one to one and a half bins, setting a lower limit on the diameter of at least 75 meters and an upper limit of 300 meters.

The limited observation duration for 2019 OK left us unable to obtain shape information.

Astrometry. Using the JPL On-Site Orbit Determination software (OSOD) for new ephemeris solution calculation, the three-sigma uncertainties for ephemeris used were calculated during observation. After adding one Doppler and two delay measurements to the orbit solution computation, the cumulative improvement of the orbit uncertainty was 75.3% on pointing, 95.53% for Doppler, and 99.93% for range, during our observation window. Those measurements reduced the orbit uncertainty parameter (U,[9]) from 6 to 4, increasing the encounter predictability window from only 1 to 395 years, which allows us to know its orbit precisely for another century. The next Earth encounter was determined to be in 2093 at 0.052 au.

The expected location of the center bandwidth was 'off' by +31 Hz, which translates to a correction in the line-of-sight velocity of 1.95 m/s for the ephemeris Doppler correction from CW data. The ephemeris delay corrections for observations at 4 and 0.5 µs were -21.81 and -22.59 µs, respectively. These correspond to line-of-sight distance corrections of 3.280 km and -3.386 km.

Summary: Rapid response planetary radar systems are a fundamental asset for post-discovery physical and orbital characterization of near-Earth objects. With only 41 hours from optical discovery to radar characterization by the Planetary Radar Project at Arecibo Observatory, 2019 OK demonstrated the capabilities of this ground-based asset. At the time of observations, the radar astrometry reduced Doppler and delay uncertainties by 99.93% compared to the initial optical-only ephemeris. Although differences between the predicted ephemeris and submitted corrections are small (~3 km in delay), these measurements highlight the precision of this instrument. Depending on the orbital trajectory and object size, these measurements are so accurate they can take objects off the potential impactors lists, such as in the recent case of 2020 NK_1 [10].

From these radar measurements, we can confidently state that 2019 OK's optical geometric albedo must be smaller than 0.05, to match the lower diameter limit of 75 m, and the upper limit of 300 m obtained based on the radar data. 2019 OK must have a very low albedo (p<=0.02) to be bigger than 200 m. Regardless of its small diameter, the rotation of 0.10-0.13 hr makes this small object (D < 0.3 km) part of the small fast rotators.

Acknowledgments: We would like to acknowledge the Arecibo Observatory staff, especially the S-band electronics team and telescope operations., as well as the Arecibo Observatory Management Team. This research was supported by NASA's Solar System Observations Program through Grant No. 80NSSC19K0523 awarded to the University of Central Florida. The Arecibo Observatory is a facility of the National Science Foundation operated under cooperative agreement by the University of Central Florida in alliance with Yang Enterprises, Inc. and Ana G. Mendez University.

References: [1] Black G. J. (2002) *Single-Dish Radio Astronomy: Techniques and Applications, 278,* 271-290. [2] Virkki A. K. and Muinonen K. (2016), *Icarus, 269,* 38-49. [3] Magri C. et. al (2007), *Icarus, 186-1,* 152-177. [4] Ostro S.J. (1993, *Rev. Mod. Phys.*, 65-4, 1235-1279. [5] Benner L. et al. (2008), *Icarus, 198-2,* 294--304. [6] Polishook D. et. al. (2016), *Icarus, 297*, 126-133. [7] Holsapple K.A. (2006), *Icarus, 187,*500–509 [8] Taylor P.A. et.al. (2019), *Planetary & Space Science, 167,* 1–8. [9] Marsden et al., (1978), *Astron. J. 83,* 64-71. [10] Venditti F.C.F et. al. (2020), *AAS/Division for Planetary Sciences Meeting, Vol. 52,* 6. [11] Aponte-Hernandez et. al. (2020) *LXI 51st Lunar and Planetary Science Conference,* 2940.