The Next-Generation Arecibo Telescope

Future Visions of Planetary Radar Projects

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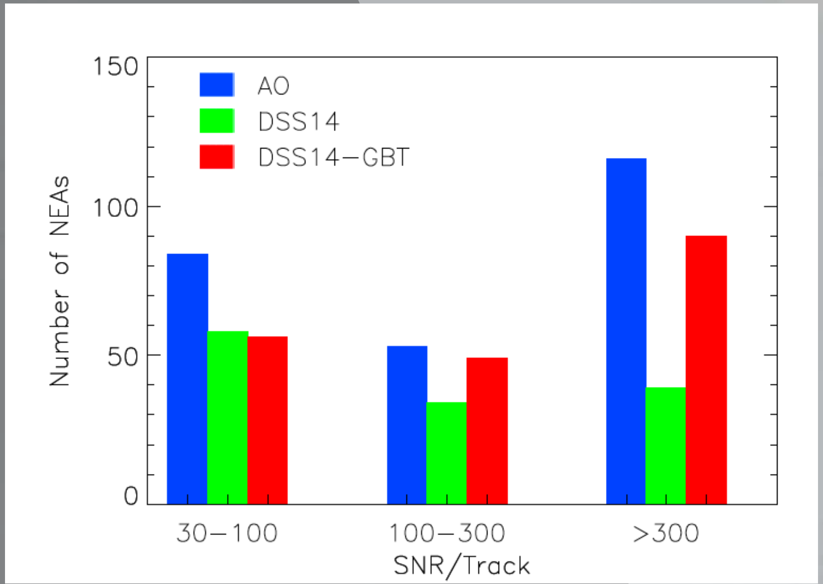
Executive summary

- When the platform of the William E. Gordon telescope collapsed, it destroyed the largest radio telescope of the Western hemisphere
- Although it was 57 years old, it was still the world-leading **radar** telescope benefitting planetary sciences and defense, space and atmospheric sciences, and radio astronomy as a passive radio telescope
- I will present why the Next-Generation Arecibo Telescope (NGAT) is needed for securing the future of planetary radar science

Ricardo Arduengo/AFP

Science motivation – Planetary defense

- The Arecibo Telescope was capable of observing in a few hours:
  - Range with a precision as fine as tens of meters
  - Radial velocity with a precision as fine as millimeters per second (incl. Yarkovsky effect measurements)
  - Size, spin, and morphology
  - Detection of natural satellites (if larger than ~10 m)
- Up to 125 near-Earth asteroids per year were observed in the last decade (Goldstone will be able to go up to ~60-80), with astrometry reported for the majority of them
- Flexible scheduling allowed observations of recently discovered asteroids with one-day notice
- The weather was (almost) never a problem (apart from hurricane lockdowns)



Number of radar-detectable asteroids in the low, medium, and high SNR categories. Source: (Naidu et al. 2016)

Science motivation – Planetary defense

- According to the current estimates, only one third of NEOs with D ≥ 140 m have been identified, and the currently operational NEO surveys such as the Catalina Sky Survey, PanSTARRS, NEOWISE, ZTF, and ATLAS cannot reach the goal of finding them all for at least several decades due to their limited sensitivity and field of regard (Mainzer et al. 2020)
- After the Rubin Observatory and NEOSM start surveying for new asteroids, one radar facility will likely not be able to keep up
- **The new radar system proposed here will allow us to observe more than 90% of the virtual impactors during their discovery apparition**

Recent planetary radar science results for reference

- Removed the 1-km 2020 NK1 from CNEOS sentry list (had a 1:70,000 impact probability for later in the century before the radar observations)
- Observations of 2019 OK that passed the Earth at less than 0.2 lunar distances (an example of a fast response one day after its discovery)
- Shape models of the Double Asteroid Redirection Test mission target Didymos, Bennu, Psyche, and others (Naidu et al. 2020, Nolan et al. 2013, Shepard et al. 2017,…)
- Detailed radar imaging and shape constraints of 99942 Apophis (Brozovic et al. 2018)
- Yarkovsky drift detections of hundreds of asteroids (radar + optical; Greenberg et al. 2020)
- Binaries and three-body systems among the near-Earth asteroids (*e.g.,* Florence observed in 2017 with a detection of two moons)
- Radar polarimetry observations and mapping allow asteroid, lunar, and planetary surface and cometary coma characterization studies using ground-based instruments (Hickson et al. 2020, Virkki et al. 2019, Patterson et al. 2017, Campbell et al. 2015,…)
- Studies of the motions of Venus and Galilean moons (Brozovic et al. 2020, Campbell et al. 2019)

Science motivation – Planetary science

- **Planetary studies:** The Arecibo Legacy Telescope was the only ground-based telescope capable of observing the surface of Titan and high-res mapping of the surfaces of Mercury, Venus, and Mars (Goldstone's DSS-14 was 15 times less sensitive)
  - Physical characterization + Landing site characterization for space missions (e.g., INSIGHT)
  - 1 hr of Arecibo radar data gave the same SNR for Mercury than 14 hrs with DSS-14
- It allowed radar studies of the ~150 largest main-belt asteroids, comets, Galilean Moons, and the rings of Saturn
- **Space mission support:** It helped the Lunar Reconnaissance Orbiter's Mini-RF instrument by radar transmission after its own transmitter failed; e.g., to look for ice in the permanently shadowed polar craters of the Moon (DSS-14 can still help at X band), and would have provided invaluable astrometry for the DART mission
- **Rebuilding could return all of these capabilities and bring in new fields of study, such as space debris tracking and characterization, particularly in the geostationary orbit**

Science motivation – Radio astronomy

- Discovery of pulsars orbiting the black hole in the center of the Milky Way
- Detection of nanohertz gravitational waves using pulsar timing
- Detection of faint radio bursts
- Supermassive black hole binaries and active galactic nuclei
- Discovery and habitability of exoplanets
- Discovery of prebiotic molecules in the interstellar medium
- Technosignatures
- Space weather forecasting with warning capabilities

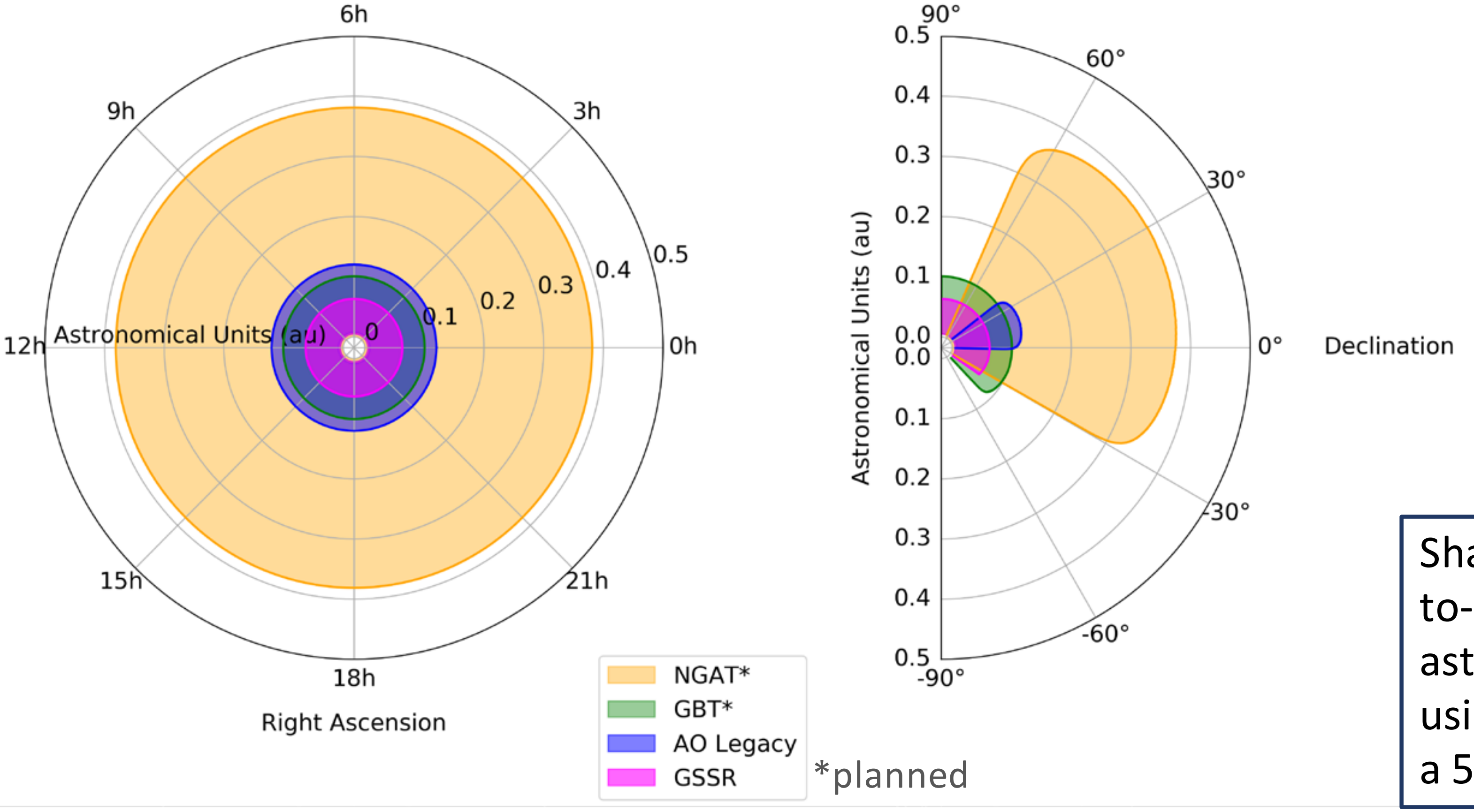
Science motivation – Space and atmospheric sciences

- Climate change and its relation with extreme weather phenomena
- Experiments on climate influence on a local scale
- Studies on ionospheric structure and dynamics by the influence of solar and geomagnetic activity
- Incoherent scatter radar studies on the fine structure of the ionosphere and its responses by the lower atmospheric forcing via vertical coupling
- Better spatial and temporal resolution, making possible the studies of small-scale ionospheric structures, natural or man-made, never possible before.

The Next-Generation Arecibo Telescope

- The goal is to build a world-leading radio+radar telescope, which will have:
  - 2.5 times more sky coverage (zenith angle range up to 48 degrees)
  - more than 4 times the radio signal transmitting power
  - nearly double the sensitivity to receive radio signals when compared with the legacy Arecibo telescope
  - greater frequency coverage and a field of view 500 times larger than the legacy Arecibo telescope to benefit radio astronomy surveys
  - an active system to cancel radio frequency interference
  - easier to maintain and a smaller risk of a single-point failure than the legacy Arecibo telescope

Comparing radar systems



*planned

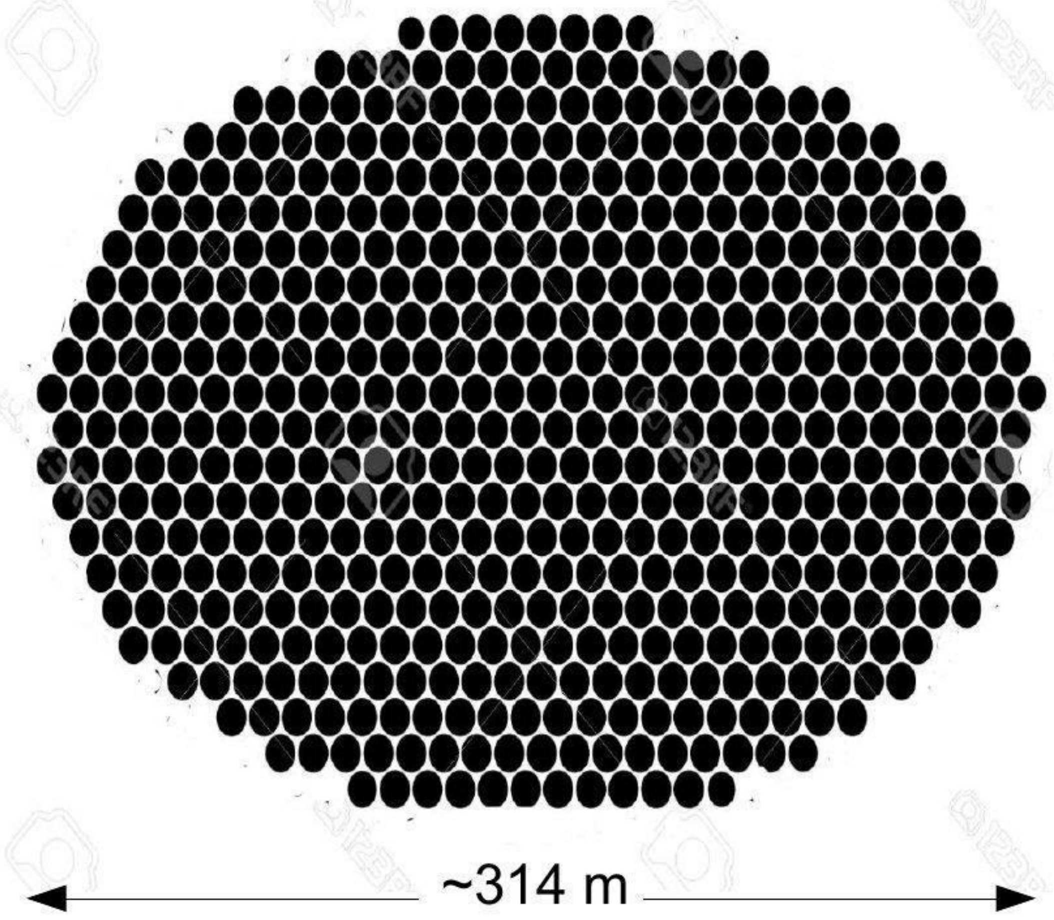
Goals for the new planetary radar system:

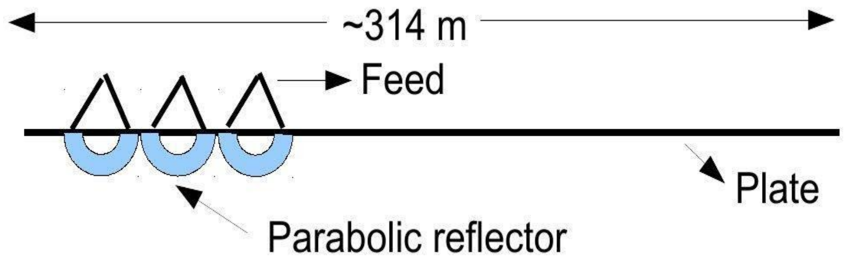
- 2-5 GHz
- 4-8 MW of power
- Zenith angle range 48 degrees

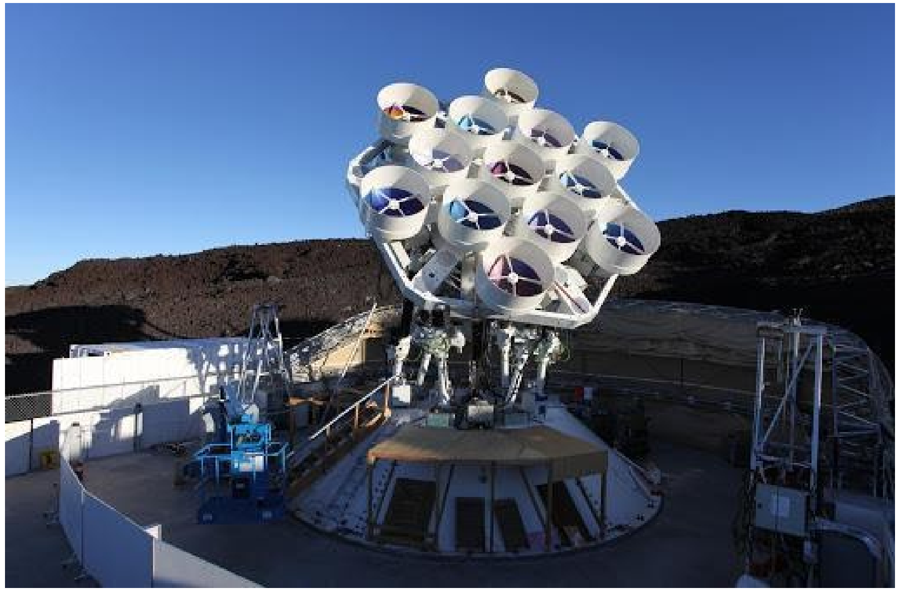
Shaded area boundaries: Signal-to-noise ratio of 6 for a 140-meter asteroid with a spin rate of 2.1 h using different radar systems with a 5-MW 5-GHz radar system

An initial design concept (example)

A compact array of ~1000 9-meter dishes







An initial design concept – Why this?

- Pros:
  - Can fulfill the science goals
  - Allows greater radar transmission power than a single transmitter and a use of commercially more easily available transmitters (we used to have problems with obtaining the 500 kW S-band klystrons)
  - Decreases the risk of a single-point failure of a single radar transmitter (and structurally if not implemented as a single plate)
  - Compact structure allows a coherent transmission
- Cons (to be resolved in further engineering studies):
  - Phasing the transmitted signal has never been tried in this way and size scale before
  - Weight, structural and alignment issues?

Why Arecibo, Puerto Rico?

- Similar to the Arecibo Legacy telescope, Puerto Rico was selected for its geographic location close to the equator: at latitudes further from the equator, more inclination would be needed for the purpose
- The karst sinkhole provided natural support for the single-dish structure, but it also provides radio frequency interference protection
- The radio telescope had massive **socio-economic influence** on Puerto Rico, provided **educational opportunities,** and it was considered a national landmark and **a source of pride and motivation to the locals**; the govt of PR has demonstrated strong support for rebuilding

Recommendations

- New planetary radar instruments are desperately needed: GSSR can do some of the work but relying on just one 60-year-old telescope in a state with a high risk of large earthquakes is **not a long-term solution**. GBT's new radar system will help but also should not be the only available radar facility due to demand issues
- Telescope scheduling of the facility has to be very flexible, if not a fully dedicated NEO radar, because the observing windows for newly discovered NEAs are often short
- An ideal instrument would not depend on weather issues (using 35 GHz in *dry air* doubles T_{sys} and is not useful at all in rain) and should have large enough beam to account for pointing uncertainties in asteroid orbits
- NASA had some plans for a Space Object Array Radar (SOAR) to be used at X and/or Ka bands. The radar capabilities would be comparable, but the timeline and funding for SOAR is unclear. NGAT could either replace SOAR or speed up the technology development it needs and eventually complement it using a lower frequency allowing multiwavelength comparisons.