THE FUTURE OF THE ARECIBO OBSERVATORY: THE NEXT GENERATION ARECIBO TELESCOPE

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Executive Summary

The Arecibo Observatory (AO) hosted the most powerful radar system and the most sensitive radio telescope in the world until the unexpected collapse of the 1000-ft "legacy" AO telescope (LAT) on December 1, 2020. For 57 years, the facility uniquely excelled in three separate, major scientific areas: planetary science, space and atmospheric sciences, and astronomy. Through its final day of operation, the LAT continued to produce new, groundbreaking science, adding to its long history of extraordinary achievements, including a Nobel Prize in Physics. Its collapse has produced a significant void in these scientific fields, which echoed across the extensive, world-wide scientific community. It also produced a deeply-felt cultural, socioeconomic, and educational loss for Puerto Ricans, and a tragic deprivation of opportunity, inspiration, and training for Science, Technology, Engineering, and Mathematics (STEM) students in Puerto Rico and across the U.S., all of whom represent the next generation of America's scientists and engineers.

In the tremendous wake of the LAT, we envision a new, unparalleled facility, one which will push forward the boundaries of the planetary, atmospheric, and radio astronomical sciences for decades to come. A future multidisciplinary facility at the site should enable cutting-edge capabilities for all three of the science branches that form the cornerstones of AO exploration. To facilitate the novel, consequential science goals described in this document, the new facility must meet the capability requirements described below, which ultimately drive our telescope concept design.

Planetary Science: **5 MW of continuous wave transmitting power at 2 - 6 GHz, 1-2 arcmin beamwidth at these frequencies, and increased sky coverage.**

Atmospheric Science: **0° to 45° sky coverage from zenith to observe both parallel and perpendicular directions to the geomagnetic field, 10 MW peak transmitting power at 430 MHz (also at 220 MHz under consideration) and excellent surface brightness sensitivity.**

Astronomical Science: **Excellent sensitivity over 200 MHz to 30 GHz frequency range, increased sky coverage and telescope pointing up to 48° from zenith to observe the Galactic Center.**

In the following sections of this summary, we describe the key scientific objectives and novel capabilities that the new facility will offer to the three science areas and space weather forecasting, a unique new interdisciplinary application.

Planetary Radar Science

A key role of the LAT as the host to the world's most powerful radar system was to characterize the physical and dynamical properties of near-Earth objects (NEOs), in support of NASA's Planetary Defense Coordination Office and in line with national interest and security. In recent years, AO observed hundreds of NEOs as a part of NASA's mandate by the US Congress [George E. Brown, Jr. [ADD: Near-Earth Object Survey] Act (Public Law 109-155 Sec. 321)] to detect, track, catalogue, and characterize 90% of all NEOs larger than 140 meters in size. Post-discovery tracking of NEOs with radar is an unparalleled technique for accurately determining their future trajectory and assessing whether they pose a real impact threat to Earth. These radar measurements secure the position and velocity of NEOs with a precision of tens of meters and millimeters per second, respectively. The LAT radar was also used to map the surfaces of Mercury, Venus, Mars, and the Moon, *supporting human and robotic exploration of the Moon, Mars, and near-Earth asteroids*. A new facility, with a more powerful radar system (5 MW at 2 to 6 GHz) and large sky coverage, will support Planetary Defense, Solar System science, and Space Situational Awareness by providing the following capabilities:

Planetary Defense and Solar System Exploration		
Post-discovery characterization and orbit determination of up to 90% of possible asteroid impactors	Study the surface and sub-surface of ocean worlds around Jupiter, Saturn and other Solar System objects	Observe asteroids in the outer regions of the main-belt and beyond
Space Situational Awareness (SSA) to categorize space debris down to mm-size in LEO, and smaller than one meter in GEO and cislunar space	Support NASA Human Exploration program by characterizing spacecraft landing sites and identifying potential hazards at low cost	Support and extend the science return of missions including NASA's DART, Janus, Europa Clipper, and Dragonfly missions; and ESA's JUICE mission

Radio Astronomy

LAT's unique capabilities enabled several key discoveries in radio astronomy. The loss of the instrument was felt most keenly by pulsar, galactic and extragalactic researchers. The new facility should enable complementary observations with other existing and upcoming radio facilities. For example, the new facility must provide a substantial increase in sensitivity for Very Large Baseline Interferometry, of which the LAT was a contributing instrument whenever higher sensitivity was required. In addition, wider sky coverage, greater collecting area, increased frequency coverage, and a larger field-of-view (FoV) will substantially increase the research potential in a wide range of fields, some of which are highlighted below.

New Frontiers in Radio Astronomy		
Test General Relativity with Galactic Center pulsars	Illuminate underlying physics of pulsars, the emission mechanism, and propagation of radio waves in the interstellar medium	Gain new insights into the causes and physical processes of Fast Radio Bursts
Constrain cosmological theories for Dark Matter in the local Universe	Search for Exoplanets and Earth-like Worlds including studies on habitability and magnetic fields	Measure the distribution of matter to moderate redshifts to constrain Dark Energy
Probe Extreme Astrophysical Regimes with Very Long Baseline Interferometry	Detect the fingerprints of prebiotic molecules in our Galaxy and beyond	Detect and study Gravitational Waves using pulsar timing
Explore the star formation history of the Universe by observing ^{12}CO emission from massive galaxies at redshift > 3	Study the formation of massive stars through ammonia observations	Search for Technosignatures from advanced life forms

Interdisciplinary science - Space Weather Studies

The US "space weather preparedness" bill [116th Congress Public Law 181 (10/21/2020)] emphasizes the importance of space weather research and forecasting efforts. It is important to efficiently track and understand the propagation and dynamics of solar storms to improve space weather forecasting and to provide sufficient warnings for the safety of the technological systems and humans in space. The new capabilities for interplanetary space observations enabled by extended FoV coverage will facilitate solar wind measurements that probe the dynamics of space weather between the Sun and Earth at several points inaccessible to current space missions, with the goal of improving the lead time and advanced warning capabilities for space weather events.

Forecasting Space Weather		
Protect humans in space and ground and space-based technology by tracking solar storms and predicting their arrival at Earth	Study the effects of space weather on Earth's atmosphere and the near-Sun environment	Perform high frequency and spatial resolution observations of solar radio bursts associated with powerful coronal mass ejections

The Concept of a Next Generation Arecibo Telescope

In order to accomplish the overarching scientific goals stated above, we present a concept for the Next Generation Arecibo Telescope (NGAT) - an innovative combination of a compact, phased array of dishes on a steerable plate-like structure. ***Compared to the LAT, the NGAT will provide 500 times wider field of view, 2.3 times larger sky coverage, 3 times more frequency coverage, nearly double the sensitivity in receiving radio astronomy signals, and more than four times greater transmitting power required for both Planetary and Atmospheric investigations.*** We summarize the new capabilities and direct applications of this facility in Table 1. The new telescope will coexist with an extended High Frequency (HF) facility, and a diverse set of radio and optical instrumentation that continue to operate at AO and at the Remote Optical Facility (ROF). The largely new proposed concept for a radio science instrument requires extensive engineering studies that will be the next step to ensure the new facility achieves the driving scientific requirements for the aforementioned science objectives.

Table 1: The significant technical improvements of the proposed concept and their impacts on the science studies.

	New NGAT Capability	Comparison with legacy Arecibo Telescope (LAT)	Enabled/Improved science
Structural and Instrumental Improvements	High sensitivity (Gain > 18 K/Jy)	1.8 - 3.6 times more sensitive from 0.3 to 10 GHz	All fields of science enhanced by increased sensitivity, field of view, and frequency coverage
	Large sky coverage; zenith angle range 0°- 48°	2.3 times coverage increase	All fields of science benefit from increased sky coverage
	Beam Width of each dish[1] ~6 deg. at 0.3 GHz ~3.5 arcmin at 30 GHz	~500 times increase in FoV	All survey observations immensely benefit from increased field of view
	Frequency coverage from ~200 MHz to 30 GHz	A factor of 3x more frequency coverage	Enhanced spectroscopic capabilities, crucial for Space Weather studies
	High survey speed	Added Capability	Pulsar, FRB, and spectroscopic surveys at various frequencies
	Capable of mitigating radio frequency interference (RFI) through phased nulling	Added Capability	All observations benefit from RFI mitigation
	Dual observing modes as a phased array and interferometer	Added Capability	Improves HI intensity mapping, Detecting and monitoring Coronal Mass Ejections
Improved Transmitting Capabilities for Planetary Radar and Atmospheric Sciences	5 MW of continuous wave radar transmitter power at 2 - 6 GHz	A factor of 5× more power; maximum transmitter power was 900 kW at 2.38 MHz	Planetary defense: 90% of the virtual impactors can be tracked New space situational awareness capabilities and space mission support Radar of surfaces and subsurfaces of icy worlds
	10 MW peak transmitter power at 430 MHz (also at 220 MHz under consideration)	A factor of 4× more power	ISR studies: Better spatial and temporal resolution to study small-scale ionospheric structures, natural or human-caused, to unprecedented levels

[1] For the configuration given in Table 2a in the document.

The Necessity to Rebuild in Arecibo, Puerto Rico

We propose that NGAT be located at the Arecibo Observatory, preferably at the location of the LAT to take advantage of the existing infrastructure and the extension of the RFI active cancellation system, an active project in development at the AO location. Several other advantages for the Arecibo site include:

Advantages of Arecibo, Puerto Rico as a site

Scientific

- The proximity to equatorial latitudes is ideal for observing Solar System objects.
- The location uniquely enables ISR studies both parallel and perpendicular to the Earth's magnetic field lines.
- The geographic and geomagnetic location provides unique latitude coverage which is not offered by other facilities in the world.
- It is a strategic location from which to study the effects of the South Atlantic Magnetic Anomaly (SAMA) in the Caribbean upper atmosphere as well as on the trans-ionospheric radio signals.
- The location is critical for studying acoustic and gravity waves generated by extreme weather systems approaching the U.S. and Caribbean.

Socioeconomic

- To serve the minority population of Puerto Rico by inspiring and educating new generations while contributing to the socioeconomics of the island.
- To take advantage of the existing infrastructure, which is on federal property, and has the local government support, significantly offsetting costs.
- To leverage the strategic location in the Caribbean Sea, a region with the largest traffic vessels and for which accurate geopositioning is critical, and the ISR inputs for space weather forecast models are crucial.

Technical

AO is located in a Radio Frequency Interference (RFI) Coordination Zone which minimizes the effects of RFI, protecting the radio bands needed for science operations.

Legacy

To extend and further strengthen the 'long-term legacy' ionospheric data for future climate change investigations.

Contents of the white paper

This white paper was developed in the two months following the collapse of LAT through discussions with hundreds of scientists and engineers around the world who support the construction of a new and more powerful telescope at AO site. Our goal is to acquire vastly enhanced capabilities that will open exciting new possibilities for the future of radio science with direct applications for planetary defense and the protection of US satellites and astronauts. The remainder of this white paper is outlined as follows: the Introduction (Section 1) includes the context for the push to construct NGAT at the AO site. We discuss the Key Science Goals for planetary science, atmospheric science, and astronomy in Section 2 after first defining the new facility's projected capabilities. In Section 3 we discuss the NGAT concept. Following the main text, we discuss alternative concepts considered for the new facility in Appendix A. An important extension of the NGAT's capabilities in space and atmospheric sciences relies on relocating the High Frequency facility within the AO site, and we describe these plans in Appendix B. Appendix C describes additional science objectives the NGAT concept will enable to continue or improve, and finally, we discuss other AO science activities that interlock with NGAT in Appendices D and E. A summary of the contents of Appendix C and D is listed below. The acronyms used in the document are defined in Appendix F.

Additional science studies that are enhanced by new NGAT capabilities

C.1 Additional Planetary Science Studies including
- **Radar of comets**
- **Spectroscopic studies of comets and interstellar visitors**
- **Additional missions for spacecraft support**

C.2 Solar Wind and Space Weather Studies including
- **Tracking Coronal Mass Ejections (CMEs)**
- **Faraday Rotation and the internal magnetic field of CMEs**
- **Solar Radio Studies**
- **Solar Wind and Space Weather Impacts on the AIMI System**
- **In-situ Data Comparison and Cometary Plasma Tail Investigations**

C.3 Pulsars Studies including
- **Wide searches for**
  - new pulsars
  - Binary pulsar studies
- **Pulsar emission mechanism and individual pulses**

C.4 VLBI Studies including
- **General Relativity field tests**
- **Applications to Stellar Physics**
- **Observations of Extragalactic Continuum Polarization**

C.5 Radio Astronomy at high frequencies
- **Probing the nature of early and late-type stellar evolution from the local to the distant Universe**
- **Pulsars and Transients at high frequencies**

C.6 A Comprehensive Snapshot of the Galactic plane

C.7 Further discussion of Near-Field HI 21 cm Line Cosmology

C.8 Detection of Cold Dark Matter and Testing the Standard Model of Particle Physics

C.9 Additional Space and Atmospheric Science studies
- **Ion-Neutral Interactions in the Atmosphere**
- **Sudden Stratospheric Warming Events**
- **Plasmaspheric studies and modeling**
- **Inter-hemispheric flux of particles and its impacts on the Caribbean Sector**
- **Atmosphere-ionosphere-magnetosphere interactions (AIMI)**
- **Vertical Coupling of the Earth's atmospheric layers**
  - Science driver for the NGAT 220MHz Coherent Radar
  - Wave energy in the F-region thermosphere
  - Climatology, morphology and equatorward propagation of MS-TIDs
  - Tropospheric Forcing on the upper atmosphere during Extreme Weather Systems
  - Aerosol and Coupling Processes in the Lower Atmosphere

Other Science Activities at the Arecibo Observatory that interlock with NGAT

D.1 Complementary Space and Atmospheric Science studies
- **Ion Transport processes using Lidars and ISR**
- **Climate Studies and Forcing of the Ionosphere from below using LidarsGeocoronal hydrogen: Secular change and storm response**
- **Horizontal winds as a function of altitude: New wind measurements above the exobase**
- **The AO Remote Optical Facility (ROF) in Culebra Island**
  - High Doppler resolution measurements of vertical motion in the thermosphere
  - Field line diffusion of HF produced electrons as a function of energy
  - First Caribbean Meteor Radar and its application to enhance the atmospheric probing

D.2 12m Telescope for radio astronomy

D.3 e-CALLISTO spectrometer

E. Planetary subsurface studies with 40-60 MHz radar observations.