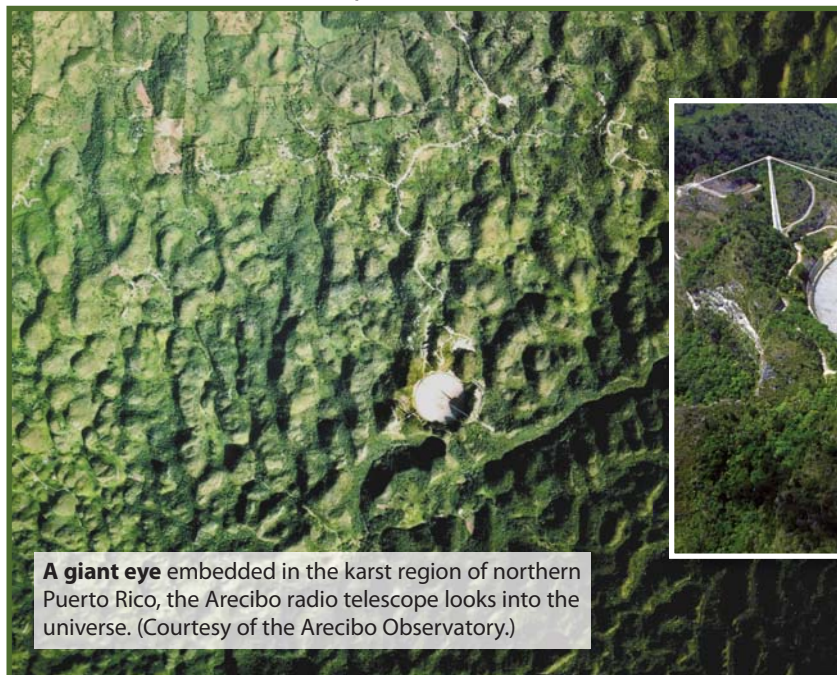


The Arecibo Observatory:

Fifty astronomical years

Daniel R. Altschuler
and Christopher J. Salter



A giant eye embedded in the karst region of northern Puerto Rico, the Arecibo radio telescope looks into the universe. (Courtesy of the Arecibo Observatory.)



Among its many accomplishments, the world's largest single-dish telescope has detailed properties of the ionosphere, spotted the first planets discovered outside our solar system, and helped confirm the general theory of relativity.

Running along the north coast of Puerto Rico, a modern expressway links the bustling capital of San Juan with the town of Arecibo to the west. As you turn south from Arecibo and head into the interior of the island, the roads become progressively narrower and the curves sharper. The route ascends the rugged karst terrain, and images of the modern metropolis rapidly fade into rustic scenes in which dogs and chickens roam freely and ferns, grasses, wild orchids, and the broad shiny leaves of banana plants cover the slopes. This is the Puerto Rico of the past, now rapidly changing.

A few kilometers beyond the small town of Esperanza, you arrive at the gate of a different kind of island—the Arecibo Observatory, an NSF facility operated for its first 48 years by Cornell University and since 1 October 2011 by the research institute SRI International, the Universities Space Research Association, and Universidad Metropolitana, a private university in San Juan.

Suddenly, the rural scenery gives way to an ultramodern technological landscape. For half a century, Arecibo's giant metal eye has operated at the cutting edge of research, gathering feeble radio waves as they arrive from the cosmos, enabling radar experiments on both solar-system bodies and our planet's ionosphere, and contributing a wealth

of information to humankind's astronomical and geophysical knowledge base.

Evolution of a giant

The Arecibo Observatory, incorporated since 1971 into the National Astronomy and Ionosphere Center, grew from an idea of William E. Gordon (shown in figure 1), then a professor of electrical engineering at Cornell University. Gordon's research interest was the ionosphere, the highly rarefied region of Earth's atmosphere above about 80 km. At that altitude, high-energy UV and x-ray photons arriving from the Sun interact with the atmospheric gases and create a plasma of positively charged ions and negatively charged electrons. When a powerful radio wave is transmitted toward the ionosphere, a very small fraction gets scattered back by the electrons. Studying the returned radiation with a technique called incoherent scatter radar (ISR) can provide details of the density and temperature of ionospheric electrons, ionic composition, ionospheric winds, and more.

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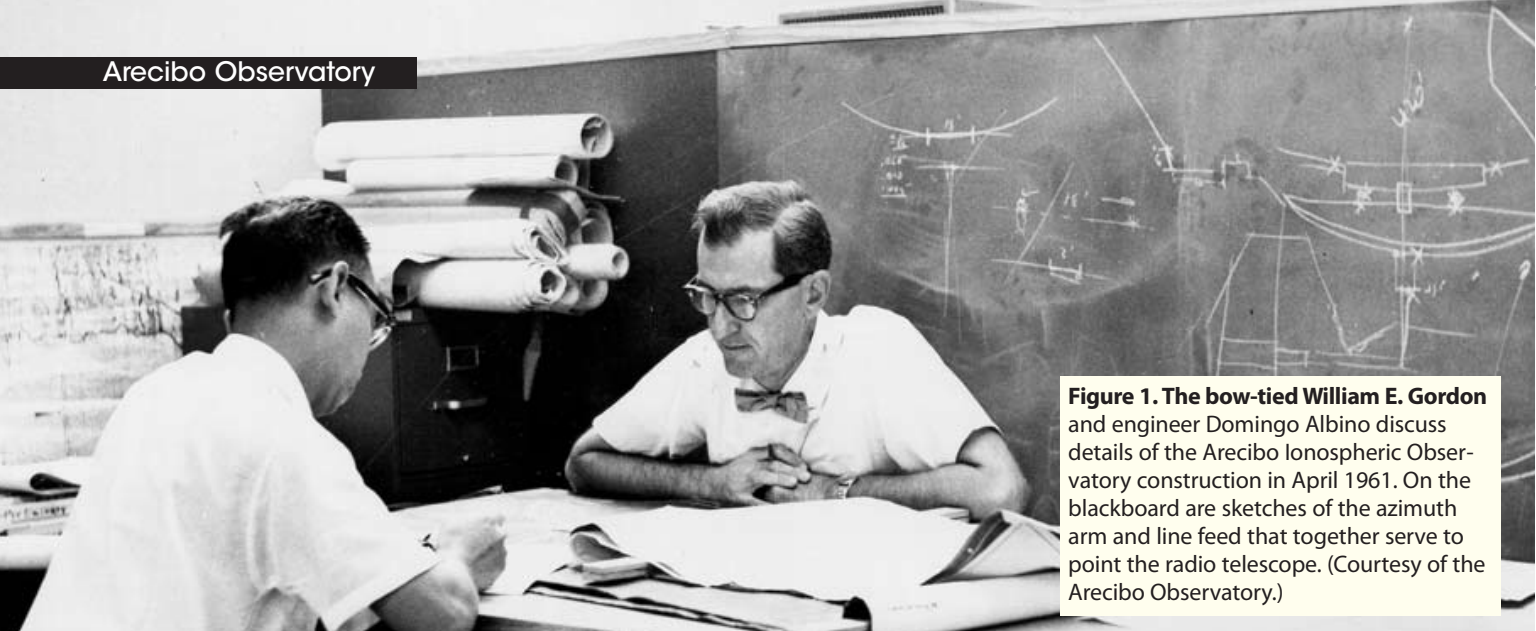


Figure 1. The bow-tied William E. Gordon and engineer Domingo Albino discuss details of the Arecibo Ionospheric Observatory construction in April 1961. On the blackboard are sketches of the azimuth arm and line feed that together serve to point the radio telescope. (Courtesy of the Arecibo Observatory.)

By Gordon's calculations, useful ISR measurements required an antenna with a diameter of about 1000 feet (305 m). To construct it, he and collaborators decided to use a spherical reflector, fixed to the ground but with a movable transmitter–receiver suspended above it.

In the summer of 1960, men and machines funded by the US Department of Defense moved into a sinkhole in the northern karst region of Puerto Rico and began transforming Gordon's vision into reality. Three years and \$9 million later, the Arecibo Ionospheric Observatory was in operation under Gordon's personal direction; it formally opened on 1 November 1963. As planned, the antenna proved capable not only of investigating Earth's ionosphere but also of studying our solar system via radar techniques and researching objects at the farthest reaches of the universe. However, even those who planned and built the telescope could not have foreseen its career of scientific stardom. Indeed, 50 years and two major upgrades later, their brainchild is still Earth's largest single-dish telescope. In 2011 the instrument was christened the William E. Gordon Telescope.

The secret of pointing

Fixed to the ground, the Arecibo reflector cannot move. By contrast, the next-largest radio dishes—the 105-m-diameter Robert C. Byrd Green Bank Telescope in West Virginia and the Effelsberg 100-m telescope in Germany—can move and point to any chosen celestial position.

So, how does Arecibo point? Its secret lies in its being a spherical reflector. Whereas a paraboloid brings all radiation arriving parallel to its principal axis to a point focus on that axis, a spherical reflector focuses along a radius of the sphere; figure 2a illustrates the situation. Originally, so-called line feeds were employed to collect the reflected radiation. Those line feeds, when moved to lie along different radii, enable the telescope to point because, as shown in figure 2b, only radiation from the direction in which the line feed is pointing will be received.

A line feed has hundreds of slots through which radiation enters—or exits, if the antenna is

transmitting. Their placement, and the cross section of the feed along its length, must be precisely controlled if the waves arriving at different heights along the line feed are to arrive in phase at its output flange. Unfortunately, a line feed has an inherent limitation due to dispersion, the dependence of phase velocity on frequency. Because of dispersion, a line feed has a central design frequency at which it works best, and performance deteriorates as the signal frequency moves away from that central value. In other words, a line feed works well only over a limited bandwidth—typically 10–40 MHz for the Arecibo equipment. As a consequence, multi-frequency observations require a number of different line feeds.

Upgrades

Two main characteristics explain why, 50 years on, the Arecibo telescope still ranks among the world's premier instruments. First, it is the world's largest collecting area and will remain so for some time yet. Whereas other telescopes may need to observe a given radio source for several hours to collect sufficient photons for analysis, Arecibo would need just a few minutes. Second, having undergone two major upgrades, today's telescope is very different from the one inaugurated in 1963.

By the late 1960s, astronomers wanted to operate at higher frequencies for both radio astronomy and planetary radar. Arecibo's original 430-MHz (70-cm) radar could study the Moon and the terrestrial planets, Mercury, Venus, and Mars. However, a so-called S-band radar operating at 2380 MHz (12.6 cm) with 0.5 MW power would not only provide much higher resolution on those targets, it would also enable investigations of bodies at the distances of Jupiter and Saturn.

However, if scientists were to use S-band frequencies, the Arecibo telescope would need a new transmitter and receiver, plus a new, more finely crafted reflector. In general, the surface of a reflector requires a precision of 1/20 of the shortest operating wavelength. To operate at 430 MHz, Arecibo's original reflector had to be a perfect sphere to within about 3 cm—quite a feat for a 300-m-diameter dish, but still feasible. To work efficiently at the 12-cm

S-band wavelength required a precision of better than 6 mm, a much greater challenge.

The new reflector has a surface accuracy of 3 mm. The old mesh was replaced by 38 778 shaped aluminum panels, each about 1 m × 2 m; the total weight of aluminum in the reflector is about 350 tons. Small holes in each panel allow 44% of impinging sunlight to pass through. That feature helps vegetation to grow beneath the dish, which controls soil erosion and ensures structural stability. The upgraded telescope was dedicated in November 1974. During the ceremonies, the new radar made a celebrated transmission toward the globular cluster M13: the three-minute Arecibo message encoding information about humankind and our solar system.

The second upgrade was completed in 1997; figure 3 shows the result. A so-called Gregorian dome containing two large subreflectors was suspended from the feed arm. The subreflectors correct the spherical aberration of the primary reflector, bringing radio waves to a point focus at which any of a suite of receivers can be positioned. The observatory's receivers now explore the frequency range from 300 MHz to 10 GHz and essentially cover the complete 1- to 10-GHz window. The new system is achromatic; that is, it eliminates the dispersion problem that necessitated multiple line feeds for observations over a range of frequencies. Nevertheless, a 430-MHz line feed suspended from a movable carriage house still serves for atmospheric radar work.

The 1997 upgrade incorporated several other changes. A 16-m-high stainless steel mesh screen now surrounds the 1-km perimeter of the reflector. The screen shields the receivers from thermal radiation coming from the ground when the antenna is pointing near the telescope's limiting angle of about 20° off the vertical. A new transmitter located within the dome doubled the previously available S-band radar power to 1 MW. Together with the other improvements, that power boost has, in some cases, enhanced radar sensitivity by better than a factor of 10.

A noteworthy upgrade in its own right, the Arecibo L-band Feed Array (ALFA), installed in 2004, provided another significant advance in telescope capability. Previously, telescope usage for surveys had been limited by the relatively small field of view available with traditional single-pixel observations. ALFA, which operates over the 1225- to 1525-MHz band containing the 21-cm hydrogen hyperfine line, is a cluster of seven cooled receivers. A fiber-optic transmission system and back-end signal processors complete a seven-pixel radio camera.

From the Milky Way to deepest space

The 21-cm spectral line from the Milky Way's interstellar neutral hydrogen (HI) was first detected in 1951 at Harvard University's Lyman Laboratory by Edward Purcell and Harold Ewen. That radiation comes from hyperfine transitions in which the spin of a ground-state electron flips—before the transition, electron and proton spins are parallel; afterward, they are antiparallel. That hyperfine line is important because hydrogen is by far the most abundant element in the universe. Its intensity, line

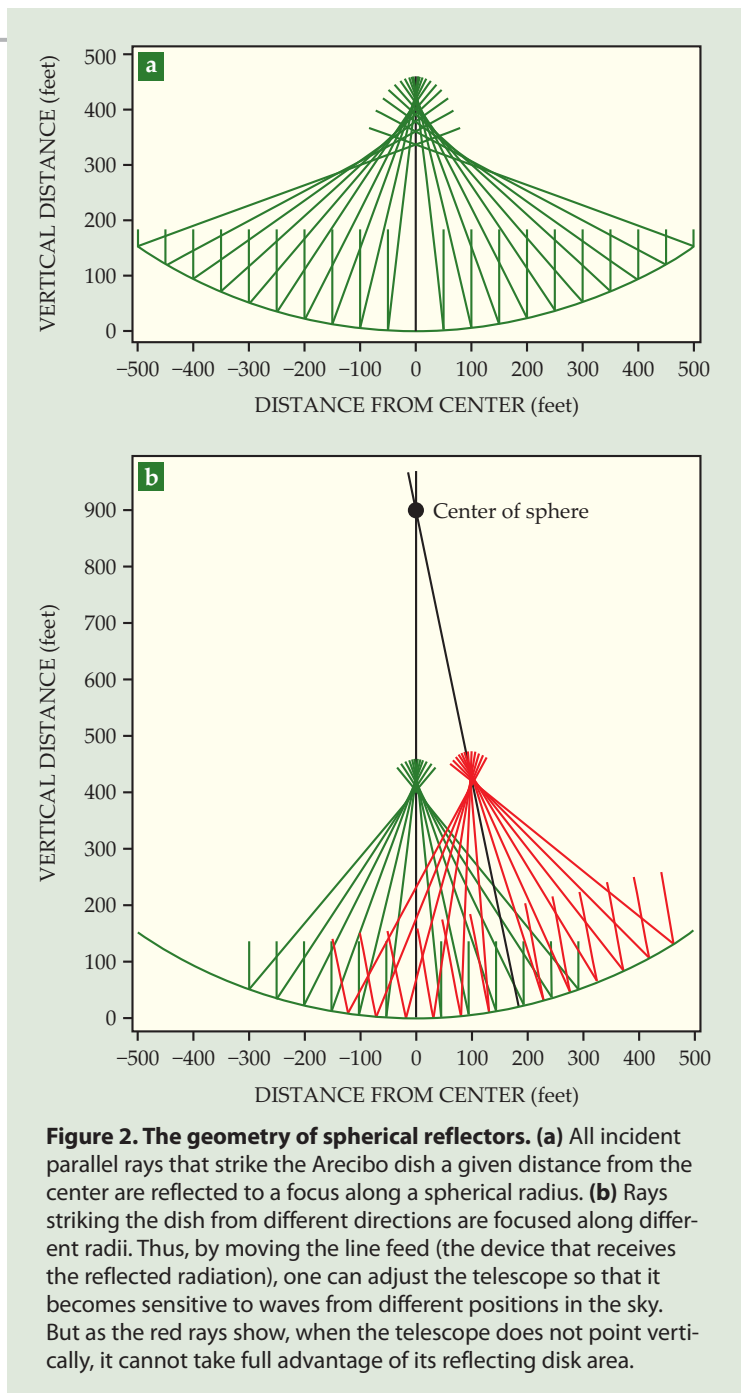


Figure 2. The geometry of spherical reflectors. (a) All incident parallel rays that strike the Arecibo dish a given distance from the center are reflected to a focus along a spherical radius. **(b)** Rays striking the dish from different directions are focused along different radii. Thus, by moving the line feed (the device that receives the reflected radiation), one can adjust the telescope so that it becomes sensitive to waves from different positions in the sky. But as the red rays show, when the telescope does not point vertically, it cannot take full advantage of its reflecting disk area.

profile, and measured frequency provide information about the physical state of the emitting gas and, via the Doppler effect, its velocity along the line of sight. The first detection of HI outside the Milky Way occurred in 1953, when Frank Kerr and James Hindman detected it in the Magellanic Clouds. By 1960 a few tens of galaxies had had their HI signatures measured, but the study of HI in other galaxies was still in its infancy. The weakness of the detected signals necessitated the use of large antennas and sensitive receivers.

After Arecibo's 1974 upgrade, studies of the 21-cm HI line became an important area of the observatory's research. The early work involved detailed examination of individual galaxies and of the distribution of galaxies in space. Continuing



Figure 3. Arecibo today.

In this view of the observatory, the reflector is surrounded by a mesh screen that shields the telescope receivers from radiation emitted by the ground. Pairs of cables attached to each corner of the suspended triangular platform control the height and orientation of the platform as the geodesic Gregorian dome moves. The dome's internal mirrors focus radio waves reflected off the main dish to a point. The visitor center is located at the base of the right-most of the three 80-m-high towers. (Courtesy of the Arecibo Observatory.)

investigations of HI in galaxies have contributed hugely to our understanding of the large-scale structure of the universe, and Arecibo isn't done yet. In particular, three ALFA surveys are looking for galaxies—through their HI contents alone—at latitudes away from the plane of the Milky Way. Those three surveys complement each other. One covers a very wide area and is expected to detect more than 30 000 galaxies when fully analyzed. A second, deeper survey is studying specific galaxy environments—from specific isolated galaxies, through galaxy groups, to rich galaxy clusters. Deepest of all is a survey searching with unprecedented sensitivity for the HI in galaxies located within two tiny areas of sky.

Since the 1997 upgrade, which enabled observations up to 10 GHz, Arecibo has made several full 1- to 10-GHz spectral scans of luminous IR galaxies—objects that are forming stars at the highest known rate. Those scans have provided spectral censuses of molecules in the galaxies and have yielded a number of unexpected detections, including that of the prebiotic molecule methanimine, CH_2NH .

Pulsars

Perhaps Arecibo's most significant discovery to date, which earned Joseph Taylor Jr and Russell Hulse the 1993 Nobel Prize in Physics, was the 1974 discovery of the pulsar PSR B1913+16. Pulsars—rapidly rotating, highly magnetized neutron stars formed during the supernova explosions of massive stars—had been discovered seven years earlier by Jocelyn Bell and Antony Hewish at the University of Cambridge. As a pulsar rotates, opposing beams of radio emission originate from above its magnetic poles. If those beams sweep across Earth, they are

detected as pulses. The Hulse–Taylor pulsar was the first one found to be part of a binary system, its companion being another neutron star. The orbital period of the system is only 7 hours and 45 minutes, roughly 1/1000 the yearlong orbital period of Earth about the Sun. Precise measurements of its pulses' arrival times, which continue at Arecibo to this day, confirmed the general theory of relativity's prediction of gravitational waves.

At the start of the 1990s upgrade, Alex Wolszczan undertook a pulsar search and found the first known extrasolar planetary system, PSR B1257+12, a pulsar orbited by three planets. By now, some 2000 pulsars have been identified, many of them discovered at Arecibo. ALFA is presently searching for new pulsars on the galactic plane and has made 123 new discoveries.

Some pulsars provide unique opportunities for testing theories of gravity and studying the properties of matter at extremely high densities. A fraction of pulsars belong to binary systems, in which orbital dynamics modulate the arrival times of pulses at Earth. The pulsar companions may be another neutron star, a white dwarf, or a main-sequence star. In one binary system, PSR J0737–3039, both components are radio pulsars; potentially, astronomers will discover other double-pulsar systems. The additional clock in those systems—that is, the second set of regular pulsations—permits novel tests of strong-field gravity. A radio pulsar with a black hole companion is perhaps the ultimate goal of pulsar searches; such a system would provide a unique laboratory for studying gravity in the strong-field regime.

Currently, the fastest spinning pulsar rotates 716 times per second. Next in line is PSR 1937+21, discovered by Arecibo in 1982, which spins 641 times per second. The discovery of pulsars that spin

even more rapidly would help discriminate between the various equations of state proposed for neutron-star matter. Precise timing of millisecond pulsars is expected to reveal nanohertz-frequency gravitational waves. The North American Nanohertz Observatory for Gravitational Waves, or NANOGrav, has begun such an undertaking, with the Green Bank and Arecibo telescopes as its indispensable tools.

Synthesizing a vast telescope

Very long baseline interferometry (VLBI) is a variant of astronomical interferometry that uses simultaneous observations of an object made by an array of widely spaced telescopes. The various telescope signals are transferred to a central correlator after being recorded on disk packs or, in so-called eVLBI, after being passed directly over the internet. They are then combined to simulate a virtual telescope whose size equals the maximum separation between the telescopes involved. Thus VLBI achieves an impressive angular resolution, on the order of milliarcseconds or finer.

Given the faintness of many interesting radio sources, VLBI requires large collecting areas in its arrays. For example, the High Sensitivity Array includes the National Radio Astronomy Observatory's Very Long Baseline Array, the Green Bank Telescope, the Effelsberg 100-m telescope, and the Arecibo dish. Arecibo is also a member of the European VLBI Network and from 1997 to 2001 was involved in a new venture: space VLBI. During that time it was part of the terrestrial network supporting *HALCA*, the 8-m-diameter orbiting telescope operated by Japan's VLBI Space Observatory Programme.

As an example of Arecibo's contributions to VLBI (in this case, as part of the European VLBI Network), figure 4 presents a 5-GHz image of the famous jet in the Virgo-cluster galaxy M87. Arecibo provided the resolution needed to resolve the inner jet and the sensitivity needed to reveal the weak complex visible some 0.9 arcseconds from the core. Interestingly, the complex appears to move at superluminal velocities of 4–6.5 c . The apparent relativity-violating speeds are an optical illusion due to the motion of jets, ejected from the active galactic nucleus, that are traveling very near the speed of light at an angle close to the observer's line of sight.

Closer to home

At the public astronomy talks we've given, it seems that no matter the topic, someone in the audience

eventually asks, Are we alone? or Have you detected *them* at Arecibo? Such musings are very old. More than 2000 years ago, Lucretius wrote in his *De rerum natura* (*On the Nature of Things*),

I tell you
Over and over—out beyond our world
There are, elsewhere, other assemblages
Of matter, making other worlds. Oh, ours
Is not the only one in air's embrace.

The search for extraterrestrial intelligence (SETI) is an attempt to settle the issue. If, on another planet, a civilization has developed a communications technology that uses electromagnetic waves, we on Earth might be able to detect a message with a sufficiently sensitive telescope. Radio waves propagate unhindered through the interstellar dust that obscures starlight, so it seems appropriate to search in the RF waveband. Between April and July 1960, an 85-foot-diameter radio telescope in Green Bank, West Virginia, pointed at the stars τ Ceti and ϵ Eridani, some 11 light-years away. That was Project Ozma, the first search for signals from an alien technology, conducted by Frank Drake, who later became director of the Arecibo Observatory.

Until 2004, scientists of the SETI Institute took advantage of Arecibo's unsurpassed sensitivity to study a set of nearby solar-type stars in the hope of detecting an alien signal. Contrary to what many believe, no contact was made. Today several million people participate globally in the SETI@home program, in which recent Arecibo data are analyzed by home computers. The idea of a globally distributed computer network has been adopted for other large computing tasks such as molecular folding studies, climate simulations, and pulsar searches.

In our own solar system, radar had detected feeble echoes from the Moon as early as 1946. However, the planets remained elusive targets. In 1961 the NASA Jet Propulsion Laboratory's Goldstone radar obtained radio echoes from Venus. It used two 26-m antennas, one transmitting with 10-kW power—modest by today's standards—and the other receiving the echo. The Goldstone radar work paved the way for a greatly improved value of the astronomical unit, the average distance between Earth and the Sun—a quantity of critical importance to space exploration.

In April 1964, shortly after the Arecibo telescope's inauguration, Gordon Pettengill's team used it to determine that the rotation rate of Mercury was not the previously believed 88 days but instead only

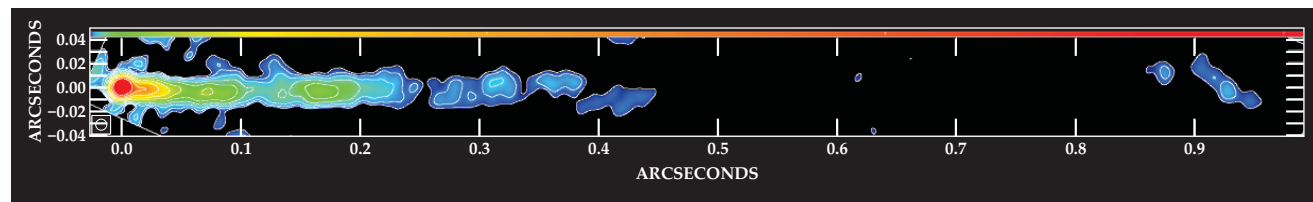


Figure 4. The inner region of the Virgo-cluster elliptical galaxy M87. Arecibo was an integral part of the European VLBI Network that generated the image. The nucleus of M87 lies at the far left; due to an optical illusion, the feature 0.9 arcseconds (260 light-years) to the right appears to move faster than the speed of light. Colors represent the intensity of emitted radiation—red regions are brightest; blue, faintest. (Courtesy of Marcello Giroletti.)

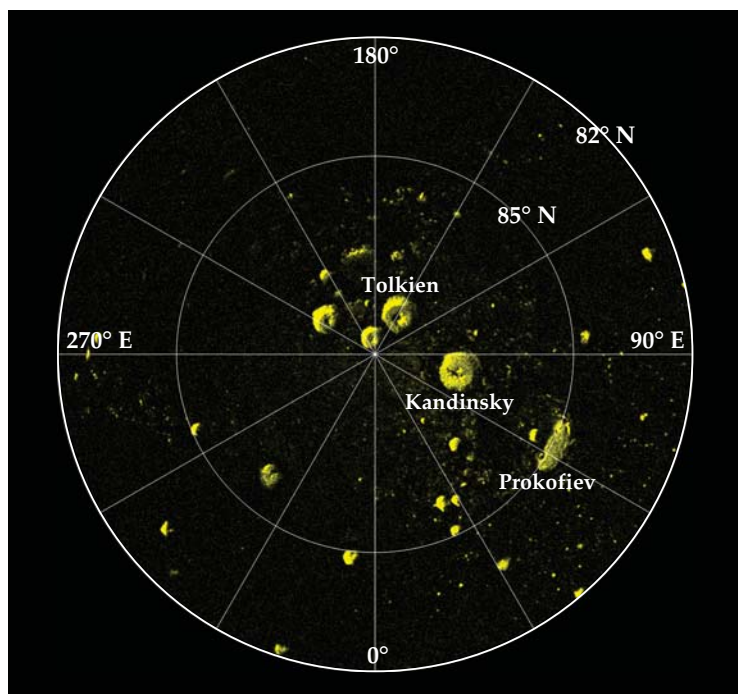


Figure 5. Deposits of volatile compounds lie on the shadowed floors of impact craters at the poles of Mercury. Because their radar scattering properties are similar to those of icy surfaces, the deposits are thought to be water ice. The discovery and imaging of such volatiles was a major contribution of the Arecibo Observatory to planetary astronomy. The figure shows the north polar region of Mercury with a resolution of 1.5 km. The donut shape of the deposits close to the pole is due to central peaks in the craters. Following the convention established by the International Astronomical Union for naming features on the innermost world, the names of craters on Mercury honor deceased writers, artists, and musicians. (Courtesy of John Harmon.)

59 days. Another surprising discovery concerning Mercury came in the late 1990s, when John Harmon found water-ice deposits at the bottoms of the planet's polar craters, where sunlight never reaches (see figure 5).

Over the years, the terrestrial planets, some moons of Jupiter and Saturn, Saturn's rings, and some comets have yielded their secrets to the Arecibo radar. So have a rapidly growing number of asteroids, especially the so-called near-Earth asteroids (NEAs) that come relatively close to our planet. To date, more than 300 NEAs, some as small as 50 m across, have been studied by the Arecibo radar with resolutions as fine as a few meters. The radar can obtain distances with a precision of 10 m and speeds accurate to 1 mm/s. The NEAs are of interest not only because of their potential to smash into us but also because the details of their structures hold clues to the origin and evolution of the solar system. About 15% of them are binary systems, consisting of two objects whose orbits about their center of mass allow accurate determination of their masses and densities. In 2008 Arecibo discovered a triple system, asteroid 2001 SN263. The Arecibo measurements yielded 75-m-resolution images of the 3-km-diameter asteroid, whose two moons are about 1.1 km and 400 m across. At the time, the triplet was 11 million kilometers away; imaging it with Arecibo's 75-m resolution was analogous to using a camera in New York to photograph a person in Los Angeles with 3-cm resolution.

Education and outreach

To the general public, Arecibo is best known from stories—false ones, to be sure—of how the observatory regularly communicates with “them,” or from its extensive exposure in popular media. The observatory had a role in the major films *GoldenEye* and *Contact* and it placed first among the Learning

Channel's “The Ultimate Ten Biggest Structures,” where it beat out aircraft carriers, oil rigs, and the Hong Kong airport.

The 1997 inauguration of the Angel Ramos Foundation Visitor Center greatly enhanced the observatory's role in public outreach and education. Arecibo's visitor center is the only science museum serving Puerto Rico's population and its public and private schools, and it is setting an example for research centers nationwide. Pride in the observatory and an effective fundraising campaign inspired Puerto Rican organizations to contribute the funds needed for construction of the center. Particularly important was the contribution of the Angel Ramos Foundation, a philanthropic organization dedicated to improving educational, cultural, and civic conditions in Puerto Rico. NSF funded the exhibits.

Prior to 1997 about 25 000 visitors came to the observatory annually to view the telescope and listen to a rudimentary 10-minute audiotape. With the visitor center, that number has increased to about 100 000 per year; about one-third are students. Visitors encounter a modern facility with professionally prepared exhibits on physics, aeronomy, and astronomy, along with outdoor exhibits such as a solar-system model built to scale. An observation platform provides a unique view of the giant dish. Well over a million people have visited the center since its opening, and successful science-teacher workshops and high school research experiences have formed part of its educational activities.

A healthy future

Arecibo's 305-m eye has peered near and far for 50 years, contributing significantly to science. In parallel, its educational programs are contributing much to an interested public. Looking to the future, the observatory still has much to offer. This marvel of human inventiveness stands as a symbol of what humanity is, or should be, all about. Its three tall towers point skyward like the spires of a modern cathedral pointing to the heavens. It symbolizes a great human endeavor: our quest to understand the universe, which took off 400 years ago when Galileo Galilei first pointed his elementary optical telescope toward the sky.

The Arecibo telescope has had an important impact on large-telescope design. It is said that imitation is the sincerest form of flattery. The compliment was offered during 1975–85, when the 54-m-diameter spherical-reflector Radio-Optical Telescope was constructed in Armenia to enable work at millimeter wavelengths. Even today, the Arecibo model is serving as the basis for a new telescope, the Five Hundred Meter Aperture Spherical Telescope. Currently under construction in Guizhou Province, China, it should be completed in 2016. Its active surface will have a diameter of 500 m, with 300 m illuminated at any given time. It should operate at frequencies up to about 3 GHz and will have a slightly higher resolution than Arecibo for the most commonly used frequencies.

Arecibo itself continues to offer new and improved instrumentation to its user community. Within the past 12 months, it has upgraded its VLBI equipment to allow data recording at 2 Gbit/s. One exciting VLBI development has been Arecibo's collaboration with the Russian-led RadioAstron mission, whose 10-m antenna is in orbit. Recently, correlation of Arecibo data for the quasar B0235+164 with 5-GHz RadioAstron data taken 18 Earth diameters away produced a detection with a good signal-to-noise ratio and a resolution of about 55 microarcseconds.

The astronomical community can now take advantage of a new broadband pulsar recorder, PUPPI. For observers of both pulsars and HI, a next-generation L-band receiver array (AO40) is being developed to replace ALFA. Whereas ALFA observes 7 celestial positions simultaneously, the planned device will observe 40 and will open up remarkable possibilities for new surveys. A first cryogenically-cooled prototype with 19 reception elements was tested on the telescope this past July in a collaboration of Arecibo, Brigham Young University, and Cornell University.

Being astronomers, the two of us have concentrated almost totally on astronomical aspects of the Arecibo Observatory in this article. Sadly, we have hardly mentioned Arecibo's remarkable work in atmospheric and ionospheric physics during the past 50 years.¹ One aspect of that work has been ionospheric heating, in which the telescope transmits intense, low-frequency (less than 10 MHz) radio waves to the ionosphere, where they accelerate electrons. The resulting collisional heating generates plasma waves and other phenomena that can be studied with the 305-m dish via incoherent scatter radar. A new ionospheric heater is currently being installed on the main telescope and should commence operations soon.

A 2006 headline in the journal *Nature* declared that Arecibo might be “no longer dish of the day”; but then it never was! It has always been something of a gourmet dish, and definitely something very special.

Reference

1. For an excellent history of geophysical radar at the Arecibo Observatory, see J. D. Mathews, *Hist. Geo Space Sci.* 4, 19 (2013). ■

ANDREW GEMANT AWARD

CALL FOR NOMINATIONS

The Andrew Gemant Award, made possible by a bequest of Andrew Gemant to the American Institute of Physics, recognizes the accomplishments of a person who has made significant contributions to the understanding of the relationship of physics to its surrounding culture and to the communication of that understanding. The Selection Committee invites nominees for the 2014 award.

Criteria

The awardee is chosen based on contributions in one or more of the following areas:

- Creative work in the arts and humanities that derives from a deep knowledge of and love for physics
- The interpretation of physics to the public through such means as mass media presentation or public lectures
- The enlightenment of physicists and the public regarding the history of physics or other cultural aspects of physics
- Clear communication of physics to students who are learning physics as part of their general education

Nature of the Award

The awardee will be invited to deliver a public lecture in a suitable forum; the awardee will receive a cash award of \$5,000 and will also be asked to designate an academic institution to receive a grant of \$3,000 to further the public communication of physics.

Applications should consist of a cover letter from the nominator, a copy of the CV of the nominee, and any supporting letters. The nomination deadline is 31 January 2014.

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