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The National Astronomy and Ionosphere Center's (NAIC) Arecibo Observatory in Puerto Rico

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Abstract. This paper reviews the history of the Arecibo Observatory, its genesis, construction, and the two upgrades through which the remarkable 305-m telescope continues to contribute significant results in many areas of astronomy and atmospheric physics.

1. Introduction

The Arecibo Observatory is part of the National Astronomy and Ionosphere Center (NAIC), a national research center operated by Cornell University under a cooperative agreement with the National Science Foundation (NSF). The Observatory operates on a continuous basis, 24 hours a day every day, providing observing time, electronic, computer, travel and logistic support to visiting scientists. The Observatory is located on the Caribbean island of Puerto Rico, about 10 km south of the town of Arecibo, which is located on the north coast of the island (Figure 1).

All research results are published in the scientific literature which is publicly available. As the site of the world's largest single-dish radio telescope, the Observatory is recognized as one of the most important national centers for research in radio astronomy, planetary studies (via radar and passive observation) and space and atmospheric science. Use of the Arecibo Observatory is available on an equal, competitive basis to scientists from throughout the world. Observing time is granted on the basis of the most promising research as ascertained by a panel of independent referees who review all proposals sent to the Observatory by interested scientists.

In addition, the Observatory hosts an Optical Laboratory with a variety of instrumentation used for the passive study of terrestrial airglow. A lidar (Light Detection and Ranging) facility is used to measure the neutral winds, composition, and temperature of the middle atmosphere. This instrumentation complements the incoherent scatter radar used to study the Earth's ionosphere, giving Arecibo a unique capability for aeronomic research.

The Observatory had its origins in an idea of Professor William E. Gordon, then of Cornell University, who was interested in the study of the Ionosphere. During the fifties, Gordon's research led him to the idea of radar back scatter studies of the ionosphere. His persistence culminated in the construction of the Arecibo Observatory, which began in the Summer of 1960. Three years later,

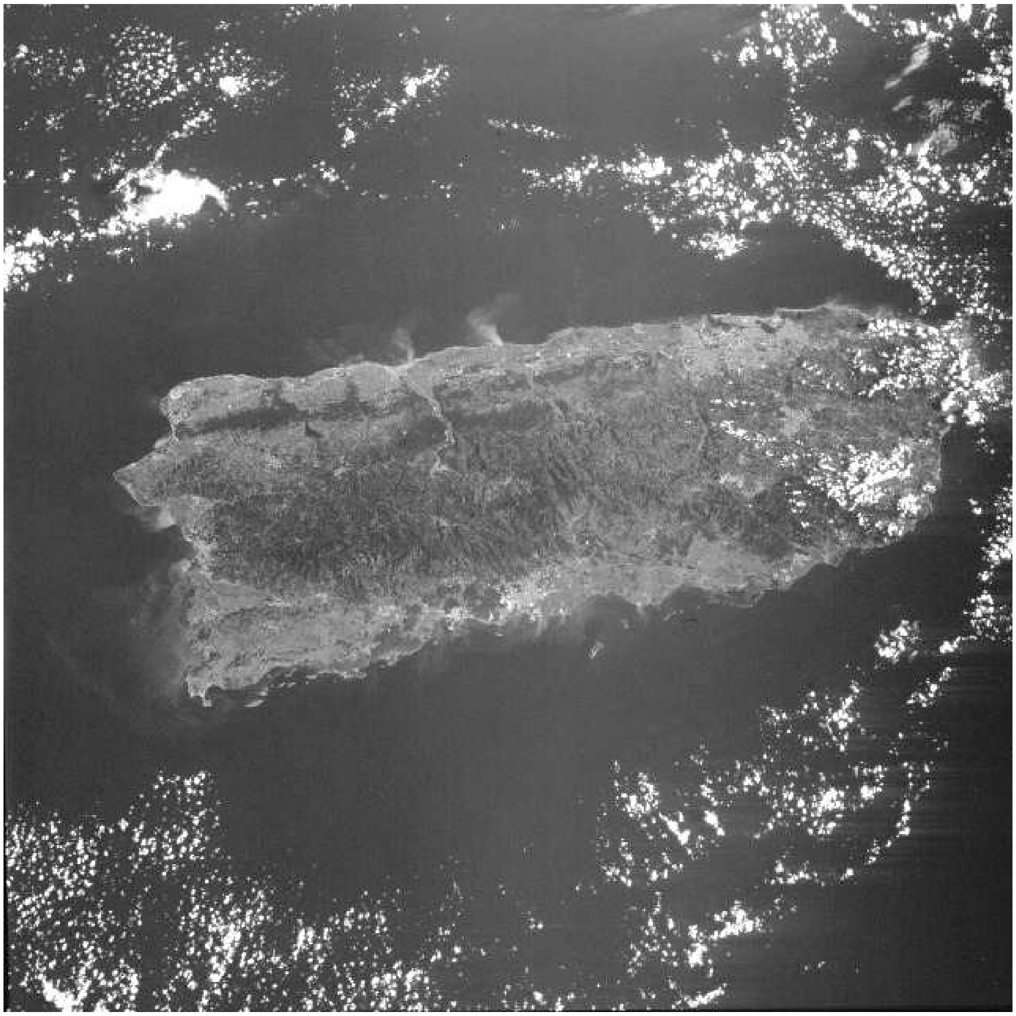


Figure 1. The island of Puerto Rico is about 100 by 40 miles in size. You can just see a white dot about one quarter from the west shore (left) and one quarter from the north shore (top). This is the Arecibo Reflector. (NASA)

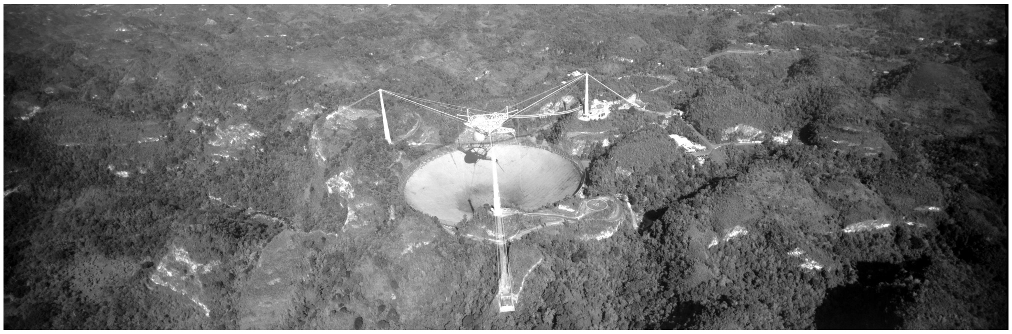


Figure 2. A panoramic view of the Arecibo Observatory in the Karst of northern Puerto Rico (Courtesy Stephane Aubin, Ciel et Espace).

the Arecibo Ionospheric Observatory (AIO) was in operation under the direction of Gordon, the formal opening ceremony taking place on November 1, 1963.

In 1960, the science of radio astronomy was still in its infancy. The ubiquitous 21-cm line emitted by neutral hydrogen (HI) atoms in the interstellar space of the Milky Way had been detected in 1951 with a special horn antenna built at Harvard's Lyman Laboratory by Edward Purcell and his graduate student Harold Ewen (Ewen & Purcell 1951), but studies of neutral hydrogen in galaxies was still in its infancy. The first extragalactic HI detection was obtained in 1953 when Frank Kerr and collaborators detected the line from the Magellanic Clouds (Kerr, Hindman, & Robinson 1954), and by 1960 HI in just a few tens of galaxies had been detected. The problem was the extreme weakness of the signals from distant sources which could therefore only be detected with very large antennas and sensitive receivers.

Also in 1960, the investigations which lead to the discovery of Quasars by Maarten Schmidt in 1963 had just begun, and only a few powerful radio galaxies had by then been identified (Schmidt 1963).

It would be seven years before pulsars were discovered in November 1967 by Jocelyn Bell and Anthony Hewish (Hewish et. al. 1968) using an antenna they had built in Cambridge, England.

Between April and July of 1960, an 85-foot radio telescope of the NRAO located at Green Bank, West Virginia, pointed at the stars Tau Ceti and Epsilon Eridani, some eleven light years away. This was project Ozma, the first search for signals from another technology, conducted by Frank Drake, later to become Director of the Arecibo Observatory (from 1966 to 1968).

Radar astronomy had gotten a few feeble echoes from the Moon as early as 1946, but the planets remained elusive targets. On March 10, 1961, echoes from Venus were finally obtained by the JPL Goldstone radars. Two antennas of 26 meter diameter, one used to transmit a radio wave using a modest (by today standards) 10 kilowatt transmitter and the other to receive the echo, were used. After a round trip of 113 million km, the weak echo was detected by the second antenna after about six minutes of travel time. This work paved the way for a greatly improved value of the Astronomical Unit (Muhleman, Holdrige, & Block 1962).

Over forty long years have elapsed since then and the Arecibo telescope, still the largest telescope on Earth, has become a household word. To the scientific community it is known for its many contributions to science, one of which earned the Nobel Prize in Physics in 1993, and to the public it is known from uncountable media exposures, including two major films (Golden Eye and Contact), as well as for the many (false) stories about how at the Arecibo Observatory we regularly communicate with "Them".

Those who see the Arecibo radio telescope for the first time are astounded by the enormity of its reflecting surface, or radio mirror. This huge "dish" is 305 m (1,000 feet) in diameter, 167 feet deep, and covers an area of about twenty acres. Suspended 450 feet above the reflector is the 900-ton platform supporting the antennas and receivers which can be positioned with millimeter precision to point at any direction in the "Arecibo" sky, a forty degree cone of visibility about the local zenith (between -1 and 38 degrees of declination). Just below the triangular frame of the upper platform is a circular track on which the azimuth arm turns. The azimuth arm is a bow-shaped structure, 304 feet (93 m) long. Fixed to the curved part of the arm is a second track, on one side of which a carriage house moves and on the other side moves the Gregorian dome (not named for a pope or for music but in honor of James Gregory, one of the foremost mathematicians of the seventeenth century, being the first professor of mathematics at the University of Edinburgh). This can be positioned anywhere up to twenty degrees from the center of the arm.

Similar in design to a bridge, the platform hangs in midair on eighteen cables, which are strung from three reinforced concrete towers. One tower is 365 feet high and the other two are 265 feet high. All three tower tops are at the same elevation. Each tower is back stayed to large concrete ground anchors with seven 3.25-inch diameter steel bridge cables (Figure 2).

2. Gestation

The headlines of the New York Times for October 5, 1957 read:

> *"Soviet Fires Earth Satellite Into Space; It Is Circling the Globe at 18,000 M.P.H.; Sphere Tracked in 4 Crossings Over U.S."*

The Soviets had launched Sputnik 1, (Satellite 1), the first man-made satellite, an aluminum sphere with a diameter of twenty-two inches and a weight of 184 pounds (83 kg), on October 4, 1957. It circled the globe 500 miles above the surface every 96 minutes and sent a beeping sound that both disturbed and fascinated the world. It was disturbing because it meant that the Soviets had the capability to send missiles toward the US. It was fascinating since it was the first step in our conquest of space. It represented a sensational goal that temporarily set the score as USSR – 1, USA – 0 in the long and frightening game called the Cold War.

But, four months later, on January 31, 1958, a US Army team lead by Wernher von Braun, and composed of experts who had worked on the German war efforts to build rockets (the infamous V2), and had post-war emigrated to the US, launched Explorer 1 from Cape Canaveral in Florida. The small 30 pound

(14 kg) satellite carried a Geiger-Mueller counter built by James Van Allen, a physicist at the University of Iowa, that could detect high energy particles. Explorer 1 discovered what later came to be known as the Van Allen Radiation Belts (Van Allen, McIlwain, & Ludwig 1959).

One of the consequences of Sputnik was the creation of the National Aeronautics and Space Administration (NASA). In July 1958, Congress passed the National Aeronautics and Space Act (commonly called the "Space Act"), which created NASA as of October 1, 1958. On February 7, 1958, the Advanced Research Projects Agency (ARPA) was established by the Department of Defense (DoD). ARPA was responsible "for the direction or performance of such advanced projects in the field of research and development as the Secretary of Defense shall, from time to time, designate by individual project or by category". In 1969 ARPA created the ARPAnet to research the transfer of data between computers across systems, thus initiating the predecessor of the Internet.

The introduction to the December 1958 engineering report No. 3 of the School of Electrical Engineering of Cornell University authored by W. E. Gordon, H. G. Booker, & B. Nichols entitled "Design study of a radar to explore the earth's ionosphere and surrounding space" reads as follows (Gordon, Booker, & Nichols 1958a):

> *"The discovery that free electrons in the Earth's ionosphere incoherently scatter signals that are weak but detectable with a powerful radar makes possible the exploration of the upper atmosphere and surrounding space by radar. The fact that the radar components, while sensitive, are all within the state of the art means that the exploration can begin as soon as the radar is assembled.*
>
> *The radar for the first time will measure directly the electron density and electron temperature as functions of height and time through the ionosphere not only in the recognized layers but also between and above them. The formation and disappearance of these layers, their structure and the diurnal and seasonal changes in them will be observed. These observations should contribute substantially to our understanding of the ionosphere and its effect on radar waves.*
>
> *In addition to exploration of the ionosphere, the radar has the following exciting capabilities: a) the observation of transient streams of charged particles traveling through space near the earth, b) the search for the existence of a ring current around the earth, c) radar observation of the planets Venus and Mars and an improved measurement of the astronomical unit of distance, d) the possibility of radar observation of the Sun and its irregular atmosphere, e) the sensitivity to observe heretofore undetected radio stars in a limited region of the sky."*

The ionosphere begins at a height of about 60 km, a region where solar ultraviolet radiation and X-rays ionize the gas. Gordon wanted to use a radar to study the ionosphere. Most of the radar energy would pass through the ionosphere and be lost into space, but a tiny fraction would be scattered in all directions by the electrons and a small part of that would be returned back to Earth (backscattered) where a very sensitive antenna could detect and study it, providing information about the ionosphere. Thus the fundamental scientific

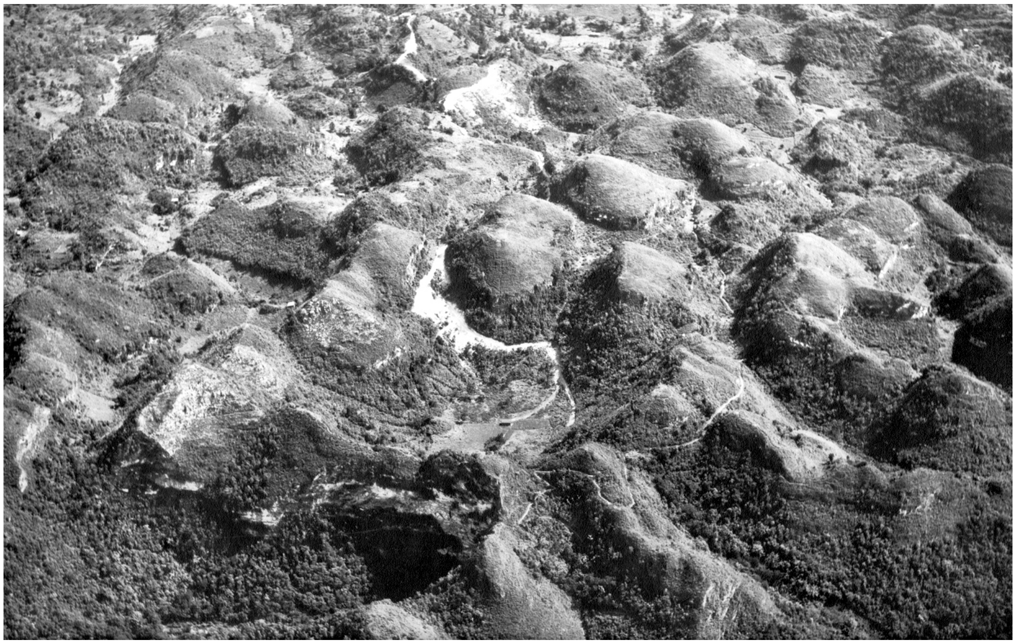


Figure 3. In this photo taken in 1960, the beginning of earth movement can be seen on the site of the future Arecibo Observatory.

mission for the AIO as seen by Gordon was to determine the electron density and temperature of the ionosphere as a function of height and time.

Being "within the state of the art" meant a reflector with a diameter of 1,000 feet (305 meters), a transmitter with one megawatt of power operating at a frequency of 430 MHz (70-cm wavelength), and the best receivers then available. The frequency was low enough that the surface of the reflector needed only to be within about 3 cm of perfect to be an efficient reflector. Nevertheless this was still a major engineering challenge for such a large surface.

The minimum size of the reflector was determined by Gordon in a paper published in the Proceedings of the IRE (Institute of Radio Engineers) in 1958 (Gordon 1958b). This is the same journal which in 1922 published a paper by Guglielmo Marconi, in which the concept of Radar was spelled out (Marconi 1922), and where in 1933 Karl Jansky published his results that mark the birth of radio astronomy (Jansky 1933).

Gordon's paper also stated: "Streams of charged particles originating in outer space and flowing near the Earth may or may not be detected, depending on their range from the radar and electron density..." Perhaps this did not escape those at ARPA who had to decide on funding. In the wake of Sputnik it offered a possible way to detect these satellites which would leave a transient trail of ionization as they moved in their orbit at a height of some 500 miles.

Originally, a fixed parabolic reflector was envisioned, pointing in a fixed direction with a 500 foot tower to hold equipment at the focus. Such a design would have had a very limited use for other potential areas of research – plane-

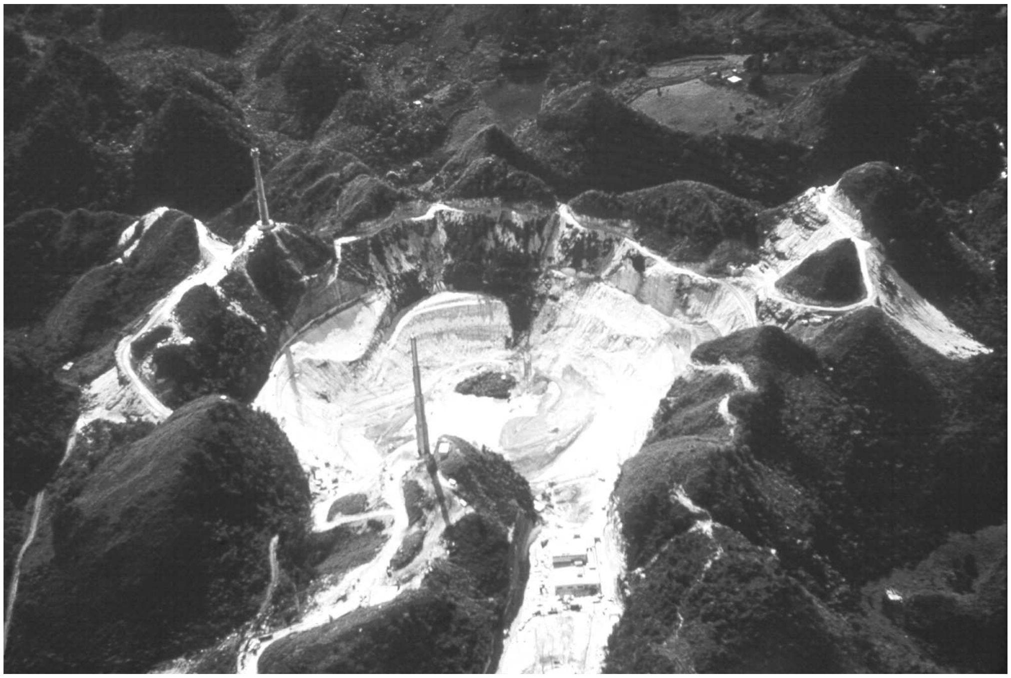


Figure 4. On this photo of 1962, two towers are almost completed, as is the operations building and long stairs to the Visiting Scientists Quarters.

tary studies and radio astronomy – which require the ability to point at different positions in the sky, and to track those positions for an extended period.

It was Ward Low, an official at ARPA and a secret hero in the story of Arecibo, who thought that this was a serious limitation and who suggested to Gordon that he should get in touch with the Air Force Cambridge Research Laboratory (AFCRL), in Boston, Massachusetts. There, a group headed by Phil Blacksmith was working on spherical reflectors, while another group was engaged in an intense study of the upper atmosphere and its effects on radio wave propagation. This effort was related to Signal Intelligence, the attempt to obtain information from intercepted radio waves. Cornell University proposed the project to ARPA in the summer of 1958 and a contract was signed between the AFCRL and the University in November of 1959.

3. Construction

There were four requirements for the site. It had to be in the tropics so that all objects in the solar system would pass overhead. This was an important consideration for planetary radar work since the telescope could not look down to the horizon. If a natural bowl with roughly the size of the reflector could be found it would save significantly on construction costs as otherwise it would be necessary to dig a gigantic hole or build a tall suspension for the reflector. The

Figure 5. The triangular platform was raised with pulleys attached to auxiliary cables strung between the three towers.

site should also have a reasonable climate, be of easy access, and in a politically stable country (Figure 3).

Donald J. Belcher, a professor of Civil Engineering at Cornell and an expert in mapping and aerial photography, was asked to locate an appropriate hole in the ground. In passing, in 1953, Professor Belcher had been involved in locating Brasilia, the new capital of Brasil. After considering such places as Hawaii, Mexico, Cuba and some smaller islands in the Caribbean, Puerto Rico was selected. Belcher studied the Karst topography of northern Puerto Rico and located three possible sites, one in the municipality of Florida, one in that of San Sebastian and the third in Barrio Esperanza, Arecibo. The latter was chosen after an on-site inspection. Not only did it fulfill all the above criteria, it also helped that at the time a faculty member of the engineering department of the University of Puerto Rico at Mayaguez, Braulio Dueño, (now an emeritus professor), was pursuing a doctorate degree at Cornell. There he met and worked with Gordon.

Despite the general shape of the sinkhole within which the telescope was built, nature had to be improved upon by excavating about 270,000 cubic yards of soil, some of it rock requiring blasting. The contractors for this also had to place 200,000 cubic yards of compacted fill to shape the excavation.

Each of the three concrete towers, two of them 265 feet high and the third 365 feet high (111 m), was poured in a slip form that was raised at a rate of about 9 inches/hour so that new concrete was exposed about five hours after it was poured. A total of 9,100 cubic yards of concrete was utilized, the equivalent

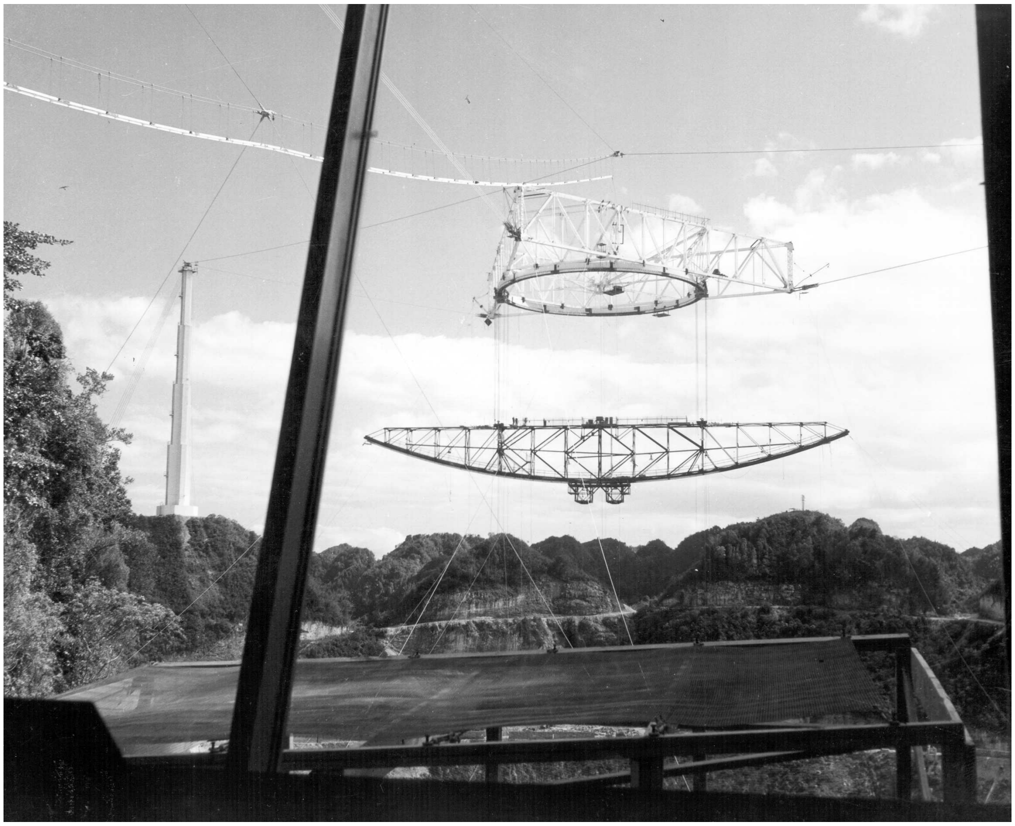


Figure 6. On March 3, 1963, the azimuth arm was on its way to the platform.

of 1,000 standard cement trucks. A concrete production plant was installed on site to make this possible.

A 265 feet tower took about 375 hours to pour, ($\sim$ 16 days of continuous pouring). Each tower sits on a reinforced concrete footing 36 x 38 ft by 15 ft deep. The anchors contain a total of 4,650 cubic yards of concrete. The towers are labeled T4, T8, and T12 following the numbers on the face of a watch, T12 being the one due north.

The feed platform, suspended 150 m above the ground, had a total weight of 550 tons. (It later was increased to about 900 tons after the Gregorian upgrade.) It is suspended from four three-inch diameter cables that run from each platform corner to the top of the corresponding tower. Five three-and-a-quarter inch diameter cables run from the top of the towers to the concrete anchors resting on the ground. (The reason for the different size and number of the cables is related to the different angle at which they carry the loads).

Visitors to the Observatory often wonder how the platform was raised in the first place. In fact, it was assembled at the center of the bowl. A cable spider was strung between the towers which supported a block and tackle to raise the platform. The blocks were made of 100 tons of concrete embedded in the ground.

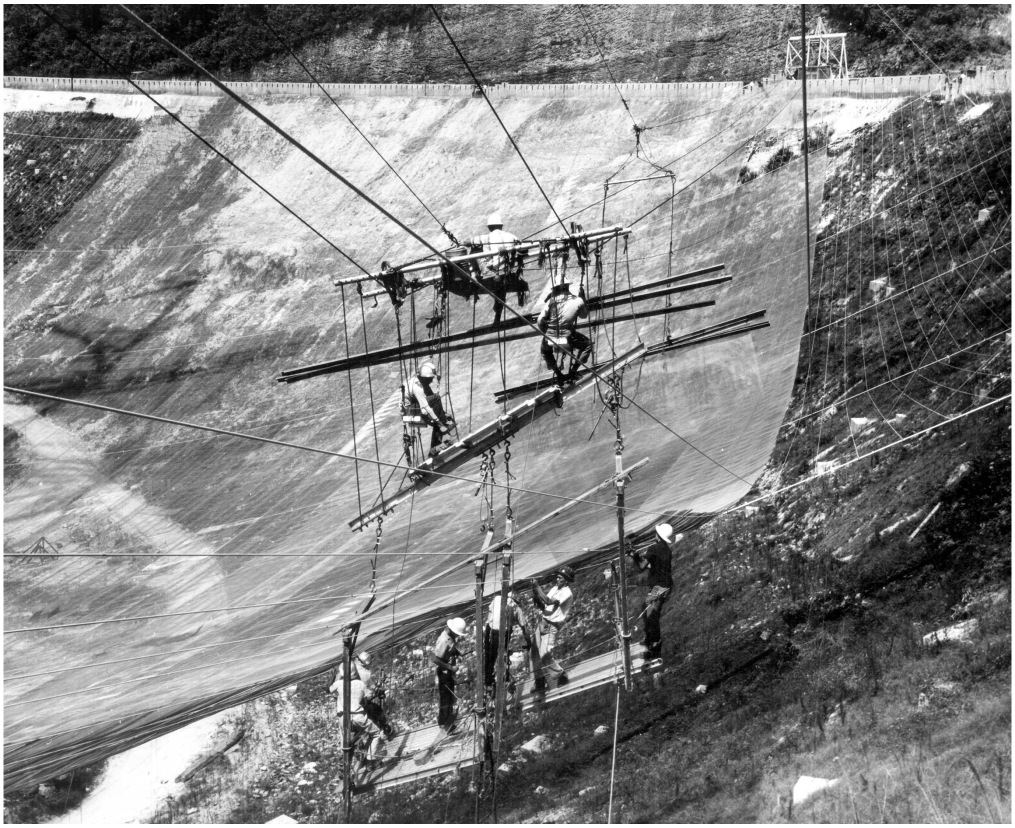


Figure 7. June 13, 1963, the mesh of the reflector is placed over the supporting cables.

The platform lift at the end of October 1962 proceeded at about 50 feet per hour during which a delicate balance was kept between the backstays and the spider and main cables so that tower deflection stayed within the permissible limits of ±2 inches. This was the most critical operation of the entire project and took three days. After the lift, the three inch diameter main cables, which had been hanging from the three corners of the platform, were attached to the tops of the towers. Next, the ring girder, holding the azimuth track and the feed arm were raised to the platform (Figures 4, 5 and 6).

The contractor for the reflector proceeded with construction after the platform was in place. The reflector consisted of 16 x 19 gauge standard inch square mesh soldered at every joint and held by a network of cables suspended from the concrete rim of the reflector. Three hundred and eighteen three-eighths inch cables run east-west, and these are stabilized by 10 (increased to 39 after the first upgrade) one and one quarter inch cables running north-south. These are tied to concrete blocks on the ground to provide the required circular profile (since a free hanging cable will have the form of a catenary – not a circle).

The reflector is a portion of a sphere of radius 870 feet (265 m), has a surface area of 18 acres, and had a total weight of 207 tons (Figure 7).

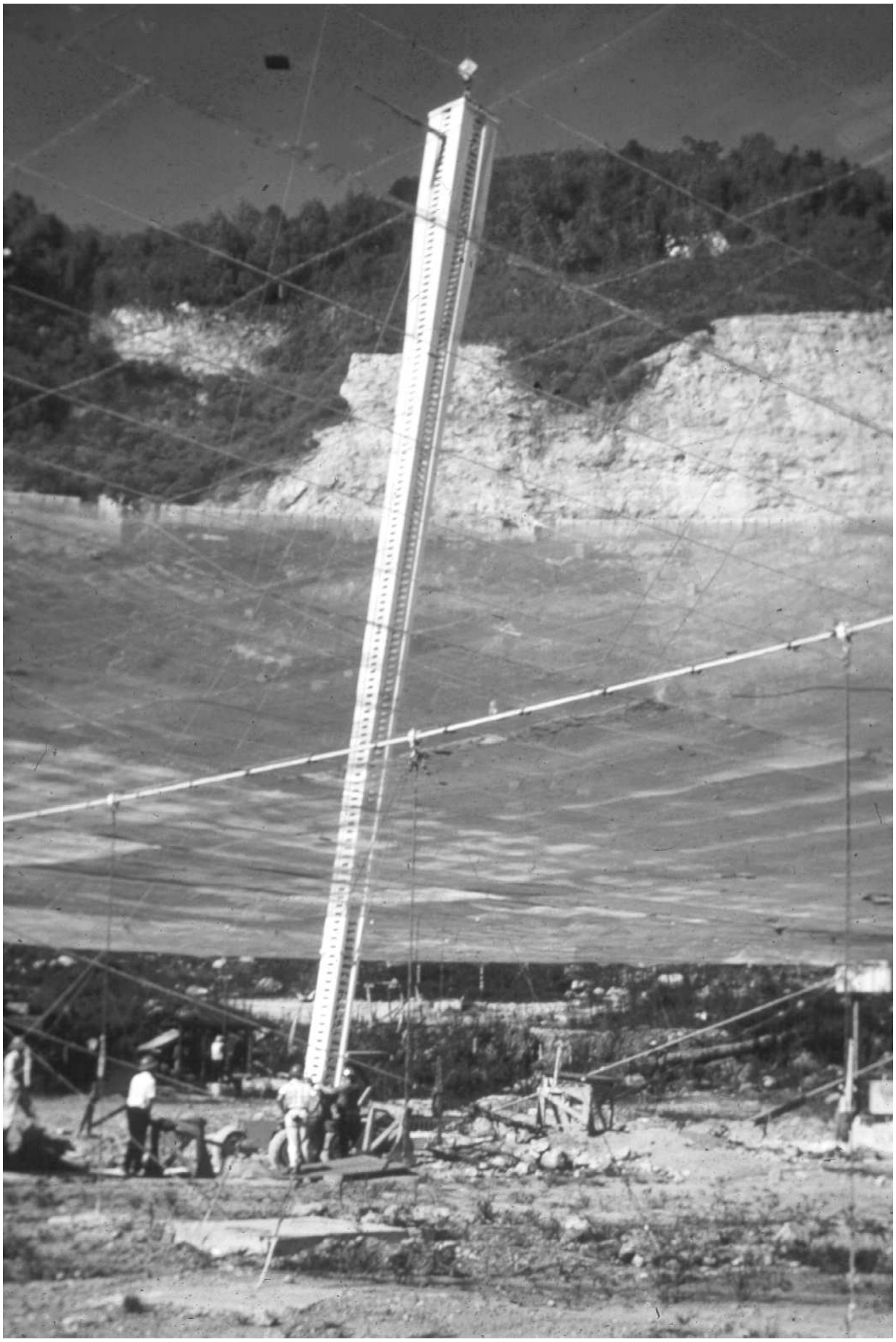


Figure 8. August 14, 1963, the 430-MHz line feed is lifted.

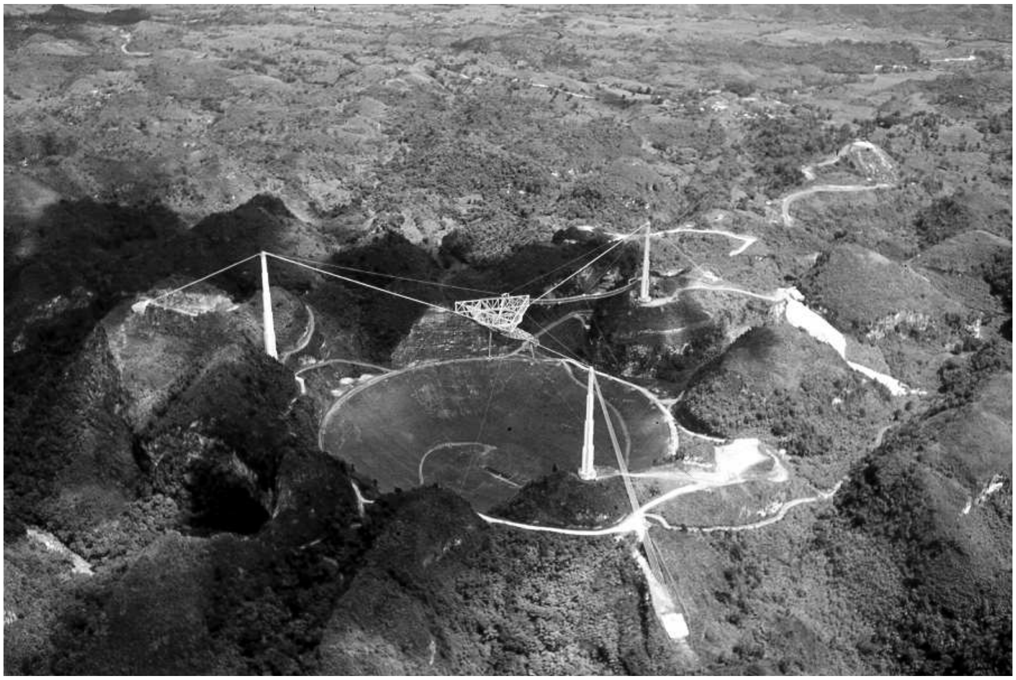
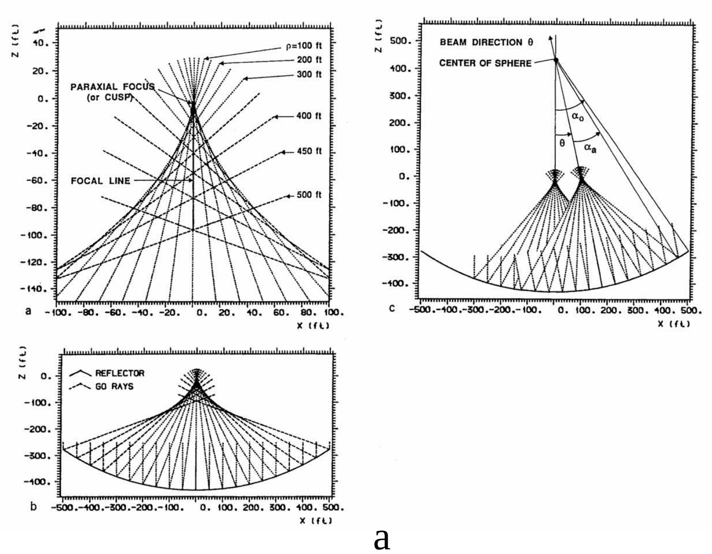


Figure 9. An aerial view of the site in 1969.

Finally on August 14, 1963, the first 96-foot long line feed operating at 430 MHz was lifted through the central opening of the reflector and attached to the receiver and transmitter (Kavanagh 1963; Gordon 1964), see Figures 8 and 9.

As illustrated in Figure 10, a spherical reflector does not have a focal point along a principal axis, as is the case for a parabolic reflector. In fact, it has no principal axis since you can view the surface along any radius and it looks the same. Waves incident on a sphere will be concentrated along a focal line which lies along a radius parallel to the direction of incidence. Therefore, if a device can be built to collect the waves in an efficient manner, by placing the device along radii at different angles it becomes possible to point the telescope at different directions in the sky without moving the reflector.

It is, however, not trivial to build an efficient device to collect the waves - a line feed - and in fact the first one used, was quite inefficient. It was a 96-foot (29 meter) long tapered aluminum device with a square cross section and an arrangement of slots through which radiation would pass (this original line feed now graces the entrance of the Observatory's Learning Center). In order for the waves arriving at the line feed at different heights to add coherently, the cross section of the line feed along its length and the design and placement of hundreds of slots through which radiation enters (or exits in the case of transmission) must be controlled precisely. Line feeds also have an inherent limitation caused by dispersion (the phase of the wave being a function of frequency) so that a line feed will operate optimally at one central frequency for which it was designed and increasingly poorly as the frequency diverges from this central frequency. This limits the range of frequencies over which a line feed can operate (the



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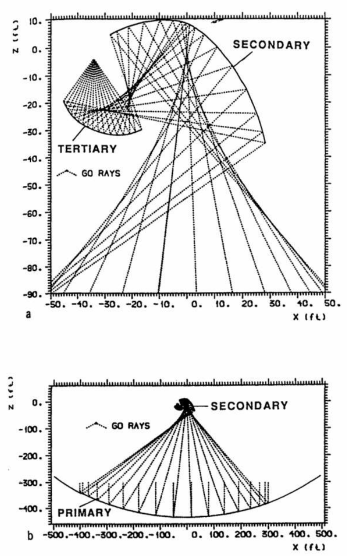

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Figure 10. Ray optics for the Arecibo spherical reflector (Kildal 1989). a. Top left. Rays from the rim of the reflector (500 ft radius) will intersect 96 feet below the paraxial focus - the point at which rays from near the center intersect. Bottom. Overall focusing of rays from the 1000 ft aperture. Top Right. Steering of the beam with a 700 ft illumination pattern. b. Top. Dual reflector feed geometry. Bottom. Complete Gregorian system.

bandwidth - which for Arecibo line feeds is between 10 and 40 MHz) which in many cases limited the sensitivity of the telescope and forced the use of several different line feeds to obtain the desired measurements.

Soon after its inauguration, on April 7 1964, the first radar contact with Mercury was achieved, under the leadership of Gordon H. Pettengill, then associate director of the Observatory. The Arecibo radar then made its first surprising discovery: the rotation rate of Mercury was not 88 days, as previously thought, but 59 days (Pettengill & Dyce 1965). An early experiment, under the guise of a study of "lunar temperature", was able to intercept and study the characteristics of a soviet radar operating on the Arctic coast. The giant reflector captured these signals reflected from the Moon and, after a careful study of the changing geometry over time, was able to determine the source of the signal (Gerson 1984).

On October 1, 1969, the National Science Foundation (NSF) took over the facility from the DoD and the Observatory was made a national research center. In September 1971 the AIO became the National Astronomy and Ionosphere Center (NAIC).

4. The First Upgrade

The desire to be able to operate at higher frequencies, both for radio astronomy and for planetary radar, was behind the idea that it was worthwhile to upgrade the surface of the reflector. It was concluded that this would be possible after it was found that the suspended platform was much more stable (something needed for work at centimeter wavelengths) than had originally been thought. The proof of this stability came in August 28, 1966, as Hurricane Inez roared across Puerto Rico subjecting the platform to 70 miles per hour winds. The platform moved barely half an inch (LaLonde 1974).

A high frequency S-band (2380 MHz, 12.6 cm) radar with half a megawatt of power was proposed to greatly enhance the planetary radar capability. Whereas the 430 MHz radar had been able to study the Moon and the terrestrial planets (Mercury, Venus and Mars), the S-band radar would provide much higher resolution on these bodies and be able to study objects at the distance of Jupiter and Saturn. The surface of Venus, eternally shrouded under a thick cloudy atmosphere would become "visible".

A scientific panel, convened by the NSF in July of 1967, and chaired by Robert Dicke at Princeton University concluded that upgrading the reflector of the Arecibo telescope was the best and most economical way to obtain a radio telescope of unprecedented capabilities. However, the NSF felt that until a successful line feed could be constructed, investing in a multimillion dollar upgrade of the reflector was not warranted. It was not until early in 1972 that the difficult problem of designing a more efficient line feed was solved by Alan Love and Merle LaLonde. Merle had acted as chief engineer during the AIO construction. (The ultimate resolution of the limited bandwidth problem, as we shall see later, was part of the second Arecibo upgrade). Once this problem was resolved, the NSF made funds available; this after the Dicke committee expressed in 1969 that, "Resurfacing the Arecibo telescope should be carried out immediately."

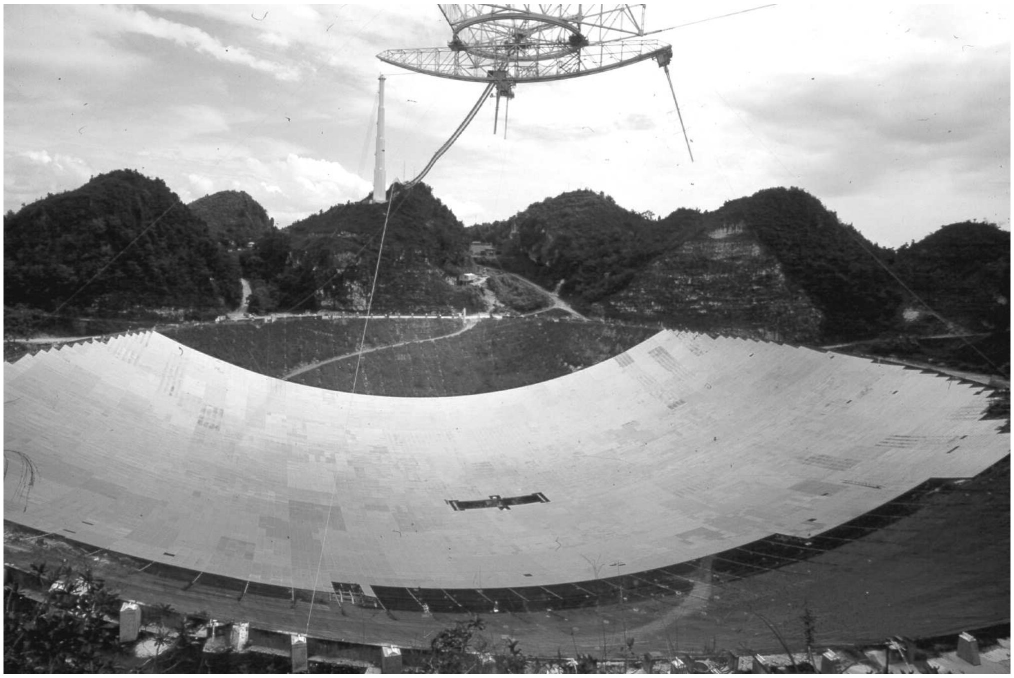

Figure 11. In this view of the first upgrade, a large fraction of the reflector had already been replaced.

To work at S-band, several changes were needed, including the new transmitter and a new receiver and, most importantly, the replacement of the reflector by one of much higher precision. As a general rule, the surface of a reflector will need to be constructed with a precision of one twentieth the wavelength at which it will be used. So for a reflector to operate efficiently at 430 MHz (70 cm), such as the original surface, it was sufficient to have the surface not deviate from a perfect sphere by more than about 3 cm, quite a feat over a diameter of 300 meters, but feasible. To have it work efficiently at the wavelength of an S-band radar meant a precision of better than 6 millimeters, a tremendous challenge. The new reflector was expected to achieve a surface accuracy of 3 mm RMS. The old mesh was replaced by 38,778 precisely shaped aluminum panels each 40 by 80 inches in size. A special factory was built on site to fabricate the panels out of perforated aluminum sheets. The holes in the panels allow 44 percent of available sunlight to pass through the reflector allowing vegetation to grow beneath and in this way to control erosion. The total weight of aluminum on the reflector is 692,000 pounds (350 tons) and without the holes it would be much higher. The holes also set an absolute upper limit to the operating frequency since at some point the holes will affect the surface reflectivity adversely. The panel frames were made of aluminum belt. A total of 227 miles of this material was used, enough to build a railing all around the island of Puerto Rico (Figures 11 and 12).

Figure 12. The last panel, number 38,778 is placed on the reflector in November 1973.

The upgraded telescope was dedicated on 15-16 November 1974. As part of the ceremonies the famous Arecibo Message was sent by the new radar. The three-minute-short message was beamed toward the globular cluster M13.

Over the next twenty years, the study of the "21-cm line" of neutral hydrogen, made possible by this new surface, became an important area of Arecibo research. Also in 1974, a professor and his graduate student from the University of Massachusetts arrived at Arecibo to pursue a search for pulsars. The search was initiated during the time when the reflector was being upgraded, since this work did not interfere with continued observations at 430 MHz. The results of studying one of the new pulsars discovered, the binary pulsar PSR1913+16, led to the confirmation of the existence of gravitational waves as predicted by Einstein's theory of gravitation. (Taylor, Fowler, & McCulloch 1979). The 1993 Nobel Prize in Physics was awarded to Joseph Taylor and Russell Hulse for their work at Arecibo.

5. The Second Upgrade

The second and major upgrade to the telescope was completed in 1997 and provides a geometrical optics correction for the spherical aberration of the primary reflector, allowing receivers to be fed by standard horns instead of by line feeds. Several important changes to the telescope were introduced (Goldsmith 1996).

A 16-meter high stainless steel mesh screen surrounding the one kilometer perimeter of the reflector shields the feeds from radiation coming from the ground

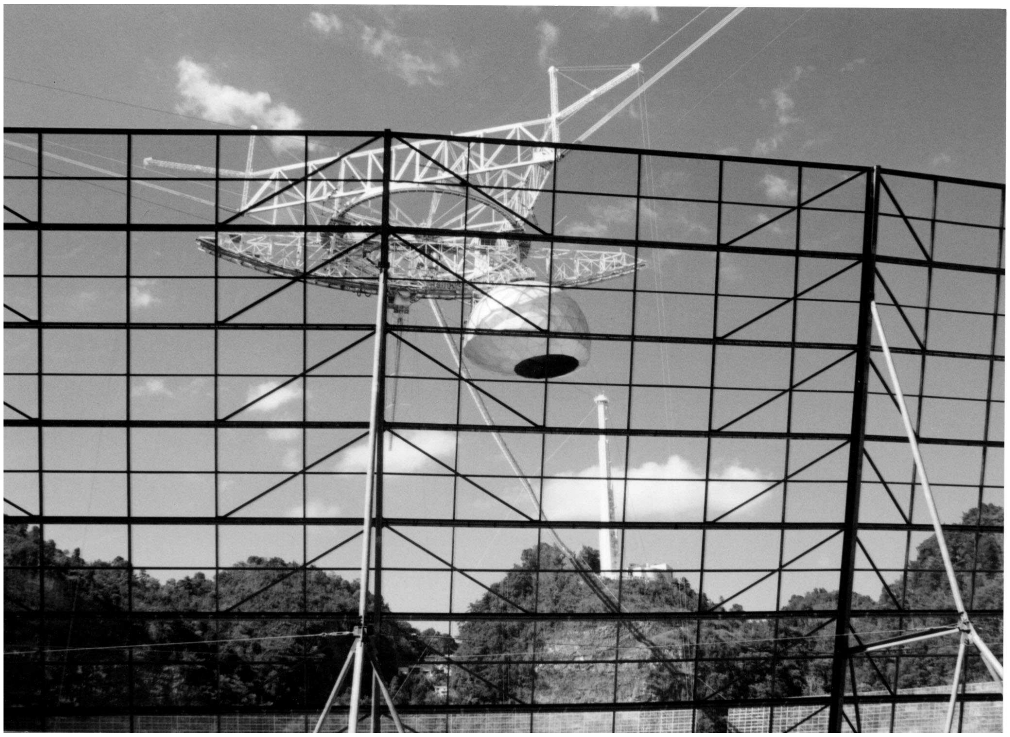

Figure 13. The telescope as viewed through the ground screen.

as the illumination pattern spills over. This was completed in August 1993 (Figure 13).

A pair of large sub reflectors (a 22-meter diameter secondary and a 9-meter tertiary reflector) are enclosed in the Gregorian dome, 30 meters in diameter, suspended from the feed arm. The dome was assembled at the center of the main reflector and then lifted to the platform on May 16, 1996. The secondary and tertiary reflectors correct the spherical aberration of the primary and bring radio waves to a point focus where a set of receivers mounted on a rotating floor can be positioned. This eliminates the above mentioned limitations of the line feeds (Figures 14, 15 and 16).

The new S-band transmitter, located in a special room inside the dome, doubles the power of the previous one (to 1 MW). A new 3.3 MW turbine was installed on site to provide power for this radar. Together with the other improvements, this enhances radar sensitivity by a factor of more than ten in some cases. The capability of transmitting from the Gregorian at 430 MHz allowed operation of the atmospheric radar in a dual beam (simultaneously from the line feed and the Gregorian) mode providing new capabilities to measure ionospheric winds.

To support the additional weight of the Gregorian dome considerable work was needed to stiffen the platform and support the 50% increase in the suspended weight. Two additional main and backstay cables with new anchors were installed at each tower. A further system of three pairs of vertical cables

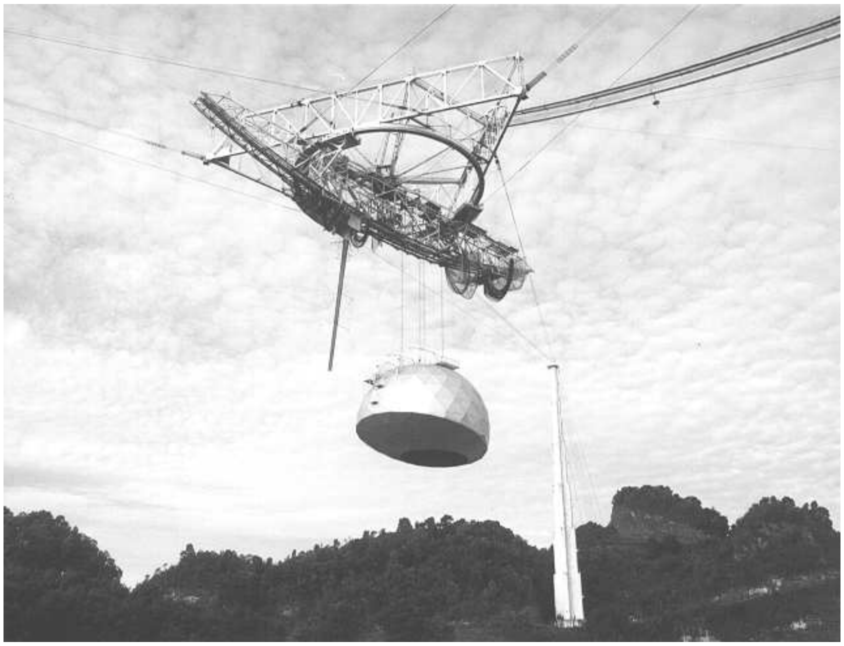

Figure 14. On May 16, 1996, the new Gregorian dome was lifted to the platform.

runs from each corner of the platform to large concrete blocks under the reflector. They are attached to giant jacks so as to adjust the height of each corner with millimeter precision.

A total of 26 new electric motors were installed to control the various new drive systems. These motors drive the azimuth, the Gregorian dome, and the carriage house to any position with millimeter precision. The tertiary reflector can also be moved to improve focusing and pointing, receivers are moved into focus on a rotating floor and the dynamical tie downs are activated as needed to maintain platform position. A complete new system of receivers and associated electronics is located in the dome and covers the frequency range from 300 MHz to 10 GHz. Signals are sent to the control room via optical fibers. New computers were installed and software developed for data acquisition and to perform monitor and control tasks. Special purpose instrumentation, such as a new spectrometer, a new radar decoder and new pulsar signal processors were designed and built at the Observatory.

To reach the required efficiency at the highest frequency range of operation (5 – 10 GHz), the surface of the reflector has been surveyed by photogrammetry with a precision of one millimeter, after which each of the almost 40,000 panels was adjusted to reach an overall RMS of better than 2 mm. A new VLBA4 system has enabled the telescope to participate in VLBI studies of weak sources, and in the future a seven-feed L-band system, now under construction, will further enhance the capabilities of the Arecibo telescope. This system will allow large-scale surveys of the sky with unprecedented sensitivity, in particu-

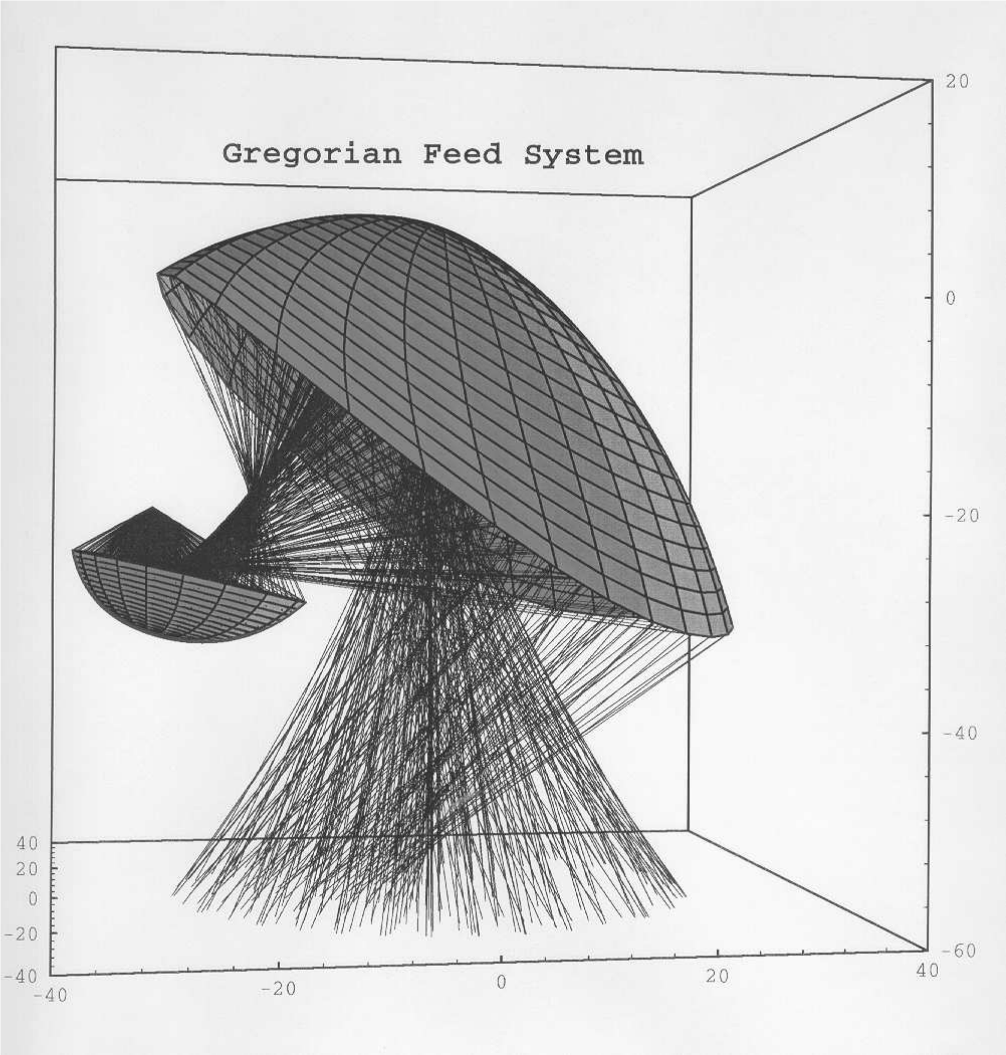

Figure 15. Two sub reflectors correct for the spherical aberration of the primary as shown. Compare with Figure 10(b).

Figure 16. A view inside the Gregorian showing part of the secondary reflector, the tertiary (bottom) and the feed tower.

lar searching for new pulsars, studying the neutral hydrogen in the Galaxy and searching for intergalactic hydrogen clouds.

In preparation for the upgrading work, during the exchange of some structural components, the azimuth arm had to be parked for several weeks. During that time a search for new pulsars at high galactic latitudes was undertaken by Alex Wolszczan (Wolszczan & Frail 1992). As a result, he found PSR1257+12, a pulsar with a planetary system, the first extra-solar one known, albeit not associated with an ordinary star.

The capabilities of the new S-band radar are astounding. As an example, the Near Earth Asteroid 1999 JM 8 was observed at a distance of about 9 million km from Earth. Images of this 3-km sized object with a resolution of 15 meters were obtained (Figure 17). With its radar vision, Arecibo is the leading facility for studies of the properties of planets, comets and asteroids.

The Arecibo telescope has scrutinized our atmosphere, from a few kilometers to a few thousand kilometers, where it smoothly connects with interplanetary space. In our Galaxy it detects the faint pulses emitted hundreds of times per second from millisecond pulsars. Also, from the farthest reaches of the Universe quasars and galaxies emit radio waves which arrive at earth hundreds of millions of years later as signals so weak that they can only be detected by a giant eye such as this one.

The giant size of the reflector is what makes the Arecibo telescope so special to scientists. It is the largest curved focusing antenna on the planet, which means

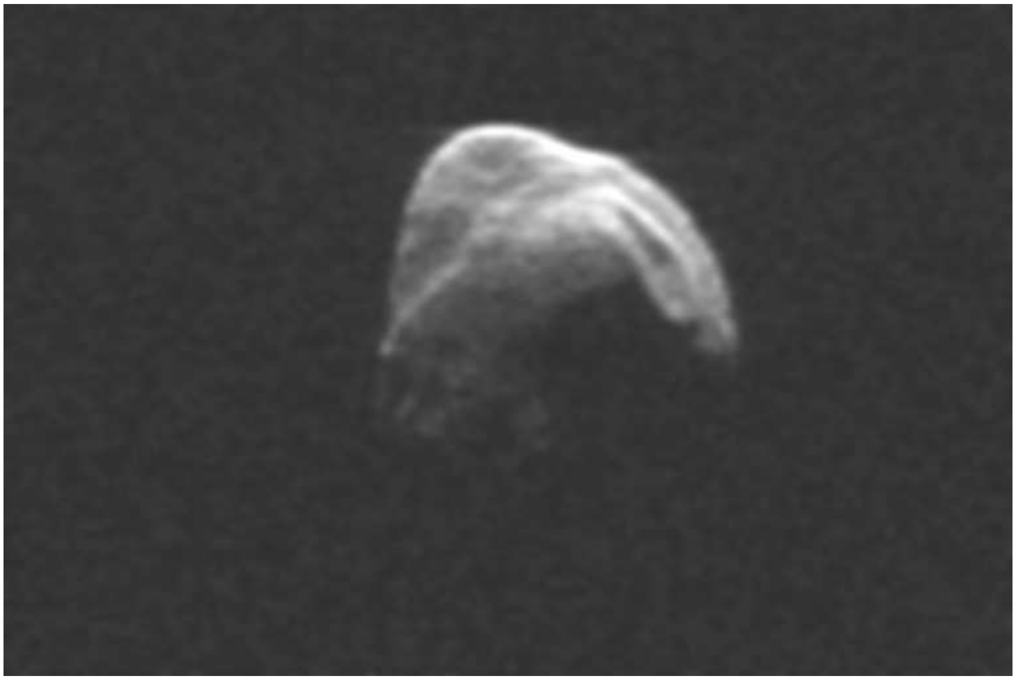

Figure 17. Asteroid 1999 JM8 is an irregular shaped object about 3 km in size. Its closest approach to Earth occurred in August of 1999 at a distance of 8.5 million km. Small impact craters can be seen in this Delay-Doppler image (Benner et. al. 2001, in preparation) (see http://echo.jpl.nasa.gov/~lance/1999JM8/press_release.html).

that it is the world's most sensitive radio telescope. Other telescopes may require several hours observing a given radio source to collect enough energy for analysis whereas at Arecibo this may require just a few minutes of observation.

6. Education and Outreach

Finally, let me also point out that beginning in 1997, with the inauguration of the "Angel Ramos Foundation" Visitor Center, the role of the Observatory in public outreach and education was greatly enhanced. It is the only facility of its kind serving the general public and the public and private schools of Puerto Rico, and we believe sets an example for other initiatives at other research centers throughout the Nation. Pride in the Observatory, and an effective fund raising campaign, caused local Puerto Rican organizations, in particular the Angel Ramos Foundation, a philanthropic organization that contributes to improving the educational, cultural and civic conditions of Puerto Rican society, to contribute the funds necessary for the construction of the Center. The NSF provided the funds for the exhibits (Figure 18).

Prior to 1997, 35,000 visitors per year came to the Observatory to view the telescope and listen to a rudimentary 10 minute audio tape. With the Visitor Center, this number has increased to 125,000, about one third being of school

Figure 18. The “Angel Ramos Foundation” Visitor Center.

age. Visitors enjoy a modern facility with a professionally prepared exhibit program offering a wide ranging menu. A special theater presentation “A Day in the Life of the Arecibo Observatory” plus various outdoor exhibits such as a scale model of the solar system, are part of the offering. And then comes the main dish – the unique view of the giant dish.

The opening in 2001 of the Conference Center, (a project supported in part by the Angel Ramos Foundation), a separate building housing a conference room and service areas, further enhances our activities, providing a venue for the science-teacher workshops which take place and have already hosted 200 teachers, plus scientific workshops such as this “Single-Dish School” (Figure 19).

In 2001, the Arecibo Telescope was declared an Electrical Engineering Milestone by the Institute of Electrical and Electronic Engineers (IEEE) and an Historic Mechanical Engineering Landmark by the American Society of Mechanical Engineers (ASME) in recognition of its significance.

About 140 persons are employed by the Observatory providing everything from food to software support for the operation. A scientific staff of about 16 divides their time between scientific research and assisting visiting scientists. Engineers, computer experts, and technicians design and build new instrumentation and keep it in operation. A large maintenance staff keeps the telescope and associated instrumentation, as well as the site, in optimal condition. A staff of telescope operators support observing twenty-four hour per day. Here I wish to acknowledge the collective work of all these dedicated people, of which I know first hand, and without which nothing would be possible.

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Figure 19. The Conference Center and the original line feed, now a monument gracing its front.