The Upgraded Arecibo Observatory

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For the past 11 years Arecibo Observatory, Puerto Rico, has—by virtue of its 305-meter-diameter antenna aperture—been a leader in research in the fields of aeronomy, radio astronomy, and radar astronomy. The facility was conceived in 1958 by William E. Gordon, who was then professor of electrical engineering at Cornell. The design parameters for the observatory were largely dictated by Gordon's newly proposed technique for exploring the earth's ionosphere, which he called incoherent backscatter (*1*). While Gordon's original proposal called for a vertically directed parabola, 305 m in diameter, it was soon apparent that a minimal additional expenditure could provide some steerability to the giant antenna, and thus give it a powerful capability in the fields of radio and radar astronomy.

In November 1963 the observatory was completed and became operational (Fig. 1). It consists of a 305-m spherical reflector antenna with a line feed designed to illuminate the full aperture at 430 megahertz. The associated radar transmitter operates at 2.5 megawatts peak power and 150 kilowatts average power, and has extreme flexibility in its modulation capabilities. The feed support structure, which is suspended 150 m above the ground (see Fig. 1), provides motion of the feed along the bottom of the bowstring truss; this permits coverage to an elevation angle of 20° from the zenith, and with special devices this can be extended to 24°. The bowstring truss is rotated on a circular track about a central bearing to permit full azimuth coverage of 360°. The sky coverage of the antenna is thus a cone centered on the local zenith with an included angle of 40° or slightly more. For astronomical observations this motion and the rotation of the earth lead to an ability to observe some 39 percent of the celestial sphere.

The reflector is entirely supported from 3⁄8-inch cables and stabilized by a system of 1¼-inch prestressed cables which are tied down to concrete anchors on the ground beneath the surface. The reflector is a 70° spherical cap with a radius of curvature of 870 feet (265 m), and was built to an original accuracy of 1.2 to 1.5 inches root mean square (r.m.s.). The original surface consisted of square steel mesh with wires spaced on ½-inch centers.

The structural design of the facility [led by Thomas Kavanagh (*2*) of the firm Praeger, Kavanagh, and Waterbury, New York] proved in the first years of operation to be exceptional. In particular, the stability of the triangular platform and feed support structure to unpredictable loads far exceeded the requirements for operation at 70 centimeters. The major motion of the superstructure was found to be vertical and temperature-dependent, with a rate of drop of 5.4 millimeters per degree Celsius temperature rise. Winds to 17 miles per hour cause no significant displacement of the structure.

Similarly, "upper" cables supporting the mesh exhibited a predictable thermal sag in the 100-foot east-west bays bounded by the prestressed "lower" support cables. In the north-south direction there was a corresponding "ripple" of the mesh between the upper cables, which caused a sinusoidal surface pattern with a wavelength of about 1 m and a peak-to-peak amplitude of about 8 cm.

It became clear that the antenna operating frequency could be substantially increased by providing a more accurate and stable reflector surface and reducing the thermal motion of the feed support platform. In 1968 a study was made by Rohr Industries (Chula Vista, California) to determine the feasibility and cost of increasing the accuracy of the reflector surface. The study showed that a surface accuracy of 3.2 mm r.m.s., operationally consistent with the stability of the platform, was attainable at a cost of approximately $5½ million.

Only one problem remained to be solved before funding could be approved for the upgraded reflector. The original line feed had realized a gain of 56.25 decibels at 70 cm, with an aperture efficiency of 22 percent—somewhat less than half the efficiency expected from a high-quality feed. The prime sources of the loss of efficiency were traced to the geometry and waveguide configuration of the dual polarized feed. In 1969 a linearly polarized feed at 318 Mhz was installed, which obtained the extremely high aperture efficiency of 70 percent (*3*). This was quickly followed by similar successful feeds at 606 Mhz (designed by Allan Love of North American Rockwell) and 1667 Mhz (designed at Cornell). These feeds proved the feasibility of obtaining very high aperture efficiencies with the spherical reflector. In January 1972 a dual polarized 70-cm line feed designed by Love (*4*) was installed, which illuminates the full aperture with an efficiency of 70 percent on a perfect reflector. This demonstrated the existence of a complete solution to the problem of feeding spherical reflectors with high power transmission levels and full polarization flexibility.

Upgraded Reflector

Following strong recommendations from the ad hoc committee on radio telescopes (the so-called Dicke committee), the National Science Foundation approved funding to upgrade the reflector and Cornell issued a competitive request for proposal. E-Systems, Inc., of Dallas, Texas, was selected as prime contractor for the reflector upgrading. E-Systems' proposal showed an imaginative and cost-effective approach to the problem, which used all the existing reflector structure except the steel mesh, and preserved growth potential with regard to surface quality.

The adopted design led to the addition of 29 lower (prestressed) cables to the existing 10, providing a plan spacing of 25 feet. The new reflector surface consists of framed aluminum panels directly supported from the upper cables, which in turn are clamped to and supported by the larger, prestressed lower cables (Fig.

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2). As a result, the surface cable supports are subjected to thermal sags which are approximately 1/16 those of the original reflector.

The panels are rectangular with approximate dimensions of 1 by 2 m. The skin is 0.040-inch aluminum sheet perforated with 3/16-inch holes spaced ¼ inch apart in a staggered pattern. This allows 44 percent of the available sunlight to pass through the reflector and support the vegetation needed to control erosion of the earth beneath the reflector.

Panel frames are Z-sections rolled to the radius of curvature of the reflector. The skin is fastened to the frame by stainless steel staples. Each corner of the panel frame has a mounting bracket, which is attached to an adjustment cup common to the corners of four adjacent panels. These are shown in Fig. 2, as is the adjustment stud, which may be turned from above or below the surface. The panels are designed to carry the weight of workmen walking on them but are extremely light, weighing approximately 5 kilograms each. The 20-acre (8-hectare) reflector surface required 38,778 panels, which were manufactured by E-Systems at the site to avoid transportation problems.

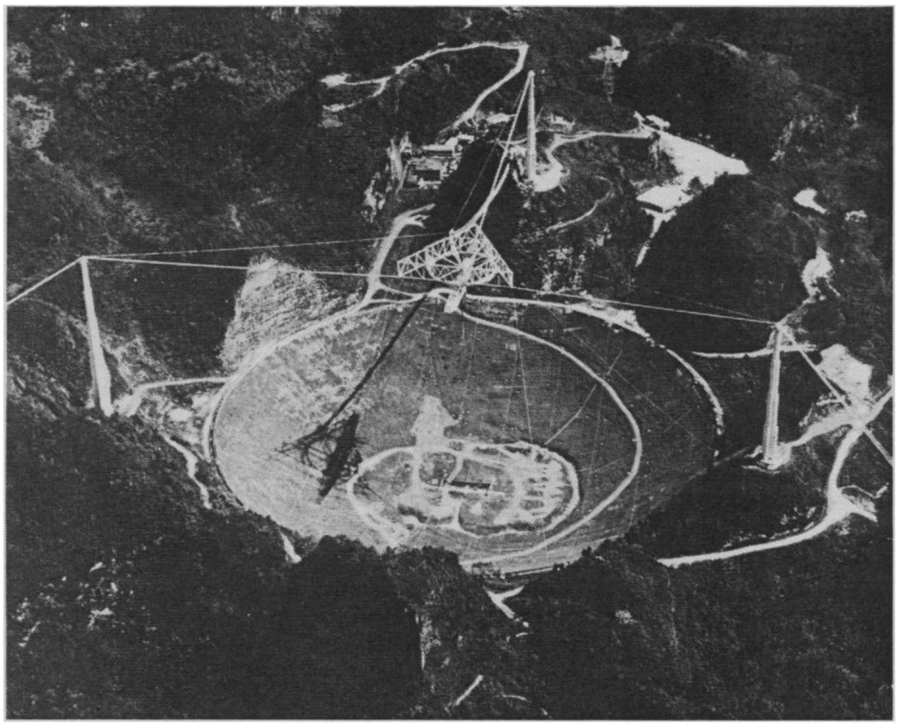

Fig. 1. Aerial view of the Arecibo facility as it appeared after the original construction was completed in 1963.

Fig. 2. Underside of the new reflector surface during placement of the panels. Note the cups fastening the common corners of four panels and the adjustment studs connecting to support cables.

E-Systems' method of adjustment of the surface involved a hybrid system of optical survey of targets and fairing-in to a dial-indicated template between the surveyed targets. Optical targets were placed on the panel corners over the tie-down points of the lower cable system, on a grid of approximately 5 by 7½ m. Each of these was set precisely by first adjusting the cables connecting the main reflector cables to the ground, and then finally through adjustment of the panel adjustment stud. A fairing tool or template was then used on the surface in line with the lower cables to adjust the panels between targets in a north-south direction. When this operation was completed, the fairing tool was turned 90°, and the panels were adjusted across the lower cables to the proper curvature. As a final check of the surface accuracy, 2000 targets evenly distributed over the surface were surveyed; one-quarter of these were over the lower cables, one-quarter midway between the lower cables, and one-half at the quarter points of the span of the ⅜-inch cables between the lower cables. The surveyed coordinates of these targets were fit to a "best-fit" sphere and the r.m.s. deviation from this sphere was computed. The tolerance is 3.2 mm r.m.s. to a sphere of radius 265.176 ± 0.024 m.

Checks on the optical survey are made by measuring the wavelength dependence of antenna gain when an aperture 137 in diameter is used. Feeds have been provided at a number of frequencies from 0.611 to 4.83 gigahertz with carefully measured primary patterns from which the amplitude and phase error across the aperture may be determined. Gain measurements with these feeds allow one to compute the loss due to the reflector error in the illuminated zone, and a number of zones 137 m in diameter may be measured over the 305-m-diameter reflector. This procedure permits "mapping" of the reflector surface error.

The upgraded reflector is shown in Fig. 3. Comparison of Figs. 1 and 3 shows the visible effect of closing and smoothing the reflector surface.

Maintenance of the Upgraded Reflector

The 38,778 panels and adjustment points can be reached either by walking on the surface with special load-distributing footwear (which is discouraged) or by going beneath the reflector in most areas. Hand-operated tramways have been constructed beneath the reflector and are supported from an independent cable network. Some areas are simply accessible from the ground, and about 5 percent of the surface area is above excavated rock which is too close to the panels to permit access from below. This arrangement permits most of the repair and adjustment to be done from the underside, without subjecting the reflector surface to man loads.

A unique measurement system, developed at Cornell by Victor Herrero, is used to survey points adjacent to each adjustment stud. A 4-watt argon-ion laser modulated at 960 Mhz is mounted on one corner of the triangular feed support platform (Fig. 4). The modulated laser beam is split into four beams, three of which are directed at permanent, precisely located targets mounted around the rim of the reflector. The distance from the laser to each of these targets is measured to a precision of 1 mm. The three beams, and thus the position of the laser, are continuously monitored by a fully dedicated minicomputer.

On the surface of the reflector there are 38,778 white vinyl targets fastened at panel corners adjacent to the adjustment studs. The fourth laser beam is directed toward any preselected target by a digitally controlled steering mirror, and the distance through which the beam is backscattered is measured. A computer-controlled steering mirror located above the surface along a line extended through the laser to the center of curvature of the reflector is positioned to reflect the oblique scatter from the illuminated target back to the laser. This permits a total path measurement, allowing solution of the three sides of the triangle and location of the target.

The precision of the surveyed position of the targets varies over the reflector surface from 0.8 mm close to the surface steering mirror to 2.7 mm at the rim farthest away from this mirror. Survey of a single target, with a real-time output of its position (and error) from the minicomputer, is accomplished in 60 seconds. With further system improvements it should be possible to survey approximately one target per second, so that an entire reflector survey can be performed in one night.

Upgrading the Suspended Structure

The suspended structure is shown in Fig. 5. The sole purpose of this structure is to position any one of a number of line feeds on a radius of the sphere within the tolerances required to illuminate the aperture properly and obtain beam pointing with required precision. The feeds are mounted on either of two "carriage houses" on the underside of the bowstring truss. Either carriage house may be driven as "master" by the pointing computer, with the other being "slaved" to it as a counterbalance. Motion of a carriage house along rails on the underside of the truss provides elevation (or zenith angle) adjustment.

The truss is supported from the triangular platform on a circular set of rails with a nominal diameter of 37 m. Diametrically opposite trolleys with four crane wheels on each are pinned to the truss. Azimuth motion is provided by driving one end of the truss about a central bearing with friction drive from the crane wheel to the rail. A positive pick-off is used for position readout from a pinion on a circular rack gear around the box girder supporting the azimuth rails.

The system was originally designed to operate primarily at a frequency of 430 Mhz; it has successfully operated at a frequency of 834 Mhz, albeit with rather poor efficiency and marginal pointing accuracy at the higher frequencies.

The feasibility, extent, and cost of work required to upgrade this structure were established with the help of the consulting engineering firm of Ammann and Whitney, New York. First, the consultants were asked to examine the structure for adequacy and general condition after 10 years of use. Second, they made the feasibility study and developed concepts and cost estimates for upgrading the structure to meet the design goal performance for an operating frequency of 7.2 Ghz. In short, they found the structure in general good health, and determined that the stability and pointing requirements at 7.2 Ghz could be met with an expenditure of approximately $3 million.

It is worth noting that the defocusing and pointing requirements at 7.2 Ghz make it necessary to hold a reference point on a line feed at the paraxial focal point with an "error cylinder" cen-

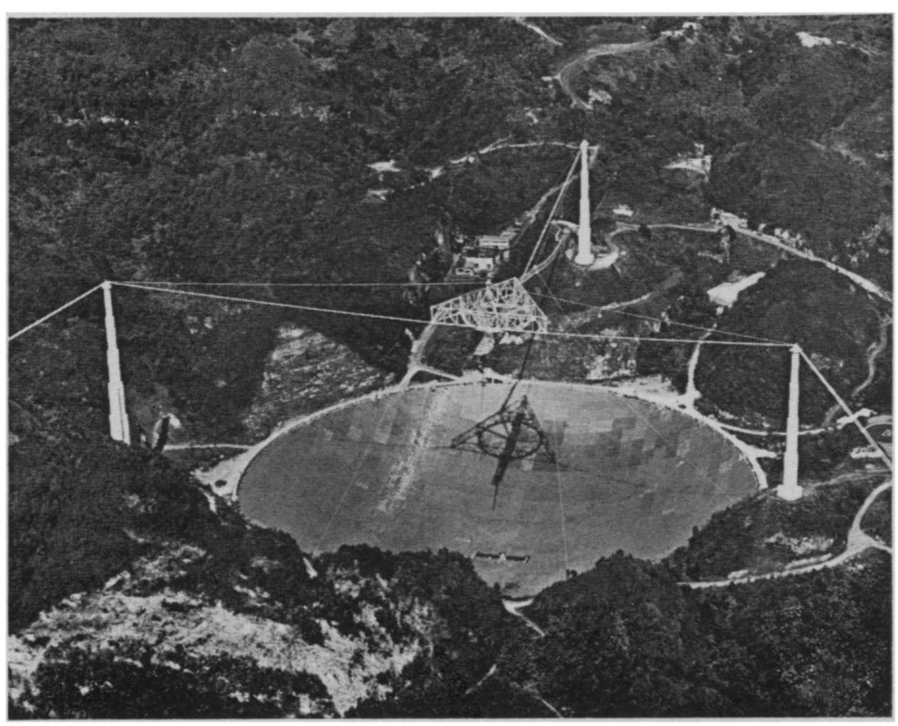

Fig. 3. Aerial view of the antenna as it appears with the new surface panels in place.

tered on the axis of the sphere. This cylinder is only 0.64 cm in diameter and 1.02 cm long. While this is an oversimplification of the problem, it demonstrates the minute scale of the tolerances involved for this otherwise large structure suspended 150 m above the ground.

The upgrading of the suspended structure to date has been supported primarily by funds made available to the observatory by the National Aeronautics and Space Administration (through the National Science Foundation) for a very specific purpose: to construct an S-band radar system primarily for the surface mapping of Venus during the 1975 conjunction of that planet. NASA made available $3 million for a high-power S-band transmitter, receivers, and associated radar system components, and a limited amount of structural modification to increase the pointing accuracy sufficiently for operation at the radar frequency of 2380 Mhz. This requirement expands the tolerance cylinder described above to 1.94 cm in diameter and 3.09 cm in length.

The immediate goal of the suspended structure upgrading was thus defined: we had to accommodate the weight of the S-band radar system on the structure and increase the stability and positioning accuracy of the S-band feed to remain within the tolerance cylinder. The general philosophy followed in this interim upgrading was to perform the tasks necessary to accommodate the increased weight on the structure first, and then those which give the greatest improvement in performance with the least expenditure of funds.

S-Band System

The heart of the S-band system is a 450-kw continuous-wave transmitter built by Continental Electronics Manufacturing Company, Dallas, Texas. This transmitter is built around the X3070A klystron developed for the Jet Propulsion Laboratory by Varian Associates. The transmitter is similar in principle to those in existence at JPL, and operates at a frequency of 2380 Mhz with a 20-Mhz instantaneous bandwidth.

For our purposes here, only a brief description of the transmitter is required. First, the scale of the antenna prevents location of the transmitter on the ground, since 330 m of waveguide would be needed between the transmitter and feed at S-band and this would lead to unacceptable power losses. Therefore, the klystron, magnets, and associated cooling equipment must be located on the suspended structure, with the klystron in the carriage house closely coupled to the feed. The total weight of the equipment mounted on the structure is about 12,000 kilograms, with roughly 9,000 kg on the feed arm and 3,000 in the carriage house. Other system components added to the structure increase the total additional load to more than 13,000 kg.

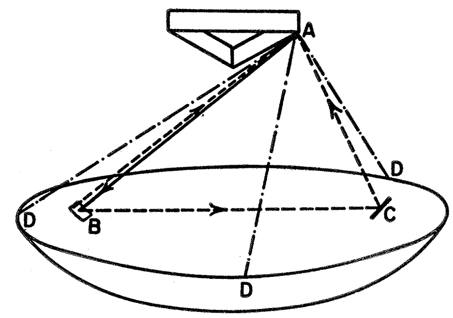

Fig. 4. Schematic of the laser survey method. The laser and its steering mirror are at *A*, the panel target at *B*, the surface steering mirror at *C*, and the reference targets at *D*; hence CA is on a radius of the sphere.

The feed is a linearly polarized line source which illuminates an aperture 213 m in diameter. The gain of the antenna at this frequency is approximately 72 decibels and the beam width at half power is 2.7 arc minutes. Two feeds are provided, one fixed to the transmitter and a second, used for receiving, located approxiamtely 3½ m away (outside the caustic surface of the first feed). The receiving feed is rotatable to allow tracking of the polarization through the relatively long round-trip flight times of Venus. The receiving feed is equipped with a ruby maser provided by NASA from JPL stocks as a receiver preamplifier.

An important part of the S-band system was the addition of on-site generating equipment to supply primary power for the transmitter. This consists of two turbine-driven generators using liquid fuel which can furnish 1500 kilovolt-amperes a-c. The d-c power supply is located on the ground and connected by a triaxial cable to the carriage house. Primary control of the transmitter is in the operations building on the ground, and remote control is available in the carriage house.

Modified Tie-Down System

Two off-vertical cables called tie-downs are installed from each corner of the suspended platform (see Fig. 1) and anchored to concrete blocks near the rim of the reflector. These cables functioned in the original system as catenaries, mainly to give torsional stability to the platform. They are 1½-inch strands and were adjusted to a nominal tension of 10,000 kg, which reduced the vertical sag of the catenaries to approximately 2 m and permitted them to have a reasonably high effective modulus of elasticity.

At the outset of the program it was suggested by Thomas Gold of Cornell that an effective way of reducing the vertical load on the structure and increasing the stiffness would be to suspend the tie-downs from a light carrier cable to hold them straight, thus eliminating the catenaries and obtaining the full modulus of the strand under light loadings. This system was designed by Ammann and Whitney, and the net result is a decrease in vertical loading of 20,000 kg and an increase in rotational stability of about 75 percent.

This tie-down modification more than compensates for the increased weight on the structure, and leads to a small decrease in the main support cable tensions while giving greater rigidity. In the redesign, jackscrews were added at the lower ends of the tie-downs to permit control of the height of each corner of the platform. In the fully upgraded system a height sensor will be located on each corner of the triangle to measure the distance to a reference position on the ground. A servo loop will close through the jackscrews and tie-down strands to control the tilt and elevation of the feed support platform within 3 mm at each corner. This will eliminate the temperature-dependent diurnal rise and fall of the suspended structure.

New Carriage House No. 2

The carriage houses were originally identical units since they were designed to counterbalance one another. The design was dictated by the requirement for carriage house No. 1 to hold the line feed, which was 29 m long and weighed 4500 kg, on a true radius to within 7½ cm at the tip. A very stiff steel structure with a useful inside volume of 3 by 3½ by 3 m was required.

In considering the upgrading, space

had to be made for the S-band transmitter in carriage house No. 2. It was also desired to provide locations for attaching more than one feed. Ammann and Whitney designed a new carirage house in aluminum, so that it has sufficient rigidity and can still accommodate six feeds with no increase in weight. The new carriage house has a floor area of 4 by 8 m with a separation between adjacent feed locations of 3½ m. Thus each feed, which is capable of illuminating an aperture 213 m in diameter, can be mounted outside the caustic surface of its neighboring feed.

An air-conditioned receiver room with approximately 9 m^2 of floor space is located in the center of the carriage house. The transmitter klystron and associated equipment are housed in a separate room (the floor of which is a detachable chassis) adjacent to the receiver room. Cooling water for the transmitter and wave guide is circulated to the carriage house from the heat exchangers located atop the feed arm via articulating sections of 4-inch pipe.

The accuracy of the elevation rails on the lower side of the bowstring truss is to be improved so that the rolling surface along which the carriage house moves will be held to the design radius of curvature within 0.8 mm. This improvement is required to make the pointing accuracy of the system closely compatible with operation at 7.2 Ghz with an aperture 213 m in diameter.

Further Planned Upgrading

With the completion of all the currently funded upgrading steps described above, the pointing accuracy of the antenna will satisfy S-band requirements but will fall short of requirements for operation at 7.2 Ghz. The azimuth rails and drive system and the elevation drive system can certainly be improved. These are the main objectives of future upgrading of the antenna system.

In a sense, funding restrictions are forcing the upgrading to be done in a logical sequence. Considering that the initial improvements that have been made increase the upper frequency limit of the system from 0.6 to 3 Ghz, the research capability of the observatory has been vastly increased. In the first few months of operation we will learn the deficiencies in the system, particularly in pointing accuracy. An analysis of repeatable and nonrepeatable pointing errors will permit us to confidently and economically design and implement the additional upgrading to reach the desired final pointing accuracy: one-tenth of a beam width with a 213-m aperture at 7.2 Ghz, or 2.4×10^{-5} radian. While this is admittedly an ambitious goal, studies have shown that it is attainable.

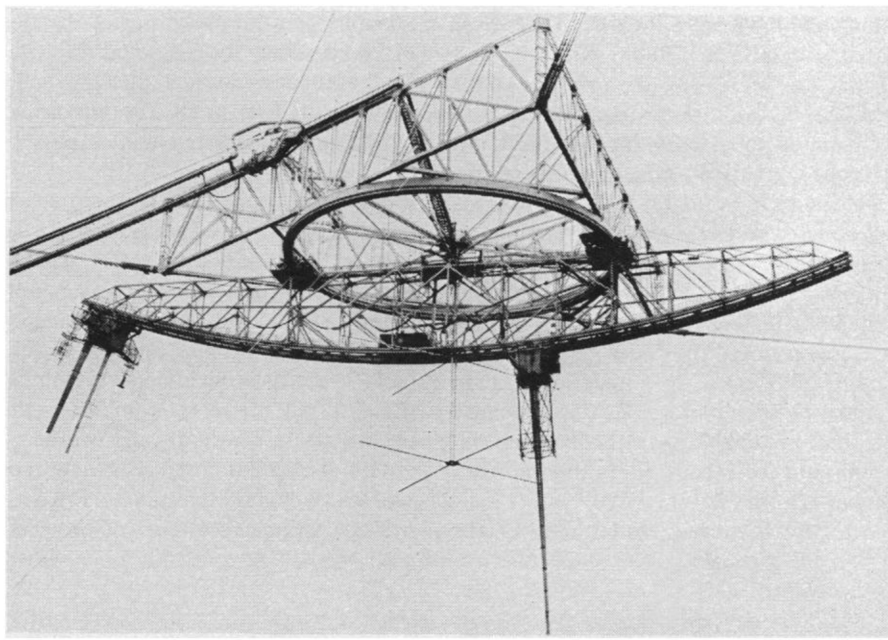

Fig. 5. Triangular support platform and rotatable feed arm truss suspended 150 m above the reflector. In this photograph, feeds mounted on the feed arm and carriage houses cover the range of frequencies from 6 to 611 Mhz, demonstrating the extreme versatility of the spherical reflector antenna.

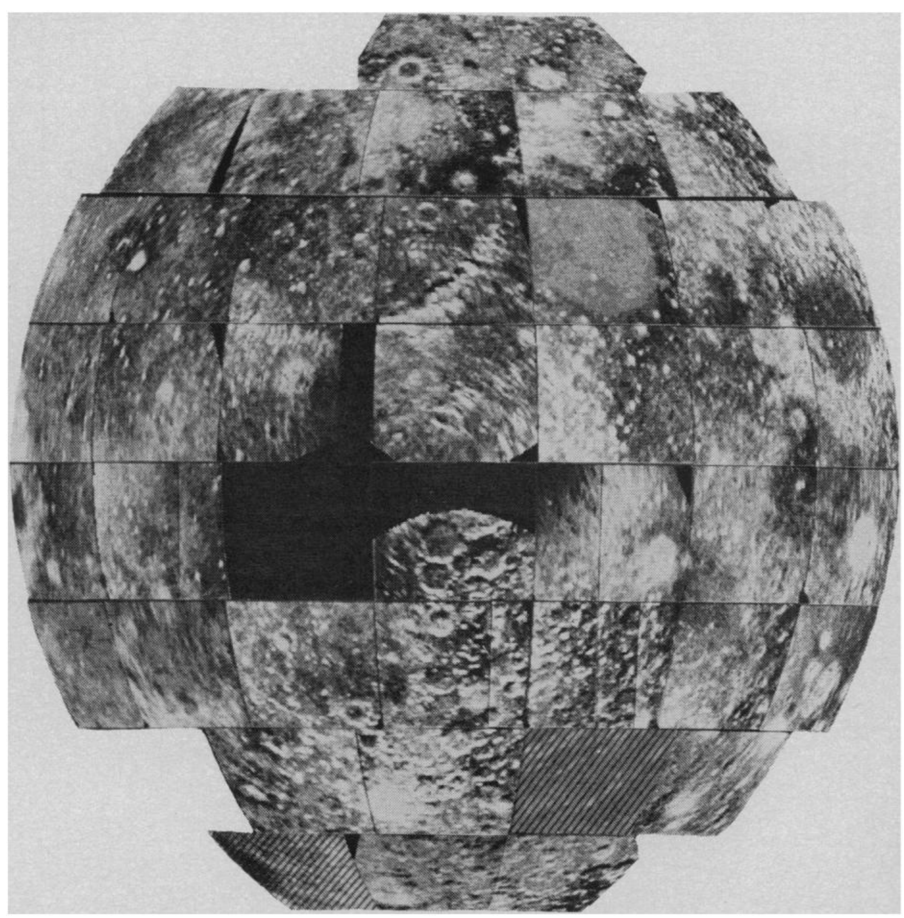

Fig. 6. Composite radar map of the lunar surface made with the UHF system at Arecibo. [From Thompson *et al.* (*5*)]

Scientific Capabilities of the Upgraded System

Research in radar astronomy, the primary reason for the upgrading, will be vastly extended and improved. Operation at a wavelength of 12 cm with half the physical aperture increases the antenna gain by a factor of 17 over that obtained at 70 cm with the full aperture. Increasing the average power of the S-band transmitter to 450 kw, compared to 150 kw for the ultrahigh-frequency (UHF) system, increases the sensitivity by a factor of 3. Addition of the maser will lower the noise temperature of the system, giving a further improvement of 2 to 7 in the signal-to-noise ratio, depending on the surface temperature of the radar target. In the case of Venus, the improvement in signal-to-noise ratio is 20 db compared to that obtainable with the existing system, and for other objects the improvement is some 25 db.

Figure 6 shows a radar map of the lunar surface obtained with the UHF system. Mapping of the surface of Venus with the upgraded system will be of similar quality, with a grid resolution of 1 km and an altitude resolution of 100 m.

In addition, mapping of the major moons of Jupiter and Saturn will be possible, and the properties of the rings of Saturn may be explored in detail. Radar echoes from Jupiter's satellites may be used to probe the atmosphere of the planet as the satellites pass behind it.

Potential in the field of radio astronomy is also greatly increased. The spectral lines of H, OH, CH, HCOH, and undoubtedly a host of other molecules lie with the frequency range of the radio telescope. Study of these molecules will provide important understanding of the very complex stellar chemistry only recently discovered.

Hundreds of thousands of new radio sources will be detectable. Figure 7 shows a strip scan of part of the galactic plane 1 hour right ascension by 1¼° declination made with a multibeam system at 611 Mhz. Ten independent beams formed by 137-m apertures were simultaneously recorded. Similar multibeam mapping may now be performed at higher frequencies with increased resolution. This technique depends on positional stability but not pointing accuracy, and therefore lends itself well to use in the interim period prior to attainment of the final pointing accuracy that is required for the fully upgraded system.

The telescope will now also be useful at the frequency judged by many scientists to be the optimum frequency for communications between civilizations in space, and very likely will be used to search for signals of this nature.

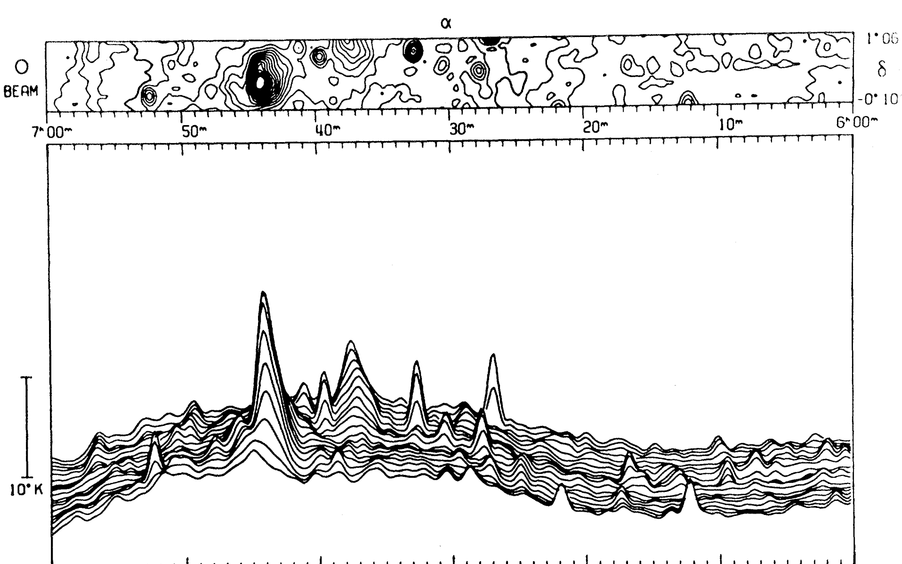

Fig. 7. Single 611-Mhz multibeam strip map and contour plot. The circle to the left of the contour plot gives the size of the beam on the same scale; α is the hour angle and δ is declination. The total survey covers −2° to +20° declination and 23 to 12 hours right ascension. [Courtesy of the Arecibo multibeam group]

Summary

Arecibo Observatory's giant spherical reflector antenna has undergone a massive upgrading over the past 3 years. The surface of the reflector has been replaced with aluminum panels to obtain an accuracy of 3.2 mm r.m.s. over the reflector surface. The superstructure has been stabilized and modified to permit operation at S-band frequencies. A high-power S-band radar transmitter has been added to the existing UHF system. These additions and improvements provide the observatory with new and promising research capabilities in the fields of radio and radar astronomy.

References and Notes

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6. The National Astronomy and Ionosphere Center is operated by Cornell University under contract to the National Science Foundation.