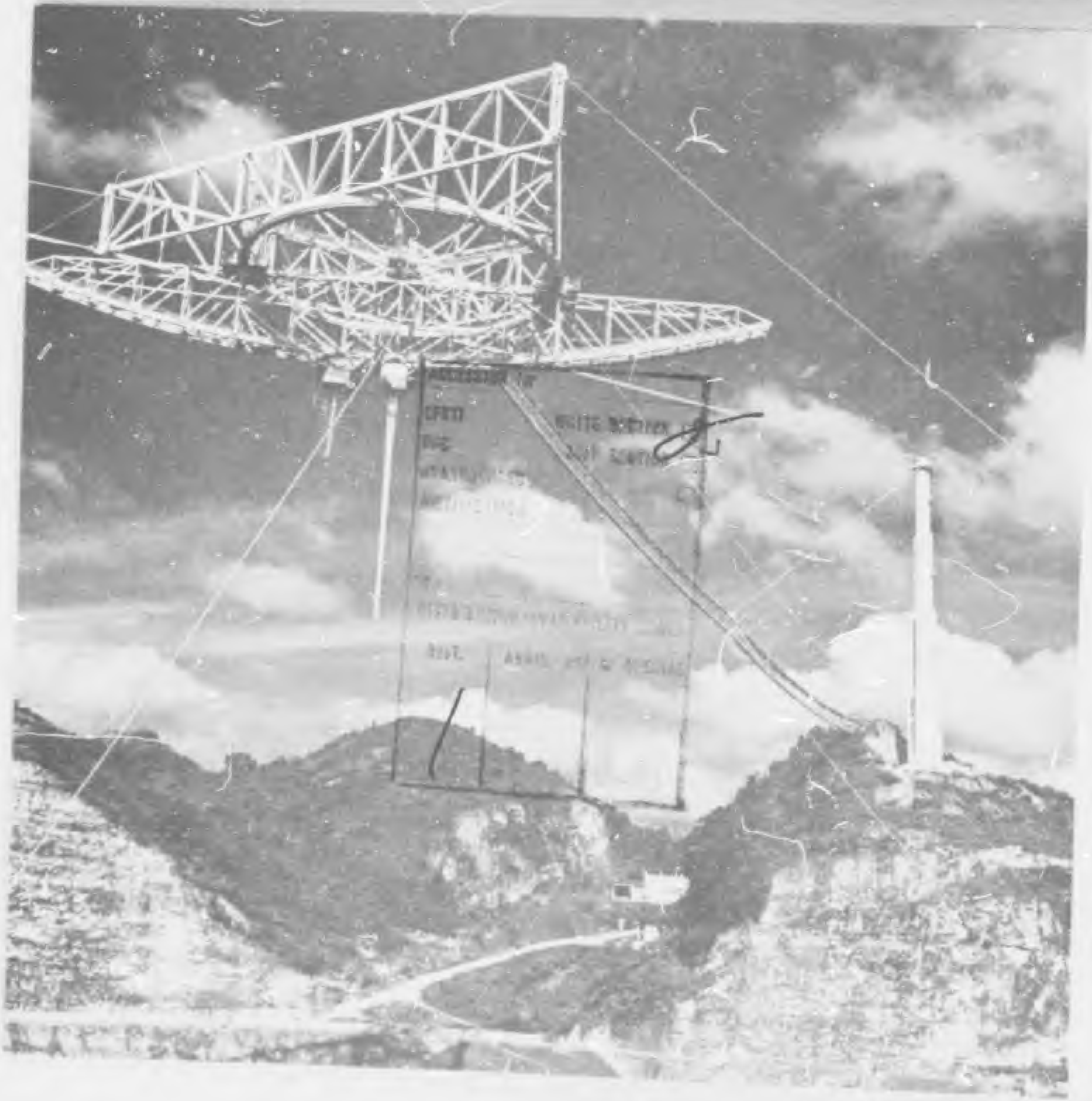
# ARECIBO IONOSPHERIC OBSERVATORY



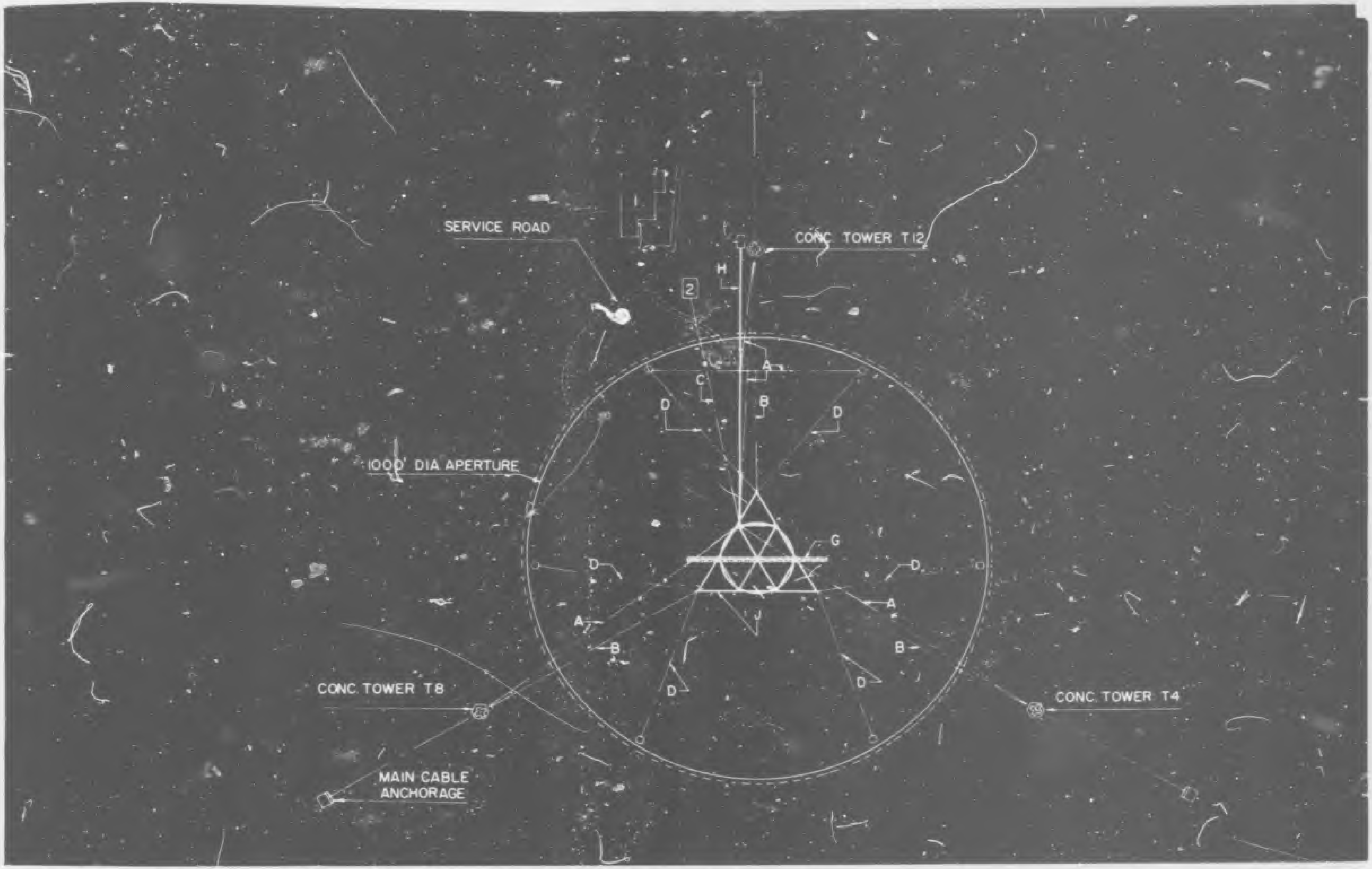
**THIS BROCHURE** describes the Arecibo Ionospheric Observatory and the scientific research program being carried out there with the world's largest radio-radar telescope.

# Arecibo
# Ionospheric
# Observatory

*is operated by*
**Cornell University**

*with funding provided by the*
**Advanced Research
Projects Agency
of the Department of Defense**

*under a research contract with the*
**Air Force Office of
Scientific Research
Office of Aerospace Research, USAF
AFOSR research contract F 44620–67–C–0066**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PUERTO RICO

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The facilities of the Arecibo Ionospheric Observatory are available to qualified scientists worldwide. Technical data is provided here for detailed assessment of the capabilities of the instrument for research.

Inquiries from the scientific community may be made to the Director, Arecibo Ionospheric Observatory, Box 995, Arecibo, Puerto Rico 00612.

Requests for public information may be made to **Cornell University News Bureau, Ithaca, N.Y. 14850**; to the **Air Force Office of Scientific Research, Staff Information Officer, Arlington, Va. 22209**; or to **AIO, Box 995, Arecibo, Puerto Rico 00612.**

July 1967

# Arecibo Ionospheric Observatory

**Arecibo, Puerto Rico**

410
590

# The Arecibo Radio-Radar Telescope

Technician feeds computer with paper tape bearing a punched program to control operation of the Arecibo radar-radio telescope so it can track a celestial object.

The Arecibo Ionospheric Observatory makes available to atmospheric physicists and to astronomers a research tool of great versatility.

The instrument functions either actively as a radar telescope, or passively as a radio telescope. The primary function of the installation is the radar study of the Earth's ionosphere. As a radar, the instrument transmits a pulsed signal, and receives between pulses that portion of the signal which is reflected back by electrons in the ionosphere, or from the Moon, or planets such as Mars and Venus.

As a radio telescope, the instrument is used to listen to radio energy emitted by the sun, the planets, and distant celestial radio sources.

The capabilities of the instrument derive from its unique design, which includes:

☐ A reflector of great size. This horizontal, fixed position, radio wave-reflecting surface is 1,000 feet in diameter across the rim, and in the shape of a bowl of spherical curvature. The reflector, made of half-inch-square wire mesh, is suspended over the ground on cables which closely maintain its spherical surface. Its size, by far the largest of its type, and its surface accuracy provide the telescope with extreme sensitivity when used as a receiver.

☐ Directional capabilities. A movable line feed 96 feet long is suspended 435 feet above the reflector. The line feed can be moved along the curved track of the feed arm, which in turn can rotate under the stationary triangular platform, providing the telescope's "steerability." The instrument can thus be aimed 20 degrees in any direction from the zenith, the point directly overhead. Because of the location of the telescope site in the tropics (18 degrees north latitude), during part of the year the sun and planets pass nearly overhead, thro the antenna's cone of view. When used as ra e, for the study of ionospheric physic astronomy, the line feed directs puls down upon the reflecting surface, ar ves, between pulses, to receive returning radar echoes from the reflector. When used as a radio telescope, the reflector collects the faint celestial radio signals, directing them to the line feed.

☐ High performance transmitters and receivers, and computers for data handling. One transmitter generates radio energy at 430 megacycles per second, with peak powers of 2.5 million watts and pulse lengths from two microseconds to 10 milliseconds. A second transmitter with similar specifications operates at 40 megacycles per second. Enhanced sensitivity is achieved by processing (usually averaging or correlating) the signal in the electronic circuits or in the computer or both. Radar receivers operate at 430 and 40 megacycles, corresponding to the fixed transmitter frequencies.

Radio receivers operate in addition at 195, 608, and 1420 megacycles per second—international radio astronomy frequencies—and other frequencies as needed. The 1420 megacycle per second frequency is that of radiation from interstellar hydrogen.

**The 96-foot slotted wave guide at right is for transmitting and receiving at 430 mc. Around its base is the 40 mc. antenna. At left on a two-degree off-set boom are the 430, 195, and 73.8 mc. receiving antennas. The 611, 430, and 195 mc. receiving antennas are beneath the carriage house.**

## Planning and Construction

The primary purpose of the Arecibo telescope is the detailed study of the terrestrial ionosphere and its tenuous, charged medium. This outer shell of the atmosphere, extending upward from about 50 kilometers (30 miles) above the Earth, contains electrically charged particles which reflect radio energy. This useful property makes possible, for example, radio communication between distant points on Earth.

Radio waves and their interactions with the ionosphere have long interested scientific researchers trying to understand the continually changing atmosphere and ways to predict changes more accurately. Study over the years suggested that a sufficiently powerful radar with a sufficiently large antenna would receive some reflections from all levels of the ionosphere and thus obtain a complete cross section of ionospheric electron densities and motions. This information would significantly advance studies of the overall dynamics of the region, and its influences upon weather and communications.

Dr. William E. Gordon, professor of electrical engineering at Cornell University, determined in 1957 that transmitter-receiver technology had advanced to a point at which a 1,000-foot diameter dish-type reflector would accomplish the objective. Furthermore, engineering studies indicated that such a reflector could be built.

Dr. Gordon's original conception of the antenna was a nonsteerable device. A proposal embodying this design was submitted by Cornell in 1958 to the Advanced Research Projects Agency (ARPA) of the Department of Defense, an agency interested in ionospheric studies. A steering capability was suggested by ARPA and for its final design, Cornell drew upon a decade of research on spherical antennas by the Air Force Cambridge Research Laboratories (AFCRL), a unit of the Office of Aerospace Research, USAF. Cornell then proposed a movable antenna feed which would permit directing the beam within a 40-degree cone centered overhead. With ARPA support a contract for the construction was signed between Cornell and AFCRL in November, 1959. Dr. Gordon directed the construction and was named the first Director of the observatory, serving until September, 1965.

The site required was a natural bowl (to minimize excavation for the huge dish) in the tropics (where solar system objects pass more nearly overhead), in a climate of moderate temperature changes (to reduce problems of expansion and contraction in the structure) and steady wind velocities (to reduce sway in the suspended line feed), and away from populous areas and air lanes (to reduce electrical interference).

The 125-acre site was first located by an aerial survey of an area whose sinkhole topography was caused by the collapse of huge caves formed by the solution of limestone in water. The installation was designed to withstand winds of more than 150 miles an hour, even though major tropical storms are rare in Puerto Rico. The chosen location is 11 miles from Arecibo and the coast and protected by surrounding hills.

All materials for construction were brought to the site over a circuitous access road. Construction of the observatory was completed in November, 1963, at a total cost of more than $9 million. Title to the installation is held by the U.S. Government.

# The Research Program

The Arecibo Ionospheric Observatory (AIO) is operated by Cornell University under a research contract with the Air Force Office of Scientific Research, a unit of the Office of Aerospace Research. Funds for the research program and the operation of the facility are provided by the Advanced Research Projects Agency.

The Arecibo facility is available to all qualified scientists. It is used each year by members of the staffs of many universities. The organization of the Cornell-Sydney University Astronomy Center in 1964 makes possible joint research work by staff and students at Cornell and the University of Sydney in Australia. Arecibo facilities, and astronomical instruments in Australia, are at the Center's disposal. Staff and students at both universities engaged in such programs may be interchanged if it seems advantageous for the work.

Numbers of graduate students in ionospheric physics, radar, and radio astronomy acquire research experience at Arecibo. Providing this training is an important function of the observatory.

The scientific program at the Arecibo Ionospheric Observatory consists of three major concurrent subprograms: ionospheric, planetary radar, and radio astronomy studies.

**William E. Gordon, designer and developer of the Arecibo instrument, talks from the control room to technicians at work on the feed structure.**

## Ionospheric Studies

The thin atmosphere above a height of about 50 kilometers (about 30 miles) contains electrons that have been freed by solar radiation from their attachment to molecules of gases. On a macroscopic basis the atmosphere is electrically neutral, but on a microscopic basis the electrons and the resulting positive ions exist in numbers that vary with height and with time.

At some height, usually between 100 and 300 kilometers (60 and 180 miles), there are normally a sufficient number of electrons to act as a reflector for waves at radio frequencies near 10 megacycles. It is this property that permits long-distance radio communications by reflecting the radio signal back to the ground one or more times as it travels around the earth from transmitter to receiver.

At the frequency of 430 megacycles per second, as used at Arecibo, radio waves travel through the ionosphere and continue into space without being reflected or attenuated. Another type of reflection takes place, however. This is a very weak diffuse scattering of radio waves by the natural irregularities in the density of the charge. This very slight effect was neglected until the advent of very powerful radar systems. Since each electron scatters a small amount of the power incident on it, and the electrons act independently of each other, the total power scattered in any direction is proportional to the number of scatterers and, therefore, to the number of electrons.

Thus a powerful radar can measure the number of electrons in a volume determined by the cross section of the antenna beam and the length of the radio pulse along the beam. By recording the total power back-scattered to the antenna at different times, one can measure the number of electrons at different heights and thus produce a profile of electron density. The Arecibo radar is now providing measurements of electron densities upward through the ionosphere.

The charged particles have been shown to be in thermal motion. While it is the electrons that scatter the radio waves, it is the positive ions that dominate the motions (through coulomb forces). A radio signal scattered by a particle with a component of motion along the line of sight will have its frequency shifted by an amount proportional to the line of sight velocity. The velocity will be higher for warmer, lighter ions. The temperatures of the charged particles and the ionic species may be deduced by comparing the single transmitted frequency with those frequencies contained in the signal scattered back from a volume of the upper atmosphere. Studies are now being made of temperature as a function of height, and the ionic composition of the upper atmosphere is being determined.

The significance of the radar "backscatter" technique is that it allows density and temperature measurements to be made continuously in time and height over a range of heights from 100 to 10,000 kilometers (about 60 to 6,000 miles) or more; for the major portion of this range, measurements previously could not be made with any continuity. The great promise of the backscatter measurements is the possibility of establishing ionic composition as a function of height and time, contributing greatly to the understanding of the dynamics of the ionosphere.

## Planetary Radar Studies

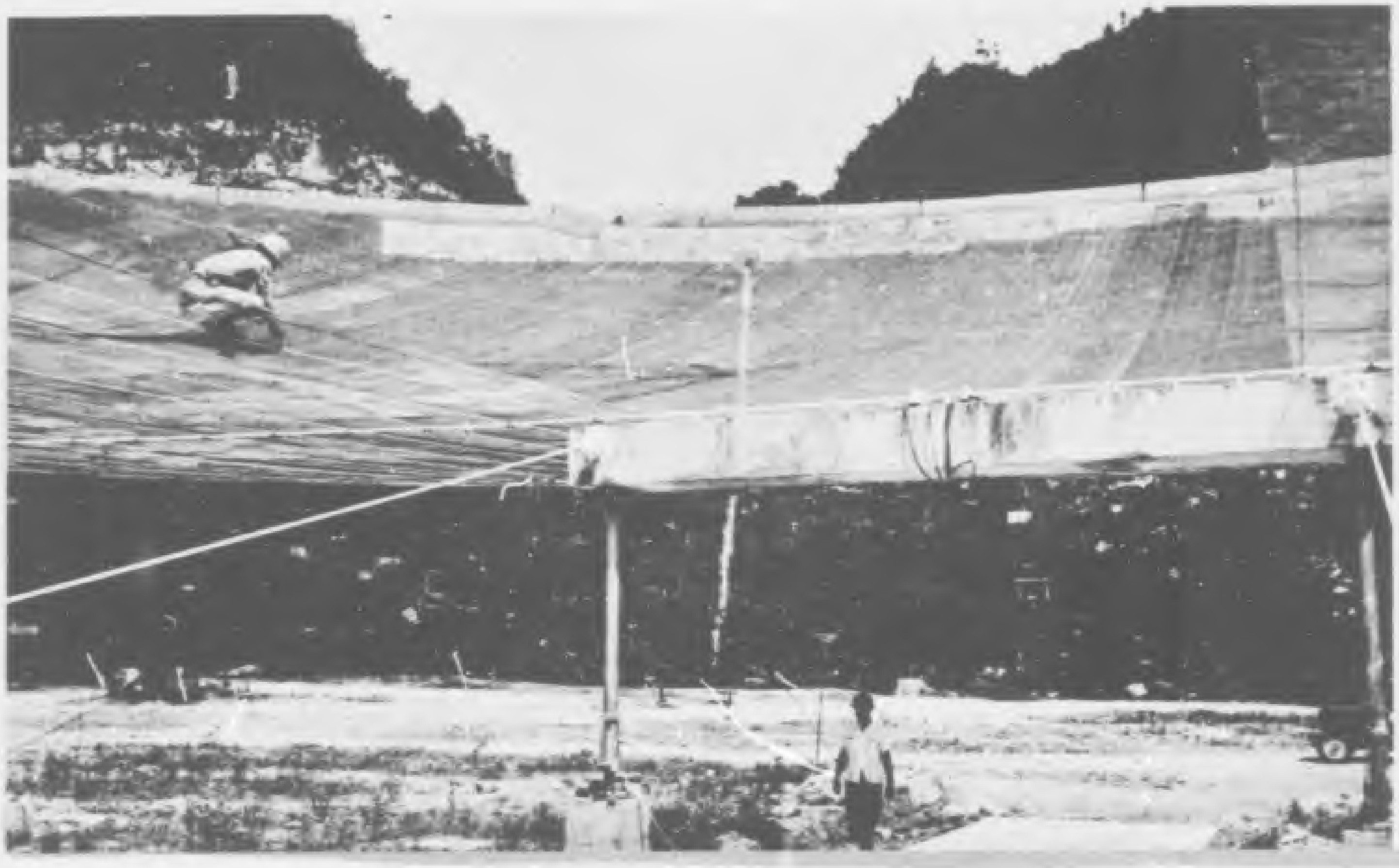
The Arecibo antenna's enormous size, transmitting power, and receiving sensitivity give it virgin territory to explore. Used as an astronomical radar, the facility is being used in important programs to study the moon and inner planets. The radar makes it possible to obtain more precise values of echo delay, a measurement of range, from which it is possible to determine more accurately the orbits of these bodies. For the Moon, Venus, and Mercury, it is possible also to measure precisely the Doppler shift in the frequency of a returned echo. This shift indicates a planet's approach or recession. A related technique, Doppler broadening of the frequency of a return signal, provides information on the direction of rotation of a body. For example, the period of rotation of Venus has been determined at AIO with greater accuracy and confirmation has been obtained of its retrograde rotation on its axis opposite to the rotation of the Earth and most planets.

The planet Mercury has been found to be rotating so that there is an alternation of day and night on it, rather than permanent sunlight on one-half and night on the other half, as had been believed on the basis of optical information. The Arecibo instrument has increased the precision of predictions for the position and orbits of Venus and Mercury, improving the accuracy of the Astronomical Unit, the measure of the size of the solar system.

Even features on the surfaces of the Moon and planets may be observed with the instrument, and work is in progress on the first map of the surface of Venus, never observed optically because of its dense cloud cover. A moon mapping program is producing indications of variations in surface structure there. Contour maps are being obtained of some lunar features as small as about 20 kilometers across (roughly 12 miles). This information supplements that obtained about these features by optical astronomy.

The planetary radar programs will continue with more detailed observations of the Moon, Venus, Mercury, Mars, and Jupiter.

**Antenna mesh, which weighs 207 tons and forms a "dish" 1,000 feet in diameter covering 19.8 acres, is suspended high enough above the bottom of the natural bowl in which it is located so trucks or other vehicles can pass beneath it when necessary. Workmen generally wear skiis when walking on mesh surface.**



## Radio Astronomy

In its passive mode, used solely as a radio listening device, the Arecibo instrument is one of unsurpassed sensitivity. This capability enables it to listen to the furthest reaches of the universe in the search for radio sources. Many, but far from all, celestial objects are strong radio sources. Of the more than 3,000 radio sources mapped so far, only about 100 have been identified optically. Among these are the Sun, the Moon, some planets, the Milky Way and other galaxies, and many nebulae. Most radio sources are thought to be galaxies beyond the range of optical instruments. Radio energy from some sources requires more than ten billion years to reach the Earth. Celestial signals are so faint that it has been estimated that all the energy collected in the 30-year history of radio astronomy is not equal to that released when a few snowflakes fall on the ground. Yet some of the most distant star-like sources are of such a size and emit such fantastic amounts of radio energy that no good explanation of them has yet been found in terms of known astronomical conditions and accepted physical laws.

Radar-radio telescopes can be operated both day and night, and in any weather. Furthermore they are capable of observing through a range of the electromagnetic spectrum far wider than the relatively narrow band of visible light to which optical instruments are limited.

The design of the Arecibo instrument for radio astronomy combines great collecting area with the ability to resolve fine detail in the sky. Furthermore, its smooth, filled area reflecting surface permits its use over a wide frequency range. Thus, this instrument demonstrates particular promise for radio astronomy.

The observatory's program includes both a search for weak radio sources and their study, including their emission spectra, radio appearance, and variation. Radio sources are mapped against a grid of stronger, discrete radio sources whose position is well determined. (However, the distance of a radio source cannot be determined unless it is also visible optically.)

The extremely useful technique of lunar occultation is used to determine positions, shapes, and sizes of radio sources with great accuracy. This is accomplished by precise observations at the moment the edge of the moon, whose position is known, passes between the telescope and the source, interrupting its emissions. As the moon continues its course, it next uncovers the source, providing a second chance to observe it. Often it is possible in this manner to gain information on the structure of a source, which may have more than one radio-emitting center.

When radio sources of very small apparent size are observed within about 90 degrees of the sun, the received radio energy is found to vary by as much as 50 percent in less than one second. This scintillation of radio sources is caused by clouds of ionized gas, ejected from the sun, passing in front of the radio source. Studies of this phenomenon are being made at Arecibo to reveal information about both the material ejected from the sun, and the sizes of the radio sources.

Observations of the planets at radio frequencies have revealed remarkable contrasts in the

apparent temperatures of Venus observed at Arecibo in the radio spectrum, and elsewhere in the infrared. Interesting new properties of both Venus and Jupiter are being found, and it is now clear that the dominant radio characteristics of these planets result from different and as yet unknown phenomena.

Future plans for the Arecibo instrument include surveys at 40 megacycles per second of the Milky Way and extra-galactic sources.

Part of the observing time at Arecibo is devoted to experiments to calibrate the system's components and to determine operating characteristics. Such studies, which are helping to bring the instrument up to its fullest operating potential, help determine the degree of accuracy of the scientific observations. Improvements and modifications are being made continually in circuitry, in data handling facilities, in the surface of the dish, and in the line feed. Radio sources of known position are particularly useful in work to further improve the calibration of the antenna.

# Some History of Radio and Radar Astronomy

While the picture of the universe seen through optical telescopes has become familiar over the past 350 years, only in the last 20 years have astronomers begun a concerted effort to explore the radio sky.

Radio astronomy began in 1931 with the accidental discovery by a radio engineer, Karl G. Jansky, of radio waves of extraterrestrial origin.

The first modern radio telescope was a parabolic dish 31 feet in diameter built in 1937 as a hobby by Grote Reber of Wheaton, Illinois, in his backyard. With it he made the first maps of the radio sky.

During World War II, both British and German radar operators found interference which was identified as of solor origin, also independently detected by Reber and others.

Radar contact with the moon was achieved at a U.S. Army Signal Corps laboratory in 1946, and for more than a decade the moon remained the only radar astronomy target. In 1959, radar contact with the Sun was made at Stanford University, and with Venus in 1961 by a number of groups. Technical developments over the past two decades have made possible such instruments as Arecibo, capable of detecting a radar signal 20,000 times weaker than that which accomplished the first radar detection of the moon. Other radio-radar astronomy developments have contributed to techniques for satellite and space probe communications.

Every object in the heavens emits radiation in the form of electromagnetic waves, some of which pass through the atmosphere and reach the surface of the Earth. Until fairly recently, man could observe only those objects which emitted visible light—a very narrow portion of the electromagnetic wave spectrum. Within the last century by means of optical telescopes and photographic techniques, he was able to extend his view to a slightly wider spectrum. These few wavelengths provide man's optical window to the universe.

A quarter of a century ago, another window was discovered—the radio window. Through this window pass radio waves which can be detected by antennas and receivers like those used for the reception of radio and television signals. This radio window is vastly larger than the optical window and, therefore, may make possible even more fruitful studies of the universe. Already, scientists have discovered radiation sources of types previously unknown and even unsuspected.

Radiation sources are two types—thermal and nonthermal. Any hot object, such as an electric light bulb, is a thermal source. It emits electromagnetic waves whose intensity increases as the temperature of the object increases. Nonthermal sources, however, emit electromagnetic radiation through processes which involve the motion of large quantities of electrons travelling at much higher speeds than they would have thermally, at the temperature of the gas. The very energetic radio galaxies, and the strange, recently discovered quasi-stellar radio sources, radiate by nonthermal means.

Radio telescopes in general are limited in their ability to resolve detail in the sky. Unlike optical instruments, radio telescopes today are far from their theoretical ultimate limitations in performance. The resolution limitation for radio telescopes imposed by the atmosphere is believed to be roughly the same as for optical types, a fraction of a second of arc. No existing radio telescope is large enough, measured in units of the wavelength of the received radiation, to narrow the instrumental diffraction pattern to such levels. The Arecibo telescope can have a resolution, for example, of about five minutes of arc, when used at the wavelength of 21 centimeters.

Depending upon their intended use, radio and radar telescopes take many forms. The parabolic dish is the most common. The largest fully steerable parabolic dish is the 250-foot one at the Nuffield Radio Astronomy Laboratory of Manchester University, at Jodrell Bank, England. Another notable fully steerable instrument is the 210-foot radio telescope at the Australian National Radio Astronomy Observatory at Parkes, New South Wales.

Large antennas may be achieved more economically by partially steerable designs. In these, the instruments may be steerable only from north to south, using the Earth's rotation to sweep west to east. An example of this type is the 300-foot transit telescope at the National Radio Astronomy Observatory at Green Bank, West Virginia.

In the case of the Arecibo instrument, the use of a movable feed calls for a fixed reflector, but dictates for it a spherical rather than parabolic reflecting surface. Other telescopes illustrate different approaches to the design problem of keeping fixed as much of the reflector surface as possible, in order to achieve accuracy at low cost. For example, the almost horizontal parabolic antenna shaped like a portion of a cylinder, at the University of Illinois, is 400 by 600 feet, with a linear feed.

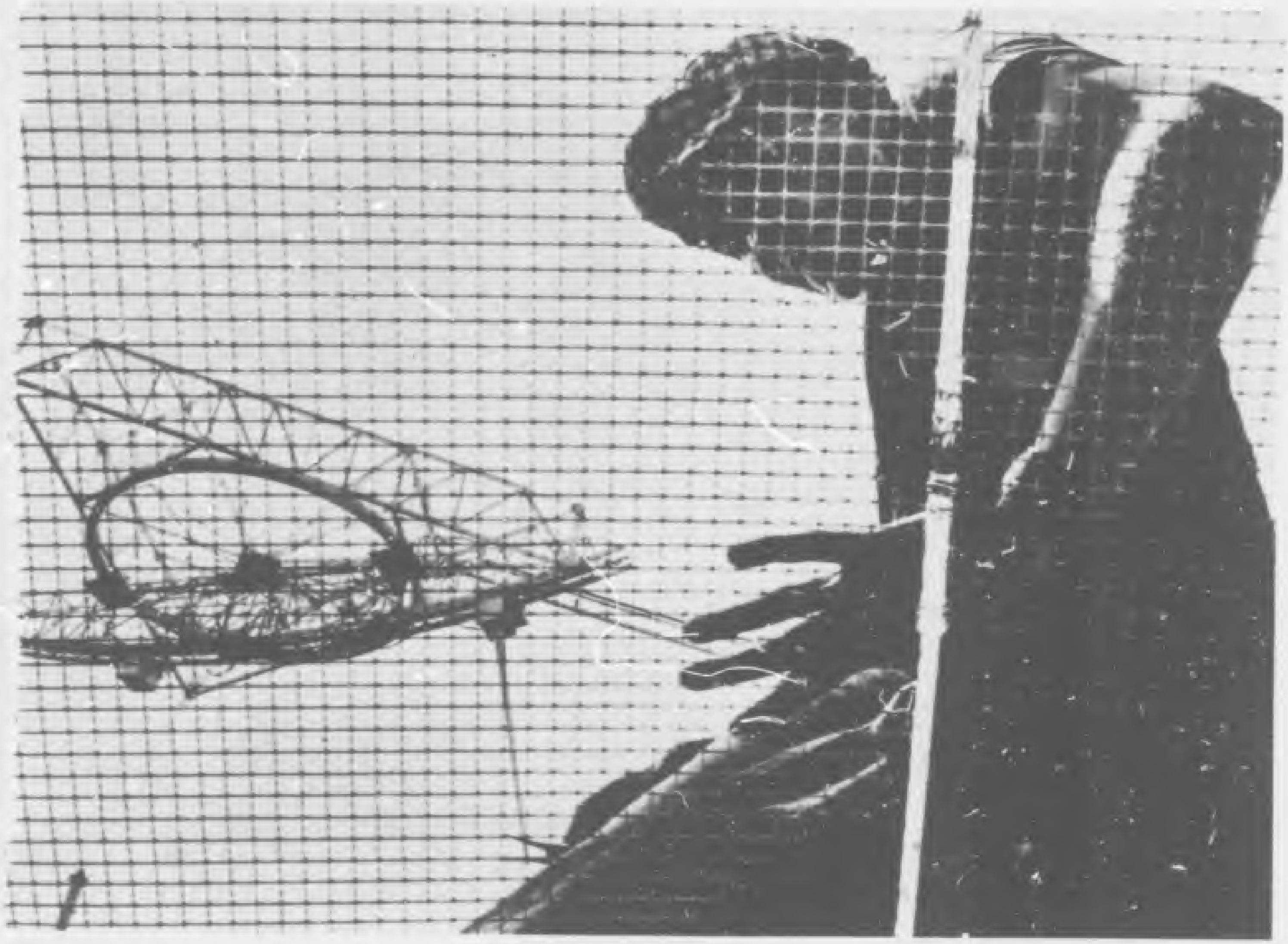
A modified Kraus-type radio astronomy antenna has been built at the Nancay station of the Paris Observatory. This uses a vertical, fixed reflector, a rectangular portion of a sphere about 915 feet long and about 118 feet tall. Radio energy is reflected upon the fixed surface by a tiltable plane reflector about 610 feet long by about 118 feet wide.

Another type of instrument is a partially filled antenna structure such as a Mills Cross. This achieves great resolution, the ability to distinguish fine structure within a radio source, but with less sensitivity than would be achieved with a filled area antenna like a dish. A Mills Cross of the University of Sydney, near Canberra, has two horizontal crossed arms each one mile long.

Another approach to the resolution problem is the interferometer, in which the antenna is separated into two or more parts which can be widely spaced. A system of this kind with two 90-foot parabolic fully steerable dish antennas, whose separation distance can be varied, has been used at the Owens Valley Radio Observatory of the California Institute of Technology. This instrument has successfully measured the size of many radio sources.

**Even though workmen sit or walk on the many acres of Arecibo antenna mesh to make repairs or changes, the antenna's curvature (surface accuracy) is maintained to within an inch of the required dimensions.**

## Research and General Information



All research work carried on at the Arecibo Ionospheric Observatory is intended for publication in scientific journals. In addition, papers are published as Cornell University Center for Radiophysics and Space Research reports.

The following is a selected bibliography of articles about the observatory.

Gordon, William E. "Arecibo Ionospheric Observatory," **Science,** 2 October 1964.

"Space Explorers Build Their Dream Telescope," **Fortune,** August 1964.

Federer, Charles A., Jr. "Some Current Programs at Arecibo," **Sky and Telescope,** July and August, 1964.

Kavanagh, Thomas C. "1,000-Foot Telescope Takes Shape in Mountain Hollow," **Engineering News Record,** 10 January 1963.

## Technical Data

The following technical information is provided to indicate the research capabilities of the Arecibo instrument.

Construction begun: June 1960

Observatory dedicated: 1 November 1963

Total construction cost: $9.3 million.

### Fixed reflector

Circular aperture, diameter 1,000 feet

870 foot radius of curvature

70 degree sector of spherical cap

Area of aperture: 18 acres

Area of surface: 19.8 acres

Surface: 16-gauge wire crossed by 19-gauge wire, 0.5 inches on centers

Surface tolerance: ±1.5 cm. at 60 deg. F.

Total weight: 207 tons.

### Towers

T–4, 250 feet; T–8, 365 feet; T–12, 250 feet; tops at same altitude

Each tower back-guyed to ground anchors with five 3.25-inch bridge strands

Combined volume: 9,100 cu. yards reinforced concrete.

### Feed support structure

Triangular platform 216 feet on sides, 30 feet high

Azimuth track circular with 130-foot diam.

Feed arm 304 feet long, 12 feet wide, 33.5 feet high, rotates around central bearing, lower track is concentric with reflector surface; feed arm weighs 220 tons

Carriage houses travel on lower feed arm track with lowest point 435 feet above reflector surface

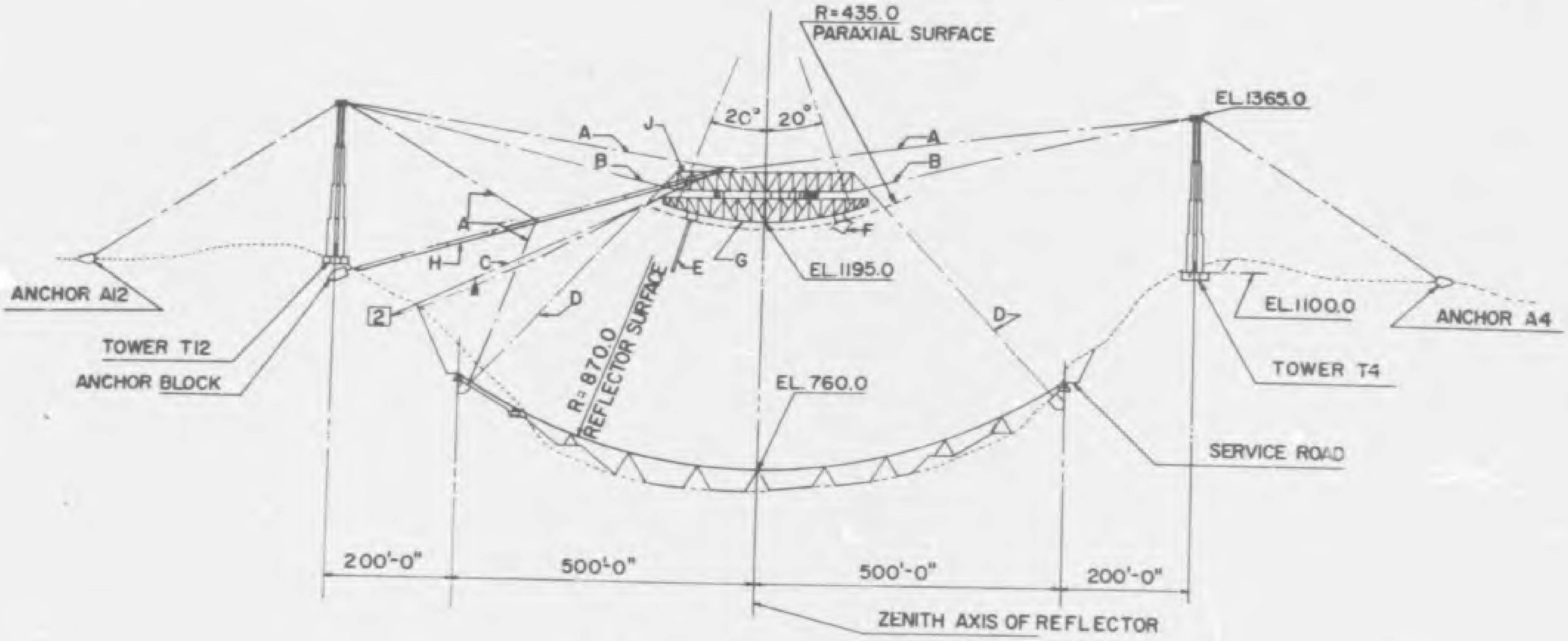
Total weight feed support structure is 525 tons.

### Suspension system

Main cables are four 3-inch bridge strands from each corner of platform to corresponding tower

Platform connections are 20-foot U-bolts

Cables tensioned to 250 tons each.



ELEVATION

1 = OPERATIONS BUILDING
2 = CABLE CAR BUILDING

A = SERVICE CABLES
B = MAIN CABLES
C = CABLE CAR
D = PRETENSIONED CABLES
E = LINE FEED NO. 1
F = FEED NO.2
G = FEED ARM
H = CATWALK & CABLES
J = FEED PLATFORM

## Transmitting-receiving feeds

430 mc/s slotted waveguide 96 feet long, tapering square cross section, full aperture illumination, linear or circular polarization. Two simultaneous orthogonal polarizations can be received

40 mc/s square dipole array, full aperture illumination, linear or circular polarization, two simultaneous orthogonal polarizations can be received.

## Receiving feeds

40, 195, 430, 608, and 1420 mc/s; others as required.

## Transmitters

40 and 430 mc/s

2.5 megawatts peak power, 150 kilowatts average, 100 kilowatts continuous

Pulsed energy 2 microseconds to 10 milliseconds; 1 to 1,000 pulses per second

Duty cycles: 430 mc/s, 6% maximum; 40 mc/s 4% maximum.

## Beam

Width: 10 minutes of arc at 430 mc/s

Scan: 20 degrees off zenith, 540 degrees in azimuth

Pointing accuracy: plus or minus 0.1 minutes of arc.

## Data processing

CDC 3200 scientific computer

Memory: 32,768 words of 24 bits

Four tape handlers capable of 800 bits per inch at 150 inches per second

Transfer rate: 120,000 bits/sec.

Memory cycle: 1.25 microseconds

Digital plotter, on-line typewriter, slow speed line printer, paper tape handler, flexowriters.

1 = OPERATIONS BUILDING
2 = CABLE CAR BUILDING

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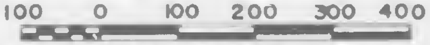
PLAN



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13. ABSTRACT

This brochure describes the Arecibo Ionospheric Observatory and the scientific research program being carried there with the world's largest radio-radar telescope. Arecibo is operated by Cornell University with funding provided by the Advanced Research Projects Agency of the Department of Defense under a research contract with the Air Force Office of Scientific Research, Office of Aerospace Research, USAF. The brochure provides general and technical information on the facility, its capabilities and uses, and on radio-radar astronomy techniques and history. Technical data on the facility enables potential users of the facility to assess its applicabilities to their projects.

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Security Classification

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| radio telescope | | | | | | |
| radar telescope | | | | | | |
| radio astronomy | | | | | | |
| radar astronomy | | | | | | |
| ionospheric physics | | | | | | |
| backscatter technique | | | | | | |
| electron density and motion | | | | | | |
| planetary radar studies | | | | | | |
| history of radio and radar astronomy | | | | | | |
| technical data | | | | | | |
| Puerto Rico | | | | | | |