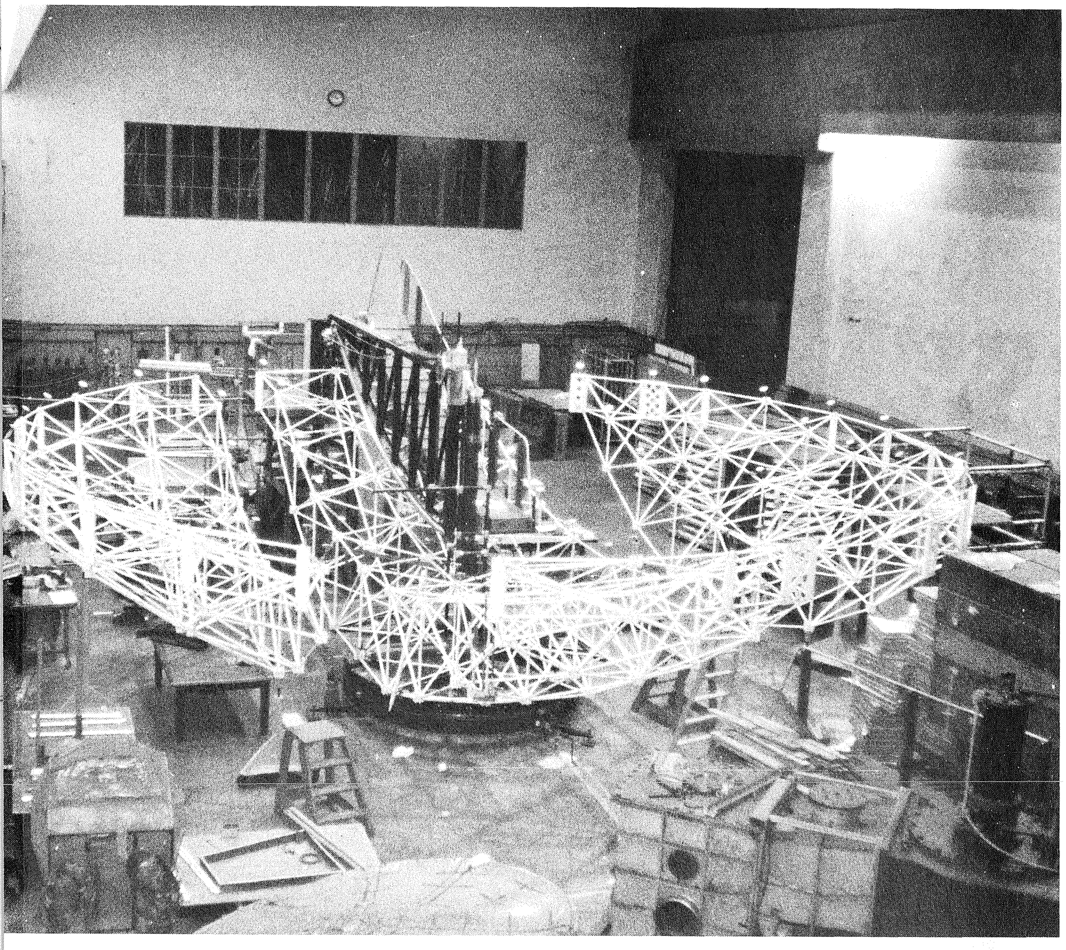
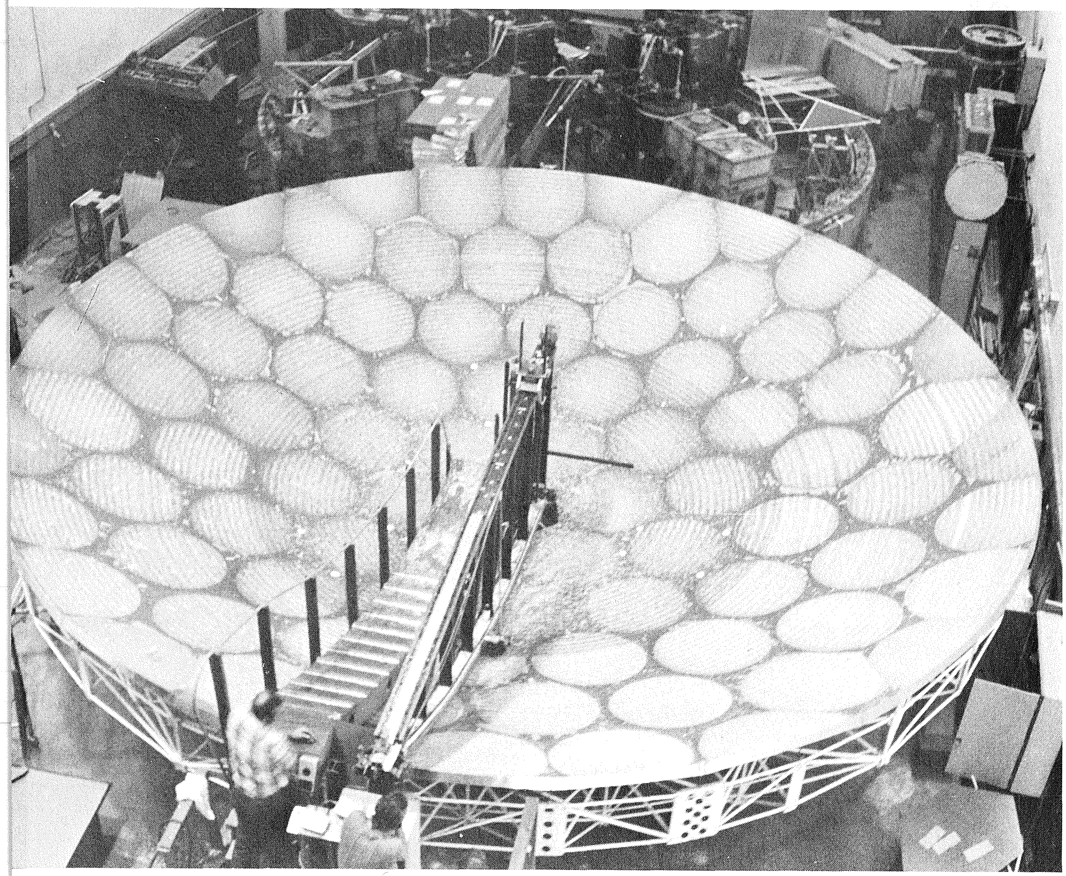


Telescopes As Right As Can Be

by Marcia Bartusiak

Radio astronomers press the limits of technology to achieve and maintain the precision of their instruments.



Radio telescope design was not on Karl Jansky's mind in 1931 when he stretched a network of brass pipes over a wooden frame amid New Jersey's potato fields. A young engineer for the Bell Telephone Laboratories, he was at the outstation to investigate strange hissing noises that were disrupting transatlantic radio-telephone communications.

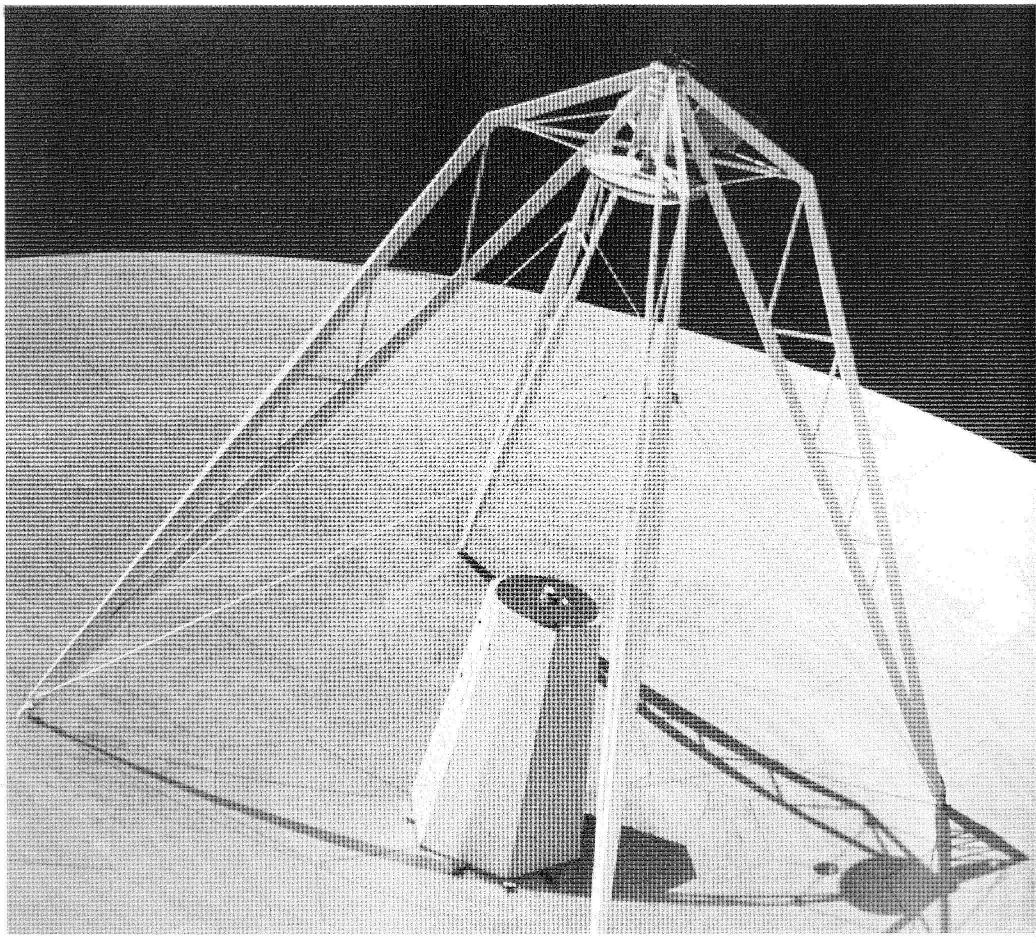
After a year of dogged detective work with his crude detector, Jansky firmly established that the source of the static was neither in the earth's atmosphere nor in the solar system, but came from a fixed locus in space—from the direction of the center of the Milky Way.

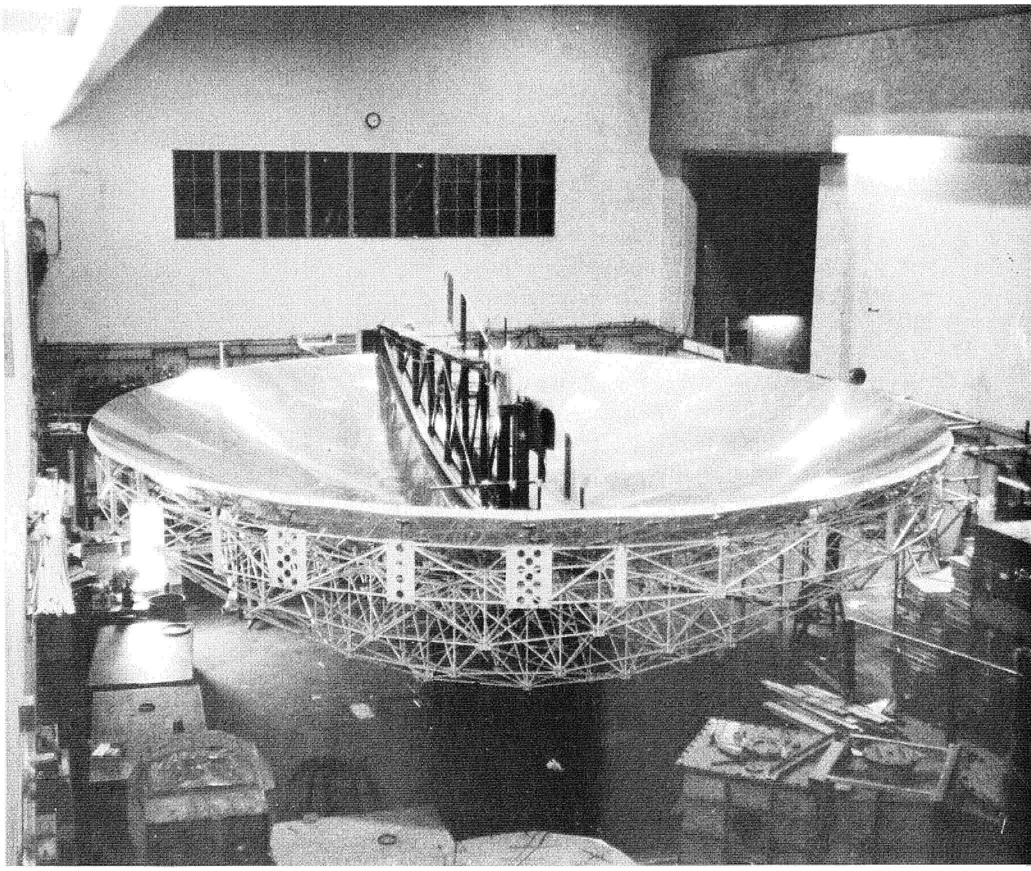
Committed to other projects, Jansky was unable to pursue his finding. Instead, in 1937, an eager Illinois radio engineer and amateur astronomer named Grote Reber built the first antenna specifically designed to receive extraterrestrial radio waves. Today, radio telescopes come in many shapes and sizes, but Reber's 9.6-meter-wide dishlike antenna, erected in his backyard on his own time and with his own money, was a design that has become radio astronomy's trademark: the parabolic reflector.

A radio telescope, as it is commonly called, operates very much like an optical reflector. Incoming radio waves are collected by its curved surface—often made up of panels or mesh—and reflected to a receiver at the focus above the paraboloid. Since radio waves carry only about one hundred-thousandth the energy of visible light, astronomers pursuing radio signals with greater and greater avidity in the decades after World War II were eager to construct ever bigger radio dishes. An increase in the antenna surface not only gathered more energy, but it also improved the telescope's angular resolution—its ability to distinguish between adjacent sources. The largest antennas so far are the 305-meter dish at Arecibo in Puerto Rico, the 40-kilometer VLA interferometer in New Mexico, and the long baseline interferometers that synthesize dishes as big as the earth. (See "The Great Astronomical Ear," *Mosaic*, Volume 11, Number 2; "The V(ery) L(arge) A(rray) Turns On," *Mosaic*, Volume 9, Number 2; and "Faster Than the Speed of Light?" *Mosaic*, Volume 13, Number 4.)

Finer detail in the radio sky can also be discerned by working at higher frequencies, shorter wavelengths, which involves not the size of the dish but its geometric precision. Jansky's crude array of pipes and planks detected the Milky Way at a frequency of 20 megahertz, a wavelength of 15 meters; Reber's paraboloid worked at 1.9 meters. Continued advances in instrumentation produced sensitivity to shorter and shorter wavelengths, and by the 1960s, receiver technology reached the point that detection at what is called the millimeter window was finally accomplished.

To astronomers, millimeter waves provided a vital link between the long-wave radio and the optical regions of the electromagnetic spectrum. Studies of planetary atmospheres, stellar outbursts, supernovas, and active galaxies and quasars are much enhanced by the opening of this additional window. But more important, millimeter-wave telescopes have enabled researchers to discover nearly 60 kinds of molecules tumbling and colliding within the Milky Way's interstellar clouds, the birthplace





Beginning to end. Caltech's antennas for millimeter-wave astronomy comprises 84 hexogonal panels, each supported by a tubular parabolic backstructure (top, left) and machined as a single piece (below, left). A completed dish is checked by an electronic transducer on the cutter track (below, right), before a subreflector is installed at the focus (top, right).

of new stars. (See "Astrochemistry Comes of Age," *Mosaic*, Volume 10, Number 1.)

Not good enough

"But then, in the middle of all this progress, we came across a major obstacle," recalls Mark Gordon, assistant director for Arizona operations of the National Radio Astronomy Observatory, operator of a millimeter-wave radio telescope on Kitt Peak. "We became limited by the surface of the dish itself."

As a general rule, astronomers need their reflecting surfaces to be accurate to about one-sixteenth the wavelength being collected, a level of smoothness known as the r.m.s. (root of the mean of the squares) deviation. Such accuracy in the surface regularity assures that each wavefront reflected by the antenna will march toward the focus in step with each other, in phase, adding to each other and producing the strongest signal possible.

For centimeter-wave telescopes, this precision requirement has posed no great problem. But for millimeter-wave dishes, it becomes quite a constraint. Ideally, a surface designed to collect one-millimeter waves, for example, should be accurate to within 63 microns. With such a tiny margin for error, the signal can be seriously degraded when the dish merely tilts and sags under its own weight, deflects under high wind gusts, or distorts as it is heated by sunlight.

Many ways have been developed to achieve and maintain micron precision in high-frequency antenna dishes. As Bobby L. Ulich, assistant director for engineering for the Multiple Mirror Telescope in Arizona, noted in a report, "It seems that a new technique has been invented for practically every telescope." Some antenna designers take advantage of advances in structural theory, and some use innovative composite materials in constructing the dish panels. Others are inventing surface measurement techniques to detect for correction the smallest of distortions. Older methods, updated with laser and computer controls, are still proving to be quite useful.

At the California Institute of Technology, physicist Robert Leighton and a three-man staff have been applying familiar but sophisticated machine-shop techniques. They are producing a series of ten-meter-wide dishes with r.m.s. deviations ranging from 10 to 30 microns. For their size, the Caltech dishes are probably

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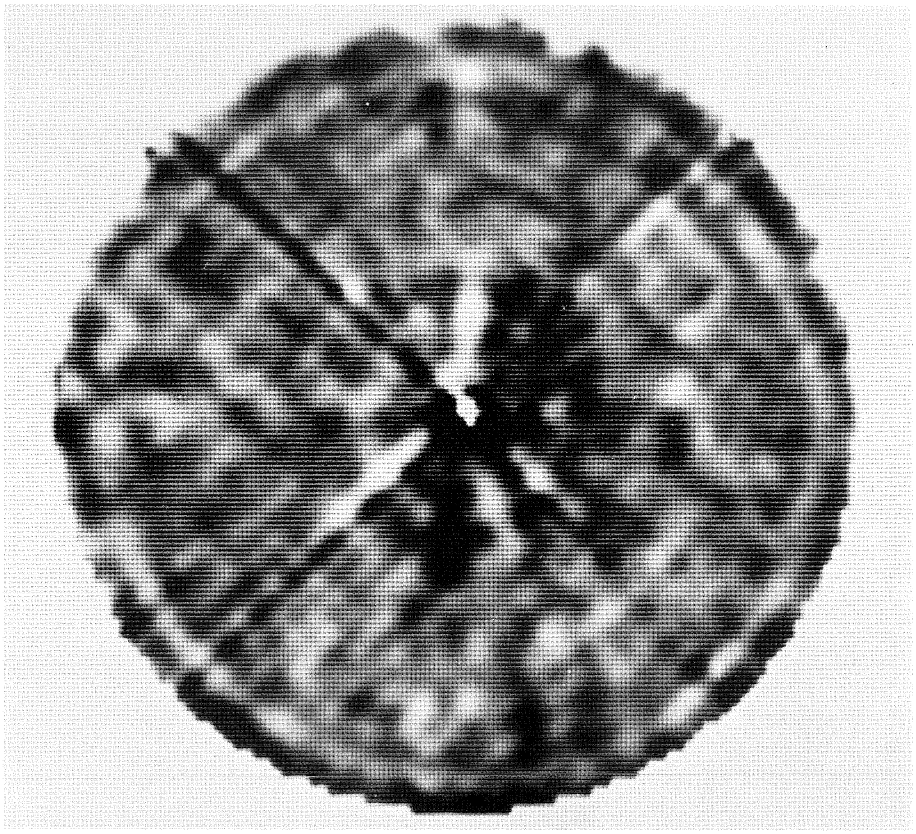
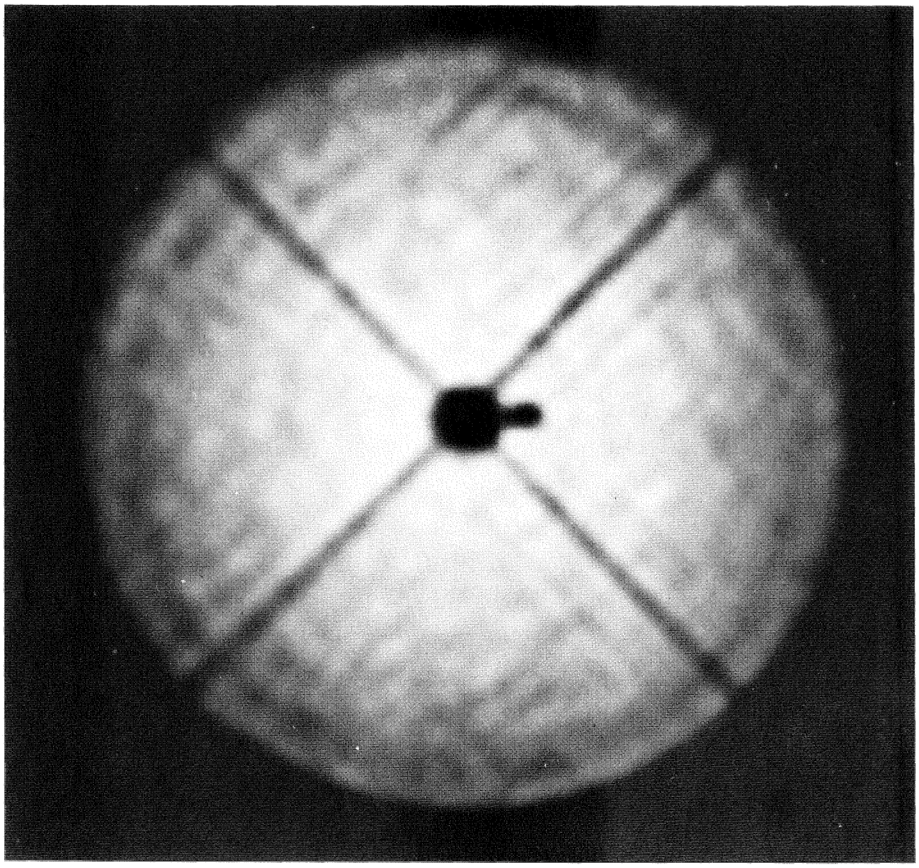
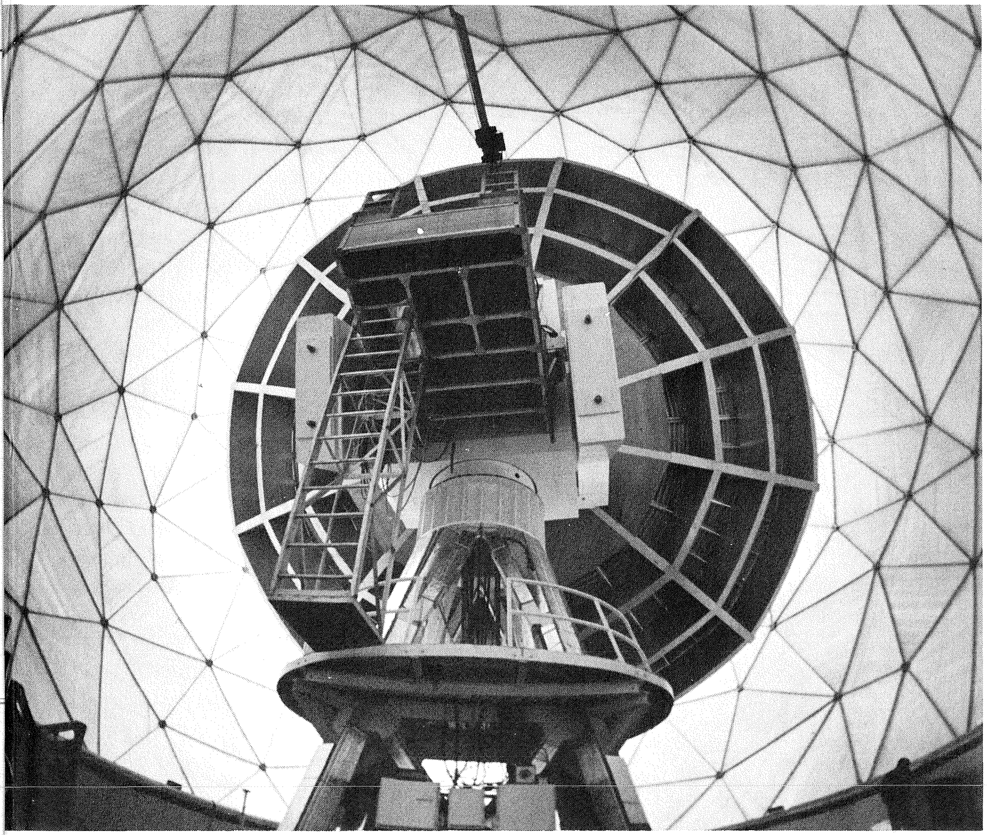


Precision checks. Holographic maps of the phase (above) and amplitude distributions show deformation of the telescope dish seen (right) in its dome at Five College Radio Astronomy Observatory. Adjustments are made with screws located behind the antenna panels.





the most accurate in existence. Three are already set up at Owens Valley, California, as a millimeter-wave interferometer; a fourth, now under construction, may be installed on Mauna Kea in Hawaii for sub-millimeter work.

Getting there

The Caltech group begins by assembling the antenna's backstructure, a tubular steel frame arranged as a rigid network of equilateral triangles. The surface, attached to this skeleton, is a lattice of 84 hexagonal panels made of lightweight, honeycomb aluminum. Leighton's key to attaining precision smoothness begins after the surface is in place. He and his team machine the entire honeycombed parabolic surface as one piece, as if they had it on a lathe.

As it points upward in the cavernous hall once used to polish Mount Palomar's five-meter telescope mirror, an aluminum Caltech dish is slowly rotated on an air bearing. While the curved bowl revolves like a carousel, a high-speed cutter mounted on a curved track suspended just above the surface moves slowly out along its radius. One complete cutting can be finished in four to eight hours. The precision of the cutter track, set long before the first piece of aluminum is peeled away, is achieved with simple geometry and a laser beam.

A parabolic reflector reflects every ray in a plane wavefront across an identical distance to the focus. Leighton takes advantage of this principle, mimicking the rays making up the plane wave with a laser mounted on the cutter's supporting girder. With the use of mirrors, the laser beam is directed down to the curved cutter track, up to the focus, and back to the laser. This process is repeated at many positions along the level, horizontal strut.

Because of the dish's parabolic geometry, the beam's pathlength should always remain constant. If the laser measurement shows a different reading at any point, the cutter track is adjusted to bring it into line. "In this way, we can be assured that the track forms a precise, well-defined parabola within an accuracy of two microns," notes Leighton. "The track has remained stable, without further adjustment, for two years now. That makes our process amenable to producing lots of dishes. We've already done four, and in our business, that's mass production."

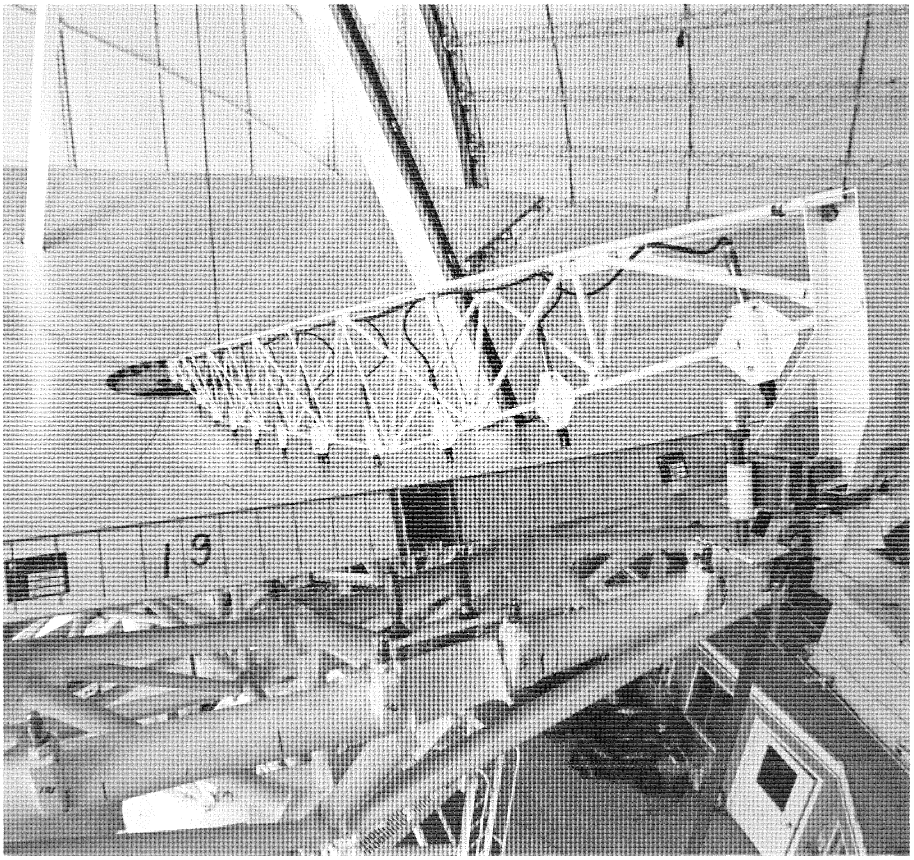
Once the honeycomb is machined, the reflecting-surface panels—sheet aluminum one millimeter thick—are fastened in place with epoxy. The machining of the honeycomb is sufficiently accurate that no further finishing is usually needed. An electronic transducer mounted on the cutter track makes the final check of surface smoothness. While the dish rotates, this device rolls outward along the radius, much like a record player pickup in reverse, building a contour map of the peaks and valleys in the surface. Given these data, a computer can calculate just how the seven adjustment screws behind each panel must be turned to bring the panels into proper alignment. So far, only the Mauna Kea dish actually needed to be adjusted at this point, because of the higher accuracy requirement of sub-millimeter wave detection.

Replacing tape-and-transit

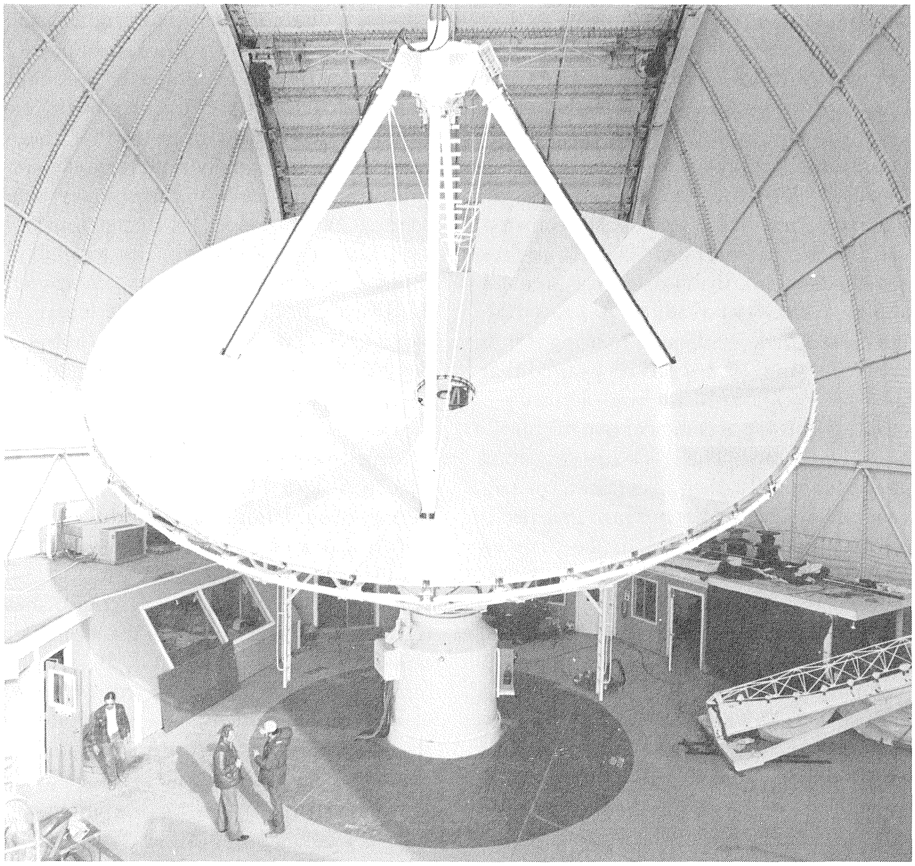
Caltech's unique ability to handcraft a precision telescope would be impossible without its temperature-controlled building. Other observatories must buy and assemble commercially produced panels in more difficult surroundings, most often the telescope site itself. This was recently done on Kitt Peak in Arizona where NRAO staff members completely refurbished their 16-year-old millimeter-wave telescope, one of the first ever built for that range of wavelengths. That 11-meter dish, a single piece of aluminum machined to an accuracy of 140 microns, was an engineering triumph for its time, says Gordon, "but thermally it was a nightmare. If as little as fifteen minutes of sunlight fell on it, it took ten hours for it to relax back to its original shape."

The decision was made to dismantle the telescope down to its supporting axis and replace the old dish with a new one 12 meters across. To maintain the parabolic precision needed in millimeter work, the new dish was given a backstructure design based on the extremely rigid form successfully used in the Very Large Array telescopes. "What helped us tremendously," says Gordon, "was the ability to analyze this design ahead of time on a computer. This could not have been done ten years ago." Overlaid on top of the steel support are 72 aluminum panels, molded to order by the Electronic Space Systems Corporation in Massachusetts. Measuring and then setting the panels to the desired r.m.s. accuracy of 75 microns, a level that would permit observations in the radio sky between 0.8 and 10 millimeters, was the greatest challenge.

In the past, many radio telescope dishes have been measured by the theodolite, or tape-and-transit, method. In this technique, familiar to surveyors, targets are mounted at various locations on the dish, and the smoothness of the surface is calculated by measuring the distance and elevation angle of each target from the center of the reflector. Some groups have improved the



Composite. An electronic template, or reference jig, is used as the fundamental reference for the dish surface at the National Radio Astronomy Observatory. Thinness of the sandwich panels complicates the adjustments. Finished dish has optical-quality surface.



technique by using the beam of a laser as the tape. The renovated NRAO telescope required even greater accuracy. To achieve it, physicist John Findlay, a veteran inventor of methods for measuring and setting telescope surfaces, designed a system in which the required parabolic curve is transferred from a reference shape on the ground to the antenna itself.

First, a truss-like template equipped with electronic depth sensors is placed on the reference shape so that the sensors can align with the curvature and have their positions stored in computer memory. This template is hoisted into the telescope dish and supported with its depth sensors resting along a line of panels. The adjusting bolts behind each panel are then turned until the computer indicates that the surface curvature, as measured by the sensors, finally matches the stored ideal curve.

New composites

In the future, telescope designers expect advanced technologies to enable them to increase the smoothness of large reflectors even more. The University of Arizona and West Germany's Max Planck Institute for Radio Astronomy are collaborating on a 10-meter-diameter sub-millimeter-wave telescope on Mount Lemmon, north of Tucson, designed for a surface accuracy of 15 microns. "This will be done with the use of newly developed composite materials," explains Ulich, project engineer for the telescope.

Each reflector panel will be made of six-centimeter-thick aluminum honeycomb sandwiched between sheets of graphite-epoxy. This novel composite will make the reflector lightweight yet strong and resistant to shape changes caused by fluctuating temperatures. The University of Arizona Optical Sciences Center is responsible for the molds for the panels, as a West German firm is for using the molds to manufacture the panels. Added precision will come from making the dish's back-structure homologous. That means that the dish will be designed in such a way that as the telescope tilts, it will always deform to a parabolic shape under gravity's pull. (The concept was first developed by NRAO's Sebastian von Hoerner.)

The thinness of the panels of the proposed sub-millimeter telescope introduces added difficulty in setting the surface. Many traditional techniques, which involve walking on the dish, are automatically eliminated. One possibility, says Ulich, is to point the dish at a bright, visible star and test it optically. This can be done because the Mount Lemmon telescope, unlike any others, will have a mirror-like surface; it will look like a giant solar collector. Screws on the back of each panel can be adjusted until the images of the star produced by the panels finally merge at the focus.

"But what these mechanical methods for measuring antenna surfaces do not have," points out Neal Erickson of the Five College Radio Astronomy Observatory in Massachusetts, "is the ability to measure the dish very quickly, within a few hours, and at any angle." To do this, many observatories are turning to radio holography, an electromagnetic way to map the deformations in a telescope surface. As Erickson puts it, "It's like taking a snapshot of the dish."

A snapshot

Several British radio astronomers, notably J. C. Bennett of the University of Sheffield, pioneered radio holography in the 1970s as a way to measure large centimeter-wave reflectors. As in optical holography, the method involves two beams of radiation—one scanning the object under study (in this case, the telescope surface), the other serving as a reference beam. However, in the radio regime, the hologram must be painstakingly constructed in a computer memory. The availability of relatively cheap mini-computers is finally enabling this mathematically intensive technique to be widely used at telescope sites.

To date, the most precise measurement of an antenna using radio holography has been done by Charles Mayer and John Davis of the electrical engineering department of the University of Texas at Austin. They measured the surface of the university's 4.9-meter millimeter-wave telescope at the McDonald Observatory in West Texas to an accuracy of four microns.

The Texas holographic system works this way: the 4.9-meter antenna is pointed at a transmitter, erected on a mountain eight miles away, which is putting out a pure 86-gigahertz (billions of cycles per second) signal. A computer records variations in the telescope's reception of that signal in both amplitude and phase as the dish slowly scans the 86-gigahertz beam. The changes are compared to the steady reference signal from a horn mounted behind the telescope focus. A complete scan of the surface, some 7,000 points, usually takes a few hours. Once the data are collected, a computer program translates the amplitude and phase deviations into a map of the dish's deformations, down to variations as small as four microns.

Using this map to reset the surface of the 4.9-meter Texas dish was tricky, since the surface is a single piece of machined steel coated with epoxy and a thin layer of gold; further machining is out of the question. The solution Davis and Mayer arrived at was the use of the holographic information to mount a compensating sub-reflector at the telescope focus. Davis explains: "Suppose we see from our holographic mapping that there's a dent in the primary dish causing a ray to travel a bit further to the focus. Then, we can put a bump on our secondary mirror to correct that pathlength difference." Since the secondary mirror is only 25 centimeters wide, it was relatively easy to construct on a computer-controlled milling machine that had the holographic map of the 4.9-meter dish stored in its memory.

"Normally, our dish deviates about 90 microns from a true parabola," notes Davis. "This new sub-reflector system better focuses the beam and makes it look as if the dish had an accuracy of 10 microns."

Astronomers at the university are enthusiastic. "The better the quality of the surface of the antenna, the higher the frequency at which we can operate," says Frank Bash, chairman of the Austin astronomy department. "This will open up an enormous amount of radio spectrum that was just impractical to observe before, because it took such a long time to get the data."

Bash expects the new results to affect current models of molecular clouds—their chemistry, isotope ratios, and lifetimes. "By checking the molecular transitions that occur at these higher frequencies, we can finally check many assumptions we've made about the clouds, such as their temperature distributions. In the past, our assumptions usually turned out to be wrong."

Not every radio observatory inclined to measure holographically can point its telescope at a transmitter on the horizon, but there are alternatives. Two years ago, for instance, astronomers from the University of California at Berkeley used Jupiter and Venus as radio sources when measuring the two six-meter dishes that form Berkeley's Hat Creek millimeter-wave interferometer; both planets emit strongly at 88 gigahertz.

Astronomers at the Five College Radio Astronomy Observatory in Massachusetts solved their problem by using a satellite for a scanning beacon. Erickson, who headed the group making that recent holographic measurement, explains: "We found we could scan our 14-meter dish with the satellite signal on one night, reduce the data on the computer over the next two days to generate a map of the dish deformations, and then in one or two days adjust the screws behind our paneled telescope to correct any misalignments. The whole cycle took just a week. We could even do it again to fine tune the dish."

The improvement in the Five College Observatory telescope was appreciable. With a theodolite, the observatory staff could set the surface to an accuracy of only 170 microns; with the holographic map as a guide, they produced 135-micron precision. The difference seems minute, but that 35-micron improvement has tripled the efficiency of their telescope at wavelengths of 1.3 millimeters. Because of such results, many other teams—the NRAO group at Kitt Peak, the sub-millimeter group in Arizona and West Germany, and Caltech astronomers, for example—plan to use radio holography as a final check on their telescope measurements.

The next major advance may take place in space. In the mid-1990s, the National Aeronautics and Space Administration hopes to launch what will be called the Large Deployable Reflector into earth orbit. It will be a 20-meter-wide dish designed to collect at wavelengths ranging from 30 to 300 microns, at which the earth's atmosphere is opaque. The telescope's major components may be assembled by astronauts working from either a space shuttle or a space station.

The deployable reflector will not have to contend with gravitational sags or atmospheric interference. Its requirement is nonetheless extreme: to maintain three-micron parabolic precision. The technologies to accomplish this have yet to be developed.

Back on the ground, the University of Arizona is looking into the construction of eight-meter telescopes of aluminum-coated pyrex, a material long used in optical telescopes because it can be polished to extremely high accuracies and resists heat distortion. For rigidity, the backstructure might even be imbedded in the glass itself. As Ulich concludes, "We have now reached the point that the new generation of radio telescopes and optical telescopes are beginning to merge." •

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