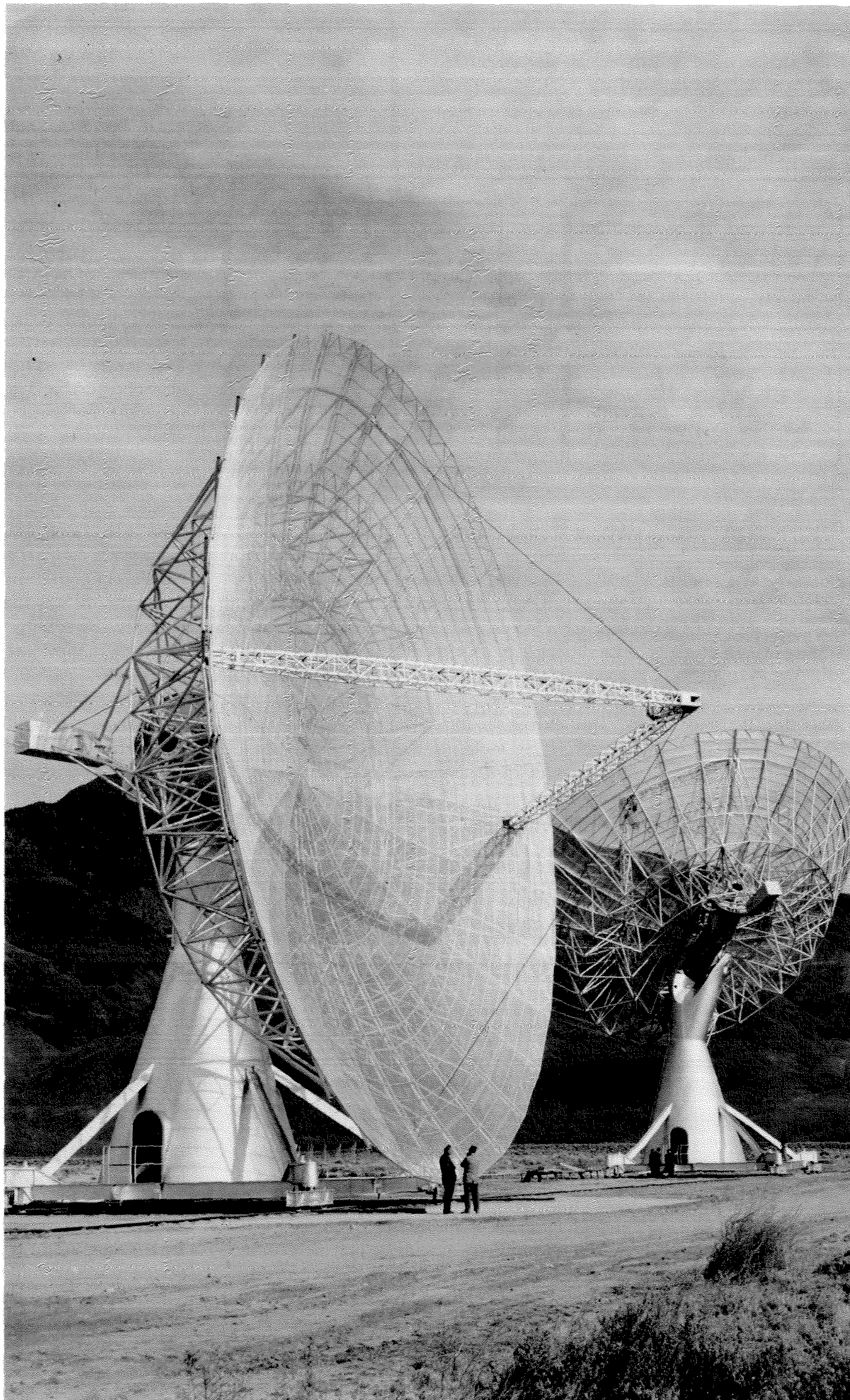


The Owens Valley Radio Observatory: Early Years

The early radio astronomy students were an exceptional group. They lived for long periods at OVRO and participated in the exciting task of building a large, novel scientific instrument.

by Marshall H. Cohen

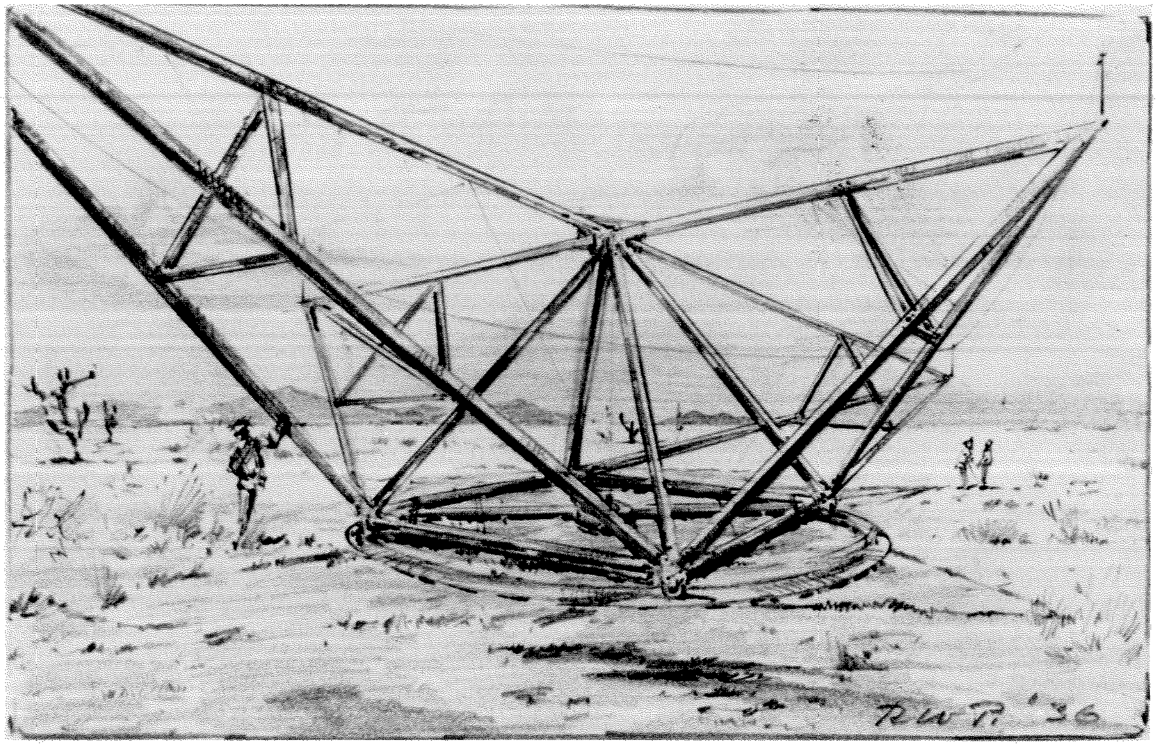
The two 90-foot antennas of the radio interferometer at Owens Valley, shown here after the completion of the dishes in 1959, formed one of the largest and most sensitive radio telescopes in the world. Each dish alone was larger than any in the United States at that time.

Heinrich Hertz demonstrated the existence of radio waves in 1888. Scientists immediately thought of looking at the sun for radio waves, but the early experiments, between 1894 and 1900, were hopelessly lost in noise. Thirty years later the sensitivity of radio receivers was enormously improved, mainly by the invention of vacuum-tube amplifiers, and cosmic radio waves were discovered in 1933. This discovery came by accident, and, moreover, the waves were not coming from the sun. As Karl Jansky at the Bell Labs was studying interference, he found a component of static that was fixed among the stars; that is, it came four minutes earlier on successive nights. Jansky recognized it as radiation from the Milky Way. During the thirties he and Grote Reber, a radio amateur from Illinois, mapped the source of this radiation, but for the most part it remained a minor curiosity.

Caltech, however, did have an abortive program in those early years of radio astronomy. Professor of Physics Gennady W. Potapenko, who was interested in Jansky's work, got his student Donald Folland (MS '36) to build a receiver to detect the cosmic radiation. In 1936 they tried observing with loop antennas on the roof of East Bridge, but it was too noisy. They then moved into the Mojave Desert, where they succeeded in confirming Jansky's results. Although their work was crude and never was published, it was promising and showed the need for a much larger antenna. They made a rough design for a rotating rhombic antenna, 90 by 180 feet, and persuaded R. W. Porter, the artist who made all the wonderful cutaway drawings of the 200-inch Palomar Telescope, to sketch it. Some question exists over how much money was needed to fund the project—Potapenko is quoted as asking for $1,000, but Fritz Zwicky, who also was involved, later said that it was only $200. In any event, Millikan refused to fund the project, and that was the end of radio astronomy at Caltech for 20 years.

During those years Jesse Greenstein, as a graduate student at Harvard, became interested in the problem of the origin of the cosmic radiation. He tried to understand Jansky's radiation in terms of thermal radiation from dust, and in 1937, with Fred Whipple, wrote the world's first scientific paper on interpretations of radio astronomical data. In that paper they showed that dust failed to produce the observed radiation by a factor of 10,000, but they had no alternatives. It was many years and many incorrect explanations later before anyone understood that the radiation actually was due to the synchrotron effect, from relativistic electrons gyrating in a magnetic field. Greenstein went on to play a major role in establishing the radio astronomy program at Caltech.

During World War II the sensitivity and reliability of radio systems again improved enormously, and after the war a number of radar engineers turned to the study of cosmic radio waves. The sun and the Milky Way came under immediate observation, but then many small sources also began to turn up. They were called "radio stars" but they clearly were not stars like the sun. In order to find and study these objects, radio astronomers in England and Australia built



In 1936 R. W. Porter sketched Potapenko and Folland's design for a rotating rhombic antenna, 90 by 180 feet, with which they wanted to detect cosmic radio waves. The project was never funded, and Caltech waited two decades before taking up radio astronomy again.

interferometers, antenna pairs that act together to give higher angular resolution than either antenna alone. In its simplest form, an interferometer comprises two antennas which behave exactly as a 2-slit interference experiment in elementary physics, producing fringes (a pattern of strong and weak bands), whose angular spacing is λ/s radians (λ is the wavelength, s is the linear spacing between the antennas). The spacing s can be large, so the angular resolution can be much greater than that available from one antenna alone, which is merely λ/d, where d is the diameter of the antenna.

In the early 1950s the most important interferometers or antenna arrays were at the Universities of Cambridge and Manchester in England, and at the Commonwealth Scientific and Industrial Research Organization (CSIRO, then called CSIR) in Australia. These groups produced lists of radio sources, but there were substantial disagreements that ultimately were traced to "confusion," that is, to artifacts produced when many weak sources are seen simultaneously. Not until the early sixties was the entire sky reliably surveyed. At that point several thousand radio sources were known, but most of them were "unidentified"; that is, they had no known optical counterpart. Identifying the sources—matching them up with something visible, such as a star or a galaxy—was laborious, and proceeded slowly. This work was important because the radio objects were very mysterious—their workings were unknown, and even their distances were unknown until the identifications were made.

Two of the main players in the identification work were John Bolton and Gordon Stanley of CSIR. In 1949 they made the first three optical identifications of compact, or discrete, radio sources: a galactic supernova remnant called the Crab Nebula, and two galaxies in Virgo and Centaurus—M 87 and NGC 5128. Interestingly, in their 1949 paper Bolton, Stanley, and Slee noted that although M 87 and NGC 5128 were generally called external galaxies, they had not yet been resolved into stars. If their proposed identifications were correct, their radio luminosities had to be unrealistically large, and they probably were nearby galactic nebulosities rather than distant galaxies composed of stars. This idea was wrong, but is only one of the many failures of the human imagination to grasp the size and complexity of the universe. Fifteen years later similar weak arguments were used to suggest that quasars were not at the enormous distances implied by their redshifts.

In 1951 Palomar Observatory got into the act when Graham Smith of Cambridge sent accurate positions for the strong radio sources in Cygnus and Cassiopeia to Walter Baade and Rudolph Minkowski, who were on the staff of the Mount Wilson Observatory (operated jointly with Palomar by Caltech and the Carnegie Institution of Washington). With the 200-inch telescope they found that Cassiopeia was a pale galactic nebulosity, the remnant of a supernova explosion, but the Cygnus source astounded them and everyone else, because the radio signals appeared to come from a very distant pair of galaxies in collision. (We know now that it is only one galaxy, but it has a dust lane which makes it look double.) The

The Observatory Committee . . . decreed that radio observations were outside the charter for Palomar Observatory, which spoke of using "light" to study the universe.

source had to have a million times more radio luminosity than is produced in the Milky Way to be so bright from such a distance, so this was indeed a remarkable object. Furthermore, astronomers then realized that some of the many weaker discrete sources should be even more distant, and radio galaxies might provide a powerful tool for probing the distant universe and studying cosmology. The potential of radio astronomy for exciting extragalactic research now appeared very high.

Jesse Greenstein, here in 1957 with a more famous Porter drawing, was one of the prime movers behind the establishment of radio astronomy at Caltech.

Radio Astronomy at Caltech

In the late 1940s three people with an interest in radio astronomy arrived at Caltech: Lee DuBridge, the new president; Robert Bacher, professor of physics and chairman of the Division of Physics, Mathematics and Astronomy; and Jesse Greenstein, professor of astrophysics and founder of the astronomy department. Greenstein had continued the interest in radio astronomy that originated at Harvard, and had tried, but failed, to establish a radio astronomy program at the University of Chicago, when he went to Chicago's Yerkes Observatory in Williams Bay, Wisconsin, after graduation. DuBridge had been director of the Radiation Laboratory at MIT during the war, and Bacher had worked there for two years before moving to Los Alamos; they were familiar with the wartime developments in radio astronomy. An important connection for both DuBridge and Bacher was the Australian Edward G. "Taffy" Bowen, who had worked in British radar since 1935 and had been a frequent visitor to the Rad Lab. After the war Bowen became chief of the radiophysics division at CSIRO in Sydney, where so much of the postwar development of radio astronomy occurred.

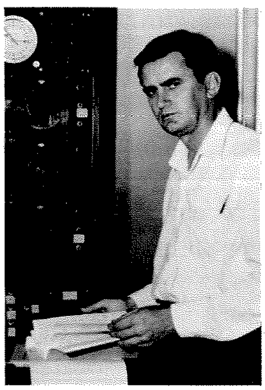
At first, most of the conventional astronomers at Caltech (and elsewhere) regarded radio astronomy as unimportant and even uninteresting, but that view changed when the exotic nature of the radio sources became appreciated. Around that time it also was generally recognized that the United States, where so much radar development had gone on, was rapidly falling behind Australia and Europe in this new field. Bowen and senior American scientists he knew from his radar years, including DuBridge and Bacher, met over this problem on a number of occasions. They considered the possibilities for large projects in both the U.S. and Australia, and conceived of the U.S. project as being at Caltech. In 1952 Bowen even wrote a "Draft Programme for a Radio Observatory" in which he stated that the next great advances in radio astronomy would come from associating radio and optical measurements, and that a very large dish, 200 to 250 feet in diameter, would be needed.

Meanwhile, Greenstein, along with the Mount Wilson astronomers Baade and Minkowski, was lobbying the Caltech administration to set up a radio astronomy program. DuBridge, however, had what in current officialese is called "programmatic concerns." Astronomy was organized under the joint Palomar and Mount Wilson Observatories, but radio astronomy was foreign to the astronomers—the techniques and style were completely different. The Observatory Committee, which advised the director, Ira "Ike" Bowen, on important matters, decreed that radio observations were outside the charter for Palomar Observatory, which spoke of using "light" to study the universe. Radio astronomy would have to be a separate operation in the Division of Physics, Mathematics and Astronomy.

In 1953 Greenstein organized a conference on radio astronomy to demonstrate the vitality and prospects of the field, and to prod the administration. It was held at the Carnegie Institution of Washington in January 1954. All the major radio astronomers of the world were there, and DuBridge underscored the importance of radio astronomy to Caltech by attending, along with Greenstein and Minkowski. This meeting was a great success, for not only did it impress DuBridge and thus set the stage for the Caltech project, but it also catalyzed the founding of the National Radio Astronomy Observatory (NRAO).

In 1954 it still was necessary to look to

Right: John Bolton with a model of the 90-foot dish. Below: Gordon Stanley, the receiver expert, another member of the Australian team imported for OVRO.



Australia or Europe for someone with experience in large radio astronomy projects, and DuBridge naturally consulted Taffy Bowen. (The Old-Boy Network was in full flower.) Bowen recommended the Englishman John Bolton, a prominent radio astronomer at CSIRO. Bolton had graduated in 1942 from the University of Cambridge with a physics honors degree, and then had immediately gone into military radar work. Settling in Australia after the war, he joined the CSIRO radiophysics group, a team that included a number of very talented but also very determined people. Bolton had differences with them, especially group leader Joe Pawsey, which led to his leaving radio astronomy temporarily in 1952 and joining the cloud physics group at CSIRO—with a promise from Bowen of a major role in the large telescope planned for Australia.

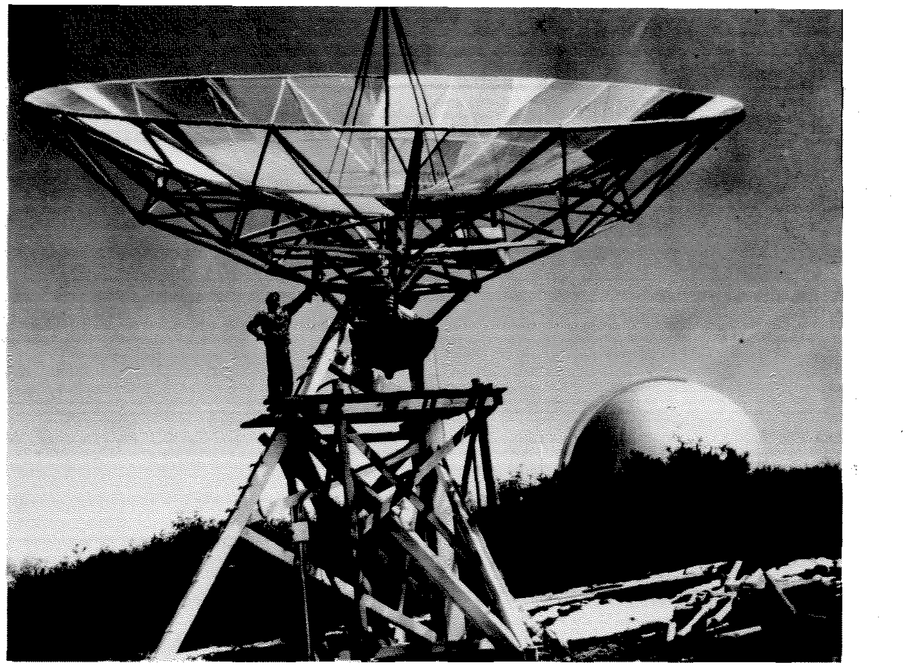
The Australian project started in early 1954, when the Carnegie Corporation, using funds restricted to projects in the British Commonwealth, granted $250,000 to CSIRO for the construction of a large dish. This was followed by a similar grant from the Rockefeller Foundation and these grants led to what became the 210-foot telescope at Parkes, in the countryside 200 miles west of Sydney.

So Caltech's timing in mid–1954 was right. The Institute wanted to start a program, and the talented and ambitious Bolton was available. A three-way discussion evidently took place, and Bowen later wrote, ". . . I arranged for Bolton and Stanley to be seconded to Caltech. This was to prove the starting point for radio astronomy in California." DuBridge offered Bolton a job (a two-year term appointment as senior research fellow in physics and astronomy, with a commitment to discuss a long-term association at the end of the term), and Bowen urged him to take it, adding (according to Bolton) that he could come back and run the new Australian dish when it was built. Bolton accepted the offer, and in January 1955 arrived in Pasadena with his wife, Letty, and their two sons. He was 32 years old, and famous for his work on discrete radio sources. Two years later he was promoted to professor of radio astronomy, and six years after he arrived, after establishing the Owens Valley Radio Observatory (OVRO), he did return to Australia, to the regret of the Caltech community. It is not clear how much the Caltech astronomers knew of the deal that had been devised to attract Bolton, but Greenstein and others were surprised and disappointed when he left.

Establishing OVRO

Bolton's war service and his work at CSIRO gave him an exceptionally wide background, and he was a talented jack-of-all-trades. But he needed help for the Caltech undertaking, and he brought along Gordon Stanley, who arrived a few months later. Stanley, a radio astronomer and receiver expert, had worked with Bolton at CSIRO, and was part of the team that made the first identifications of discrete radio sources. By the time Stanley arrived, Bolton had already decided to build a two-element, variable-spacing interferometer. This was not a new idea; Bolton and Stanley had considered a similar system a few years earlier, but it never got beyond the planning stage at CSIRO. For identification work the important goal was precise positions, and the high frequency and versatility provided by an interferometer were vital. DuBridge had already lined up support from the Office of Naval Research (ONR), and the project got under way immediately. (Getting new projects started was far, far easier in those days than it is today.)

Design and construction of the interferometer would take a few years, and Bolton and Stanley decided to use that time to build a modest prototype antenna. Its main purpose would be to test the advanced concepts they planned for the main instrument. Ike Bowen agreed to let them build it on Palomar Mountain, and so, in 1956 Caltech got its first radio telescope, a 32-foot dish outfitted with a 21-cm receiver. Interference was bad, but scientific observations were carried out anyway while receiving systems were tested. The study of hydrogen clouds by their radiation at a



Right: Bolton shows off Caltech's first radio telescope (here still unfinished)—a 32-foot antenna constructed on Palomar Mountain in 1956. In 1958 it was moved to Owens Valley (left) and re-erected with a solid fiberglass surface. A corner of the low-frequency array, the second instrument completed at OVRO, is visible at left.

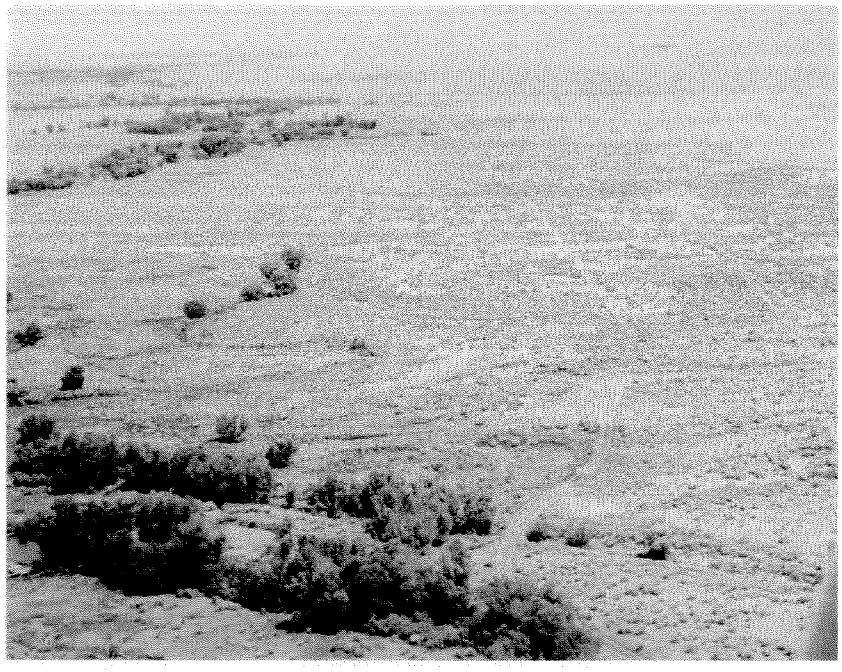
wavelength of 21 centimeters was still in its youth, and from Palomar the southern Milky Way was available for exploration. The first paper from the Caltech radio astronomy group, "A 21-cm Line Survey for Galactic Longitudes 294° to 328°, Latitudes ±8°," by Bolton, Stanley, and Harris, appeared in the *Publications of the Astronomical Society of the Pacific* in December 1958. The third author, Dan Harris (MS '57, PhD '61), was the first Caltech graduate student in radio astronomy. He arrived in June 1956 and spent much of the summer observing at Palomar.

In those days data reductions were often done by an assistant (called a "computer") using a mechanical calculator. Mildred Matthews, daughter of the famous Harvard astronomer Harlow Shapley, was a computer for Jesse Greenstein, and her daughter June, who had just graduated from high school, similarly helped the radio astronomy group by working on the data from the 32-foot telescope. June Matthews is now professor of physics at MIT.

All that remains of it now are some fragments at OVRO and pieces of concrete in the ground at Palomar, across the road from the museum.

The 32-foot telescope (shown above) was primitive by modern standards. It had an hour-angle drive controlled by the difference between two gear trains, one driven by a sidereal clock and the other set to the desired right ascension. The declination was set by moving the antenna with a large wrench. (Right ascension and declination are the same as longitude and latitude, only with respect to the stars rather than to the earth. As the earth turns, a star at a fixed right ascension appears to move across the sky, and the antenna must track its motion. The sky "rotates" once per sidereal day, which is 23 hours and 56 minutes: the missing 4 minutes is made up by the motion of the earth around the sun.) The receiver was of the single-channel, double-comparison variety (two comparison bands), with a bandwidth of 25 kc/s, and a receiver noise figure of 3. This was good for its time, even if recent generations of students will not know what these units mean. The telescope was dismantled in 1958 and installed at OVRO with a better surface. The astronomers intended to connect it as part of the interferometer, but it was never used that way. All that remains of it now are some fragments at OVRO and pieces of concrete in the ground at Palomar, across the road from the museum.

The site-selection process for the main observatory began soon after Bolton arrived. The chief requirements were for a large flat area and low radio interference. The latter meant that it had to be rather isolated, since the radio-noise level is roughly proportional to the local population density; it comes from noisy motors (or anything that sparks) and from communication devices of all kinds; taxis, police cars, and airplanes are a particular nuisance, as well as fixed strong sources such as radio stations. Nowadays the interference is worse, because of cellular telephones and other modern devices, and it is impossible to hide from satellites; but even in the mid-fifties the San Gabriel Valley was far too noisy for radio astronomy. (Indeed, it had been too noisy for Potapenko in 1936.) The Palomar area was desirable but also was too noisy, and the best nearby location had the ominous name of Earthquake Valley. So the search turned to the valleys to the north.



The Owens Valley site of the radio observatory (shown here "before") was, and still is, a ranching area. Before the DWP discovered it, there was extensive farming here also. The tree-lined Owens River, which winds around to the left, can be seen along the lower edge of the "after" photo on page 21.

By the time Stanley arrived, Bolton had already selected a location near Ojai, but that turned out to be a military site and unavailable. They then looked into more remote areas and in the summer of 1955, while Bolton was off at the general assembly of the International Astronomical Union in Dublin, Stanley and Temple Larrabee began investigating Owens Valley and other desert areas. Larrabee, a Caltech mechanical engineer, had helped build the 32-foot telescope and supervised much of the early construction at OVRO, especially ground clearance and the erection of buildings.

Stanley and Larrabee went through Owens Valley to the Mammoth Lakes area. They also tested the Saline Valley, which was very quiet but too remote; the nearest towns were 50 miles away on a bad road across the Inyo Mountains. Owens Valley was more civilized. The southern part was too close to military bases, but the northern part of the valley formed a good compromise between interference and accessibility. The Sierra Nevada shielded it from Fresno and other cities to the west and south; Los Angeles was 250 miles away, beyond the mountains; and, best of all, the Los Angeles Department of Water and Power (DWP) owned most of the land up and down the valley and was unlikely to allow much development to occur. The astronomers finally selected a site a few miles north of the Zurich railroad station, on the east side of the valley, five miles north of Big Pine. The east side was chosen because every 20 years or so the valley experiences exceedingly high winds, which decrease in strength from west to east.

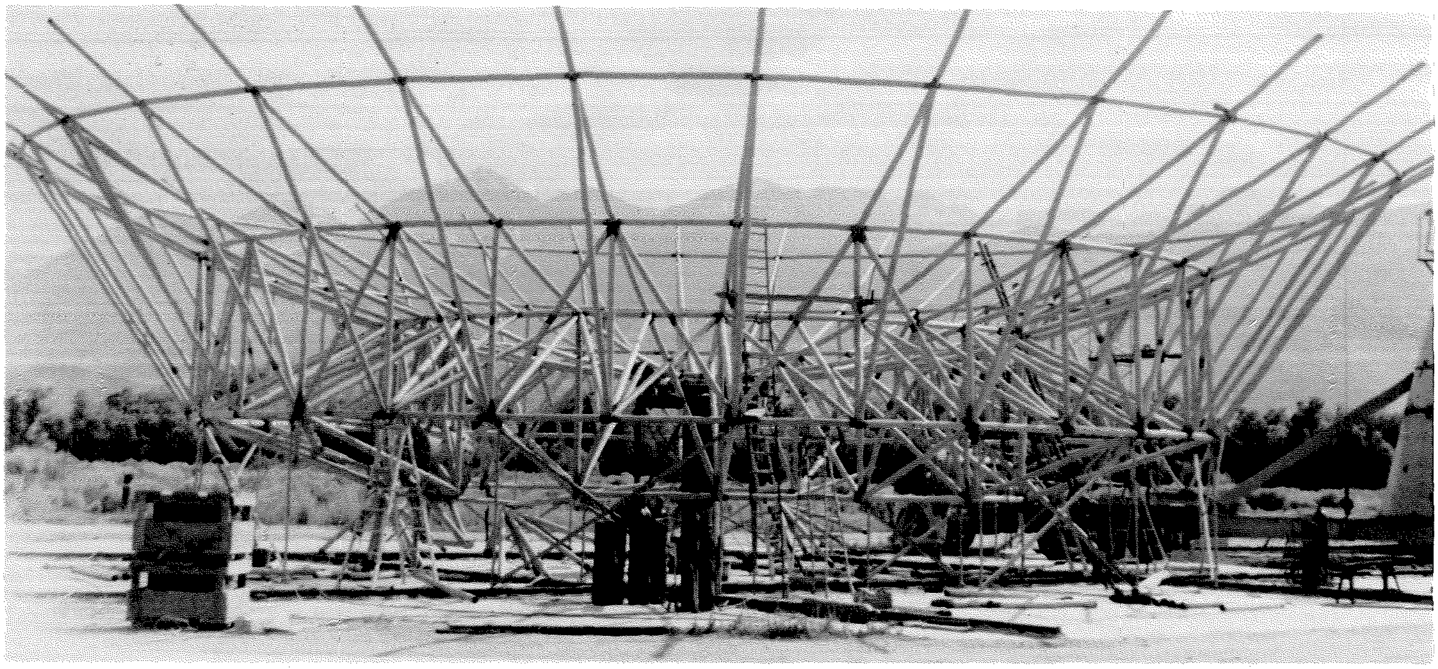
In 1956 Caltech arranged a 300-acre lease with the DWP. The lease was renegotiated in 1965, and an extensive area was added in anticipation of a large array that was never built. In 1988 a sub-lease was arranged with the NRAO, which then built an antenna for the Very Long Baseline Array.

The DWP is the biggest employer in Owens Valley, but there still is contention between the valley's citizens and the city of Los Angeles. Particular problems include the low water level in Mono Lake, the trout population in Rush Creek, groundwater pumping in the Owens Valley, and especially the dry condition of Owens Lake, which ranks as the worst dust pollution source in the United States. (On bad days alkaline dust from Owens Lake falls on the city of San Bernardino.) The current chief of the Great Basin Unified Air Pollution Control District (Inyo, Mono, and Alpine counties) is Ellen Hardebeck, who came to Caltech in 1969 as a research fellow in radio astronomy, and moved to Bishop in 1972, when her husband, Harry (another radio astronomer), accepted a job as an engineer at OVRO. The population ratio between Los Angeles and the Owens Valley is rather extreme, but Ellen is aided by the Clean Air Act, and manages to win many points against the city.

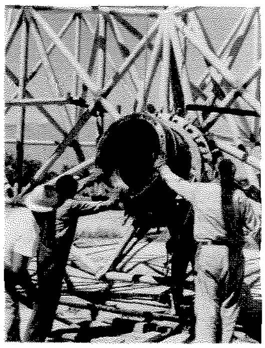
Control of Owens Valley water and land by the DWP may make life difficult for people who live close to Owens Lake, but it has kept development away, and the observatory remains one of the quieter sites still being used for radio astronomy. The contrast could not be stronger than between the regions around OVRO and the Palomar Observatory. A half million people now live in the valleys east and north of Temecula, and their communities creep to within 15 miles of Palomar Mountain, but the Owens Valley has changed only slightly in the 39 years since the observatory was founded.

Building the Interferometer

Bolton's goal was to make a two-antenna interferometer to be used mainly for determining the precise positions of radio sources. The antennas would be 90 feet in diameter, a size representing a compromise between cost and sensitivity. The antennas, like the 32-foot prototype, were polar-mounted; the modern efficient design with azimuth and elevation axes was awkward before computers became available. The mount had an axis parallel to the earth's pole (the polar axis) and another at right angles (the declination axis). The polar motion was limited to ±4 hours, or ±60°. This feature was economi-



Above: The skeleton of one of the 90-foot dishes rises against the Sierra Nevada, which borders the valley on the west. Below: Workers position the hub at the center of the dish.

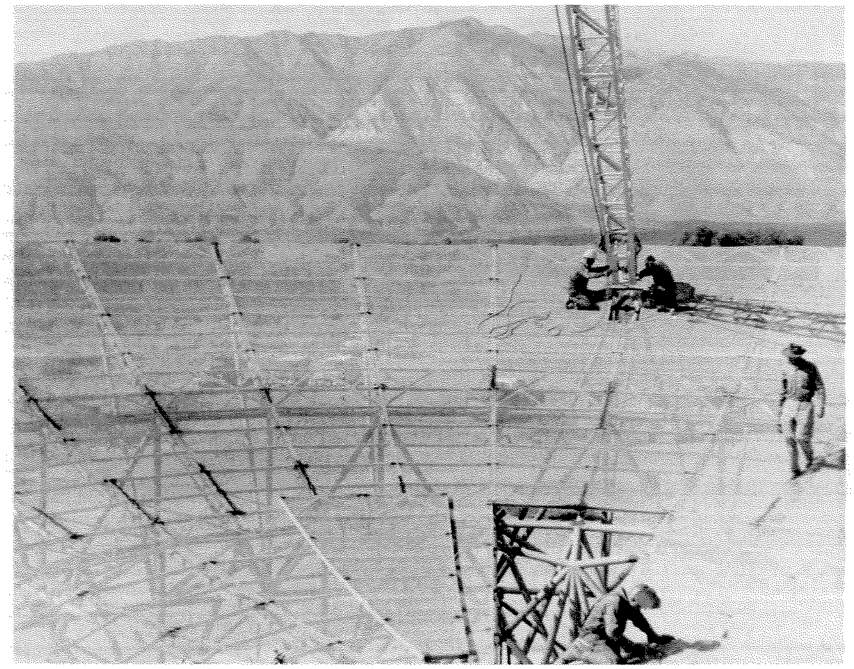


cal because the axes did not have to be cantilevered; thus there were no off-axis wind loads, and less stress to be resisted. This was a compromise between cost and versatility, and has sometimes been a liability; for example, it currently limits observations of the sun to eight hours per day. A more dramatic design feature was the railroad track: the antennas were movable on tracks extending in an L-shape 1,600 feet east and north from a central station. At a wavelength of 75 cm this would give a minimum fringe spacing of 5 arcminutes, and on a strong point source the positional accuracy would be a few seconds of arc. This was adequate for the planned optical identification work.

The objective, of course, was more general than simply pinpointing the sources and associating them with optical objects. It also was important to find their sizes and spectra so that the physics of the radio sources could be studied. This required a range of angular resolutions, which is why the antennas had to have variable spacing. The idea is that for each spacing between the antennas there is a characteristic angular scale, and measuring the interferometer output (the "fringe" amplitude) gives information for that particular scale. By measuring at many spacings, the full information on the source can be developed. (Technically speaking, the fringes are sine waves which modulate the brightness distribution of the source, and a measurement of the complex fringe amplitude is an integration over this modulation, which yields one component of the Fourier transform of the source. After measurements are made at all the spacings, the inverse transform is calculated; this is the desired image.) The antennas had to be exceptionally stable when in use, and were set at stations on the tracks, which had electrical connections and also provided precise support and positioning. There was a station at the center of the L, and stations were set at 200, 400, 800, and 1,600 feet both east and north of the center. This gave many differential spacings, but most could not be used because the outlying stations were connected only to the center and not to each other. In later years more stations were added, and the track was extended to 600 feet west of the center.

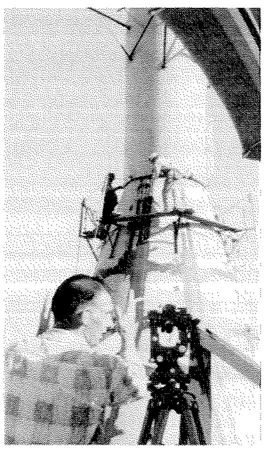
The original intention was to operate the interferometer at 400 MHz, with a buried waveguide connecting the dishes. During the design and construction years, however, higher frequencies became both desirable and convenient, and the first system installed was at 750 MHz, with a buried cable rather than a waveguide. That system in turn was quickly replaced with 960 MHz, which was in a protected space-communication band. The JPL systems on the Explorer satellites operated at that frequency, and they used receiver front-ends designed by Stanley at OVRO. This was one of the first of many mutually beneficial close collaborations between JPL and the Caltech radio astronomy group.

Bruce Rule, Caltech's chief engineer, who had already distinguished himself in telescope design through his major role in the 200-inch Palomar project, designed the antennas, with the substantial assistance of Charlie Jones (BS '32) , who ran a Pasadena engineering firm. The reflector was made of steel mesh with 1-cm holes—sufficiently



The reflectors (far left) were made of steel mesh with 1-cm holes. The 45-foot pedestals, or towers (below), were constructed separately and the dishes hoisted onto them later.

Right: It took three cranes, manned by a rigging crew of 12, to lift one of the huge dishes onto its pedestal. Securing it in position involved meshing the pedestal gears with the driving gears on the dish, and welding two counterweights of 18 tons each onto the dish before the cranes could release their grip.



Bolton, with a theodolite, checks the installation of the top section of the tower for one of the antennas in 1958. Bolton spent a lot of time at OVRO, watching the details of construction and doing some of it himself.

smaller than the wavelength, first 75, then 40, then 31 cm. Still shorter wavelengths were steadily introduced, however, and today the short-wavelength limit of the antennas is 2 cm. To keep up with the shorter wavelengths, the surface was substantially improved in 1964. A quadrupod replaced the original feed support bipod, the backup structure was strengthened, and the reflector's mesh changed to solid aluminum (perforated near the rim).

Stanley supervised the electronics for the interferometer, and he designed and built the receivers. At the beginning these had crystal mixer front ends, using the wartime-developed 1N21 crystals. The local oscillator used a planar triode that had been developed for use in rockets. For stability and tuning this was secured inside a rugged brass cylinder with various protruding rods; it looked like a 19th-century steam engine and so, of course, was always known as a Stanley Steamer. These receivers were probably the best in the world at the time, with system temperatures in the range 300–400 K. They were retired in the 1960s as parametric amplifiers became available, and yet later the paramps were mercifully replaced with transistor amplifiers, which had lower noise, more stability, more bandwidth, and also were cheaper and much easier to work with. Maser amplifiers also have been used; although tricky and expensive, they give the lowest noise.

Charlie Jones oversaw construction at OVRO, which took place between 1956 and 1960. A Los Angeles contractor prepared the site and built the east arm. The money for the north arm, however, began to disappear too soon, and Bolton himself became the site contractor. He involved himself with every detail of the construction and, indeed, had immersed himself in nearly every facet of the project from its beginning.

The total cost of preparing the site, including roads, buildings, utilities, and the tracks and antenna caissons for the east arm, amounted to somewhat over $100,000. This money came from the Institute and was the first of many generous contributions that Caltech has made to radio astronomy. ONR provided the rest of the construction cost, and the operating costs. The capital construction costs through 1960 were about $900,000, while the yearly operating costs increased from about $90,000 in 1956 to $136,000 in 1961.

After the war the ONR was an important source of funding for basic scientific research in the U.S. and helped many programs get started. This continued even after the National Science Foundation (NSF) was founded in 1950, and in the late sixties both NSF and ONR supported OVRO. Congress, however, grew unhappy with what it saw as misspent defense funds, and in 1970 passed the Mansfield Amendment, which restricted Defense Department funds to projects with military applications. At that point ONR had to drop OVRO. The NSF picked up the slack and since then has provided most of the support.

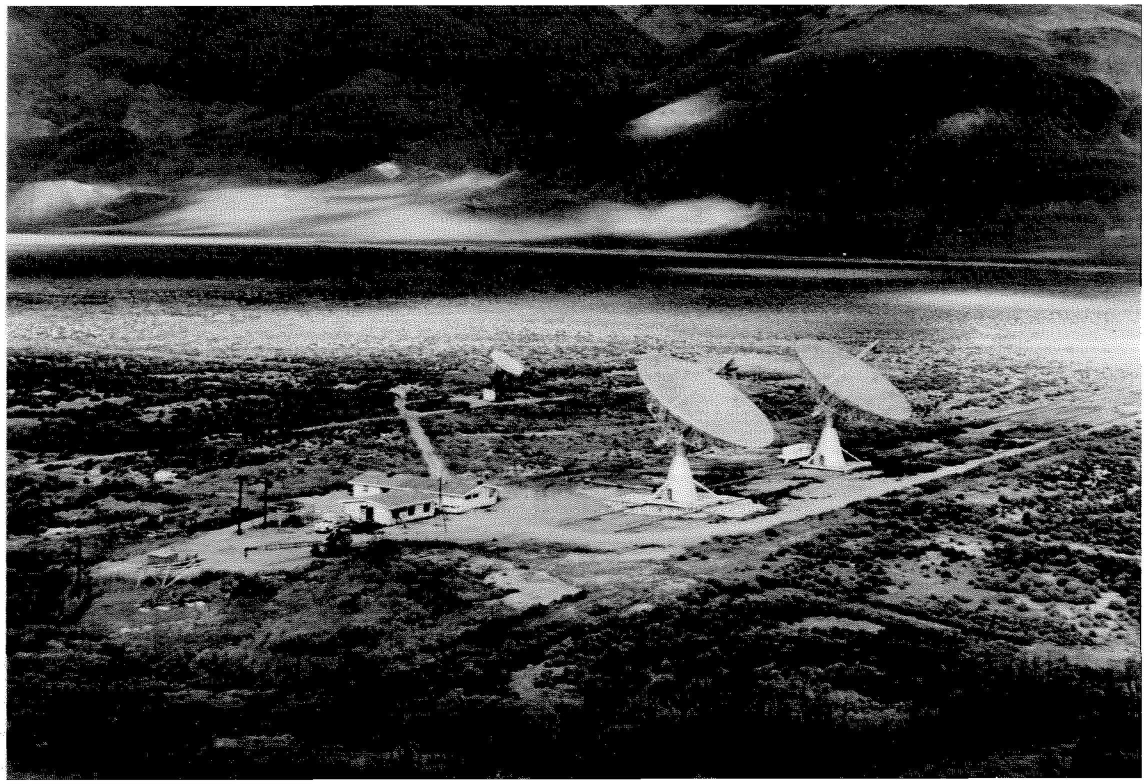
Arnold Shostak was the genial program manager at ONR, and for many years he helped promote radio astronomy throughout the United States. Surplus military equipment was available

We can only speculate as to how such elderly German rails ended up at a naval station in Southern California.

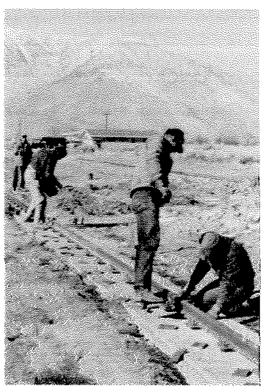
to those with the right connections, and Shostak scrounged the world over for OVRO. Most important, he found lead weights from the submarine base at Subic Bay in the Philippines and railroad tracks from the Navy depot at Port Hueneme. Most of the rails were stamped "Krupp 1880"; we can only speculate as to how such elderly German rails ended up at a naval station in Southern California.

The interferometer was dedicated in December 1958, although the north arm had not yet been built. DuBridge attended, as well as Albert B. Ruddock, chairman of the Caltech Board of Trustees. Rear Admiral Rawson Bennett II, chief of naval research, represented the ONR. The second reflector had been hoisted up on its pedestal a few weeks earlier, so that, superficially, the system looked complete, but the distinguished group of visitors probably was not fooled. As always at such affairs, the system was a long way from being operational.

Observations with one antenna started in April 1959, and the first fringes with the complete east-west interferometer were obtained at the end of the year. Bolton and research fellow Dave Morris completed the final linking of the two dishes at Christmas, and they endured an agonizing four days during which they tore apart and rebuilt the whole system; every component worked correctly but no fringes showed up. Finally, they discovered that the IF cables, still on their drums as provided by the manufacturer, were not identical but differed in length by 500 feet. Once found, that problem was readily cured, and the interferometer worked as expected.



Right: OVRO from the air before the north arm was begun, probably in 1959. The living quarters and the shop are visible in the foreground and the 32-foot dish just above it. Between the 90-foot dishes, behind them, the low-frequency array of dipoles is also faintly visible. Below: Workers construct the tracks of the east arm in 1957.



The North Arm

The observatory staff itself, in particular the graduate students, built most of the north arm of the interferometer in 1960. Dick Read (BS '55, PhD '62), who still works with the interferometer as a senior research engineer in solar physics at Caltech, did the survey work. Glenn Berge (MS '62, PhD '65), currently a senior scientist in planetary sciences, did much of the welding of the reinforcing rods in the sleepers under the tracks. A local construction company poured the cement for the sleepers; one of its employees, then-18-year-old Chick Lackore later got a permanent job at OVRO and still works there, the only current OVRO employee involved in the original construction. Bolton himself and "Big Al" Munger also helped with the welding. Big Al worked at OVRO for 10 years as a general technician and handyman.

He and Ken Kellermann (PhD '63) strung many miles of wire for the north arm; Barry Clark (BS '59, PhD '64), with Bolton and George Seielstad (PhD '63), did the same for the east arm. Clark had worked summers at OVRO since 1957, helping with the construction of the low-frequency array and the installation of the 32-foot dish. Clark and Kellermann joined the National Radio Astronomy Observatory after graduation, the latter after a stint as postdoc at CSIRO, and they, along with later graduates, played major roles in the development of the various arrays at the NRAO. Kellermann has returned to Caltech twice as a Fairchild Scholar, in 1981 and again in 1992–93.

Seielstad also operated the crane and moved the rails about. He went to the University of Alaska when he graduated, but after a year returned to OVRO, where he remained for many years. In 1984 he left for NRAO to be the assistant director for Greenbank operations. He is currently an associate dean at the University of North Dakota. Another early graduate student was Alan Moffet (PhD '61), "Little Al," who as a graduate student first worked in nuclear physics, but joined the OVRO team in 1959. After a year in Germany as a Fulbright Scholar, he returned to Caltech as a postdoc and ultimately became radio astronomy professor and director of OVRO.

The most senior student, Dan Harris, had already done a good share of work on the 32-foot antenna, but still had to help on the north arm. Harris worked at a number of radio observatories after graduation (in Argentina, Italy, the Netherlands, Puerto Rico, and Canada), and currently works at the Harvard-Smithsonian Center for Astrophysics. Another early student was Fritz Bartlett (MS '61), whose chief interest lay in computers and programming; he introduced modern computing into the observatory. Bartlett never finished his doctorate, and after a number of years he left OVRO and worked as a programmer in high-energy physics at Caltech.

Several of the students worked with Stanley on the electronics, in particular Moffet, Read, and Bob Wilson (PhD '62). Wilson joined Bell Labs after graduating, and a few years later, in a painstaking search with coworker Arno Penzias for spurious noise sources in their receiving system, discovered the cosmic background radiation left over from the Big Bang. There are many parallels between this discovery and that of Jansky 32 years earlier. Jansky did not live to get the Nobel prize, but Wilson and Penzias did, in 1978.

Work on the north arm stretched through the hot summer of 1960. Living quarters at the observatory were very crowded, and Bolton established a strict set of rules and duties, sorted by seniority. In particular, first- and second-year students were warned about neatness: "All clothing, shoes and other personal effects are to be stored in drawers or closets and not left lying around." Third- and fourth-year students were merely enjoined to keep their rooms as tidy as possible. The cook and housekeeper was a warm-hearted, if formidable, woman named Rachel Gates (now deceased), and she ran the kitchen with an iron hand. She prepared three meals a day: lunch, afternoon tea, and dinner. The custom of morning coffee and afternoon tea is still rigidly observed at OVRO.

Bolton started what became a vital tradition of students spending long periods at the observatory, first building and then using the telescopes.

The early radio astronomy students were an exceptional group. They lived for long periods at OVRO and participated in the exciting task of building a large, novel scientific instrument. They worked closely with Bolton and Stanley and with a talented group of research fellows, including Jim Roberts and Kevin Westfold (actually, a visiting associate professor) from Australia, Dave Morris from England, Tom Matthews from Canada, Per Maltby from Norway, and V. Radhakrishnan (Rad) from India, who returned to Caltech in 1980–81 as a Fairchild Scholar. Some of them were fairly adventurous. Rad bought a trimaran and, with Morris and Harris as crew, sailed from England to Australia in 1962–63. On the way they called at Puerto Rico, where Harris left the boat and took up a radio astronomy position working with me at the Arecibo Observatory.

Bolton started what became a vital tradition of students spending long periods at the observatory, first building and then using the telescopes. They also had to work in the electronics lab in Robinson. Under the tutelage of technician Johnny Harriman, each new student had to build a power supply for the interferometer, and some of them did a great deal of electronics work. Caltech students have always been thoroughly trained in the tricky art of interferometry. They have provided much of the expertise needed to build interferometers at NRAO and at other institutions. Caltech still provides students with hands-on experience at building telescopes and their instrumentation, but there are only a few institutions left in the world where such opportunities now exist. It is much more difficult to provide this experience to graduate students now than it was 30 years ago, because radio observatories everywhere have become more expensive, more formal, and more automated. Most forefront research now requires large and expensive telescopes, and most of these are run by professional staffs. Graduate students (and professors) are welcome as users but participate little as builders, and this split between "user-astronomers" and "builders" becomes ever wider. At Caltech we always have regarded this as unhealthy and have worked to maintain an environment where students use their hands for more than typing on a keyboard.

The Early Science Program

The first instrument working at OVRO, apart from the 32-foot dish, was a low-frequency interferometer consisting of two large arrays of dipoles. In the summer of 1957 this device monitored the Crab Nebula as it passed near the sun. Two years earlier radio astronomers had discovered that the flux from the Crab decreased during this period, and suggested that it was due to scattering in the solar corona. The OVRO work aimed to extend this study by measuring at a new wavelength, 12 meters. In 1957 solar interference in fact was too strong for the OVRO group to make the measurement, but they achieved success in 1958. This generated the first paper in the "yellow jacket" preprint series: "A Solar Occultation of the Crab Nebula at a Wavelength of 12 Meters," by Bolton, Stanley, and Clark, published in December 1958. (The yellow jackets have yellow covers, of course, but the name derives from the nasty ground wasps that seriously annoyed the early workers at OVRO.) The arrays really were built, however, to study the fluctuations imposed on a radio signal as it passed through the earth's ionosphere (ionospheric scintillations), a phenomenon that also interested the Thompson Ramo Wooldridge Corporation (TRW). Some of the data given to TRW were classified because they were useful in tracking ICBMs, or so TRW thought. These low-frequency arrays were used until early 1959, when the first 90-footer began to work, and they were dismantled a few years later.

When the first antenna came on line early in 1959, observations started immediately, even as the second antenna was being finished and the interferometer electronics perfected. The scientific staff included six students and four research fellows in addition to Bolton and Stanley; within a year these numbers rose to nine and six, respectively. As design and construction were a group effort, so were scientific observations. Different observing projects were defined and became the property of a small group—one or two people—but all observed for each other as they worked their shifts. Many of the students worked with a postdoc. Observing in the 1950s, without a computer, was *real* observing, with continuous manual setting of selsyn dials, interpolations in calibration curves, filling the pens of ink recorders, adjusting the voltages, and occasionally chasing away a cow.

In 1959 a single 90-foot antenna, operating at a frequency of 960 MHz, was all by itself a world-class instrument. Other large dishes in the U.S. (at the Naval Research Laboratory, the University of Michigan, and NRAO) had diameters of 84 or 85 feet. The OVRO 90-foot telescope was also bigger than any instrument in the Netherlands where much of the world's hydrogen line studies of the Milky Way had been made. The only one in the world that had more sensitivity and comparable versatility was the 250-foot telescope at Jodrell Bank in England.

Observing in the 1950s, without a computer, was real observing, with continuous manual setting of selsyn dials, interpolations in calibration curves, filling the pens of ink recorders, adjusting the voltages, and occasionally chasing away a cow.

A group from the Convair Corporation, led by Gail Moreton and Bill Erickson, started a program of monitoring the sun on the first 90-footer. They had a swept-frequency receiver and did simultaneous radio and optical observations (the latter with a 4-inch Questar). The Convair group included Chuck Spencer, an engineer who stayed on after the solar program stopped, and worked at OVRO until his retirement in 1985. This program operated during the International Geophysical Year (1958–59) and was one of many that followed the sun and its interactions with the terrestrial atmosphere.

In the spring and summer of 1959 Stanley and postdoc Jim Roberts measured the radiation from Jupiter at a wavelength of 31 cm and showed that its apparent temperature indeed was high (5,500 K) and that Jupiter had a Van Allen belt like Earth, as had been suggested by observations at shorter wavelengths. Bob Wilson and Bolton made maps of the galactic plane and cataloged point sources in the Milky Way; many of these would turn out to be supernova remnants. Wilson's PhD thesis grew out of this work.

Using a 21-cm receiver in the second 90-foot dish, when it became available, Radhakrishnan studied self-absorption in hydrogen clouds, and proved that the temperature of clouds near the supernova remnant IC 443 could be no more than 60 K. At the time the consensus had been that these clouds were at a temperature of about 125 K (although there had been suggestions that some were colder) but Rad's work showed that the clouds came in greater variety and were more complex than had been assumed.

Much of the work with the single antenna, however, was directly related to the prime motivation behind the whole project—identification of the discrete radio sources. By 1959 the Cambridge and Sydney catalogs had been refined well beyond the early work, which had contained many errors and false sources. But there still were discrepancies, and errors in position of minutes of arc, 10 to 100 times worse than required for identifications. Harris and Roberts studied about 100 objects from the third Cambridge catalog, in order to prepare an accurate finding list for later studies with the interferometer.

The CTA (for Cal Tech List A) catalog, the result of the work by Harris and Roberts, also contained a number of new objects discovered by chance. One of these, CTA 102, was seen to fluctuate by Sholomitsky in the USSR in 1965. Unfortunately, this observation was coupled with the notion of external civilizations sending us radio signals, and a popular song was even written about CTA 102. Although Sholomitsky's work was not believed and indeed "proved" wrong, that view has changed and now it is realized that Sholomitsky could well have been correct. CTA 102 and other small sources do fluctuate at decimeter wavelengths, because irregularities in the interstellar medium cause "seeing" much like the twinkling of stars.

When the east-west arm of the interferometer became operational in February 1960, it immediately began to measure accurate right ascensions (RA) of known strong sources, to get at the identification problem that had been driving the project from the beginning. The most spectacular success came with the object 3C 295, which was thought to be a distant analog of the Cygnus A radio source. A reasonably good position had been supplied by the Cambridge group in 1959. The improvement in RA provided by the Caltech interferometer then enabled Rudolph Minkowski, using the Palomar 200-inch telescope, to identify 3C 295 with a distant galaxy with a redshift of 0.461. This made it about eight times farther away than Cygnus A, and for many years it was the most distant galaxy known.

One of the first programs was a study of galactic clouds composed of neutral hydrogen. Such studies in the previous decade (made with a single dish) had led to a mapping of the Milky Way, but no one had a clear idea of the size and structure of the clouds themselves. The interferometer, with its high resolution, could give detailed information on the size, density, and temperature in the clouds. Barry Clark's thesis grew out of this work, and several later students

The completed L-shaped interferometer in the early 1960s, looking east (top) toward the railroad and the White Mountains, and north (bottom) along the floodplain of the river valley.

also wrote theses on interferometric studies of hydrogen clouds. In recent years this has become a major industry at OVRO, with many people studying interstellar clouds with the new millimeter interferometer. Most radio astronomers nowadays, however, study exotic molecules such as carbon monoxide, hydrogen cyanide, or formaldehyde, rather than neutral hydrogen atoms.

Kellermann and Harris conducted another early program with the east-west interferometer, observing 739 sources from the Sydney catalog in order to check its reliability. The OVRO interferometer was well suited for this, as it operated on a much higher frequency than the system used at Sydney (960 MHz vs 86 MHz) and had better positional accuracy. Checking the existing catalogs was important, not only to improve positions but also to establish the degree of completeness, to settle a statistical argument. The data suggested that there was a strong cosmological evolution in the density of extragalactic radio objects—that they had been much more numerous in the distant past. This conclusion depended critically, however, on having complete and accurate data. By 1960 the main discrepancies between the Cambridge and Sydney data had been eliminated; but many uncertainties remained and there were fierce arguments over the correct interpretation.

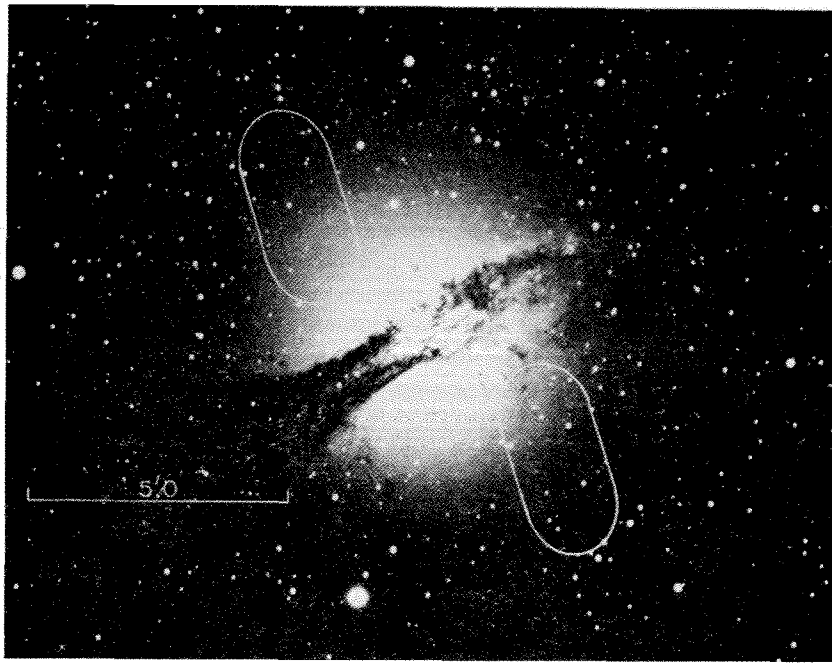
Kellermann and Harris found approximately three-quarters of the Sydney objects. Some of the missing sources were too weak to be seen at the high OVRO frequency, but many apparently had substantial position errors. Further, some of the Sydney sources listed as "extended" actually were blends of two or more independent objects. The result of this work was that the major catalogs were corrected, but still the arguments over evolution persisted. Indeed they have not totally died down now, 30 years later. Although the evidence for an evolutionary universe is regarded as overwhelming by nearly all astronomers, a small but ingenious band of astrophysicists still returns regularly to the idea of a steady-state, nonevolving universe.

The Full Interferometer

In late 1960 the north-south arm also started functioning. Dick Read was able to use it to determine accurate declinations for many sources, and this formed part of his thesis. His work reduced the error boxes for the location of many of these objects, and allowed the important identification program to accelerate. This involved a major collaboration between the radio astronomers, who measured positions with the interferometer, and the optical astronomers, who tried to find the corresponding objects with the Palomar telescope.

With two-dimensional measurements, two-dimensional models or even crude maps could be made, and a new level of investigation began. The maps were the best the world had seen to that time, although primitive by modern standards, and a number of striking results were obtained in the first few years. The procedure was developed in Cambridge and Sydney in the 1950s and is called "aperture synthesis" or "earth-rotation synthesis." In this scheme a simple interferometer is used at many spacings, and the measurements are combined to give the result of the entire set working at once, that is, a large aperture is synthesized. Observations out of the meridian plane give more data because the earth's rotation gives a variety of projected spacings (as seen from the sky) without physically moving the antennas. This is not as easy as it sounds, however, because the differential delay in the two sides must be compensated by extra cable inserted into the short side, and the delay change must be tracked with high precision. At first the OVRO interferometer was used only in the meridian plane; then observations were made at fixed-hour angles, and, after a few years of technical development, continuous tracking became possible. Fritz Bartlett and Dick Read, following Stanley's suggestions, built a wonderful analog computer to accomplish part of this. It was full of interesting wheels and cams, and it was a sad day when it was replaced by a microprocessor.

Barry Clark recently wrote of this device, "I



This picture of the galaxy NGC 5128, photographed with the Palomar 200-inch telescope, is taken from an article published by Per Maltby in *Nature* in 1961. Superimposed is a model of the radio emission (the two ovals) made with east-west and north-south observations at two frequencies with the interferometer. The radio source is double and lies outside the dust region (the black bands along the equator). NGC 5128 also has a gigantic outer radio source that stretches for a full 10° across the sky.

Right: This circa-1960 view of the OVRO variable-spacing interferometer looks from the northeast toward the Sierra Crest skyline. The system has been through many modifications and improvements, and currently is used exclusively to study the sun.

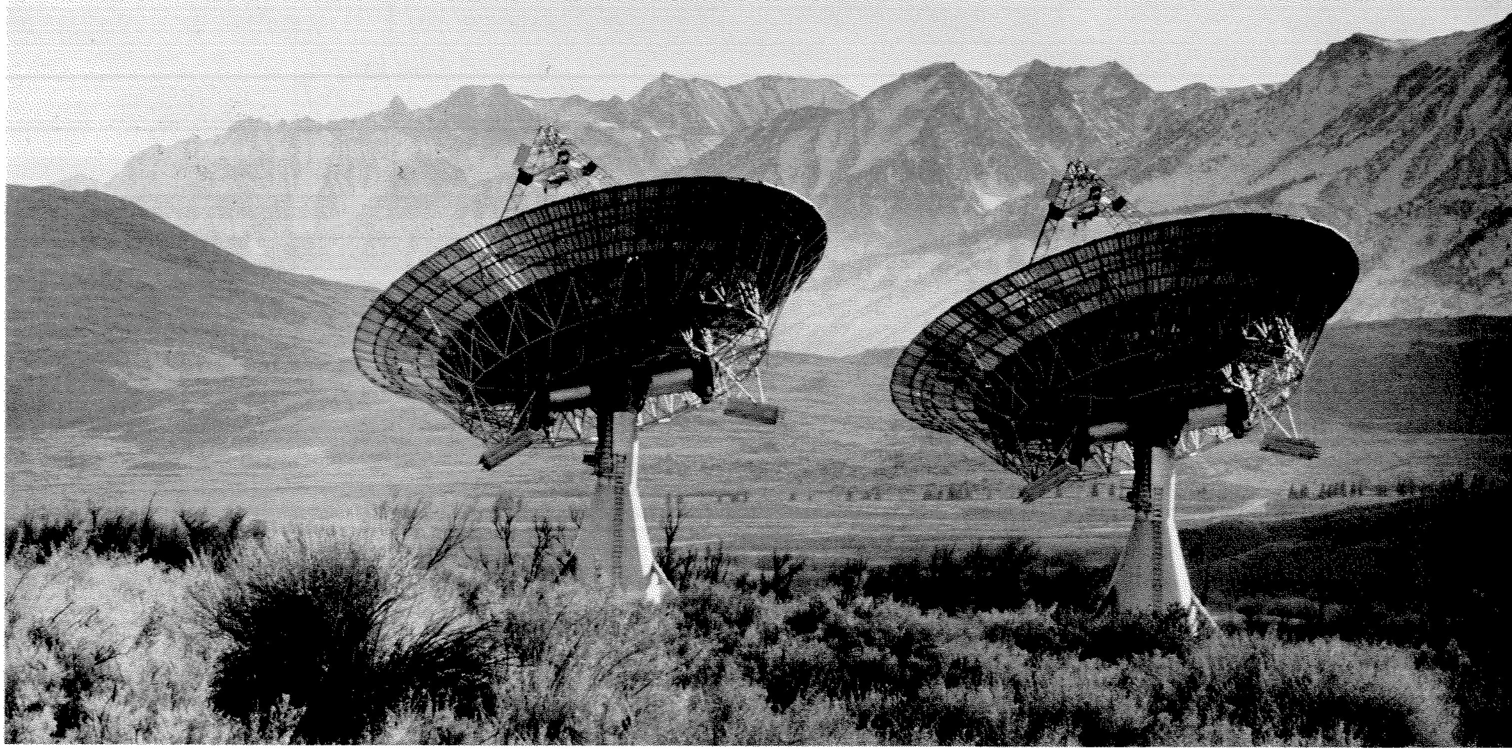
have fond memories of the ball-and-disk analog computer. My memory is that the realization that the integral of the fringe function was the delay was an afterthought, and that the integral was then brought out on a pulley, over which a string ran to another pulley mounted on the shaft of a lumped-constant delay line. For years the final piece of the apparatus was a four-inch crescent wrench tied on the end of the string to provide the motive power to turn the delay line. It was while watching that machine, and thinking 'there oughta be a better way' that I thought up the three-level lobe rotator used in the Mk II correlator, and calculated its signal-to-noise ratio." (The last refers to developments in computerized interferometry that Clark made several years later while at NRAO.)

Alan Moffet, Per Maltby and Tom Matthews did the first synthesis program on the complete interferometer: a study of a number of radio sources, essentially all those that had been identified with optical objects. While many of these objects had been identified earlier, the Caltech program was able to identify others because of its superior positional accuracy. The east-west portion of these observations began in February 1960, and together with the north-south observations lasted into the winter of 1960–61. Their results were published in 1962 in an important series of four papers; part of the work also formed Moffet's PhD thesis.

The image restoration procedures used in these papers are familiar to the modern student of radio interferometry, but they were carried out in the old-fashioned way. Digital computers were not common in 1961, and the authors took the trouble to inform the reader that the visibility functions ". . . were numerically inverted using an electronic digital computer." They performed the interpolation and gridding operation by plotting the visibility points by hand, joining them with a smooth hand-drawn curve, and reading off the appropriate values at the grid points.

The most significant fact discovered in these observations was that most extragalactic radio sources are double; that is, they consist of two well-separated clumps (lobes) of radio emission. The centroid of this brightness distribution often coincides with a faint galaxy, even when the radio lobes are well outside all the visible light. Maltby, Matthews, and Moffet noted further that the visible "radio galaxies" typically have unusual shapes: they are distorted, or have jets, or are located in a small group of galaxies. This story is still valid, although, of course, it has been enhanced by later developments.

During that period there was intense but friendly competition in the study of the structure of the extragalactic radio sources. The double nature of the majority of extragalactic radio sources is regarded as a major discovery and has generally been attributed to Maltby and Moffet. The idea, however, circulated around at the time, and in their first published note in *Nature* in 1961, Moffet and Maltby acknowledge that Palmer and Brown at Manchester also had evidence that many sources were double. The Manchester interferometer had stations much farther apart and so had more angular resolution than OVRO, but did not give detailed two-dimensional information. The first signs of double structure had actually come from Manchester nearly a decade earlier, when Jennison and Das Gupta showed that the Cygnus radio source was double. By 1961 it even was known, from the work by Lequeux in France, that the lobes in Cygnus were brightened at their forward edges, causing speculation about shock waves. But in



1961 the OVRO interferometer was superior to all others and the full survey carried out by Moffet and Maltby became the standard reference.

Another important early program was the study of the polarization and size of the radio-emitting cloud around the planet Jupiter. In several papers published between 1959 and 1961, Roberts and Stanley, Radhakrishnan and Roberts, and Morris and Berge reported increasingly improved observations of Jupiter. Two-dimensional measurements at two wavelengths, 31 and 22 cm, showed that the cloud was elliptical, with equatorial diameter three times the polar diameter, and the radiation was strongly polarized in the equatorial direction. This was a sure sign of synchrotron radiation from electrons trapped in a Van Allen belt around Jupiter. The observations even showed that the magnetic axis was offset by 9° from the rotation axis. Glenn Berge extended this work to shorter wavelengths to get a more detailed picture, and wrote his thesis on this topic. All this was confirmed many years later when Voyagers 1 and 2 flew by Jupiter and directly measured the particles and fields.

John Bolton

This article is dedicated to John Bolton. At the end of 1960, six years after establishing the Owens Valley Radio Observatory, Bolton returned to Australia to supervise the commissioning of the 210-foot telescope at Parkes. (Stanley was appointed his successor at OVRO, and the next installment of this story will describe how new instruments and new people changed its direction.) Bolton became director of the Parkes Observatory when the telescope became operational, and remained in that position for 10 years. In 1969–1973 he directed the Parkes program to receive signals from the moon for the NASA Apollo program. He remained interested in identifications of radio sources during his entire career, and also did extensive optical work in that area. Bolton retired to Buderim, Queensland, on the Sunshine Coast north of Brisbane in 1981, for reasons of health. I was fortunate to have visited John and Letty at their home in June 1993, to talk with them about the observatory and many other projects. He died a week after my visit.

Since he didn't come to Caltech until 1968, Professor of Astronomy Marshall Cohen was not actually on the Owens Valley scene during the years he has described above, and is grateful to Jesse Greenstein, Gordon Stanley, Robert Bacher, Glenn Berge, Barry Clark, Dan Harris, Ken Kellermann, Dick Read, Jim Roberts, and George Seilestad for their discussions with him and their comments on the manuscript of this history. Cohen studied electrical engineering (BEE 1948) and physics (PhD 1952) at Ohio State University, and began work in radio astronomy in 1954 when he joined the School of Electrical Engineering at Cornell as an assistant professor. In the late fifties he helped plan the large reflector that Cornell built at the Arecibo Ionospheric Observatory, and participated in its commissioning in 1961-62. After two years at UC San Diego, he came to Caltech as professor of radio astronomy. Cohen then worked at OVRO for many years, but to his regret has been there only infrequently since the late eighties. His most recent interests involve optical polarimetric studies of active galactic nuclei at the Palomar and Keck observatories.