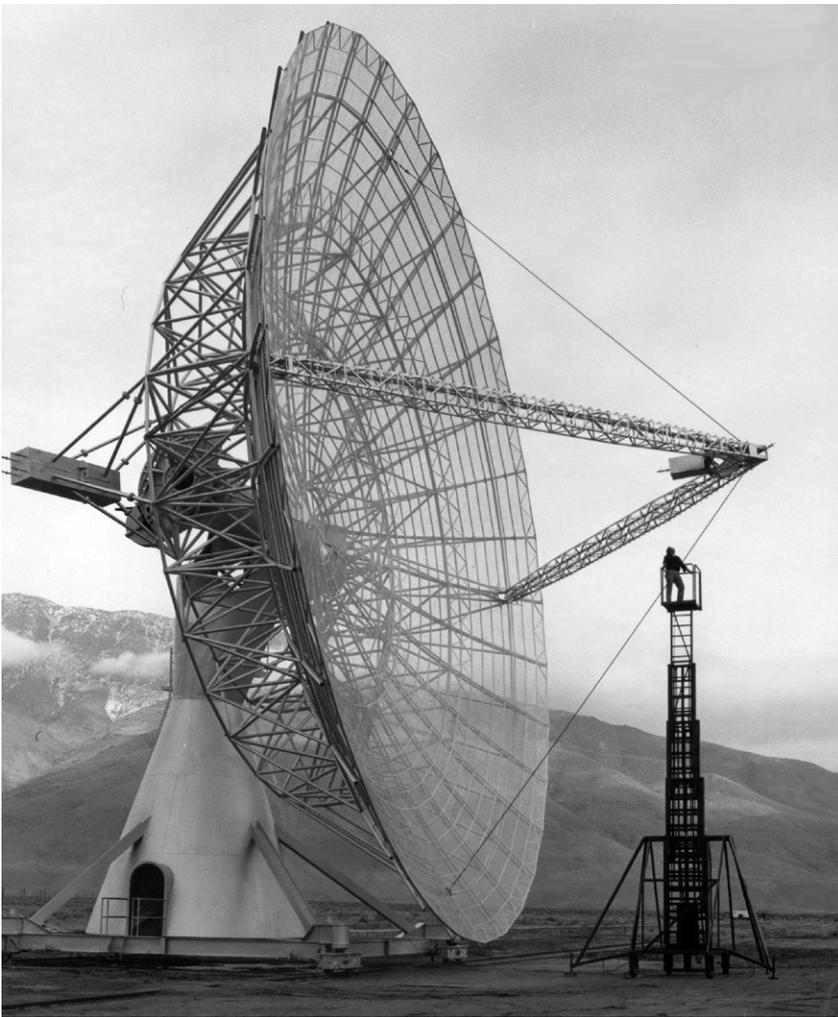


A History of OVRO: Part II

By Marshall H. Cohen



Banner: The 27.4-meter interferometer. The left dish is at the central station, and the other one is at the far end of the east-extending track. The Owens River is in the foreground.

Above: Adjusting receivers was not for the vertiginous. This photo was shot before 1964, when the steel mesh of the dishes was upgraded to solid aluminum, and the bipods supporting the focus boxes were replaced with much stiffer quadrupods.

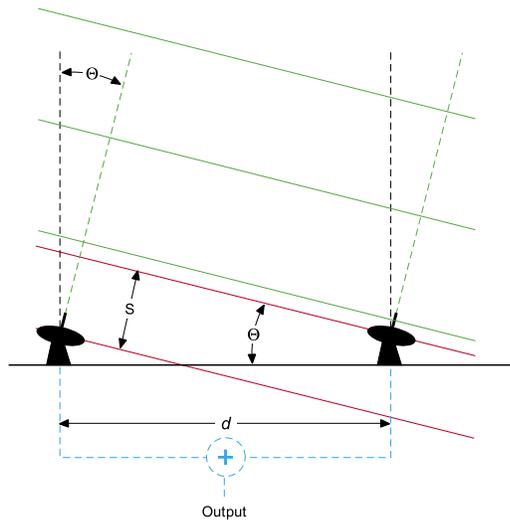
The Caltech radio astronomy program began in the late 1950s with the founding of the Owens Valley Radio Observatory (OVRO). Two prominent Australian radio astronomers, Gordon Stanley and expatriate Englishman John Bolton, found a radio-quiet site near Big Pine, in the Owens Valley 250 miles north of Pasadena, and built an interferometer—two 27.4-meter dish antennas movable to various stations on railroad tracks stretching nearly 500 meters east and north from a central station. At the time, it was one of the largest such systems in the world, unsurpassed for many purposes. OVRO's birth was described in detail in the spring 1994 issue of *E&S*; here I carry the story into the 1970s.

THE OVRO INTERFEROMETER

By 1960 the pioneer days of radio astronomy were over, and the revolution they had wrought had changed our view of the universe. However, visible-light spectra of the newly discovered radio sources were needed in order to measure their redshifts (a proxy for distance) and determine their compositions; and for this their optical counterparts had to be identified. To do so, their positions in the sky had to be known to within a few seconds of arc, and this requirement was a major driver of OVRO's design—an interferometer's resolution increases with the number of waves separating the two antennas, and OVRO's long baseline and short operating wavelength (30 centimeters) provided the needed precision. The optical spectroscopy was mainly done by Caltech and Carnegie astronomers, using the five-meter Hale Telescope on Palomar Mountain.

OVRO's movable antennas allowed for more than simply fixing the sources' locations. In order to study the physics of the sources, their radio-frequency spectra needed to be analyzed, and their brightness distributions at radio wavelengths

In radio-telescope interferometry the two dishes, separated by a distance d , are illuminated at a wavelength λ by a distant source. The signals from the two dishes are added together. As the earth rotates, the angle θ changes, and the combined signal from the two dishes goes through a series of maxima and minima. A rotation of θ by approximately λ/d changes the differential path length s by one full wavelength, producing one full cycle, or fringe, in the output voltage. Hence λ/d is the angular scale, or resolution at which the source can be mapped.



needed to be mapped. In other words, intensity contours, analogous to the elevation contours on topographic maps, had to be plotted. This required a range of angular scales, each of which needed its own spacing between the antennas. Measuring the interferometer's output—the “fringe amplitude”—at that spacing gave information for that scale. By measuring at many spacings a complete picture was built up, in a process called “aperture synthesis.” (Technically speaking, the fringes are sine waves that modulate the source's brightness distribution. Each measurement is an integration over this modulation, yielding one component of the Fourier transform of the source. After measurements are made at all spacings, the desired image is found by calculating the inverse transform.)

By 1960 ingenious interferometers had been built in many countries. The one that most closely resembled OVRO's was at Nançay, France. It

Gordon Stanley was very good at electronics, and he was building the world's

best centimeter-wavelength receivers for OVRO.

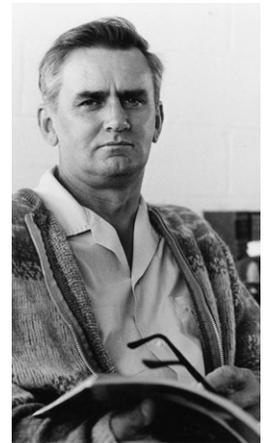
consisted of two modest, 7.5-meter dishes on tracks 1,480 meters long east-west and 380 north-south, and operated at a wavelength of 21 centimeters. These “Würzburg” dishes had seen service in German radar during World War II, and were used at almost every European radio observatory for at least two decades afterward. Both interferometers took measurements at many spacings, and the observations were either fit to a model, or the image was estimated using the inverse Fourier transform. Both instruments operated at similar wavelengths, but OVRO's baseline was only a third as long and so it had less angular resolution. But OVRO's dishes had 13 times the collecting area, and its electronics were superior, giving it a much

higher sensitivity that often was decisive.

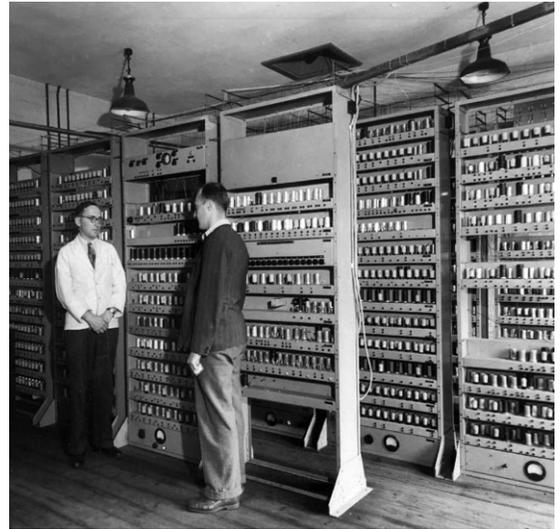
Gordon Stanley was very good at electronics, and he was building the world's best centimeter-wavelength receivers for OVRO. In addition to greater stability, the OVRO “front ends” had an equivalent noise temperature of 300 K versus 700 K at Nançay, giving OVRO an advantage of 7/3 on top of the factor of 13 from the antenna size. The result was that OVRO could study the entire Third Cambridge (England) Catalogue of Radio Sources, whereas Nançay was effectively restricted to the three dozen brightest sources. OVRO was also more flexible, as its receivers were modular and could be changed quickly. By 1963, measurements could be made at five wavelengths ranging from 63 to 10.6 centimeters.

However, the one-centimeter steel mesh that formed the radio dish was inefficient at 10.6 centimeters—generally speaking, $s/\lambda > 20$ for full efficiency, where λ is the wavelength and s is the size of the holes. In 1964 the mesh was replaced with solid aluminum, perforated near the rim to reduce the weight and wind resistance. This allowed shorter wavelengths to be used, and observations at three centimeters started in 1967, with an antenna efficiency of 30 percent. (A more typical figure for a paraboloid is 55 percent, but 30 percent is good for a dish operating at 10 times its original design frequency!) Such short wavelengths gave OVRO an advantage over other interferometers because of the higher resolution (the resolution attainable at three centimeters is 10 times that available at 30 centimeters), and because many compact radio sources have an “inverted” spectrum in which their emissions increase with frequency, making them easier to see at shorter wavelengths.

As described above, measurements made at many baselines can be converted into an image of the source. If the source is at the north pole, then east-west baselines alone suffice. As the declination—the astronomical equivalent of latitude—decreases, more north-south baselines must be used. Equatorial sources require diagonal baselines for a complete image restoration. Resolution along the east-west and diagonal baselines was improved by a 192-meter western extension of the baseline over the 1960s and '70s. However,



Gordon Stanley became OVRO's acting director when John Bolton returned to Australia in 1961. He became director in 1965 and retired in 1975.

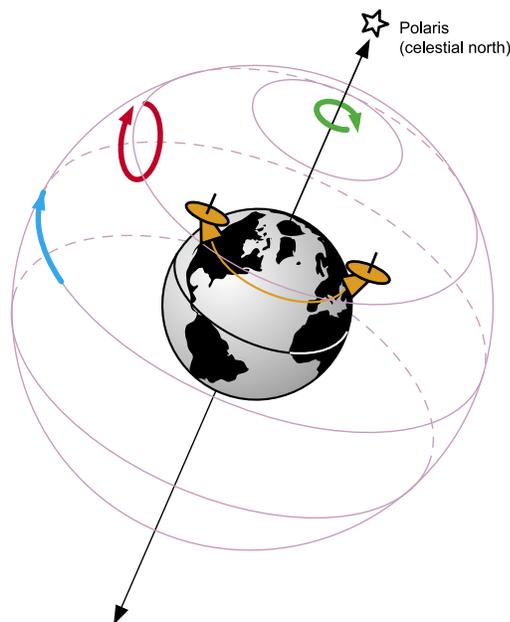


The Cambridge Mathematical Laboratory built EDSAC (for Electronic Delay and Storage Automatic Calculator), which ran on 3,000 vacuum tubes and debuted by computing the squares of the integers from 1 to 99 on May 6, 1949. It served Cambridge meteorologists, geneticists, and X-ray crystallographers, as well as radio astronomers from 1953 through 1958. Maurice Wilkes, its designer, is at left.

most observations were taken with only one or two baselines, which usually was sufficient to measure positions or flux densities.

Aperture synthesis is nearly impossible to do by hand, although the earliest work at OVRO, with a modest number of baselines, was done that way. In the 1950s radio astronomers at the University of Cambridge had access to EDSAC, the world's first practical stored-program digital computer, and with it they pioneered the techniques needed for aperture synthesis. But by 1960 university computing centers were common, and mechanical calculators and tables of trigonometric (and other) functions were disappearing. Caltech was late in developing a center for digital computing, but in 1962, when the first Fourier analyses from OVRO were published, we used a Burroughs 220 located in the Computing Center in the Spalding Laboratory of Engineering.

When a radio source is at the celestial pole, the east-west baseline (orange) of the interferometer effectively wheels in a circle (green) as the earth turns, giving full two-dimensional information about the source. But as the source moves toward the equator, the baseline's apparent rotation becomes an increasingly flatter ellipse (red), and north-south baselines must be added. When the source is on the celestial equator, the baseline does not rotate at all (blue), and diagonal baselines are required as well.



SCIENCE WITH THE INTERFEROMETER

The compact extragalactic sources that were so exciting in the '50s were originally thought to be exotic stars, and the key to understanding their peculiar spectra had to wait for a source called 3C 273—the 273rd object in the original Third Cambridge Catalog. In 1962 the 64-meter radio telescope in Parkes, Australia, measured the diffraction pattern produced as the moon passed in front of 3C 273, to get an accurate position. Then in 1963 Caltech associate professor of astronomy Maarten Schmidt realized that its puzzling spectrum, obtained at Palomar, could be explained as ordinary emission lines, mostly of hydrogen, whose wavelengths had been shifted toward the red end of the spectrum by the source's great distance, about two billion light-years. However, 3C 273 had been measured at OVRO earlier, probably in 1961. Grad student Richard Read's (BS '55) 1962 PhD thesis speaks of an identification of 3C 273 with a faint object—in retrospect it seems possible that the correct bright object was simply ignored as a nearby star, and the error box was searched deeper until

a suspicious galaxy was found. Alternatively, the measurement may have been in error; but in any event an opportunity was lost. OVRO could have preceded Parkes by a year in providing the position that allowed quasars to be identified.

Besides making accurate position measurements, OVRO also devoted substantial effort to measuring spectra and brightness distributions. As described in the 1994 article, graduate student Alan Moffet (PhD '61), together with postdocs Per Maltby and Tom Mathews, discovered that many extragalactic radio sources consisted of two lobes surrounding a central galaxy. Understanding this so-called "duplicity" has been a major concern of astronomers ever since. The equivalent brightness temperature—that is, the temperature of a black body that would produce the same intensity as the source, at radio wavelengths—of these sources was generally high, a million degrees or more. Synchrotron theory, in which electrons spiral in a magnetic field, was used to explain this radiation. The estimated field strengths usually turned out to be a few microgauss, which is tiny (the surface field on Earth is about half a gauss), but the enormous volumes occupied by these fields implied a huge amount of energy. The origin and evolution of this magnetism is still an important topic.

Synchrotron radiation is polarized, and a powerful new method for measuring polarized brightness distributions was worked out by postdocs Dave Morris, V. "Rad" Radhakrishnan, and George Seielstad (PhD '63, later OVRO assistant director), who used it to estimate the energetics and evolution of many sources through analyses of their magnetic fields. In addition, the variation of polarization with wavelength provided a way to study the electron density and magnetic field of our own galaxy, along the line of sight. Seielstad and Glenn Berge (MS '62, PhD '65) attempted to correlate the galactic magnetic field with the spiral arms of the Milky Way, but their mapping effort

was hampered by limited data. Berge's PhD work revealed that clouds of energetic particles exist around Jupiter, analogous to the Van Allen belts around Earth. Confirmed by JPL's Voyager 1 and 2 spacecraft, these belts were an important consideration in designing the Galileo Jupiter orbiter.

Hydrogen is the most abundant element in the universe, and studying the 21-centimeter emission line of neutral atomic hydrogen (HI) was one of OVRO's largest programs. The first studies used a single-channel receiver that had to be sequentially stepped in frequency. Around 1964, a 12-channel receiver was built; this sped up the measurements by a large factor. In a series of papers published in the '60s and early '70s, the distribution, kinematics, and physical state of hydrogen in the Milky Way and in external galaxies was explored. Many people participated in this work: postdocs, students, and visitors. The most significant results were published in 1971–73 by then-postdoc David Rogstad (BS '62, MS '64, PhD '67) and Seth Shostak (PhD '72), whose HI maps of a number of spiral galaxies showed three things. First, the hydrogen motions were roughly consistent with the predictions of spiral density-wave theory. Second, the hydrogen was often in a warped disc, with a twisted hat-brim shape.

But most importantly, the extended disk of hydrogen, beyond the stars, did not rotate according to Kepler's law: $v \sim r^{-1/2}$, where v is the rotational velocity and r is the distance from the galactic nucleus. Instead, the rotation rate decreased more slowly with distance, or even stayed at a constant velocity. This showed that spiral galaxies did not have most of their mass at their centers, in the way that the sun dominates the solar system, even though the vast majority of the stars are near the galaxies' cores. Instead, the galaxies seemed to have unseen mass distributed far beyond the visible stars. The kinematics of spiral galaxies was a hot topic in 1970, with players at all the new large instruments

Below, left: The radio source Cygnus A lies in a galaxy some 600 million light-years away. The radio waves come from electrons propelled at nearly the speed of light in a long, thin jet emanating from the vicinity of the black hole at the core of the galaxy. The electrons end up in the giant radio lobes rendered here in swirls of orange and red. The lobes span 500,000 light-years.

Below, right: Jupiter's radiation belts as mapped by the Cassini spacecraft at three different points in the planet's 10-hour rotation.

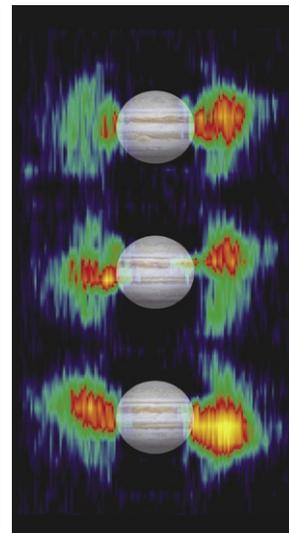
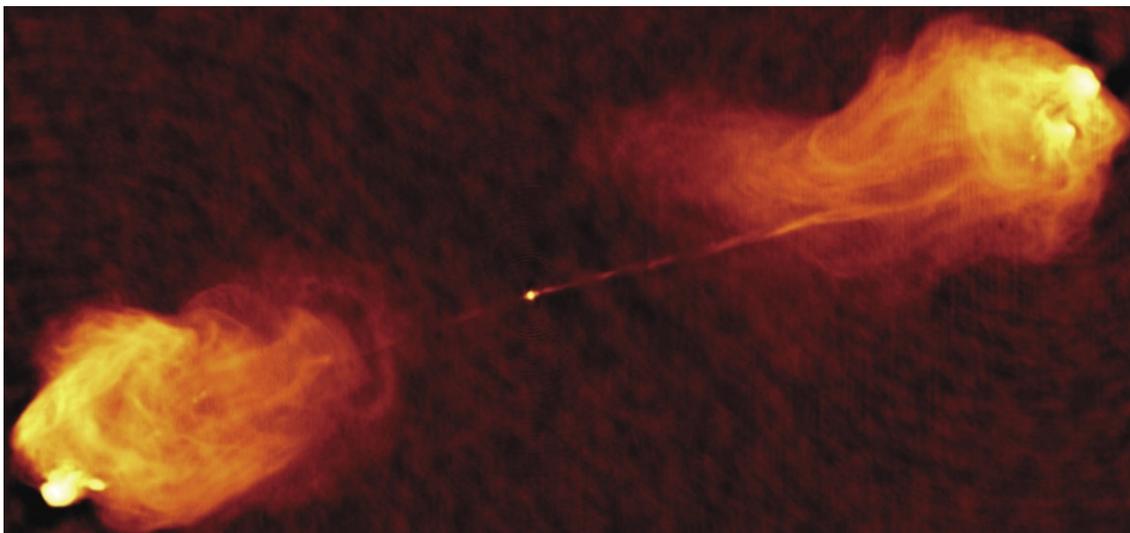


Image courtesy of the National Radio Astronomy Observatory/Associated Universities, Inc./National Science Foundation. Investigators: R. Perley, C. Carilli, and J. Dreher.

Image courtesy NASA/JPL.



Shostak hard at work at the 24.7-meter interferometer's controls.

around the world. Shostak's PhD thesis contained the first unambiguously flat rotation curve. His and Rogstad's results furthered the idea that dark matter was a basic constituent of the universe, and in a few years it became the received wisdom. The nature of dark matter is still unknown nearly 40 years later.

During the 1970s OVRO's two-dish interferometer was overtaken by larger and faster multi-element interferometers in Holland and England, and larger, more sensitive dishes, especially those in Germany and Puerto Rico. In 1979 the decision was made to devote the interferometer to solar physics, where it continues to serve, mapping the sun daily over the range 1 to 18 GHz with frequency-agile receivers.

THE OWENS VALLEY ARRAY

Stanley and Bolton were already planning to enlarge the interferometer in the late '50s, well before it was finished. This got a boost in 1961, when the National Science Foundation (NSF) issued a report pointing out the need for new large radio telescopes in the United States. In 1962 Caltech, with Stanley as the principal investigator, submitted a proposal to the NSF for a six-element interferometer, incorporating four new 38-meter dishes and extending the track 366 meters to the south. Turning the existing L into a T would add a second, perpendicular set of diagonal baselines, increasing the array's ability to build up detailed images. The NSF funded engineering studies in 1963, and in 1964 funded the construction of a prototype dish.

The first of the National Research Council's Astronomy and Astrophysics Decadal Survey reports, issued in 1964, recommended enlarging OVRO. In response, in 1966 OVRO proposed the Owens Valley Array (OVA), consisting of eight new 40-meter telescopes on tracks three kilometers long

east-west, and five kilometers north-south. Westinghouse Electric Corporation was already building a 40-meter dish, using the NSF's 38-meter prototype money, and the budget for the seven remaining antennas, tracks, and electronics was close to 15 million dollars. Bruce Rule (BS '32), Caltech's chief engineer, was responsible for the design of the dish, as he had been for the 27.4-meter telescopes. But by now the National Radio Astronomy Observatory (NRAO) wanted to build a very large array consisting of 35 25-meter dishes, and MIT wanted to build a single huge dish 134 meters in diameter. In response, the NSF established a committee, chaired by Princeton's Robert Dicke. The committee chose OVA, and recommended it be managed as a national facility. (Meanwhile, Caltech and the University of California had submitted a separate proposal for a 100-meter telescope at OVRO; the committee turned this one down.)

In 1969 the NSF asked the Dicke committee to meet again. OVRO's presentations were repeated, with a revised budget of \$19 million and an increased emphasis on radio spectroscopy, a subject that had gained importance in the preceding years. The committee's report this time was less explicit, recommending building all three: NRAO's Very Large Array (VLA), as it was now formally known; OVA; and MIT's big dish. That, of course, did not happen. NRAO and OVRO staff discussed the possibility of joining forces and building one array, perhaps in Owens Valley; this also came to naught.

The buck was passed to yet another committee—the National Research Council's second decadal survey committee, established in 1969 with Caltech professor of astrophysics Jesse Greenstein as chair. I was on the radio panel, which was charged with prioritizing the three proposals. It was a difficult job. Most members preferred an array because of its versatility, but which array? In the end we recommended the VLA. It was larger, and would be on a higher site, an important consideration because atmospheric water vapor

partially absorbs radio-frequency waves, and water vapor decreases with altitude. Also, some panelists felt that a large national array should be built and managed by a national organization, not one university. The VLA was subsequently built near Socorro, New Mexico, although with only 27 antennas, and the MIT and Caltech projects were dropped . . . but by that time the prototype 40-meter telescope was already operating at OVRO.



The 40-meter radio telescope dish being lifted onto its pedestal in July 1967. Once the dish is high enough, the base, which has already been mounted onto its railroad tracks, will be driven into place underneath it.

THE 40-METER TELESCOPE

The 40-meter dish was dedicated on October 18, 1968. It was located on short tracks one kilometer east of the center of the interferometer, and was soon connected to that instrument, giving a three-element interferometer with a maximum east-west spacing of one kilometer, later increased to 1.25 kilometers by adding track to the west. However, adding the full electronics to go from one to three baselines was a substantial undertaking, and the antennas were used pairwise for several years.

OVRO's improved resolution benefited a number of studies, especially of the planets, where obtaining more pixels is always important. But the 40-meter made its mark in single-dish spectroscopy and in very long baseline interferometry, or VLBI, paired with antennas thousands of kilometers away.

Spectroscopy requires measuring the signal strength at closely spaced points along a continuum of frequencies. This is accurately and easily done digitally, and the world's first digital spectrometer, with 100 channels, was built in 1962 by Sander ("Sandy") Weinreb, now at JPL and a faculty associate in electrical engineering at Caltech, as part of his PhD thesis at MIT. Weinreb then built a better one at NRAO, which we later inherited and installed at OVRO in 1970. It rapidly became out-classed as Moore's Law came into play, and in a few years 1,000-channel spectrometers were the norm. These allowed astronomers to analyze increasingly

From left: John Bolton, Alan Moffet, and Bruce Rule at the dedication of the 40-meter dish; photo by Curtis Phillips. Moffet became OVRO's director in 1975 upon Stanley's retirement.



larger chunks of spectrum, or to split the channels among the many baselines of a multi-element interferometer. A modern spectrometer might have millions of channels. But OVRO's first 1,000-channel receiver was not built until around 1975, and then for the millimeter-wavelength array.

In spite of its out-of-date spectrometer, the 40-meter had a major advantage: it was lightly scheduled. Some studies require large blocks of observing time, and two-week programs were common at OVRO. Non-Caltech astronomers who needed time on a large dish were welcomed, and often found it easier to get sufficient time at OVRO than to compete for a shorter window on better-instrumented but much more heavily subscribed telescopes.

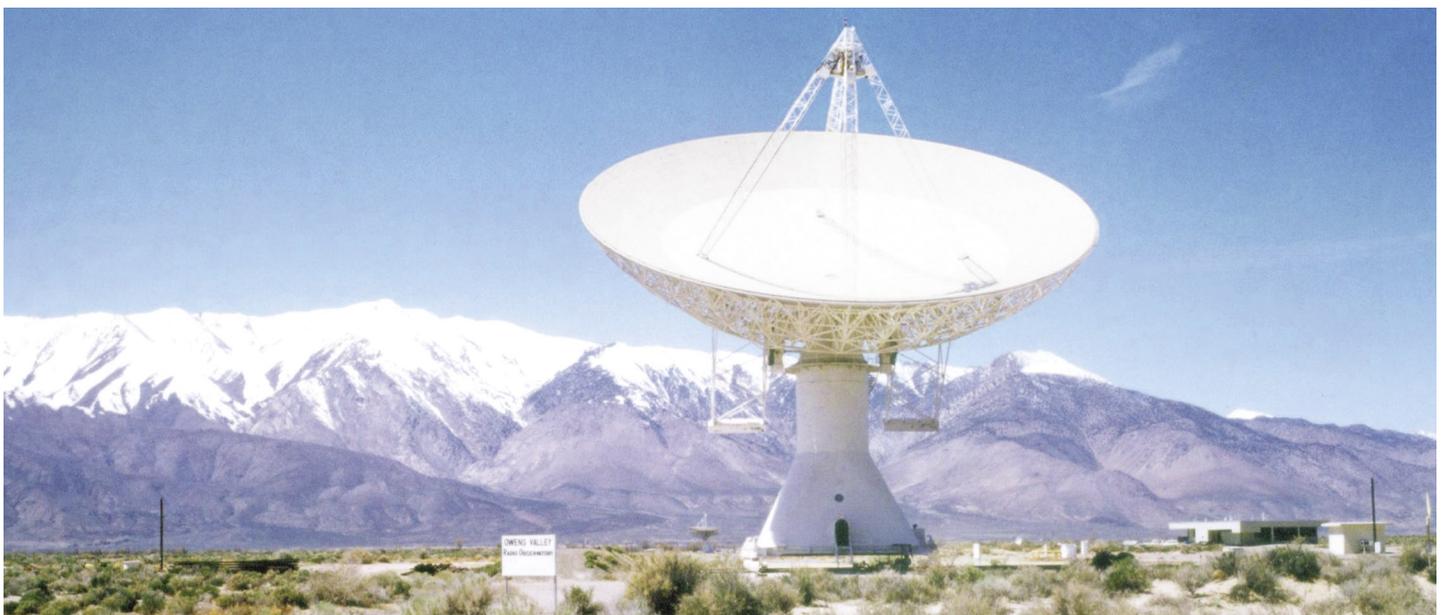
Most of the 40-meter's spectroscopy involved interstellar clouds. In the 1960s and '70s these clouds had been found to contain a dozen or so different species of molecules. Each one emitted a characteristic set of lines in the centimeter portion of the spectrum—a fingerprint whose details also reflected the molecule's concentration and the ambient temperature. Furthermore, different molecules are appropriately excited at different densities and pressures, so by looking at, say ammonia versus hydrogen cyanide, you would be seeing different depths within the cloud. This work ranged from "classical" astronomical studies of the composition, mass, and dynamics of clouds and their relation to star-forming regions, to "astrochemistry"—isotope studies and investigations of the gas-phase equilibrium. One long-running series of observations had to do with the maser lines from OH, the hydroxyl molecule. These lines are seen in the atmospheres of stars as well as in interstellar clouds, and in the latter case can be extremely strong, allowing clouds to be investigated that would otherwise be too distant.

VERY LONG BASELINE INTERFEROMETRY (VLBI)

Interferometry requires exacting measurements of small differences in the phase of a signal at two or more widely spaced receivers. When the dishes are directly connected to one another, via wire or radio, the signals are combined in real time and the measurement is fairly straightforward. However, this arrangement limits the separation that can be achieved between the receivers, which in turn limits the system's angular resolution—the longer the baseline, the finer the discrimination. In the mid-1960s, it became possible to tape-record data at widely separated dishes and do the correlation later. Angular resolution improved a hundredfold as the baselines quickly spread across the globe. When I arrived at Caltech in 1968, the 40-meter telescope was being commissioned, and as part of that process we added receivers and terminal equipment for VLBI. In April 1969 we mounted a three-station, six-centimeter experiment using OVRO, the NRAO 43-meter telescope at Green Bank, West Virginia, and the 64-meter dish at Parkes, Australia. The baseline from West Virginia to Australia proved marginally too long to be useful, as there was excessive phase noise caused by the antennas pointing so close to the horizon. OVRO-Parkes, however, worked well. A number of quasars showed strong fringes, indicating that their size was less than about 0.4 milli-arcseconds. Theoretical work had suggested that these sources should be extremely small, and our experimental confirmation was a major early success for VLBI. We also confirmed that the quasars' brightness temperature had to be at least 10^{11} K. This meant that they were very energetic objects, containing clouds of electrons spiraling in a magnetic field at very nearly the speed of light, and giving off synchrotron radiation as explained previously. The

The 40-meter dish gleams against the Sierra Nevada.

One of the 24.7-meter dishes is barely visible in the background just to the left of the pedestal. The low building to the right of the pedestal is the Oscar Mayer Control Center.



From left: Cohen, Barry Clark (BS '59, PhD '64) of NRAO, and I.G. Moiseev, director of the Crimean Astrophysical Observatory, stand in front of the 22-meter dish at Simeis near Yalta, on the Black Sea, during the 1971 US-USSR VLBI run. This experiment also used the 64-meter Deep Space Network antenna at JPL's Goldstone station in the Mojave Desert (radio astronomers are allowed to use the dish when it isn't tracking spacecraft), as well as NRAO's 43-meter dish in Green Bank. The photo was taken by Leonid Matveenko of the Space Research Institute, Moscow, a long-time collaborator.



OVRO-Parkes baseline was 1.7×10^8 wavelengths (10,200 kilometers) long, a record that lasted only six months. The current record is 4.2×10^9 wavelengths, between telescopes in Arizona and Spain using a wavelength of two millimeters.

Each VLBI station had to have its own clock, and they had to be synchronized to within a few microseconds. At some stations the Navy's LORAN (LONG RANGE Navigation) signals could be used, but OVRO was too far inland. We generally "transported time" from the Point Mugu Naval Air Station, near Oxnard, or from JPL's Goldstone tracking station, near Barstow. Grad students George Purcell (MS '68, PhD '73) and Dave

VLBI differs from most astronomy in that you only know if you have data after the tapes are correlated, which in the old days could be weeks or even months after the observations. There is no chance to fix setup problems, because they don't reveal themselves until after the fact.

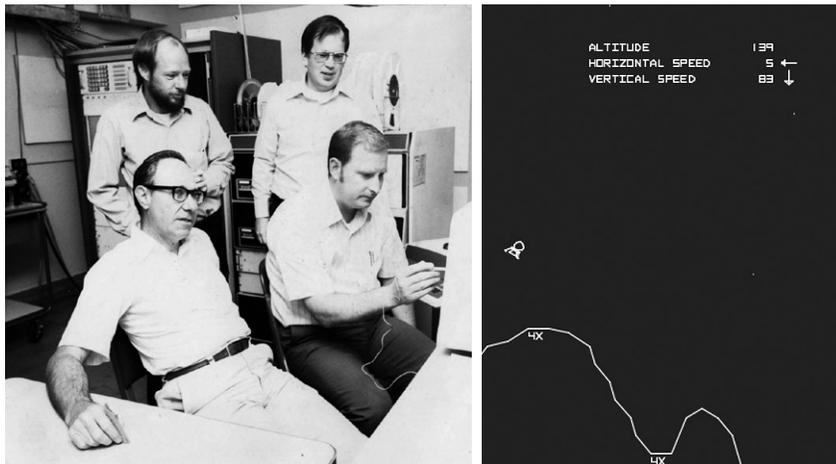
Shaffer (PhD '74) were usually pressed into service to drive the clock to OVRO, as they had to go to the telescope anyway to keep changing the data tapes. The transfer clock itself was either a very stable quartz-crystal oscillator or a rubidium standard oscillator, which was based on a narrow emission line produced by gaseous rubidium-87 atoms. These gave a stability of about one part in 10^{11} , and were ultimately replaced with a hydrogen maser, which was good to one part in 10^{14} . The maser was expensive and bulky, while the others were relatively cheap and small. The crystal oscillator clock was outfitted like a small suitcase, and in 1971 I took it from Pasadena to the 22-meter telescope in Simeiz, on the Crimean peninsula near Yalta, to synchronize clocks for our second US-USSR VLBI run.

The clock and I passed through airport security in Los Angeles, London, Moscow, and Simferopol without a hitch, something that might not happen today. As a precaution, I had armed myself with a letter (signed by me) explaining that Professor Marshall Cohen was on an important scientific mission and that it was vital for this particular clock to get to Crimea as rapidly as possible. I don't remember if anyone even looked at it.

The Mark I VLBI system, installed at OVRO in 1969, used half-inch reel-to-reel tapes with seven tracks recording one bit each at 720 kilobits per second, and had a net bandwidth of 330 kHz. A tape lasted about three minutes, and we typically ran tapes 10 minutes apart. They were correlated back at Caltech on an IBM 360-75 mainframe computer; correlation of a pair of three-minute tapes took about 10 minutes. This system was replaced by the Mark II, which obtained a better signal-to-noise ratio by recording a two-megahertz (MHz) band on two-inch tapes that held two hours' worth of data. These tapes had been designed for TV studio use, and were actually the first videotapes. The Mark II required a special hardware correlator, built at NRAO in 1970 or so, that was hard to use—the Ampex tape drives were extraordinarily touchy on playback, a situation compounded by the fact that we could not afford new tapes. We got used ones for free, and they had many dropouts. (We would eventually go to new one-inch RCA videotapes, which we actually purchased, and then to much better and cheaper video cassettes. Recently developed experimental systems simply store the data on removable hard drives.)

VLBI differs from most astronomy in that you only know if you have data after the tapes are correlated, which in the old days could be weeks or even months after the observations. In such a case, there is no chance to fix setup problems, because they don't reveal themselves until after the fact. And, unlike some wayward instruments on spacecraft, problems cannot be rectified with new

Dave Rogstad (right, seated at console) might be doing interferometry, but the odds are he's playing Lunar Lander—note the probe in his hand in lieu of a joystick. Cohen sits beside him, while Art Neill (with beard) and Marty Ewing look on. Lunar Lander (far right) was a very early computer game, with no hope of success without a good grasp of Newton's Laws. If you landed successfully a McDonald's appeared, and the pilot walked over and got a hamburger.



software ex post facto. This problem may become a thing of the past, however, as experimentation using fiber optics to transport the data in real time is now under way.

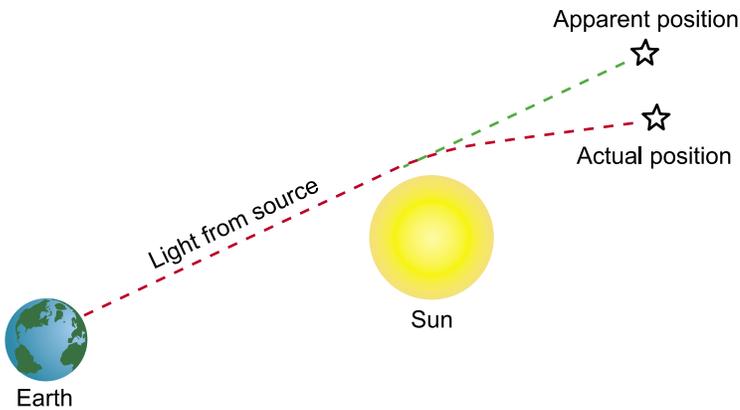
In the early days of VLBI, the delay between observation and correlation kept growing as more users and telescopes entered the field. (An N -station experiment requires $N \times (N - 1) / 2$ passes through the correlator.) By 1972 the Mark II system at NRAO was clogged, and Art Neill from JPL and I decided to build a new VLBI correlator here in Pasadena. The resulting collaboration lasted for 20 years. We first built a two-station Mark II system, compatible with the one at NRAO, but with the possibility of expansion to five stations. It reached this capability, with the simultaneous

correlation of 10 baselines, in 1978. Dave Rogstad, by then at JPL, was the software chief for this project, and former postdoc Martin Ewing, by then on staff at OVRO, was the main hardware designer. (Ewing later moved to Yale; he and Rogstad both retired a few years ago.) Around 1980 JPL started a new effort to build a broadband correlator, and this soon became part of the collaboration. In 1986 this "Block II" system reached its full capacity, with the ability to process four 28-MHz channels, or up to 16 two-MHz channels. The five-station Mark II processor was retired when it became overshadowed by the big Block II system, and was given to the Bologna Istituto di Radioastronomia. It was used there for a number of years.

For about 15 years the correlator lab in the basement of Robinson was a world center for VLBI. At the beginning it was run like the OVRO telescope: a user came in with a stack of tapes and a student and they did nearly everything themselves. (For VLBI observations, of course, you also had to have a friend at the other end of the interferometer.) This became impractical as larger experiments became common, and "friends" were provided at both the telescopes and at the correlator. The organization that grew up to manage VLBI would require a separate story, but we had NSF support for students and postdocs to man the 40-meter, and we had both NSF and JPL support for the correlator. Stephen Unwin, who had been a postdoc in the VLBI group, became the manager of the processor laboratory, and he moved to JPL when the Block II system went there in 1992. The facility was open to all comers—in fact, OVRO or Goldstone did not have to be one of the observing stations. Most of the users were from outside Caltech, with many from Europe and Australia. Depending on the load, we would run two or three shifts a day, sometimes including weekends, with undergraduates providing much of the routine labor. This ended in 1992, when the NSF funding was transferred to NRAO's Very Long Baseline



At left is Ken Kellermann (PhD '63), now a senior scientist at NRAO, where he's been since 1965. At right is Tom Clark of the Goddard Space Flight Center. This photo, shot in May 1969, shows a VLBI experiment being run from within the "tepee"—the pyramidal base—of the 40-meter telescope. Kellermann stands in front of the telescope's manual controls; the computer-control system is out of frame to the right. The half-inch tape recorder is on the right. The strip-chart recorder monitors the system noise and the source's flux density.



When a radio source passes behind the sun, its gravitational field bends the path of the waves. To an observer tracing the waves' path back in a straight line, the source's position will appear to have shifted.

One 24.7-meter dish as shot from the catwalk of the other, circa 1966. The view is from the central station to the west, and the first leg of the western baseline extension is just getting under way.

Array (VLBA), a system of 10 dedicated telescopes stretching from Hawaii to the Virgin Islands. This operation works very differently. Everything—telescopes, tapes, and correlator—is run by NRAO. The users have nothing to do with the telescopes or the equipment; they simply apply for observing time, and the results are shipped to them if their proposals are successful.

In 1969, several groups of radio astronomers proposed to use the power of interferometry to measure the gravitational bending of radio waves, when the sun, on its annual path, passed in front of the quasar 3C 279. Predicted by the theory of general relativity, this effect would cause the quasar's apparent position to change—a phenomenon first documented in the solar eclipse of 1919, when teams in Brazil and on the west African island of Principe measured shifts in the Hyades star cluster

in a spectacular vindication of Einstein's theory. George Seielstad, with graduate students Dick Sramek (PhD '70) and Kurt Weiler (PhD '70), proposed to use the 40-meter with one of OVRO's 27.4-meter dishes connected in the normal way, so that the position shift would be seen as a small time shift in the interferometer fringes.

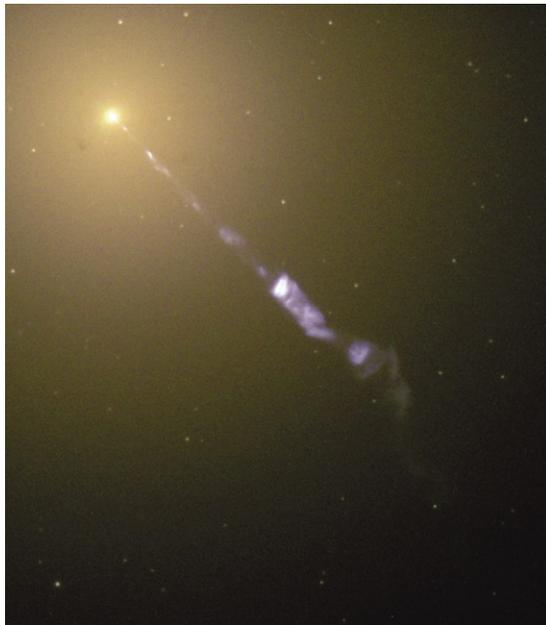
Two other groups, one led by Irwin Shapiro of MIT and the other by Tom Clark of the NASA Goddard Space Flight Center (GSFC), independently proposed to use the OVRO 40-meter in VLBI mode with the 37-meter dish at MIT's Haystack Observatory near Westford, Massachusetts. Since both groups proposed to do the same experiment with the same dish at the same time, Gordon Stanley arranged for them to work together. While this particular VLBI run ultimately proved unsuccessful, the collaboration it forged lasted for some 30 years and was very productive.

Seielstad's experiment found a solar limb bending of 1.77 ± 0.2 seconds of arc. The predicted value from general relativity was 1.75 arc seconds. (Meanwhile, Caltech associate professor of planetary science and OVRO staff member Duane Muhleman and postdocs Ron Ekers and Ed Fomalont (PhD '67), using two radio telescopes at Goldstone, measured 1.82 ± 0.2 arc seconds.) These measurements were substantially more accurate than previous optical measurements; currently, VLBI has shown the bending to agree with general relativity to about 0.02 percent.

But most of Caltech's VLBI research involved active galactic nuclei, or AGNs—the quasars or other energetic objects that lie in the hearts of some galaxies. Some of these objects seemed to be moving faster than light, which was explained by the emitting clouds moving at nearly the speed of light toward the observer. If the object's path is close to the line of sight, the apparent time scale shrinks and the transverse motion appears "superluminal." This follows from normal physics, but it made quite a stir when it was first seen



Perhaps the most photogenic AGN belongs to the giant elliptical galaxy M 87, some 50 million light-years from Earth in the constellation Virgo. It is one of the brightest objects in the sky at radio wavelengths, and is known to radio astronomers as Virgo A. This Hubble Space Telescope image combines ultraviolet, visible, and infrared light to show M 87's black-hole-powered jet of electrons. Synchrotron radiation at ultraviolet wavelengths gives the jet its bluish color. The jet shows superluminal motion—a Hubble team led by John Biretta (PhD '86) found apparent velocities of four to six times the speed of light near the black hole, which contains two billion times the mass of our sun.



in 1971, by a Caltech-NRAO-Cornell group and an MIT-Haystack-GSFC group. Actually, superluminal motion had been detected by Al Moffet and collaborators in a series of VLBI experiments in 1969 and 1970, using JPL's Deep Space Network antennas at Goldstone and Canberra, Australia; but an early component of that work did not stand up, and the results did not receive the recognition they deserved. These superluminal motions are still studied at Caltech.

For many years the VLBI program, including the correlator, was a large part of radio astronomy at Caltech. From its inception, many of its investigations were collaborations between Caltech people and astronomers from around the world. In a sense, we were ahead of the times—now, especially with space missions, multi-institution collaborations are the norm. VLBI changed completely in the late 1980s and early '90s, as the VLBA, a national facility, came into operation. The university systems were closed, and the researchers became users, much as particle physicists had in the '60s with the advent of big national (or even inter-

national) facilities such as Fermilab and CERN. In 1988, Anthony Readhead, the Rawn Professor of Astronomy, took over running OVRO's VLBI program, and I turned to optical astronomy using the Palomar and then the Keck telescopes. A half dozen years later the Caltech effort wound down as the money dried up, although I still maintain membership in a VLBI collaboration of a dozen members from California to Germany that still concentrates on AGNs.

Interferometry is more complex than using a single dish. It fits the Caltech style of doing difficult things well, and has always been OVRO's strength: first with the twin 27.4-meter dishes; then with the unfunded OVA that yielded the 40-meter dish, which made a three-element interferometer; and then with VLBI. The '80s would bring a millimeter array that, recently relocated to Cedar Flat, has morphed into the 15-element CARMA (Combined Array for Research in Millimeter-wave Astronomy) telescope; and the '90s, the CBI (Cosmic Background Imager), a 13-antenna microwave array in Chile built by Tony Readhead and his group. Caltech students have had a central role in the construction and operation of these instruments, and our graduates and postdocs have provided NRAO much of the expertise needed to build the succession of interferometers that have pushed back our horizons of knowledge over the last four decades. □

Professor of Astronomy, Emeritus, Marshall Cohen is one of the founders of modern radio astronomy. He earned his BEE from Ohio State in 1948, his MS in '49, and his PhD in '52, both in physics. He was a research associate in the Ohio State Antenna Laboratory from 1951 to 1954 and was a professor of electrical engineering, then of astronomy at Cornell from 1954 to 1966. He came to Caltech briefly as a visiting associate professor while at Cornell, but wound up at U.C. San Diego as a professor of applied electrophysics (!) for two years. He returned for good as a professor of radio astronomy in 1968. He also served as executive officer for radio astronomy from 1981–85.

This article was edited by Douglas L. Smith.

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