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# MOSAIC

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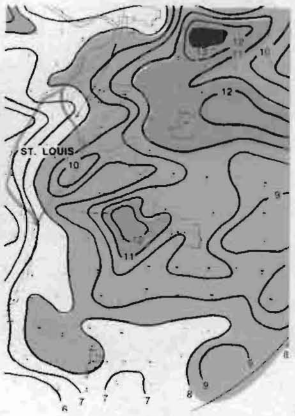


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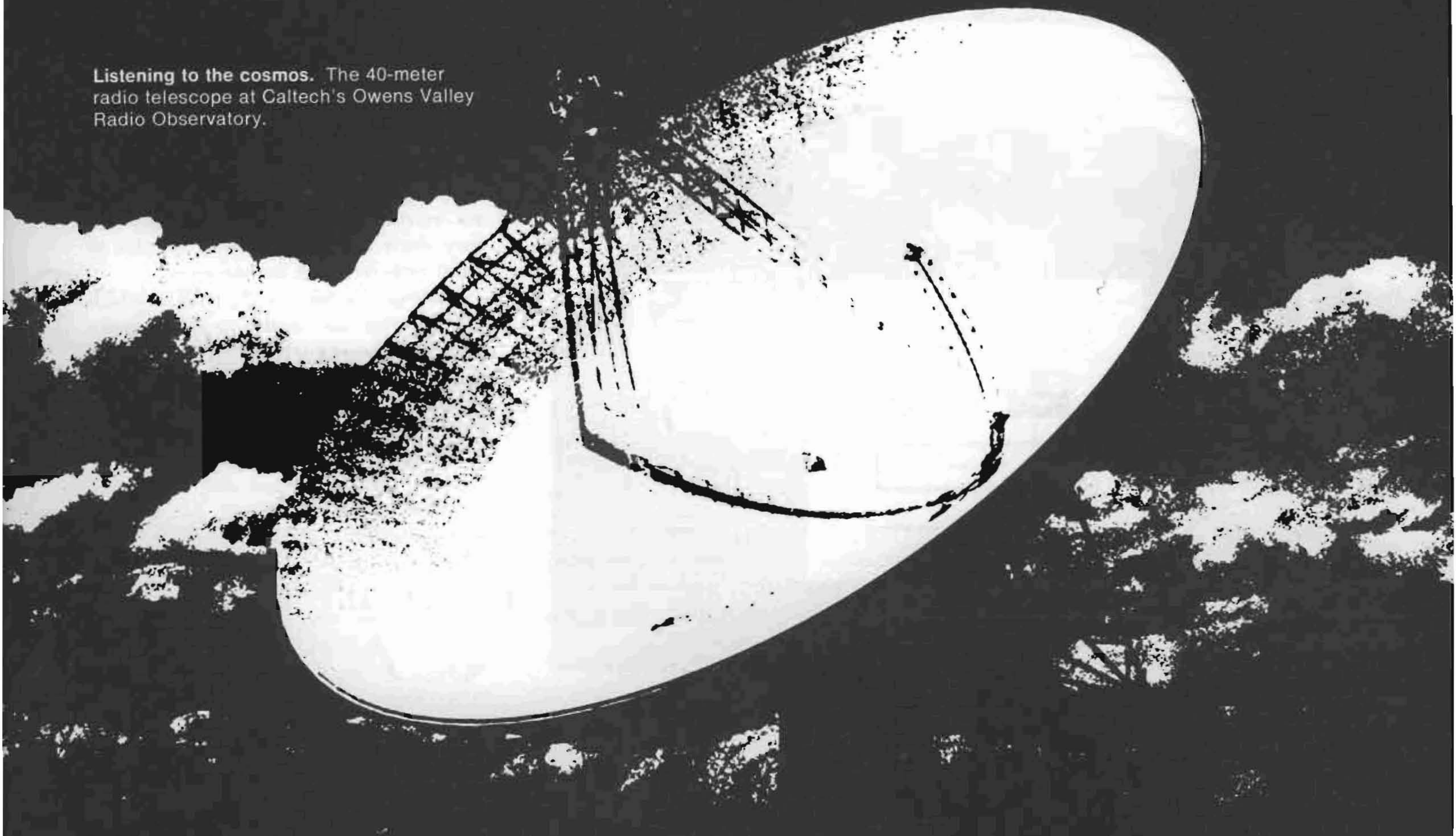
*Cover:* Reston, Virginia, one of 15 new towns whose residents were surveyed as part of an evaluation of new communities. See page 2.

# Telescopes As Big As The Earth



**Listening to the cosmos.** The 40-meter radio telescope at Caltech's Owens Valley Radio Observatory.

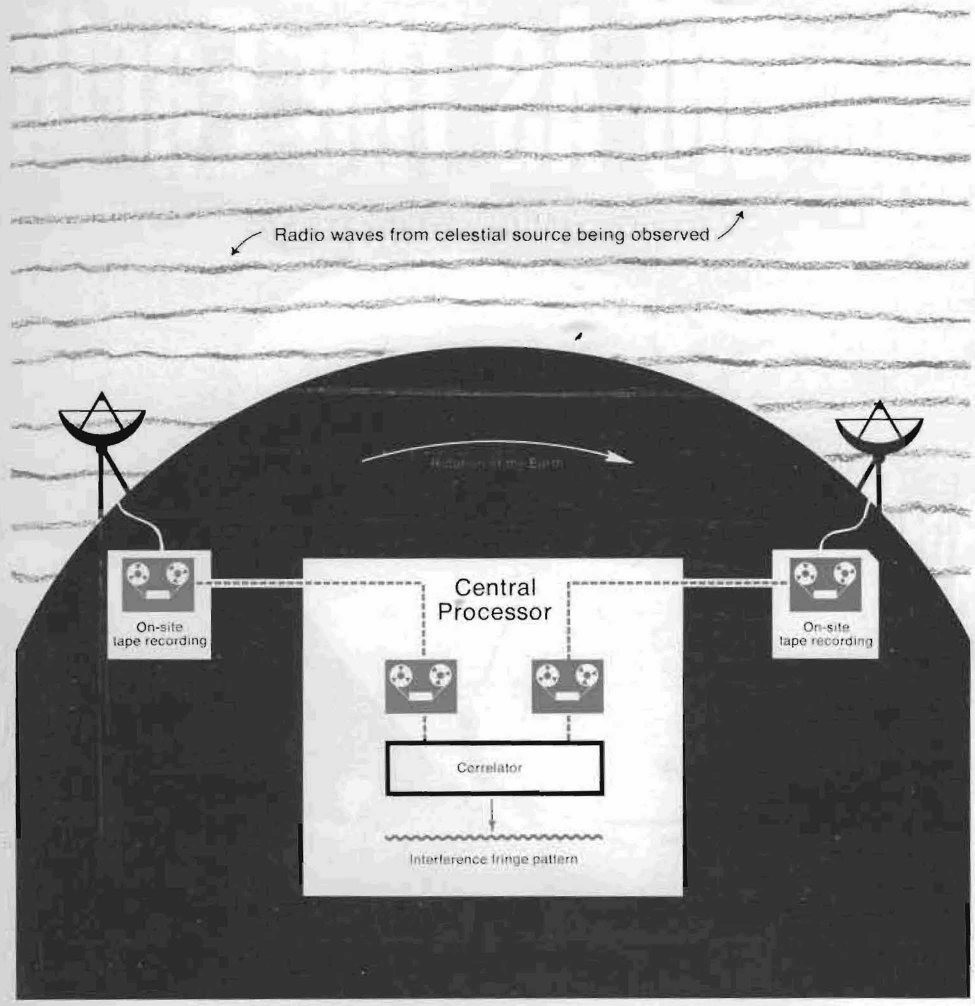
**Making simultaneous observations with radio antennas continents apart, astronomers get their most detailed look yet at cosmological mysteries.**

And from above, the thin squeaks of radio static
The captured fume of space foams in our ears—

Hart Crane

These lines, from Crane's prophetic poem "Cape Hatteras," were written just a few years before Karl Jansky at Bell Telephone Laboratories accidentally discovered cosmic radio noise in 1931. Jansky had built an antenna specifically to measure terrestrial radio noise, such as that from lightning flashes. Like Columbus, he discovered the "wrong" thing: cosmic radio noise that seemed to come from the direction of the Milky Way. Just before World War II, a radio amateur named Grote Reber built a dish-type antenna—which is highly directional—in his backyard in Wheaton, Illinois. Using that antenna, Reber drew the first radio noise maps of the heavens.

For astronomy and cosmology these unheralded developments were momentous. The feeble radio signals that continuously bathe the Earth have truly revolutionized our concept of the universe. In only four decades radio astronomy has opened as many scientific vistas as optical astronomy did from Stonehenge to today. In that time it has stretched from a backyard beginning to intercontinental experiments in Very Long Baseline Interferometry. Hart Crane, ever the champion of unfolding visions, would have heartily applauded this great enlargement of the knowable universe.




**How VLBI works.** With two widely separated radio telescopes observing the same object simultaneously, precisely timed signals are recorded on tapes. When played together later, the tapes produce an interference pattern rich in detail about the observed object.

## Harbingers of a new cosmology

While radio astronomy was shelved during World War II, electronic technology was making great strides. In addition, an unexpected wartime discovery further piqued the curiosity of astronomers. Shortly after the Normandy landing, a number of Allied radar sets detected strong radio noise. A new German radar-jamming device was suspected; but ultimately the Sun, which was intensely active at the time, was identified as the noise source. This event, plus Reber's curious radio noise maps of the sky, stimulated post-war construction of radio telescopes, first in England and Australia, and later the United States.

As these new dishlike antennas scanned the sky, they saw not the hard points of light familiar to optical astronomy but diffuse regions of high and low radio noise punctuated by a few more sharply defined "radio stars." It was a fuzzy view of the cosmos; fuzzy because the resolution of a radio telescope depends on its diameter measured in wavelengths, and radio telescopes were not big enough to provide sharp pictures of whatever was generating radio noise—which, like light, is a form of electromagnetic radiation, but of lower frequency—far out in space. Of course, the resolution of an optical telescope is subject to the same rule, but the wavelengths of visible light are so small—about 100,000 times shorter than radio waves—that lens size ordinarily doesn't limit resolution. (Actually, the turbulence of the atmosphere limits resolution, which is why placing an optical telescope in orbit above the atmosphere provides better resolution.) But at radio wavelengths, it takes impossibly large radio dishes to even approach the resolutions of optical telescopes.

Consequently, radio astronomers have built ever larger radio telescopes. Behemoth dishes 60, 90, even 300 meters in diameter are nestled in sparsely populated, radio-quiet areas all over the world. They're so big that wind distorts their shapes and they sag under gravity's pull. Given the practical limitations of money and engineering, the best single radio telescopes have resolutions approaching 1.0 minute of arc. Optical telescopes are about 100 times better. So, early, radio telescopes gained the reputation of having inherently low resolution. That generalization turned out to be hasty.

But even fuzzy pictures of the universe recorded by single, large radio dishes are exciting—and strange, too, because they show the universe as it appears to radio receivers, not human eyes.

Hydrogen is the primary stuff of which the universe was made, so astronomers weren't surprised when they detected its characteristic 1,420 MHz radio note between the radio stars and radio galaxies. Then they found simple radicals and molecules, such as hydroxide, water, cyanide, and ammonia, and even more complex structures, such as methylacetylene ($CH_3C_2H$). Apparently, somewhere in space there are places cool enough for molecules to form.

Suspended in this very thin chemical broth are the discrete sources of radio energy. Some, like the last gasps of supernovas, seem to be familiar extensions from the optical spectrum; but others pose profound questions for science. The quasar riddle is by far the most bothersome. The facts are these: Most quasars are very strong radio sources that can be identified with visual objects possessing very large red shifts. If the red shifts are interpreted as cosmological (which says that the object, as part of the general expansion of the universe, is moving away from us at great speed) and proportional to distance, then the quasars are so far away that the physicist cannot easily explain how such prodigious quantities of energy are generated. If, in truth, the quasars are close to the Earth, the energy generation problems becomes tractable but the red shift phenomenon becomes a mystery. Most cosmologies, particularly the popular Big-Bang model of the universe, lead to the conclusion that the red shift *is* proportional to distance. If this interpretation is on shaky ground, so is our present conception of the universe. An answer to the quasar riddle remains of utmost importance to cosmology.

 NSF publication

## The synthetic apertures

For the radioastronomer, using only single radio telescopes of limited diameter is a little like watching a mystery movie on a poorly focused TV screen. But a clever technique called interferometry can sharpen parts of the picture tremendously. If two or more widely separated radio telescopes are used, the acuity at radio wavelengths can be increased dramatically—to the point where the radio instruments have many times the resolving power of conventional optical telescopes.

At first glance, the Interferometer Principle appears far removed from the telescope idea, which is magnification (for most terrestrial applications) and light-gathering (for most astronomical work). The basic interferometer consists of two or more detectors of electromagnetic signals separated by many wavelengths. Each detector is pointed at the object of interest, and the signals generated by the incoming waves are sent to a "mixer" where they are combined. If the signals can be put in phase, then the slightest change in the angular position of the source is easily discerned. (This assumes sources with small angular diameters.) The interferometer's sensitivity to angular position allowed A. A. Michelson and F. G. Pease to measure the angular diameters of some of the brighter optical stars in 1920.

The classic Michelson-Pease interferometer used two detectors six meters apart. That separation amounted to roughly ten million times the wavelength of visible light, which is about 1/20,000 of a centimeter. To achieve the same resolution when studying a quasar emitting waves at ten centimeters, the separation between the radio telescopes should be 100 million centimeters or 1,000 kilometers. If the separation were 10,000 kilometers, the radio interferometer would have ten times the resolution of the optical interferometer.

When astronomers first began to think about the possibilities of radio telescope interferometers, they could only dream about 10,000-kilometer baselines. To get usable observations, separate telescopes had to be connected so that the radio waves could be combined in a mixer.

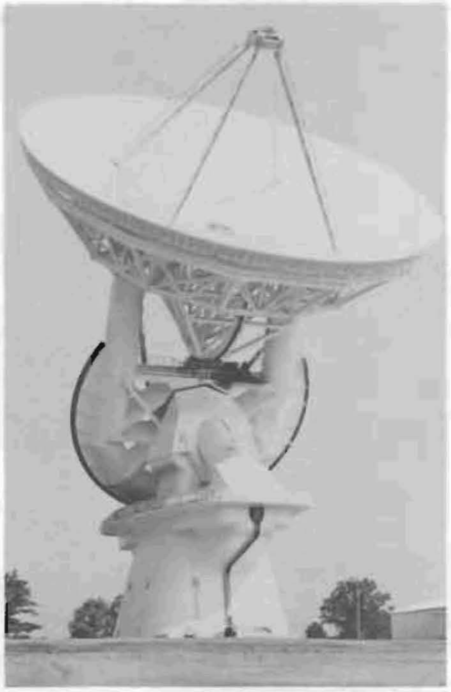
So the interconnection problems restricted radio interferometer baselines to the lengths of the cables—only a few kilometers long—during the middle 1960's. Even when cables were replaced by microwave communication links, as they were in England and Australia, a barrier remained at about 100 kilometers. Still within that limitaton, radio interferometry has been and continues to be a valued tool.

A physically appealing way to think of this type of interferometry is to consider each radio telescope as a small piece or element in an immense fictitious radio telescope—like one of the tiny lenses in the compound eye of an insect. As the Earth turns and as the radio telescopes are moved relative to one another, the picture seen by the artificial radio dish is built up hour by hour in a process caller "aperture synthesis."

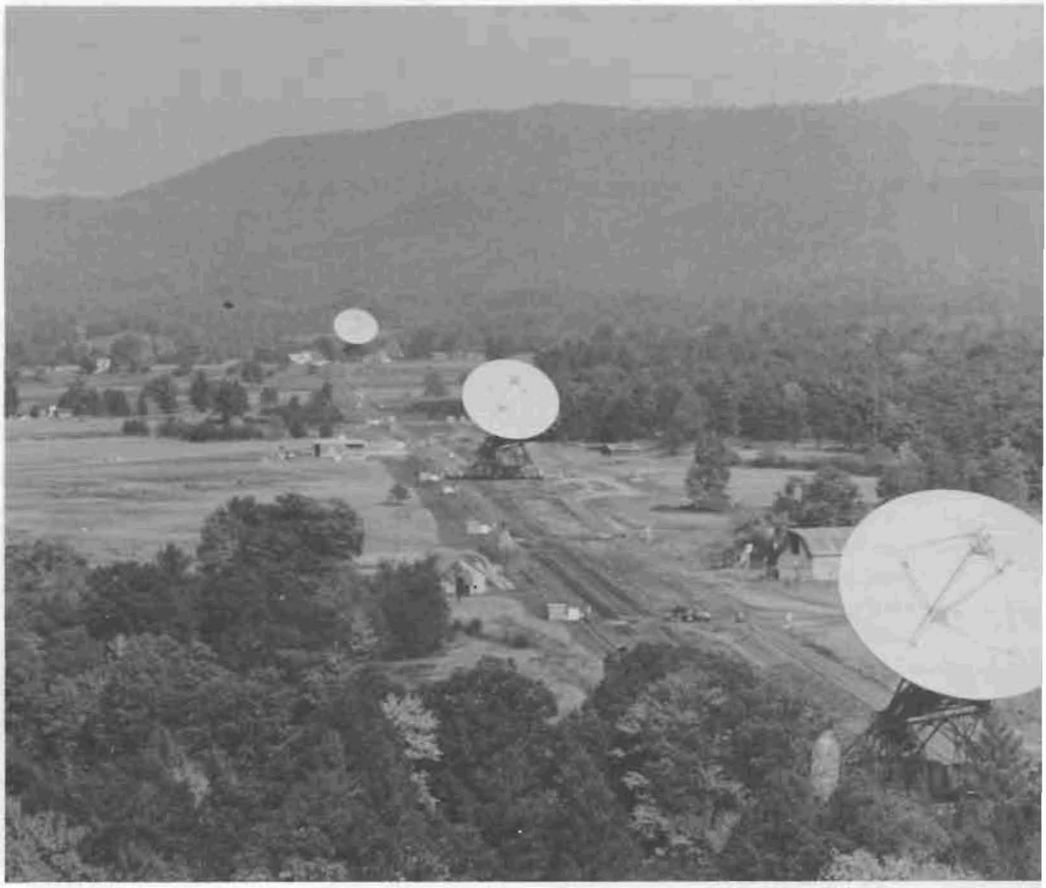
## Cutting the cord

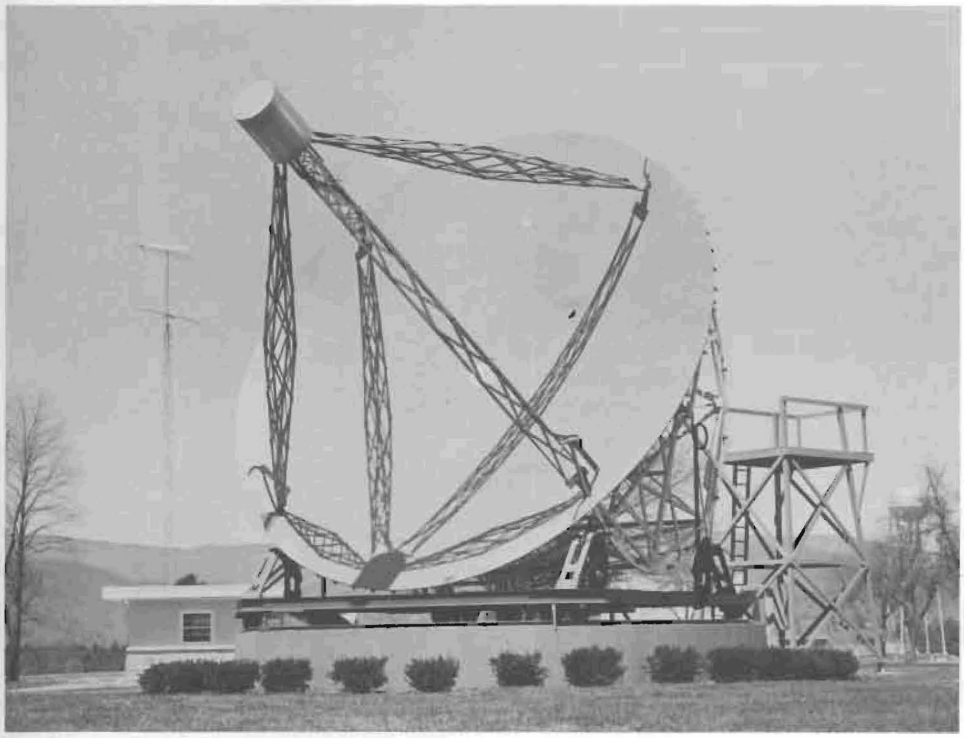
Once radio astronomers realized the possibilities inherent in a baseline of thousands of kilometers, they were determined to find a way to create that immense synthetic aperture, regardless of the natural, political, and administrative barriers in their way.

Actually, Very Long Baseline proponents recognized early that they could sever that restrictive real-time communication link if they had some way to record the signals on tape simultaneously



**Interferometry at Green Bank, West Virginia.** The National Radio Astronomy Observatory's 43-meter telescope (above) has been used in many two- and three-element very long baseline experiments. The three-element interconnected array (below) operates along a 1,500-meter baseline.





**The prototype radio telescope.** With this 10-meter dish in his Illinois backyard, radio amateur Grote Reber drew the first radio noise maps of the sky in the late 1930's.

at the two separate antennas, then bring the two recordings together and play them back into the mixer. The difficulty was in synchronizing the two recordings. A slight timing error in one recording would have the effect of shifting the phases of the recorded signals.

The key to breaking that 100-kilometer limitation has been the high precision atomic clock, available thanks to years of work by physicists investigating atomic frequency standards. An atomic clock can generate time marks for the tape recorder and also stabilize the needed local oscillator, which serves as a phase reference but which tends to wander slightly in frequency over observation times of several hours.

Stability is only half the answer though. Stable as atomic clocks are, there is no guarantee that all clocks along the baseline are synchronized. Two solutions exist. One is to carry one clock physically to the others and synchronize them on the spot. The other is to set the geographically separated clocks by referring to a common signal each station can hear—a radio starting gun, so to speak. Both methods work, but the latter is easier. The radio timing signals broadcast by Loran-C navigation stations blanket most of the Northern Hemisphere. With some simple corrections for distance, Loran-C timing pulses can synchronize atomic clocks with sufficient accuracy.

The first VLB experiment based on tape recordings was completed in 1965 by a group of radio astronomers at the University of Florida, using receivers only 55 kilometers apart. Their target was Jupiter—a very strong radio source, relatively speaking, compared to the distant quasars. Results indicated that Jupiter's radio noise sources were less than a few thousand kilometers in diameter, inferring a radio telescope resolution far greater than that typical of optical telescopes.

Since that initial work, refinements have been continually added to the basic VLB concept. The amount of data the tape recorders can handle still limits the sensitivity of VLB. The NRAO Mark II terminals, which use modified TV tape recorders and are now widely used around the world, have a bandwidth of 2 MHz. An MIT group and others are attempting to adapt a multichannel instrumentation tape recorder to where it has 25 times the bandwidth of the Mark II. With each bandwidth increase, fainter and fainter radio sources can be studied. Tape recorder bandwidth is roughly analogous to the diameter of the mirror in a reflecting telescope—the bigger it is, the fainter the objects that can be seen.

Another VLB limitation has been the atomic clocks usually employed. Inexpensive models are stable to better than one part in 100 billion, but even more stability is desired. Hydrogen maser clocks, while very expensive and cranky, are about 100 times more stable. A few have been installed at radio telescopes being used in VLB work, and as more are added the cosmos will come into better focus.

Meanwhile, some radio astronomers are frustrated by delays in data processing. All VLB tapes recorded on the NRAO-designed Mark II terminals are presently processed at the NRAO facility in Charlottesville, Virginia. Although the tapes are easily processed, it's still a lengthy task because each VLB experiment generates many hours of tape. If a triangle of three stations is used for a more complete synthetic aperture, tapes from the three different pairs of stations must be analyzed separately in the NRAO system.

## Assembling a network

Arranging a VLB experiment is like getting together a pick-up game of baseball. The teams are not permanent and the equipment is not standardized. A radio astronomer who wants to look at some specific objects can't put together a long baseline on his own; he must convince other radio astronomers to become part of the experiment and contribute their radio telescopes. Radio telescopes are scheduled far in advance, but with a three-month lead time an experimenter can usually set up a baseline within the United States. VLB pairs have been made up between the United States and Canada, Sweden, Australia, Germany, England, South Africa, and the Soviet Union. A typical experiment will enlist two or three telescopes for as many days during which perhaps a half dozen objects will be studied. Longer experiments and more antennas would provide better pictures, but most VLB groups are already saturated with data and couldn't use more telescope time without constructing more data processing facilities.

About two dozen radio telescopes have been used in the 100 or so VLB experiments completed to date. Few of these instruments were constructed with VLB in mind. They vary widely in size, in sensitivity, in frequency response, and

Baselines. Telescopes in three continents have been linked in various combinations for VLBI observations. The longest baseline to date is the 10,500 kilometers between Goldstone, California, and Tidbinbilla, Australia.

in their ability to see and track specific celestial objects. In addition, the research interests of the group controlling the telescope have much to do with whether it is used in VLB work. The major U.S. VLB groups are at NRAO, MIT, and Caltech. Each group has access to several radio telescopes, and among the common VLB triangles are: Goldstone (California)/Haystack (Massachusetts)/Green Bank (West Virginia), and Owens Valley (California)/Fort Davis (Texas)/Green Bank (West Virginia). Canada can add another North American station at Algonquin Park (Ontario). So far, the Goldstone-Tidbinbilla (Australia) baseline is the longest: 10,500 kilometers.

The 10,500-kilometer baseline approaches the diameter of the Earth, and one wonders whether VLB has reached the end of the line (available baseline, that is). Terrestrial real estate can't be stretched farther, but higher resolution can still be achieved by observing at shorter wavelengths. (Remember that an interferometer's resolution is proportional to the length of the baseline in wavelengths, not kilometers.) Radio astronomers at MIT and elsewhere are constructing or have already built radio interferometers at wavelengths of 13 millimeters with baselines about one kilometer long. Of course, baselines could also be extended by placing an automated radio telescope on the Moon. Timing and antenna control signals could be telemetered up from Earth, while data recorded by the telescope would flow from Moon to Earth. A radio telescope on an Earth satellite in an eccentric orbit is also a possibility. A question that arises with extraterrestrial baselines is: Do radio astronomers really need the resolution that would be provided, say, by the Earth-Moon 384,000-kilometer baseline? Some astronomers wonder if there is anything that small worth seeing, but the discoveries made so far by VLB methods should teach them to expect the unexpected.

## A most perplexing universe

The modest beginnings of Jansky and Reber did not hint at the convulsions of astronomy they would engender. Astronomy, the "queen" of the sciences, once dealt with pure, pristine stars organized into rather tidy galaxies. In the classic view, the galaxies recede from one another according to the dictates of the expanding universe. During the first half of this century, astronomy seemed to be coverging upon a rational, well-tuned model of the universe. Then, a few micro-microwatts of radio static from outer space destroyed that cozy picture.

The quasar paradox in itself was enough to require a complete reassessment of distance scales and modes of energy generation. In addition, radio astronomy revealed that the centers of some galaxies, possibly the centers of all galaxies, are copious sources of matter that is being ejected into space at speeds on the order of 1,000 km/sec. Where this matter comes from and what propels it are mysteries. Some astronomers surmise that the galactic nuclei may be strange maelstroms of matter with masses of 100 million suns confined within spheres only one light year in diameter. Such concentrations of mass and energy hardly fit the conventional picture of a universe running down according to the Second Law of Thermodynamics.

The structure of a galactic center cannot be seen in visible light; the intervening mass of dust and debris renders optical telescopes useless. Radio waves penetrate the dust clouds and bring us some inkling of what transpires behind the veil. Only VLB radio astronomy can see into these centers with enough acuity to resolve details.

A similar situation prevails for quasars: VLB is needed to see the fine structure. Ordinary radio telescopes first revealed that quasars had complex structures when the quasar 3C273 was observed passing behind the Moon. Analysis of the diffraction pattern created by the Moon suggested that 3C273 was actually shaped like a dumbbell. VLB can now easily "see" much finer detail. But what these structural details mean to astrophysics is anyone's guess.

VLB's acuity has generated a new problem; one that has caught the public's fancy. The structures of quasars have been observed to change appreciably over a period of a few months. In the cases of quasars 3C273 and 3C279, these changes *seem* to be propagated at several times the speed of light. The popular press (and some scientists) immediately assumed (almost gleefully) that this meant that Einstein's famous assumption about the velocity of light being an upper limit had been violated. But the breaking of the speed-of-light barrier is the most unlikely interpretation of the data. More probable is the explanation that these quasars really have a triple or even more complex structure instead of the dumbbell shape or, different portions of the quasars may be blinking on and off independently of one another, giving a false impression of motion, like the lights on a theater marquee. Whatever interpretation is correct, quasar dynamics are far from being understood.

Quasars, as it develops, are merely enigmas separated by mysteries. The space between them is far from empty. In fact, the bulk of the universe may lie *between* the stars and galaxies—unseen visually and virtually unknowable until the advent of radio astronomy. This vast region between the stars seethes with dust, debris, and energy. Radio telescopes discern thin populations of atoms, ions, radicals, and molecules that act in concert to generate radio signals. Assemblages of molecules are caught up in maser action, emitting radio signals characteristic of OH, $H_2O$, SiO, and other chemical species.

Through VLB interferometry, radio astronomers have pinpointed small regions of maser activity. Indeed, interstellar space is a veritable plum pudding of matter, with the plums being masers of solar-system size. Some cosmologists suspect that these celestial masers, if that is what they really are, represent embryonic star stuff, which will coalesce millions of years hence into new suns and planets.

Radio astronomy has taught us one truth about the universe: Cosmologies built upon a narrow portion of the spectrum are apt to collapse when the wavelength blinders are removed.

## The practical value of precision

Surveyors and geodesists need stable reference systems. The precise measurement of the distances between points on the Earth's surface depends upon being able to see a fixed reference point. While surveyors are quite happy with the benchmarks set out by the Coast and Geodetic Survey, geodesists are not. The Earth is not sufficiently rigid for their purposes. It wobbles; its continents drift about; its crust is cracked by Earth tides. Some of these irregularities can be measured by careful optical observations of the fixed stars, which constitute what is termed an "inertial frame of reference." But VLB interferometers operate on a much better reference frame—quasars, so far away that no apparent motion can be discerned. Instead of sighting on a terrestrial benchmark with a transit, the position of terrestrial points can be located much more accurately by making one radio telescope a benchmark and taking a portable radio telescope to the point to be measured. The VLB's angular precision is 0.001 arcsecond, something an ordinary transit can't approach.

Radio interferometers have already measured distances between terrestrial points with very high accuracy. In 1969, the 845.130-kilometer baseline between an NRAO radio telescope at Green Bank, West Virginia, and another telescope at the Haystack Observatory in Massachusetts was measured to within two meters. Today, an error of a few centimeters looks possible.

Such precision opens the door to several important measurements:

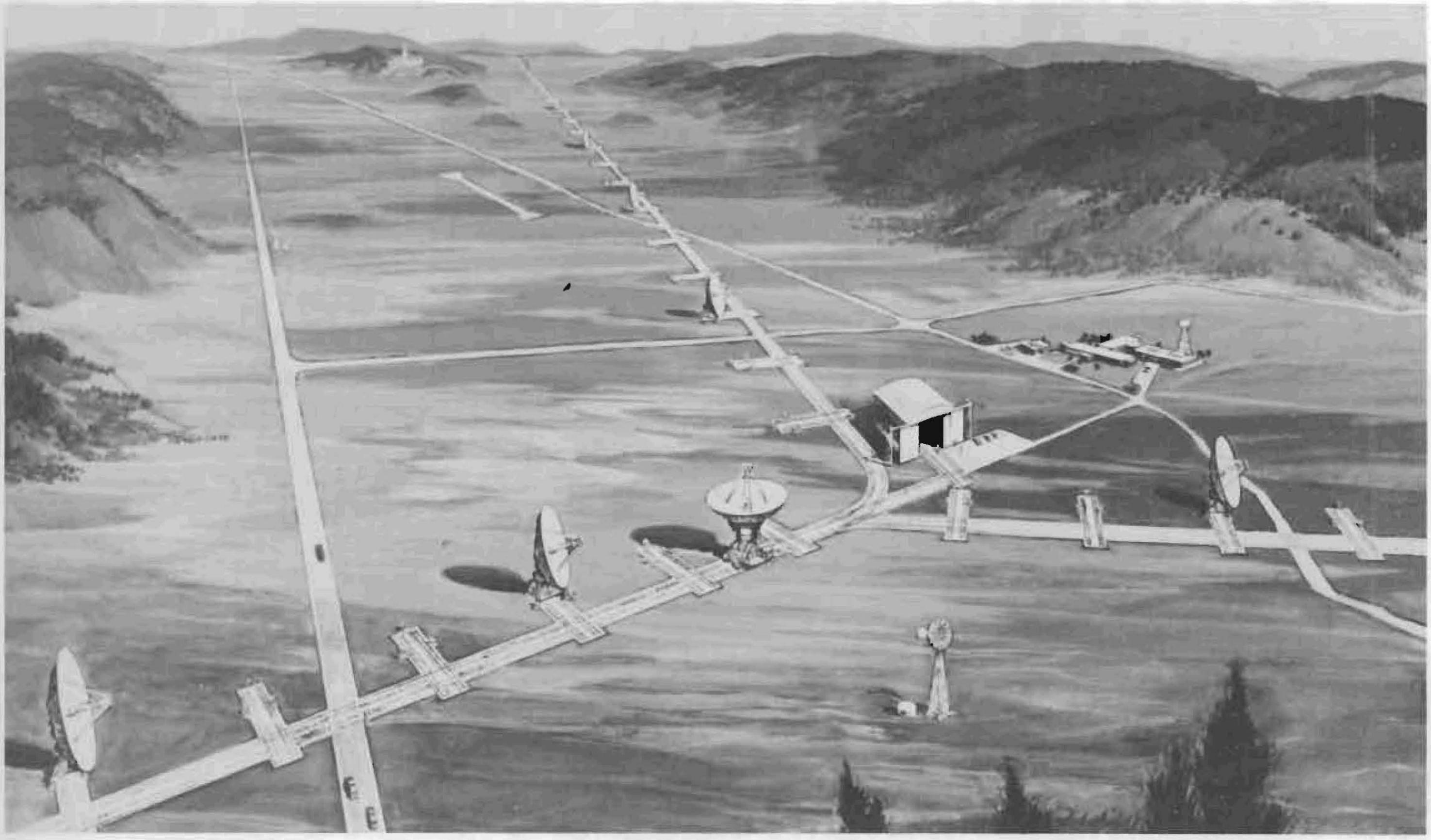
- Continental drift, which assuming it occurs, is probably in the range of a few centimeters per year and almost impossible to measure with more conventional instruments.
- The rates of continental uplift and subsidence.

### The Very Large Array

The indisputable advantage of very long baseline interferometry is its ability to resolve detail. But it's a cumbersome research tool, and only a limited number of observations have been made. In 1962 a group at the National Radio Astronomy Observatory, a National Research Center supported by NSF, began developing an idea that was ultimately to result in the design of a radio telescope with the resolution, speed, and sensitivity to obtain radio "images" in near real time. This high-speed interferometer being built near Socorro, New Mexico, consisting of 27 interconnected radio telescopes, was given the name "Very Large Array," or VLA.

Each of the 25-meter-diameter antennas is free to move along railroad tracks in the shape of a Y. Two arms are 20.8 kilometers long; the third is 19 kilometers. The diameter of the array can be expanded and contracted by moving the telescopes. At its maximum extension, about 32-kilometer-diameter, the array provides its greatest resolution (about one-tenth of a second of arc), and its smallest field of view. When the telescopes are moved closer together, the resolution is reduced and the field of view is increased. This feature of the VLA is the radio equivalent of the zoom camera lens.

Many of the operating principles of the VLA are derived from a three-element array at the National Radio Astronomy Observatory in Green Bank, West Virginia. That interferometer consists of one fixed telescope and two telescopes movable along a 1500-meter baseline. Obviously, the VLA, with its much larger synthetic aperture, will have much higher resolution. And with 27 detectors instead of three, the aperture can be synthesized much more quickly and completely to provide richly detailed information on weak radio sources. When completed in the early 1980's, the VLA will be the most advanced radio telescope in existence.



Most advanced radio telescope. Under construction in New Mexico by the National Radio Astronomy Observatory is the Very Large Array, a 27-telescope interferometer in the shape of a Y with a 32-kilometer diameter.

• The diurnal Earth tides—much smaller than the ocean tides.

• The Earth's dynamic vagaries. Variations in the 14-month Chandler wobble, which may be related to earthquake frequency, can be measured quickly and accurately with VLB. The Earth's rotation also speeds up and slows down in response to atmospheric changes, some of which are Sun-induced. VLB may be the key to investigating a whole new class of interactions between the Earth's core, mantle, atmosphere, and the effects of the Sun.

## Differential VLB

Extremely accurate though it may be, VLB interferometry is limited by: unknown, variable errors in phase caused by the different atmospheric and ionospheric layers above the far-separated receiving antennas; and slight drifts in the frequencies of the local timing equipment. These limitations can be removed in what are called "differential" measurements. The differential technique requires radio sources with small angular separation, so that what the atmosphere and ionosphere do to one signal they also do to the other. When differences are taken between observations of the different sources, the errors are subtracted.

Where in space does one find nearby radio sources at different frequencies? One place is on the Moon, where astronauts left behind nuclear-powered ALSEP instrument packages radiating at frequencies between 2275.5 and 2279.5 MHz. Teams of radio astronomers from MIT and JPL used NASA's far-flung spacecraft tracking antennas for differential VLB measurements. The relative separation of the ALSEP's was measured to within about one meter at a distance of some 384,000 kilometers. The same technique was used to track the Apollo-16 Lunar Rover in April 1972, as it threaded its way among lunar craters. In this case, one radio source was in the the Lunar Module and the other on the Rover itself.

The Viking 1975 Mars missions will hopefully place two orbiters around Mars and two landers on its surface, each with different signal sources. Differential VLBI should be useful here in making precision measurements of this intriguing planet.

Differential VLB is just one proliferation of the basic VLB concept. Another is long baseline radar interferometry. Here, a signal sent from a terrestrial transmitter is reflected from the surface of a planet or some other denizen of the solar system. VLB stations back on Earth can use the echo as they would radiation from a quasar or spacecraft transmitter. Precision topographic maps of planetary surfaces, such as that of cloud-mantled Venus, can be made even though visual observations of the surface are virtually impossible.

## L'Envoi

Crane's "thin squeaks of radio static" are so useful in our efforts to explore the universe that, where nature herself fails to provide squeaks, we send out our own noisemakers: spacecraft and radar pulses. But we can provide them with only enough energy to reach the other planets of the solar system. To tune in on the rest of the universe, which is essentially all of it, we can only listen better—with bigger antennas or more sensitive detectors in other regions of the spectrum. •