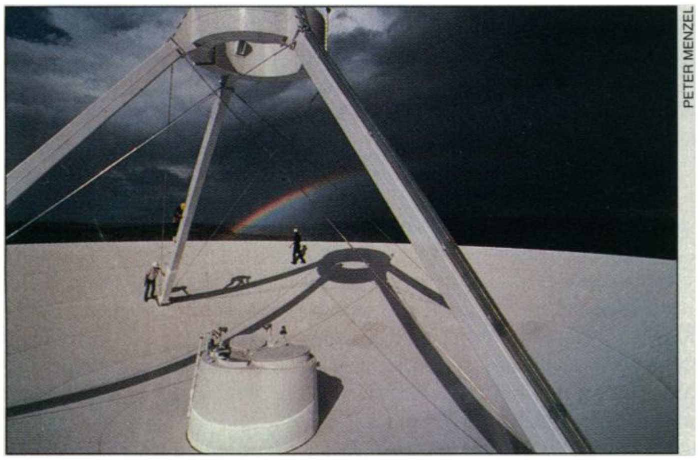
A Continent-Sized Ear on the Cosmos

U.S. and European astronomers will soon be routinely using arrays of radio telescopes that mimic a single instrument thousands of kilometers across to produce images with unparalleled resolution

In the months leading up to the launch of the Hubble Space Telescope in 1990, it was hard to open a newspaper or magazine without finding an article enthusing about the unprecedented high-resolution images the National Aeronautics and Space Administration's new spacecraft was expected to beam back to Earth. Yet a telescope system whose resolving power makes the Hubble seem like a toy magnifying glass is about to be completed, and it's garnered nary a headline. True, the instrument lacks the drama of a powerful eye-in-the-sky, but among radio astronomers, the anticipation is just as intense as it was before the Hubble went up.

The instrument they're salivating over is the $80 million Very Long Baseline Array (VLBA)—a network of 10 new radio antennas spread from Mauna Kea in Hawaii to St. Croix in the Virgin Islands. Each dish is only 25 meters in diameter, but run together, they will mimic a single radio telescope some 8000 kilometers across. When the last VLBA antenna is brought on line sometime this spring, the VLBA operations center at the National Radio Astronomy Observatory's (NRAO) site in Socorro, New Mexico, will start churning out images with an angular resolution of two ten-thousandths of an arc second—500 times better than the Hubble Space Telescope will ever achieve, even with its promised package of corrective optics.


PETER MENZEL

More than the sum of its parts. One of the VLBA's 10 25-meter antennas that together simulate an 8000-kilometer telescope.

With that kind of resolving power available on a routine basis for the first time, astronomers should get a new perspective on such intriguing objects as jets of radio-emitting material that shoot from the center of distant radio galaxies and quasars. They will also produce accurate measurements of distance on a cosmic scale, and they even hope to discover exotic new types of extragalactic radio source. The power of their new instrument to provide fine-grain images results from a simple formula: The resolving power of any telescope depends on the diameter of its collecting area divided by the wavelength at which it operates. Although radio wavelengths are many times longer than those of visible light, a continent-sized array like the VLBA can provide resolution that easily surpasses that of any optical telescope.

It won't be the first time astronomers have linked antennas together to simulate a single giant telescope. NRAO's Very Large Array—a 27-dish network spread across tens of kilometers on the plains of San Augustin near Socorro—has been producing images for more than a decade with a resolution matching that of the best ground-based optical telescopes. And Britain's MERLIN array (see box) is at the forefront of research into gravitational lensing. But in the past, it's only been possible to operate very long baseline, continent-sized arrays by linking existing radio dishes on an ad hoc basis for a few weeks each year. Now the VLBA, together with a new initiative that will permit European radio astronomers to link their existing telescopes more effectively, promises to put such capabilities into the hands of astronomers on a routine basis.

Indeed, the VLBA and the European program represent the coming of age of very long baseline interferometry (VLBI), a technique that relies on the fact that radio signals arriving from nearby points in the sky reach two widely spaced telescopes at slightly different times, and are therefore out of phase. When the signals are merged electronically, they interfere with each other. The amount of interference depends on the separation between radio-emitting regions in a source, the distance between the two telescopes, and the frequency of the radiation. If the last two are known, the interference can be used to obtain information about the location and structure of an observed source—and by building up data from many pairs of telescopes, it's possible to produce detailed images.

But in order to gain the advantages that come from linking radio telescopes separated by thousands of kilometers, researchers must overcome a string of problems. Not only is it hard to determine the precise distance between individual telescopes, but errors creep into the data due to variations in the atmospheric conditions over the telescopes in the array. In the past, that has made data processing a nightmare and limited VLBI to a hard core of well-versed exponents.

The VLBA should change all that. NRAO has produced user-friendly software packages for data analysis, and VLBI novices will be able to fall back on NRAO staff for advice. And because the VLBA has a high-capacity data correlator able to combine the signals from 20 telescopes in one go, data processing backlogs should become a thing of the past. "[VLBI] will go from being something a few black belters can do with a considerable degree of difficulty, to something the community can do," predicts Craig Walker, an NRAO astronomer at Socorro.

European radio astronomers are similarly aiming to bring VLBI to the masses. Although they can't afford to build a dedicated instrument like the VLBA, VLBI astronomers have been promised more time for their observations on existing European radio telescopes. They have also persuaded the European Community to help fund a user support service based at the Dwingeloo Observatory in the Netherlands, and they're working on a new data correlator, which should be ready by 1997. Although the upgraded European network will be available only on a part-time basis for VLBI, it does have one advantage over its American counterpart: It will include several very large radio telescopes, giving it the ability to detect radio sources four times fainter than the weakest visible to the VLBA. For that reason, there are also plans to link these telescopes from time to time with the VLBA.

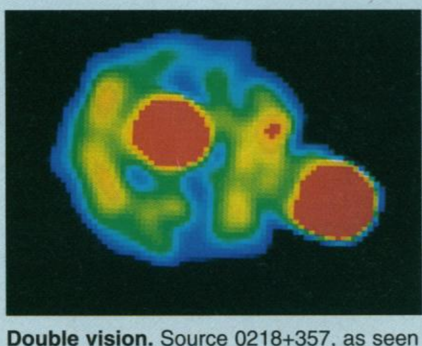
VLBI's greatest hits

One reason astronomers are keenly awaiting the VLBA and the developments in Europe is that in recent years VLBI observations have yielded a series of startling discoveries. In the

MERLIN Gets the Hubble Constant in Focus

Radio astronomers at the University of Manchester's observatory at Jodrell Bank believe they may be closing in on a long-sought prize: Determination of the Hubble constant—the elusive figure that defines the rate at which the universe is expanding. If so, it will be one more feather in the cap of radio interferometry, as current estimates of the constant vary by a factor of two.

The Jodrell Bank researchers are using an array of antennas called MERLIN (Multi-Element Radio-Linked Interferometer Network) to hunt for examples of gravitational lensing. That process is the bending of radiation from a distant source to form multiple images, which results from the presence of a massive object such as a galaxy lying directly in the line of sight. With antennas distributed across England, MERLIN simulates a telescope 220 kilometers across. It can't match the resolution of the continent-sized VLBA, but a resolving power equal to that of the Hubble Space Telescope, combined with good sensitivity and relative ease of use, has made MERLIN the instrument of choice in the search for multiply imaged systems. In July 1991, only 10 such systems were known. Following a preliminary search for candidates using the Very Large Array in New Mexico, MERLIN has since added another three to the list and included in its haul is a source called 0218+357 that may lead to the determination of the Hubble constant.



ALOK PATNAIK ET AL/JODRELL BANK

Double vision. Source 0218+357, as seen by MERLIN through a gravitational lens.

MERLIN maps of 0218+357 show two images of a single quasar, separated by only one-third of an arc second. One of those quasar images is surrounded by a circular "Einstein ring," an effect that occurs when part of the source lies directly behind the lensing galaxy. In 0218+357, the ring is almost certainly a lensed image of a jet of plasma shooting from the quasar's core—and it's this feature, together with the fact that the radio emissions from the quasar seem to vary over time, that provides the key to determining the Hubble constant.

The trick depends on determining the geometry of the paths taken by the radiation forming the two quasar images. To do that, the Jodrell astronomers need to work out the distribution of mass in the lensing galaxy and the relative distances to the galaxy and the imaged quasar. The former can be determined from the size of the Einstein ring, the latter by recording the red shifts of the galaxy and quasar. Then it's a matter of putting real distances onto the scale diagram showing the lens system's geometry.

That's where the varying emissions from the quasar come in. Because the paths taken by the rays forming each image are of slightly different lengths, the two images should show the same pattern of variation, but with a time delay—rather like two tape decks playing back the same recording, with one started a few seconds after the other. This delay will reveal the actual difference in the length of the paths taken by emissions forming the two images, allowing the Jodrell team to work out the actual distances to the galaxy and quasar. The Hubble constant will then drop out of the simple equation that relates the red shift of a distant object to its distance.

Dennis Walsh, one of the Jodrell team that discovered the first gravitational lens back in 1979, says that observations with the 4.2-meter Anglo-Dutch William Herschel optical telescope, at La Palma in the Canary Islands, have already revealed the red shift of the lensing galaxy unanimously. He says it may be possible to obtain a red shift for the distant quasar by observing in the infrared. Of course, an experiment with a sample size of one may not be enough to convince the astronomical community that gravitational lenses are the best way to determine the Hubble constant. So Jodrell radio astronomers Ian Browne and Peter Wilkinson, together with Tony Readhead of the California Institute of Technology, are now planning a 3-year survey of 20,000 radio sources, using a single pair of widely spaced telescopes, to filter out new candidate lenses. "We hope it will turn up 20 to 40 gravitational lenses," says Readhead. If just a few of those share the characteristics of 0218+357, the slippery Hubble constant may at last be within grasp.

–P.A.

early 1970s, astronomers fitted data from widely spaced telescopes to mathematical models and came up with an observation that seemed to flout Einstein's theory of special relativity. Specifically, they detected blobs of material emitting strong radio signals in jets streaming from the nuclei of some active galaxies and quasars—which seemed to be moving faster than the speed of light.

This surprising observation, confirmed later in the decade by some of the first true VLBI images, is now thought to be due to plasma shooting almost directly toward the earth at speeds approaching that of light. Because the material is moving almost as fast as the radiation it emits, radio signals reaching the earth a few years apart may actually have been emitted over many tens of years, greatly boosting the signal and creating the illusion of motion faster than that of light. Since then, these boosting effects have been observed by astronomers working at a variety of wavelengths.

But this "superluminal" motion may soon face some serious competition as VLBI's "greatest hit." Radio astronomers from the California Institute of Technology and the University of Manchester's radio observatory at Jodrell Bank have recently completed a VLBI survey of 135 radio sources, and they intend to use the VLBA to extend this to between 500 and 1000 objects. Caltech radio astronomer Tony Readhead is willing to bet that this survey will turn up "a number of weird and wonderful objects"—like the source discovered by the Caltech/Jodrell team that seems to belong to an entirely new class of active galaxy. The source, catalogued as 2352+495, consists of a compact, strongly radio-emitting core, straddled by two bright arcs—giving the whole structure an "S" shape measuring about 150 parsecs from end to end.

Once the VLBA is in full swing, astronomers expect to find other cosmic curiosities —as well as exploit it as a cosmic measuring stick. In the 1980s, a group at the Harvard-Smithsonian Center for Astrophysics led by Mark Reid pioneered a distance measuring technique that depends on recording the motions and red shifts of maser sources—compact cloudlets of gas found in star-forming regions, and around aging red giant stars. With those data, astronomers can use a statistical model to estimate the masers' distance from the earth—much as you can calculate the distance to an automobile moving along a far-off highway from its apparent motion, if you know its actual speed and the direction in which it's going.

In 1988, Reid's group used this technique to calculate that the center of our Milky Way galaxy lies 7100±1500 parsecs away—rather than the 10,000 parsecs that had been accepted as a standard by the International Astronomical Union. "It was a little bit of a shock to some people that the galaxy was 20% to 30% smaller than they had thought," says Reid. Now Reid and his colleagues plan to use the VLBA to measure the distance to the nearby galaxy M33 by observing masers consisting of water vapor.

Astronomers are also looking to the VLBA to open up areas even the most skilled VLBI exponents have considered daunting—tasks such as extracting data on the polarization of signals received by the VLBI arrays. David Roberts and John Wardle of Brandeis University in Waltham, Massachusetts, are among the few researchers who have the skill and patience to try this kind of analysis routinely, which is valuable because it reveals the structure of the magnetic fields running down radio jets shooting from distant active galaxies—which in turn sheds light on the fluid flows taking place. From the studies Roberts and Wardle have carried out so far, the structure of the magnetic fields suggests that the speeding blobs of plasma observed in radio jets aren't discrete "cannonballs being shot out," says Wardle, but areas of compression in a steadily flowing jet. Studies of this type should multiply rapidly in number over the next few years, he predicts, as the correlator and software designed for the VLBA have been set up to allow astronomers to conduct polarization studies with unprecedented ease.

The instrument should also incorporate a technique called phase referencing that will allow astronomers to observe faint radio sources over long periods—just as photographers use long exposures to take pictures in poor light. That's currently very difficult with VLBI because the atomic clocks used to synchronize the signals recorded at each telescope slip out of time with one another after a few minutes, and atmospheric conditions change—both of which cause errors in the phase of the recorded signals. But in phase-referenced observations, the array is pointed alternately at the target and then at a previously imaged nearby reference source. By tracking the errors that appear over time in the reference signal, it's possible to correct the target signal, and build up an image from several hours of data.

If, as NRAO's Walker hopes, phased referenced observations become routine at the VLBA by the end of the year, stellar astronomers will be able to bring its immense resolving power to bear on weakly radio-emitting stars in our own galaxy. Indeed, technical advances like phase referencing, together with the anticipated influx of new VLBI users, should make for a heady cocktail. "It's really going to have a major impact on astronomy," says Caltech's Readhead. "We're in the middle of a revolution." And perhaps the VLBA will start making headlines.

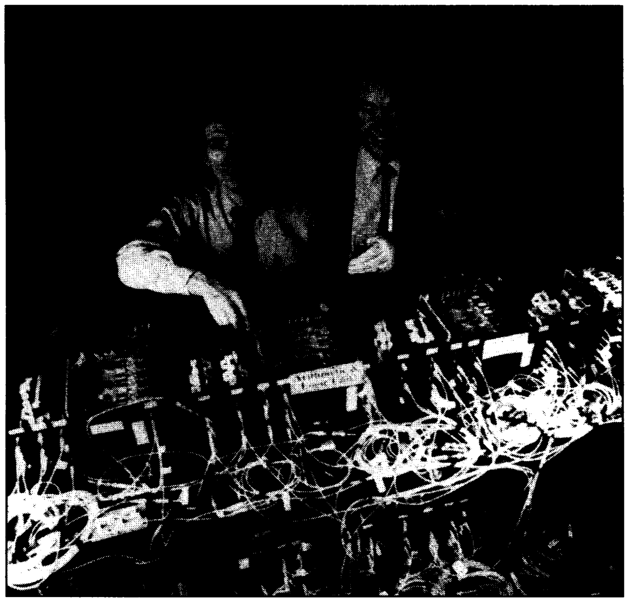
–Peter Aldhous

OPTOELECTRONICS

Computing at the Speed of Light

A University of Colorado research team provided a glimpse of the future on 12 January when it unveiled the world's first general-purpose optical computer: a machine that stores its programs and processes information by means of light rather than electrons. Although principal investigators Harry Jordan and Vincent Heuring compare the desktop-sized array of lasers, switches, and optical fibers to electronic technology in the days of vacuum tubes, their creation has the power of a small personal computer. And it points the way toward future optical computers that could function hundreds or thousands of times faster than conventional machines.

"This finally gets the computational aspect of optical computing off the ground," says Donald Chiarulli of the University of Pittsburgh, a long-time researcher in the field. "It's significant because it's gone so far beyond the conceptual stage," agrees William Rhodes of the Georgia Institute of Technology, editor of the journal *Applied Optics*.



U. OF COLORADO

No laptop. Vincent Heuring *(left)* and Harry Jordan with their prototype optical computer.

What distinguishes the Colorado computer from earlier optical devices is its ability to store and manipulate its own instructions internally, explains Jordan. Indeed, he says, "the idea of a stored program was the breakthrough in the 1940s that made computing what it is today." By contrast, an optical processor unveiled in 1990 by Bell Laboratories' Alan Huang was able to perform simple calculations using light beams, but could only respond to instructions and data fed to it by an electronic computer.

To accomplish their feat, Jordan and Heuring made use of a "bit-serial" architecture. The idea is to encode the computer's instructions and data as a linear string of infrared laser pulses circulating at the speed of light around a tightly spooled loop of optical fiber. Each 4-meter-long pulse, representing a single binary digit, circulates through the 4-kilometer loop some 50,000 times a second, which is the computer's fundamental clock speed. Other laser beams route these pulses through lithium niobate "optical switches" for processing. In fact, notes Heuring, since the light circulates through the computer at a known velocity—186,000 miles per second—the arrival time of any pulse can be predicted very precisely and used in the fundamental design of the circuitry. "In effect," he says, "we are storing information in space-time, which is a concept you only used to see in science fiction or relativity."

Unfortunately, Jordan and Heuring admit, this bit-serial architecture deliberately gives up on parallel computing, which many researchers regard as optical computing's greatest single advantage over electronics. Because photons (unlike electrons) can pass right through each other without hindrance, the Holy Grail of the field has always been an optical circuit that could carry out zillions of computations simultaneously in criss-crossing data channels. But the Colorado team felt the bit-serial approach was a better choice for the time being, because of cost—the design calls for only 66 lithium niobate switches, costing $3,000 apiece—and because it could be well suited for use in telecommunications, where transcontinental fiber optic cables already carry optical data pulses in bit-serial form.

The Colorado team has estimated that with the use of technologies already demonstrated in the laboratory, they could build a palm-sized bit-serial computer smaller by a factor of 400 than the current prototype. And since the velocity of light is constant, the speed of such a computer would rise by that same factor of 400, to 20 billion cycles per second—hundreds of times faster than the fastest personal computer today.

–M. Mitchell Waldrop