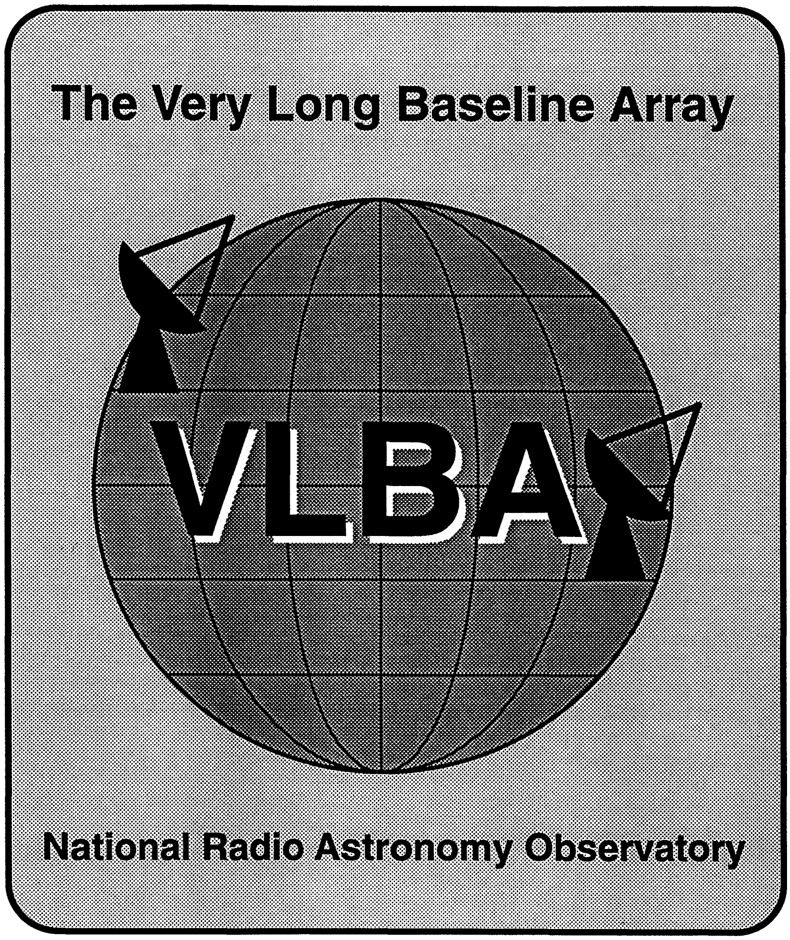
The VLBA

Background and Details



Opening Ceremony
20 August 1993

NRAO

The National Radio Astronomy Observatory (NRAO)

The VLBA, an instrument of the NRAO, is a national facility made available to the astronomical community through funding provided by the National Science Foundation (NSF). The NRAO is operated by Associated Universities, Inc., a nonprofit corporation organized in 1946 to establish and operate large-scale scientific research facilities. In addition to NRAO, AUI operates the Brookhaven National Laboratory, an institution covering a broad range of physical and applied sciences. AUI operates the NRAO under cooperative agreement with the NSF.

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A System of Superlatives

***The VLBA** -- It's the world's largest dedicated astronomical instrument, spanning 5,000 miles from Hawaii to the Virgin Islands. Its radio "vision" is sharp enough to read a newspaper in New York from the distance of Los Angeles. Its atomic clocks are accurate within one second in a million years. Its state-of-the-art radio receivers are cooled to within a few degrees of absolute zero to detect radio signals billions of times weaker than those of ordinary communication systems. Its superfast tape recorders pack as much information in just 2/5 of an inch of tape as your PC does on an entire floppy disk. Its central computer can perform 750 billion multiplications every second.*

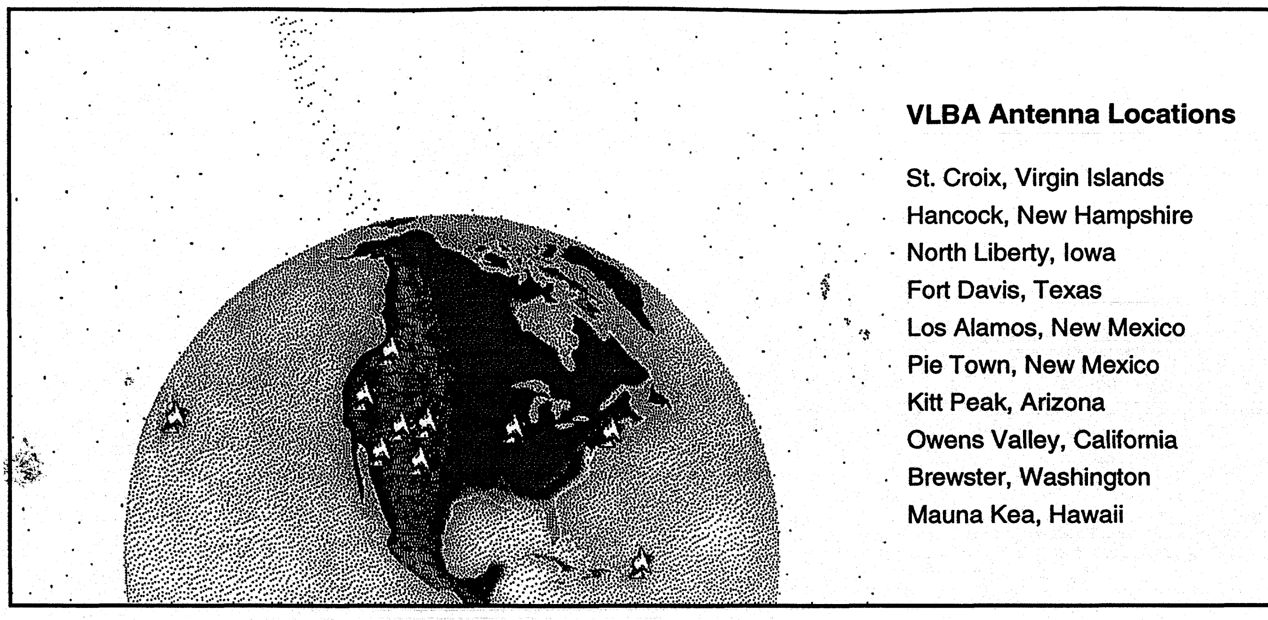
These elements combine to provide scientists with the best resolution -- the sharpest images -- of any telescope on earth or in space. The VLBA will provide valuable new insights into such questions as: how stars are born and die; how galaxies evolve; what the early Universe was like; and just how old and how big is our Universe? Astronomy, however, will not be the only beneficiary of the VLBA's tremendous capability. The VLBA will provide greatly improved information that will contribute to research on global climate changes, earthquake prediction, and improved spacecraft navigation.

Radio Astronomy: A Science of Revolutionary Revelations

Though radio astronomy is little more than 50 years old, it has revolutionized our understanding and concepts of the universe. Almost everything we know about the universe beyond our solar system was learned by studying and analyzing *electromagnetic radiation* arriving at the Earth from distant astronomical bodies. Electromagnetic radiation comes in many forms, including the light our eyes see, the radio waves that bring us music and pictures from broadcast stations, the ultraviolet that tans (and damages) our skin, the infrared that we feel as heat, the X-rays that doctors use to look inside our bodies, and the gamma rays that can be deadly. All these forms of electromagnetic radiation differ by the lengths of their waves and make up what scientists call the *electromagnetic spectrum.*

The visible light that we see constitutes only a small percentage of the electromagnetic spectrum, but, until the advent of radio astronomy in the 1930s, it was the only part of the spectrum that astronomers were able to use in their studies of the cosmos. Radio astronomy provided scientists with a whole new window on the universe. Observing the universe with radio telescopes reveals evidence of processes that had been unknown through the entire history of optical astronomy. Because of radio astronomy, we now have a much more complete understanding of our universe, its past history, the possibilities for its future, and the fascinating objects that make it up, than would ever have been possible with optical astronomy alone. Radio telescopes have shown that our universe is filled with phenomena of power and violence that were unimagined a half-century ago.

Today, astronomers have viewed the universe using telescopes able to "see" nearly all parts of the electromagnetic spectrum. Electromagnetic waves in the visible and radio parts of the spectrum (and some infrared waves) are the only ones able to pass through Earth's atmosphere well enough to be observed on



the ground. Satellites have carried infrared, ultraviolet, X-ray and gamma ray telescopes into orbit. Radio telescopes can observe a wider range of wavelengths than any other type of astronomical instrument. Radio observatories, able to operate 24 hours a day, are among the most productive facilities available to astronomers.

Since radio astronomy began, scientists have sought to build radio telescopes with greater *resolution* -- the ability to discern fine detail. Resolution is measured as angles, or, how close together can two objects appear to be before the telescope cannot distinguish them from each other. For example, your eyes probably can distinguish objects separated by about one minute of arc -- 1/60 of a degree. In contrast, a typical outside television antenna has a resolution of about 60 degrees, comparable to some of the earliest radio telescopes. Ground-based optical telescopes are limited by atmospheric effects to a resolution of about one second of arc (1/3600 of a degree), and NRAO's Very Large Array (VLA) radio telescope in New Mexico offers similar resolution to radio astronomers. Still, because of the vast distances in the universe, astronomers need greater resolution to study many of the most interesting celestial objects.

A telescope's resolution is determined by the wavelength of the electromagnetic radiation it receives and the diameter of its "mirror" -- the dish antenna in the case of a radio telescope. In the early days of radio astronomy, greater resolution was gained by building bigger and bigger dish antennas, but a practical size limit was quickly reached. However, astronomers some years ago developed the technique of combining the signals from two or more widely-separated antennas to obtain the resolution of a single, giant antenna. For example, the VLA in New Mexico uses 27 different antennas, some separated by as much as 22 miles. This technique of combining signals from different antennas is called *interferometry,* because it utilizes the phenomenon of wave interference.

When doing interferometry, the resolution obtained grows as the separation between antennas -- called the *baseline* -- grows. While most radio interferometers, as these instruments are known, utilize baselines of a few miles, the search for greater resolution led astronomers to try ever larger baselines. In the late 1960s, scientists began using baselines comparable in length to a continent, and this technique was called Very Long Baseline Interferometry (VLBI). VLBI observations have proven to yield very exciting scientific results, but VLBI observing has been difficult because it involved coordinating the efforts of several radio telescopes under different managements and which may not all be particularly suited technically to this type of work.

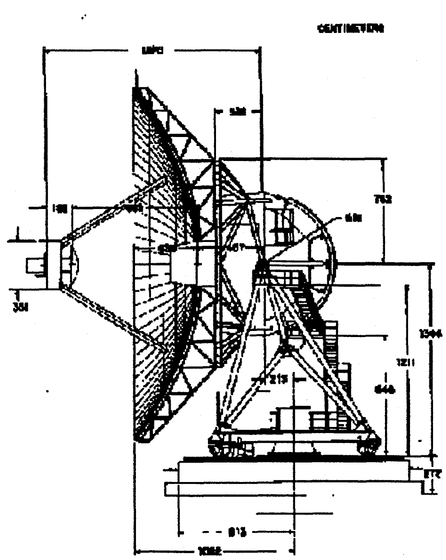
Because of the important, exciting work that requires VLBI, the National Radio Astronomy Observatory has built the Very Long Baseline Array (VLBA), a set of ten identical radio telescopes distributed across United States territory from Hawaii to the Virgin Islands. The VLBA was designed from the start to operate as a single instrument, providing a dedicated facility for VLBI observations and making VLBI much more easily accessible to astronomers from a wide variety of subspecialities. With a maximum baseline of 5,000 miles, the VLBA is the largest dedicated astronomical instrument in the world. It offers astronomers the ability to observe celestial objects with a resolution of less than a thousandth of a second of arc -- sufficient to read a newspaper in New York from the distance of Los Angeles. The VLBA provides unparalleled versatility for high-resolution observations and is a national instrument open to all scientists in the U.S. and abroad.

From the Mountaintops to the Seashore -- The Ten VLBA Stations

The drawing at left shows the locations of the ten VLBA stations -- from St. Croix in the Caribbean to the lofty height of Mauna Kea on Hawaii. These locations were carefully chosen to make the VLBA an effective scientific instrument while minimizing the costs of construction and operation. All the sites are on U.S. territory. Each site is important to the whole system's performance. The configuration of the ten sites provides both long and intermediate-length east-west and north-south baselines. In addition, the sites in the Southwest offer shorter baselines when combined with the existing VLA and also provide high, dry locations needed for some of the shorter-wavelength observations. Careful surveys of many potential sites were made and the ten selected were chosen because they met the scientific objectives of the VLBA while providing relatively easy access, acceptable climate, and, in some cases, proximity to existing astronomical facilities and their support organizations. The sites also were chosen to minimize radio interference from broadcast stations, industrial and other two-way radio systems, and power lines.

Each installation is identical to all the others -- all the control buildings were built from the same blueprints. Each has identical computers to control the antenna and receivers and identical-format tape drives. Since the stations are operated remotely from Socorro, New Mexico, each has a weather station to alert the operators to high winds, snow, and other conditions that could hamper observations or endanger the antenna. If such conditions occur, the antenna is "stowed" in a safe, straight-up position.

In addition to the VLBA, there is a world-wide distribution of radio telescopes that can be used for VLBI observations. The VLBA will work in conjunction with many of these for special observations. This is particularly important to obtain more and longer baselines and when an astronomical object must be observed on a 24-hour basis -- other observatories can observe it when it is below the horizon for VLBA telescopes. The VLBA routinely operates in conjunction with telescopes in Europe, Australia, and other locations worldwide. In addition, the VLBA will be an important part of space VLBI observations using orbiting radio telescopes planned for the mid 1990s.



The VLBA's Antennas

The VLBA antennas collect the radio waves from the astronomical objects. The path a signal follows through its processing by the VLBA is illustrated in the diagram on the back page. The VLBA antennas were designed to provide the maximum in efficiency, accuracy and reliability. Each antenna is fully steerable, can point anywhere in the sky, and can move rapidly between different observing targets. The VLBA antennas, parabolic dishes 25 meters (82 feet) in diameter, were designed with an advanced support structure that allows operation at

VLBA Radio Receivers

Wavelengths and Frequencies

90 cm	50 cm	20 cm	13 cm	6 cm	4 cm	2 cm	1 cm	7 mm
330 MHz	610 MHz	1.5 GHz	2.3 GHz	4.8 GHz	8.4 GHz	15 GHz	23 GHz	43 GHz

higher frequencies (shorter wavelengths). This is important for two reasons. First, shorter wavelengths mean better resolution, always an important goal. Second, some important molecules found in space emit radio waves of these shorter wavelengths, and the ability to receive those shorter waves thus allows astronomers to discover new information about a variety of cosmic objects. In order to effectively receive shorter waves, the antenna structure must be constructed to closer tolerances and also must retain its shape under the stresses of gravity and wind. The VLBA antennas were designed with all this in mind.

Receiving the Radio Waves

Radio astronomy receivers must be extremely sensitive -- the signals received from astronomical sources are typically millions or billions of times weaker than those received from ordinary communication systems. In order to achieve this type of sensitivity, the noise -- like the "hiss" you hear in your radio when tuning between stations -- must be reduced. Most of this noise comes from within the receiver itself, caused by the motions of the atoms in the transistors. This motion, and thus the noise, can be reduced by cooling the receiver. (Remember that at absolute zero, -273 C or -459 F, atomic motion ceases.) The VLBA receivers are cooled to a temperature of 15 Kelvin or -432 F. To do this, we use refrigerators that work on the same principle as your home refrigerator -- a gas is compressed, and when the pressure is released, the gas expands and cools. You often experience this effect when holding a can of spray paint. As the pressure is released in the can, the gas expands and the can feels cool to you. The VLBA cryogenic refrigerators use Helium as the expanding gas instead of the Freon your home refrigerator uses.

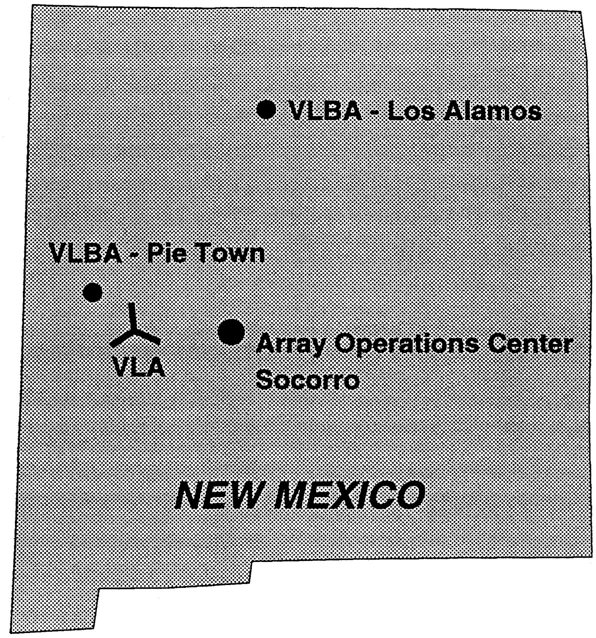
The VLBA radio receivers were constructed by NRAO and represent the state of the art in microwave radio receiving systems. Radio astronomy has a long history of driving technical developments in receiving systems. Much of the technology in the widely-used satellite communication systems of today has its roots in radio astronomy laboratories. Tomorrow's satellite systems will likewise be more efficient and useful to millions of people because radio astronomers' need for ever-better equipment is producing technology applicable to making better communication systems.

The chart above indicates the frequency bands of the VLBA stations. For comparison, the VHF television bands lie between 54 and 216 MHz; the UHF television bands are between 470 and 806 MHz; communication satellites commonly operate near 4 GHz, 7.5 GHz, and 11 GHz; radar uses frequencies near 3 GHz, 10 GHz and 16 GHz; and microwave ovens operate at about 2.5 GHz.

Recording the Data

Data from the receivers is digitized and recorded on magnetic tapes at each VLBA station. The recorded data is "time-tagged" with information from an extremely accurate hydrogen maser atomic clock. This atomic clock uses a precise frequency of radio emission from the hydrogen atom to produce an accuracy equivalent to no more than one second's error in a million years. Each reel used by the VLBA recorders contains 3.4 miles of tape, enough to record the data from nearly 12 hours of observations. The tapes from all the stations are sent to Socorro where the processing and analysis of the data are done.

The VLBA tape recorders are special-purpose machines, based on commercial units but essentially rebuilt for the extreme demands of radio astronomy. They represent the cutting edge of magnetic-tape recording technology. Some of their advanced features include ultra-narrow recording heads and advanced control electronics. These recorders write 504 tracks across the width of a one-inch tape. They pack more than 3.5 MegaBytes of information on an inch of tape. (Compare this to 1.44 MegaBytes on a high-density 3.5-inch floppy disk.) Each VLBA station has two of these recorders.



Array Operations Center, Socorro

The Array Operations Center (AOC) in Socorro, New Mexico is headquarters for the VLBA as well as for the Very Large Array (VLA) radio telescope, which is 52 miles west of Socorro. Completed in 1988, the AOC is located on the campus of the New Mexico Institute of Mining and Technology (New Mexico Tech), a 104-year-old institution offering undergraduate and graduate degrees, primarily in the physical sciences. The AOC was constructed with financial assistance from the State of New Mexico.

About 180 staff members work at the AOC, which includes the VLBA control room, offices for management and administrative personnel, electronics laboratories, and offices for nearly 40 staff astronomers who manage the facilities, develop long-range upgrade programs for the VLBA and VLA, assist and train visiting astronomers in using the radio telescopes, and pursue research programs in radio astronomy.

From the VLBA control room at the AOC, operators can control each of the VLBA stations, performing such operations as pointing the antenna, changing from one wavelength band to another, and starting and stopping the tape recorders. The control room in Socorro and each VLBA station are connected by computer network links. Computers at each station relay information on the station's status to the control room.

Though normal operations are controlled from the AOC, any facility as complex as a VLBA station does, however, require people on-site. There is a large amount of equipment, both electronic and mechanical, that requires regular attention and maintenance. In addition, tapes must be mounted and removed from the tape recorders, and completed tapes sent to Socorro. Each VLBA station has two full-time employees, highly-qualified technicians who are responsible for the smooth operation of their state-of-the-art facility. The VLBA is a 24-hour, seven-day-a-week operation, and the site technicians are on call to respond whenever equipment difficulties may require their presence.

Assembling the Data -- The VLBA Correlator

The VLBA *correlator* is a special-purpose high-performance computer where data from all ten VLBA stations are combined to yield the information from which astronomers produce images of celestial objects as if from a single giant antenna 5,000 miles wide. It receives data from all stations through a bank of VLBA tape recorders. Tapes from all stations are played back simultaneously, and, through the precise "time tags" placed on the tapes by the hydrogen maser atomic clocks at each station, the observation is essentially re-created for the correlator.

Signals from different stations are manipulated mathematically to make it appear that all stations are on the same plane surface perpendicular to the direction toward the object observed, despite the great distances between the stations and the curvature and rotation of the earth. Tiny differences in the arrival times of radio waves from different parts of the celestial body modify the combined signal detected by pairs of antennas. Data from all pairs of the array are combined to produce the information necessary to make an image of the observed object. The correlator's output can then be used by astronomers with workstations or other computers with image-processing software.

The correlator can handle 20 streams of incoming recorded station information at a time, so it is capable of processing observations from all ten VLBA stations plus 10 other VLBI stations elsewhere in the world.

The VLBA correlator was designed and built by NRAO scientists and engineers. It is in effect a thoroughly specialized, extraordinarily high-performance computer, operating routinely at a speed of 750 billion floating point operations per second (0.75 TeraFLOP). A one-of-a-kind machine, it incorporates special-purpose integrated circuits designed by NRAO and manufactured under contract.

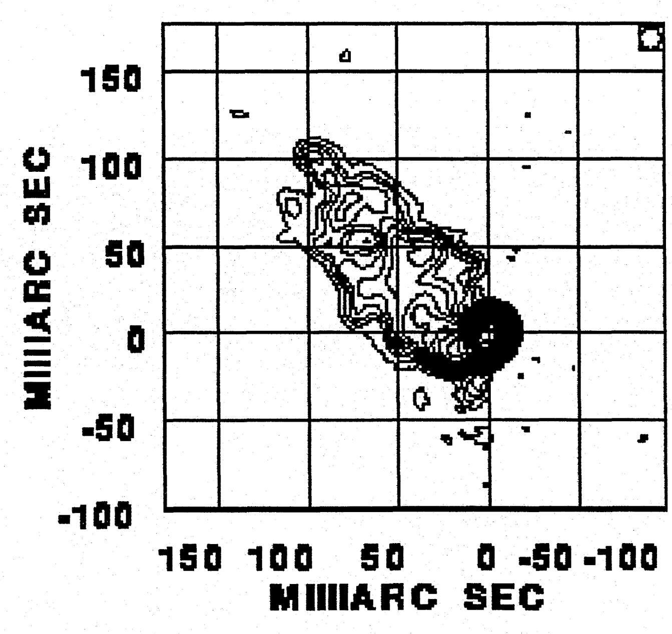
(Let's put 750 billion floating-point operations in perspective. If everyone in the U.S. -- 250 million of us -- had let our checkbooks fall behind by 3,000 checks, 0.75-TeraFLOPS would balance all those checkbooks in a single second.)

Pushing the Frontiers -- Science With the VLBA

The VLBA will dramatically improve our knowledge of a wide variety of astronomical phenomena, and also will make valuable contributions to research areas important to understanding the Earth we live on.

As a dedicated instrument, the VLBA will be able to monitor astronomical radio sources that are variable on timescales of days to weeks to months. Such monitoring can be a routine part of operations, performed without the need for special arrangements among several observatories. Similarly, the VLBA will be able to respond quickly when events such as supernova explosions require immediate observation to avoid missing valuable scientific data. In addition, because the entire VLBA system is designed to operate 24 hours a day, 7 days a week, astronomers will be able to obtain images of large numbers of celestial objects that cannot be resolved without VLBI, providing a wealth of new information about these objects.

The VLBA will bring astronomers new capabilities to observe regions with extreme differences in the radio "brightness" -- high dynamic range observations. Because all of the VLBA stations are identical, and because of the technical capabilities of the stations, it will become much easier for astronomers to make highly-detailed maps of the polarization of radio sources.



The galaxy Markarian 501's twisted jet, nearly 400 million light-years distant. VLBA image by J.M. Wrobel and J.E. Conway.

All these capabilities will be turned to work on some of the greatest challenges facing astronomers -- including attempts to understand the nature of quasars and the powerful nuclei of galaxies; studies of pulsars, supernova remnants, and other phenomena within our own Galaxy; studies of the life cycles of stars; and direct trigonometric measurements of greater distances than possible before, thus refining our understanding of the scale of the universe. In addition, the history of astronomy shows that new instruments with improved capabilities nearly always yield surprising information that was unexpected by thier builders. The VLBA will undoubtedly be no exception.

The applications of Very Long Baseline Interferometry are not limited to astronomy; indeed, VLBI is a major contributor to some very down-to-Earth research with potential benefit to millions of people. The Earth's solid surface is composed of giant *plates* of rocky crust that "float" atop the semi-fluid and slowly-moving *mantle*. Where these plates meet each other is where most of the Earth's violence -- in the form of earthquakes and volcanoes -- occurs. In order to better understand the processes that bring about these violent events, geophysicists need to have better measurements of the actual movements of the crustal plates. This is where VLBI can help.

Just as VLBI techniques provide greater resolution to astronomers looking for fine detail in celestial bodies, these techniques can be "turned around" to provide extremely fine measurements of the baselines between VLBI stations. By using extremely distant quasars as an ultra-stable reference system, the distance between VLBI (and VLBA) stations can be measured to an accuracy of about one centimeter. By making measurements among multiple stations over several years, the changing positions of those stations with respect to each other can be tracked -- thus indicating the motion of the continental plates on which they sit. This gives geophysicists the detailed information that they use to test theories in a number of fields, including the still-infant field of earthquake prediction.

Building the VLBA

Long a dream of radio astronomers, the VLBA began its road to reality with the formal submission of a proposal for the instrument in May of 1982. Design of the VLBA was authorized in 1984 and construction was authorized in 1985. Construction began on the first station, at Pie Town, in February of 1986, and the last station, at Mauna Kea, was completed in April of 1993. The first scientific observations were made with the partially-completed VLBA in October of 1987. On 29 May 1993, the VLBA made its first astronomical observation with all ten stations recording scientific data.

Further Reading:

Gordon, Mark A., "VLBA -- A Continent-Size Radio Telescope," *Sky & Telescope*, **69**:6, pp. 487-490 (June 1985).

Kellermann, K.I. and Thompson, A.R., "The Very Long Baseline Array," *Science*, 229, pp. 123-130 (12 July 1985).

Kellermann, Kenneth I. and Thompson, A. Richard, "The Very-Long-Baseline Array," *Scientific American*, **258**:1, pp. 54-63 (January 1988).

From Sky to Slide -- The Parts of the VLBA