The Synergy of VLBI and GPS

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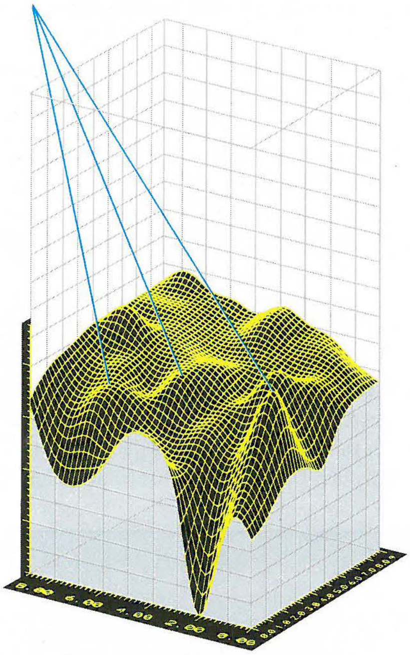


Although developed in the mid-1960s by rival teams of American and Canadian radio astronomers for studying compact extragalactic radio sources such as quasars, very long baseline interferometry (VLBI) was quickly taken up by geoscientists as a tool for studying the earth. VLBI uses two or more radio telescopes to pick up the extremely faint signals from quasars and their kin. The technique is extremely sensitive to the relative positions of the radio telescope antennas and, with the appropriate signal processing, these positions can be determined to the subcentimeter level, even if the baselines connecting the antennas span a continent or an ocean.

In this month's column, Dr. John Gipson, who works with the VLBI group at the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center in Greenbelt, Maryland, describes the VLBI technique, how it has been used to learn more about how the earth "works," and the similarities and differences between VLBI and GPS and their important synergistic relationship. Gipson is a member of the small cadre of scientists and engineers using VLBI to further our geodetic and geophysical knowledge. He earned a Ph.D. in theoretical physics in 1982 from Yale University. After a brief stint as an assistant professor at Virginia Polytechnic Institute and State University in Blacksburg, Virginia, he went to work in the telecommunications industry and now holds a patent on a system that determines the position of ground-based transmitters. For the past several years he has worked as a senior scientist for NVI, Inc., with the NASA VLBI group. His current research interests include improvements in the VLBI technique, comparisons of VLBI-derived results with those of GPS, and the development of improved geophysical models of the earth.

"Innovation" is a regular column in GPS World *featuring discussions on recent advances in GPS technology and its applications as well as on the fundamentals of GPS positioning. The column is coordinated by Richard Langley and Alfred Kleusberg of the Department of Geodesy and Geomatics Engineering at the University of New Brunswick, who appreciate receiving your comments as well as suggestions of topics for future columns. To contact them, see page 4 of this issue, under the "Columnists" section.*

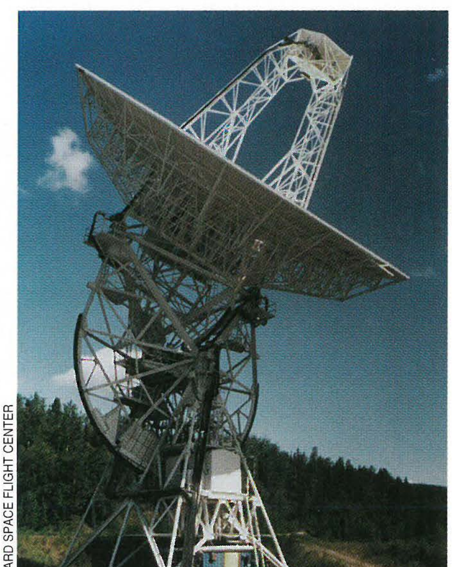
Radio astronomers developed very long baseline interferometry (VLBI) in the mid-1960s to study the structure of quasars at the far ends of the universe. Existing tools, such as cable-connected and microwave-linked interferometers, couldn't resolve these very compact objects. But with the then-newly available atomic frequency standards and wideband tape recorders, the necessity for a real-time umbilical link between elements of a radio interferometer was removed. It became possible for each end of the interferometer to faithfully record the quasar signals independently and combine them later (see sidebar "How an Interferometer Works").

In the late 1960s and early 1970s, VLBI was adapted to measure the relative positions of large radio antennas. The precision of these early measurements was about 10 centimeters on a 4,000-kilometer-long baseline. The technique has continued to evolve and remains an important scientific tool. The current precision of the best VLBI measurements is 1 millimeter in the horizontal direction (latitude and longitude or north and east), and 2–3 millimeters in the vertical. Repeated measurements over time enable us to determine the relative motion of sites, and this has been, and remains, an important focus of VLBI measurements.

VLBI AND GEOPHYSICS

The use of VLBI to measure site displacement is supplying geophysicists with much new information about the earth. In the early 1980s, VLBI provided one of the first direct confirmations of contemporary continental drift — a cornerstone of the modern theory of plate tectonics, which describes the behavior of the earth's lithosphere (the crust and rigid upper layers of the mantle). The measurements were made using networks of fixed VLBI antennas on different tectonic plates. In the early and mid-1980s, a series of successful VLBI campaigns was conducted by the National Aeronautics and Space Administration (NASA) and other organizations to measure crustal deformation near plate boundaries. These campaigns used mobile VLBI antennas and made measurements in southern California, Alaska, and western Canada.

The gravitational pull of the sun and moon is another source of site displacement. The pull causes an elastic response in the earth: the earth directly below the moon (and at a spot on the opposite side of the earth) is more than 30 centimeters higher than it would be otherwise. Atmospheric pressure loading also causes local site displacement: the weight of the air in a high-pressure region depresses the crust of the earth. The distribution of ocean mass, which varies with the tides, causes similar displacements. These and other effects have been confirmed by



GODDARD SPACE FLIGHT CENTER

The Gilmore Creek Geophysical Observatory's 26-meter-diameter VLBI antenna near Fairbanks, Alaska, is operated by NASA's Space Geodesy Program in cooperation with the U.S. Naval Observatory.

VLBI, which is an extremely sensitive probe of subtle geophysical effects.

The quasars and other radio sources used by VLBI are essentially fixed in inertial space (ignoring their recessional motion, which is of no concern), and the VLBI stations are fixed on the earth. Therefore VLBI measurements provide a means of determining the orientation of the earth with respect to inertial space. Among competing techniques, GPS included, VLBI leads in accuracy, precision, and high time resolution of absolute measurements of earth orientation. VLBI can measure this orientation to 50 micro-arcseconds (μas) or about 1.4×10^{-8} degrees. This is smaller than the angle a postage stamp in San Francisco subtends as viewed from New York. (Contrast this with the overall accuracy of GPS earth-orientation results, which, although continually improving, is currently less accurate than the VLBI results by perhaps a factor of four or more.)

Precise measurements of the earth's orientation are extremely useful in improving and validating geophysical models of the earth. The reason for this is simple. Changes in the orientation of the earth and its rate of spin are caused by one of two factors — internal or external. A redistribution of the angular momentum of the earth-atmosphere-ocean system will cause changes in the position of the earth's rotation pole (polar motion) or rate of rotation (related to changes in Universal Time, UT1). For example, because of the unequal distribution of landmass on either side of the equator, when it is summer in the northern hemisphere, there is a net increase in the temperature of the atmosphere, the atmosphere expands, and the earth slows down. (The earth slows down for exactly the same reason that ice skaters slow down when they extend their arms.) So not only do summer days *seem* longer than winter days, they actually are, by about 1 millisecond. External

How an Interferometer Works

In VLBI, a band of radio signals is recorded on magnetic tape at each site after first converting or shifting them to baseband and then digitally sampling them. The conversion to baseband must be accomplished using a very stable local oscillator at each site — one that does not have phase fluctuations any larger than about one radian at the mean observation frequency, during the interval of time over which a single observation is made. Because of the typical use of X-band frequencies in geodetic VLBI (8.4 GHz or so), the local oscillator must remain stable to about three parts in 10^{13} for a one-minute observation. Such stabilities can usually be achieved only with hydrogen maser frequency standards. The hydrogen masers are also used to provide the frequency signal of the clock that controls the timing of the digital samples at each site. Timing information accompanies the digitized signals on the magnetic tapes.

After completion of all observations, the tapes are sent to a processing facility where the recorded signals from pairs of stations are cross-correlated using specially designed equipment. Basically, if the data bits on a tape from one of the stations are exactly delayed or advanced in time to match the corresponding bits on the tape from the other station (akin to delaying the pseudorandom noise code generated in a GPS receiver to match the incoming code), then the peak will be found in the so-called cross-correlation function. The primary geodetic observation, the group delay, is then derived from the position of the correlation peak.

As the earth rotates, the delay varies and this gives rise to a sinusoidal variation in the output of the correlator with a frequency proportional to the phase delay rate of change. These oscillations are similar in concept to the dark and light bands or interference "fringes" seen in the Young's double-slit experiment of classical optics that many of us performed in our high-school or undergraduate physics classes. The fringes result from the constructive and destructive interference of the light waves emanating from two narrowly spaced slits in an otherwise opaque barrier. By analogy, the two slits in Young's experiment are the two radio telescopes making up a very long baseline interferometer, and the output of the correlator is basically an interference pattern that is also referred to as *fringes*. The frequency of the fringe oscillations or the corresponding phase delay rate is a secondary geodetic VLBI observable. A third observable is the phase delay itself. This observable is difficult to measure, except for short baselines, and so is not often used in geodetic VLBI.

There is additional information in the correlation function that radio astronomers use to map radio sources with very high resolution. According to an important relationship in optics known as the Van Cittert–Zernike theorem, the distribution of brightness in a radio source is related to the Fourier transform of part of the correlation function. By tracking a radio source for a number of hours using an array of VLBI sites and then suitably processing the subsequent correlator output, radio astronomers can generate a map or picture of the source — something like a photograph but as seen with radio eyes.
— R.B.L.

What Is a Quasar?

Astronomers aren't really sure and have been working on the answer to this question for the past 30 years or so.

Quasars (also called *quasi stellar objects* or *QSOs*) were first discovered in the early 1960s. Radio astronomers had detected radio emissions from a few objects, for which there was no apparent optical counterpart on photographic plates taken with large telescopes except what appeared to be very faint stars. On inspection of the spectra of these "stars," however, astronomers discovered that they were unlike any known star or any other class of celestial objects. The lines in their optical spectra (caused by energy transitions of hydrogen and other atoms) were shifted significantly toward the red end of the electromagnetic spectrum. This Doppler shift implied that the objects are receding from us at very high speeds. If this motion is caused by the general expansion of the universe, as is generally believed, then the objects must be very distant — well outside our galaxy.

Some quasars have corresponding wavelength changes of three or four, which means that they are moving with speeds approaching the speed of light and are, in fact, billions of light-years away. If quasars are indeed this far away, then in order for us to see and hear them, they must be incredibly energetic: up to 1,000 times more luminous than a normal galaxy. Astronomers have also observed that quasars can change their brightness significantly in time intervals as short as a week or even a day. This means that the size of a such a quasar can't be more than one light-week (the distance traveled by light in one week) or one light-day in diameter. Compared with a typical spiral galaxy with a diameter of about 300,000 light-years, quasars are extremely compact.

Clearly, these objects are not stars or ordinary galaxies. So do astronomers have any idea what they really are? The presiding theory is that they are enormous black holes at the centers of galaxies that are in the very early stages of development (the light and radio waves we currently receive from these objects, left them billions of years ago). The black hole is swallowing up the central mass of the host galaxy. As matter falls into the black hole, it radiates huge amounts of energy. Whole star systems could be swallowed by these active galactic nuclei. (Incidentally, the current theory of what a quasar might be makes it difficult to understand how in the *Star Trek: The Next Generation* episode "The Pegasus," the USS *Enterprise*, traveling our Milky Way Galaxy, could examine the Mecoria Quasar at close quarters! First of all, quasars don't exist within our galaxy and secondly, a close encounter with a quasar would be fatal, precluding a long life for Capt. Jean-Luc Picard and his crew — prosperous or otherwise.)

Not all quasars emit detectable radio waves, but many of them do. This property, coupled with their compact size and negligible motion perpendicular to the line of sight, makes quasars ideal radiobeacons for geodetic VLBI.
— R.B.L.

torques on the earth caused by the gravitational forces of the sun, moon, and the other planets cause the orientation of the spin axis to change in space. The amount of change depends on the detailed structure of the earth. As a result, by studying VLBI measurements, geophysicists have been able to develop improved models of the earth's interior (see the "Innovation" column, "Measuring the Earth's Rotation and Orientation with GPS," in the May 1992 issue of *GPS World* for further details on the determination of the earth's spin and orientation).

THE VLBI TECHNIQUE

VLBI is a geometric technique (as illustrated in Figure 1): It measures the difference in arrival time of a signal from extragalactic radio sources at two or more antennas. A typical VLBI experiment is 24 hours long, uses antennas at four or more sites, and involves thousands of measurements using 50 or more radio sources. By looking at sources in many different directions, it is possible to determine the relative positions and orientation of the receiving antennas to a few millimeters. The radio signal, which is pure noise, is sampled, time-tagged, and tape recorded on 18-

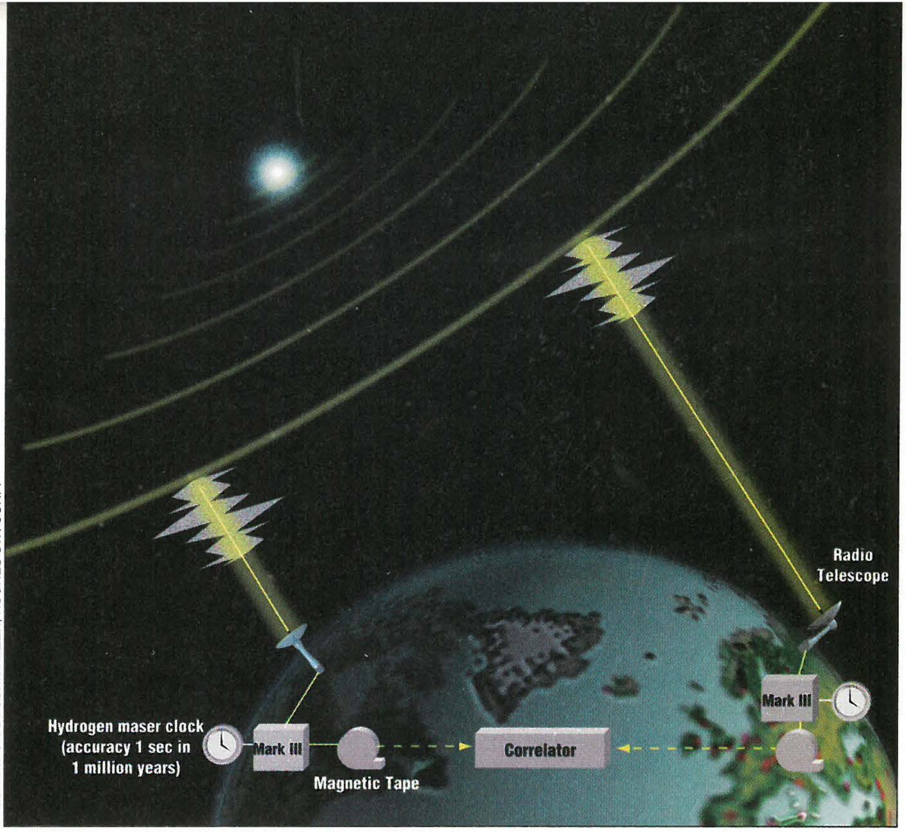


ILLUSTRATION BY JOHN HAZEN, HUGHES STX CORP.

Figure 1. VLBI measures the difference in time of arrival of a wavefront emitted by an extragalactic radio source, such as a quasar, as received at two earth-based antennas. Using large numbers of time-difference measurements from many sources observed with a global network of antennas, VLBI determines the inertial reference frame defined by the sources and simultaneously the precise positions of the antennas.

inch-diameter reels of professional-quality video tape at each site. Each site generates a few of these tapes in a day. All of the tapes are shipped to a central facility where they are cross-correlated to determine the series of differences in arrival time (the *delay*), and the rate of change of the delay (the *delay rate*) on the VLBI baselines. The delay and delay rate are analogous to the GPS pseudorange and Doppler observations (GPS carrier-phase measurements are integrated Doppler observations). The delay, delay rate, and calibration information are put into a VLBI database for later processing. In the absence of error sources (discussed later), the delay is proportional to the projection of the baseline vector between the receiving sites onto the unit vector in the direction of the radio source. In equation form it is given approximately by

$$\tau = \frac{\hat{\mathbf{s}} \cdot \mathbf{B}}{c}$$

where $\hat{s}$ is the unit vector in the direction of the source, B is the baseline vector, and c is the speed of light.

Several sources of error contaminate the VLBI measurements. Propagation through the ionosphere delays the radio signal. This delay depends on the direction to the radio source and the state of the ionosphere and is impossible to model or predict accurately. Fortunately, the delay depends on the frequency of the signal. By measuring the delay at two frequencies, we can determine and compensate for the ionospheric delay. Passage of the radiation through the troposphere introduces additional delay, which depends on the refractive index of air, which, in turn, depends on the temperature, pressure, and relative humidity of the air along the ray path. Most of the tropospheric delay can be calculated based on measurements of the surface pressure at the antenna site; the rest must be estimated from the data. The offset and drifts of the atomic clocks at each site are also estimated. In addition, there are various systematic sources of error. For example, thermal and mechanical deformation of the antennas can introduce errors at the millimeter level. Errors in geophysical modeling also introduce effects at this same level.

The radio sources involved in VLBI are extremely weak. Typical flux densities are -255 dBW/Hz/m^2 (or about 3×10^{-26} watts per hertz per square meter). Because of this, VLBI antennas tend to be large parabolic dishes (a typical dish measures 20 meters in diameter) and involve sophisticated electronics including cryogenically cooled receivers. The signal-to-noise ratio (SNR) of the VLBI measurements depends on the processed bandwidth of the signal. The signals from the VLBI radio sources span a huge, continuous chunk of the electromagnetic spectrum from radio frequencies to those of light and beyond. The best VLBI experiments employing the current Mark III equipment use a total bandwidth of 56 MHz. The signal in this bandwidth is recorded on special high-speed, high-density tape recorders. All of these factors make VLBI operations quite expensive.

COMPARISON OF VLBI AND GPS

GPS is similar to VLBI in that it operates in the radio part of the electromagnetic spectrum. The frequencies of GPS signals are somewhat lower than those used for VLBI, but they are susceptible to many of the same error sources as VLBI — in particular, ionospheric and tropospheric delay and drifts in the clocks at each site. GPS uses the same techniques as VLBI to compensate for these error sources.

The greatest difference between VLBI and

GPS is the nature of the signal. The GPS signal is an artificial one originating from satellites, purposefully designed to provide real-time position information. Also, the intrinsic signal strength of the GPS signal is -210 dBW/Hz/m^2 — a factor of 10^5 or so stronger than those used in VLBI. Hence, the simplest GPS receivers are very small and fairly inexpensive.

Another difference between VLBI and GPS signals is the structure of the signals themselves. The VLBI signals are true noise; the GPS signals are pseudorandom sequences. Because of this, the effective SNR of the GPS signal is a factor of 10^3–10^6 larger than an equivalent VLBI signal. As mentioned earlier, VLBI experiments typically sample a bandwidth of about 56 MHz. The bandwidth of the GPS signals is about 20 MHz. Much of the signal processing of the GPS signal is done at the receiver site. Inexpensive GPS receivers can almost instantaneously determine the local station position to a few tens of meters on site.

For geodetic GPS applications, which demand subcentimeter-level accuracy, the phase and pseudorange are extracted on site and placed in a RINEX (Receiver Independent Exchange) file for later processing. For the data collected by a single station in one day, this file easily fits on a standard 3.5-inch diskette, or can be downloaded remotely. Given the orbits and clock behavior of the GPS satellites, this is all that is required to determine the station position.

Determining the GPS orbits requires a solution with a broadly distributed network of stations. The International GPS Service for Geodynamics (IGS) is an international organization whose processing centers calculate such orbits using roughly 40 of the more than 100 globally distributed stations and then make them available on the Internet. These orbits are used by geologists and geophysicists, for example, to determine the positions of their stations with respect to the IGS network.

Table 1 shows a comparison of the essential characteristics of the VLBI and GPS techniques as used for geodetic applications. The precision listed in this table is that for estimates of station position using 24 hours of data from the best VLBI and GPS measurements as of the end of 1995. For a daily estimate of station position, VLBI is a factor of 2–3 times more precise than GPS, but much more expensive per station.

The high comparative cost of a VLBI antenna needs to be balanced with the realization that geodetic VLBI is not the main purpose of most of the antennas used for this technique. Some of the best antennas are run by the National Radio Astronomy Observatory, headquartered in Charlottesville, Virginia, and are used primarily for radio astronomy research. Accurate station positions make the processing of the astronomers' radio maps easier. Other antennas used for geodetic VLBI belong, for example, to the NASA Deep Space Network and are primarily used for spacecraft communication. A number of the antennas that primarily perform geodetic VLBI are involved in the weekly National Earth Orientation Service (NEOS) observations, coordinated by the U.S. Naval Observatory (USNO) and run by USNO, the NASA Goddard Space Flight Center VLBI group, and the Geosciences Laboratory of the National Oceanic and Atmospheric Administration. The observations are analyzed to produce precise measurements of the earth's orientation in space. These measurements are used to "navigate" many different vehicles including missiles and satellites. One of the largest groups of users of this service are the many people involved in the operational maintenance of satellite orbits, including those of the GPS satellites. VLBI is the only technique that can make these measurements with the required accuracy and time resolution.

STATION POSITIONS

Many VLBI sites have collocated GPS antennas, which enable us to compare station positions (and velocities) derived independently by GPS and VLBI. These comparisons are useful for several reasons. First, they validate the two techniques. These comparisons have uncovered large-scale modeling errors and also site-specific errors. Second, the comparisons confirm anomalous results. For example, there are always some stations whose motion is unexpected, and if VLBI and GPS detect the same motion at these sites, the motion is probably real. Third, these comparisons allow us to mix historical VLBI data with current GPS data. For example, it is unlikely that any of the mobile VLBI sites visited in the mid-1980s will ever be revisited by VLBI. However, many of these sites have been revisited by GPS receivers.

Comparing these two techniques has many potential pitfalls, and I will mention only a few of them. Because GPS and VLBI antennas cannot physically occupy exactly the same space, a survey has to be done to connect the two antennas. Unfortunately, there is some ambiguity about the correct reference point to use for the two techniques. The GPS reference point is the phase center of the antenna. But which one? The L1 and L2 phase centers are in general different at the few-millimeters level. Furthermore, putting a protective radome over the GPS antenna will change the phase center unless extreme care is taken. For VLBI, the reference point is conventionally a stationary point on the VLBI antenna — typically the intersection of the antenna drive axes. The identification of this point depends on a mechanical model of the antenna. If the model is wrong, we will be using an incorrect reference point. Yet another complication arises in that the origins of the VLBI and GPS coordinate systems, as well as the orientation of their axes, are not identical. To compare the results from the two techniques we must translate and rotate one station network to minimize the "misfit" with respect to the other. These translations and rotations are small and amount to changing the station positions by only a few centimeters.

The current root-mean-square (rms) level of agreement between VLBI- and GPS-determined station position is six millimeters in the horizontal plane and 12 millimeters in the vertical. The VLBI and GPS velocities agree at three millimeters per year. This level of agreement is truly astounding, considering the many possible sources of error associated with each technique. It is roughly twice as good as the agreement in mid-1994, which had an rms disagreement of 15 millimeters in horizontal station position, and 30 millimeters in vertical. The improvement can be traced to many factors, including better local surveys, modeling, and data processing. Many of these improvements would not have been made without the external comparison. These improvements have also resulted in better internal consistency of the data within each technique.

Table 1. Summary of VLBI and GPS techniques

	VLBI	GPS
Radio sources	**Quasars**	**Satellites**
Frequency (GHz)	2.2, 8.4	1.2, 1.6
Signal strength	-255 dBW/Hz/m^2	-210 dBW/Hz/m^2
Bandwidth	56 MHz	20 MHz
Number of sources	~50	~25
Initial signal processing	At correlator	On site
Stations		
Cost	$3,000,000	$50,000
Size	20 meters	1 meter
Number	125	>40 core, 1,000s of auxiliary
Error sources		
Ionosphere	X	X
Troposphere	X	X
Clocks	X	X
Orbits	—	X
Quasar position	X	—
Reference point	X	X
Antenna modeling	X	X
Observables		
	Phase	Phase
	Delay	Pseudorange
	Delay rate	Pseudorange rate
Quality data span		
	>1979	>1988
Station precision		
Up	1 millimeter	3 millimeters
East	2 millimeters	7 millimeters
Earth orientation		
Useful time resolution	1 hour	1 day
Daily estimates		
Polar motion	50 μas	200 μas
UT1	2 μs	—
Hourly estimates		
Polar motion	200 μas	—
UT1	8 μs	—
Orbits		
	—	10 centimeters
Quasar position		
	50 μas	—

THE FUTURE

The focus of VLBI measurements is shifting from campaigns with small networks, designed expressly to measure station positions in a regional frame, to measurements involving larger numbers of stations distributed globally. This is in large part due to the cost advantages GPS offers in local campaigns. The large VLBI networks are sensitive to large-scale geophysical phenomena, and the great sensitivity of VLBI is a good test of geophysical models. Another area of interest is VLBI measurements at higher time resolutions. For example, in the best VLBI measurements we now routinely make *hourly* estimates of the earth's orientation with a precision obtained by the best *daily* estimates a few years ago. These estimates have resulted in improvements in models describing the dynamics of the oceans and the atmosphere. Current estimates of station position consist of one-day averages. There are subdaily variations in station position caused by ocean loading and other effects. Can these be measured directly? Are there deficiencies in the current models? The validity of many of the models describing station motion is at the one-millimeter level; that is, the same level as the accuracy of the best VLBI measurements.

The precision of geodetic measurements of both station position and earth orientation has improved by a factor of 10 for each decade of VLBI's existence. Enhancements in hardware, scheduling methods, analysis methods, and better modeling have all played a role in this improvement. The next generation of VLBI hardware, the Mark IV system, is scheduled for deployment within the next two years. With this new system, we will be able to process larger experiments involving more stations and more data per station. The precision of the measurements is expected to improve by a factor of 4, bringing submillimeter-level VLBI within reach. It is impossible to predict exactly what will be uncovered with this new sensitivity. The only thing that is certain is that we will find something new. ■

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Further Reading

For an overview of the research carried out in geodetic VLBI between 1991–1994, see

■ "VLBI Data, Acquisition, Environmental Effects," by T.A. Herring, published in the U.S. National Report to International Union of Geodesy and Geophysics 1991–1994 as a supplement to *Reviews of Geophysics*, Vol. 33, 1995. Companion overviews on GPS, crustal dynamics, and other research areas may also be of interest. The report is also available in electronic format on the World Wide Web at <http://earth.agu.org:80/revgeophys/contents.html>.

For a discussion about modern geodetic VLBI instrumentation and data-processing techniques, see

■ "Improvements in the Accuracy of Geodetic VLBI," by A.E.E.E. Rogers — and 34 (!) other scientists and engineers — published in *Contributions of Space Geodesy to Geodynamics*, Vol. 25 of the American Geophysical Union's Geodynamics Series; pp. 47–63, 1993.

For a comparison of site positions determined by GPS and VLBI data, see

■ "GPS Results Are Consistent with VLBI," by J. Gipson, J. Ryan, E. Himwich, and T. Clark, published in the *Proceedings* of ION GPS-94, the 7th International Technical Meeting of the Satellite Division of The Institute of Navigation, held in Salt Lake City, Utah, September 20–23, 1994; pp. 383–390.

An introduction to geodetic VLBI, including its history and future, is provided on the Web site maintained by the Goddard Space Flight Center VLBI group. The URL of its home page is

■ <http://lupus.gsfc.nasa.gov/vlbi.html>

Recruitment