VERY LONG BASELINE INTERFEROMETRY

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The technique of very long baseline interferometry (VLBI) has undergone two decades of steady growth and refinement since its inception in 1967. In the beginning, only crude measurements of visibility on single baselines were possible. Now 18-station arrays have been used to produce images with dynamic ranges exceeding 2000:1; relative motions of cosmic masers have been tracked at the microarcsecond level of accuracy; and angular size measurements have been made with baseline lengths up to 2 two earth diameters with an orbiting satellite as a receiving element.

VLBI has two characteristics that usually differentiate it from linked-element interferometry: (1) coherence is maintained by independent atomic frequency standards at each station that provide stable local oscillator signals for heterodyne conversion and time tags for the received signal, and (2) the received signals are recorded on magnetic tape at the Nyquist rate (e.g., 10^8 bits s^{-1} for a bandwidth of 50 MHz) and processed at a later time. These characteristics are not fundamental but dictated by economics: the feasibility of distributing the local oscillator signal by satellite and the real time transmission of data via satellite have been demonstrated. Most linked-element radio interferometers maintain phase coherence by frequently observing calibration sources near the source to be imaged. Few such calibration sources are available to VLBI, so that maintaining coherence is a problem.

The first step in the postcorrelation data analysis is to find the interference fringes in the two-dimensional space of delay and fringe frequency, which is proportional to the rate of change of delay. This search can be carried out on each baseline. Alternatively, a global analysis of all the data from an array of telescopes can be carried out and clock (delay) and clock rate (fringe rate) parameters determined for each station (Global Fringe Fitting). This is closely related to the phase closure technique and is particularly effective in facilitating the detection of fringes on baselines formed with stations of low sensitivity. Once the fringe fitting analysis is complete, the data can be passed to image formation procedures such as self calibration or hybrid-mapping.

Currently, VLBI observations are conducted with telescopes scheduled on an ad hoc basis or with telescopes in networks that are organized for routine VLBI observations. The oldest network is the US VLBI Network, which was formed in 1976 and consists of six continental US stations and the MPI 100 m telescope. Observing sessions are scheduled for about 2 weeks every 3 months at wavelengths from 1.3 to 90 cm. The European VLBI Network (EVN) consists of nine telescopes. The operations of the EVN and US networks are closely coordinated. The IRIS (International Radio Interferometric Surveying) Network

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consists of five telescopes, and, although it is dedicated to studying geodetic and geophysical phenomena, it provides useful astrophysical images. Other networks are under development in Russia (six elements), China (five elements), US (ten elements: VLBA), and Australia (five elements: Australia Telescope). The number of telescopes that have participated in VLBI experiments at one time or another is more than 50.

The VLBI images with the greatest dynamic range and detail have been produced at 18 cm wavelength with "world array" observations involving 18 telescopes. Maps of 3C120, 3C236 and M87 have unprecedented dynamic range. The high quality of these images is due to good (u,v) plane coverage, careful editing and calibration of the data, and the use of self-calibration programs.

The resolution of VLBI is ultimately limited by scintillation caused by irregularities in the ionized component of the interstellar medium. The seeing limit is approximately

$$\theta_s \sim \frac{1.5\lambda^2}{\sqrt{|sin b|}} \mu as,$$

where b is the galactic latitude, and λ is the wavelength in cm.

Imaging at mm wavelengths is an important new frontier in VLBI research. The image quality currently available resembles that achieved at cm wavelengths about 15 years ago. VLBI at mm wavelengths is difficult because of the lack of sensitivity, the small number of telescopes currently available, and the problems of phase stability at the shorter wavelengths. Nevertheless, images of 3C84 at 3 and 7 mm wavelengths have been produced with 4- and 6-station arrays at resolutions of 150 and 100 μas, respectively.

The Very Long Baseline Array (VLBA), now under construction by NRAO, consists of ten 25 m diameter antennas, located in Hawaii, in mainland U.S.A. and in the Virgin Islands. The array will operate at 9 wavelengths from 0.7 to 90 cm, providing a maximum resolution of about 200 μas at 0.7 cm. The VLBA correlator will be able to process data from up to 20 stations simultaneously and will provide 256,000 frequency-baseline or delay-baseline channels. It can be organized in many ways to accommodate different requirements (e.g., 20 stations [190 baselines], 8 IF bands, 128 spectral channels each). The VLBA is expected to improve greatly the quality and diversity of VLBI images because (1) the station locations provide excellent (u,v) plane coverage, (2) the electronics are well matched to reduce closure errors, (3) the array can operate well at short wavelengths, and (4) the large correlator makes ambitious spectral line projects possible.

The worldwide capability for VLBI work will continue to improve as more telescopes are equipped with terminals and frequency standards. The EVN has a plan to build a correlator of capacity similar to the one for the VLBA.

Interferometers with baselines longer than an earth diameter require stations in earth orbit. The feasibility of VLBI with satellite-borne stations has recently been demonstrated with the TDRS satellite. There are currently three viable projects for large antenna ($\sim$ 15 m) VLBI stations in earth orbit. The Russian project, RADIOASTRON, is well advanced, and the station could be deployed by 1991 in an orbit with apogee radius of 75,000 km. The QUASAT project is in a phase A study at ESA. Its initial orbit has an apogee radius of 42,000 km. Finally, plans for the Japanese project VSOP call for a station with apogee radius of 16,000 km. All these projects require a high degree of international cooperation to make effective use of ground stations and data transmission facilities. The relative timing of these projects will undoubtedly emerge as an important issue. Having two satellites available simultaneously would increase their (u,v) plane coverage greatly because of the different orbits and make satellite-to-satellite VLBI possible.