Reports

Real-Time, Very-Long-Baseline Interferometry Based on the Use of a Communications Satellite

Abstract. *The Hermes satellite, a joint Canadian-American program, has been used to provide a communication channel between radio telescopes in West Virginia and Ontario, for very-long-baseline interferometry (VLBI). This system makes possible instantaneous correlation of the data as well as a sensitivity substantially better than that of earlier VLBI systems, by virtue of a broader observational bandwidth. With the use of a geostationary communications satellite it is possible to eliminate the tape recorders and the most troublesome part of the postobservational data processing. A further possibility is the development of a phase-coherent interferometer.*

In 1967 very-long-baseline interferometry (VLBI) was established as an important new technique in radio astronomy (*1*); with this technique two radio telescopes separated by continental or intercontinental distances could be used in synchronism to yield unprecedented angular resolving power. In succeeding years this technique has been refined and extended (*2*) to provide important new information about very distant radio galaxies, quasars, and interstellar molecular masers. The angular resolution is now approaching 10^{-4} arcsecond on the longest baselines and shortest wavelengths. Significant advances in precision time-transfer (*3*), geodetic measurements (*4*), and astrometry (*5*) appear to be imminent. Observational programs are in progress in which as many as eight synchronized telescopes distributed over North America are being used to synthesize maps of galactic and extragalactic sources to resolutions of 10^{-2} arcsecond.

This powerful technique has been realized in three principal forms (*6*), differing somewhat in technical detail but depending upon a broadband tape recorder and an extremely stable atomic frequency standard at each telescope. The tapes from two or more telescopes are processed later in a specialized computer which synchronizes the data from the tape playback machines and computes the cross-correlation coefficient as a function of time in each of several delay channels. The postobservational tape processing usually requires considerably more time than the observing itself, especially for multibaseline sessions, and so the amount of scientific labor involved in an experiment is inordinately large. Furthermore, the time interval between the observing session and the production of processed data can run to several months. Large amounts of magnetic tape are involved in a major observing program, and there are thus significant logistical problems.

A fundamental difficulty with the tape recording system is the lack of information in real time concerning the performance of the individual telescopes and peripheral equipment. Frequently a subtle failure of a minor yet vital component will be unrecognized until after tape processing has commenced, perhaps weeks or months after the observations. Such occurrences have resulted in much wasted observing time and scientific and technical effort. Program changes during an observing session, based on preliminary examination of the correlated data, are frequently desirable; such changes are impossible with the VLBI systems currently in use.

Short-baseline interferometer systems (*7*), whose antennas are interconnected by guided-wave transmission systems, suffer from none of the disadvantages mentioned above. The contrast in efficiency and convenience with current VLBI systems has led to consideration of suitable long-distance, broadband communications media for VLBI use. These include dedicated microwave radio links, the continental television network, and communications satellites, all of which could permit real-time, long-baseline interferometry, although they are apparently much more expensive than the magnetic tape system.

The advent of the Communications Technology Satellite (now known as Hermes) provided an opportunity to test this medium as a VLBI communication channel. The satellite, a joint project of the Department of Communications of Canada and the U.S. National Aeronautics and Space Administration, is in a geostationary orbit at 116° west longitude. It receives signals at 14.0525 Ghz and retransmits these signals at 11.8855 Ghz with a power of 20 watts (a 200-watt transmitter is available but was not used in this experiment). The transmitting and receiving antennas whose beam widths are 2.5° are pointed separately at the two ground terminals. A total bandwidth of 85 Mhz can be accommodated.

The VLBI communication system designed for use with the Hermes satellite is illustrated in Fig. 1. Cosmic signals from two radio telescopes are clipped and sampled under the control of clock pulses derived from two independent hydrogen maser oscillators to obtain two binary signals. For time synchronization after transmission through the satellite channel, synchronization words are inserted into the data stream every second at station 1. The binary signal thus formatted is used to modulate a 150-Mhz intermediate-frequency (IF) carrier phase-locked to the hydrogen maser oscillator. The modulation employed is differential phase shift keying (DPSK). This modulated IF carrier is then converted to 14 Ghz for transmission to the satellite, which translates it to 12 Ghz and relays it to the communications antenna at station 2.

The received signal is demodulated, and a phase-locked loop is used to recover the clock pulses. The data and the recovered clock from station 1 are then delivered to the delay and correlation system for combination with the binary signal from telescope 2. The two astronomical signals must be exactly synchronized before being cross-correlated. Because the signal arriving by the satellite path suffers a delay of approximately 0.25 second, it is necessary to delay the signal from telescope 2 by a corresponding amount. A sampling rate of 20 megabits per second was chosen as a compromise between the desire for increased sensitivity and the need to restrict the delay line to a reasonable size. At this sampling rate, the DPSK signal occupies a radio frequency bandwidth of 40 Mhz, thus utilizing about half of the available satellite channel bandwidth. More efficient use of the satellite bandwidth could be achieved by use of different modulation schemes. Since the satellite channel has more than adequate bandwidth to accommodate the delay line characteristics, the simplest scheme to implement was used for this first experiment.

The 5.5-million-bit delay line delays the local data stream (20 megabits per second) for a maximum of 270 msec. It contains 5500 shift registers of 1024 bits each and a small but fast 32-kilobit read-write memory which is used as a first in–first out silo. Shift registers and memory operate in the 16-bit parallel mode, to reduce the bit rate to 1.25 megabits per second. This procedure achieves a compromise between power dissipation in the shift registers and complexity in the backplane wiring. The memory writes at the rate of the station 2 clock and reads at the rate received by way of the satellite, which compensates for the motion of the satellite. This arrangement also serves to align the two data streams to an accuracy of 1 bit. The amount of delay is set by control circuitry which detects synchronization words in the received data stream and compares them with a 1-second pulse from the local clock. Multiplexers select the amount of delay to be used to within 16 kilobits, and the memory resolves the delay to 1 bit. Two separate counters keep track of each bit of the local and remote data streams, provide write and read addresses for the memory, and set the multiplexers. The amount of delay can be modified by as much as ± 26.2 msec under program control.

The control computer calculates the geometric delay and relative Doppler shift for the two stations. After both data streams are aligned in time, a digital fringe rotator reduces the natural fringe rate to near zero. Cross correlation is then carried out in a 64-channel digital correlator with a total delay range of 3.2 μsec. Data are accumulated in the correlator for 100 msec, read into the control computer, and further accumulated for 1 second. Then the 64 complex numbers are stored in a core memory buffer. After 60 such samples have been accumulated, the whole buffer, along with all other necessary information, is dumped onto magnetic tape. These data are intended for detailed postexperiment analysis. In addition, each minute of data is analyzed on-line to provide a cathode-ray tube display of fringe amplitude versus delay and residual rate. These three quantities are also printed out at this time.

The system was successfully used for astronomical observations on 27 and 28 November 1976, in conjunction with the 43-m radio telescope of the National Radio Astronomy Observatory (*8*) at Green Bank, West Virginia, and the 46-m instrument of the Algonquin Radio Observatory (*9*) at Lake Traverse, Ontario. The wavelength was 2.8 cm, the video bandwidth was 10 Mhz, and the system noise was about 120 K at each telescope. The West Virginia station served as station 1 and the Ontario station as station 2 (Fig. 1). The up-link transmitter (at Green Bank) utilized a 26-m parabolic antenna and the down-link receiver a 10-m antenna, each of which was provided with a receiver for the 14-Ghz beacon transmitter on the satellite. The beacon receivers permitted precision pointing of the narrow-beam communication antennas. With an up-link transmitter power of 5 watts and a down-link receiver noise temperature of 900 K, the ratio of the received energy per bit-to-noise power density *E/N* is 14 db. With this signal-to-noise ratio the error probability including the recovered bit clock error is less than 10^{-5}. The satellite link therefore does not impair the sensitivity of the interferometer.

We conducted continuous operations for approximately 45 hours, during which time 18 radio sources were observed. Interference fringes were detected in real time for ten of these sources, all of which have been reported in the literature as having unresolved components on similar baselines. The on-line detection limit (1 minute of integration) is about 0.3 jansky. Postobservational processing permits a longer integration time and hence a higher sensitivity.

During the observations the hydrogen maser at station 2 failed temporarily, and it was necessary to substitute a rubidium vapor frequency standard. The superiority of the maser oscillator was immediately apparent from the display of fringe amplitude versus residual rate.

Another observing session was conducted on 20 and 21 February 1977. Approximately 140 cosmic sources were observed, of which 25 percent exhibited fringes in real time (1 minute of integration) (*10*).

The use of a real-time data link, which eliminates the restrictions inherent in the use of video tape signal recording, makes feasible many extensions of the VLBI technique. The ability to see results in real time, although important for radio astronomy, is of particular significance for all operational and applied uses of the VLBI technique. Applications visualized include highly precise time transfer, earthquake prediction, and station location. In all of these applications the laborious and failure-prone use of magnetic tape has proved a major practical drawback.

The real-time system also eliminates the artificial restriction placed on signal bandwidth by video tape techniques. The bandwidth of our experimental system, 10 Mhz, is 2.5 times as wide as the

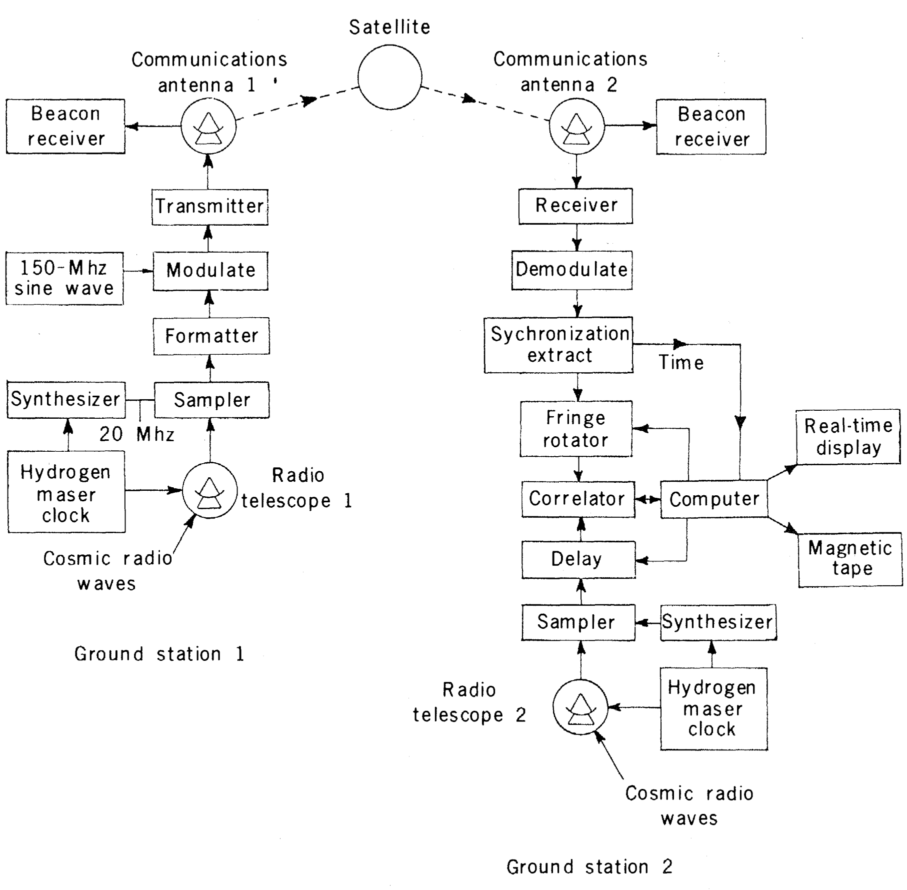

Fig. 1. Block diagram of the satellite VLBI system.

widest bandwidth system now in use. Since the signal-to-noise ratio for a wide-band radio astronomy signal varies as the square root of the bandwidth, this wider bandwidth results in a significant improvement. Much larger bandwidths are possible with existing technology.

A further possibility is the development of a true phase-coherent interferometer by a two-way transmission of the local oscillator signal by way of the satellite, thus making possible compensation for the phase change over the satellite path. The preservation of phase would be an important step toward the removal of ambiguities associated with model fitting techniques. A precision in the angular measurements of the order of 10^{-4} arcsecond should also be possible. In order to reconstruct reliable brightness distributions, multistation experiments are essential. This type of experiment is more easily implemented in real time than with magnetic tapes.

Advances in technology are increasingly lowering the cost of satellite communication channels. Simple ground stations with antennas 5 to 10 m in diameter are adequate for the service. A real-time VLBI network based on the use of a communications satellite is technically feasible and may indeed become a real possibility.

Note added in proof: Following the successful system demonstrations described above, the transmitting equipment of ground station 1 was moved to the Owens Valley Radio Observatory, California Institute of Technology, in order to utilize the transcontinental baseline between there and Algonquin Radio Observatory. This extended-baseline interferometer was successfully placed in operation on 28 and 29 May 1977, using a 27.5-m equatorial paraboloid for data transmission and the 40-m altazimuth paraboloid for reception of cosmic radiation of 2.9-cm wavelength.

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Paleodemography of the Libben Site, Ottawa County, Ohio

Abstract. *The Libben site, a Late Woodland ossuary and occupation site from the Great Black Swamp of northern Ohio has yielded a well-preserved skeletal sample of 1327 articulated individuals. The outstanding preservation and completeness of the site and the utilization of an exhaustive aging methodology make this the largest and most comprehensively censused North American prehistoric cemetery. Survivorship data indicate a robust, successful population. Life expectancy at birth was 20 years. Among adults, male mortality was consistently higher than female, a condition possibly related to high interpersonal and intergroup aggression. Infant mortality was generally low, and a general hypothesis concerning the elevation of infant mortality and the simultaneous depression of adult mortality among aboriginal peoples after European contact is suggested.*

The Libben site, located on the north bank of the Portage River in Ottawa County, Ohio, was excavated in 1967–1968. The site lies 6 miles (9.6 km) upstream of Lake Erie and would have thus been located at the edge of the Great Black Swamp in aboriginal times (*1*). An area of approximately 30,000 square feet (2790 m^2) was excavated, constituting 85 to 90 percent of the extant site. All indications are of a perennial occupation (*2*) with a time span of 250 to 300 years (*3*). Radiocarbon dates place the site between A.D. 800 and 1100 (*4*). Faunal and floral analyses indicate a diet rich in animal protein (especially fish, small mammal, and migratory bird) with vegetable foods surprisingly sparse (with the possible exception of wild rice) (*5*). Mollusks and white-tailed deer are relatively rare. There may have been marginal corn agriculture at some time during the occupation. The site clearly belongs within the Western Basin Tradition of southern Michigan (*3*, *6*), although it constitutes a novel "Libben phase." While a small number of intrusive refuse pits representing a distinctly later Mississippian-related component were thinly scattered about the site, the vast majority of recovered cultural material is referable to the Libben phase.

A total of 1327 individuals (*7*) were removed from the site, and great care was taken to obtain all individuals of all age classes. Fine-mesh screening was employed to recover term and preterm infants. The age range of recovered burials was 16 weeks in utero to 70+ years. Because only articulated (*7*) remains were considered in the demographic census presented here, no skewing of adult representation should occur in our data; the sex ratio is .97 (*8*). There was no evidence of infanticide or of differential preservation of age classes. We believe that this is, therefore, the largest and best-preserved North American cemetery excavated and analyzed to date.

Infants were aged primarily by dental maturity and secondarily by long bone length and metaphyseal breadth. All dentitions were seriated with respect to crown and root development. Target ages at 1-month intervals for the first year and at 1-year intervals thereafter were judged on the basis of published standards (*9*). Long bone lengths, metaphyseal breadths, and cranial base metrics were then used to age specimens without dentitions from polynomial regressions. All correlation coefficients were .97 or greater.

Adolescents (12 to 18 years) were aged