# Reports

## Very-Long-Baseline Radio Interferometry: The Mark III System for Geodesy, Astrometry, and Aperture Synthesis

Abstract. *The Mark III very-long-baseline interferometry (VLBI) system allows recording and later processing of up to 112 megabits per second from each radio telescope of an interferometer array. For astrometric and geodetic measurements, signals from two radio-frequency bands (2.2 to 2.3 and 8.2 to 8.6 gigahertz) are sampled and recorded simultaneously at all antenna sites. From these dual-band recordings the relative group delays of signals arriving at each pair of sites can be corrected for the contributions due to the ionosphere. For many radio sources for which the signals are sufficiently intense, these group delays can be determined with uncertainties under 50 picoseconds. Relative positions of widely separated antennas and celestial coordinates of radio sources have been determined from such measurements with 1 standard deviation uncertainties of about 5 centimeters and 3 milliseconds of arc, respectively. Sample results are given for the lengths of baselines between three antennas in the United States and three in Europe as well as for the arc lengths between the positions of six extragalactic radio sources. There is no significant evidence of change in any of these quantities. For mapping the brightness distribution of such compact radio sources, signals of a given polarization, or of pairs of orthogonal polarizations, can be recorded in up to 28 contiguous bands each nearly 2 megahertz wide. The ability to record large bandwidths and to link together many large radio telescopes allows detection and study of compact sources with flux densities under 1 millijansky.*

Radio interferometers are now routinely operated by recording signals from extraterrestrial radio sources received simultaneously at widely separated antennas and later cross-correlating the recordings at a central processing facility. Use of this technique of very-long-baseline interferometry (VLBI) has allowed astronomers to achieve submillisecond-of-arc angular resolution in observations of celestial radio sources (*1*) and to discover apparent superluminal expansion in quasars (*2*). VLBI is also being applied to geophysical and astrometric research (*3*). Here we describe a new VLBI system, about six times more sensitive than its immediate predecessor, and some of the geodetic and astrometric results obtained with it. A companion report (*4*) describes the discovery made with this system of a very faint radio source, perhaps the third gravitational image of a single distant quasar.

The first VLBI experiments in the United States (*5*) utilized a standard computer digital recording system, known as the Mark (Mk) I, to record a signal with a nearly 360-kHz bandwidth. This digital signal was produced by sampling the sign of the analog signal at the Nyquist rate and was recorded on standard ½-inch (~ 1.3-cm) computer tape along with the epoch of the signal and other relevant information. Each tape was filled with bits after 3 minutes of recording. A Mk II system, also digital, based on a helical scanning television recorder (*6*), was subsequently developed by the National Radio Astronomy Observatory to increase both the bandwidth of the recording and the packing density of the bits on the magnetic tape. In the current version of this Mk II system, slightly modified video cassette recorders are used to record a signal with a nearly 2-MHz bandwidth. Some tapes with this system can record for 4 hours and weigh only ~ 0.23 kg each.

In our new Mk III system (*7*) an instrumentation magnetic tape recorder is used to record simultaneously up to 28 signals, each with up to a 2-MHz bandwidth on each of 28 parallel tracks along a tape 9200 feet (~ 2800 m) long and 1 inch (~ 2.5 cm) wide. The recorded 1-bit samples have a longitudinal density of 33,000 bits per inch. With a head stack that can move transversely across the tape it should be possible to increase more than tenfold the number of tracks recorded (*8*). One tape would then store about $10^{12}$ bits and take about 3 hours to fill when running forward and backward on successive passes at its normal rate of 135 inches per second.

The Mk III system can handle the intermediate-frequency (IF) outputs (100 to 500 MHz) of two independent receivers. The IF outputs can be routed through 14 separately controllable frequency converters to produce "video" signals from the (~ 2 MHz) upper and lower side bands adjacent to the total local-oscillator frequencies corresponding to the settings of each of these converters. The actual bandwidth recorded and the corresponding low-pass filter through which the signal is passed depend on the recorder speed used; this speed, nominally 135 inches per second for 2 MHz, can be as high as 270 or as low as 17 inches per second. As in the

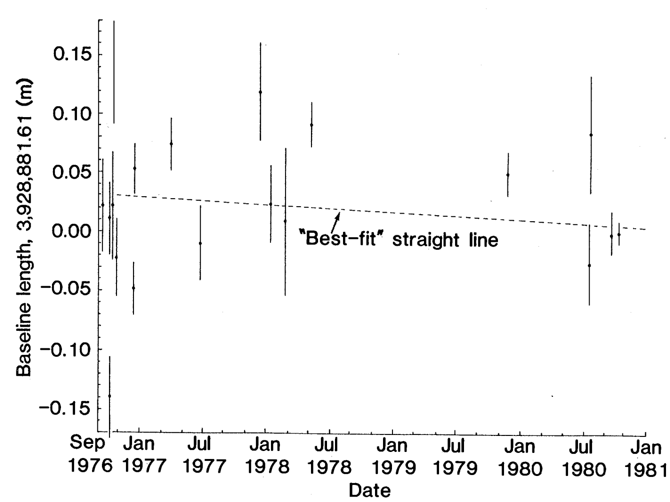


Fig. 1. Estimates of the length of the baseline between Haystack and Owens Valley. Before 1980 all data were obtained at only a single radio-frequency band; hence no corrections for ionospheric effects were made. The data obtained in July 1980 were compromised in part by the use of a portion of the observing time for special experiments. The estimates shown for September and October 1981 are composites of individual estimates for separate days which were too closely spaced in time to plot separately; the error bars represent the weighted r.m.s. scatter of the individual estimates. The other error bars represent plus and minus 1 standard deviation, determined in each case for chi squared per degree of freedom equaling unity; this latter result was attained by root-sum squaring the measurement errors, originally assigned on the basis of signal-to-noise ratios, with suitable, baseline-dependent numbers. The slope of the best-fit straight line does not differ significantly from zero (see text).


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earlier systems, the output of each side band of each converter is amplified, hard limited ("clipped"), and the sign sampled at the Nyquist rate prior to recording in the same format on the assigned tape track. For geodetic and astrometric measurements, the frequency settings of the 14 converters are given values which collectively span as large a bandwidth as allowed by the receivers and the IF system, in order to yield accurate group delays (*9*). In our present system, these settings are distributed over both *S*-band (2.2 to 2.3 GHz) and *X*-band (8.2 to 8.6 GHz). Such dual-band measurements allow the contribution of the ionosphere to the interferometric measurements to be determined from the difference of the group delays measured at the two bands (*3*). For studies of source structure (*4*), the frequencies are usually chosen so that the 28 2-MHz channels are adjacent to each other. In experiments to measure polarization, the frequency converters can be paired to record in the same frequency band each of two orthogonal polarization components of the radiation.

For each received radio band at each site, low-intensity signals spaced 1 MHz apart, and controlled by the site frequency standard, are injected into the receiver and pass through the entire system, serving to calibrate the phase delays undergone by the observed signals in each interferometer terminal. The delays incurred by the calibration signals between their point of generation and the input to the receivers are monitored by an auxiliary system and recorded in an auxiliary log for use in the data processing.

The entire data acquisition system can be operated either manually, through front-panel controls on each module, or under computer control, save for the changing of tapes. In the latter mode, very complicated schedules, prepared in advance on a floppy disk, can be accommodated easily; in addition, module settings, system temperature measurements, and so on are all automatically recorded, usually on a hard disk. Twelve of these systems are currently in operation in the United States and Europe; several more are under construction, including one for use in Japan.

A dedicated processor cross-correlates the recorded bits in a standard manner: the tapes from each pair of sites in the interferometer array are aligned under computer control to account for any known epoch offset between the clocks at the two sites as well as for the difference in the times of propagation of the signals to the sites (delay). The rate of change of this difference (delay rate) is also taken into account. The phase-calibration information for each site is also extracted in the processing.

The processor is of modular design so that bits on a corresponding track on each of the two tapes from one pair of sites are correlated in one of 28 identical modules, all under the control of an HP1000 series minicomputer. The detection of interference fringes and the determination of the maximum likelihood estimates of the delay and delay rate for each observation of each source for each pair of sites are also carried out on the HP1000, which has an array processor attached to perform the two-dimensional Fourier transforms relating frequency and time to delay and delay rate.

For observations of a sufficiently strong source, the Mk III system can detect fringes at virtually the same time the observations are made by use of a 1-megabit data buffer incorporated in the data acquisition system at each site. The bits are stored in this buffer and then transferred over commercial telephone lines at 1200 bits per second to any computer which has software suitable

Table 1. Arc lengths between compact radio sources determined from VLBI observations.

| Source pair | Number of experiments | Arc length (deg min sec) | Differences from 1972–1978 estimate (arc sec) |
|---|---|---|---|
| 0355 + 508–0851 + 202* | 14† | 64 25 16.343 ± 0.004‡ | 0.003 ± 0.006§ |
| 0355 + 508–0923 + 392 | 14 | 56 03 52.200 ± 0.002 | 0.003 ± 0.003 |
| 0355 + 508–1226 + 023 | 9 | 110 45 46.616 ± 0.007 | 0.007 ± 0.009 |
| 0355 + 508–1641 + 399 | 16 | 88 43 41.706 ± 0.003 | 0.007 ± 0.004 |
| 0355 + 508–2200 + 420 | 14 | 58 03 19.715 ± 0.002 | 0.002 ± 0.003 |
| 0851 + 202–0923 + 392 | 14 | 20 09 50.748 ± 0.003 | 0.001 ± 0.004 |
| 0851 + 202–1226 + 023 | 7 | 55 16 54.597 ± 0.003 | 0.002 ± 0.005 |
| 0851 + 202–1641 + 399 | 12 | 96 11 25.040 ± 0.004 | 0.005 ± 0.006 |
| 0851 + 202–2200 + 420 | 14 | 115 40 22.150 + 0.005 | 0.005 ± 0.007 |
| 0923 + 392–1226 + 023 | 9 | 55 29 44.839 ± 0.006 | 0.003 ± 0.009 |
| 0923 + 392–1641 + 399 | 16 | 77 55 31.868 ± 0.003 | 0.005 ± 0.004 |
| 0923 + 392–2200 + 420 | 16 | 96 16 50.403 ± 0.003 | 0.004 ± 0.004 |
| 1226 + 023–1641 + 399 | 9 | 68 32 22.402 ± 0.007 | 0.002 ± 0.009 |
| 1226 + 023–2200 + 420 | 9 | 124 43 06.302 ± 0.009 | 0.005 ± 0.011 |
| 1641 + 399–2200 + 420 | 16 | 57 59 31.251 ± 0.002 | 0.002 ± 0.003 |

*The source name, by convention of the International Astronomical Union, is given in terms of right ascension and declination. For example, 0355 + 508 denotes a right ascension of 3 hours 55 minutes and a declination of +50.8°. †Each experiment involved antennas at four or more of the following six sites: Chilbolton Observatory, Chilbolton, England; Max-Planck-Institut für Radioastronomie, Effelsberg, Federal Republic of Germany; Harvard Radio Astronomy Station (HRAS), Fort Davis, Texas; Haystack Observatory, Westford, Massachusetts; Onsala Space Observatory, Onsala, Sweden; and Owens Valley Radio Observatory (OVRO), Big Pine, California. ‡The uncertainties quoted represent the r.m.s. scatter about the mean of the individual determinations and are in all cases at least twice the standard deviation of the mean. Effects of elliptic aberration have been removed. §The differences are given as new minus old. The 1972–1978 estimates are from Mk I data for April 1972 to May 1978 (*12*). The uncertainties quoted represent the root-sum squares of the r.m.s. scatters from the two sets of estimates.

Table 2. Summary of baseline length estimates.

| | Baseline length (m) | | | | |
|---|---|---|---|---|---|
| | Owens Valley | Fort Davis | Onsala | Effelsberg | Chilbolton |
| Haystack | 3,928,881.59 ± 0.02* | 3,135,640.98 ± 0.04 | 5,599,714.43 ± 0.05† | 5,591,903.50 ± 0.03 | 5,072,314.41 ± 0.06 |
| Owens Valley | | 1,508,195.37 ± 0.02 | 7,914,130.92 ± 0.09† | 8,203,742.44 ± 0.04 | 7,846,991.19 ± 0.11 |
| Fort Davis | | | 7,940,732.17 ± 0.10 | 8,084,184.82 ± 0.09 | 7,663,737.32 ± 0.12 |
| Onsala | | | | 832,210.49 ± 0.01 | 1,109,864.31 ± 0.02 |

*The baseline lengths were estimated from 8924 observations of group delays obtained in July, September, and October 1980. In this least-squares analysis 468 parameters were estimated by an arc-elimination technique. The root-mean-square of the weighted postfit residuals was ~ 0.1 nsec (~ 3 cm). The uncertainties quoted are the weighted r.m.s. scatter of the results from the separate least-squares analyses of the data from the individual experiments about the values given. The number of individual experiments was 16 for Owens Valley, Fort Davis, and Onsala; 5 for Effelsberg; and 7 for Chilbolton. Only observations at elevation angles greater than 10° were used in this analysis. The speed of light used to convert measured delays to distances was $2.99792458 \times 10^8$ m/sec. †These distances are 0.23 m (Haystack-Onsala) and 0.27 m (Owens Valley–Onsala) less than the Mk I values (*11*). We believe, but are not certain, that these differences are due to the uncorrected effects of the ionosphere on the single, *X*-band–Mk I observations.

for correlation. This technique is useful for verifying that the equipment at each site is operating properly before proceeding with an experiment.

The only processor for the Mk III system currently in operation is at Haystack Observatory, Westford, Massachusetts. This processor can correlate simultaneously 28 tracks on tapes from three sites or 14 tracks on tapes from four sites. A similar processor for correlating tapes from three sites at once, to be used at the Max-Planck-Institut für Radioastronomie in Bonn, is nearing completion at Haystack. Another processor of slightly different design, with more emphasis on the use of microprocessors, is being developed and built at Jet Propulsion Laboratory.

Astrometric and geodetic measurements with the Mk III system were started in 1979. The most extensive series of such measurements was carried out during the international MERIT (monitor the earth rotation and intercompare techniques) campaign (*10*) in September and October 1980. Virtually the same daily schedule of observations of sources was used for all but 2 days of the two 1-week periods of the VLBI part of this experiment. Similar schedules were used in earlier and later experiments. The delay and delay rate data from each day of observation separately were analyzed with the scheme outlined by Herring *et al.* (*11*) and yielded estimates of the celestial positions of the sources and of the baselines between the sites. Simultaneous estimates were, in fact, made of parameters representing (i) these positions and baselines, (ii) daily or twice-daily changes in corrections for tropospheric delays for each site, and (iii) daily or twice-daily differences in epoch and rate of the clocks at the various sites. There were typically ten times as many observations as estimated parameters. Representative results are given in Table 1 for the arc lengths between sources, since these lengths have the virtue of being independent of coordinate system. The uncertainties quoted represent the root-mean-square (r.m.s.) scatter about the weighted mean of the results from each day of observation. Except for pairs which include a source at low declination, the scatter is typically a few milliseconds of arc. Also included in Table 1 are the differences between these estimates and those from Mk I experiments (*12*); the agreement in all but two cases is within the root-sum square of the r.m.s. scatter of each set about its mean value. The positive bias in the differences is probably due to the earlier Mk I observations being confined to one frequency band (~ 8 GHz) and hence affected by the ionosphere: if no correction is made for the ionosphere, the sources tend to appear closer together.

Our various observations involved 15 baseline vectors connecting six antennas, three in the continental United States and three in Europe. The directions of these vectors at different epochs are related to changes in the pole position and rotation of the earth and will not be discussed further here (*13*). We will consider results only for the baseline lengths which, like arc lengths, are independent of the choice of coordinate system. A sample of these results for the lengths of baselines connecting antennas in the United States and Europe is shown in Table 2 (*14*). On average, these estimates are repeatable within about 5 cm.

To discern any significant changes in baseline lengths, many measurements well spread in epoch are necessary. Measurements of the distance between Haystack Observatory and Owens Valley Radio Observatory (near Big Pine, California) best fit these criteria. Measurements with the telescopes at these sites started in September 1976 with the Mk I system and continued with the Mk III system. The results (Fig. 1) show good agreement and indicate a high degree of stability for this baseline. A weighted least-squares estimate of the intercept and slope of the straight line determined by the points in Fig. 1 yields a baseline length given by $B(t) = 3{,}928{,}881.61 \pm 0.01 - (0.005 \pm 0.005)\ \Delta t$ m, where $\Delta t$ (years) is the time elapsed since 1980.0. The estimated slope is not significant (*15*); the small decrease in length is most likely due to a positive bias in the baseline lengths determined with the Mk I system, for reasons analogous to those discussed above for arc length estimates. The Mk III results, which have much higher signal-to-noise ratios and dual-band capability, are limited mainly by systematic errors attributable to the unmodeled parts of tropospheric delay and clock "wander." When these sources of systematic error are better understood and partially eliminated, it should be possible to determine these baselines with an uncertainty under 2 cm and the source positions with an uncertainty under 1 millisecond of arc.

The Mk III system, as mentioned, is also a powerful instrument with which to study very faint, compact radio sources. By linking together many large radio telescopes in an interferometer array, sources with flux densities below 1 millijansky can be studied effectively. In the following report, by far the weakest source yet detected with VLBI is described, but its identification is uncertain; it is either the dim third image of a gravitational lens, the radio emission from the center of a distant elliptical galaxy, or a combination of these.


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### References and Notes


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7. More detailed information on the Mk III system is contained in a user's manual entitled "Mk III VLBI data acquisition terminal," which is available upon request to Crustal Dynamics Project Office, Goddard Space Flight Center, Code 904, Greenbelt, Md. 20771.
8. Such a development is now in progress.
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12. T. A. Clark *et al.*, *Astron. J.* **81**, 599 (1976). A complete description of the more recent results, discussed here in part, will be given by C. Ma *et al.*, in preparation.

13. D. S. Robertson *et al.*, in preparation.
14. T. A. Herring *et al.*, in preparation.
15. A weighted-least-squares solution using all of the data from these (and other) experiments simultaneously yields consistent results (J. W. Ryan *et al.*, in preparation).
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## Detection of a Compact Radio Source near the Center of a Gravitational Lens: Quasar Image or Galactic Core?

Abstract. *By use of a new, very sensitive interferometric system, a faint, compact radio source has been detected near the center of the galaxy that acts as the main part of a gravitational lens. This lens forms two previously discovered images of the quasar Q0957+561, which lies in the direction of the constellation Ursa Major. The newly detected source has a core smaller than 0.002 arc second in diameter with a flux density of 0.6 ± 0.1 millijansky at the 13-centimeter wavelength of the radio observations. This source could be the predicted third image of the transparent gravitational lens, the central core of the galaxy, or some combination of the two. It is not yet possible to choose reliably between these alternatives.*

Albert Einstein's theory of general relativity predicted that mass would deflect light rays and hence could form images. The theoretical properties of such gravitational lenses have been studied in detail over the past five decades (*1, 2*), but no astronomical examples were discovered until 1979 (*3*), a few weeks after the hundredth anniversary of Einstein's birth. The two images, A and B, of the quasar Q0957+561 then discovered are 6 arc sec apart on the sky, with A almost due north of B (*4*). They have the same emission features in their optical spectra, which yield redshifts of 1.4136, identical within their measurement uncertainties of 0.0002 (*5*). The imaging is caused by a cluster of very faint foreground galaxies (redshift ≃ 0.36) (*6*), with the principal role being played by a large elliptical galaxy (designated G1), the brightest member of the cluster, located 1.00 ± 0.03 arc sec north and 0.19 ± 0.03 arc sec east of the B image (*7*). The cluster is spread over a region about 4 arc min in diameter and comprises over 100 galaxies.

Because such a gravitational lens is transparent, one can predict (*2, 8*) from theory that, except for degenerate cases, there should be an odd number of images. After the discovery of the galactic lens, the central remaining question concerned the missing third image. Different models predicted that it would be very near to either the B image or the center of G1 (*6*). Observations with the Very Large Array (VLA) of radio telescopes near Socorro, New Mexico, showed pointlike emission which came from the positions of the A and B optical images and weaker emission (designated G) which came from a position 1.06 ± 0.02 arc sec north and 0.15 ± 0.02 arc sec east of the B radio image (*9, 10*) coincident, within the measurement uncertainty, with the apparent optical center of G1, referenced to the corresponding center of B. The angular resolution of these VLA measurements, about 0.3 arc sec FWHM (full width at half-maximum), was too crude to allow one to discern any structure within the images. The flux densities of the A, B, and G components, interpolated to our 13-cm observation wavelength (~ 2300 MHz), were 49 ± 1, 37 ± 1, and 3.3 ± 0.3 mJy, respectively (*9*). The spectral index of the radio emission from G differed significantly from those of the A and B images, suggesting that part, if not all, of this weak emission was from G1 (*11*).

Soon after the discovery of this gravitational lens system, we undertook a program of very-long-baseline interferometry (VLBI) observations of the region of the quasar images (*12*). Here we report on the first phase of analysis of our most recent observations, conducted on 15 and 16 March 1981 with a VLBI array more sensitive than any previously available, and within a factor of 2 of the highest sensitivity achievable with the VLA. This increase in sensitivity was brought about primarily by the use of the new Mark III VLBI terminals (*13*) in combination with the 100-m-diameter radio telescope at Effelsberg, Federal Republic of Germany; the 64-m-diameter telescopes at the National Aeronautics and Space Administration's radio tracking stations in Goldstone, California, and Madrid, Spain; and three other telescopes with smaller diameters. Our observations with these telescopes of right circularly polarized radiation covered about 12 hours for most baselines. Because the separation of 6 arc sec between the A and B images is small compared to the antenna beam widths, both images were observed simultaneously at each site.

The properties of the galactic gravitational lens lead to the prediction that the third image, if near G1, should be smaller and therefore dimmer than the A or B image, but of similar shape (*6, 14*). Analysis of the data obtained in 1980 with the Effelsberg-Goldstone interferometer (*15*) disclosed single compact radio cores with largest dimensions between 0.001 and 0.002 arc sec in both the A and B images. The corresponding flux densities in these parts of the A and B images were 23 ± 1 and 19 ± 1 mJy, respectively. In searching for a similar but fainter radio core in the vicinity of G we used the 1981 data from the most sensitive (Madrid-Goldstone) interferometer, whose fringe spacing was ~ 0.0035 arc sec. To increase detection sensitivity we used the technique of phase referencing to average together coherently all the data from 13 "scans," each 12 minutes in duration, obtained with this interferometer (*16*).

The region around G that we searched showed no radio radiation above the (5 standard deviation) noise level of 0.3 mJy, save for a spot less than 0.002 arc sec in extent with a flux density of ~ 0.6 mJy detected with a signal-to-noise ratio (SNR) of 10. This detection represents

Table 1. Positions of G1, G, and G′

| Object | Method of observation | Resolution (FWHM arc sec) | Position relative to B image (epoch 1950.0): Right ascension (arc sec) | Position relative to B image (epoch 1950.0): Declination (arc sec) |
|---|---|---|---|---|
| G1 | Optical (*7*) | 0.5* | 0.19 ± 0.03 | 1.00 ± 0.03 |
| G | VLA (*10*) | 0.3 | 0.15 ± 0.02 | 1.06 ± 0.02 |
| G′ | VLBI | 0.002 | 0.181 ± 0.001 | 1.029 ± 0.001 |

*The resolutions for the optical and VLA observations are from the respective references; the VLBI resolution is given as one-half the fringe spacing on the long California-Europe baselines.


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