Reports

Very Long Baseline Interferometric Observations Made with an Orbiting Radio Telescope

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An orbiting spacecraft and ground observatories have been used to obtain interferometric observations of cosmic radio sources. The Tracking and Data Relay Satellite System (TDRSS) was used as the orbiting observatory in conjunction with two 64-meter radio telescopes at ground observatories, one in Australia and one in Japan. The quasars 1730–130 (NRAO 530), 1510–089, and 1741–038 were observed at a frequency of 2.3 gigahertz, and a maximum projected baseline of 1.4 earth diameters was achieved. All quasar observations for which valid data were acquired resulted in detected fringes. Many of the techniques proposed for a dedicated very long baseline interferometry observatory in space were used successfully in this experiment.

Very long baseline interferometry (VLBI) has been practiced in radio astronomy for more than 20 years (*1, 2*). In VLBI observations, radio sources are observed simultaneously by two or more widely separated radio telescopes and independent frequency standards are used at each site. The data are later brought together at a central processing facility where the signal from one telescope is cross-correlated with the signal from the other. The angular resolution achieved by this technique is, at present, superior to that of any other method of astronomical observation. At frequencies of 10 GHz or more, resolutions of better than 1 milliarc second are routinely obtained, for baselines (the vector between two telescopes) less than an earth diameter in length. The resolution of Earth-based VLBI, however, is limited by the physical dimensions of Earth. For this reason, it has been proposed that the angular resolution of radio interferometry might be extended by using radio telescopes in space (*3–6*). The QUASAT (quasar satellite) project (*7*) being studied by NASA and the European Space Agency (ESA) would use a dedicated orbiting observatory for such a purpose. Other orbiting VLBI (OVLBI) missions are being considered by the Soviet Union and Japan (*8, 9*). One benefit of increasing the resolution is the ability to better probe energy generation and motions at the heart of exotic objects like quasars. More accurate measurements of the relative positions and motions of water maser emission features within star-forming regions can also be made. These measurements have applications to the establishment of the fundamental distance scale of the universe.

We have performed an OVLBI experiment, using an existing spacecraft in order to test the technical concept and probe the scientific potential. The Tracking and Data Relay Satellite System (TDRSS) was selected because it appeared to have all the prerequisites for performing an OVLBI experiment.

TDRSS (*10*) was designed to relay data between ground stations and satellites in low Earth orbit via satellites in geosynchronous orbit. Of three satellites planned, only the eastern one (TDRSE) has been deployed, at 41°W. For communications with satellites TDRSE has two 4.9-m-diameter antennas, both of which operate at 2.3 and 15 GHz. There is a smaller antenna for the uplink (15 GHz) and the downlink (14 GHz) with a ground control station located at White Sands, New Mexico. Radio frequency signals received by the 4.9-m antennas are amplified, coherently translated to 14 GHz, and relayed to Earth. A tone from a frequency standard on the ground is transmitted to the satellite, where it is used to phase-lock all the onboard oscillators, similar to the method planned for QUASAT.

OVLBI imposes more stringent requirements on phase stability than normal TDRSS communications operations. A phase stability in the frequency standard and local oscillator chain of at least one part in 10^{12} is required for a signal received at 2.3 GHz. OVLBI also requires an accurate knowledge of the spacecraft orbit. Unmodeled spacecraft accelerations must be sufficiently small that the quadratic phase error in a coherent integration period (typically 100 to 800 seconds) is a small fraction of a radian at twice the downlink frequency. If this condition is not met, the coherence of the data will be degraded, reducing the sensitivity and the calibration accuracy.

The orbit of the TDRSE satellite is measured by range and Doppler data, using ground-based transponders at two widely spaced locations. To demonstrate the adequacy of TDRSS for OVLBI, we conducted coherence tests in December 1985. A 2.3-GHz signal was transmitted from White Sands to TDRSE, received with one of the 4.9-m antennas, and then transmitted to White Sands on the 14-GHz downlink. The received phase was compared with that predicted from the orbit ephemeris. The resulting coherence was marginal for OVLBI with TDRSS; the coherence time was about 100 seconds. The observed coherence loss may be due to phase instabilities in the TDRSE electronics, propagation medium effects, or small unmodeled motions of the spacecraft.

To investigate improvement of the coherence, we performed a second test in which both TDRSE 4.9-m antennas received a 2.3-GHz tone and transmitted it back to the ground. The two antenna channels have separate receivers but derive their local oscillator frequencies from the same source. With one channel used to continuously calibrate the round-trip phase, as is planned for QUASAT, the coherence between the two channels was as high as 0.99 over 800 seconds.

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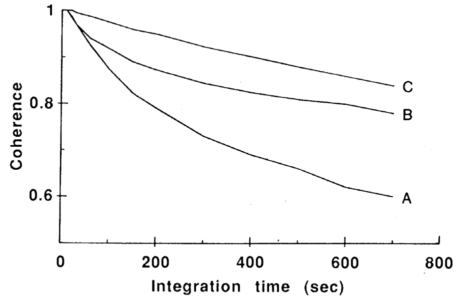

Fig. 1. Preliminary average coherence obtained between TDRSE and the ground stations for the radio sources 1730–130 and 1741–038 as a function of integration time. Curve A shows the coherence obtained when only the ephemeris data are used to correct for spacecraft motion. Curve B includes a correction for the White Sands cesium frequency standard, derived by comparing the cesium to a more stable hydrogen maser. Curve C includes additional corrections for the White Sands–TDRSE link based on the 2.3-GHz ground beacon signal tracked by TDRSE.

The quasar observations were conducted during July and August 1986, with TDRSE used as one of the observatories. The satellite antenna had its pointing restricted to a relatively small region near the nadir. Therefore, only radio sources near transit on the opposite side of Earth (139°E) could be observed. This circumstance, and the limited sensitivity of the orbiting observatory, restricted the choice of ground antennas that could be used as VLBI observatories. The two most suitable observatories were the 64-m antenna of the NASA Deep Space Network at Tidbinbilla, Australia, and the 64-m antenna of the Institute for Space and Astronautical Science, located at Usuda, Japan. Both facilities were used for the OVLBI experiment. The 25-m antenna of the Radio Research Laboratory at Kashima, Japan, was also used for most of the observations to verify the performance of the two more sensitive ground telescopes. The Mark III VLBI recording system (*11*) was used at each of the observing stations. The 3-dB bandwidth of the TDRSE 2.3-GHz receiver is 16 MHz. We recorded a total bandwidth of 14 MHz, from 2270.99 to 2284.99 MHz at each observatory.

Standard local oscillator chains and coherent mixing were used at Usuda, Tidbinbilla, and Kashima to derive the baseband recorded on the magnetic tapes. For Usuda, a Mark III recording system and rubidium frequency standard were borrowed from the Nobeyama Radio Observatory. A 2.3-GHz maser amplifier from the Jet Propulsion Laboratory was used to reduce the system temperature at the Usuda observatory. Aboard TDRSE, the received 2.3-GHz signal from the radio source was amplified and then coherently translated to 14 GHz. This signal was transmitted to the ground station at White Sands, where it was shifted to an intermediate frequency of 370 MHz and supplied to the Mark III terminal.

Both 4.9-m antennas on the spacecraft were used during the OVLBI observations. One of these antennas observed the celestial radio source, while the other observed a 2.3-GHz beacon signal sent from White Sands. The frequency-shifted signals from the two channels were transmitted to White Sands, where the radio source signal was recorded on the Mark III system, and the beacon signal was processed and recorded by a computer. Phase information from the beacon signal was used to calibrate motion of the spacecraft along the vector between TDRSE and White Sands and to calibrate phase instabilities common to both channels. Motion in other directions caused much smaller phase shifts, and could be adequately determined from the orbit ephemeris.

The White Sands ground terminal uses a cesium frequency standard for all TDRSS operations. To improve the ultimate phase coherence, the phase of the cesium standard was compared to that of a hydrogen maser of greater phase stability to obtain corrections used in correlation.

One and one-half recordings of useful data from 29 July and four recordings from 2 August were obtained. Each full recording was approximately 800 seconds in length. The data tapes were processed on the Mark IIIA VLBI correlator at the Haystack Observatory in Massachusetts (*11*). Modifications to the standard correlator software were required to process data from the orbiting observatory. The signal delay correction for TDRSE is separated into two components. The first component is the standard geometric delay, that is, the arrival time of the wavefront from the source, relative to the center of Earth. The second component, the link delay, is due to the downlink between TDRSE and White Sands. Unlike ground-based VLBI, the total signal delay for TDRSE is not linearly related to the total phase. The phase for TDRSE consists of the geometric delay multiplied by the observing frequency (the product being the geometric phase), plus the link phase. The link phase is the one-way link delay multiplied by a frequency of approximately 25 GHz (twice the downlink frequency minus the observing frequency).

For each 800-second integration, the spacecraft ephemeris was used to calculate the spacecraft position at a reference time near the middle of the integration. Polynomials were derived that modeled the variations in signal delay and phase for other times during the 800-second period. These polynomials and the spacecraft position at the reference time were used to compute both components of delay and the geometric component of phase. The link component of phase was derived from beacon measurements taken at White Sands during the experiment.

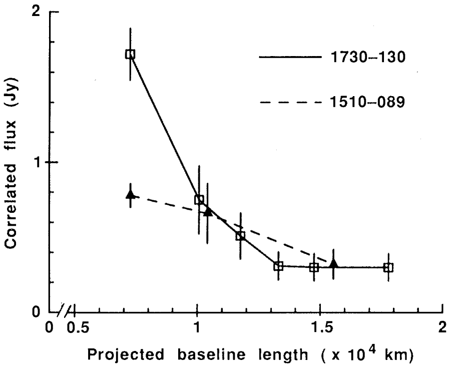

Fig. 2. Preliminary correlated flux versus projected baseline length ("visibility curve") for quasars 1730–130 (□) and 1510-089 (▲). Error bars are based on measured signal-to-noise ratio and errors in measurement of antenna gain-to-temperature ratio. The diameter of the earth is 12,743 km.

Using the orbital corrections and the correction for the cesium standard, we successfully correlated all six recordings of valid data. There were three observations of the quasar 1730−130, two observations of 1510−089, and one observation of 1741−038. We validated the ability to correct for orbital motion using the orbit ephemeris and link phase measurements by measuring the coherence of the OVLBI observations under different circumstances (Fig. 1). The maximum coherence on baselines to the TDRSS spacecraft is achieved when all the corrections described above are applied, and when the ground observatory uses a hydrogen maser frequency standard. In this case, coherence of 97.5% over 100 seconds, 95% over 200 seconds, and 84% over 700 seconds was measured. These values measure the combined coherence of the two hydrogen masers, the TDRSE spacecraft, the link, and the ground system, after calibration. When the real-time beacon calibration was not used, the coherence dropped to 92% over 100 seconds, 87% over 200 seconds, and 78% over 700 seconds. Because the coherence was limited primarily by the high link frequency, we expect that there would not be a great degradation in coherence at observing frequencies up to 30 GHz in a system designed as an OVLBI observatory.

The longest observed baseline was 17,800 km (on quasar 1730−130 between TDRSE and Usuda), or about 1.4 earth diameters. On this baseline, the approximate fringe spacing is 1.5 milliarc seconds. Maximum projected baselines of approximately 1.22 and 1.02 earth diameters were achieved for quasars 1510−089 and 1741−038 on the TDRSE-Usuda baseline. Most baselines between TDRSE and Tidbinbilla were less than 1 earth diameter.

We calibrated data from Tidbinbilla and Usuda with a standard technique, using noise diodes to monitor the system temperature and by observing sources of known flux density to measure antenna gain. Calibration of TDRSE was more difficult, because of its limited sensitivity and its automatic gain control. The method for calibrating TDRSE took advantage of the fact that our baselines between the spacecraft and Tidbinbilla were at certain times similar to the spacings on baselines between Australia and Japan, or Australia and California, for the same source. On 19 May and 2 June we conducted 2.3-GHz VLBI observations between Goldstone, California; Tidbinbilla, Australia; and Usuda, Japan. The correlated flux density at these two available "crossing points" was used with measured correlations on baselines to TDRSE to derive the ratio of antenna gain to system temperature. It was assumed that the correlated flux density was constant from May through August and that the gain to system temperature ratio of TDRSE was constant. The preliminary result was a 320 K system temperature, with an aperture efficiency of 0.4; this result was used to derive correlated fluxes. By comparison, the gain to system temperature ratios of the 64-m ground antennas were 4000 to 5000 times that of the TDRSE telescope.

For quasar 1730−130, the correlated flux density dropped rapidly with increasing baseline length, from 1.8 ± 0.2 janskys (Jy) on a 7300-km projected baseline to 0.3 ± 0.1 Jy for a 17,800-km projected baseline (Fig. 2). For quasar 1510−089, the falloff was less dramatic: 0.78 ± 0.1 Jy on a 7300-km projected baseline and 0.32 ± 0.1 Jy on a 15,500-km projected baseline. We did not have a ground baseline on quasar 1741−038, but the correlated flux on a 13,000-km projected baseline was 1.2 ± 0.4 Jy. For any VLBI observations with TDRSS, only a few baseline orientations will be available. Therefore, only rudimentary details of the structure of these radio sources can be determined. For proper mapping, a more sensitive telescope in an optimized orbit is needed.

We have demonstrated that correlation can be achieved in a VLBI experiment, with a free-orbiting satellite used as one of the observing stations in the interferometer. Corrections of the phase and delay variations along the spacecraft-ground link and along the directions to the radio sources were sufficiently accurate to achieve 84% coherence for integrations of 700 seconds in length. Fringes were detected on projected baselines in excess of 1 earth diameter for all three sources. This experiment, which used an operational TDRSS spacecraft as an orbiting VLBI telescope, demonstrates the feasibility and potential of using a dedicated observatory in space.

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12. We thank the many individuals at the several institutions involved who provided useful suggestions and help with the experiment planning and the data acquisition and reduction. The efforts of the entire TDRSS organization in making it possible to use the TDRSE spacecraft in a new and untested mode was critical to the success of the demonstration. We specifically recognize the encouragement and support provided by H. Fosque, G. Newton, G. Resch, J. G. Smith, N. A. Renzetti, V. True, and W. Wells. We also thank the National Radio Astronomy Observatory (operated by Associated Universities, Inc., under contract with the National Science Foundation) for the loan of the Mark III recording system and hydrogen maser from the Very Large Array. The VLBI program at the Haystack Observatory is jointly supported by NASA and the National Science Foundation. A portion of this research was performed by the Jet Propulsion Laboratory, California Institute of Technology under contract with NASA.

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Lightning Strike Fusion: Extreme Reduction and Metal-Silicate Liquid Immiscibility

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A glassy fulgurite, formed recently on a morainal ridge in southeastern Michigan, contains micrometer- to centimeter-sized metallic globules rich in native silicon, which unmixed from a silica-rich liquid. The unusual character of these globules and their potential for elucidating conditions of fulgurite formation prompted further study. Thermodynamic calculations indicate that temperatures in excess of 2000 K and reducing conditions approaching those of the SiO_2-Si buffer were needed to form the coexisting metallic and silicate liquids. The phases produced are among the most highly reduced naturally occurring materials known. Some occurrences of other highly reduced minerals may also be due to lightning strike reduction. Extreme reduction and volatilization may also occur during high-temperature events such as lightning strikes in presolar nebulae and impacts of extraterrestrial bodies. As a result of scavenging of platinum-group elements by highly reduced metallic liquids, geochemical anomalies associated with the Cretaceous-Tertiary boundary may have a significant terrestrial component even if produced through bolide impact.

LIGHTNING IS AN EXCEEDINGLY common terrestrial phenomenon, occurring at a rate of 100 sec^{-1} around the earth, with an average energy release of 10^9 J for each flash (*1*). Air temperatures momentarily reach 10,000 K and, in some instances, 30,000 K (*2*). Measured peak currents of 10 kA and as much as 200 kA are reached in microseconds (*3*). Under such conditions, it is not surprising that solids may melt or vaporize, or both, when struck by lightning.

Fulgurites (products of lightning strike fusion) are abundant and widely distributed on the surface of the earth (*4*) and have attracted scientific interest since the expeditions of von Humboldt and Darwin (*5*). Fulgurites are commonly formed in sand but are also reported in rock and soil (*6*). Most sand fulgurites are tubules only a few centimeters in diameter, but they may extend laterally or vertically for up to 10 m. Rock and soil fulgurites are highly vesicular and show only occasional development of crude tubelike shapes. Only a few workers have systematically analyzed the resultant silicate glasses, which are heterogeneous on a micrometer scale (*6, 7*). Comparison of glass chemistries with initial rock compositions sometimes (*6*), though not always (*7*), reveals differential volatilization of major

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