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RESULTS AND COMMUNICATIONS CONSIDERATIONS OF THE VERY LONG BASELINE INTERFEROMETRY DEMONSTRATION USING THE TRACKING AND DATA RELAY SATELLITE SYSTEM†

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Abstract—A desire for increased angular resolution at microwave frequencies has led to the development of radio telescopes with very large effective apertures. Very long baseline interferometry (VLBI) has made it possible to synthesize telescopes with effective dimensions of a large fraction of an Earth diameter. By using a satellite-borne radio telescope as part of a VLBI array, the dimensions of the Earth cease to be a limitation. The use of a satellite VLBI telescope puts stringent requirements on the communication links between the spacecraft and the ground. A demonstration was performed to show that the orbiting VLBI (OVLBI) concept is feasible. The Tracking and Data Relay Satellite System (TDRSS) was used as the orbiting element of the VLBI demonstration. Stability tests were made before the observations to determine the suitability of the TDRSS for OVLBI use. The first successful OVLBI observations were performed using the 64-m antenna observatories of NASA's Deep Space Network in Tidbinbilla, Australia, and of the Institute for Space and Astronautical Science in Usuda, Japan in conjunction with the TDRSS. Data from three quasars were successfully correlated at the Haystack Observatory in Westford, Mass.; the results were used to deduce the system performance.

1. INTRODUCTION

The desire for higher angular resolution has been a consistent thrust in astronomy. In the field of radio astronomy, this has resulted in the construction of ever larger antennas as exemplified by the 100-m steerable antenna at Bonn, F.R.G. and the 300-m spherical segment antenna at Arecibo, Puerto Rico. These antennas have reached the practical limit for single-aperture resolution in the microwave portion of the electromagnetic spectrum. Any greater angular resolution requires the use of interferometers. The Very Large Array (VLA) and the MERLIN telescope are examples of connected-element interferometers that have angular resolution equivalent to antennas with diameters of tens to hundreds of kilometers. Figure 1 is a simplified diagram of a connected-element interferometer. One frequency standard is used to drive the local oscillators of all the antenna receivers. The video data streams go to a correlator where they are processed in real time.

Because it is not feasible to connect elements of interferometers with baselines of thousands of kilometers, the technique of very long baseline interferometry (VLBI) was developed[1], as illustrated in Fig. 2. Each radio telescope is equipped with an independent frequency standard and a wideband video recorder. The magnetic tapes are shipped to a central correlator facility for later processing. The local oscillator of each radio telescope must be stable to a very small fraction of a radian over an integration period of 30–800 s.

VLBI has proved to be an extremely effective method for obtaining very high resolution maps of compact celestial objects. Common visibility considerations limit the maximum terrestrial baselines to roughly 0.8 Earth diameters. Orbiting radio telescopes, as in Fig. 3, offer the possibility of removing this constraint[2–4].

2. SATELLITE VLBI MISSIONS

Dedicated spacecraft missions for performing VLBI observation programs are being actively pursued by several agencies. The European Space

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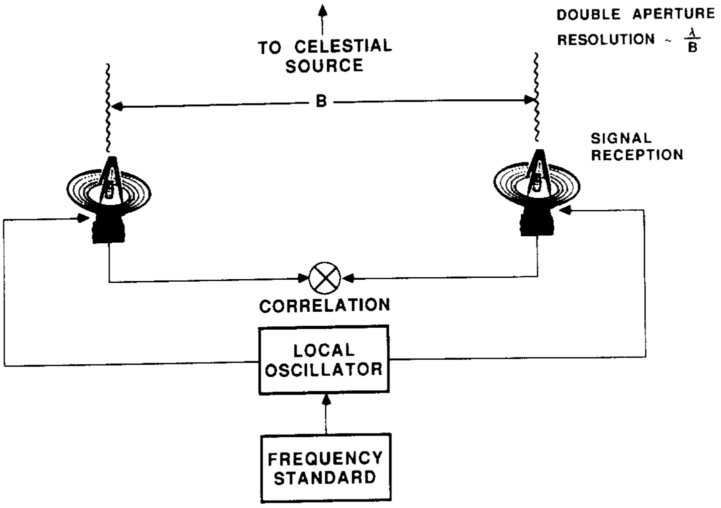

Fig. 1. Connected-element interferometer.

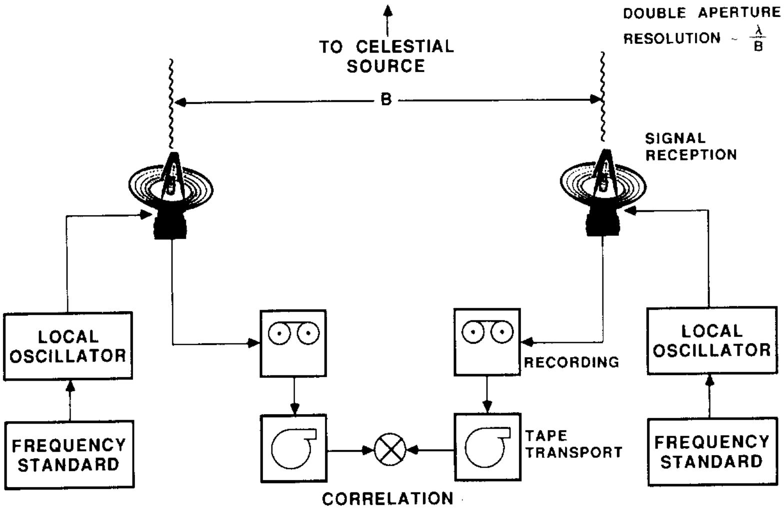

Fig. 2. Very long baseline interferometry.

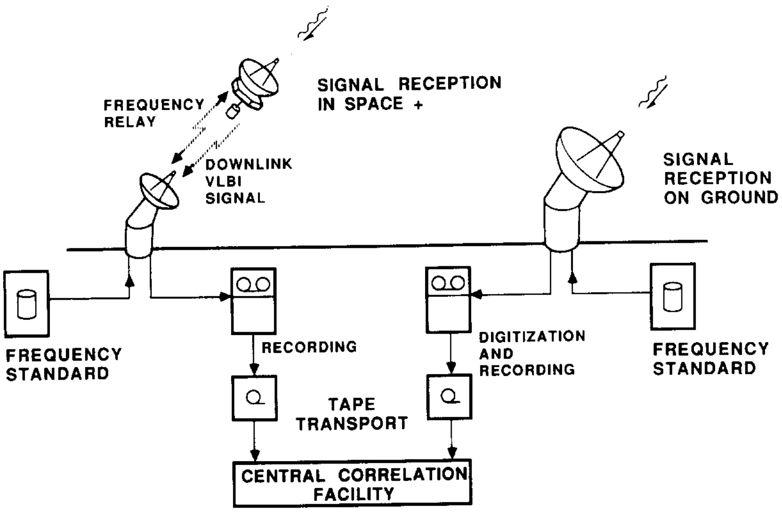

Fig. 3. Space VLBI system.

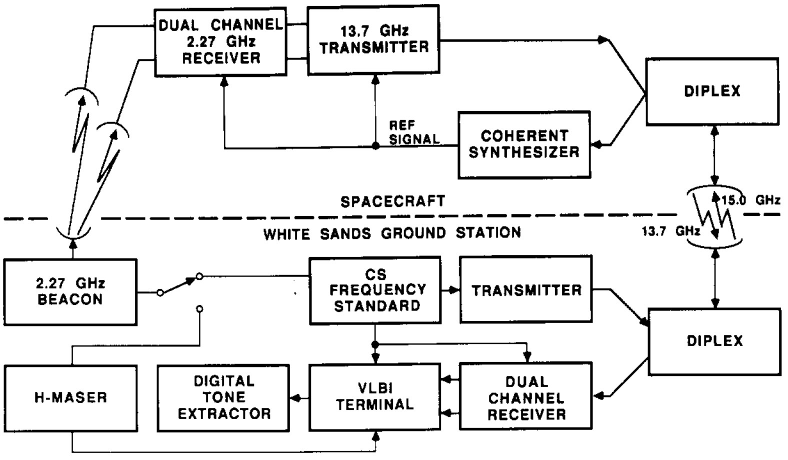

Fig. 4. Stability test configuration.

Agency (ESA) and the U.S. National Aeronautics and Space Administration (NASA) are cooperating on a program called QUASAT[5,6]. The Soviet Union is engaged in their RADIOASTRON mission[7], and a consortium in Japan is studying an orbiting VLBI (OVLBI) mission[8].

The QUASAT mission will use an orbiting radio telescope observing celestial objects simultaneously with a ground array. The spacecraft will have its frequency reference transferred from ground-based hydrogen masers via a microwave uplink. The astronomical data will be relayed back to the ground on a wideband downlink, to be recorded on a VLBI terminal and then shipped to a central processing facility. There the spacecraft data will be correlated with data from the ground observatories.

3. OVLBI DEMONSTRATION

An OVLBI demonstration using an existing satellite was considered to be a test of the technical concept and a probe of the scientific potential[9].

The Tracking and Data Relay Satellite System (TDRSS) appeared to have all the essential prerequisites for an OVLBI demonstration. TDRSS was designed to relay data between satellites in low Earth orbit and the ground via relay satellites in geosynchronous orbit[10,11]. At present, only the eastern satellite (TDRSE) has been deployed; it is at 41 deg W. longitude. Two steerable 4.9-m diameter antennas, which operate at 2.3 and 15 GHz, are used for communication with satellites. A smaller 13- to 15-GHz antenna is used to communicate with the ground control station at White Sands, N. Mex. All the oscillators on the spacecraft are coherent with an uplink pilot tone derived from a cesium frequency standard at White Sands. Radiometric data received through the 4.9-m antenna are amplified and coherently frequency translated to the 14-GHz band for transmission to the ground.

Because the field of view of the TDRSE was restricted to a relatively small region near the nadir and because of the limited sensitivity of the TDRSE, the choice of ground observatories was limited. The two most suitable observatories were the NASA Deep Space Network 64-m antenna at Tidbinbilla, Australia, and the Institute for Space and Astronautical Science 64-m antenna at Usuda, Japan. The 26-m antenna of the Radio Research Laboratory at Kashima, Japan was used to verify the performance of the two more sensitive ground telescopes.

The two major communication issues were the following:

(1) The capability of transferring the ground-based frequency standard to the spacecraft with the required phase stability.

(2) The coherent transfer of the radiometric data from the spacecraft through the ground station to the VLBI recording terminal.

In December 1985, a series of tests were conducted using TDRSS. Figure 4 is a block diagram of the configuration. A pilot tone at 15 GHz from White Sands is always used to coherently drive all the oscillators on the spacecraft. A 2.27-GHz signal, derived from either a cesium or hydrogen maser frequency standard, was transmitted from a ground station antenna through both 4.9-m spacecraft antennas where it was received, amplified, frequency translated to 13.7 GHz, and transmitted back to the ground station. The tones from each channel were received, separated, digitally processed, and recorded for further analysis.

The upper left portion of Fig. 5 shows the phase residual of the received tone from one channel compared to the value predicted from the ephemeris. The upper right portion of Fig. 5 shows the coherence of a single channel as a function of integration time. The single channel peak-to-peak variation is approximately ±0.4 cycles, and the coherence with an integration time of 1000 s is approximately 0.6, which is marginal for OVLBI. The differential phase stabilities

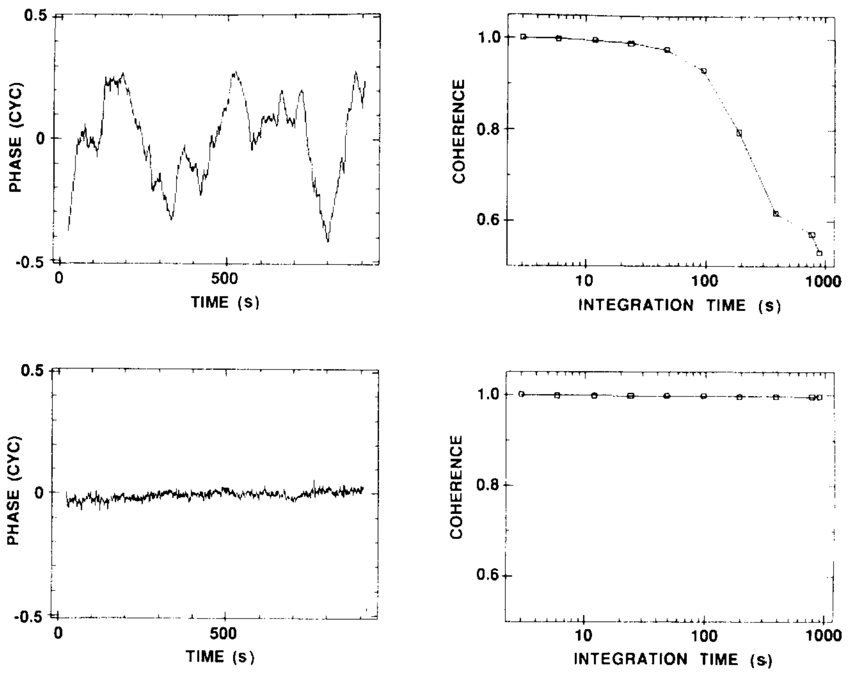

Fig. 5. Phase stability and coherence results: single channel (top) and dual channel (bottom).

of the two channels are compared in the lower left panel of Fig. 5, and the resulting coherence is shown in the lower right panel. The differential stability between the two 2.27-GHz channels can be seen to be excellent.

In another test, both 4.9-m antennas were used together as a connected-element interferometric radiometer (Fig. 6). The local oscillators were offset from each other by approximately one kHz. Using this technique, it was possible to obtain a usable beat in approximately 10 s while observing Orion A at a frequency of 2.25 GHz. The antenna-pointing software modifications were validated, and an approximate value for sensitivity was obtained. This is the first use of a connected-element microwave radiometric interferometer in space.

A second sensitivity calibration method was found to be more reliable. Selected quasars were observed by VLBI from Owens Valley, California; Tidbinbilla, Australia; and Usuda, Japan on 19 May and 2 June, 1986 at 2.3 GHz. This calibration method took advantage of the fact that baselines between TDRSE

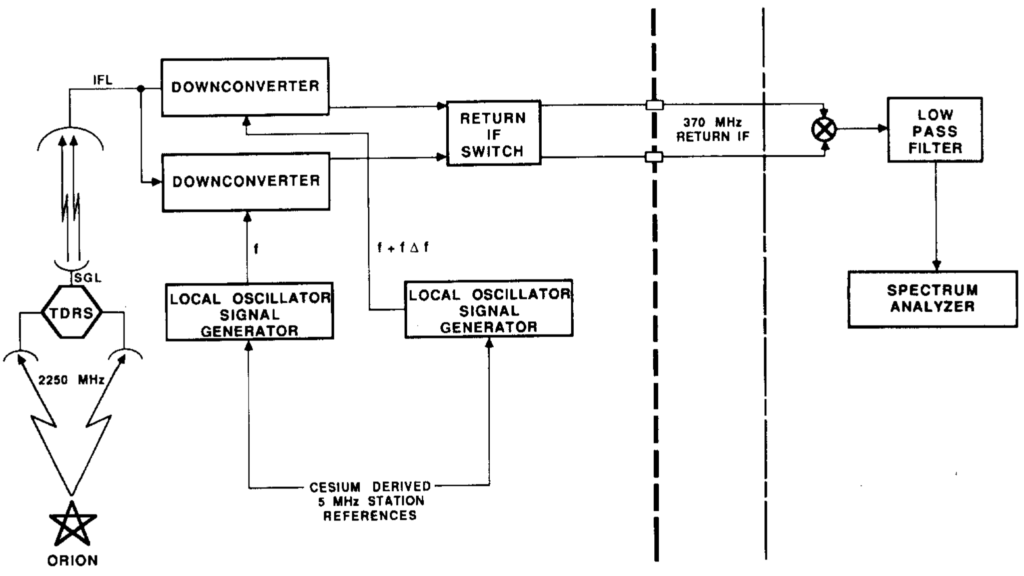

Fig. 6. Orbiting connected-element interferometer.

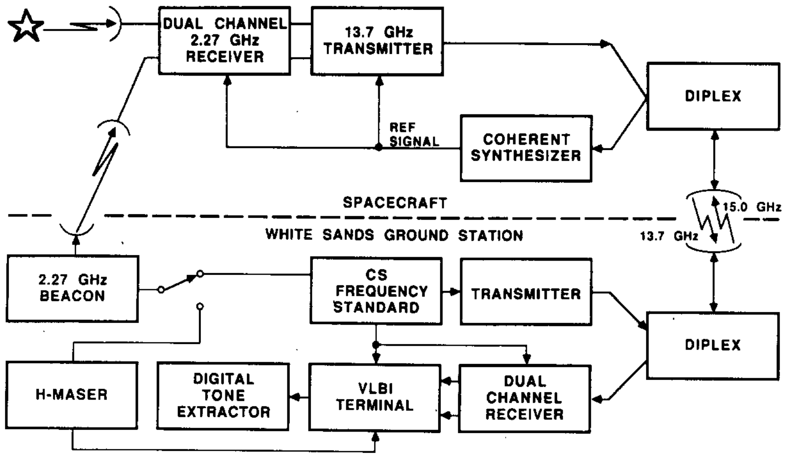

Fig. 7. Astronomical observation configuration.

and Tidbinbilla were at certain times similar to the spacings on baselines between Australia and Japan, or between Australia and California for the same source. The correlated flux density at the two available "crossing points" was later used with measured correlation coefficients on baselines to TDRSE to determine the ratio of the antenna gain to the system temperature.

4. TDRSS OVLBI OBSERVATIONS

As a result of the phase stability tests, it was decided to use one 4.9-m antenna for quasar observations while the second 4.9-m antenna received a phase reference tone from White Sands (Fig. 7). Each of the 4.9-m channels was separately amplified and frequency translated to the 14-GHz band for transmission to White Sands. At the ground station, the signals were separated into individual channels and translated to an intermediate frequency. The radiometric data were processed and recorded by a Mark III VLBI terminal. The cesium frequency standard and beacon tones were compared to the hydrogen maser output, and the phase residuals were digitally recorded.

The data tapes were processed on the Mark IIIA VLBI correlator at the Haystack Observatory in Massachusetts[12]. Modifications to the standard correlator software were required to correlate data from an orbiting observatory. The signal delay correction for TDRSE has one component due to the arrival time of the wavefront from the source and a second component due to the link delay of the downlink from TDRSE to White Sands. The geometric phase consists of geometric delay multiplied by the observing frequency. The link phase is the one-way link delay multiplied by a frequency of 25 GHz (twice the downlink frequency minus the observing frequency).

Successful OVLBI observations were made of 1510–089 on 29 July and of 1730–130 and 1741–038 on 2 August 1986. The ability to correct for orbital motion using the orbit ephemeris and link phase measurements was validated. Using the orbital corrections and the corrections for the cesium standard, all six scans of valid data were correlated. The average coherence obtained between TDRSE and the ground stations for the quasars 1730–130 and 1740–038 is plotted as a function of integration time (Fig. 8). Curve A shows the coherence using only the ephemeris data to correct for spacecraft motion. Curve B also includes a correction for the White Sands frequency standard, that correction being derived by comparing the cesium to a more stable hydrogen maser. Curve C further includes improved corrections for the White Sands–TDRSE link based on the 2.27-GHz ground beacon signal tracked by TDRSE.

Using the "crossing point calibrations," 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 1730–130, the correlated flux density dropped rapidly with increasing baseline length, from 1.8 ± 0.2

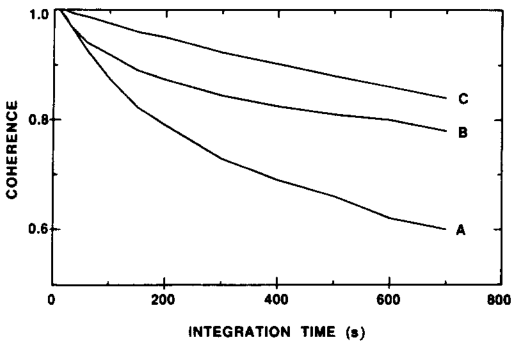

Fig. 8. TDRSS OVLBI coherence results.

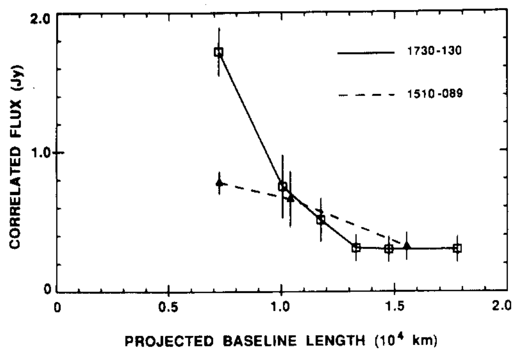

Fig. 9. TDRSS OVLBI correlated flux results.

Jansky (Jy) on a 7300-km projected baseline to 0.3 ± 0.1 Jy for a 17,800-km projected baseline (Fig. 9). For 1510–089, the decrease was less dramatic: 0.78 ± 0.1 Jy on a 7300-km projected baseline and 0.32 ± 0.1 on a 15,500-km projected baseline. We did not have a ground baseline on 1741–038, but the correlated flux on a 13,000-km projected baseline was 1.2 ± 0.4 Jy.

As viewed from the radio source, an interferometer has an effective spacing and orientation determined by its projection perpendicular to the direction to the source. The projected interferometer spacing measures a particular spatial frequency of the Fourier transform of the intensity distribution of the source. This can be represented as a plot on the *u*-*v* plane shown in Fig. 10. The longest observed baseline was 17,800 km (on quasar 1730–130 between TDRSE and Usuda), about 1.4 Earth diameters. On this baseline, the approximate fringe spacing is 1.5 mas.

For any VLBI observations with TDRSS, only a few baseline orientations will be available. Therefore, only rudimentary details of the source can be determined, as shown in a *u*-*v* plot for 1730–130 (Fig. 11). For comparison, a *u*-*v* plot for a simulation of QUASAT and the U.S. Very Long Baseline Array (VLBA) plus Tidbinbilla, Australia and Itapetinga, Brazil for a duration of 48 h is shown in Fig. 12.

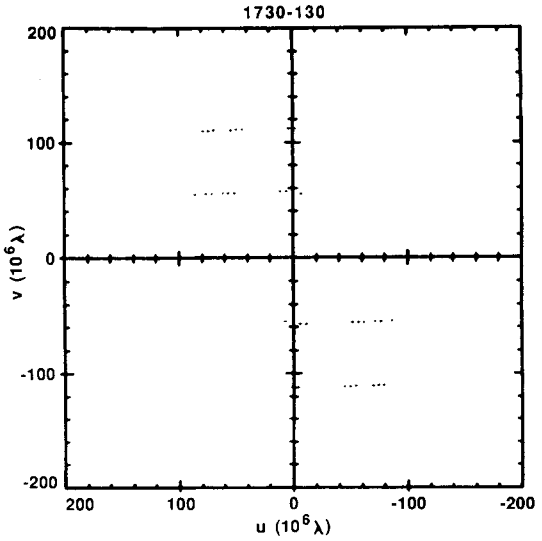

Fig. 11. *u*-*v* plot from TDRSS; Tidbinbilla, Australia; and Usuda, Japan.

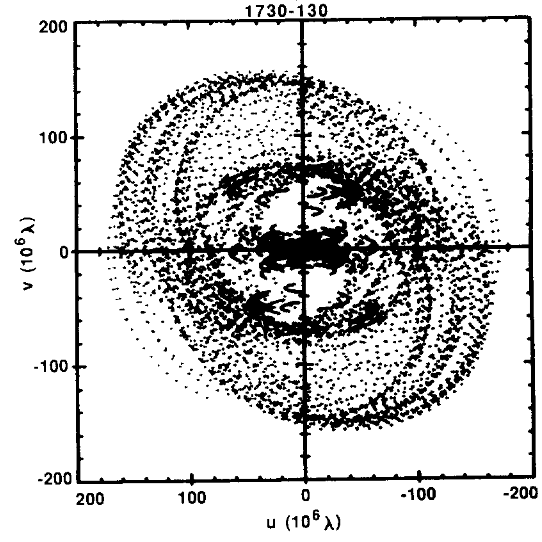

Fig. 12. *u*-*v* plot of a simulated measurement by QUASAT; VLBA; Tidbinvilla, Australia; and Itapetinga, Brazil.

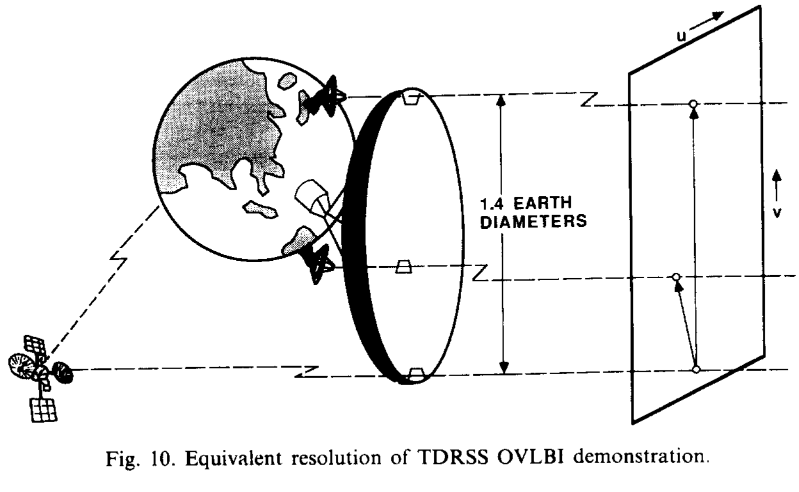

Fig. 10. Equivalent resolution of TDRSS OVLBI demonstration.

5. FUTURE OBSERVATIONS

Plans are being made for additional TDRSS OVLBI observations in January 1987. It is expected that the limits on the TDRSE antenna field of view will be increased so that projected baselines of approximately two Earth diameters will be possible. Observations of additional sources will be made, and the calibration of the TDRSE gain to system temperature ratio will be improved through the use of multiple crossing points.

6. CONCLUSION

Using an orbiting satellite, OVLBI fringes have been achieved. A coherence of 0.84 has been obtained for an integration time of 700 s by correcting for phase and delay variations. Baselines in excess of an Earth diameter yielded fringes for all three quasars observed. The feasibility of and potential for using a dedicated VLBI observatory in space has been demonstrated.

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