ORBITING VLBI: A SURVEY[+]

Bernard F. Burke
Massachusetts Institute of Technology
Cambridge, Massachusetts

ASTRACT

The Very-Long-Baseline Interferometry technique is not limited by the size of the Earth. Near-Earth-orbiting space vehicles can carry radio telescopes that can serve as VLBI stations using existing technology. By proper use of ground VLB arrays, a single orbiting VLBI satellite can yield radio maps with 2-dimensional coverage and high dynamic range at all declinations. A single orbiter can be used out to orbits that yield an effective aperture greater than two Earth diameters. Interstellar scintillations are a limiting factor only in the micro-arc-second range.

I. SUMMARY

Radio Interferometry has provided ever-increasing angular resolution, progressing from the first hard-wired, two-element systems through radio-linked, multiantenna arrays, and culminating in Very-Long-Baseline Interferometry, for which the Earth's size is the current limit. At the same time, a parallel requirement for complete Fourier coverage has generally developed, since rough angular sizes are useful as a first guide, but eventually maps of high dynamic range are needed to settle the crucial questions. The VLA was developed in response to this need, and a strong demonstration of the usefulness of this capability is illustrated by Perley's recent Cygnus A maps, which show in striking detail the nature of the source and reveal, for the first time, the relativistic beam that powers the double-lobed radio source. The necessary high dynamic range is only possible when there is complete coverage of the Fourier transform.

When orbiting radio telescopes were first contemplated as a means of extending VLBI baselines beyond the confines of the Earth, it quickly became apparent that there were three significant advantages to the technique: firstly, the desired improvement in angular resolution was achieved, secondly, it would be possible, using the orbiting VLB station in conjunction with ground-based arrays, to obtain "snapshots"

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of rapidly changing sources such as SS433 and Cygnus X-3 that were otherwise ambiguously studied by Earth-rotation synthesis; thirdly, a single orbiting VLB station in an inclined orbit, used in conjunction with several ground stations, naturally gave complete coverage of the u-v plane for all declinations. Finally, it has become evident that ground-based VLB arrays and orbiting systems are essentially complementary.

The concept of Orbiting VLBI, OVLBI for short, originated in several places within the first few years of VLBI development. The subject was discussed on two occasions in 1971 at Byurakhan, in conversations that involved N.S. Kardashev, J.S. Shlovskii, L.I. Matveyenko, K.I. Kellermann, and B.F. Burke. Transformation from concepts to proposals occurred in the 1970's. Work was started in 1973 by a group under N.S. Kardashev, using the Salyut space station as a mount for a 10 meter antenna, to be used at 75 cm wavelengths. In 1976, a group headed by B.F. Burke proposed the use of a 4-m telescope on the Spacelab 2 mission: this was then re-proposed in 1978 with the participation of a broadly-based team consisting of T.A. Clark, M.H. Cohen, K. Johnston, K.I. Kellermann, J.M. Moran, R. Preston, A.E.E. Rogers, and I.I. Shapiro, with B.F. Burke as principal investigator. The project was jointly submitted by MIT, JPL, and Goddard Space Flight Center. The antenna, a 3.7-m carbon-epoxy paraboloid, would have been used at wavelengths of 3.8 and 18 cm.

In 1979, the first international proposal was made by B.F. Burke and N.S. Kardashev, who proposed to make use of NASA's VOIR spacecraft during the cruise phase of its mission to study the plasma fluctuations of the interstellar medium by making VLBI observations of pulsars. The spacecraft had been planned to use a 5-m paraboloid for wide-band telemetry, and was to have a high-capacity memory on board: Kardashev and Burke proposed to use the paraboloid first in receiving mode to store pulsar signals on board, and then to re-transmit the data to Earth. Subsequent re-scoping of the mission eliminated the VLB possibility, but VLBI astronomers should remain alert to such possibilities in the future.

More recently, several studies have been published, taking a detailed look at the potential problems and technical feasibility of OVLBI. A brief paper on OVLBI was presented in 1976 by Preston, Hagar, and Finley at a meeting of the American Astromonical Society. An early study by V.I. Bujakas *et al*. was presented in 1973 to the 23rd IAF Congress, giving the outline of a proposed "infinitely built-up space radio telescope", together with an analysis of the potential for OVLBI. In 1980, Kardashev, Pogrebenko, and Tsarevsky published an analysis of OVLBI with million-kilometer baselines by Andrezanov and Kardashev(1981). A detailed analysis of a Space Shuttle mission carrying a 50-m paraboloid was carried out by a Technical Working Group composed of scientists and engineers from Marshall Space Center, Jet Propulsion Laboratory, Naval Research Laboratory, Draper Laboratory, and the Massachusetts Institute of Technology, the report being published in 1982. A related report, investigating the general capabilities of the Space Shuttle for OVLBI and the technical applicability of existing VLB systems, was published in 1982 by Roberts, Doxsey, and Burke.

The major planning exercises known to be under way at the present time are:

1) The Shuttle-attached OVLBI studies of NASA, now concentrating on antennas in the 15-meter size range.

2) The QUASAT concept, originated at JPL and now the subject of a joint study by NASA and ESA, currently conceived of as a free-flying 15-meter paraboloid in an eccentric orbit, using ground-based VLB arrays to fill in the holes in the u-v plane. Frequently coverage would range from 1.6 to 23 GHz.

3) A low-Earth-orbit mission planned by the Soviet Academy of Sciences, comprising a 30-m paraboloid for use at λ = 18 cm.

4) A million-kilometer eccentric-orbit mission of the Soviet Academy of Sciences, utilizing a 10-m antenna at 18 cm wavelength.

II. TECHNICAL AND SCIENTIFIC CONSIDERATIONS

The work of the NASA Technical Working Group provides a useful reference point for the guidance of future studies. A particular mission was studied in detail: a 50-meter antenna, to be carried in low-Earth-orbit by the Space Shuttle. The concept is illustrated in Figure 1. The questions addressed were (1) Could such an antenna be

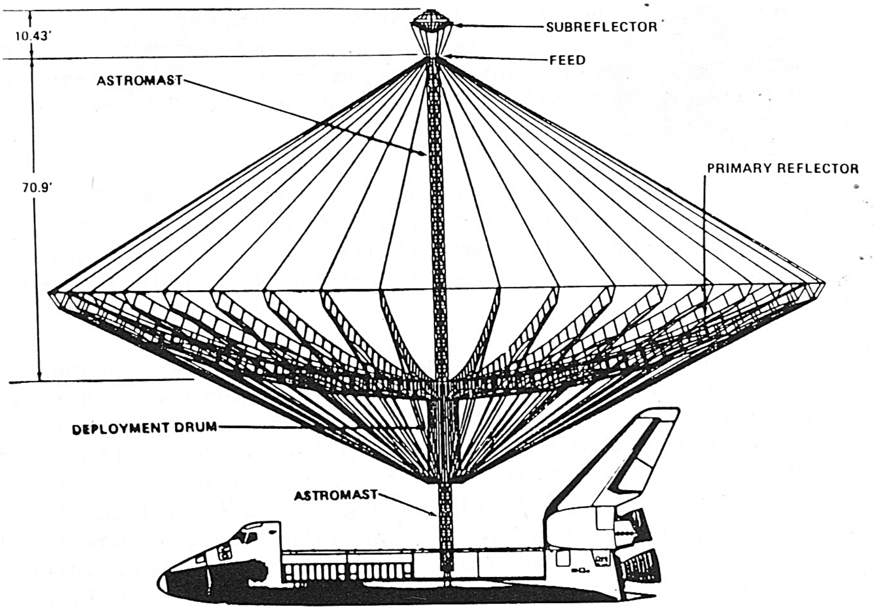

Figure 1. The 50-meter OVLBI concept, shown deployed from the Space Shuttle. (MSC)

built to work at 3 cm wavelength; (2) Could the antenna system be pointed with sufficient accuracy to serve OVLBI purposes; (3) Were the mechanical properties of the system stable; (4) Were the required electronic systems technically ready; (5) Could the data flow be handled; (6) Could the Mark III VLB system be used to reduce the data; and (7) Was the scientific program viable? The answers to all questions were favorable.

The required electrical performace of the antenna turned out to be well matched to the current state-of-the-art. Presently, the best achievable ratio of antenna diameter to rms tolerance, D/ε is 1.5×10^4. This implies that an antenna of 50-m diameter would reach its Ruze maximum in gain at 10.2 GHz. Ordinarily, one might suppose that the Ruze maximum, where the antenna efficiency is $(1/4\pi)$ of its ideal value, imposes too high a price. For an interferometer pair, however, the effective area is the geometric mean of the two antenna areas, so the penalty paid by having one antenna at the Ruze maximum is only -2 db, a price well worth the ability to make X-band observations.

The pointing requirements appeared initially to be severe; the solution was to recognize that the antenna pointing error had to be known, and then simply entered into the reduction procedure. The dynamical properties of the antenna were a challenging problem, since antenna pointing was complicated by the coupling between the large structure and the Space Shuttle to which it was attached. Simulation studies by Draper Laboratory showed that the potential instabilities could be controlled by proper specification of standard Space Shuttle control parameters. The work served as an example of dynamic interaction of the Shuttle flight control system with a deployed payload, Sackett and Kirchway, 1982 AIAA Guidance and Control Conference, Aug. 9-11, San Diego, CA.

There were few problems concerning electronics, data handling, and data reduction. Some software modifications were needed for the Mark III VLB data system, but no fundamental difficulties were found. The conclusion was that there was a complete state of technical readiness for OVLBI.

The 50-m radio telescope exercise was not likely to become an active mission, but served as a useful planning exercise. There was clear realization in the Technical Working Group that there were two concepts that were far more realistic: 15-m low-Earth orbiting payload on a space shuttle, a space platform, or a free-flying satellite. The QUASAT concept, put together jointly by a group of US and European scientists, is an example of a free-flying satellite that makes full use of the ground-based VLBI arrays. It is currently under intensive study, and in this conference is described in detail by Schilizzi et al.

III GENERAL MISSION CONSIDERATIONS

Given the technical feasibility of operating a VLBI terminal in space, one might still be wary of the problems that arise from the rapid motion of the spacecraft. The concern is easily answered, however: even normal ground-based VLBI stations are moving at 1500 km/sec because of the Earth's rotation, a problem that is routinely solved. A spacecraft in low-Earth orbit moves at 16 times this velocity, giving fringe rates (i.e. Doppler shifts) that are only slightly more than an order of magnitude higher than those normally encountered in practice. The additional complication can be compared to the changes that occured over a decade ago when VLB frequencies moved upward from L-band to K-band.

The low-Earth orbit mission (such as the shuttle-based concept) and mid-orbit mission (such as QUASAT) cover the u-v plane with such density that truly high quality maps should result from OVLBI observations. The improvement over ground-based arrays is demonstrated by the comparison in Figure 2 between the capability of the U.S., VLB and a single low-Earth orbit OVLBI station used in conjunction with the ground-based array. A few basic principles determine the system capabilities; the best angular resolution in the low-Earth orbit case is given when the source under observation is normal to the orbital plane, and complete coverage requires that the OVLBI satellite orbit passes over the ground station at some point. D. Roberts showed that an ideal orbital inclination exists: if one defines a figure of merit as the number of beamwidths summed over the entire sky, the optimum orbital inclination is 57°, a convenient orbit for launching such vehicles. The optimum is broad, so the exact inclination is not critical, but neither polar nor equatorial orbits have desirable characteristics.

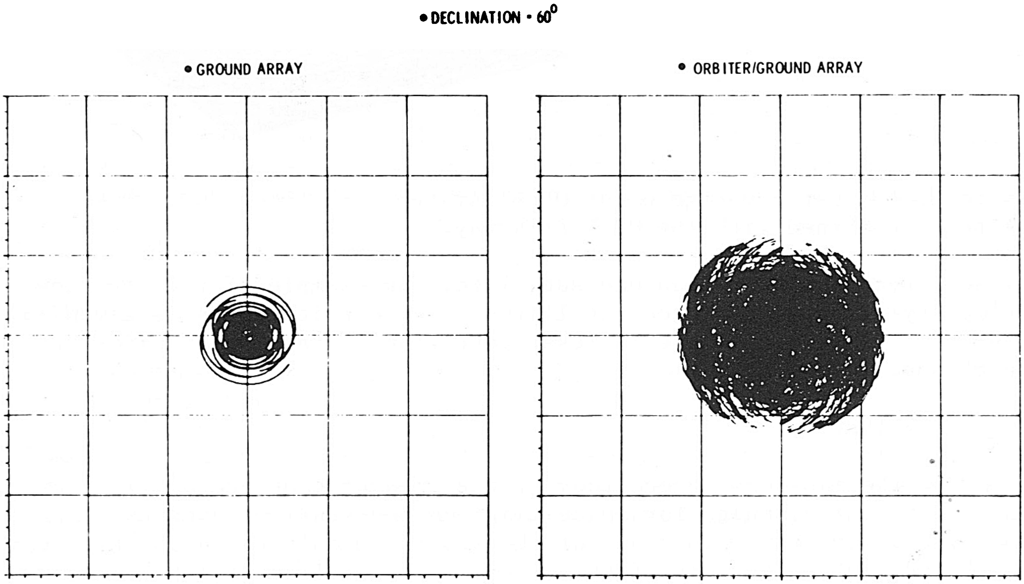

Figure 2. Comparison of u-v coverage by the US VLB Array, compared to the coverage when combined with a low-Earth-orbit OVLBI terminal.

The QUASAT studies now underway indicate that optimal orbits can also be specified for the mid-orbit case. When one goes to still higher orbits, however, holes develop in the u-v coverage. Both the studies of Kardashev, Pogrebenko, and Tsarevsky and of Roberts, Doxsey, and Burke concluded that high-quality mapping for orbits in the 10^5 - 10^6 km range required more than one satellite. An example of the coverage yielded by a system of three satellites in eccentric orbits is given in Figure 3. The u-v coverage is less dense than in the low-and mid-Earth orbit case.

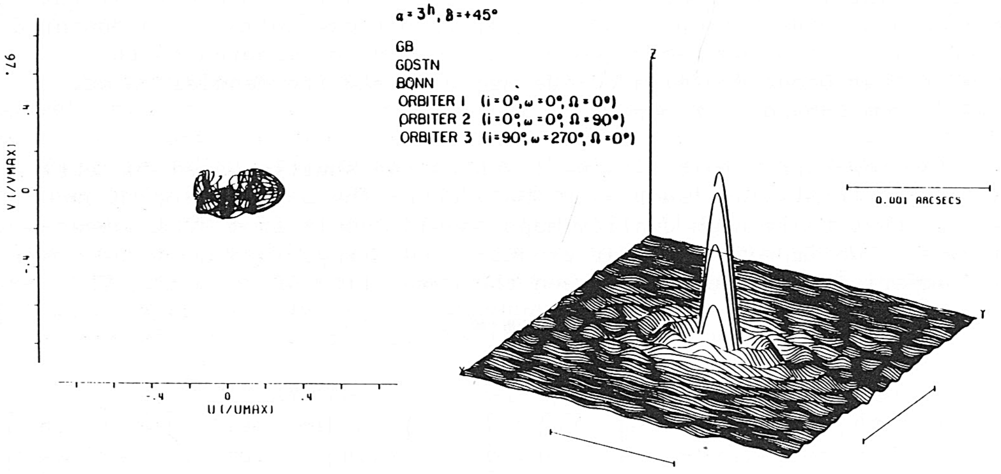

Figure 3. Fourier coverage of an OVLBI system with three 200,000-km orbiters, combined with the US VLBI array.

IV. THE FUTURE

Even the missions under study at the present time are a number of years away, but planning for space missions necessarily involves long lead times. These missions are of the scale commonly known as "Explorer Class" and involve budgets of the order of 100 million dollars, a class referred to as "moderate missions" in the recent Astronomy Survey Committee Report by G. Field et al. If one assumes that these initiatives are successful, however, it is not too soon to contemplate the next step.

A variety of arguments lead to the expectation that interstellar scintillation and scattering is not a major limitation for orbit reaching to a million kilometers. At galactic latitudes above 20°, the mean scattering angle is of the order of 10^{-6} arc-seconds at 1 cm wavelength, or half the resolution of the million-km baseline referred to above. One therefore concludes that a million kilometer OVLBI system would not be seeing limited at wavelengths of the order of 2-4cm and shorter. A more conservative system, composed of 3 satellites in 200,000 km orbits, would function at L-band; the ultimate choice of scale must await further discussion. The project would certainly be an international one, and could be a viable mission before the turn of the millenium.

A look into the still more distant future shows exciting prospects within the framework of our present knowledge of physics. Interstellar scintillation is indeed a problem, if interferometry over interplanetary distances is contemplated. Kardashev and Burke, in the VOIR proposal, drew on recent image-restoration work that shows promise for such long baselines. Some of the possible goals of interplanetary VLBI are dramatic: the entire universe can be brought within the near field of a 1 cm interferometer system that spans 10 astronomical units; the emitting region of pulsars could be resolved; and radio holography might be performed on objects like the Crab Nebula, giving 3-dimensional representations. The methods would require very large apertures, such as the "infinitely built-up space radio telescope" of Bujakis et al., in order to achieve the necessary signal-to-noise ratio. The required technology is beyond the current state-of-the-art in some areas, and the mission costs are formidable.

On a more practical note, the main focus at present must certainly be on the modest missions. It is not too soon, however, to contemplate the next step: the 10^5 to 10^6 km missions that could take place in the later 1990's. A mission model could be developed as a world-wide collaborative effort, and its certain success would lay the groundwork for the work of another generation in another millenium.

HISTORICAL NOTE

Prior to the Byurakhan conversations, the subject of OVLBI had been discussed in the USSR and the USA. In 1970, a Space Science Board study on priorities in space science took place at Woods Hole, with the astronomy panel recommending that an exploratory "Very Long Baseline Interferometer" be built. There were similar proposals made by Soviet radio astronomers at about the same time.

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