

An Affordable Advanced Space VLBI Mission

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Abstract. We have defined an affordable Advanced Space VLBI mission that would be a successor to the VSOP and RadioAstron missions scheduled to take place in the mid-1990s. The major design goal of this mission would be to improve the sensitivity over the 1990s missions by a factor of 30–100 at frequencies between 1.6 and 22 GHz, with reasonable performance also available at 43 GHz. Design parameters for the 1.6- to 22-GHz range are (1) a 30-m space antenna with 60% aperture efficiency; (2) a data rate of at least 1 Gbit/s; and (3) a system temperature of 10 K. Each of these three would provide a factor of 3–5 improvement over the interferometer sensitivity for VSOP and RadioAstron, yielding a total sensitivity improvement of a factor of 60 at 22 GHz. On a baseline to a VLBA antenna, the interferometer sensitivity would be about 10 times better than for two VLBA antennas recording 128 Mbit/s. The added sensitivity would enable new Space VLBI investigations including (1) high spatial- and time-resolution imaging of weak cores of active galactic nuclei (AGN) such as Seyfert galaxies; (2) imaging of lower-brightness-temperature features in core-dominated AGN; (3) imaging of radio stars in their quiescent states; and (4) observations of a large enough sample of extragalactic H₂O masers to derive an improved value for Hubble's constant.

1. Introduction

The first successful Space VLBI observations were made with the TDRSS satellite between 1986 and 1988 (e.g. LEVY *et al.*, 1986; LINFIELD *et al.*, 1990). In those experiments, observations were made at frequencies of 2.3 and 15 GHz using a 4.9-m-diameter antenna in geosynchronous orbit, as well as large radio telescopes in Australia and Japan. The VSOP (NISHIMURA, 1991) and RadioAstron (KARDASHEV and SLYSH, 1988) Space VLBI missions scheduled for launch in 1996 will provide much improved frequency and u - v coverage. Baselines to RadioAstron will be as long as 80,000 km, a factor of three greater than the longest baselines achieved in the TDRSS demonstrations. The larger radio telescopes (8–10 meters in diameter), lower system temperatures (50–200 K), and 128-Mbit/s data rates will provide significantly enhanced sensitivity at the VSOP and RadioAstron frequencies of 0.3 (RadioAstron only), 1.6, 5, and 22 GHz.

Since VSOP and RadioAstron will begin returning scientific results in 1997, it

is appropriate to begin defining the next-generation mission for the 2000–2010 time period. In an era of limited budgets, it is necessary to plan a mission that would give a significant enhancement in science return with a total cost no more than about \$500 million, possibly with an international collaboration to help share that cost. The work described here is an attempt to begin definition of this affordable future mission.

2. Selection of a Mission Concept

We considered several possible missions as representative of a diverse set of science goals for the next-generation Space VLBI observatory. These mission concepts ranged from a single 50-m-class antenna operating at frequencies as high as 5 GHz to multiple 20-m-class telescopes operating above 90 GHz. Examination of the scientific potential of these missions led to the conclusion that a viable mission had to operate at frequencies at least as high as 22 GHz, and preferably higher. Deployment of multiple spacecraft probably would be too expensive. Therefore, we have selected a future mission based on an orbiting radio telescope in the 30-m class, having high efficiency at frequencies up to 43 GHz, and with some part of the surface adequate for single-dish observations in the 60–70-GHz range.

The concept chosen for the advanced mission amounts to orbiting a VLBA-like antenna in order to achieve sensitivities comparable to those currently attainable on the ground. Results from VSOP and RadioAstron would be used to select the preferred orbit. The proposed mission is similar to the International VLBI Satellite (IVS) proposed several years ago (ESA, 1991), but does not include sensitive operation at 86 and 200 GHz. The design and construction of a 20–30-m telescope with an efficiency near 50% at 86 GHz would be very expensive, and interferometer sensitivity also would be compromised by the limited sensitivities of the ground-based telescopes. Therefore, we have chosen a mission that can make extremely sensitive VLBI observations at frequencies as high as 43 GHz in preference to a less sensitive mission that could do VLBI at higher frequencies.

3. Achievement of High Sensitivity

The crucial design parameters of the proposed mission are those that would give a greatly enhanced sensitivity over VSOP and RadioAstron. These parameters are (1) a 30-m diameter antenna with an aperture efficiency of 60% at 1.6, 5, and 22 GHz (50% at 43 GHz); (2) a system temperature of 10 K for the spaceborne telescope (20 K at 43 GHz); and (3) a data rate of 1 Gbit/s. Table 1 gives a comparison of the 22-GHz observing parameters with those for VSOP; the sensitivity for a baseline to the proposed spacecraft would be nearly 60 times better than for a baseline to VSOP. The improvements in antenna size, system temperature, and data rate make roughly equal contributions and must be concurrent in order to achieve the desired sensitivity enhancement.

Inflatable antenna technology provides the possibility that a 30-m space antenna with a surface good for operation at 22 GHz could be built for well under \$100 million. In 1995, a NASA IN-STEP (In-Space Technology Experiments

Table 1. Interferometer sensitivity at 22 GHz.

Factor	VSOP	Advanced	Improvement
Data rate	128 Mb/s	1024 Mb/s	2.8
Sys. temp.	200 K	10 K	4.5
Aperture	8 m, 40%	30 m, 60%	4.6
Total			58.0

Program) experiment will deploy a 14-m-diameter inflatable reflector structure, with a goal of achieving an r.m.s. surface precision better than 1 mm (FREELAND and BILYEU, 1992). The technology used for this experiment is thought to be adequate for sizes up to about 30 m. Modifications to the inflation procedure and to the milling process for the surface material may be capable of yielding a surface with an r.m.s. accuracy near 0.4 mm, providing the capability for high-aperture-efficiency observations at 43 GHz.

Because the contributions of the Earth and its atmosphere can be eliminated, a radio telescope in space can achieve a lower system temperature than is possible on the ground. POSPIESZALSKI *et al.* (1993) measured a noise temperature of 15 K for a 43-GHz amplifier cooled to an ambient temperature of 18 K, indicating that noise temperatures less than 10 K at 22 GHz are readily achievable. In order to reach total system temperatures of 10 K or less for Space VLBI, it will be necessary to develop long-lived space-qualified cryogenic coolers with capacities of tens of milliwatts that can achieve ambient temperatures of 10 K or lower.

Perhaps the easiest technological step will be to achieve a VLBI data rate of 1 Gbit/s for the future mission. The architecture of the VLBA recording and correlation system is expandable to a maximum data rate of 1 Gbit/s, while the Mark IV system under development by Haystack Observatory and the European VLBI Network should provide 1 Gbit/s by 1996, with possible expansion to 2 Gbit/s. A recent allocation of 0.5 GHz of downlink bandwidth at 40 GHz for space research, including Space VLBI, should enable a downlink of 1 Gbit/s from the proposed mission.

4. Scientific Goals

The affordable advanced Space VLBI mission should achieve significant scientific goals beyond those of VSOP and RadioAstron, as determined by the combination of frequency coverage, resolution, and sensitivity. For the observing parameters given above, and a 5-minute integration time, the r.m.s. sensitivity on a baseline to a 25-m VLBA antenna would be 0.5–0.8 mJy at 1.6–22 GHz, and 0.2–0.3 mJy for a baseline to a 70-m ground radio telescope. By comparison, the r.m.s. sensitivity achievable for a baseline between two 25-m VLBA antennas recording data at 1 Gbit/s would be 2–6 mJy. The enhanced sensitivity for the space-ground baselines is important because of the reduced correlated flux densities expected on

such long baselines.

The outstanding sensitivity available for the proposed mission would enable investigation of entire classes of sources that are not accessible to VSOP and RadioAstron. The enhanced science is described in some detail in the studies of the QUASAT and IVS missions (ESA, 1984, 1991). For example, active galactic nuclei (AGN) with extremely weak radio cores, such as Seyfert galaxies and lobe-dominated radio galaxies, could be investigated. For Seyfert galaxies such as NGC 1068, a 43-GHz observation on a 30,000-km baseline would provide spatial resolution of less than a light-week, considerably smaller than the scale of the broad-line region. In addition, the capability to image the cores of lobe-dominated sources would remove the selection effects inherent in limiting observations only to those objects with strong radio cores.

The AGN with strong cores, such as BL Lacertae objects and many quasars, could be mapped with an unprecedented combination of resolution and sensitivity. This would enable the monitoring of variable core structures on a finer temporal and spatial scale and would permit the lower-surface-brightness features in the jets to be elucidated with space-ground resolution for the first time. Polarization observations of a large number of AGN also would become possible; VSOP and RadioAstron will be capable only of acquiring low-dynamic-range polarization information on about 10–20 sources.

The proposed mission also would provide significant scientific results on other classes of sources. Radio stars could be observed in their quiescent stages, with spatial resolution on scales smaller than the stellar disks. Observations of a large number of pulsars would be possible, enabling studies of interstellar scattering on spatial scales not accessible from the ground, as a function of galactic latitude and time scale. Water masers in starbursts could be observed in a number of galaxies, enabling both an improved determination of Hubble's constant by the method of statistical parallax and a study of the starbursts themselves. Single-dish observations at 60–70 GHz using a small fraction of the antenna surface would enable investigation of atomic oxygen in the interstellar medium and of the Sunyaev-Zel'dovich effect.

5. Conclusion

All the scientific goals described above depend critically on the enhanced sensitivity of the proposed mission. The space technologies required for achievement of very high sensitivity at 1.6–43 GHz are near at hand, and the mission would be much more affordable than one requiring a large telescope operating near 100 GHz. Therefore, we recommend that a future Space VLBI mission such as the one described here should be pursued vigorously to enable the community to take advantage of the scientifically interesting results expected from VSOP and RadioAstron.

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REFERENCES

- ESA (1984): Quasat, a VLBI Observatory in Space, ESA **SP-213**.
- ESA (1991): IVS, An Orbiting Radio Telescope: Report on the Assessment Study, ESA **SCI(91)2**.
- FREELAND, R. E. and BILYEU, G. (1992): IN-STEP inflatable antenna experiment, in 43rd Congress of the International Astronautical Federation, Paper IAF-92-0301.
- KARDASHEV, N. S. and SLYSH, V. I. (1988): The RadioAstron Project, in *The Impact of VLBI on Astrophysics and Geophysics*, IAU Symposium No. 129, pp. 433–440, edited by M. J. Reid and J. M. Moran, Kluwer Academic Publishers, Dordrecht.
- LEVY, G. S. *et al.* (1986): Very long baseline interferometric observations made with an orbiting radio telescope, *Science*, **234**, 187–189.
- LINFIELD, R. P. *et al.* (1990): 15 GHz space VLBI observations using an antenna on a TDRSS satellite, *Astrophysical Journal*, **358**, 350–358.
- NISHIMURA, T. (1991): Overview of VSOP Mission, in *Frontiers of VLBI*, pp. 3–9, edited by H. Hirabayashi, M. Inoue and H. Kobayashi, Universal Academy Press, Tokyo.
- POSPIESZALSKI, M. W., LAKATOSH, W. J., LAI, R., TAN, R. L., STREIT, D. C., LIU, P. H., DIA, R. M. and VELEBIR, J. (1993): Millimeter-wave, cryogenically-coolable amplifiers using AlInAs/GaInAs/InP HEMT's, *Proceedings of International Microwave Symposium* (in press).