Paper presented at 32nd COSPAR Scientific Assembly, 12–19 July, 1998; to be published in Advances in Space Research

THE ARISE SPACE VLBI MISSION

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ABSTRACT

ARISE (Advanced Radio Interferometry between Space and Earth) is a proposed future space VLBI mission currently under consideration by NASA. The primary mission goal is to orbit a radio telescope whose performance for high-frequency VLBI is similar to a 25-meter antenna of the Very Long Baseline Array (VLBA). A VLBA antenna has a mass greater than 200 tons, but inflatable antenna technologies may enable launch of an orbiting antenna with a similar diameter, but a mass of only a few hundred kilograms. This would permit key scientific questions to be investigated, such as the nature of the innermost relativistic jets in γ-ray blazars, and the physics associated with extragalactic H_2O megamasers. If ARISE is selected by NASA, a launch date of 2008 is feasible.

INTRODUCTION

Space Very Long Baseline Interferometry (SVLBI) is an astronomical tool that has come of age with the launch, in February 1997, of the HALCA satellite. HALCA is the orbiting component of the first dedicated SVLBI mission, the VLBI Space Observatory Programme, or VSOP (Hirabayashi *et al.,* 1998). This mission has built on the successful SVLBI demonstrations with the Tracking and Data Relay Satellite System (TDRSS) in the late 1980s (e.g., Levy *et al.,* 1986), and on various mission concept studies such as QUASAT and the International VLBI Satellite (IVS). The techniques unique to SVLBI, as contrasted with ground VLBI, are described in some detail by Ulvestad (1998).

The first generation of dedicated SVLBI missions use orbiting radio telescopes that are much less sensitive than the co-observing ground arrays. This implies that only the strongest compact sources can be detected and imaged. Therefore, it is desirable for any second-generation SVLBI mission to have an orbiting radio telescope with a sensitivity similar to those of the ground observatories. ARISE (Advanced Radio Interferometry between Space and Earth), is such a mission. It is currently present on the long-term roadmap of the Structure and Evolution of the Universe theme of NASA, and addresses several of the fundamental goals summarized in NASA's Space Science Strategic Plan. A new start in 2005 and a launch date in 2008 are possible if funding is provided. Previous descriptions of the ARISE mission and its scientific goals can be found in a number of references (e.g., Ulvestad *et al.,* 1995; Gurvits *et al.,* 1996; Ulvestad *et al.,* 1997; Ulvestad & Linfield 1998).

MISSION CONCEPT

General Considerations

The Very Long Baseline Array (VLBA) of the U.S. National Radio Astronomy Observatory has revolutionized ground VLBI in the 1990s. Although the 25-meter antennas of the VLBA are not as large as many other radio telescopes, their 100% commitment to VLBI (rather than a wide variety of uses) enables system designs that have proven extremely effective in producing frontier scientific results. The ARISE mission concept, therefore, would involve an orbiting radio telescope with similar sensitivity and frequency coverage, in order to increase the linear resolution of the VLBA by a factor of 5 or more. This requires a maximum baseline of approximately 50,000 km, implying an elliptical orbit with an apogee height near 40,000 km. At the highest observing frequency, 86 GHz, this provides a resolution of approximately 15 *micro*arcseconds (μas), a factor of about 3000 better than that available from the Hubble Space Telescope (HST). Source correlated flux densities decrease on the space-ground VLBI baselines giving the highest resolution; however, an orbiting radio telescope does not have noise contributions due to the Earth, so it can be more sensitive than a ground telescope of similar size, with the decreased noise compensating for the reduced signal level.

Antenna Structure

Relatively small space antennas have been built using a variety of methods, such as the wrap-rib technology. However, such antennas are quite expensive, prohibitively so even if they could be scaled up to 25 meters. The technology used for HALCA resulted in a 250-kg, 8-m antenna; scaling the mass to a 25-m diameter by at least the square of the diameter would result in a 2500-kg antenna, too massive for an affordable launch vehicle. Therefore, the rapidly developing technology of precision space inflatable structures is the leading candidate for the ARISE antenna. This technology has many other uses, such as Earth-sensing radiometry, space communications, and solar-power concentration, so it is currently under investigation for a variety of customers. Other space technologies needed for ARISE, such as cryogenic cooling and space-qualified low-noise amplifiers, are required for other NASA missions and need not be developed specifically for ARISE.

A 25-meter inflatable antenna probably could be built with a mass no larger than 300 kg, enabling a spacecraft mass near 1700 kg, and use of an affordable launch vehicle. Such a large antenna must be rather distant from the spacecraft bus, implying that large torques would be imposed by solar radiation pressure. Trade studies performed at NASA's Jet Propulsion Laboratory have resulted in a strawman design in which the inflatable antenna is an off-axis section of a larger paraboloid, with Gregorian optics used to focus the radiation at feeds on the spacecraft. Alternative configurations are unpalatable because of significant observing constraints or structural complications.

Current indications are that it will be difficult to reach the surface accuracy near 0.2 mm required for high aperture efficiency at 86 GHz (3.5 mm wavelength), so an 86-GHz efficiency in the 10%–20% range is deemed acceptable. Reductions in the large-scale errors in the primary reflector, the possibility of a simple mechanically corrective subreflector, and the use of an array of adaptive feeds at the highest frequencies are all under active investigation for achieving the best possible performance. These methods must work for a variety of angles between the Sun and the radio source, implying minimal thermal deformations of the antenna structure, and the need to correct any pointing offsets to better than 10% of the antenna beamwidth (imposing a very stringent pointing requirement of 2–3 arcseconds at 86 GHz).

Space-Ground Observing System

The large moment of inertia for ARISE may preclude weak-source observations by means of phase referencing, which requires switching between a target and a calibrator $\sim 1^\circ$ away in tens of seconds. Therefore, to enable detection of millijansky-strength sources (1 mJy = 10^{-29} W m^{-2} Hz^{-1}), observing bandwidths of $\sim$ 2 GHz are needed for both the spacecraft and the ground telescopes. This requires real-time space-ground communication links and sustainable data recording of at least 4 Gbit s^{-1}, preferably 8 Gbit s^{-1}. Ground processing facilities must be able to cross-correlate such data in a time no greater than the actual observing time. Requirements on the entire VLBI observing system are summarized in Table 1.

Table 1. Top-Level ARISE Mission Requirements

Quantity	Requirement	Origin
Antenna Diameter	25 m	mJy sensitivity
Antenna Accuracy (corrected)	0.2–0.3 mm	$\lambda/16$ at 86 GHz
Antenna Pointing	≤ 3 arcsec	$\leq 3\%$ loss at 86 GHz
System Temperature	10 K–40 K	mJy sensitivity
Data Rate	~ 8 Gbit s^{-1}	mJy sensitivity
VLBI Frequencies	5–8, 22, 43, 86 GHz	Standard VLBI bands
Single-dish Frequency	60 GHz	O_2 in star-forming regions
Apogee Height	~40,000 km	15–100 μas resolution
Lifetime	≥ 3 yr	Source monitoring
Total Mass	≤ 1700 kg	Affordable launch vehicle

KEY SCIENCE GOALS

Active Galactic Nuclei

The high resolution of SVLBI makes it ideal for imaging the intense compact radio sources found in active galactic nuclei (AGN), such as quasars and radio galaxies. In the nearest radio galaxy, Centaurus A, 15 μas corresponds to less than a light day, compared to the resolution of several light years achievable by HST. In quasars far across the universe, at distances of $\sim 10^{26}$ meters (or $\sim 10^{10}$ light years), the ARISE resolution corresponds to a few light months, compared to resolution of ~ 1000 light years for HST. Thus, SVLBI with ARISE enables mapping of the inner parts of the accretion disks and jets associated with the massive black holes powering AGN.

A prime class of candidates for ARISE is the γ-ray "blazars". These are highly variable AGN, more than 40 of which have been found to emit high-energy γ-rays by the Energetic Gamma-Ray Experiment Telescope (EGRET) instrument aboard the Compton Gamma Ray Observatory (e.g., Mukherjee *et al.,* 1997). The γ-rays in these objects come from the inner parts of their relativistic jets, possibly by Compton scattering of accretion-disk photons off the relativistic jet electrons. The ratio of γ-ray to radio power, combined with the apparent speed of the VLBI components, constrains the physical properties of the source and the jet acceleration (e.g., Marscher 1995). However, these tests require the high resolution available with ARISE. They are greatly facilitated by observations at frequencies higher than 20 GHz, where the inner jets are optically thin. This enables imaging of the jet core rather than an optically thick surface sheath.

H_2O Megamasers

A number of nearby AGN show H_2O megamaser emission at a frequency of 22.2 GHz; the isotropic luminosity is millions of times greater than in typical galactic star-formation regions. The megamasers are visible when we have an edge-on line of sight into the sub-parsec accretion disk or torus surrounding a central black hole. Radial and angular motions of the maser spots in the nearby active galaxy NGC 4258 enable models to be constructed of the disk geometry; they also provide a precise measurement of the mass interior to the masers, yielding a mass 35 million times that of the Sun (or 7×10^{37} kg) for the central black hole (e.g., Moran *et al.,* 1995). Furthermore, the apparent line-of-sight accelerations and angular proper motions can be used to derive a precise geometrical distance to the galaxy, with only a 4% error (Herrnstein 1998).

It is desirable to make similar observations of more distant H_2O megamasers, which will be found in extensive surveys over the next 10 years, both for studying their intrinsic physics and for making direct distance measurements. However, the more distant objects have correspondingly smaller angular scales, requiring higher resolution to separate the clumps of emission and to make detailed measurements of their motions. Since the masers emit radiation at a fixed frequency, the increased resolution can be achieved only by increasing the maximum baseline length over that available on the Earth's surface. Furthermore, a very sensitive space antenna is needed to enable interferometric detection with high signal-to-noise on these long baselines. Thus, using ARISE, it will be possible to image megamasers at distances large enough so that the galaxy radial velocities are dominated by the general expansion of the universe (the "Hubble flow"). These direct distance measurements, bypassing numerous rungs in the cosmic distance ladder, can provide measurements of the scale of the universe (the Hubble constant) with accuracies better than 10%.

Additional Targets

The high sensitivity of ARISE enables investigations of several types of targets in addition to those described above. Gravitationally-lensed VLBI sources can be imaged with higher resolution, providing additional constraints on the distribution of dark matter in the lensing objects. A variety of radio stars in our Galaxy will be detectable and can be imaged, even while in their quiescent states; the maser regions around evolved stars also can be imaged. ARISE will be able to image the centers of AGN with weak compact cores, such as Seyfert galaxies and lobe-dominated radio galaxies. Finally, a single-dish capability near 60 GHz will enable mapping of the density and temperature distribution in star-formation regions in our Galaxy.

ACKNOWLEDGMENTS

I thank Artur Chmielewski and the ARISE study team at the NASA Jet Propulsion Laboratory for their work on the ARISE mission and spacecraft design.

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