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MERI: AN ULTRA-LONG-BASELINE MOON-EARTH RADIO INTERFEROMETER

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Introduction

Radiofrequency aperture synthesis, pioneered by Ryle and his colleagues at Cambridge in the 1960's, has evolved to ever longer baselines and larger arrays in recent years. The European Very Long Baseline Network and the National Radio Astronomy Observatory's Very Long Baseline Array, currently under construction, use a large fraction of the Earth's diameter to synthesize apertures with resolutions of milliarcseconds at centimeter wavelengths. These arrays sample the Fourier components of a distant radio source's brightness distribution using the Earth's rotation to increase the coverage in the Fourier domain. Maps of the radio surface brightness are produced by performing Fourier transforms on the source visibilities gathered from the correlated signals of the radio antenna pairs. Tropospheric, ionospheric, and system-related contamination of the source visibilities can be removed by iterative modeling, termed hybrid mapping or self-calibration (ref. 1). A variety of deconvolution algorithms such as CLEAN and Maximum Entropy can remove the diffraction effects in maps produced by incomplete sampling of the Fourier transform plane (i.e., incomplete aperture). This process results in maps of increasing quality with milliarcsecond resolution and dynamic ranges of hundreds to one.

The limiting resolution at a given frequency for modern ground-based very-long-baseline (VLB) interferometry (VLBI) is simply determined by the physical diameter of the Earth. There are no other technological barriers that constrain VLB observations at centimeter wavelengths. This limitation can, of course, be overcome by placing radio antennas in orbit around the Earth. A first step toward space-based VLBI may occur within the next decade. A joint mission proposed to the European Space Agency (ESA) and to NASA would place a free-flying 15-m radiofrequency antenna in elliptical orbit about the Earth (ref. 2). This project, termed Quasat for quasar satellite, would have an orbital perigee of about 4000 km and an apogee of about 15 500 km and would be inclined by 63° to the Earth's Equator. The operating frequencies would be between 22 and 1.7 GHz. The resolution would increase that of the ground-based VLBI by a factor of 3 or 4. The superior sampling of spatial frequencies (projected baselines) would also greatly enhance the quality of maps by reducing the ambiguities usually encountered in the image restoration process. The Quasat antenna would be linked to ground-based VLB antennas with telemetry commands (including clock reference) relayed from the ground. During the observations, data would be recorded on magnetic tape. Later, the tapes would be brought to a central processing station for correlation and mapping.

A second-generation, totally space-based VLB network was proposed recently by a group at the Naval Research Laboratory (NRL) (ref. 3). The Astro-Array would consist of 30 spaceborne antennas with no ground-based elements and with the correlator station also in space. Each antenna would be 50 m in diameter and placed in orbits that would yield minimum and maximum baselines of 1000 km and 200 000 km, respectively. The resolution of the Astro-Array at 5 GHz would be <0.1 marcsec. The array receivers would operate in the frequency range of 30 MHz to 300 GHz. Since the entire array would be above the Earth's atmosphere and therefore not subjected to atmospheric wave scattering and uncertainties in baseline positions, it could act as a phased-linked interferometer. Real-time correlations of source visibilities, via satellite links, would remove many of the uncertainties that limit ground-based VLBI. Diffraction-limited resolution at higher frequencies and dynamic ranges of tens of thousands to one (limited only by system clocking and correlator errors) would then be possible.

The next logical extension of space-based VLBI would be a station or stations on the Moon. I originally proposed this concept, termed MERI for Moon-Earth radio interferometer, at the NASA Symposium on Lunar Bases and Space Activities of the 21st Century held in Washington, D.C. (ref. 4). The Moon could serve as an outpost or even the primary correlator station for an extended array of space-based antennas. Because of the stability of the lunar surface, the natural cryogenic environment, and the proximity to scientists on the lunar base, one may wish to build the counterpart of the very long array (VLA) radio interferometer (ref. 5) on the Moon (fig. 1). Such a lunar VLA alone would be capable of impressive new science, especially in astrometry (ref. 6). But, as part of a larger VLBI network, the combined resolution and sensitivity would allow us to probe far deeper into the universe and with much greater spatial resolution than previously possible.

Resolutions, Wavelengths, and Sensitivities

As a guide to the potential radiofrequency science that would be possible with MERI, I propose a two-component array consisting of the Astro-Array and a lunar VLA. Furthermore, I will presume that the system parameters are those given in table I with uniform antenna apertures of 50 m. The baselines for such an array of telescopes would range from a minimum of about 200 m (for the lunar VLA) to an instantaneous maximum of about 500 000 km (about 5 times that of the Astro-Array alone). Over the 2-week, half-sidereal period of the Moon, the maximum baseline could be doubled to 10^6 km.

Such a configuration has four distinct advantages. First, this MERI array would offer an unprecedented resolving power as is discussed further below. Second, the wide range of spatial frequencies that would be sampled by these baselines offers us an opportunity to study an amazingly broad spectrum of structures in radio sources. Third, the sensitivity of the array – far greater than that of any interferometer currently in existence – would enable the resolution and mapping of weak, fine-scale structure. Fourth, the combination of short (hundreds of meters to kilometers) to intermediate (thousands of kilometers) to very long (hundreds of thousands of kilometers) spacings in an airless environment would allow us to reconstruct the radio source brightness distributions with a minimum of uncertainty.

The resolution of MERI would be governed by two factors. At high frequencies, the interferometer is diffraction-limited. The smallest resolvable feature (full width half maximum (FWHM)) is given by

$$\theta_{diff}\,(\mu\text{arcsec}) = 6.3 \times 10^{7}\,(\nu_{GHz} D_{km})^{-1} \tag{1}$$

where ν_{GHz} is the frequency in gigahertz and D_{km} is the baseline in kilometers. For an instantaneous baseline of 500 000 km, the resolution at 10 GHz is 12.6 µarcsec and at 300 GHz is 0.4 µarcsec. These resolutions are improved further by a factor of 2 for aperture synthesis using a half revolution of the Moon around the Earth.

At lower frequencies, the resolution of MERI is limited by electron density turbulence as the radiofrequency radiation passes through the interstellar medium (ISM) of the Milky Way. (See ref. 7.) This turbulence causes the radio sources to be broadened angularly in a manner that depends upon the line-of-sight direction to the source. Recent VLB measurements, interplanetary scintillations of extragalactic sources, and interstellar scintillations of pulsars have been used to constrain the amount of broadening by the ISM. Cordes et al. (ref. 8) and Dennison et al. (ref. 7) find that the scattering angle for a plane-wave source is given by

$$\theta_{ISS}(\mu\text{arcsec}) = 1.33 \times 10^5 (L_{kpc} < C_n^2 >)^{3/5} \nu_{GHz}^{-11/5}$$
$$\approx 10^3 \nu_{GHz}^{-11/5} (\sin|b|)^{-3/5} \tag{2}$$

assuming a power-law spectrum of turbulence in the form $C_n k^{-3.6}$, where k is the wave number; L_{kpc} is the effective path length in kiloparsec, ν_{GHz} is the frequency of observation in gigahertz, and b is the galactic latitude (where eq. (2) is valid for $b \gtrsim 10°$). Pulsar interstellar scintillation measurements suggest that C_n^2 is about $10^{-3.5}$.

Equating equation (1) to equation (2) yields the frequency above which the MERI observations are diffraction-limited:

$$\nu_{GHz} > 10^{-4} (\sin|b|)^{-1/2} D_{km}^{5/6} \tag{3}$$

For high galactic latitudes and an instantaneous baseline of 500 000 km, this frequency is 5.6 GHz. Above this frequency, the resolution of the MERI array is given by equation (1). Below this frequency, the resolution of the array is limited by turbulence broadening and is given by equation (2).

The sensitivity of the MERI array (ref. 9) is given by

$$S_{rms}(\text{mJy}) = 5.55 \times 10^3 (\frac{T}{\varepsilon}) D^{-2} (\Delta\nu_{MHz}\, tN(N-1)/2)^{-1/2} \tag{4}$$

where S_{rms} is the rms noise for the system with receiver system temperature T, antenna efficiency ε, antenna diameter D, bandwidth $\Delta\nu_{MHz}$, integration time t, and number of antennas N. To correspond to a one-bit digital correlator of the type currently used for VLB observations, a correlator efficiency of 64% has been assumed. For $T = 50$ K, $\varepsilon = 0.65$, $D = 50$ m, $\Delta\nu = 50$ MHz (at 10 GHz wavelength), $t = 6$ hr $\times$ 3600 sec/hr, and N = 60, the rms sensitivity is 4 μJy. This is a factor of 10 more sensitive than the VLA, which is currently the most sensitive aperture-synthesis telescope in the world.

The combination of high resolution and sensitivity with MERI will allow radio astronomers to probe a far greater range of source structures at larger distances than ever before. As a result, the science with MERI will be far ranging and should greatly advance radio astrophysics.

Radio Astrophysics With MERI

A wide variety of astronomical observations at radiofrequencies can be undertaken with the MERI array ranging from observations within our solar system of active regions on the Sun and the magnetosphere of Jupiter to examination of the nuclei of active galaxies and quasars. Table II contains the spatial resolutions of a variety of galactic and extragalactic objects that could be observed with MERI at 10-GHz and 300-GHz frequencies.

Many of the important radio observations that could be conducted with MERI involve astrometry. Let me consider a few fundamental astrometry experiments.

1. The potential <0.1-μarcsec position accuracy of MERI could be used to improve upon the current celestial coordinate system. In particular, the combination of an optical interferometer on the Moon (refs. 10 and 11) and MERI could be used to refine the relationship between the optical and the radiofrequency coordinate systems.

2. It may be possible to search for dark companion stars (black holes and neutron stars) or even planets around radio stars by measuring the perturbations of radio star proper motions.

3. Relative astrometry can be used to measure the expansion of radio source components in extragalactic jets. Resolutions and sensitivities of current VLB interferometers are generally not high enough to conduct such observations.

4. A particularly exciting prospect involves the fundamental cosmological experiments that could be performed. Morgan (ref. 12) has described the manner in which H_2O masers in our galaxy can be used as independent distance measures through the use of classical statistical parallax techniques. The angular resolution of MERI could enable radio astronomers to extend this technique to other galaxies and to accurately determine their distances. Thus, a powerful new tool is at hand for measuring the Hubble parameter. Similarly, trigonometric parallax measurements of radio galaxies in clusters combined with redshift measurements could allow us to determine distances to clusters and thus to further calibrate the extragalactic distance scale.

There are also various aperture-synthesis observations that one might wish to perform with MERI. Some of these include:

1. Mapping radio burst regions on other stars — Enough sensitivity and resolution exists with MERI to refine our understanding of the solar-stellar connection.

2. High-resolution mapping of radio stars such as SS433 and RS CVn — Some of these stars may serve as scaled-down prototypes of the engines at the cores of active galaxies and quasars.

3. Mapping the core of the Milky Way — Recent radio observations of the Sag A region of our galaxy have revealed a great deal of complex structure, both thermal and nonthermal in origin. The MERI could be used to probe the source of this activity at very high spatial resolution and sensitivity.

4. Studying the collimation of radio jets very close to the core of active galaxies and quasars — The radio jets hold the key to transporting magnetized plasma from the "engines" at the centers of galaxies to the extended lobes or tails. Currently, we cannot determine the manner in which the radio jets are first collimated; therefore, we are missing a key element in understanding the physics of radio jets.

5. Mapping the engines in nearby active galaxies — For the first time, the MERI array provides sufficient resolution and sensitivity to map the accretion disks around the compact object that is fueling the radio emission. We may be able to get a direct answer to the question, "Do giant black holes power active galaxies?"

6. Testing fundamental physics of compact extragalactic sources — Researchers such as Kellermann and Pauliny-Toth (ref. 13) believe that the region which we can resolve near the core of a galaxy will be limited by the so-called Compton catastrophe. The maximum brightness temperature that is visible from such a source is 10^{12} K. Inverse Compton scattering of radio photons by relativistic electrons near the core makes the central region of the source effectively opaque. By observing the source sizes at a variety of wavelengths and resolutions with MERI, we can test this basic physical process.

The MERI array will open an entirely new regime of wavelengths, resolutions, and sensitivities for radio astronomy. As with any such leap in astronomical instrumentation, this advancement will result in the observation of a variety of known radio sources and the exploration of their structures in unprecedented detail. Even so, it may be the serendipitous discoveries, which are by definition impossible to predict, that ultimately justify the construction of MERI.

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TABLE I.- CHARACTERISTICS OF THE MERI ARRAY

Number of antennas	[a]60
Antenna size, m	50
Antenna efficiency	0.65
Frequency coverage, MHz	30 to 300 000
Bandwidth, % of frequency	10
System temperature, K	50
Baselines	
Minimum for lunar VLA, m	200
Maximum for instantaneous observations, km	500 000
Maximum for half-sidereal period synthesis, km	10^6
Resolution	
At 100 MHz,[b] arcsec	0.2
At 10 GHz,[c] μarcsec	12.6
At 300 GHz,[c] μarcsec	0.4
Sensitivity in 6 hr, μJy rms	4

[a]30 in Earth orbit and 30 on the Moon.
[b]Limited by interstellar turbulence broadening.
[c]Assuming observations near the galactic poles.

TABLE II.- SPATIAL RESOLUTIONS AT 10 AND 300 GHz

Object	Linear resolutions (FWHM), m (AU), at frequency of –		Scientific goals or items of interest
	10 GHz	300 GHz	
Sun	9	3	Solar flare activity
Mercury	5	1.6	Differential heating of surface by solar wind
Jupiter	40	12	Mapping of magnetosphere
Ux Ari	9.7×10^7	3.1×10^7	Solar-stellar connection
Orion nebula	9.7×10^8	3.1×10^8	Starbirth; bipolar outflow
SS433	9.7×10^9	3.1×10^9	Formations of radio jets; mini-engine
Sag A (galactic center)	1.95×10^{10} (0.13)[a]	0.6×10^{10} (0.04)[b]	Engine at galaxy core
M31	109.5×10^{10} (7.3)	34.5×10^{10} (2.3)	Comparison of closest spiral galaxy to Milky Way
Centaurus A	57×10^{11} (38)	18×10^{11} (12)	Engine powering active galaxy; collimation of radio jets
Perseus cluster	136.1×10^{12} (907)	43.5×10^{12} (290)	Trigonometric parallax for radio galaxies
3C273	945×10^{12} (6300)	300×10^{12} (2000)	Radiofrequency activity in quasars

[a] $6.5R_s$; R_s = Schwarzschild radius for $10^6 M_o$ black hole.
[b] $2.1R_s$.

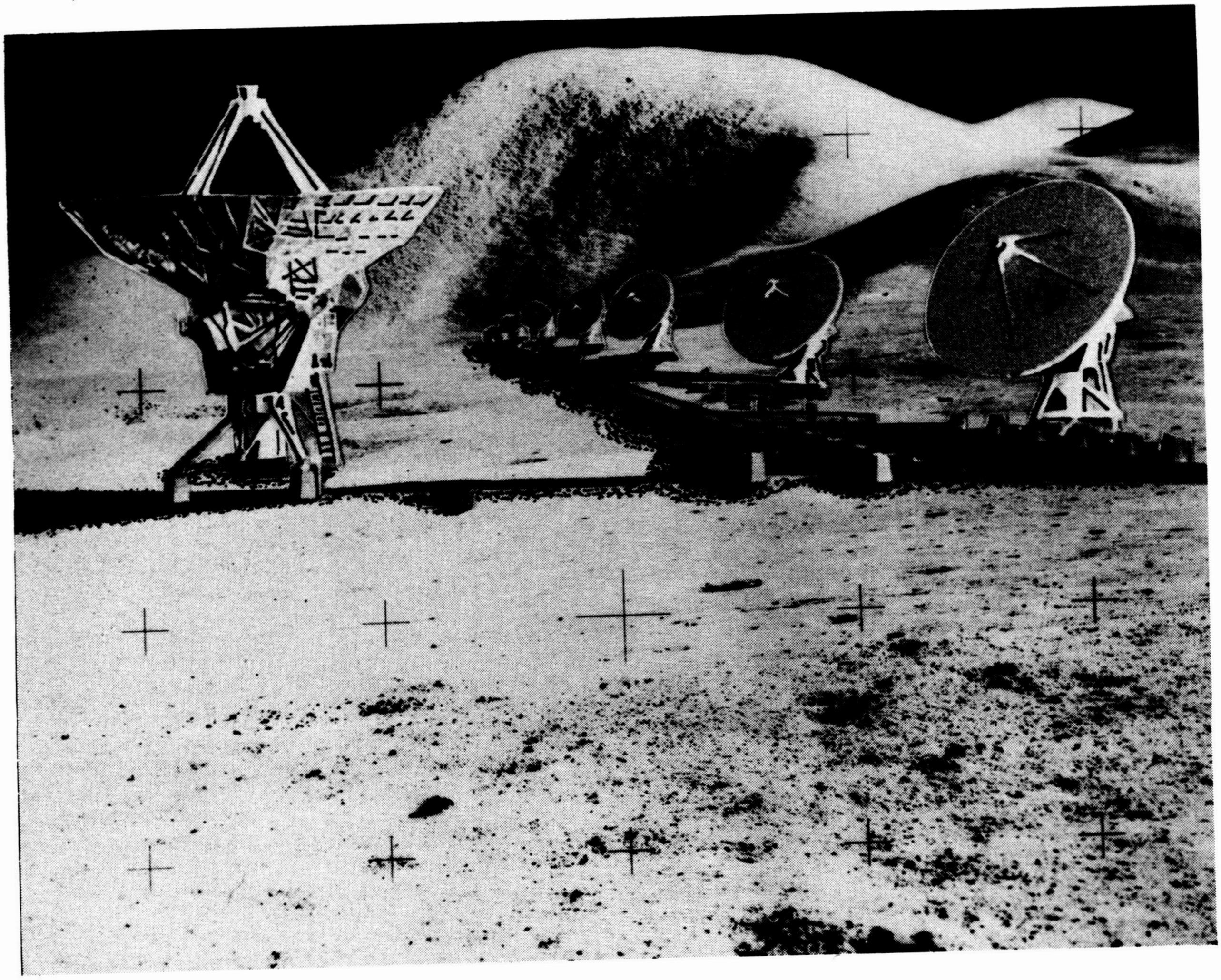

Figure 1.- Retouched photograph showing a very long array of antennas constituting a radiofrequency interferometer emplaced on the Moon.