Comparison of Two Candidate Elements for a 30–90 MHz Radio Telescope Array

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Abstract

The Long Wavelength Array (LWA) is radio telescope array, now in the planning stage, designed for operation between 30 MHz and 90 MHz. The array will consist of approximately 13,000 dipole-like elements organized into "stations" of 256 dipoles each, distributed over a region about 400 km in diameter in the U.S. Southwest. Requirements for the element include broad, slowly-varying patterns over the tuning range; dimensions on the order of one-half wavelength or less at the highest frequency of operation to facilitate alias-free beamforming; mechanical simplicity; and low cost. When used with a 288 K preamplifier with 100Ω input impedance and 25 dB gain, it is desired for the element-preamplifier combination to deliver Galactic noise at a level about 10 dB greater than the preamplifier noise. In this paper we present and compare two candidate element designs, and find that they come close to meeting these goals.

I. INTRODUCTION

The Long Wavelength Array (LWA) is radio telescope array, now in the planning stage, designed for operation between 30 MHz and 90 MHz [1]. The array will be consist of approximately 13,000 dipole-like elements. Each element is to be individually received, digitized, and then combined by beamforming into groups of 256 elements, referred to as "stations." Each station is the functional equivalent of a large dish antenna in a traditional (higher frequency) aperture synthesis radio telescope, and at this level are combined to form images. Requirements for the element include broad, slowly-varying patterns over the tuning range and dimensions on the order of one-half wavelength or less at the highest frequency of operation to facilitate alias-free beamforming. The extraordinarily large number of antennas required makes it essential that each antenna has the lowest possible cost; is easy to manufacture and install; and is rugged, preferably requiring no maintenance.

To achieve large tuning range, previous telescope arrays used antennas which have inherently large impedance bandwidth. Unfortunately, such antennas (including "fat" dipoles and conical spirals) are mechanically complex, making them expensive, difficult to construct, and prone to maintenance problems. This makes them unsuitable as elements for LWA. In contrast, simple wire dipoles are mechanically very well-suited for use in large low-frequency arrays, but have inherently narrow impedance bandwidth. However, this is not as strict a limitation at low frequencies as it is at higher frequencies because natural Galactic noise can easily dominate over the self-noise of the electronics attached to the antenna. In this case, the antenna performance is unacceptable only if the impedance mismatch between the antenna terminals and the electronics becomes so great that the antenna system is no longer "Galactic noise-limited." Once the antenna system is Galactic noise-limited by 10 dB or so, further improvement in impedance bandwidth has little effect on the sensitivity since the signal-to-noise ratio is upper-bounded by Galactic noise by that point [2]. Since Galactic noise is broadband and distributed over the entire sky, any further improvement in the sensitivity of the telescope can therefore be achieved only by adding additional antennas. Thus, even badly-mismatched antennas – such as dipole-like antennas far from resonance – may in fact yield the best possible sensitivity.

II. CANDIDATE DESIGNS

The two designs being currently being considered for the LWA are shown in Figure 1. The first candidate is a 0.68-scale version of an element currently in use at the U.S. Naval Research Laboratory's Low-frequency Test Array (NLTA), an 8-element prototype test facility located near Greenbelt, MD [3]. It is constructed from copper pipe 15.85 mm in diameter, held in place using a non-metallic (possibly PVC) support structure. The second candidate

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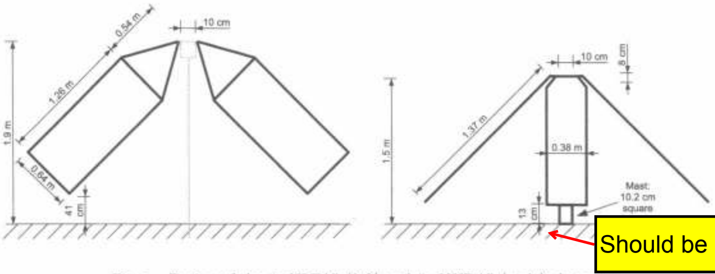


Should be 53 cm, not 13 cm

Fig. 1. Design of the "mNLTA" (*left*) and "mLWDA" (*right*) elements.

is a 1.37-scale version of an element currently planned for use in the Long Wavelength Development Array (LWDA), a prototype of LWA consisting of two stations of 256 elements operating primarily at 74 MHz, soon to be constructed near Socorro, NM. The planned LWDA element is assembled from thin aluminum "blades" mounted to an aluminum mast with non-metallic supports to hold the blades in place. We shall refer to these candidates as the "mNLTA" and "mLWDA" respectively, including the prefix "m" to indicate that they have been modified from the original designs. The scaling in each case was chosen using a process of trial and error in an attempt to optimize performance over the LWA's 30–90 MHz tuning range. Both designs under consideration include a second element at right angles in the azimuth plane to obtain orthogonal linear polarizations.

LWA elements are to be used with a preamplifier which is connected directly to the antenna terminals, for which a candidate design exists. This preamplifier has a gain of about 25 dB, noise temperature of about 288 K, and input impedance 100 Ω (balanced).

III. TERMINAL IMPEDANCE, VSWR, AND PATTERNS

Both antennas were analyzed using a NEC-2-based method-of-moments code, taking into account conductor losses (which turn out to be insignificant for either design) and ideal (perfectly conducting) ground conditions. The latter is justified in that is proposed to install a ground treatment under LWA stations to minimize loss due to finite ground conductivity. The mLWDA blades and mast were modeled using a wire grid with spacing averaging 7.5 cm and with wire diameter 1.9 cm. In all cases, we have obtained consistent answers using different wire models with two different NEC-2 implementations. Also, we obtain good agreement in impedance between a model of the unscaled LWDA element modeled in a similar fashion and measurements of an assembled prototype.

Figure 2 shows the results for impedance and VSWR. VSWR is computed assuming the 100Ω input impedance of the preamplifier. Note that both designs have reasonably good VSWR characteristics, with mNLTA being somewhat better at low frequencies and mLWDA being better between 45 MHz and 80 MHz. Figure 3 shows the patterns for each design, computed at 38 MHz and 74 MHz (corresponding to frequency bands which are allocated by Federal law for Radio Astronomy). Not surprisingly, the performance of both designs is similar. Both designs begin to show signs of undesirable sidelobe development at 74 MHz, although the mNLTA seems to be somewhat better in this respect.

IV. GALACTIC NOISE-LIMITED PERFORMANCE?

As explained above, the "bottom line" criterion for the antenna/preamplifier combination is that it is Galactic noise-limited. Galactic noise power can be described in terms of the intensity I_ν integrated over the antenna pattern, such that the power spectral density at

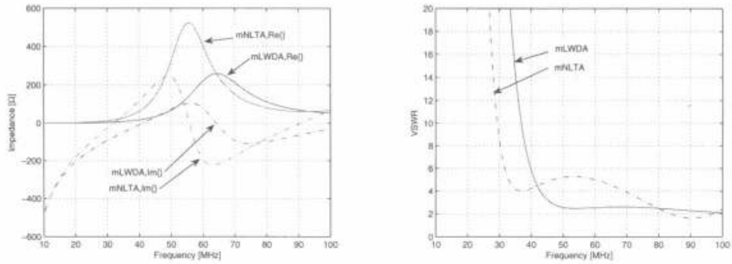


Fig. 2. *Left:* Terminal Impedance. *Right:* VSWR for 100Ω load.

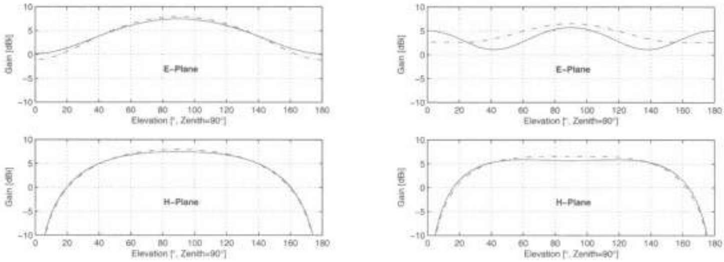


Fig. 3. Patterns: *Left:* 38 MHz, *Right:* 74 MHz. *Solid:* mLWDA, *Dash:* mNLTA.

Should be mLWDA

Should be mNLTA

the antenna terminals is given by

$$S_{sky} = \frac{1}{2}\int I_\nu A_e d\Omega \quad [\text{ W Hz}^{-1}\text{ }] \tag{1}$$

where A_e is the effective aperture, the integration is over solid angle, and the factor of $\frac{1}{2}$ accounts for the fact that any single polarization captures about half of the available power since Galactic noise is unpolarized. Since the elements under consideration are non-directional (approximately constant A_e over the field of view), the intensity of Galactic noise can be modeled as being spatially uniform and spanning the beamwidth. Thus, Equation 1 simplifies to

$$S_{sky} \sim \frac{1}{2} I_\nu A_e \Omega \tag{2}$$

where Ω is beam solid angle. Let G be the gain of the antenna. Then we have

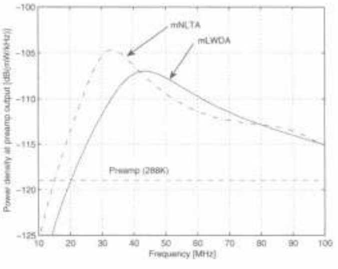
$$A_e = \frac{\lambda^2}{4\pi} G \text{ and } \Omega = \frac{4\pi}{G} \ . \tag{3}$$

Therefore, $A_e\Omega = c^2/\nu^2$ where ν is frequency, and

$$S_{sky} \sim \frac{1}{2} I_\nu \frac{c^2}{\nu^2} \tag{4}$$

where c is the speed of light. This can be expressed in terms of an equivalent temperature through the Rayleigh-Jeans Law:

$$I_\nu = \frac{2\nu^2}{c^2} k T_{sky} \tag{5}$$



Element (scale)	6 dB [MHz]	10 dB [MHz]	Width [m]
mNLTA	21–90	25–47	3.06
mLWDA	28–84	36–57	2.08

Fig. 4. *Left:* Comparison of Galactic noise captured to preamplifier noise at the output of the preamplifier. *Right:* Summary of findings, including frequency span in which each element is Galactic noise-limited by the indicated ratio, and largest horizontal dimension of the element.

where k is Boltzmann's constant (1.38×10^{-23} J/K), and T_{sky} is defined to be the antenna equivalent temperature corresponding to Galactic noise. Thus we have

$$S_{sky} \sim kT_{sky} \text{ , where } T_{sky} = \frac{1}{2k} I_\nu \frac{c^2}{\nu^2} \text{ .} \tag{6}$$

I_ν is known from measurements to be well-approximated by:

$$I_\nu = I_g \nu_M^{-0.52} \; \frac{1 - e^{-\tau(\nu_M)}}{\tau(\nu_M)} + I_{eg} \nu_M^{-0.80} \; e^{-\tau(\nu_M)} \tag{7}$$

where $I_g = 2.48 \times 10^{-20}$, $I_{eg} = 1.06 \times 10^{-20}$, $\tau(\nu_M) = 5.0\nu_M^{-2.1}$, ν_M is frequency in MHz, and I_ν has units of W m^{-2} Hz^{-1} sr^{-1} [4]. T_{sky} ranges from $\sim$200,000 K at 10 MHz to $\sim$ 800 K at 100 MHz. The Galactic noise power spectral density at the output of the preamplifier is therefore

$$S = kT_{sky} \left[1 - |\Gamma|^2\right] G_p \tag{8}$$

where $G_p = 25$ dB and Γ is the voltage reflection coefficient at the antenna terminals looking into the preamplifier. The preamplifier noise produced at the output, assuming noise temperature $T_p = 288$ K, is

$$N_p = kT_p G_p \text{ .} \tag{9}$$

Figure 4 shows the contributions from Galactic noise and preamplifier noise at the preamplifier output. We note that both elements deliver Galactic noise-limited performance over much of the tuning range, with the mLWDA being somewhat better below 40 MHz and the mLWDA being somewhat better in the range 45-70 MHz.

ACKNOWLEDGMENTS

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