Wideband Low Frequency Antennas for Radio Astronomy Arrays

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Abstract

Antennas in the frequency range 10 to 300 MHz are being designed with all-sky coverage, a low response at the horizon to minimize interference from terrestrial sources, negligible ground loss and a good low noise match to the low noise amplifier (LNA). Other features include low cost, dual polarization and good performance over more than an octave bandwidth. Extending the antenna performance over a wider frequency range and accurate calibration are remaining challenges. Modeling of the antenna and its associated low noise amplifier shows promise as a method of improving calibration accuracy.

1. Introduction

Early low frequency radio astronomy used large steerable reflectors or fixed arrays of elements in which the beam was formed and steered by phasing up the signals from antenna elements with the appropriate phases in a "beamformer". With the introduction of low cost analog electronics and powerful digital signal processing hardware low frequency telescopes are being developed to have continuous all-sky imaging over wide bandwidths with high spatial, spectral and time resolution. These new low frequency radio telescopes have small low cost antenna elements that have full sky coverage. The Murchison Widefield Array (MWA) uses sub-arrays of 16 antennas, known as "tiles", which are phased with a beamformer. The antenna elements used in a tile have full sky coverage, dual polarization and a wide bandwidth covering 80 to 300 MHz. These wideband elements maintain an antenna pattern close to that of a half-wave dipole over an infinite ground plane whose directivity, D, has the simple analytic form [1] as follows:

$$D = [(\cos((\pi/2)\cos\theta)/\sin\theta)\sin(2\pi h \sin\phi)]^2 \quad (1)$$

where θ is the angle with respect to the dipole direction, ϕ is the elevation angle and h is the height over a ground plane in wavelengths. The E and H plane patterns from Equation 1 above are shown in Figure 1. When "embedded" in a tile the mutual coupling between antennas tends to broaden the patterns as illustrated in Figure 2.

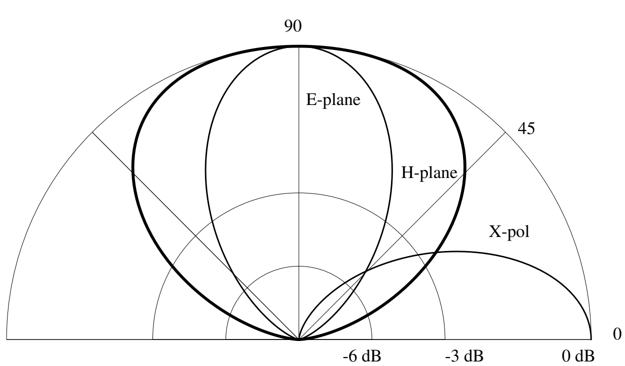

Figure 1. E and H plane patterns

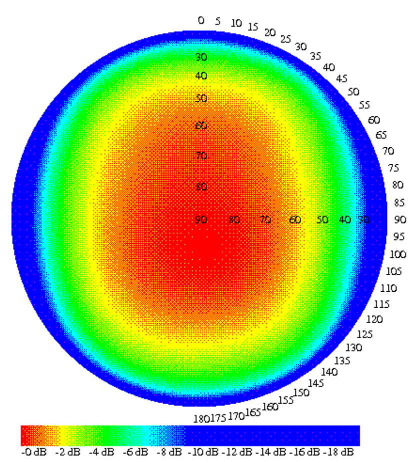

Figure 2. "Embedded" pattern of MWA antenna

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Crossed dipoles provide orthogonal linear polarizations at the zenith which depart from orthogonality away from the zenith. The curve labeled "X-pol" in Figure 1 shows the normalized cross-polarization coupling in the 45 degree azimuth plane vs elevation.

2.1 Methods of increasing the VSWR bandwidth

A thin half-wave dipole placed a quarter-wave above a ground plane has a reflection coefficient of less than -10 dB (VSWR < 2) over only about 10% bandwidth. The bandwidth can be increased to some extent by using large diameter elements but more substantial improvements can be made by using a geometry based on the intrinsically wideband biconical antenna [1,2]. A vertical planar section of the biconical antenna is the "bowtie" antenna which is used for the MWA. The "fourpoint" antenna [3,4] used for the Experiment to Detect the Global EoR Step (EDGES) [5] is an evolved version of a horizontal planar sheet from the biconical. Both the bowtie and the fourpoint can achieve a reflection coefficient under -10 dB over an octave. Other structures which have a good match over a very wide rage of frequency are the log-periodic and vivaldi antennas.

2.2 Beam pattern bandwidth

Maintaining a constant beam pattern over more than an octave bandwidth is difficult. When the height of a dipole above the ground plane exceeds a quarter wavelength the zenith gain starts to drop and at half a wavelength there is a null at the zenith. This problem can be fixed with a dipole whose elements slope down towards the ground plane. However the "droopy" dipole which is used by the Long Wavelength Array (LWA) has a pattern with a significant response to vertical polarization at the horizon making it more sensitive to terrestrial interference which mostly comes from low angles close to the horizon. The vertical bowtie used by the MWA shown in Figure 3, which covers 80 to 300 MHz, is a compromise in this respect as it has vertical components of current which only just start to produce a significant horizon response while maintaining a low enough profile to avoid a drastic reduction of zenith gain at its high frequency limit. The horizontal plates of the EDGES fourpoint antenna, shown in Figure 4, ensure that the response at the horizon is a null but the current design is limited by a degradation of the pattern which starts to develop a loss of gain at the zenith at the high frequency end. A possible solution is offered by Suh [4] who has modeled the fourpoint antenna with a tapered ground plane and shown that acceptable beam pattern can be obtained over much more than an octave of bandwidth.

2.3 Mechanical considerations

Antennas that are made from rods, pipes or beams can develop significant resonances as was experienced in an early version of the MWA antenna. The resonance at 200 MHz, which was formed via the closed path around the welded aluminum beams of the bowtie, was barely noticeable in a single element, but was greatly amplified by mutual coupling between dipoles in a tile of 16 dipoles. This resonance resulted in a strong horizon sidelobe, at azimuths aligned with the dipoles, in the "embedded" dipole patterns and a corresponding 3 dB dip in the zenith gain of the tile. The amplification of the resonance via coupling is the same mechanism that makes the parasitic elements of a yagi into a phased array and in the case of the MWA prototype the spacing between dipole elements was just right to phase-up the coupling. To avoid the resonance the MWA bowtie dimensions were changed to make it wider from tip to tip but shorter in height moving the resonance to 240 MHz where it was no longer enhanced by the parasitic coupling.

Figure 3. MWA antenna without LNAs

Figure 4. EDGES antenna

Making the elements from plates, as is done in the EDGES fourpoint antenna avoids these resonances but increases the wind loading and requires more mechanical parts to support the plates.

3. Balanced to unbalanced conversion

Dipole antennas need a "balun" to produce an unbalanced output compatible with the receiver electronics. In the case of the MWA an active balun is formed by first amplifying each arm and then combining these with a 180 degree phase shift. Typical common mode rejection is about 20 dB. In the case of EDGES a compensated ferrite choke balun is used. The passive choke balun has approximately 0.5 dB loss which results in an increased receiver noise temperature but has more than 40 dB common mode rejection. Common mode rejection is important because common mode signal from the dipole will typically be similar to that from a vertical wire with a null at the zenith and a maximum at the horizon with vertical polarization. In addition variations in the common mode rejection produce variations in the polarization.

4. Calibration

The EDGES antenna is interfaced to the LNA via a switch which connects to the antenna, an ambient load and a calibrated noise source. This 3-position switch obtains the following 3 equations:

$$p1 = g(Ta + Tr) + c \tag{2}$$

$$p2 = g(Tl + Tr) + c \tag{3}$$

$$p3 = g(Tl + Tcal + Tr) + c \tag{4}$$

where *p1,p2* and *p3* are the measured power, *g* is the bandpass gain, *Ta, Tr, Tl* and *Tcal* are the antenna, receiver, load and calibration temperatures respectively and *c* is a constant, which can be solved for *Ta*. However if the antenna impedance differs from that of the load part of the power from the antenna is reflected and the receiver noise is not constant as it changes with the antenna impedance. The effect of the changes in reflected receiver noise could be eliminated by placing an isolator between the antenna and the LNA but isolators have limited bandwidth. Another solution currently being explored is making corrections in software based on an accurate noise model for the LNA along with ancillary measurements of the antenna impedance. Preliminary results of the use of antenna impedance measurements, shown in Figure 5, along with a noise model of the LNA to predict the sky spectrum are shown in Figure 6 below:

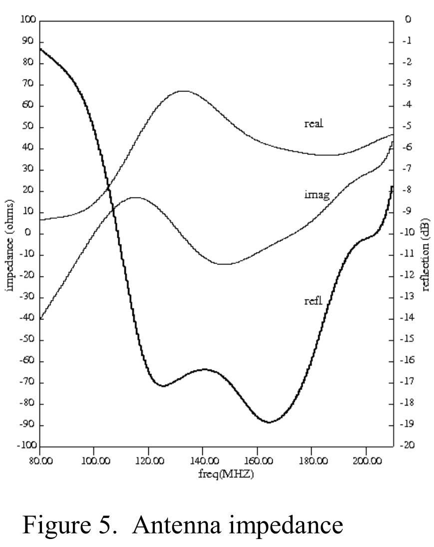

Figure 5. Antenna impedance

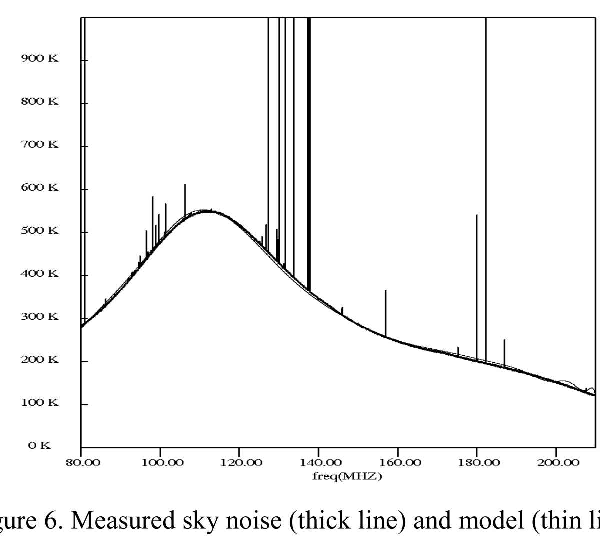

Figure 6. Measured sky noise (thick line) and model (thin line)

In the case of the MWA and other arrays which have "active" antenna elements the calibration has to be performed using measurement of known radio sources. A relatively simple method [6], which may be accurate enough for many observations, involves observing the variation of the autospectra with local sidereal time, comparing this with model of the tile beam convolved with the sky map of Haslam et al [7] and solving for the effective receiver noise. It should be noted that unknown or unmodeled variations in the gain of the LNA or receiver can bias the estimates so temperature measurements of temperature-sensitive components are needed to make gain corrections. In the future the rapidly declining cost and size of complex analog components might make it possible to include a switch and noise injection at each LNA. In addition the calibration accuracy can be improved by correlating each tile against 2 tiles or single antennas with full calibration.

5. Conclusion

Low frequency antennas in the 10 to 300 MHz frequency range can cover at least an octave bandwidth with near optimum performance and an even larger range with acceptable performance. Accurate calibration is still a challenge but progress is being made using ancillary measurements and LNA noise models.

6. Acknowledgements

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7. References

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