Analysis of a Low-Gain Antenna & Front End for Low Frequency Radio Astronomy

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1 Introduction

Proposed new low-frequency radio telescope arrays such as the Long Wavelength Array (LWA) will consist of many low-gain antennas which are combined through beamforming or correlation. The system temperature will be lower-bounded by Galactic background noise, which is very bright below 100 MHz. This report describes a method of analysis for determining the noise performance of an antenna plus front end with respect to this lower bound. A "droopy dipole" antenna with a simple active balun design is analyzed as an example.

2 Theory

In this analysis we consider the following components:

1. **A low-gain antenna.** The antenna delivers a power spectral density of $kT_{sky}(\nu)/2$ into a matched load, where k is Boltzmann's constant (1.38×10^{-23} J/K), $T_{sky}(\nu)$ is the antenna temperature due to the Galactic noise background, and the factor of $\frac{1}{2}$ accounts for the fact that two orthogonal polarizations are required to capture all of the available power. $T_{sky}(\nu)$ is quantified in [1] for low-gain antennas and frequencies below 120 MHz. The other important parameter for the antenna is the terminal impedance $Z_A(\nu)$ which, in general, varies considerably with frequency ν over the frequency range of interest.

2. **A preamplifier.** The "preamplifier" is defined as an amplifier connected directly to the terminals of the antenna, whose purposes are typically to (1) constrain the noise temperature of the system and (2) buffer the impedance of the feedline from that of the antenna. Antennas for low-frequency radio astronomy (such as dipoles) will typically be balanced, whereas coaxial cable feedlines are unbalanced; thus, the preamplifier may also serve as a balun to convert the balanced output of the antenna into a single-ended input for a coaxial cable. The preamplifier is described in terms of its input impedance Z_p, gain G_p, and noise temperature T_p, none of which typically vary significantly in frequency. T_p can be sensitive to the impedance match at the preamplifier input, however this effect is technology-dependent and is difficult to model in a generic way. In this analysis, we will simply assume that this effect is insignificant compared to other effects, and note that this issue should be considered for future study.

3. **A feedline.** The feedline connects the preamplifier to the rest of the receiver, which is typically located in a different place. The feedline is described in terms of $G_f(\nu)$, which is it's gain as a function of frequency. Note $G_f(\nu)$ is defined as *gain* (not loss) and therefore is always less than 1.

Let $S(\nu)$ be the power spectral density of the desired signal – that associated with $T_{sky}(\nu)$ – as it appears at the output of the feedline. One finds:

$$S(\nu) = \frac{1}{2} k T_{sky}(\nu)(1 - |\Gamma(\nu)|^2) G_p G_f(\nu) \tag{1}$$

where $1 - |\Gamma(\nu)|^2$ is the fraction of power sourced by the antenna which is successfully transferred to the preamplifer. This fraction is variable and often much less than 1 due to the impedance mismatch between antenna and amplifier. $\Gamma(\nu)$ is the voltage reflection coefficient at the antenna terminals looking into the preamplifier and is given by

$$\Gamma(\nu) = \frac{Z_p - Z_A(\nu)}{Z_p + Z_A(\nu)} \tag{2}$$

Also appearing at the output of the feedline is noise due to a variety of mechanisms. These include:

- **Environmental Noise**, which is defined here as the noise received by the antenna due to terrestrial noise sources. This is anticipated to be the sum of two components: (1) The temperature due to that part of the antenna pattern which intercepts the surface of the Earth, and (2) the aggregate din of man-made activity, which is known to exhibit noise-like spectra. Concerning (2), an analysis of Tan and Rohner [2] of existing data on man-made radio noise in "quiet rural" scenarios puts the associated power spectral density about a factor of 5 below that of the Galactic background toward the poles. It is difficult to refine this factor further without specific information regarding the design of the antenna and its location; thus, we will assume that this factor is sufficient to make man-made noise insignificant relative to T_{sky}. Concerning (1), a worst case would be an isotropic antenna pattern and a physical temperture of 290 K for the surface of the earth, which would yield an environmental noise temperture $T_{env} \sim 145$ K. The associated power density measured at the output of the feedline would then be:

$$N_{env}(\nu) = \frac{1}{2}kT_{env}(1 - |\Gamma(\nu)|^2)G_pG_f(\nu) \ , \ T_{env} = 145 \text{ K} \tag{3}$$

  However, this is very pessimistic since most reasonable antennas will have patterns which are "$\cos\theta$" in form; i.e., will have relatively low gain at and below the level of the horizon. Furthermore, it is noted that 145 K is small compared to the brightness temperture of the Galactic background at the frequencies of interest. Thus, we chose to neglect the contribution of environmental noise in this analysis.

- **Preamplifier-generated noise**, which can be defined in terms of the preamplifier's input-referenced noise temperture T_p as

$$N_p(\nu) = kT_pG_pG_f(\nu) \tag{4}$$

- **Feedline-generated noise**, arising from feedline loss and can be defined in terms of the physical temperture T_{phys} as

$$N_f(\nu) = kT_{phys}(1 - G_f(\nu)) \tag{5}$$

3 Example: A Droopy Dipole with a Simple Active Balun

In this section, we apply the above analysis to the case of simple antenna and active balun.

The antenna considered in this case is a very simple inverted-"V" ("droopy") dipole. Such an antenna can be constructed from inexpensive 1/2" copper pipe. Each arm of the dipole is 1.9 m long, resulting in resonance at $\sim$ 38 MHz. Bending the arms downward at a 45° improves the pattern characteristics while lowering the terminal impedance to 50Ω (balanced) at resonance. This design was analyzed using a NEC-2-based method-of-moments software package, assuming typical ground characteristics ($\sigma = 5 \times 10^{-3}$ S/m, $\epsilon_r = 13$). The results are shown in Figures 1 and 2.

For the sake of example, let us assume that the active balun consists of a cascade of two Mini-Circuits HELA-10D surface-mount balanced amplifiers followed by a transformer serving as balun. The HELA-10D is a simple and inexpensive ($\sim$\$20) device with gain $\sim$ 10 dB, noise temperature $\sim$ 360K, and input 1 dB compression point of about +20 dBm. This device has balanced 50Ω inputs and outputs, which facilitate a good match at resonance at least. If we assume that the analog signal must travel to a receiver in an electronics hut over a low-cost RG-58-type coaxial cable 500 ft long, then a second HELA-10D is required to provide sufficient gain to overcome noise due to feedline loss, as we shall see shortly.

For this configuration, Figure 3 shows the relative contributions of the Galactic background, preamplifier noise, and cable loss as seen at the input of a receiver at the far end of the feedline. Although the impedance mismatch efficiency of this antenna is very poor away from resonance, Figure 3 reveals that this design is nevertheless noise-limited by the Galactic background over a frequency span at least 10 MHz wide. The explanation for this is simply that the Galactic noise background is extremely bright at these frequencies.

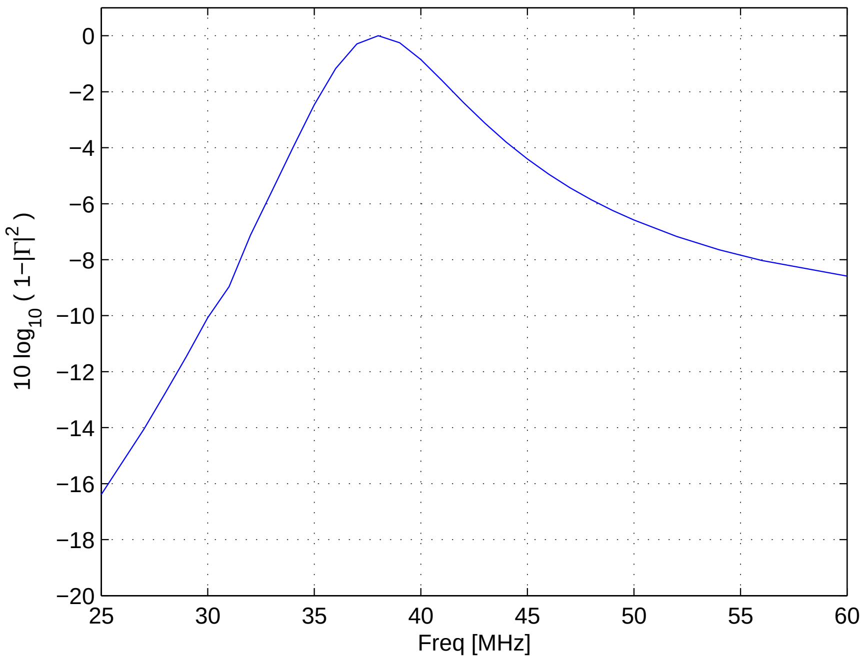
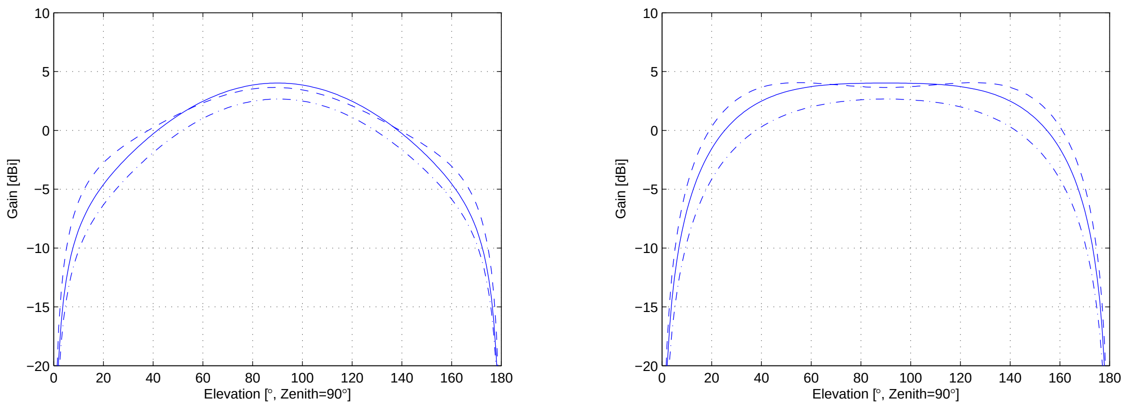


Figure 1: The "impedance mismatch efficiency" $1 - |\Gamma|^2$ for the droopy dipole taking into account the imperfect ground described in the text. This quantity is the fraction of power captured by the antenna which is accepted by an active balun with 50Ω input impedance.



(a) E-Plane

(b) H-Plane

Figure 2: Co-polarized gain of droopy dipole at 25 MHz (*Dash*), 38 MHz (*Solid*), and 55 MHz (*Dash-Dot*) taking into account the imperfect ground described in the text. Note that the gain is in fact very low at and below the horizon, suggesting that the noise contribution from the Earth's brightness temperture will be very low, as suggested in the text.

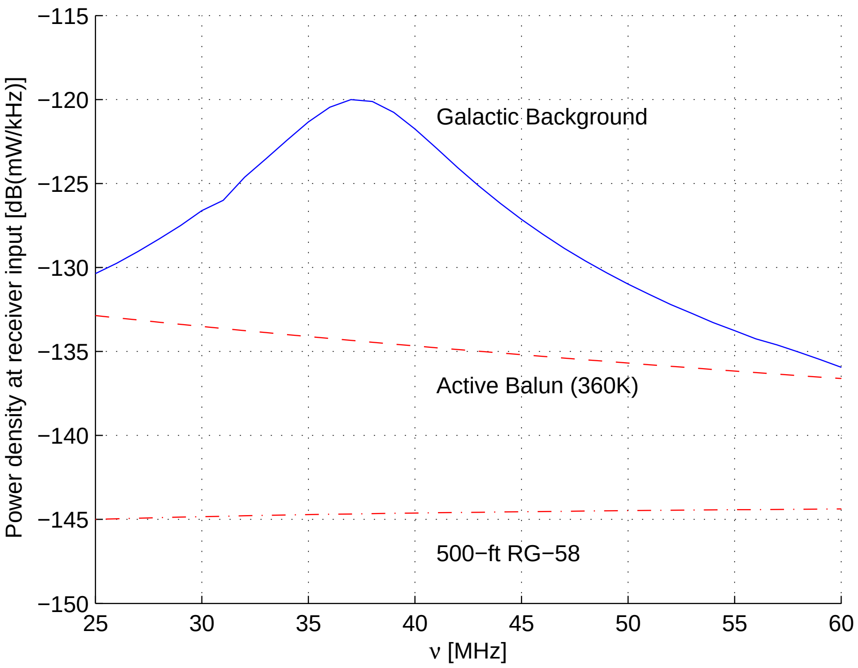


Figure 3: Power spectral density (PSD) presented to a receiver due to the Galactic background noise, the noise temperature of the proposed active balun, and the loss-induced noise temperature of 500-ft of RG-58 feedline. The Galactic background intensity was computed using the method described in [1]. Note that the receiver will be Galactic background-limited by at least 4:1 from 30 MHz to 48 MHz, and by 10:1 from 33 MHz to 43 MHz.

References

[1] S.W. Ellingson, "The Radio Sky Background below 120 MHz" (Informal report), June 19, 2004. Available at: http://www.ece.vt.edu/∼swe/lwa.

[2] G. H. Tan and C. Rohner, "The Low Frequency Array active antenna system," *SPIE*, 2000.