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Spectra of OVRO-LWA signals at correlator: predicted vs. observed

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Spectra of OVRO-LWA signals at correlator: predicted vs. observed

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Abstract— The variation with frequency of the power spectral density (PSD) of OVRO-LWA signals is significantly different than expected within the 25-85 MHz observing band, both for the core antennas (coax-connected) and the expansion antennas (fiber-connected). We observe that the peak of the spectrum is at 33 MHz and the minimum is at 85 MHz; this much is as expected. At the antenna (front end output), the ratio of PSDs at these frequencies is predicted to be 8.1 dB. At the correlator, it should be the same for fiber-connected antennas, and it should be 9.6 to 18.2 dB for coax-connected antennas, depending on cable length. We actually observe a much steeper dropoff. The range is 11.1 to 17.7 dB for fiber-connected antennas (median 14.7 dB) and 11.4 to 20.7 dB for coax-connected antennas (median 18.6 dB).

I. Predicted Spectrum

To determine the spectrum to be expected at the correlator, we must consider the spectrum of noise from the sky, the efficiency of coupling of that noise to the LNA at the antenna, the LNA's noise, and the variation in gain with frequency of the components between the antenna and the correlator. Over the 25-85 MHz observing band, the gain should be flat within about 1 dB except for the coax cables, whose attenuation increases with frequency.

Noise from the sky at our frequencies is dominated by diffuse emission from the galaxy. It was shown by Cane [1] and others that the brightness temperature in the vicinity of the galactic poles is

$$T_B = (43{,}000\ \mathrm{K})\ (f/20\mathrm{MHz})^{-2.55} \tag{1}$$

for frequencies f between 10 and 400 MHz. At times when most of the galactic plane is below the horizon, this is a good estimate of the brightness temperature of the whole sky, and thus it is the antenna temperature for any antenna that looks up from Earth.[1]

However, the LWA antenna's impedance varies widely over our frequency range. At most frequencies it is poorly matched to the first amplifier, so not all of its available power is delivered to the amplifier. The impedance and hence the mismatch efficiency have been determined by simulations, as shown in Figure 1 (from [2]). As a result of the dropoff of mismatch efficiency below 35 MHz and the continued increase in sky noise with decreasing frequency, the peak spectral density in the front end output is expected to occur at 33 MHz. Using (1) and Fig. 1, we can calculate the system temperature at the amplifier input for a few important frequencies.

- (43000K)*0.02 + 250K = 1110K at 20 MHz;
- (15300K)*0.28 + 250K = 4530K at 30 MHz;
- (11990K)*0.47 + 250K = 5890K at 33 MHz (peak);

[1] Other contributors to the antenna temperature include radiation from the ground and thermal noise from losses in the antenna itself. We assume that the antenna pattern — including ground screen — is such that there is much more gain toward the sky than toward the ground, and that losses within the antenna are small. The strongest discrete sources, Cas A and Cyg A, when above the horizon, can contribute almost as much as the galactic background at the high frequency end of the band, but much less over most of the band; we ignore those contributions here.

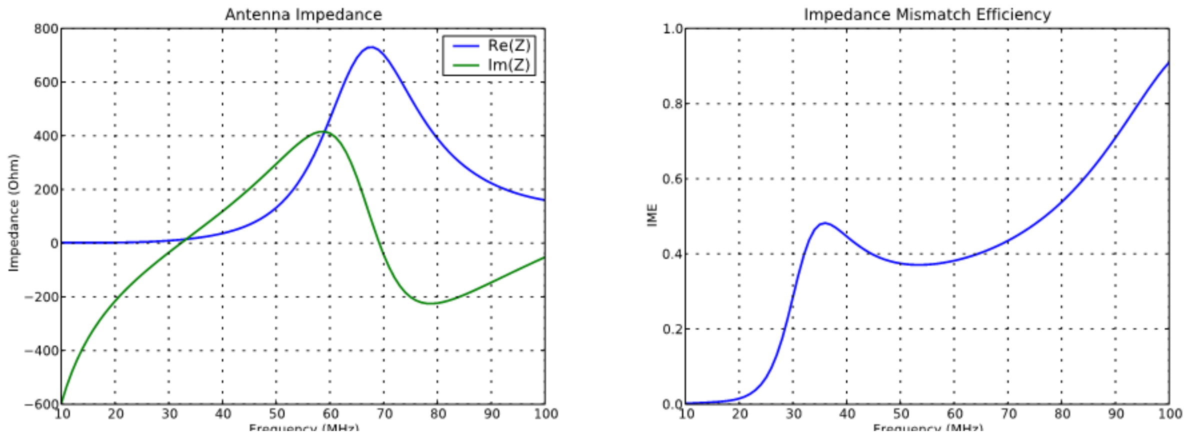

Figure 1. *Left:* Simulated terminal impedance of LWA antenna. *Right:* Resulting mismatch efficiency with respect to a 100 ohm differential load. From [2].

- (10320K)*0.49 + 250K = 5310K at 35 MHz;
- (1075K) *0.61 + 250K = 905K at 85 MHz (minimum).

This assumes that the differential amplifier's input impedance is 100 ohms (the nominal value) and that its noise temperature is flat at 250K and independent of source impedance. The latter assumption is likely inaccurate, but it is unimportant when the antenna temperature dominates.

We concentrate on the spectral densities at 33 MHz and 85 MHz, since these are the maximum and minimum within the observing band and their ratio gives the spectral dynamic range of the desired signal. At the antenna, this ratio is $R_{A:33\text{-}85}$ = 5890K/905K = 8.13 dB.

The 251 core antennas of the array are connected to the processing shelter by coaxial cables (Kingsignal PN KSR240DB, similar to Times Microwave PN LMR240) whose attenuation increases with length. The data sheet [3] gives attenuations from 150 to 2500 MHz which are well fit by

$$10 \log_{10} A = (0.109\text{dB/m}) \operatorname{sqrt}(f/150\text{MHz})$$

where A is the attenuation at frequency f. This allows us to predict the attenuations at 33 MHz and 85 MHz as 0.0511 dB/m and 0.0821 dB/m, respectively. Cables were ordered for specific lengths based on calculations [4] and measured by the vendor before delivery [5]; the lengths vary from 35.3m to 247.7m. From the termination points of these cables in the processing shelter there is an additional, similar cable for each signal that is about 5m long. This gives total lengths of 40.3m to 252.7m and estimated losses of 2.06 dB to 12.91 dB at 33 MHz and 3.31 dB to 20.75 dB at 85 MHz. Therefore the gain ratio for the cable is $R_{C:33\text{-}85}$ = 1.25 dB to 7.84 dB. Applying this to the PSD ratio at the antenna, we predict a PSD ratio (33 MHz/85MHz) at the analog receiver of

$$R_{R:33\text{-}85} = R_{A:33\text{-}85}\, R_{C:33\text{-}85} = 9.38 \text{ dB to } 15.97 \text{ dB (core)}$$

for the core antennas.

For the optically-coupled expansion antennas, the signal transmission should have negligible change in gain across the observing band, so for those we predict

$$R_{R:33\text{-}85} = R_{A:33\text{-}85} = 8.13 \text{ dB (expansion)}.$$

II. Observations

On 2019 March 11, spectra were measured digitally for the 512 digitized signals with all analog receivers set identically to wideband mode and attenuation of 24+10 dB. Wideband mode includes three cascaded filters: high-pass at 10 MHz; low-pass at 85 MHz; and band-reject at approximately 88 to 98 MHz. Figure 2 shows the simulated responses of these filters, assuming ideal components. In the practical realization, the rejection filter seems to be tuned higher in frequency, so that there is little attenuation below 85 MHz.

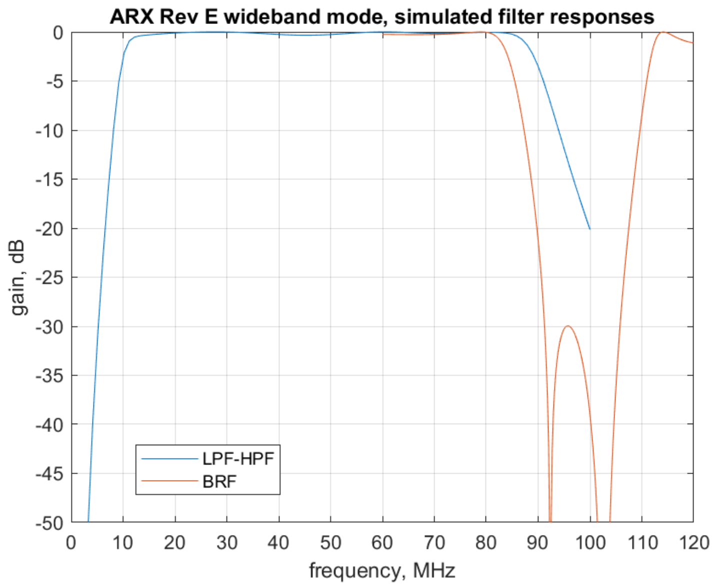

Figure 2. Simulated response of ARX filters in wideband mode, assuming ideal components.

Based on examination of all 512 spectra, those with very low signal level or obvious spectral anomalies were "flagged" and excluded from this analysis. The last 20 signals, which are reserved for the LEDA outrigger antennas, were all flagged because they do not use the ARX boards and do not have controllable gain. This left 448 unflagged signals, of which 395 (of 438, 44 flagged) are from coax-connected (core) antennas and 53 (of 64, 11 flagged) are from fiber-connected (expansion) antennas. The spectra of all unflagged signals are plotted in Figure 3, separated by core and expansion.

For nearly all signals, the maximum and minimum PSD over the observing band are near 33 MHz and 85 MHz, as expected. There is considerable power from RFI below 20 MHz and above 88 MHz, also as expected. These measurements were made at 17:33 UTC, which was 04:42 LST and 3h23m after local sunrise. The galactic center (RA 17h45m) was set (hour angle +10h57m), so sky noise was near minimum. Cyg A and Cas A were at hour angles +08h43m and +04h39m, respectively.

At 33 MHz, we see a variation in PSD among the signals of about 15 dB for the core antennas. This is more than expected from the variation in cable lengths, which accounts for less than 11 dB. The remainder is presumably variation in electronic gain; there is a total of 112 dB of gain in each signal path (37 dB it the front end and 75 dB in the ARX), so the 4 dB of excess variation is ±1.8%. There could also be some signals with excess loss in connectors or filters. For the expansion antennas, the 33 MHz PSD variation is about 12 dB, none of which can be explained by cable loss. The path has 134 dB of electronic gain (due to an additional 21.5 dB in the optical transmitter), of which the variation is ±4.5%, but there is also variation in the laser modulation sensitivity, the photodetector sensitivity, and in optical connector loss. In normal operation, all of these gain variations are easily compensated by setting the variable attenuators in each ARX, but for these measurements all attenuators were intentionally set the same. Except for the cable length variation, all these variations in overall gain should be constant with frequency.

The spectral dynamic range in the signals is also more than we predicted in Section I

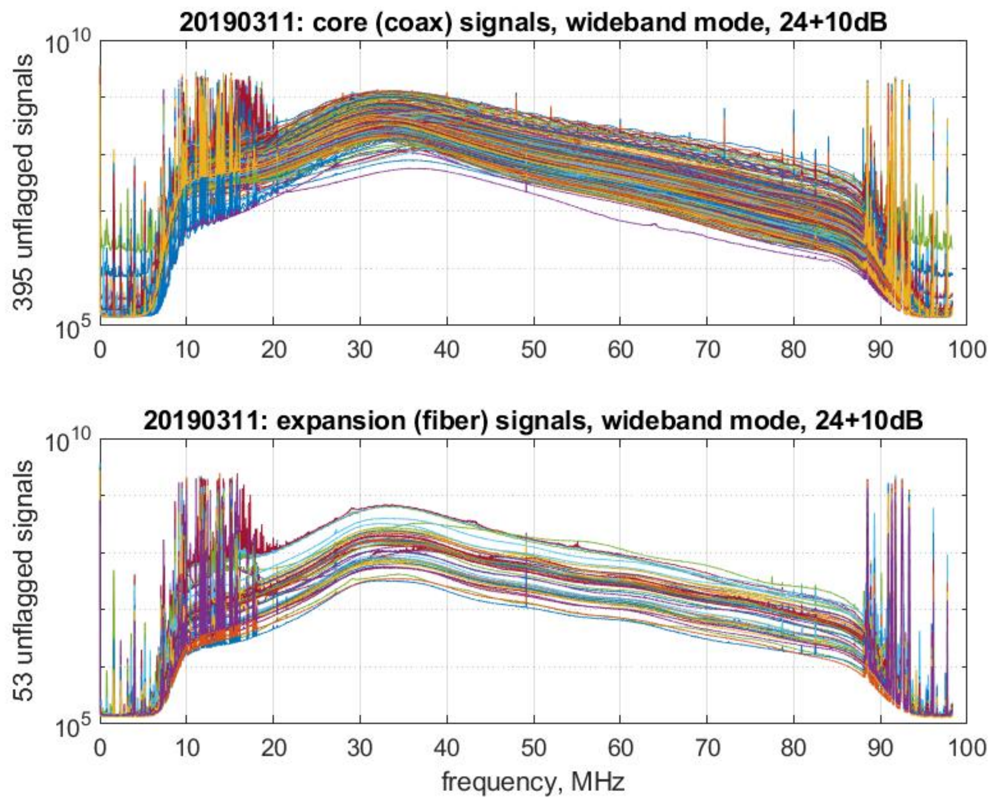

Figure 3. Spectra of the 448 unflagged signals, separated into coax-coupled and fiber-coupled.

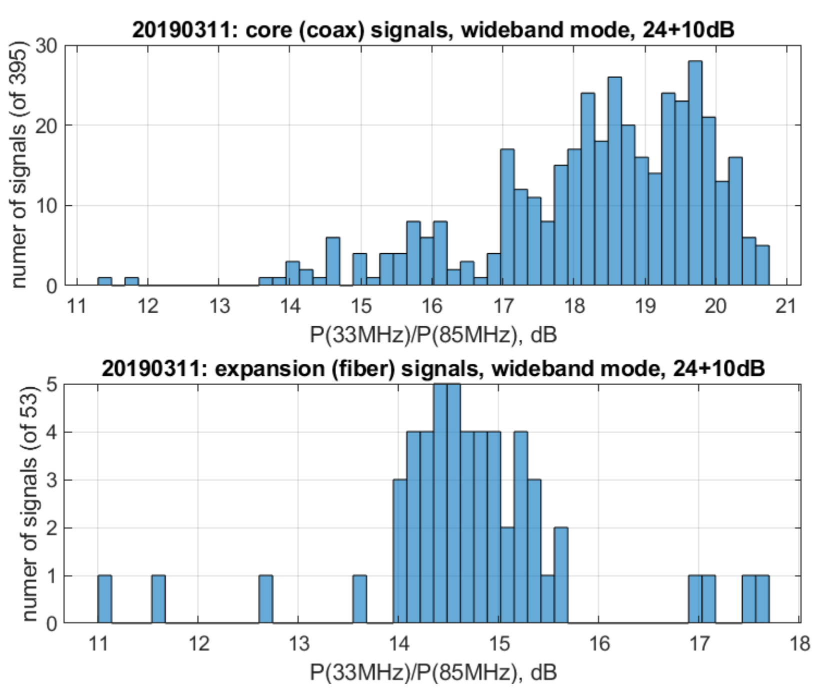

Figure 4. Observed distribution of the ratio of 33 MHz to 85 MHz power spectral density among 448 unflagged, digitized signals, showing those from core and expansion antennas separately.

above, as measured by the ratio of PSD at 33 MHz to that at 85 MHz. A histogram of that ratio for all unflagged antennas is plotted in Figure 4. Neglecting outliers, the value for the core signals ranges from 13.6 dB to 20.7 dB, far larger than the predicted 9.4 dB to 16.0 dB. For the expansion antennas, we see a tighter distribution of 14.0 dB to 15.6 dB, but all are much larger than the predicted 8.1 dB.

The effect of cable length is shown in Figure 5, where both overall gain (represented by power at 33 MHz) and gain slope (represented by the 33MHz/85 MHz power ratio) are plotted against cable length.

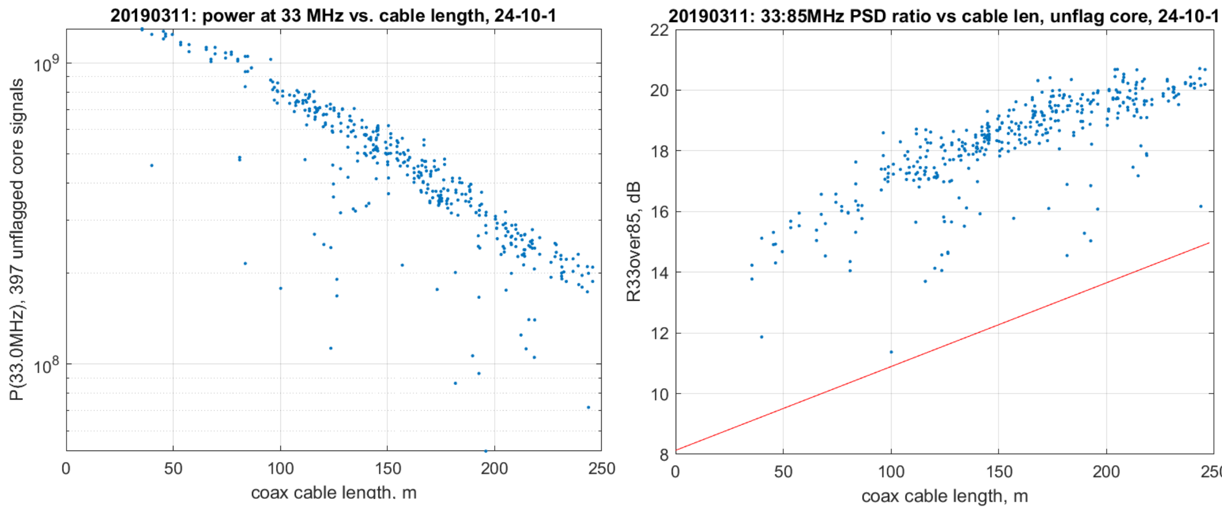

Figure 5. Overall gain (left, represented by power at 33 MHz) and gain slope (right, represented by 33 MHz to 85 MHz PSD ratio) vs. coax cable length for 395 unflagged core signals. For both quantities, the logarithm should vary in proportion to length; most signals form a reasonable fit to that line but many fall below it. For total gain, this may be due to variations in electronic gain unrelated to cable length, but for gain slope the outliers as well as total slope are unexplained. Red line is the expected 33MHz/85MHz ratio vs. length; most signals are about 6.5 dB above it.

III. Discussion

The higher-than-predicted slope in PSD is unexplained. For many of the core signals, the variation of slopes among signals is consistent with differences in coax cable lengths, but it is only some outlier signals that have slopes close to the predicted values (Fig. 5).

For the fiber-connected expansion antennas, no variation in slope is predicted. The outlier cases in Fig. 4 suggest something pathological in those signals, but they are otherwise normal so we have no idea what it might be. Even the minimum slope of 11.2 dB is significantly more than the predicted value of 8.1 dB, and the median of 14.7 dB is much more.

An early field measurement of an LWA1 antenna ([2], Fig. 2.12, reproduced here as Figure 6) showed a ratio of 12 dB, still more than predicted but smaller than we are seeing for all but the smallest-slope outliers. That measurement also showed an unexpected slope in receiver noise (3.5 dB for 33MHz to 85 MHz), suggesting that the front end gain may not be flat.

Most things that might make the spectrum at the antenna different from that predicted by the theory of Section I would cause a decrease in $R_{A:33\text{-}85}$ rather than an increase. For example, the slope would decrease if a large fraction of the sky noise were from discrete sources like Cyg A, Cas A, and the Sun rather than from the galactic background. It would also decrease if partial saturation is occurring at the spectrometer output.

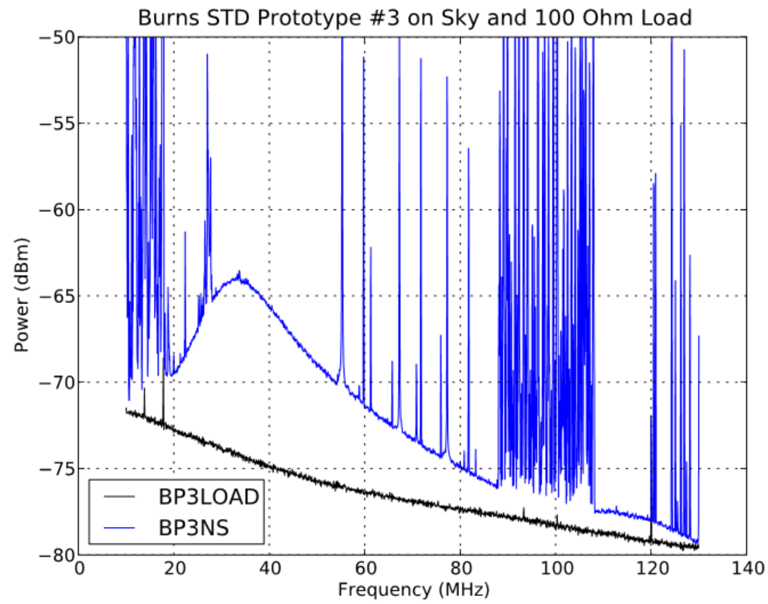

Figure 6. Spectrum at front end output of LWA1 prototype antenna, from [2]. Lower curve shows the same output with 100 ohm resistor substituted for the antenna at front end input.

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