LWA-OVRO Memo No. 7

Cable Reflections in Autocorrelation Delay Spectra

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Submitted 2020 September 10

To cite this memo in another document, use: "LWA-OVRO Memo 7, 2019 Jun 27, <u>http://tauceti.caltech.edu/LWA/lwamemos.html</u> "

OVRO-LWA REPORT #7

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Cable Reflections in Autocorrelation Delay Spectra

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1. Introduction

For the Cosmic Dawn key science goal of detecting the redshifted 21cm signal around redshift z=17 with OVRO-LWA-352, we wish to minimize spectral structure in the uncalibrated bandpass of the instrument.

An effective method to quantify bandpass spectral structure is to use the delay spectrum of the bandpass. The delay spectrum is the Fourier transform along frequency of the bandpass. In this memo, we briefly review the delay spectrum as it pertains to redshifted 21cm Cosmic Dawn measurements and then analyze existing OVRO-LWA autocorrelation spectra as a proxy for bandpass information of the current system.

Any uncorrected bandpass structure in the telescope, whether from the chromaticity in the antenna beams or from the signal chain, will convolve with the intrinsic foreground delay spectrum, spreading the foregrounds to higher delay modes and causing more contamination with the 21cm signal. Thus, one of the primary goals for 21cm instrument design is to minimize the instrument's bandpass structure. While sky-based calibration can correct some bandpass structure, minimizing the instrument's intrinsic structure alleviates burden on the calibration.

We expect the 21cm fluctuations to be ~50 dB below the total foreground power during Cosmic Dawn, although this is dependent on the frequencies and spatial scales that will be probed. Some explanations for the EDGES absorption profile predict larger 21cm fluctuations. Nevertheless, we would ideally set a requirement that instrumental bandpass structure be suppressed be at the -60 dB level on the spectral scales that correspond to 21cm fluctuations.

2. Review of delay spectrum

The delay spectrum is the square of the absolute value of the Fourier transform along frequency. In the context of 21cm cosmology, the delay spectrum of a visibility maps approximately to the component of the 21cm power spectrum that lies along the line-of-sight. The approximation approaches the ideal one-to-one mapping for small fields of view.

The delay spectrum is useful because the 21cm signal and the contaminating foregrounds fall into distinct regions in the delay spectrum. Foregrounds are spectrally smooth and intrinsically occupy modes of low-delay, whereas the 21cm signal has more spectral structure and occupies modes extending to higher delays.

Horizon limit: The range of delay modes occupied by foregrounds is dependent on the baseline length and generally should not extend above the delay that corresponds to the light travel time between the two antennas that make the baseline. This is called the "horizon limit" in the 21cm community. For the OVRO-

LWA core, with its maximum baseline length of ~200 meters, the horizon limit corresponds to a delay of about <u>667 nanoseconds</u>. Shorter baselines within in the core will have proportionally lower horizon limits, with the shortest ~10 meter baselines having horizon limits of about <u>33 ns</u>.

Range of interest for 21cm signal: The range of spatial scales of interest for the 21cm power spectrum spans approximately <u>1 to 100 comoving Mpc</u>. These spatial scales correspond to Fourier modes between 0.01 and 1 Mpc⁻¹. We can use Morales & Hewitt (2004), their Equation 4, to find the range of frequency scales observed today that correspond to spatial scales of interest:

Here, $E(z) \approx [\Omega_M (1+z)^3 + \Omega_\Lambda]^{1/2}$ for a flat universe and H_0 is the Hubble constant (and we will use τ instead of η to represent delay). The range of spatial scales of interest at z=17 corresponds to frequency scales observable today of order <u>0.043 to 4.3 MHz</u>, centered around 78 MHz. This translates to a range of delay modes spanning <u>37 ns to 3700 ns</u>. The peak in power for the 21cm signal is generally expected around 10 Mpc scales (k=0.1 Mpc⁻¹), corresponding to 0.43 MHz in frequency and 370 ns in delay.

Property	Value(s)	Units
Expected 21 cm fluctuation amplitude	10 to 100	mK
Foreground amplitude	1800	K
	(typical; at 75 MHz)	
Required dynamic range	106	
21cm spatial scales	$1 < \Delta r_z < 100$	Mpc
21cm Fourier modes	$0.01 < k_z < 1$	Mpc ⁻¹
21cm frequency scales	$0.043 < \Delta f < 4.3$	MHz
21cm delay modes	$37 < \tau < 3700$	ns
21cm peak power delay mode	~373	ns
Intrinsic (source at zenith) foreground delay modes	< 100	ns
OVRO-LWA 200-meter core "horizon limit"	667	ns

Table 1. Summary of relevant values

3. Analysis of (Phase 2) OVRO-LWA auto-correlation spectra

We analyze 1-second autocorrelation spectra from all 512 antenna inputs in the current (Phase 2) OVRO-LWA telescope acquired on 04-Apr-2019 19:17:17. Data were provided by L. D'Addario on 6/18/2019. The data are described as:

Each p value is a 1-second accumulation (24000 samples) of the magnitude-squared filter bank output into a 32b unsigned register on the FPGA, converted to a double. Thus the largest possible value is 4e9, but the FPGA register can overflow (it does not saturate); many values in the low-frequency and high-frequency RFI bands are near 4e9 and thus are not meaningful.

The data are further processed for this analysis with the following steps:

1. The sub-band spanning 40 to 80 MHz is selected and other frequencies are discarded. This is done to omit the regions with high RFI in the FM band (>87 MHz) and the ionosphere band (<20 MHz) and to focus on the part of the band of most interest to 21cm cosmology.

- 2. All spectra are crudely normalized into sky temperature units by scaling the raw values to 1800 K at 75 MHz. This is done so the spectra can be plotted along with the EDGES low-band spectrum from Bowman et al. 2018. We do not expect the OVRO-LWA spectra to have the well-calibrated bandpass of EDGES, but it is useful to see the relative amount of structure visually.
- 3. A median filter is applied to each spectrum using a sliding 10-channel box. This is done to eliminate narrow band RFI remaining in the spectra.
- 4. Bad inputs were removed from the dataset by keeping only spectra for which the median normalized temperature value across the spectrum was greater than 2500 K. 465 spectra were retained after applying this filter.

Figure 1 shows the ensemble of autocorrelation spectra after the above processing.

We next calculate the delay spectrum for each autocorrelation spectrum. It is necessary to use a window function during the Fast Fourier Transform (FFT) to reduce the sidelobe in the resulting delay spectrum, however it comes at the expense of worsening the effective delay channel resolution by correlating neighboring channels. We use a standard Blackman-Harris window function, which is multiplied to each autocorrelation spectrum before performing the FFT. Lastly, we calculate the power spectrum in delay space by taking the square of the absolute value of each delay channel after the FFT.

Figure 2 shows the calculated delay spectra. Individual summaries of each input are attached at the end of this memo.

3.1. Dynamic Range and cable reflections

The key performance metric for the instrument is the ratio in delay space between the peak foreground power and the instrument's systematic limit. We will quantify this for each input by calculating the ratio between the τ =0 peak delay value, which is dominated by the foreground power, and the largest delay spectrum amplitude found for τ >225 ns (beyond the foreground-dominated zone). To facilitate instrument design, we will express this as a dynamic range in dB in power units (square root of delay spectrum amplitude), rather than as a ratio in the delay power spectrum directly.

Figure 2 shows large peaks in the coax inputs at delays generally above $\tau \approx 500$ ns. Such peaks are interpreted as cable reflections and they limit the dynamic range for most inputs. Figure 3 shows the delay spectrum for an individual input and marks its largest peak beyond the foreground zone. As is the case with some inputs, the example in Figure 3 shows multiple peaks at integer multiples in delay of the first peak. These are interpreted as multiple cable reflections within the same cable.

Cable length: The delay of the primary cable reflection peak for a given input is related to the cable length between the antenna and the backend. The cable length, L, can be derived from the delay of the peak according to: $L = \frac{v_c \tau}{2}$, where v_c is the wave propagation speed in the cable. For this analysis we use v_c=0.84c, appropriate for the LMR 240 cables used by the LWA (we note LMR 400 has a similar v_c=0.85c). Thus, the cable length is approximately $L \approx 0.126 \left(\frac{\tau}{1 \text{ ns}}\right)$ meters.

Noise floor: In addition to dynamic range and cable length, we also estimate the noise floor in the delay spectrum by taking the median of the delay spectrum over the range of delays relevant to 21cm cosmology. We express the noise floor in dB in power, similar to the dynamic range.

Figures 4 and 5 show the dynamic range, noise floor, and inferred cable length from each of the delay spectra for all inputs. Cable reflections are evident for most inputs. Features and trends are described in the figure captions. Figure 6 shows a comparison between the inferred cable lengths from this analysis and

actual measured cable lengths from the vendor (data provided by L. D'Addario on 6/26/2019). The agreement is quite good.

3.2. Fiber-connected antennas

The fiber-connected inputs have short coaxial cables (~10 meters; S. Weinreb, private communication) from the antennas to the fiber converters. These short cables cause the first cable reflection to overlap with the foreground region in delay spectra, as show in Figure 7, making it difficult to separate the reflection peak and quantify its dynamic range. Nevertheless, inspection of the autocorrelation spectra show a clear ripple with period of 13 MHz for most fiber inputs. We can more easily identify the corresponding peak in the delay spectra if we subtract a 5th-order polynomial from the autocorrelation spectra before calculating the delay spectrum. Figure 8 shows the results of this modified processing, making the peak associated with the 13 MHz ripple clearly visible. Second reflection peaks may be evident, and higher-order peaks are not visible, although all higher-order peaks would be difficult to see given that the delay channel size is close to the peak spacing. We can place a limit on the relative amplitude of the second reflection peak compared to the first of about -15 dB.

4. Conclusions

We have seen that the delay spectrum of the autocorrelation spectra is useful to identify and quantify the cable reflections for the current system.

As noted in the introduction, the performance goal is a dynamic range for each input of $\underline{60 \text{ dB}}$ between the foreground peak at $\tau=0$ and the delay modes accessible for 21cm cosmology between approximately 150 ns and 3700 ns in order to ensure that the instrumental effects do not cause the foregrounds to contaminate the 21cm signal at delays beyond the intrinsic foreground region. In general, such performance could be accomplished by using long coaxial cables (450 meters) to connect to each antenna so that any cable reflections are beyond the range of interest. Alternatively, very short coaxial cables and fiber connections could be used for all antennas to push the first cable reflection into the foreground region of the delay spectrum. This would require using cables no longer than about ~5 meters and it would further require ensuring that second-order and higher reflections are highly suppressed since they would fall in the range of delays of interest.

In order to achieve the goal for OVRO-LWA-352 of 60 dB dynamic range, cable reflections need to be reduced by an additional 30-40 dB for OVRO-LWA-352 compared to the present Phase 2 system. Short of the comprehensive changes described in the paragraph above, this could be accomplished by careful attention to matching the ARX input impedance to the coaxial cables and/or by adding attenuators before/after the coaxial cables.

Fiber-connected antennas need special consideration. Ideally, we would limit their coaxial cable lengths to 5-10 meters. We further need to ensure that second-order and higher reflections in these short cables are highly suppressed through similar means as described above.



Figure 1. Summary of processed auto-correlation spectra that will be used for delay spectrum analysis. The ideal foreground reference curve assumes a spectral index of -2.6 in brightness temperature and an amplitude of 1800 K at 75 MHz.



Figure 2. (top) Summary of delay spectra for the 465 "good" antenna inputs. All spectra are normalized to their τ =0 power, which is dominated by the foreground power. The floor of the reference "Ideal foreground" curve is limited by the dynamic range of the Blackman-Harris window function. (bottom) Close-up of the low-delay region. Due to the reasonably smooth OVRO-LWA bandpass on large spectral scales, all curves generally track the ideal foreground shape for delay modes below ~100 ns. The noise floor for the short 1-second accumulations used here is generally around amplitude of 10⁻⁷. The large peaks rising above the noise floor in the coax inputs are assumed to be due to cable reflections and discussed in the main text.



Figure 3. Example summary of an individual input (#304). The top panel shows the autocorrelation spectrum with a clear ripple present. The middle panel shows the delay spectrum with a large peak at $\tau=0$ due to the foreground power and a second substantial peak at about $\tau=900$ ns associated with the ripple in the autocorrelation and interpreted as a cable reflection (from a cable of length ~110 meters). This peak sets the limiting dynamic range for the input at 18.7 dB. The bottom panel is a close-up of the portion of the delay spectrum relevant to 21cm observations. Additional cable reflections at harmonics of the primary reflection are evident at about 1800, 2700, and 3600 ns.



Figure 4. Dynamic range as a function of the delay spectrum noise floor for each good fiber and coax input. The dynamic range for most inputs is clustered around 20-35 dB. The noise floor for each input was estimated from the median value of the delay spectrum outside the foreground zone. Most inputs have a noise floor around -38 dB. We cannot find dynamic range better than the noise floor. We see some antennas, particularly the fiber-connected antennas are clustered near the noise floor, whereas some coax-connected antennas have considerably lower dynamic range, typically due to their cable reflections. The dynamic range plotted for the fiber-connected inputs may not represent the dynamic range set by reflections in the short cables before the fiber converter.



Figure 5. Dynamic range as a function of inferred cable length. All cable lengths plotted here are inferred from the delay of the peak in the delay spectrum that sets the dynamic range. In most cases this peak corresponds to a cable reflection, but there are some exceptions. We see two clear trends. First, fiberconnected antennas tend to be at low-delay. This is consistent with the short <20 meter coax cables that connect the antennas to the fiber relays. Although most fiber-connected inputs have relatively high dynamic range, this does not indicate that the fiber-connected inputs have low cable reflections within their short cables, but rather the cable reflection power overlaps with the foreground region that we exclude from the dynamic range calculation. We cannot infer cable reflections easily when they overlap with the foreground zone in the calculated delay spectrum, as they do for coax cables less than about 25 meters. The second main trend is that, for coax cables, the dynamic range is correlated with the cable length. The longer the cable, the better the dynamic range. Signals have increased attenuation in longer cables. Crudely fitting a slope by eye to the trend (red line), we find about 10 dB of additional dynamic range per 100 meters of cable. Recalling that a reflected signal traverses each cable twice (down and back), this indicates that the cables have approximately 5 dB attenuation per 100 meters, roughly consistent with expectations (LMR 240 has 5.4 dB attenuation per 100 meters at 50 MHz and LMR 400 has 2.9 dB). The group of outlier antennas in the upper left are antennas for which our simple peak search failed to find the cable reflection (presumably the reflection was in the noise floor) or found other structure in the delay spectrum that was larger than the cable reflection peak.



Figure 6. Comparison of estimated cable lengths from delay spectra to actual measured cable lengths by Burns Industries. The actual cable lengths plotted include both the long external cable length and an added 10 meters of internal cabling inside the electronics enclosure, based on (from L. D'Addario): "The attached file gives the cable lengths for the core antennas. The column called "Burns Industries"/"Length, m" is the actual length of the KMR-240 cable from the antenna to the Type-N bulkhead connector at the back wall of the shielded part of the shelter. From there, approximately 10m of additional cable, in two pieces, connects to the input of the ARX board." The red line shows the ideal one-to-one mapping. We assumed a cable propagation velocity of 0.84c for this analysis, based on the LMR-240 specifications. Assuming lower propagation speeds would result in shorter estimated cable lengths. The group of outlier antennas in the lower right are antennas for which our simple peak search failed to find the cable reflection (presumably the reflection was in the noise floor) or found other structure in the delay spectrum that was larger than the cable reflection peak.



Figure 7. Similar to bottom panel of Figure 2, but zoomed in even further to low-delay portion of the spectrum. Inputs connected by fiber have a clear shoulder of power beyond the foreground zone. This is likely associated with the multiple cable reflection from their short coaxial cables connecting the antenna to the fiber connection. See Figure 8 for additional discussion.



Figure 8. Delay spectra of only fiber-connected inputs processed with a modified procedure. A 5th-order polynomial was fit and removed from each input's autocorrelation spectrum before calculating the delay spectrum. A cable reflection peak at ~75 ns is clearly visible, although the exact delay of the peak is not precisely identified due to the delay channel spacing (25ns). The peak corresponds to a cable length of ~9 meters. A possible second reflection peak may be present around 175ns, contributing to the shoulder present in Figure 7.

















































































































































































































































































































































































































































































































































































































































































































































































































































































































































































































































