Status of LWDA Electronics RF Emissions Measurements, Part II

Aaron Kerkhoff

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The results of recent RF emissions measurements of LWDA components are summarized in this memorandum, which is a follow-on to [1]. First, the results of emissions measurements performed at ARL:UT of LWDA electronics boards with final enclosure designs are presented. The results of measurements performed in order to estimate the shielding provided by the electronics hut installed at the LWDA site are given. Next, the results of emissions measurements performed on the LWDA receive chain design at NRAO's reverberation chamber at the VLA are presented. Finally, the VLA emission measurements and electronics hut shielding measurements are used to estimate the shielding required from the shielded rack and rack chassis that LWDA electronics will stored in so that system emissions are below the EVLA limit.

Continuation of Emission Measurements of Individual LWDA Components at ARL:UT

Measurements were performed at ARL:UT in order to estimate the emissions of a near-final version adder board (v2) and a final version receiver (v3) when placed in final versions of their respective enclosures. The same emissions test setup and procedure as described in [1] was used to perform these measurements. Again, due to time constraints, measurements were only performed at a single position and orientation. As in [1], the raw emission measurements were reduced to an EIRP emissions estimate, which includes 300 m of free space loss to account for the distance between the LWDA and the closest VLA dish; this quantity can be directly compared with EVLA emission limits. Pictures of the enclosed adder and receiver board are given in Figures 1 and 3, respectively. These enclosures are catalog items from Compac, which they custom milled to fit our circuit boards. During measurements of each of these components, all SMA connectors were terminated in 50Ω, while all RJ-45 / USB jacks were left open.

The emissions of the enclosed adder board are compared with a bare adder board in Figure 2. The emissions of the bare adder board are relatively high with peak emissions occurring at 1.2 GHz of roughly 84 dB above EVLA limits. The shielded enclosure, however, achieves significant attenuation of the emissions, typically 30 dB between 0.4 to 2.6 GHz. The enclosure also provides 10 to 20 dB of shielding between 2.7 and 6.5 GHz. Above, 5.5 GHz, measurements with the enclosure are limited by the setup noise floor. The peak emissions of the adder, which occur at 0.9 GHz, are 44 dB above the EVLA limits, which is a 40 dB improvement over the bare adder board.

The measured emissions due to an enclosed LWDA receiver is shown in Figure 4. The emissions due a receiver placed in a prototype version of the enclosure (these results were originally shown in [1]), and a bare receiver are included for comparison. As can be seen, the emissions due to the receiver in a prototype and a final version of the enclosure are nearly identical. The maximum emissions of the receiver in the final enclosure, which occur at 1 GHz, are 36 dB over EVLA limits, which is much improved over the bare receiver board. The emissions of the enclosed receiver are mostly below EVLA limits above 3 GHz. Note that the noise floor of final enclosure measurement is less than the other two measurements shown, since a lower spectrum analyzer resolution bandwidth (10 Hz rather than the typical 30 Hz) was used in that measurement.

Fig. 1. Final design of LWDA adder board enclosure.

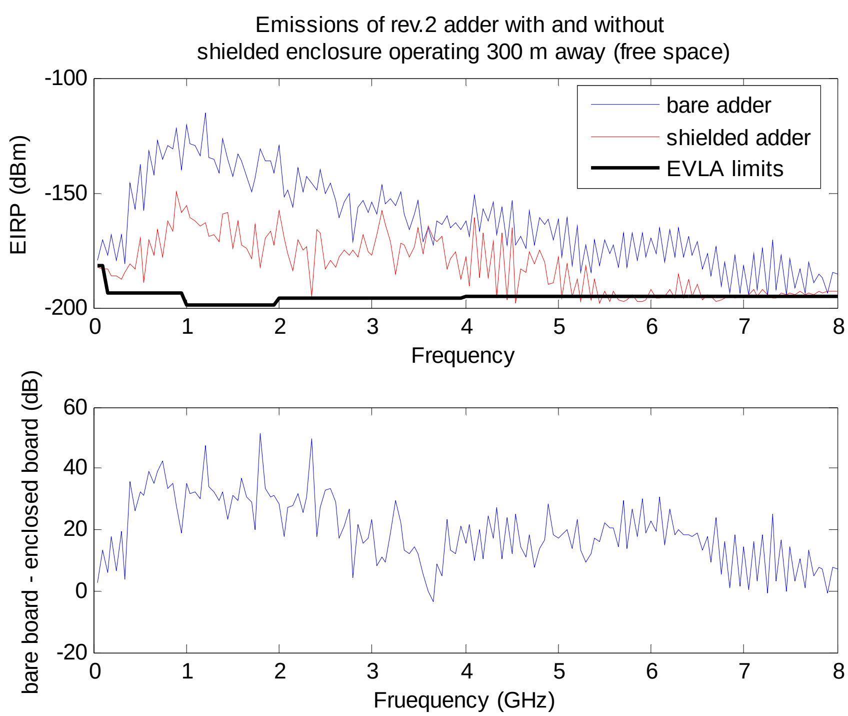

Fig. 2. Comparison of emissions by rev. 2 LWDA adder board with and without shielded enclosure (upper), shielding provided by shielded enclosure (lower).

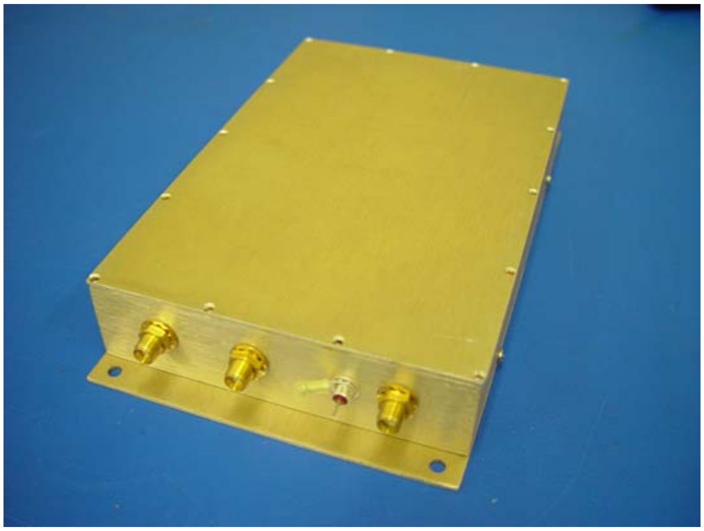

Fig. 3 Final design of LWDA receiver enclosure.

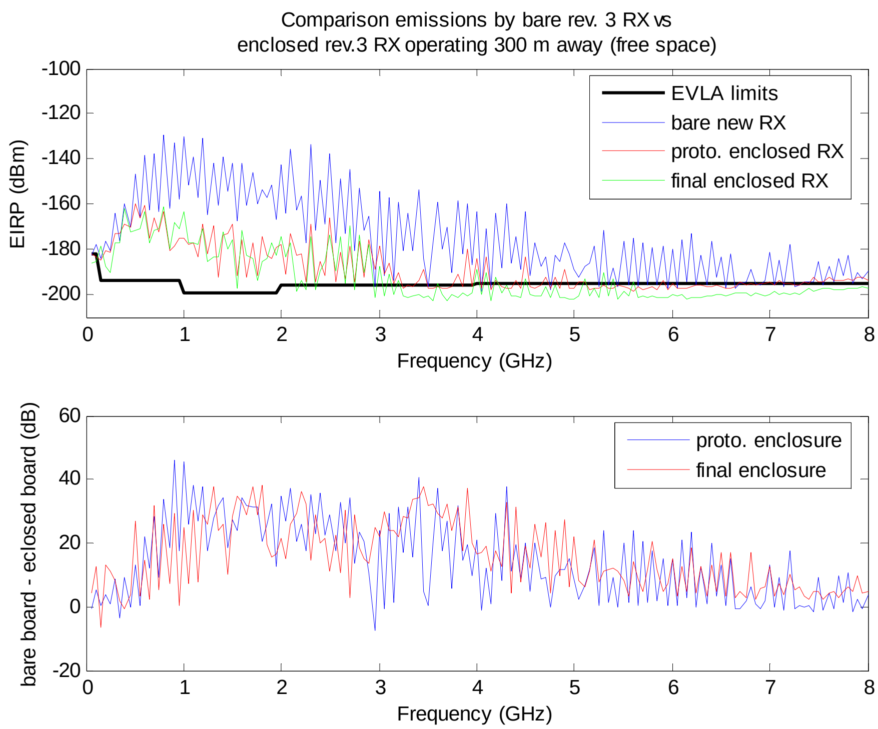

Fig. 4 Comparison of emissions (upper) and shielding (lower) performance of prototype and final enclosure designs for rev. 3 RX.

Measurements were performed to determine the effect of the CAT5 cable connected between an adder and receiver during normal operation of the system. In these measurements, a CAT5 cable was connected between a shielded receiver and a shielded adder; this setup is shown in Figure 5. Any emissions higher than those measured for either the receiver or adder alone are presumed to be due to the cable. Separate measurements were made with a COTS unshielded CAT5 cable assembly and a single-shielded CAT5 cable assembly fabricated at ARL of nearly equal lengths. Care was taken to arrange the cables in a similar fashion between measurements to avoid any discrepancy due to different cable orientations. The emission measurements taken with each cable type are compared in Figure 6. The emissions using a shielded CAT5 cable are between 10 to 20 dB lower than with unshielded CAT5 between 0.05 to roughly 2.5 GHz; emission levels are similar at higher frequencies, though. This implies that shielded CAT5 cable should be used to interface receivers and adders in the final implementation of the LWDA in order to minimize emissions. We are currently in the process of evaluating COTS shielded CAT5 cable assemblies for use in final system fabrication.

Emissions due to the receiver, adder, and shielded CAT5 cable are compared with those due to only the adder and only the receiver in Figure 7. The aggregate emissions due to all three components are similar in nature, but noticeably higher than the adder-only emissions, and much higher than receiver-only emissions. This is due to emissions from the CAT5 cable. The peak aggregate emissions, which occur at 0.8 GHz, are 53 dB above EVLA limits, which is roughly 9 dB worse than the adder-only and 17 dB worse than the receiver-only. Since it is not believed that the receive chain gain stages contribute significant emissions, this measurement can be used as an estimate of emissions due to a single receive chain. This in turn can be used to estimate the expected emissions due to all of the LWDA electronics that will be fielded.

It should be noted that with the measurement approach used above (not using a reverberation chamber and only measuring at one position / orientation), the measured emission levels due to a CAT5 cable are highly dependent upon the orientation of the cable relative to the reference antenna. Therefore, the true peak CAT5 emission levels may be somewhat higher than those presented above.

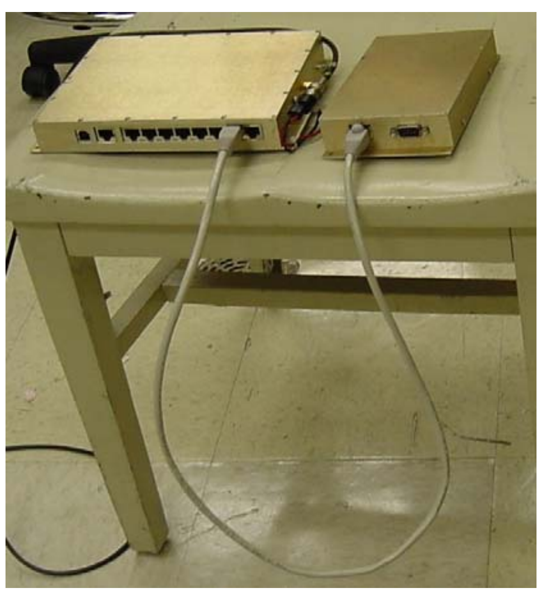

Fig. 5. Test setup for measurement of emissions by CAT5 cable

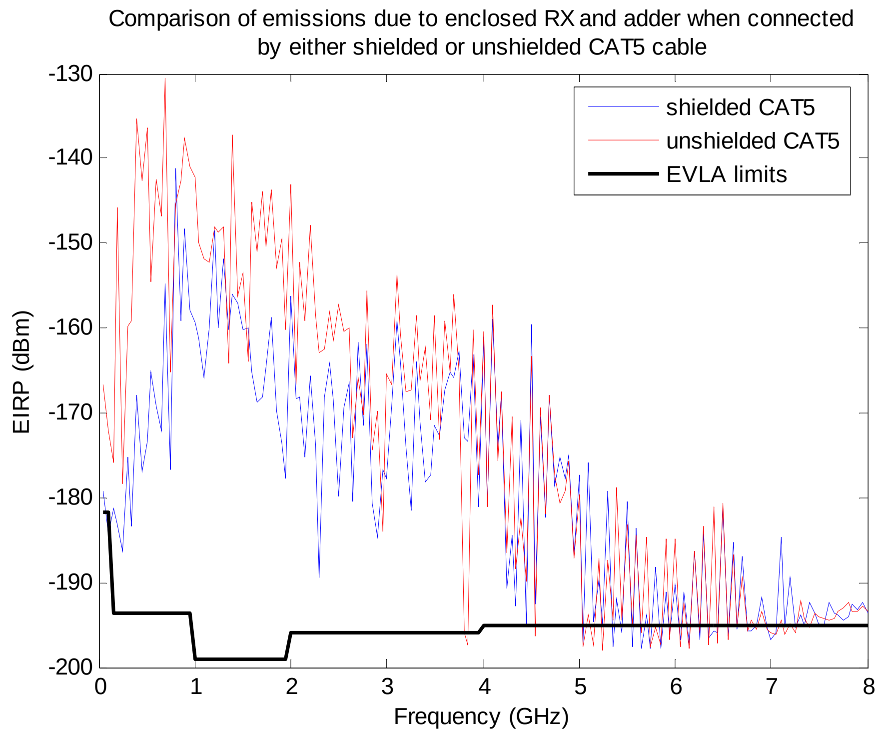

Fig. 6 Comparison of emissions due to enclosed RX and adder connected by shielded CAT5 cable and unshielded CAT5 cable.

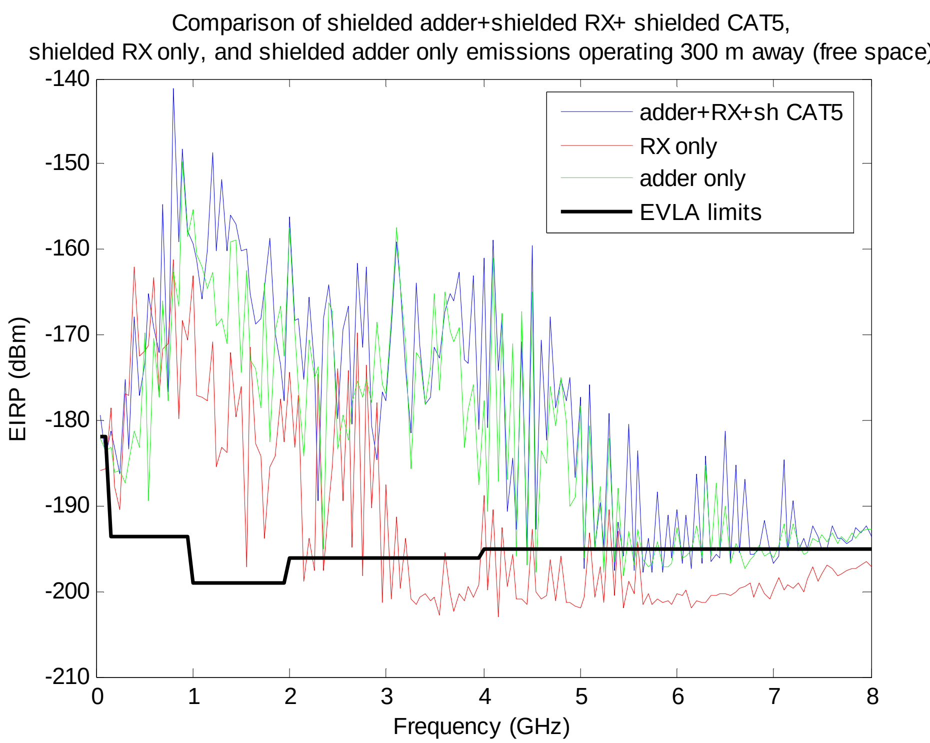

Fig. 7. Comparison of emissions of enclosed RX and adder connected by shielded CAT5 cable, enclosed adder only, and enclosed RX only

Shielding measurements of electronics hut

Prior to delivery of the LWDA electronics hut, limited measurements were performed in order to estimate the RF shielding it provides. The measurements were performed inside a large, mostly open building at ARL:UT; some racks and workbenches are scattered around the building, but were relatively far from the hut. The test setup, which is depicted in Figure 8, consisted of two identical wideband reference antennas, a high quality signal generator, and a spectrum analyzer. The signal generator was connected to one of the antennas and placed inside the hut. The other antenna was connected by a relatively long length of coaxial cable to a spectrum analyzer. A narrowband tone was emitted by the antenna inside the hut, and the power received at the antenna outside the hut was measured by the spectrum analyzer. The received power was measured both when the door to hut was open and when it was closed. The shielding provided by the hut is estimated by differencing the two measurements. Measurements were repeated at four points around and equidistant from the hut as shown in Figure 8. Measurements were performed at selected frequencies between 0.05 to 10 GHz. For measurements below 1 GHz, COTS wideband discone antennas were used. Above 1 GHz, small ultra-wideband planar monopole antennas fabricated at ARL:UT, which have previously been shown to be well matched from 0.9 GHz to well over 12 GHz, were used. One of these antennas is shown in Figure 9.

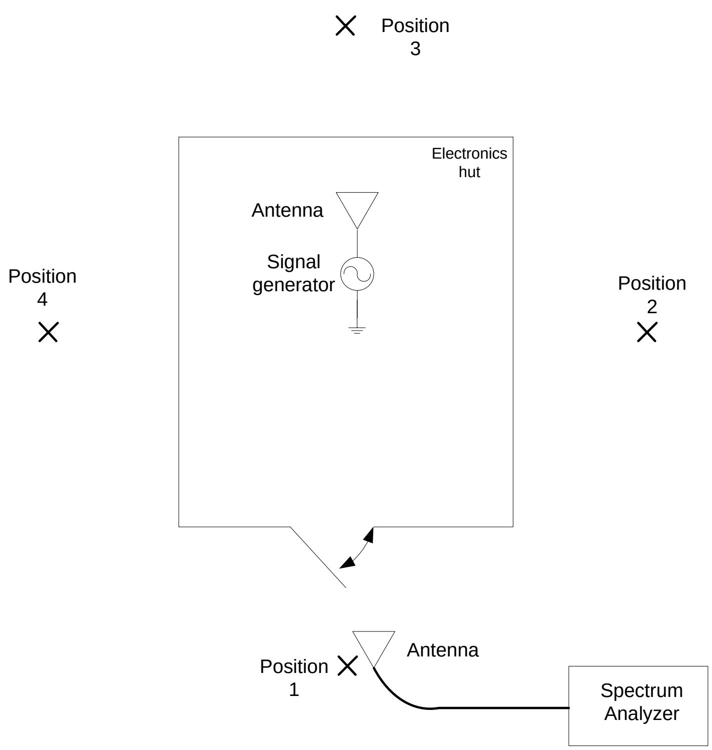

Fig. 8. Test setup used to estimate shielding provided by electronics hut.

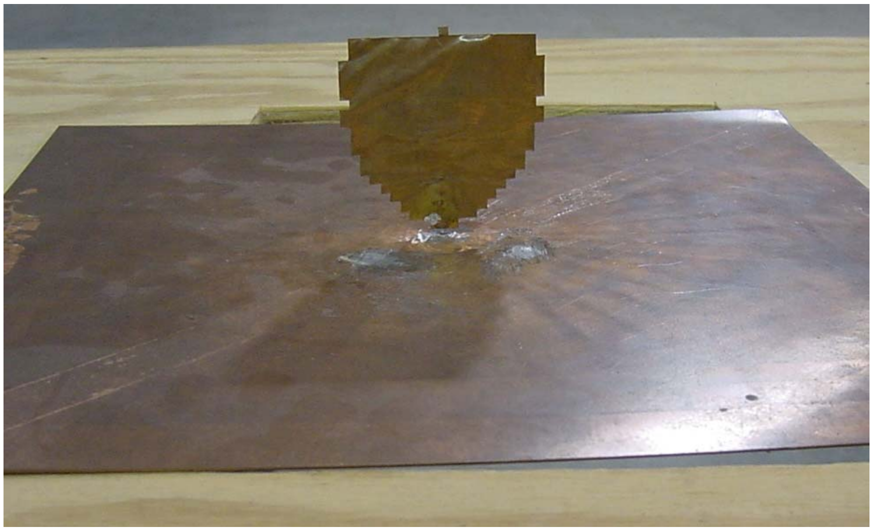

Fig. 9. Ultra-wideband planar monopole antenna used for electronics hut shielding measurements above 1 GHz.

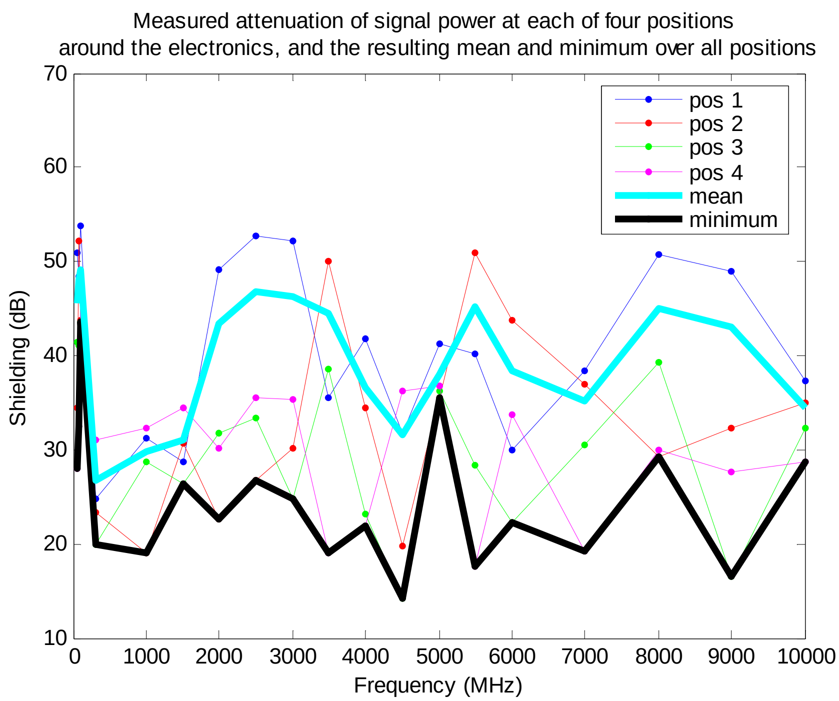

Fig. 10. Results of shielding measurements of electronics hut.

The measured shielding at each receive antenna position between 0.05 to 10 GHz is shown in Fig. 10. Also included in the figure is the mean and minimum shielding over all positions. These results suggest the electronics hut provides reasonable shielding over the entire frequency range considered. The measured shielding at position 1 (in front of the door) is relatively high, > 30 dB at almost all frequencies. Lower shielding values are measured at other positions, however. The relatively rapid variation in shielding with frequency is assumed to be due to scattering effects in the non-anechoic environment in which the measurements were conducted. While a relatively high average shielding was measured, it is more conservative to use the minimum over all positions as an estimate in forming a shielding budget. Above 100 MHz, the minimum shielding provided by the hut is typically between roughly 20 to 30 dB. The principal exception to this occurs between 4.5 to 5.0 GHz where the minimum shielding varies between 14.2 dB and 35.5 dB. Again, this rapid variation is attributed to scattering from other objects in the measurement environment.

Emissions measurements at VLA

The primary goal of this testing was to measure the emissions due to a single LWDA receive chain. The highly shielded NEMA enclosure discussed in [1], which contains all of the gain blocks needed for single two channel receive chain, a receiver, and an adder, was used in this testing. In order to measure emissions due to these components, the lid on the NEMA enclosure was left open. The receiver and adder boards were tested in the final board enclosures discussed above. The receiver and adder were connected by a shielded CAT5 cable, and the adder was connected to the USB bulkhead connector on the NEMA enclosure via a typical COTS USB cable.

Two full sets of emissions measurements were performed on the receive chain setup described above. In one set, the typical emissions measurement procedure followed by NRAO in characterizing their own equipment was followed. This procedure consists of performing two very wideband sweeps from 0-1 GHz and 1-20 GHz using a low resolution bandwidth (RBW) of 100 Hz on the spectrum analyzer. This procedure provides very good dynamic range and wideband coverage, but very coarse frequency sampling. The other measurement set was taken using a procedure similar to that used in preliminary measurements of LWDA equipment at the NRAO facility [2]. In this procedure, multiple narrower frequency spans of between 1 to 2 GHz are measured. Due to the number of spans required to cover the full frequency range of interest, higher RBW values of between 1 kHz to 10 kHz are used to reduce sweep time. While the spectrum can be sampled more densely using this method, it suffers from reduced dynamic range, which limits the level of emissions that can be detected. The frequency spans measured were 1-2 GHz, 2-4 GHz, 4-6 GHz, and 6-8 GHz. In both measurement sets, measurements for a given frequency range were performed at three reference antenna positions inside the chamber, which is the minimum recommended by NRAO. For frequencies below 1 GHz, measurements were performed using the “large cone” reference antenna, which consists of a small cone monopole placed over a ground plane with a number long metal spokes protruding from the end of the cone. Above 1 GHz, the “small cone” reference antenna was used, which is the same as the large cone, except that the spokes are removed.

In order to generate an EIRP estimate of the typical emissions of the LWDA receive chain, the following reduction was employed at each measured frequency, f,

$$EIRP(f) = \max\left\{P_{meas}(f)\right\} - G_{cal}(f) + L_{FS}$$

where P_{meas} is the raw power measured by the spectrum analyzer, f is frequency, max denotes the maximum taken over all reference antenna positions, and G_{cal} is the calibrated gain for the chamber / antenna. The factor L_{FS} is added to move the reference point of the EIRP estimate from the DUT to the expected stand-off distance between LWDA and the closest VLA antenna position, CW-7. This distance is assumed to be 300 m in this analysis. Calibration files were provided by NRAO for both the large cone, for frequencies between 0.05 and 1.5 GHz, and the small cone, for frequencies between 0.5 and 18.0 GHz. In reducing measurement data, it was necessary to interpolate in frequency the calibration data using polynomial fitting.

The EIRP emission estimates generated using the above reduction for the receive chain for both measurement sets are given in Figure 11. Also included for comparison are the EVLA emission limits. The values are expressed here as an EIRP (in dBm) by multiplying the power flux density (in dBm/m^2) limits given in [3] by the effective area due to a 0 dBi VLA antenna sidelobe. For simplicity, the emission limits at the center of each band are assumed in this analysis. It should be noted, however, that the received power limit could vary as much as +/- 3 dB within each band due to variation of effective area with frequency.

As can be seen, the two measurement approaches produce significantly different emission estimates for the receive chain. Using measurement spans of 1 to 2 GHz and RBW values between 1 to 10 kHz, the emissions due to the receive chain appear to be relatively strong, with peak emissions nearly 60 dB above the limits near 2 GHz. However, the emissions appear to be roughly 40 dB lower in the 1-20 GHz sweep with an RBW of 100 Hz. This large discrepancy is due to the particular nature of the emissions of the LWDA receiver and adder. As demonstrated in previous reports [1,2], the emissions from these components are dominated by clock harmonics spaced every 50 MHz. These harmonics are extremely narrow in frequency, which requires that the spectrum analyzer measurement frequencies be adjusted carefully to detect them, particularly if very low RBW values are used. Therefore, the frequency spacing in the measurements was set to coincide with these harmonics. However, the spectrum analyzer and LWDA components are not tied to a common frequency source, so that the spectrum analyzer is not measuring exactly at the harmonic frequencies. Therefore, when a narrow RBW is used, it is very likely that the harmonic will not be measured or only a small percentage of its power will be measured. Given the stability of VCXOs used in the LWDA equipment (its measured deviation from nominal frequency is typically +/- 1 kHz), it is possible to measure the harmonic power using wider RBW values even if components are not locked in frequency with the spectrum analyzer. The drawback of using a higher RBW is that the dynamic range of the measurement is limited. This is evident in Figure 11, where the spectrum analyzer noise floor is well above the EVLA emission limits even at the lowest frequencies. This is in contrast to using an RBW = 100 Hz, in which the spectrum analyzer noise floor is below the limits up to approximately 10 GHz. Further work will be required to determine an emissions measurement procedure got LWDA components at the NRAO facility which provides a better trade-off between measurement accuracy and dynamic range.

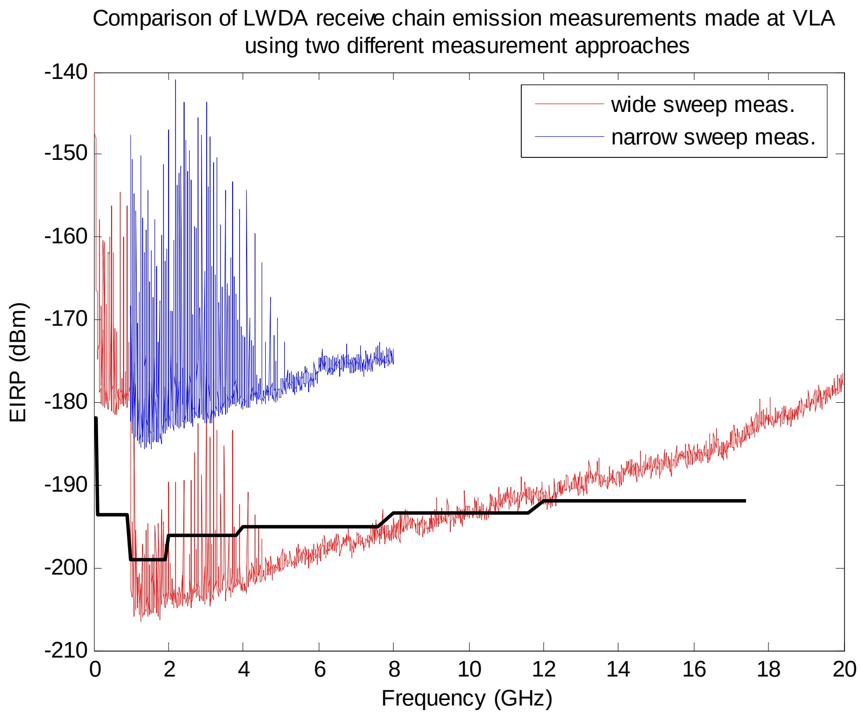

Fig. 11. Comparison of emission measurements made at VLA reverberation chamber using wide span / narrow RBW measurements and using narrow span / wider RBW measurements.

The narrow span / high RBW emission measurements taken at the VLA chamber of the full receive chain are compared in Figure 12 with the emissions measurements of the shielded adder and receiver connected by shielded CAT5 taken at ARL:UT. Below about 700 MHz, the ARL:UT measurements are not reliable, and the VLA chamber measurements are likely more indicative of emissions below this frequency. It should be noted, however, that the chamber loss increases significantly below 200 MHz, which limits the dynamic range of measurements. This is the cause of the sharp peak seen below 200 MHz in Figure 12 rather than high emissions from the receive chain. The results from ARL:UT and the VLA chamber agree reasonable well between 1-2 GHz. Between 2-4 GHz, however, the emissions measured in the VLA chamber are significantly higher than those measured at ARL:UT; the measured peak emissions in this band are nearly 20 dB higher than at ARL:UT. There are a number of factors that could contribute to such a discrepancy. A USB cable was connected to the adder at the VLA chamber but not at ARL:UT. Follow-up measurements at ARL:UT verified that connecting a USB cable to the adder does increase emissions of the setup. The accuracy of the ARL:UT measurements is somewhat limited since measurements were performed at a single position and orientation. Also, the VLA chamber estimates are somewhat conservative in that the maximum over all antenna positions is taken as the estimate rather than the mean over all positions (as is traditional with reverberation chamber measurements.) Above 4 GHz, VLA chamber and ARL:UT measurements agree reasonably well, though the VLA chamber results are limited by the spectrum analyzer noise floor above 5 GHz. The measurements indicate that the highest emissions from

LWDA equipment occur between 1 to 4 GHz. Based on VLA chamber measurements, the peak emissions of a full receive chain in L-band (1-2 GHz) are roughly 51 dB above EVLA limits while the peak emissions in S-band (2-4 GHz) are roughly 55 dB above the limits.

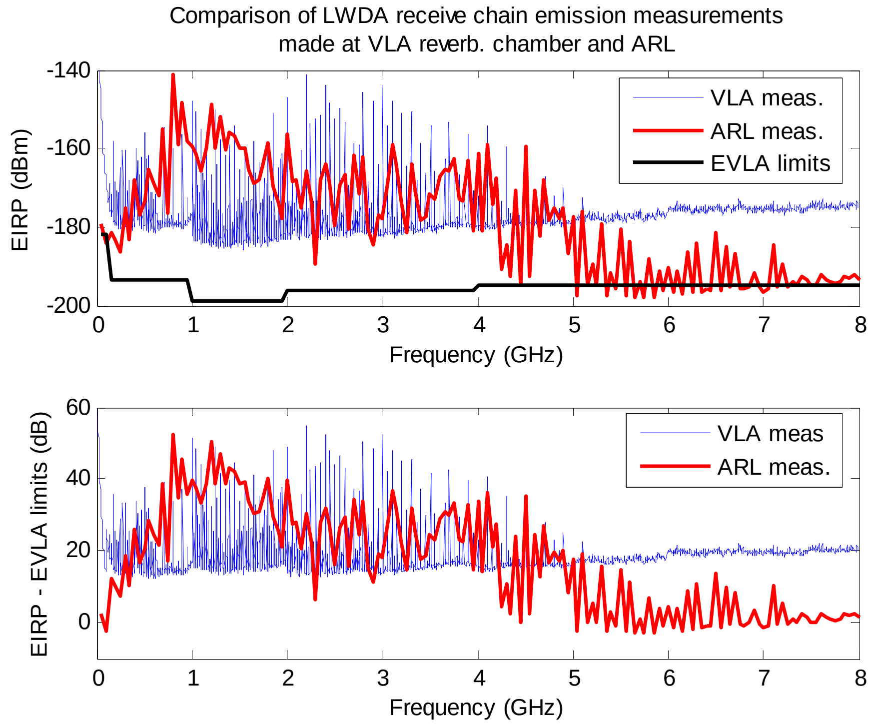

Fig. 12 Comparison of emission measurements made at VLA reverberation chamber and ARL laboratory (above), difference between each emission measurement and EVLA limit = required shielding (below.

A number of other related emissions measurements were performed in the VLA chamber. The results of these measurements are summarized briefly in the paragraphs below.

Measurements were taken with receiver operating in the NEMA enclosure with the enclosure lid shut. These measurements indicate that the NEMA enclosure does indeed provide a very high level of shielding. However, due to limited dynamic range of these measurements, the full level of shielding provided by the enclosure, which is estimated to be over 40 dB in L-band (based on ARL:UT measurements) could not be measured.

A series of measurements were performed to determine if emissions due to CAT5 and USB cables in the test setup could be reduced by fitting RF chokes around the cables. The chokes evaluated were rated to provide attenuation out to 2 GHz. Measurements were focused in the 1-2 GHz band. Very little if any reduction in emissions was noted by placing the chokes on either the CAT5 or USB cable. Therefore, it does not appear that this an effective way to reduce emissions in the LWDA.

In most measurements, including those presented above for receive chain emissions, the inputs to the setup have been terminated in 50 Ω. Limited measurements were performed to determine if injecting sinusoidal signals into the setup would significantly alter its emissions. Tests were conducted in which tones at frequencies between 60 to 80 MHz with powers at the receiver input ranging from -35 dBm (midrange on the ADC) to 0 dBm (nearly full range) were injected into the test setup. While injecting strong tones into the setup did appear to increase somewhat emissions at frequencies between clock harmonics as compared with terminated inputs, the emissions due to the harmonics themselves was still much greater (typically 20 to 30 dB higher.)

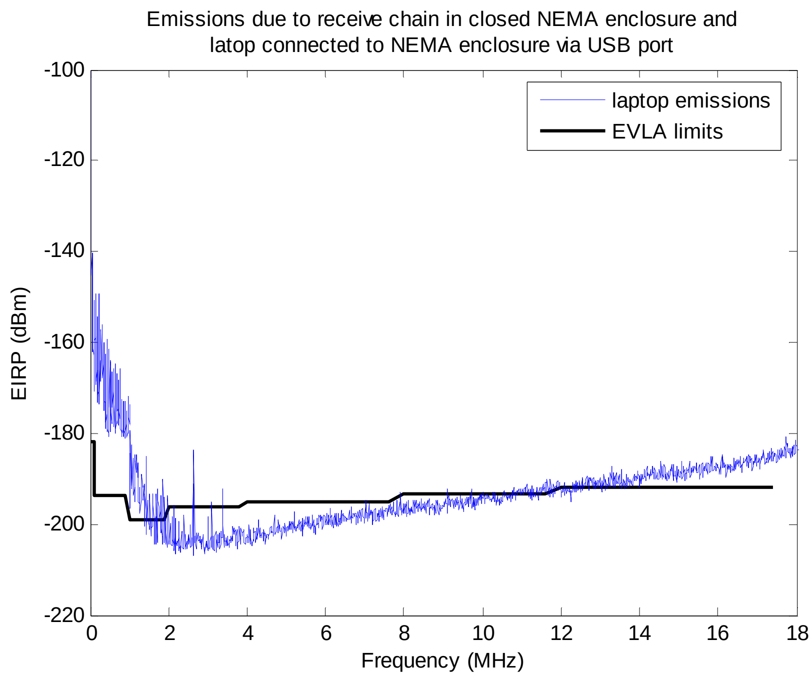

Fig. 13 Estimated emissions due to laptop computer used to control LWDA hardware.

A few measurements were conducted with a laptop running in the chamber with the receive chain. The receive chain was operating inside the NEMA enclosure with the enclosure lid shut; therefore the LWDA electronics are not expected to have contributed significantly to the emissions in this setup. The estimated emissions of the setup obtained using only a single reference antenna position is given in Figure 13. The laptop appears to radiate relatively strongly below 1 GHz. The emissions near 74 MHz are roughly 40 dB above the limit, while those in P-band (300 MHz band) are roughly 35 dB over the limit. The emissions near 74 MHz are particularly worrisome for the LWDA system itself since the stand-off distance between the electronics hut and the closest dipole is only 30 m. This implies that for LWDA, the laptop emissions are approximately 60 dB above the limit. This is not surprising since laptop emissions have previously been detected in receiver data collected during field measurements involving the full receive chain and a 2.0 m blade antenna [4]. There appear to be some emissions between 1 to 4 GHz with the highest near 1 GHz being roughly 20 dB over EVLA limits. No emissions are detected above 4 GHz. It should be noted that there could be high emissions due to clock harmonics that were not picked up in the measurement shown in Figure 13. Further measurements will be required to more fully characterize the emissions of this laptop.

Shielding Budget

With the emissions measurements given above, it is possible to estimate the emissions due to all of LWDA electronics that will soon be installed at the LWDA site. The peak emissions in each frequency band due to a single LWDA receive chain obtained through VLA chamber measurements are summarized in Table 1. Note that results are not given for the LWDA band and for frequencies above 8 GHz due to the limited measurement dynamic range at those frequencies. In the next column, the required additional shielding for a single receive chain in order to just meet EVLA limits is given. Again, the emissions are highest in L and S bands, so that at least 51 dB and 55 dB of additional shielding will be required. It is expected that the total emissions due to the LWDA system will increase proportionally to number of receive chains that are deployed. An estimate for the emissions due to the entire system can be formed by multiplying the emissions due to a single receive chain by 18. This aggregation factor was selected since 16 receive chains will originally be deployed and there are two additional CAT5 cables which connect Level 1 adder boards to the final (Level 2) adder. The maximum additional shielding required for this system is given in column 3 of Table1. Using the hut shielding estimates given in Figure 10, the amount of shielding that must be provided by the rack and rack chassis which contain the receive chains can be determined. In the last column of Table 1, the minimum measured hut shielding in each band has been subtracted from the required shielding for the whole system. As can be seen, up 49 dB of shielding in S band must be achieved with the rack and rack chassis or roughly 25 dB per layer. The chassis (otherwise known as the Level 1 box) is currently under development and measurements of a prototype will be performed in the next few weeks. The shielding of the rack will need to be measured once all of the final modifications have been made (principally adding all cable penetrations.)

It is important to note that the shielding budget given here only accounts for emissions due to LWDA circuit boards and connecting cables and not other components of the LWDA system such as the computer, networking equipment, or air conditioning system. It will be necessary, as feasible, to perform emission measurements on these components in order to verify that their emissions are not any greater than those due to receivers, adders, and CAT5/USB cables.

Table 1. Maximum emissions due to a single LWDA receive chains and maximum additional shielding required per receive chain and due to 16 receive chains (x18 factor) to meet EVLA limits in each frequency band. VLA chamber measurements used for estimates.

Frequency band	Max. emissions for single receive chain (dBm)	Max. shielding required to meet limits for a single receive chain (dB)	Max. shielding required to meet limits for a 16 receive chains (dB)	Max. shielding for 16 receive chains – min. hut shielding (dB)
0 to 100 MHz	-	-	-	-
300 MHz band	-160.5	33.2	45.8	25.8
1-2 GHz	-147.0	51.3	63.9	44.9
2-4 GHz	-140.9	55.1	67.7	48.7
4-8 GHz	-154.2	40.7	53.3	39.1

Conclusions

The results of emissions measurements performed on LWDA electronics at both ARL:UT and at NRAO's reverberation chamber at the VLA have been given. It was shown that the final designs of the board level enclosures for both the receiver and adder provide significant reduction of board emissions. For example, both enclosures reduce board emissions in L-band by 20 to 30 dB. The maximum emissions of the enclosed adder are still approximately 8 dB worse than the enclosed receiver in terms of maximum level above EVLA limits. When a shielded CAT5 cable is plugged between a receiver and adder, the peak emissions of the setup is roughly 9 dB worse than with an adder alone.

It was demonstrated that the electronics hut used for the LWDA provides reasonable shielding over the entire band measured, 0 to 10 GHz. A very high shielding estimate for the hut, > 30 dB at nearly all frequencies, was determined by calculating the average shielding over all measurement positions. The minimum shielding over all positions was somewhat lower, close to 20 dB at most frequencies, however. In order to be conservative, the minimum shielding value should be used in forming shielding budgets.

The emissions due to a full LWDA receive chain, consisting of all gain blocks, a receiver, an adder board, and all required cabling was measured at the VLA chamber. Measurements of the receive chain taken at the VLA chamber agreed reasonably well with ARL:UT measurements in L-band and above 4 GHz. However, the VLA chamber measured emissions in S-band were higher than ARL:UT measurements by as much as 20 dB. This discrepancy is believed to be due slightly different test setups used at the two facilities, and aspects of the test procedures used. Based upon VLA chamber measurements, the highest emissions due to a single receive chain occur in S-band, and are roughly 55 dB above EVLA limits. The emissions from the laptop used in LWDA development were also measured in the VLA chamber. From these measurements, the worst emission appear to occur in the 74 MHz band (35 dB over limits for the EVLA system and 60 dB over limits for the LWDA system), and the P-band, (40 dB over limits.)

Finally a shielding budget for the 16 element deployment of LWDA was presented. From this analysis, it was determined that roughly 45 dB and 49 dB of shielding in L-band and S-band, respectively, in addition to the minimum shielding provided by the hut will be needed to meet EVLA limits. It is expected that the rack and rack chassis, in which all system electronics will be stored, will each provide significant shielding in order to meet EVLA limits.

References

[1] A. Kerkhoff, "Status of LWDA Electronics RF Emissions Measurements", May 2006.

[2] Y. Pihlström, A. Kerkhoff, "LWDA Receiver Emission Levels", February 2006.

[3] Y. Pihlström, "Maximum allowed emission levels for the LWDA electronics", November 2005.

[4] A. Kerkhoff, J. York, D. Munton, "LWDA Field Measurements II Report", June 2006.