EVLA Memo # 78

EVLA Chamber Characterization confirms PCB RFI emissions Levels and module shielding goals

Robert Ridgeway 10 June 2004

Introduction

As a part of the Expanded Very Large Array (EVLA), Very Large Array (VLA) upgrade project, the current VLA analog transmission system will be replaced by a digital data transmission system (DTS). Digital data from each antenna will be conveyed to a central control building via very wide bandwidth fiber optics. High speed digital samplers will be located in the vertex room of each antenna. When pseudo random RF noise generated by antenna-based digital circuitry such as Module Interface Boards (MIBs), High speed digital formatters, 10 Gbit/s laser modulators, and 4.096 GHz clocked samplers, finds its way back into close-proximity, microwave feed horns, significant disruption of astronomical observations may result. This radio frequency interference (RFI) must be kept well below the integrated harmful level for the EVLA-D Array.

The EVLA RFI test chamber ("the chamber") and it's associated RF instrumentation were assembled with the purpose of inexpensively providing low to moderate accuracy RF microwave emissions and shielding measurements. Due to cost constraints, the chamber has been populated with uncalibrated surplus equipment. Comparative calibration reference measurements were performed in order to insure that the chamber accurately measures the RFI emissions levels generated by EVLA prototype circuitry. In addition, a study was conducted to determine whether paint on the inside surface of the chamber causes the measured 45 dB transfer function loss above 15 GHz.

To ensure that the RFI emissions from EVLA digital circuitry do not overwhelm the astronomical signals that the telescope is designed to detect, a very high level of shielding (60-120 dB), for each RFI radiating component on all printed circuit boards (PCBs), must be implemented. This report describes efforts to calibrate the emissions measured from PCB's using the chamber. Once the chamber calibration is certified as correct, the design and testing of RFI shielding for the EVLA racks, bins, and modules may be validated. The goal is to insure that all EVLA electrical and electronic devices emit RF power at a level below the EVLA harmful Spectral Flux Density levels described by Rick Pereley in EVLA Memo 46[1].

EVLA Harmful RFI levels

The harmful level depends most strongly on the receiver bandwidth and the integration time used in an observation. VLA tests also allow the shielding requirements and expectations of various digital PCB's (including the sampler) to be verified experimentally. The whole project depends on the ability to track the emissions levels of the prototype hardware as they are reduced to as low as 40 dB below EVLA harmful levels.

In order for the measures of RFI emissions to imply what shielding is required in any module, it is essential to correctly translate Harmful spectral power flux density (SPFD) (usually expressed in $dBW/m^2/Hz$ units), as RFI seen by the EVLA, into effective isotropic radiated power (EIRP) (usually expressed in dBW units) at any given distance. This is also what is measured in the RFI chamber. The intention is to try to force all of the RFI emission spectral lines below an acceptable "EIRP harmful EVLA level," for a "worst case" distance.

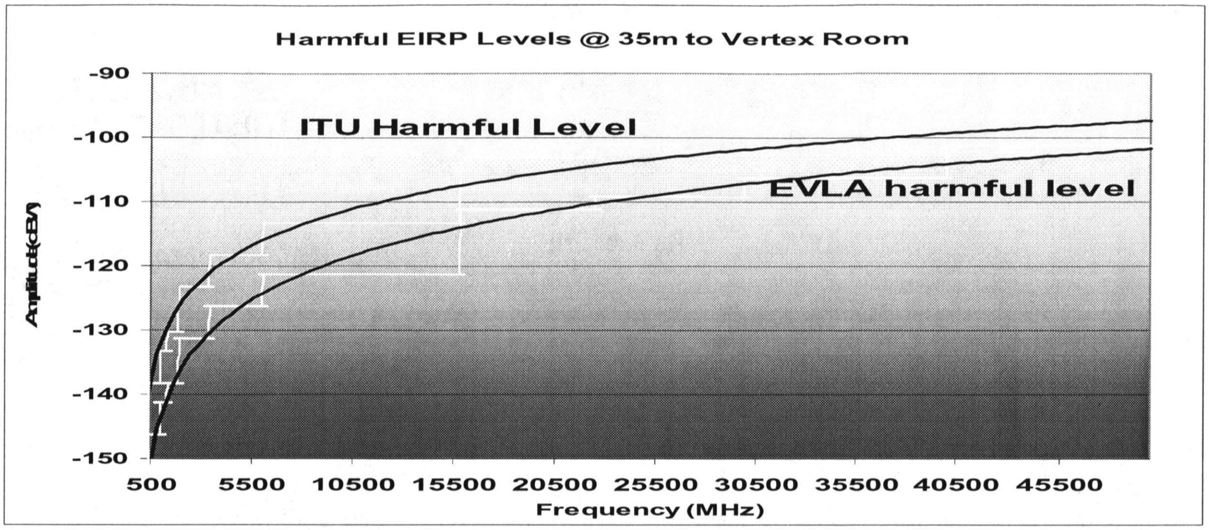


Figure 1. EVLA Harmful Levels

Most of the likely sources of interference that will be present for a significant period of time will be from the high-speed digital electronics. This can be, at times, located in the adjacent antennas only 35m away. For long observations the correlator will further reduce some of this interference because these signals change phase as the radio telescope tracks a cosmic signal coherently across the sky. The requirement is to build equipment that does not emit signals that will interfere with the radio astronomical observation. To help with this task, the maximum allowed strength of emissions, the 'Harmful EVLA Level', was determined for frequencies from 1-50 GHz. Interference below the harmful level should not significantly impact astronomical observations. The harmful levels are converted to EIRP units at 35m, the distance to the nearest neighboring antenna.

This harmful level depends on the antenna gain (0 to +15 dB) in the direction of the RFI, the receiver frequency, bandwidth, the integration time, the correlator product bandwidth, the shielding provided by the vertex room and minimum distance to the offending RFI source. The vertex room of a typical EVLA antenna has less than 30 dB shielding. Taking all of this into account, the calculated EVLA harmful level is found in EVLA Memo 46 [(1)] and is shown in Figure 1 or from the equation below.

$$\text{Harmful EIRP (dBW)}=[\text{ SPFD (dB(W/m}^2\text{/Hz)}]-[10\text{Log}(1/4\,\pi r^2)]-[10*\text{Log(BandWidth)}]-[-30\text{ dB}]$$

The first component in the above equation is the detrimental spectral power flux density values impinging on a VLA antenna, taken from EVLA Memo 46, then space loss, followed by the power level increase with the bandwidth increase, and finally the shielding loss of the vertex room. Another possible RFI transfer mechanism is single dish interference, where RFI from the vertex room and the pedestal room electronics is received by the antenna's own feed (see Table 1). The single dish path loss was measured and tabulated along with the free space RF path loss to the nearest dish. A test signal was placed in an adjacent antenna. The antenna pointing was maximized under local control, while watching a spectrum analyzer. The receiver amplifier on antenna six was tapped into just after the first amplifier. In this study the greatest RFI susceptibility was discovered to be dominated by the emissions from adjacent antennas (when at 35m), and low frequency. However, with greater antenna spacing and at higher frequency, the self-shielding of the vertex room, modules, and racks, are dominant. At each band the side lobe gain at 8 degrees is about the same, only the number of side lobes increases. The level received was checked to see that it was at the correct power level after the path loss was calculated (see table 1). Tests at L-band matched closely to the result of the equation below.

$$\text{Path loss to adjacent Antenna (dB)}=[10*\text{Log}(1/4\,\pi\, r^2)]+[10*\text{Log}(c^2/(4\,\pi\, r^2))]+[-30\text{ dB}]+[15\text{ dB}]$$

The first component in the above equation is the space loss, followed by the loss due to the effective aperture, then the vertex room shielding, and the gain of the receive antenna operating in the near side lobes.

Table 1. Comparison of path loss between adjacent antennas and a single dish

Frequency	Measured Single VLA Dish Path Loss	Calculated Adjacent Antenna Path loss
330 MHz	-70 dB	-69 dB
1.42 GHz	-83 dB	-82 dB
4.75 GHz	-86 dB	-93 dB
8.4 GHz	-75 dB	-97 dB
14.95 GHz	-77 dB	-102 dB
22.48 GHz	-105 dB	-106 dB
40.0 GHz	-115 dB	-111 dB

The EVLA & Criterion Reverberation Chamber

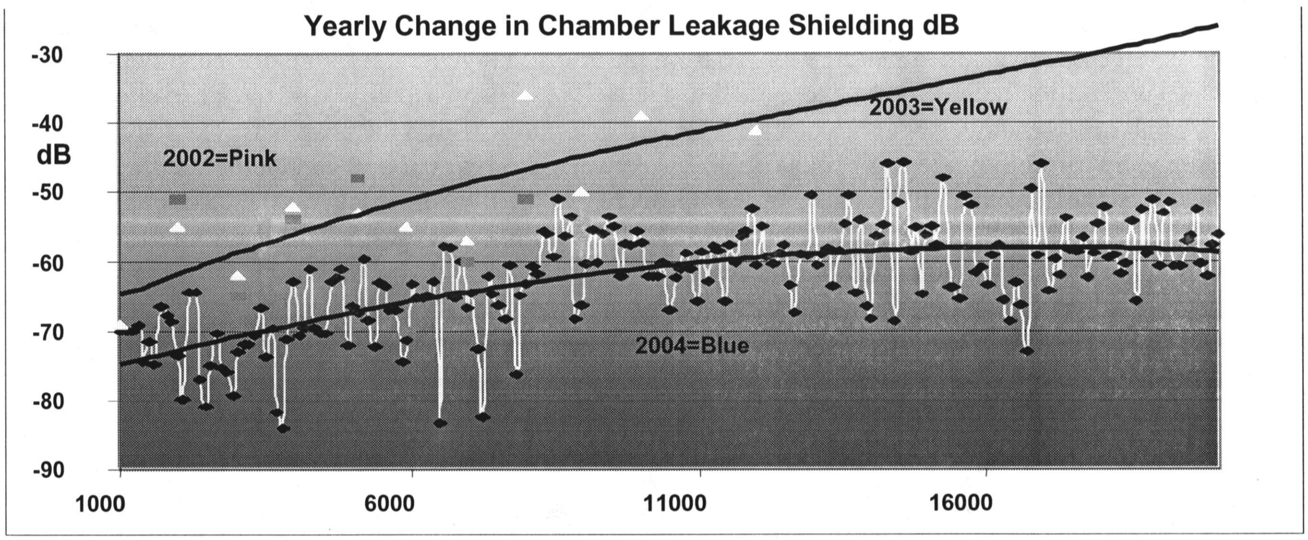


Figure 2.

As seen in figure 2, the chamber prevents outside RFI from being included in these measurements by having a leakage of -70 dB at L-band (after repairs in 2004). It also has another less obvious characteristic in that it reduces signal losses by about 30 dB or more, as compared to outdoor testing. A RF reverberation chamber acts like a hall of mirrors so more of the RFI from a device under test will eventually be picked-up by the receiving antenna. For RFI emissions testing, the typical signal to noise ratio (SNR) of a well shielded PCB like the MIB (~45 dB), is easy to see in the chamber, and thus presents no great technical challenge. The same cannot be said of outdoor test ranges. For example, the outdoor test facility belonging to Criterion Technology Corp, located just west of Boulder Colorado is one of the best in the country, yet the highest SNR seen from the same MIB PCB at three meters away was only 10 dB, even using a 2 dB noise figure pre-amp. Another difficulty encountered when using the outdoor test site was the annoying number of stray RFI signals in the environment. It made it impossible to see even the highest of RFI lines in the 1.2 GHz region of spectrum. Worse still, the number of useable noise spectral lines was less than five, which made it difficult to set a defining level. Even though Criterion's outdoor test area exceeds industry specifications, there is an unavoidable multi-path ripple (+\-2 dB) pattern in the amplitude of a noise diode and cone antenna test set. The test procedure was bogged down by a painfully slow procedure of hunting for each emission line, which took about 20 minutes each. On the other hand, once set up, the reverberation chamber took about 3 minutes for all emission lines and had a >45 dB SNR. It is only fare to say that all outdoor test facilities near large cities will have similar troubles, thus a shielded reverberation RFI test chamber has great advantages.

The RFI testing chamber system at the VLA uses a personal computer (PC) interfaced to a Hewlett Packard 70000 series spectrum analyzer via an IEEE488 (GPIB) board and cable. Custom PC software provides set-up and data extraction (dump) commands to the spectrum analyzer. The acquired data is then imported into an Excel spreadsheet for data analysis. The custom designed spreadsheet corrects for the chamber transfer function, and the Heliax transmission line transfer function, and provides calibrated plots of RFI noise power verses frequency. During shielding measurements, the PC controller steps the frequency of a signal generator that applies RF power to an antenna located inside the shielded enclosure under test. A 10 MHz external reference is connected from the HP7000 spectrum analyzer to the signal generator, insuring that the generator is exactly on frequency. This tracking generator system gives the RF chamber shielding measurement system approximately 160 dB of linear dynamic range. After a year or so of use, the mechanical structure of the chamber settled, allowing electrical ground loops to form near the SMA bulk-heads leading into the chamber. These ground loops reduced the dynamic range at the lower frequencies tested in the chamber. Fabricating new bulkhead plates, and joining them to the chamber metal walls by conductive RTV and silver paint eliminated the ground loops. Another source of RF leakage into the chamber was found to be due to a bad RF cable running from the RF signal generator to the device under test. A poor RF connection between the outer shield of the Heliax transmission line and the outer shell of the SMA bulkhead (chamber wall) connectors allowed external RFI into the chamber. The leakage was reduced by carefully injecting conductive RTV between the Heliax outer conductor and the inside of the SMA connector outer shell. After these improvements the dynamic range of the chamber was found to be nearly 120 dB, which is sufficient for the current testing program. The last limitation to achieving maximum dynamic range during shielding tests is believed to be caused by leakage from inside the signal generator chassis itself. Previous tests suggest that if the signal generator is placed inside a shielded box with absorber foam, the dynamic range may increase to better than 160 dB. The generator shielding box has about 65 dB of attenuation and is supplied with an AC power RF filter, SMA feed thorough, and optical connector to allow the GPIB to transition through two GPIB/fiber optic transceivers. This modification should make the final last few decades of sensitivity available. Once these final chamber testing system improvements are completed, the chamber can be used to directly measure the shielding of the noisiest EVLA component, the DTS-sampler module. Calculations indicate that the total DTS shielding will have to be in excess of 120 dB if we are to stay below the detrimental PFD limits documented in EVLA Memo 46. Until the chamber improvements are complete, it is only possible to measure individual layers of shielding, each less than 90 dB, and then mathematically calculate the total shielding. The accumulation of errors with each layer of shielding measurement means one might unknowingly be paying a little too much for shielding.

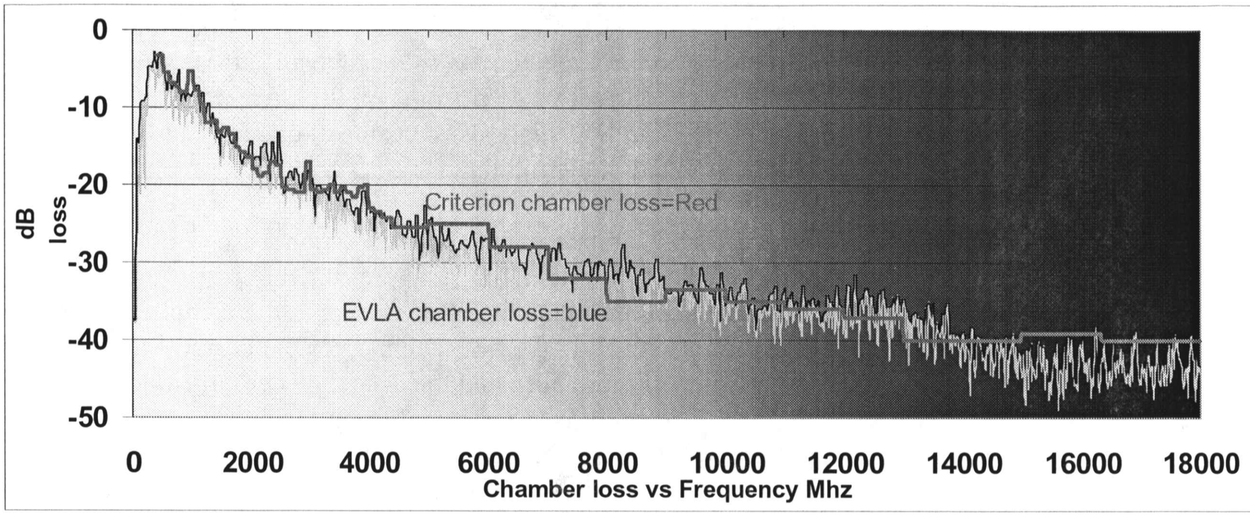


Figure 3.

Figure 3 shows the loss as a function of frequency for the RFI chamber measured with two identical cone antennas spaced eight meters apart (although that distance is not critical due to the pseudo random scattering in the chamber). The 300 MHz roll off is due to the transfer function of the two cone antennas. This plot also shows that the EVLA chamber is very similar to the unpainted chamber at Criterion, Co. (red line) when using the same two disk-cone antennas at 8m. This result indicates that the paint inside the chamber is not terribly lossy as was first suspected.

It is important to realize that the spectrum analyzer is collecting RF power through the chamber with a 3D SWR pattern that causes many nulls as the frequency is swept from 0-20 GHz.

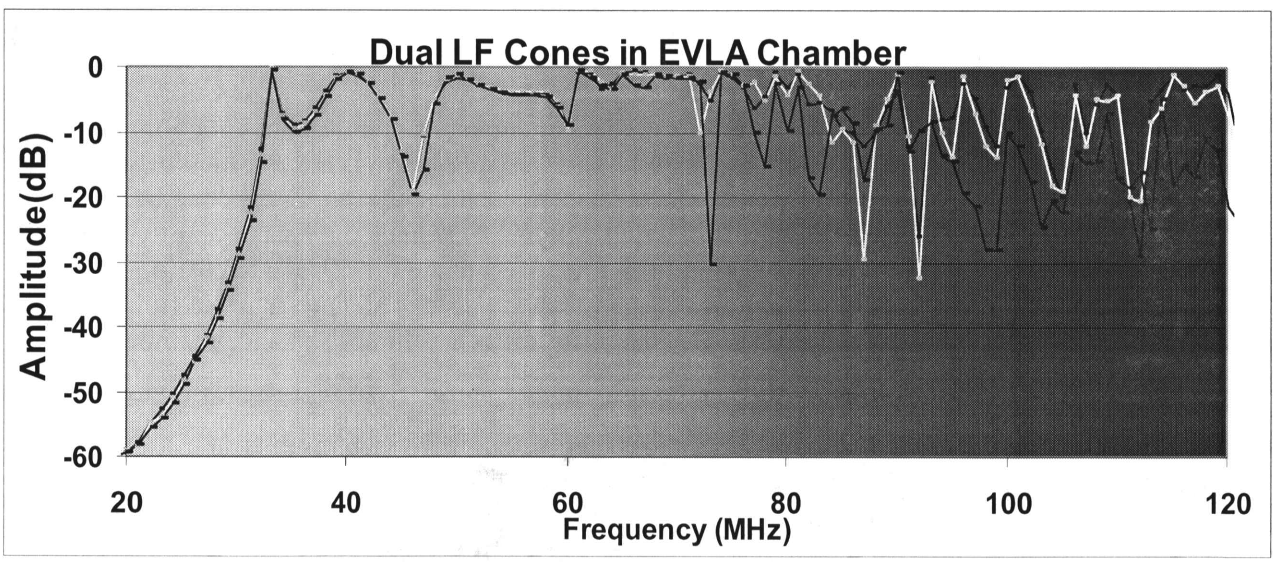
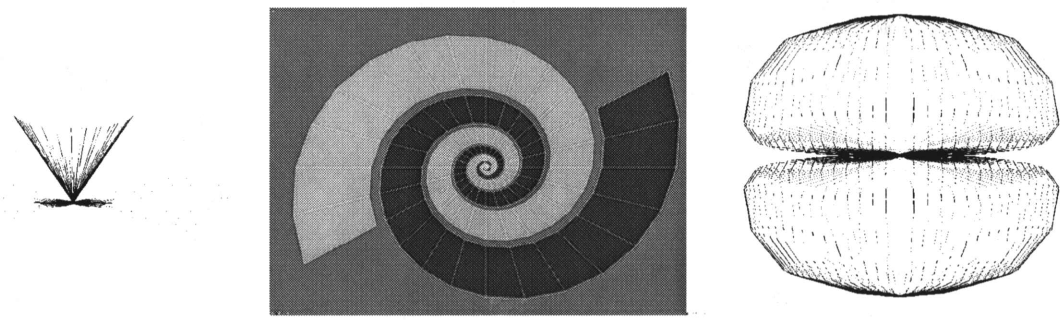


Figure 4.

As seen in figure 4, the low frequency end, less than 65 MHz becomes useless due to the limited number of modes by which the chamber can achieve coupling into the second antenna probe. If this test had used a mode stirrer, many of the amplitude curve dips would not be filled. Current plans are to improve the chamber low frequency (0.1-1 GHz) performance with the addition of a low frequency antenna and low noise preamplifier.

At mid-band (1-8 GHz) the chamber is quite useful and can provide well-calibrated amplitude measurements to +/- 2 dB. That standard deviation was obtained by taking only the peak amplitudes for three or more scans at 3 different receiving antenna locations within the chamber. The standard deviation (30 dB) for a single scan is the plot in gray and can be seen to be almost useless. It has been found that the amplitude approaches the theoretical correct value if from 3 to 20 (or more!) samples per spectrum analyzer frequency bin are used. This finding suggests the value of electronically chirped mode stirring, a procedure which may be investigated in the future.

Another unexpected property of the EVLA chamber is in the way in which a directional antenna is rendered isotropic and randomly polarized. The gain must be presumed to be 0 dB even if two high gain antennas are on axis. At this time the best antennae found for use in the chamber are 300 MHz to 40 GHz, low loss disk cones (Figure 5a), with S11<-20 dB. Other antennae currently under construction are the 0.5-50 GHz PCB planar spiral (Figure 5b.), and the 0.1-50 GHz dual-ridge horn of revolution, with rounded end caps (Figure 5c.). The spiral is the only flat antenna that can fit inside single height modules for shielding tests. The Bi-cone is useful as an ultra broadband, chamber receiving antenna.



a. NEC4 Disk-cone in use. **b.** PCB Spiral **c.** *Dual-Ridge*way

Figure 5

Another unexpected property of the EVLA chamber is in the way in which a directional antenna is rendered isotropic and randomly polarized. The gain must be presumed to be 0 dB even if two high gain antennas are on axis. At this time the best antennae found for use in the chamber are 300 MHz to 40 GHz, low loss disk cones (Figure 5a), with S11<-20 dB. Other antennae currently under construction are the 0.5-50 GHz PCB planar spiral (Figure 5b.), and the 0.1-50 GHz dual-ridge horn of revolution, with rounded end caps (Figure 5c.). The spiral is the only flat antenna that can fit inside single height modules for shielding tests. The Bi-cone is useful as an ultra broadband, chamber receiving antenna.

Figure 6 shows close agreement between the Criterion calibration lab results (sky blue) and the MIB maximum EIRP peaks in the EVLA reverberation chamber (dark blue) when changed to the equivalent dB(uV/m) units. The points tend to match better when mode stirred, or after many antenna moves or frequency steps are used per sample. This would seem to indicate that a mode stirrer or some other means of mechanically or electrically breaking-up chamber resonances will need to be installed in the future for optimum performance. The Green line shows the MIB as being 25 dB below the usual PCB RFI level.

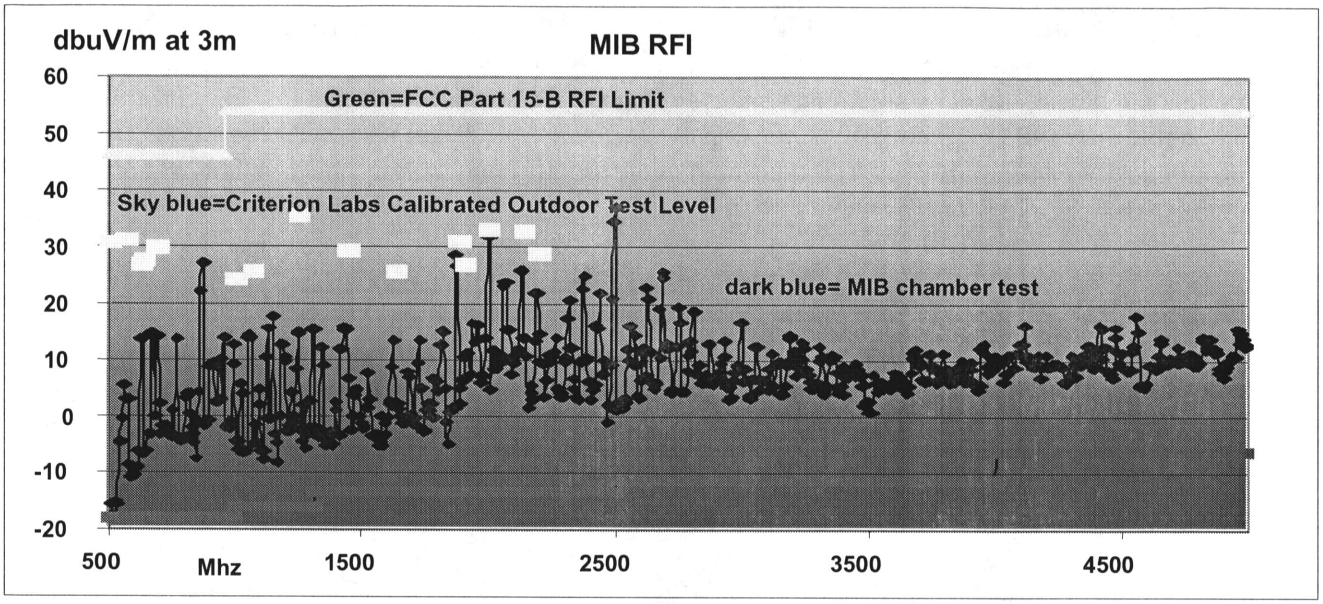


Figure 6.

This latest MIB PCB version is also 25 dB improved over the first PCB layout attempt. Near field probes and chamber testing were used to find and fix leakage points. This latest NRAO designed MIB PCB now has at least 48 dB less RFI than the VCMA 9 controller first proposed (see figure 7). This low emission PCB will save money due to the reduced shielding needed when operating in the vertex room of EVLA antennae. Any bus wires must also be shielded equally as well or the cost savings be ineffectual.

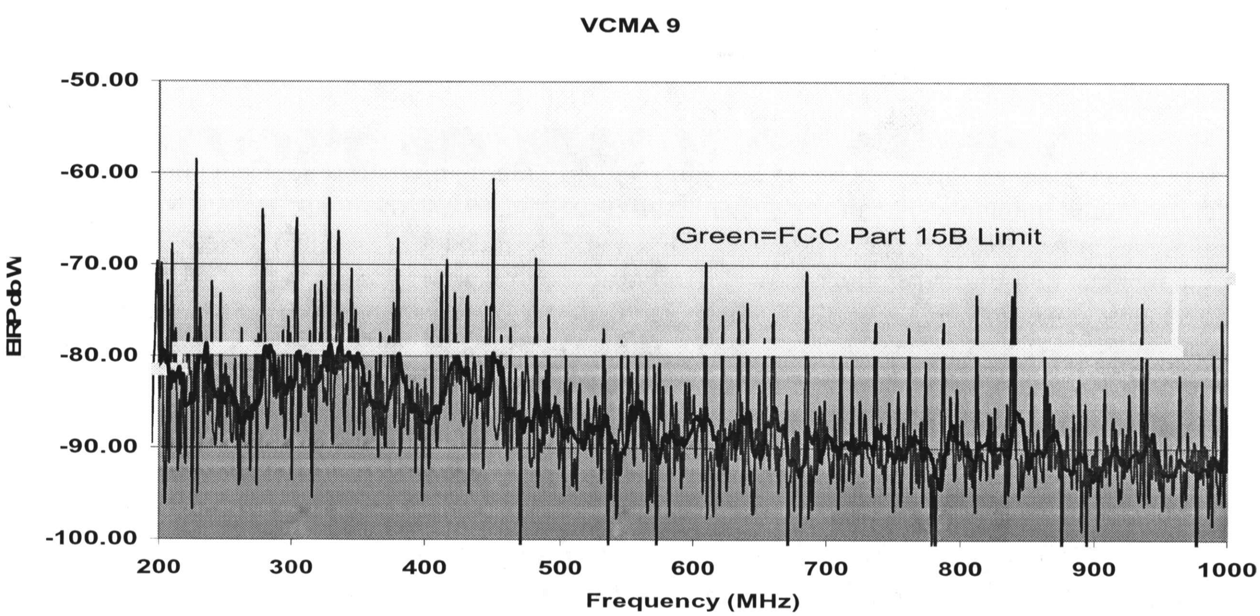


Figure 7.

The successful design of the EVLA DTS and other shielded enclosures required a multifaceted approach. The sampler module and MIB PCB layout used preventative RFI confinement techniques. It is estimated that these PCB techniques saved about 45 dB in the total shielding budget. Some of the PCB layout techniques included enclosing multi-ground planes joined every half inch with plated via's near parallel, differential, matched transmission lines going to LVPECL devices. The MIB has a shorting perimeter joining all ground planes. Preventing RFI is easier and cheaper when implemented close to its source, in this case the PCB is the first shield near PCB mounted electronic components. After examining the new DTS and MIB PCB with near field probes, it appears that additional RFI reduction could be realized by shielding some components with small metal shields. For current EVLA applications the PCB emissions are already sufficiently low, and additional reductions cannot be economically justified. However, these shielding techniques may be especially valuable to some future planetary RADAR or SETI application.

How much shielding can the EVLA chamber measure?

EIRP emissions from various PCBs have been accurately measured in the EVLA chamber and the levels have been compared to the EVLA EIRP harmful levels. These tests allow the shielding requirements of various RF and digital PCBs to be determined from their emission levels.

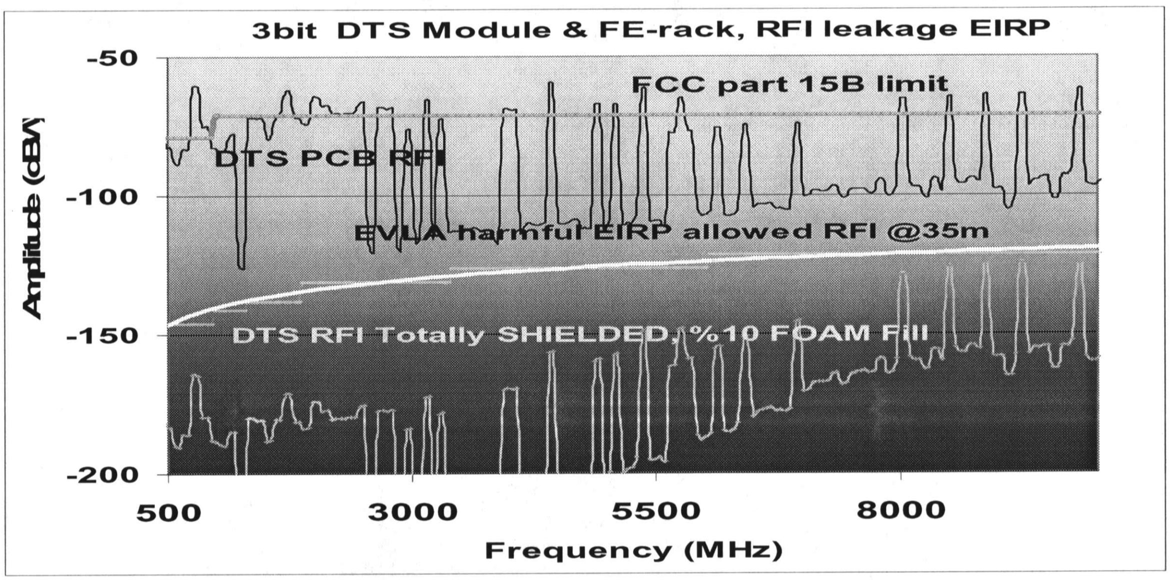


Figure 8.

Figure 8 shows the emission levels of the DTS-sampler hardware without shielding. The difference between this level and the "EVLA harmful EIRP" curve is the minimum amount of shielding required. However, an additional 30 dB should be added as a margin of safety. This safety margin may prove useful when the bandwidth of the new correlator is used at the 0.12 Hz limit. This extra shielding margin also allows for the degradation of the Ohmic contacts of the RF gaskets and any warping of lids. The Spira-gasketed Ohmic contacts are essential in the DTS-sampler module and they must be cleaned after each time it is opened. The test results shown in Figure 8 indicate that for 1km/s spectral resolution, 120 dB of shielding is desired before the DTS hardware can be installed in the EVLA antenna.

Other NRAO-designed EVLA modules have been measured to have different shielding factors that can be applied to check if they are appropriate for each PCB RFI they are intended to suppress. These harmful EIRP limits were verified using the (35m) nearest antenna elements of the VLA D-array. However, the RF generator used for the module shielding tests was not well shielded, as discussed earlier. Added RFI from the RF generator chassis may have skewed the results to the high side. As a result, additional test plans are being drawn-up which include the use of the noise diode and cone antenna setup used to cross-reference EVLA chamber calibration with the Criterion test facility in Colorado. This new test arrangement should not be as susceptible to RF leakage. It is expected that the new results may generate slightly lower the shielding requirements.

Conclusion.

It is recommend that for the DTS-sampler module, two Spira, RFI gaskets be used, one on each side of the line of the closely space screws (one inch spacing or less), that join the DTS lid and air filters to the boxes. The redundant, dual gasket arrangement was needed because of the flat joining of surfaces on the DTS lid. As seen in Figure 9, the first layer of module shielding is not enough to reach the 120 dB, L-band shielding goal.

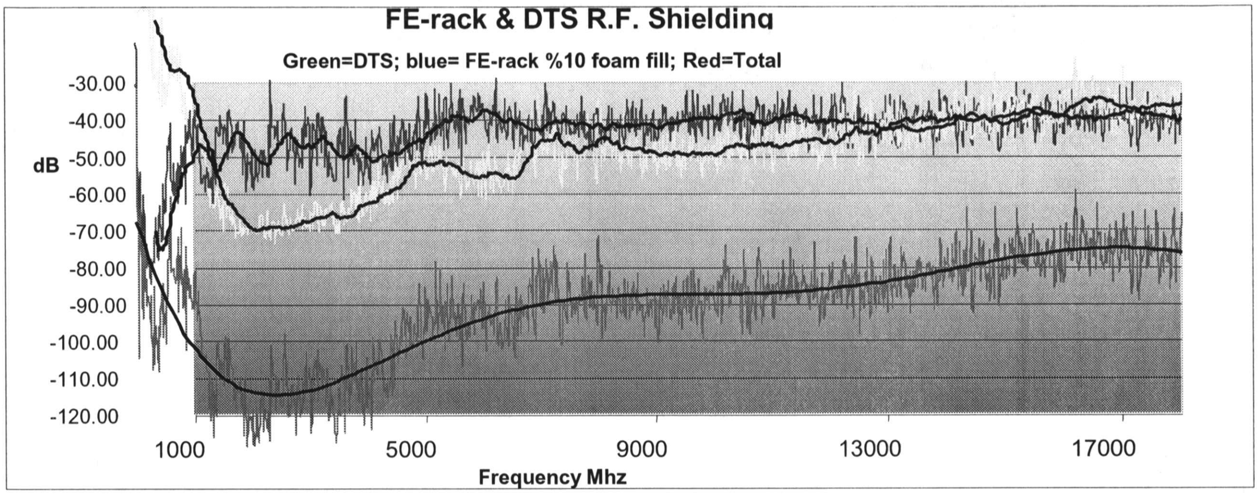


Figure 9.

A second shielded LO-rack and a second DC feed-through were needed to reach the shielding requirement. Where a lid has an inset step (as with the ELVA P301 module), the RF gasket does not appear to be needed. With these results in hand, a new lid to module body design has been suggested which eliminates the need for RF gaskets. This new lid and module design is being applied by the ALMA team, and test results are eagerly anticipated.

VLA on-array tests, used in conjunction with Criterion test range calibration data, have verified the validity of EVLA shielding requirements based on emissions and module shielding levels measured in the EVLA shielded chamber. Moreover, now that VLA and the RF chamber measurements can be related to shielding requirements, the work in the RF chamber is accurate to about +/-4 dB. These chamber calibration and test results verify the value of using chamber-measured data during EVLA hardware prototyping

The paint on the inside surface of the chamber was not found to be causing much of the -45 dB transfer function one sees above 15 GHz. This high frequency loss appears to be normal in reverberation chambers, and seems to be related to the decreasing effective area of an isotropic receiving aperture with increasing frequency.

The peak RF emissions levels of the sampler PCB were found to be 10-30 dB lower than the maximum allowed as shown on the PCB EIRP plot line in Figure 8. A reasonable extrapolation is that the final total shielding will be >110 dB below 4 GHz. This should allow the EVLA operate at the narrowest of bandwidths, with long integration times, and still not suffer RFI from the 3-bit sampler module and bin.

The EVLA systems design demands that any cables between modules must be attached via output filters. These cables must also be shielded and checked as part of the total RFI mitigation effort.

The methodology of measuring the different layers of shielding separately in the chamber to arrive at a total shielding capability was used due to dynamic range limitations of the current chamber test system. Now that the harmful RFI levels have been confirmed by experiment, it is possible to measure PCB RFI emissions levels accurately, predict what they will be at any given distance, and specify the shielding needed to reduce them to below the EVLA harmful EIRP levels. The advantage of using a controlled layering of shielding is that it is done at minimum cost, using no more shielding than is needed. However, this additive methodology requires the ability to track the shielding improvements with each new change in the shielded container. Yet, the layered approach lets us use a "less than perfect" chamber measurement system, then estimate the combined result. Recent tests of the shielded DTS circuit used the VLA to search for RFI in an adjacent (35m) antenna, and no RFI signals were seen. This result indicates that the required EVLA shielding is well understood and is verifiable.

The EVLA chamber measurement hardware has so far been adequate for emissions measurements. However, in order to detect RFI emissions lines (with shielding in place) with the same sensitivity that the EVLA would have in it's most sensitive modes, one will probably need an LNA and/or a cryogenically cooled low noise amp. Such a more sensitive measurement setup might be necessary in future years in order to diagnose the leakage points of modules with damaged shielding.

References

[1] Perley, R., 2002, EVLA Memo 46, "Minimum RFI Emission Goals for EVLA Electronics"

[2] International Telecommunication Union, Geneva, 1995, "Handbook on Radio Astronomy"