EVLA Memo # 78

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

Robert Ridgeway 10 June 2004

Introduction

The Extended Very Large Array will upgrade the existing VLA to receive 1-50 GHz initially. The samplers will be kept in the vertex room of each antenna element. The difficulty begins when pseudo random RF noise which is generated by this and other digital circuitry, such as the MIB, high speed digital formatter, the10 Gbit/s laser, and the 4.096 GHz clocked sampler module, finds its way back into a microwave feed antenna as a condition of being located near it. The RFI feedback of a single dish with all its shielding must not exceed the EVLA harmful levels. It is possible that some of the RFI in each antenna could cross-correlate if it leaks around to each antennas own feed. This RFI level must also be kept well below the integrated harmful level for each adjacent antenna in the EVLA-D Array. These levels change with frequency. It is necessary to measure RFI emissions and shielding with these objectives in mind. Toward this goal the EVLA reverberation chamber was made.

The EVLA RFI chamber and its electronic systems were constructed with surplus equipment. None of this RF hardware is in calibration to any standard. The greater question is whether or not this RF hardware can correctly measure the RFI emissions levels coming from EVLA prototype circuitry. Lastly, is the paint on the inside surface of the chamber causing the -45 dB transfer function above 15 GHz or is that a normal loss?

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 PCB's, must be implemented. This report describes these efforts to calibrate the emissions measured from PCB's using the EVLA chamber. Once certified as correct, one can validate the design and testing of RFI shielding for the EVLA racks, bins, and modules. The goal is to be below the EVLA harmful Spectral Power Flux Density (SPFD) levels as described by Rick Perley [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 3-bit sampler) to be verified experimentally. The whole EVLA project depends on the ability to track the emissions levels of the prototype hardware as they are shielded 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 SPFD in dB(W/(m2Hz)), as RFI seen by the EVLA, into EIRP at any given distance dB(W/Hz). EIRP is also what is measured in the RFI chamber. In any case, the intention is to try to force all RFI emission spectral lines below an acceptable "EVLA harmful EIRP level," for a "worst case" array spacing distance or the self feed back.

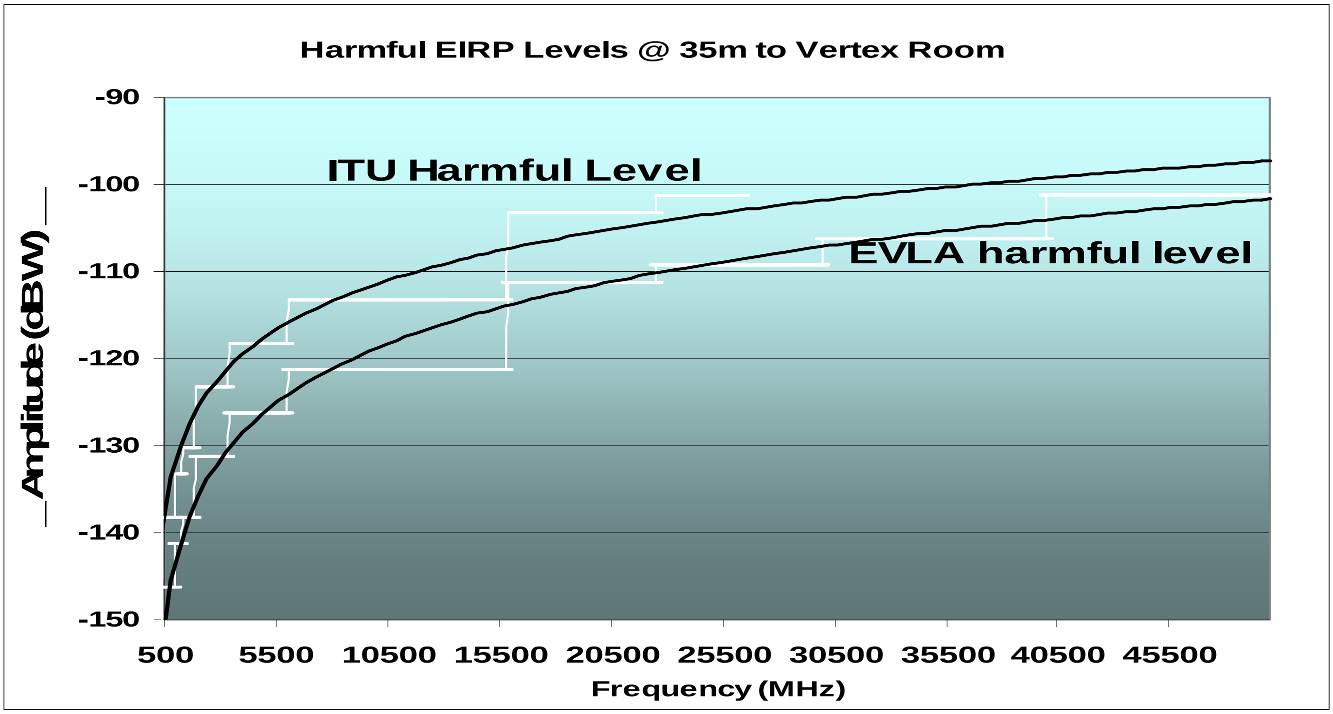

Figure 1. EVLA Harmful Levels

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 (0-20 dB) because these signals change phase and de-correlate as the radio telescope tracks a cosmic signal coherently across the sky. In any case, the requirement is to build equipment that does not emit signals that will interfere with the radio astronomical observation.

To specify this task, the maximum allowed strength of emission (the EVLA harmful EIRP level) was determined for frequencies from 1-50 GHz. These harmful EIRP limits were verified using the (35m) nearest antenna elements of the VLA D-array. Interference below the harmful level should not affect the science. The harmful levels are converted to effective isotropic radiated power (EIRP) dBW at 35m 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 about 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.

$$\text{Harmful EIRP (dBW)}=[\text{ SPFD dB(W/(m2Hz))}]-[10\text{Log}(1/4\ \pi r^2)]-[10*\text{Log(BandWidth)}]-[-30\text{ dB}]$$

The first component in the above equation is the spectral power flux density from Dr. Perley, then space loss, followed by the power level increase with the bandwidth increase, and finally the shielding loss of the vertex room.

To test the adjacent signal loss a -40dBm test signal was transmitted in a VLA antenna vertex room. The antenna pointing is optimized under local control, while maximizing the signal on 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, if at 35m, at L-band. However, with greater antenna spacing 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 power received was checked for correct power levels after the path loss was calculated; table 1. Tests at L-band matched closely to the result of the equation below.

Path loss to adjacent Antenna (dB)=[10*Log(1/4 π r^2)]+[10*Log(c^2/(4 π r^2))]+
[-30 dB]+[15 dB]

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

Frequency	**Measured Single VLA Dish Path Loss**	**Calculated Adjacent Antenna Path loss**
330 MHz	-69 dB	-69 dB
1.42 GHz	-66 dB	-82 dB
4.75 GHz	-83 dB	-93 dB
8.4 GHz	-78 dB	-97 dB
14.95 GHz	-97 dB	-102 dB
22.48 GHz	-100 dB	-106 dB
40.0 GHz	-110 dB	-111 dB

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

The other possible RFI transfer mechanism is single dish interference, where RFI from each vertex room and the pedestal room electronics are received by the antenna's own feed, Table 1. The single dish path loss was measured and tabulated with the free space RF path loss to the nearest dish. This will allow one to take the worst case at each frequency. These are VLA measurements but it is hoped that the new EVLA vertex rooms will have ~10dB improved shielding. It appears that the self leakage is the worst case for RFI in the vertex room. These single dish experiments used no correlator for simplicity, however there is about a 15 dB increase in the harmful levels due to the action of the array correlator.

The EVLA & Criterion Reverberation Chambers

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. It acts like a hall of mirrors, so 30dB more of the RFI from a device under test will eventually be funneled into an isotropic antenna then into the HP7000 spectrum analyzer. For RFI emissions level testing, the typical signal to noise ratio (~45 dB) of a well shielded PCB, like the MIB, is easy to see in the chamber, and thus presents no great technical challenge. The same cannot be said of the outdoor test facility seen in Colorado, even though it is one of the best in the country. The highest signal to noise ratio seen from the same MIB PCB at 3m away was only 10 dB, and that's using a 2 dB NF pre-amp. Another trouble with the outdoor test site at Colorado 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 area. Worse still, the number of useable lines was less than five, which made it difficult to set a defining RFI level. Even though their out door test facility exceeds specification, there was an unavoidable multi-path ripple (+\-2 dB) pattern in the amplitude of the noise diode and cone antenna test set. The MIB OATS procedure was bogged down by a painfully slow procedure of hunting for each weak emission line, which took about 20 minutes each. The reverberation chamber, once setup, took about 3 minutes for all emission lines and had a >45 dB signal to noise ratio. As covered in the IEEE EMC 2004 symposium, it is fare to say that all outdoor test facilities near large cities are in crisis, thus the shielded reverberation chamber has a lot to offer.

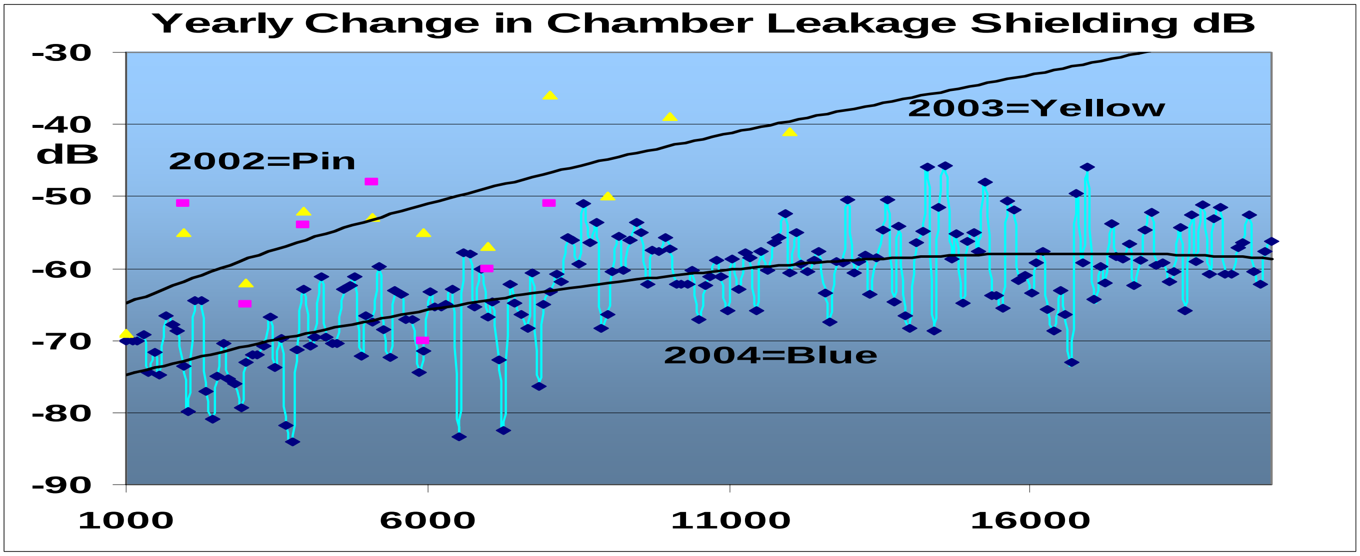

Figure 2.

In the EVLA test chamber a GPIB cable connects the computer to the RF hardware which dumps RFI emissions data into an excel file. From there one can correct for the chamber loss transfer function, and Heliax loss transfer function, and thus plot these data accurately. For shielding measurements the GPIB cable steps the frequency of a generator which applies RF power to an antenna inside the shielded enclosure under test. The 10 MHz external reference is connected from the HP7000 spectrum analyzer to the signal generator, which ensures that the generator is exactly on frequency. This allows for a 10 Hz bandwidth giving ~160 dB maximum available dynamic range in the RF chamber shielding measurement system. After the chamber settled, there were ground loops near the SMA bulk-heads leading into the chamber, which disabled the low end of this dynamic range. This was fixed with new bulk-head plates joined by conductive RTV and topped by conductive silver paint. Another problem came from the connectors used on the Heliax not having a complete connection to the outer shell of the connector. This was fixed by carefully injecting conductive RTV between the Heliax outer conductor and the inside of the heliax connector outer shell. The measured dynamic range is about 120 dB after these fixes, which is just enough for EVLA shielding tests. The last limitation to the shielding measurements' full dynamic range is caused by leakage from inside the signal generator. When the signal generator is placed inside a shielded box with absorber foam, the dynamic range should improve to the maximum 160 dB. This box has about 65 dB of shielding and is supplied with an AC power RFI filter, SMA RF feed through, and optical connectors to allow the GPIB to transition through two GPIB fiber optic transceivers. It is thought that this will make the final last few decades of sensitivity available. When this is done one can use the chamber to confirm with certainty that the total DTS shielding is near the desired 120 dB, and hopefully not too much more. Until then one can only measure layers of shielding of less than 90 dB. Excel is then used to find the sum total shielding. The accumulation of errors with each additional layer of shielding measurement (~5 dB) means one might unknowingly be paying slightly too much for shielding.

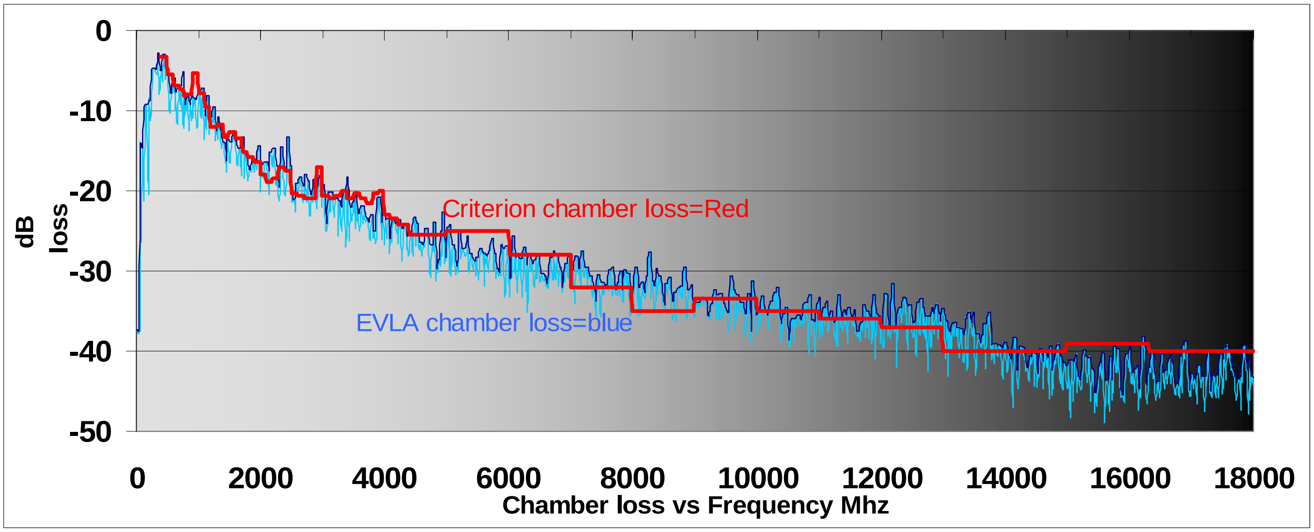

Figure 3.

Figure 3 shows the loss as a function of frequency for the RFI chamber measured with two identical cone antennas spaced 8m apart, though that distance is not critical due to the pseudo random scattering in the chamber. The 300 MHz roll off is due to the small physical size 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) using the same two disk-cone antennas at 8m. This seems to also mean that the paint inside the chamber is not terribly (40dB?) 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. The effective aperture is rendered isotropic by this scattering and the 40 dB loss reflects this.

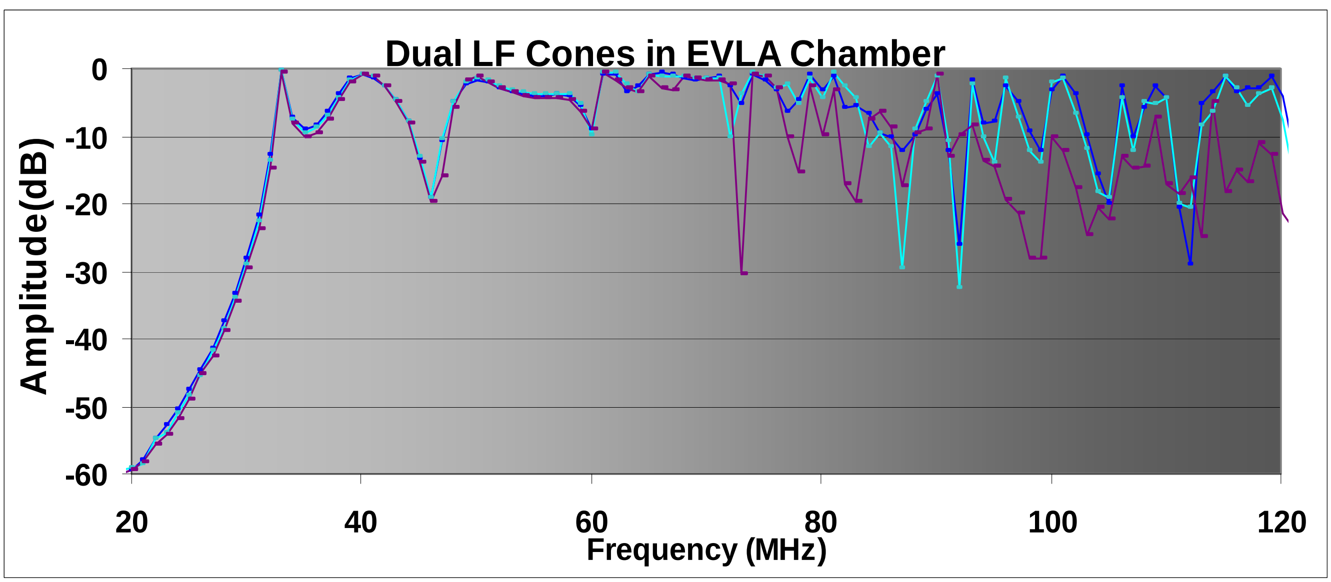

Figure 4.

As seen in figure 4, the low frequency end, less than 65 MHz cannot be mode stirred to give a flat chamber loss. Here there are a limited number of modes by which the chamber can achieve coupling into the second antenna probe. From 30-65 MHz coupling is mostly near field and thus prone to device (DUT) orientation errors. If this test had used a mode stirrer, you would still see many dips that could not be filled. A later addition to the chamber hardware will be an LF antenna, and low noise preamplifier, that will cover .1-1 GHz.

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 much more than three scans while in more than three suitable locations in the chamber. The standard deviation (~30 dB) for a single scan is almost useless for reverberation chamber tests. It has been found that the amplitude approaches its correct value if >3-20 samples per spectrum analyzer frequency bin are used. This will lead to further study in electronically chirped mode stirring.

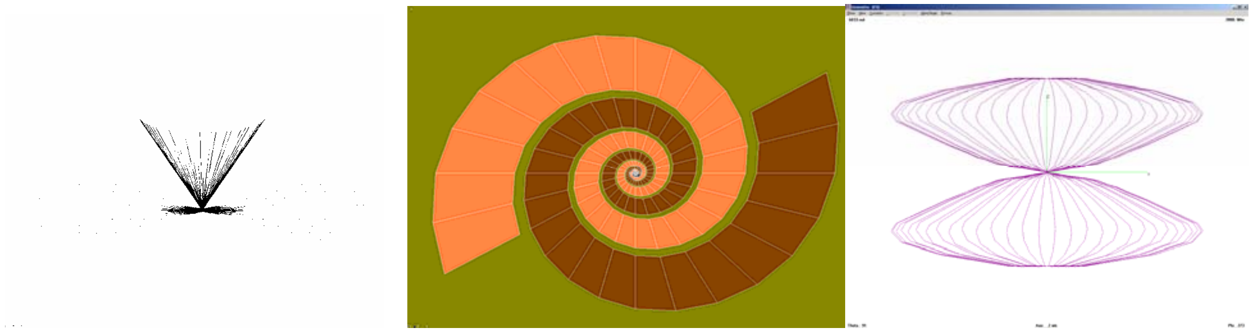

Figure 5   **a**. NEC4 Disk-cone in use.   **b.** PCB Spiral   **c.** *Dual-Ridge*way

As discovered, in the EVLA chamber a directional antenna is rendered isotropic and is randomly polarized. The gain must be presumed to be 0 dB even if two high gain antennas are on axis. Therefore the best antenna for chamber use is one that has maximum radiation efficiency meaning low loss. At this time the best antennae 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 the single height modules for shielding tests. The Bi-cone derivation is useful as an ultra broad band chamber receiving antenna.

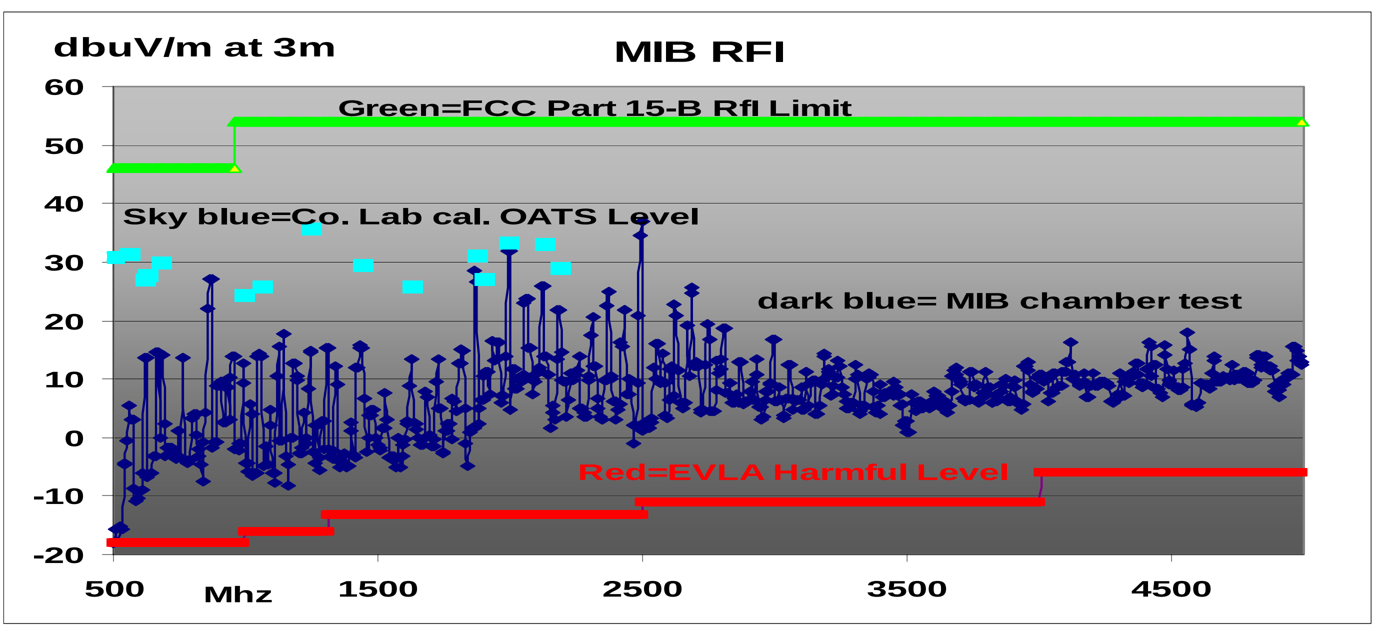

Figure 6.

Figure 6 shows close agreement between the calibration lab in Colorado (sky blue) and the MiB's maximum EIRP peaks in the EVLA echo chamber (dark blue) when changed to the equivalent dB(uV/m). 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 acknowledge that a mode stirrer or other means will need to be installed in the EVLA chamber. The green line is just for interest in that it shows the NRAO MIB being 25 dB below the usual PCB RFI level.

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 troubles. This NRAO designed *MIB PCB now has more than 48 dB less RFI than the VCMA 9* controller first proposed. See Figure 7. This low emission PCB will save us money due to the reduced shielding needed when operating 30 MIBs in each vertex room. Any bus wires must also be shielded equally as well or that cost savings will be ineffectual.

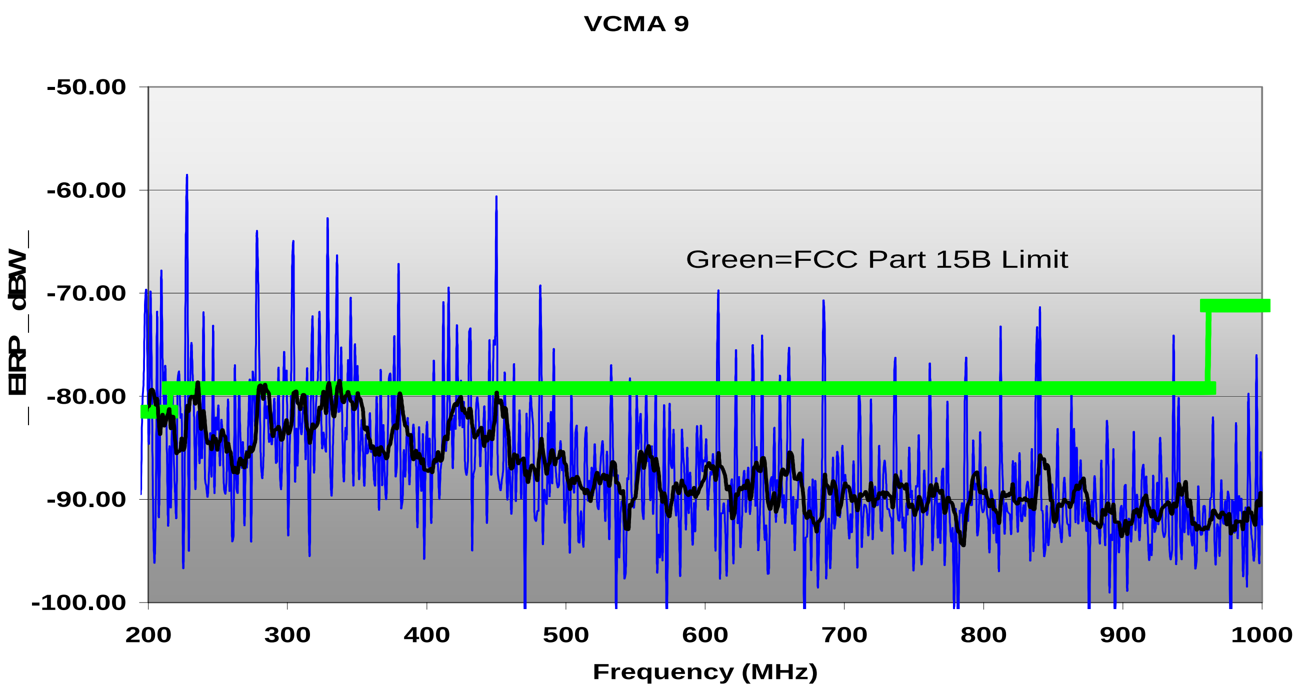

Figure 7.

How much shielding can the EVLA chamber measure?

EIRP emissions from various printed circuit boards (PCB) 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. One can choose which kind of module shielding qualities will be needed by reducing the RFI PCB emission spectrum by the shielding transfer function with in excel. This level is then compared to the EVLA harmful EIRP as in figure 8.

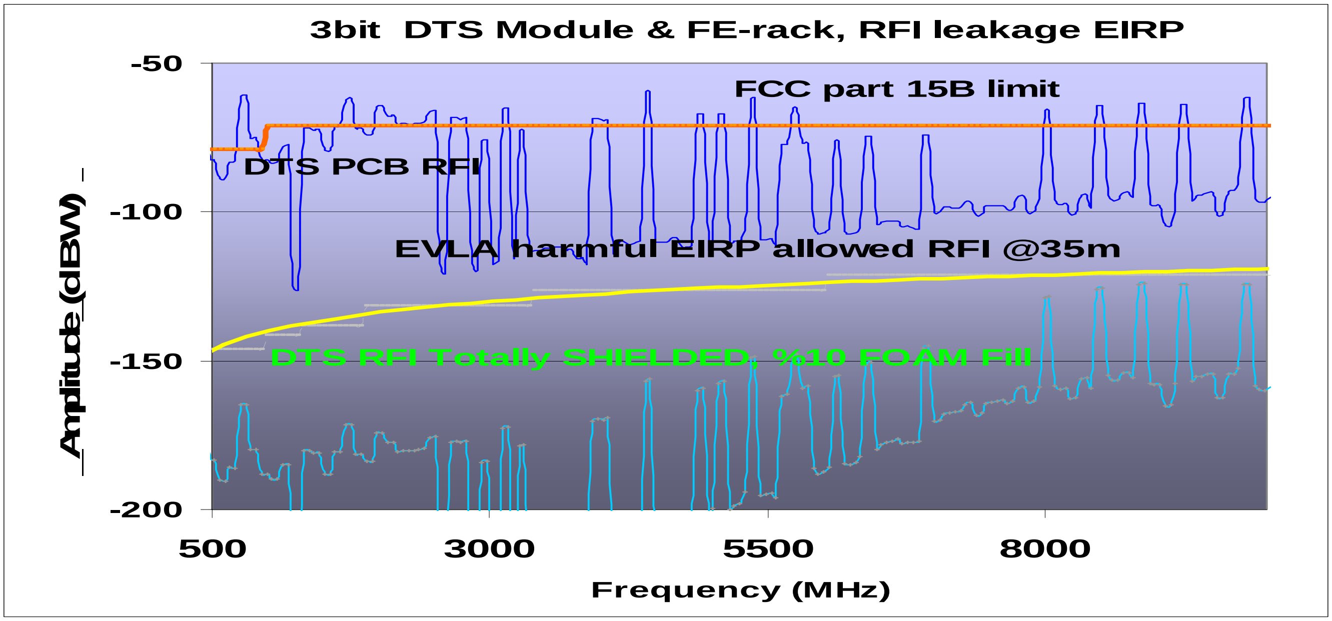

Figure 8.

Figure 8 shows the emission levels of the DTS hardware without shielding. The difference between these levels is the minimum amount of shielding required. An additional 30 dB is added as a margin of safety. This may prove useful when the bandwidth of the new correlator is used at the 0.12 Hz limit. This indicates that for 1km/s spectral resolution, 110 dB of shielding is desired before the DTS hardware can be installed in the EVLA antenna. This 110dB minimal amount of shielding was deliberately left in place for the VLA verification test. It will be improved 25 dB later by adding a lining of absorber foam in the FE-rack. If there are any hot spots above x-band, a thin layer of ferrite absorber can be glued to the inside wall of the sampler module. 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 module and they must be cleaned after each time it is opened.

Conclusion.

For the DTS it was first specified that two Spira-gaskets be used on both sides of a line of screws spaced every inch along the gasket joining the lid to the box. The redundant, dual gasket arrangement was needed because it was the main seal for two layers of shielding. This requirement is now removed with the FE-rack displacing the old G-rack. A second shielded FE-rack with a second DC feed-through in its wall, are needed to reach the desired 120 dB shielding. The first layer of module shielding is not quite enough, as seen in Figure 9.

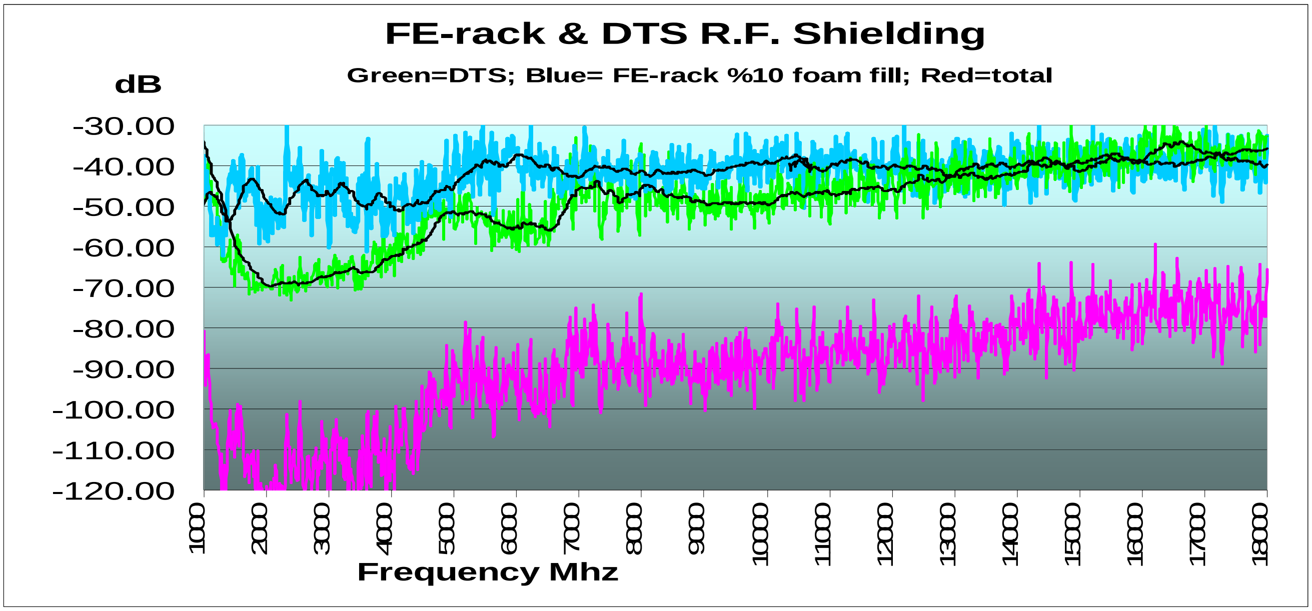

Figure 9.

Where a module lid has an inset step (as with the P301) the RF gasket only gave an additional 8dB shielding so its not needed. Now that these arrangements have been explored, I have imagined a lid and seat that needs no gasket, which will have better shielding. This lid is being tried by the ALMA team and more recently in the ATA.

The EVLA shielding requirements for the sampler PCB are correctly measured by the "Reverberation chamber"; (as verified by the VLA tests and the Criterion Lab's tests). Moreover, now that one can relate both the VLA and the RF chamber measurements to shielding requirements, the work in the RF chamber is accurate to about +/-4 dB, and is verified as relevant to the EVLA hardware prototyping. The paint on the inside surface of the chamber is not causing much of the -45 dB transfer function one sees above 15 GHz. It is normal and seems to be related to the decreasing effective area of an isotropic receiving aperture with increasing frequency.

The different layers of shielding were measured separately in the chamber and the total shielding is the sum using MS Excel. The peak RF emissions levels of the sampler PCB are 10-30 dB lower than the maximum allowed as shown on the PCB EIRP plot in figure 9. A reasonable extrapolation is that the final total shielding will be >110 dB below 4 GHz. This should make the EVLA able to run down to the narrowest of bandwidths with long integration times, and still not suffer RFI from the 3-bit sampler module and bin, at minimum cost. Any poorly shielded cables between modules must be attached via output filters. These cables must also be shielded and checked in the chamber as part of the total RFI mitigation effort.

The successful design of the EVLA Sampler/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, I believe that there is room for RFI reduction by shielding some components with small metal shields, though the boards are already too good to justify the time and money required. Such a third iteration in PCB shielding may be valuable to some future planetary RADAR or SETI application.

Now that the harmful RFI levels have also been confirmed by experiment, it is also possible to measure and control any PCB RFI emissions levels to be below the harmful EVLA EIRP levels at any distance, and to specify the required shielding. The great thing about using this controlled layering of shielding is that it is done at minimum cost by using no more resources than needed. This requires the ability to track the shielding improvements with each new change in the shielded container. However, the layered approach makes us use a "less than perfect" chamber measurement system and then estimate the combined result with accumulated errors. 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. The required EVLA shielding is well understood and is verifiable.

The EVLA chamber hardware has so far been adequate for emissions measurements. However, if one is ever to look at RFI emissions lines with the same sensitivity as the EVLA, with the shielding in place, one will probably need an LNA and/or a cryogenically cooled low noise amp. Such a setup might be useful years from now if damaged module shielding must be diagnosed.

References

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

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