The EVLA RFI Management Plan

Principles and Progress

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Introduction

- The EVLA will be particularly susceptible to unwanted RFI:
  - Very high sensitivity (low T_{sys})
  - Very high instantaneous bandwidths => no filtering
- The RFI environment is already bad, and will not likely improve with time.
- Considerable effort, and a flexible plan, will be needed.
- RFI management is a point of emphasis for EVLA: There are now 6 memos in EVLA series addressing RFI, with more to come.

EVLA RFI Memos

The following memos on RFI issues are in the EVLA Series. Other are under development.

#	**Author**	**Title**
46	Perley	RFI Emission Goals for EVLA Electronics
47	Pihlstrom	Estimated Shielding for EVLA Ethernet Switches
49	Perley	Attenuation of RFI by Interferometric Fringe Rotation
54	Mertely et al.	VLA Site Spectrum Survey: 1 – 18 GHz Results
59	Ridgeway	High Shielded Boxes for the EVLA Project
61	Perley/Cornwell	Removing RFI through Astronomical Image Processing

Why is RFI bad?

- Because it is vastly more powerful than the astronomical signals we seek. And there's a lot of it!
- Discriminate between `direct' and `indirect' effects:
  – Direct: RFI occurs at the frequency of interest.
    - Directly interferes with the imaging/sensitivity goals.
    - Must be able to remove/cancel the unwanted signal.
  – Indirect: RFI occurs within the band, but not at the frequencies of interest.
    - RFI power can cause saturation (non-linear response) in signal chain, lowering sensitivity and image fidelity across the full band.
    - Must design signal chain with very high linearity.
    - Must be prepared to blank when signals exceed linear region.

Observed RFI Powers and Characteristics

- The EMS (Environmental Monitoring System) has been operating for many years at the VLA site.
- Have used omnidirectional antennas, or low-gain rotating horns, to monitor the spectrum from 200 MHz to 18 GHz.
- A very wide range of strengths and behaviors found.
- Situation is worst in L and then S bands, where PFDs above 10^{-7} watt/m^2 are found.
- Strongest signals are always intermittent or pulsed.
- Examples drawn from L-band are shown in the accompanying table.

L-band RFI

L-band (1 – 2 GHz) has a wide range of signal types. The table shows the range of powers, as seen through isotropic sidelobes, for a single emitter. Multiple emitters are normal.

Origin	Frequency	SPFD	PFD	Power	Power/kTΔν
	MHz	Jy	$Watt/m^2$	Watt	dB
GPS	1575 – 1576	10^1	10^{-14}	3×10^{-17}	-40
Iridium (on)	1621 - 1628	10^5	10^{-10}	3×10^{-13}	0
DME (pk)	1025 - 1150	$>10^7$	10^{-8}	4×10^{-11}	+20
DME (mean)	1025 - 1150	10^3	10^{-12}	3×10^{-15}	-20

The SPFD is the apparent flux density through 0 dBi sidelobes. Multiply by 10^5 if in main beam.

Linearity

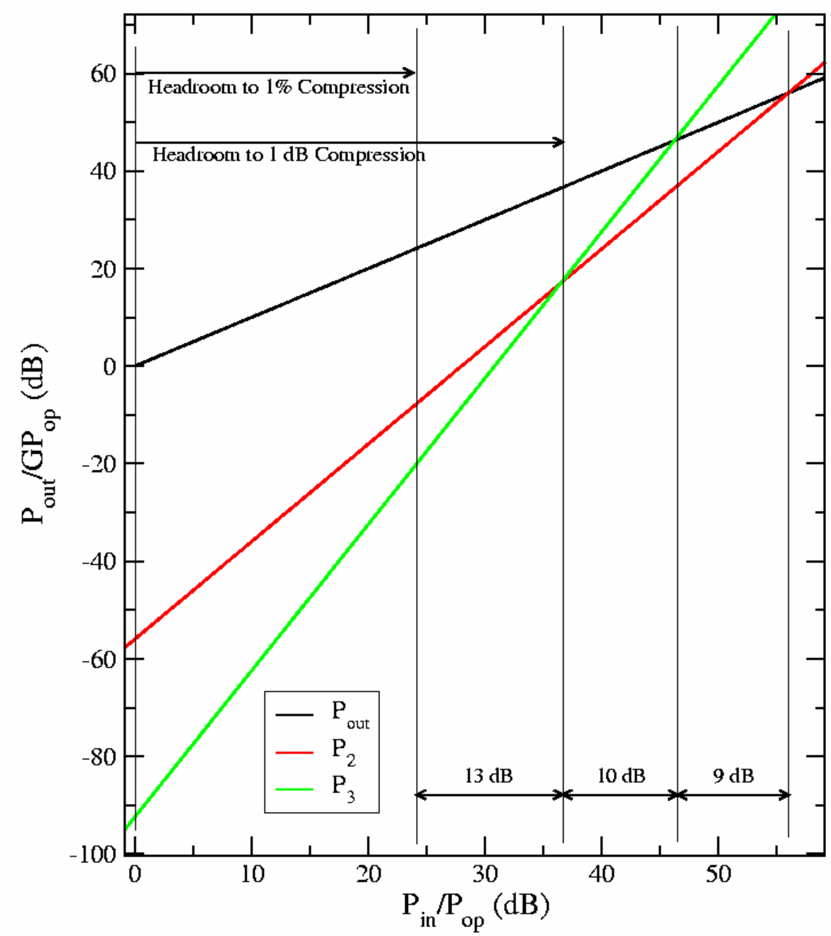
- The first line of defense is high linearity.
- Table shows the headroom from the nominal operating point to 1% compression.
- In addition, we will employ 8-bit sampling at P, L, S bands.
- The WIDAR correlator has ~55 dB spectral linearity.

Band	Headroom At Receiver	Headroom At Sampler
L	33.8	23.7
S	29.6	22.5
C	27.8	21.8
X	27.5	21.1
Ku	26.0	19.0
K	21.9	19.5
Ka	21.2	18.9
Q	13.0	13.0

NB: 1dB compression point is 13 db above 1% level.

Operating Points and Compression

- The plot shows a standard amplifier model, for the EVLA L-band system.
- The desired operating point is at (0,0) – defined as the input/output powers for kTΔν input noise power.
- The red and green lines show the power in 2nd and 3rd harmonics.

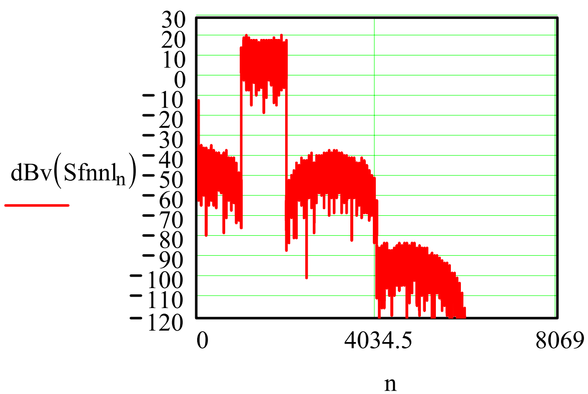


Minimizing Harmonics

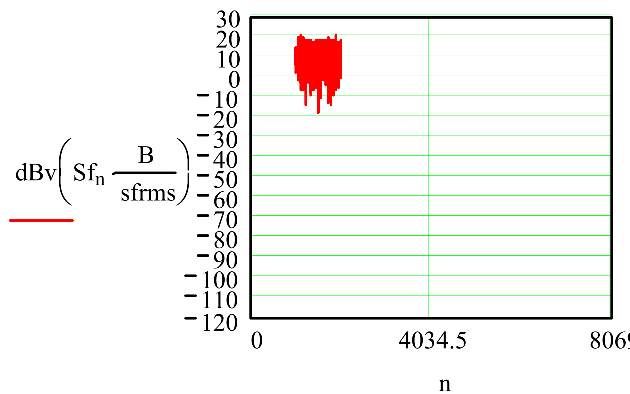
- Non-linear responses shift power from the fundamental frequency to higher harmonics. This is bad, as:
  - Spectral lines appear where they don't belong
  - Continuum power is shifted around the band, lowering sensitivity.
  - Probable `closure' errors, limiting imaging fidelity.
- We are designing for maximum `headroom', to minimize harmonic distortions and imaging errors.
- Goal is to get 1% compression point >20 dB above nominal input power level $kT\Delta\nu$.
- We are uncertain of the imaging effects of operating at high levels, near the 1% and 1 dB compression points.
- An experiment is being planned to measure this.

Noise Addition at Nominal Operating Point

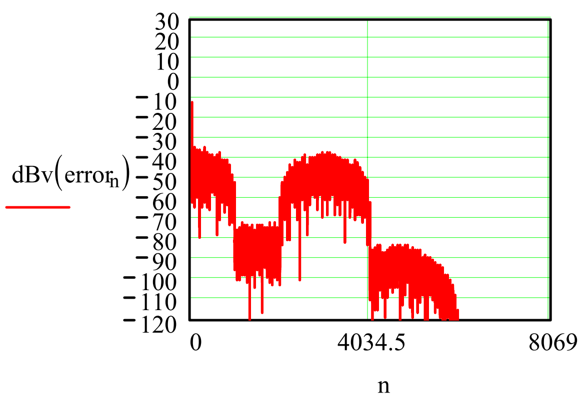
Signal after non-linearity



Signal before non linearity

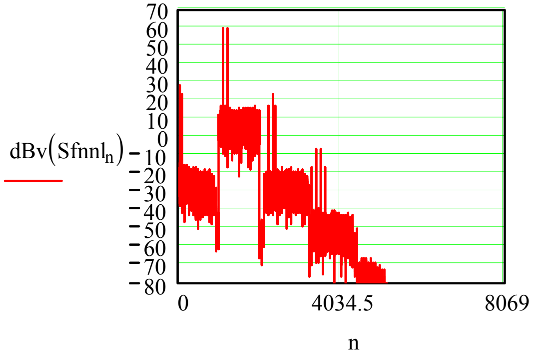


Error signal=after-before

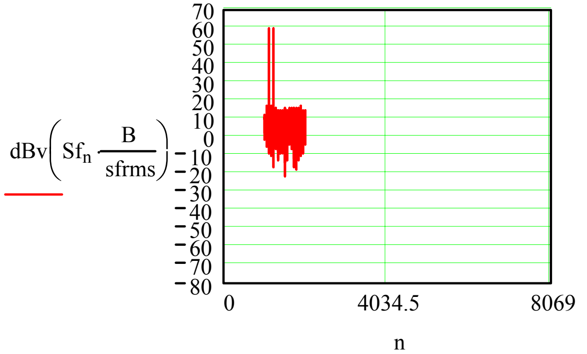


Noise at nominal operating point plus 2 CW signals +20 dB above nominal

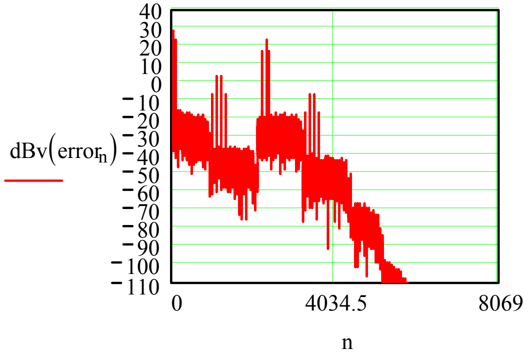
Signal after non-linearity



Signal before non linearity



Error signal=after-before

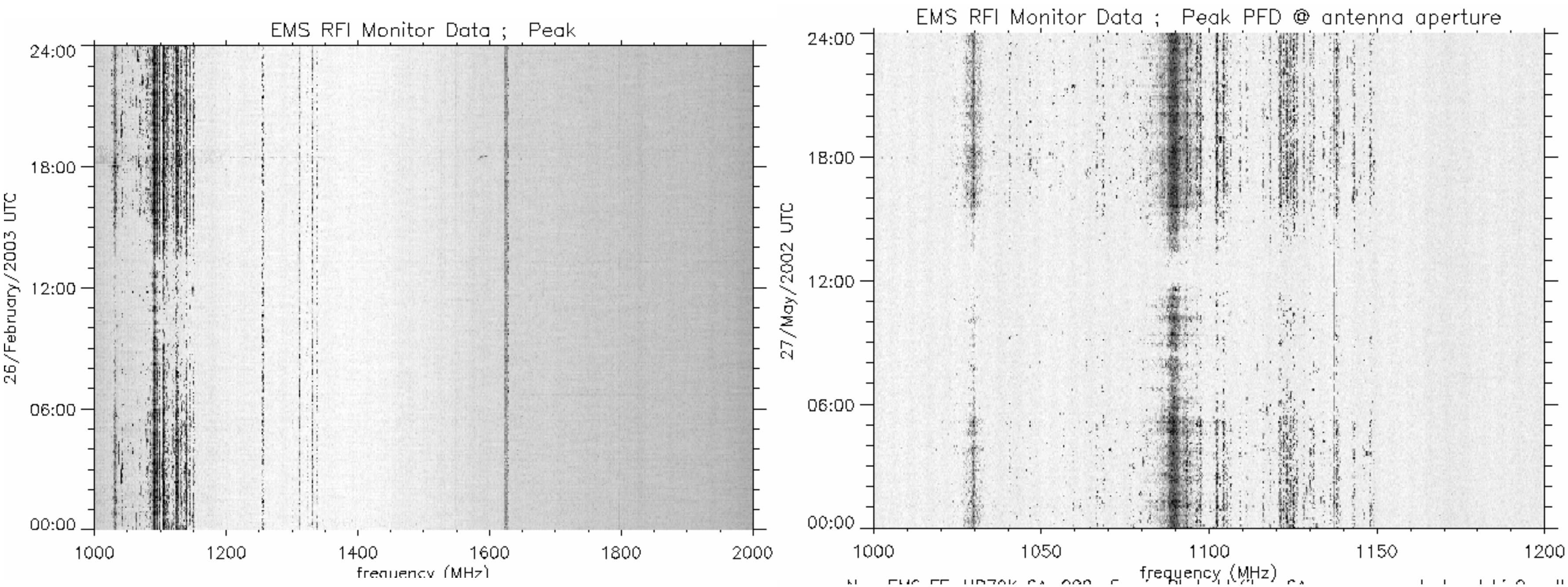


DMEs – the worst case?

- DME emission is a good ‘worst case’: not only strong, but highly pulsed:

Characteristic	Value	Comment
Transmitted power	1 kW (peak)	
Pulse width	3 μsec for two pulses	1 km long
Pulse pair separation	9 to 45 μsec	
Repetition rate	10 to 150 Hz	Tracking/acquire
Carrier Frequency	1025 to 1150 MHz	z = 0.23 to 0.39
Channel separation	1 MHz	270 km/sec.

Examples of L-Band RFI



24-hour plots of the `peak-hold' spectra at L-band. The LHS shows the entire 1 – 2 GHz band. The RHS shows the DME portion. Greyscale is black at SPFD = -140 dBW/m^2/Hz. White corresponds to –170 dBW/m^2/Hz Spectral resolution is 100 kHz.

DMEs and the EVLA

- These signals will certainly limit L-band performance!
- But how badly? We are reasonably confident we can survive emissions from aircraft >100 km distant.
- But an airplane within 10 km will probably saturate the signal chain, when the (short) pulses are on.
- Must then blank the pulse:
  - Detect when highest (8^{th}) bit is on at digitizer
  - Notify correlator that this frame of data is invalid
  - Blank all products using that frame
  - Make adjustments to correlation coefficient.
- This system will be in place at L and S bands.

Avoiding RFI

- As the EVLA will be designed to bring the full bandwidth back to correlator, we will not in general be tuning the LOs to avoid strong RFI.
- Strong, common RFI (e.g. DMEs) could be blocked by front-end filters if necessary.
- The WIDAR correlator is designed to allow tuning sub-bands to avoid strong RFI.
- Sub-band FIR filter designed with 60 dB isolation.
- Antenna-based LO offset eliminates aliasing of RFI between sub-bands (only effective with every other sub-band).

Internal RFI Control

- External RFI will be a major problem.
- We don’t want to exacerbate this with internally-generated RFI emissions.
- The EVLA has considerable digital electronics in the antenna – a natural source of emission.
- VLA IPG (Interference Protection Group) headed by dedicated engineer.
- Must first establish acceptable limits to emission from our digital electronics.
- Internal emissions above the acceptable level must be effectively shielded.

Acceptable Limits

- The `acceptable RFI' limits are based on a power flux level being less than 1/10 of the noise power fluctuation from the antenna detector. This leads to a condition:

$$F_h \leq \frac{0.4\pi k T_{sys}}{G_r \lambda^2} \sqrt{\frac{\Delta \nu}{\tau}} \qquad \text{watt/m}^2$$

  where G_r is the *g*ain of the antenna (w.r.t isotropic) in the direction of the RFI.
- Note that the forward gain of the antenna is not a factor in this susceptibility.
- This leads to a very stringent standard, as interferometric phase winding will give us considerable help.

Limits for 1 km/sec

For the EVLA, with 1 km/sec resolution, and 9-hour integration:

Band	$\Delta\nu$	T_{sys}	F_h	F_h	S_h
	kHz	K	Watt/m^2	dBW/m^2	Jy
L	5	26	4.4×10^{-21}	-204	88
S	10	29	2.8×10^{-20}	-196	280
C	20	31	1.7×10^{-19}	-188	850
X	33	34	6.6×10^{-18}	-172	2000
U	50	39	2.1×10^{-18}	-167	4200
K	77	54	8.4×10^{-18}	-171	10910
A	113	113	1.9×10^{-17}	-167	16810
Q	150	150	5.5×10^{-17}	-163	36670

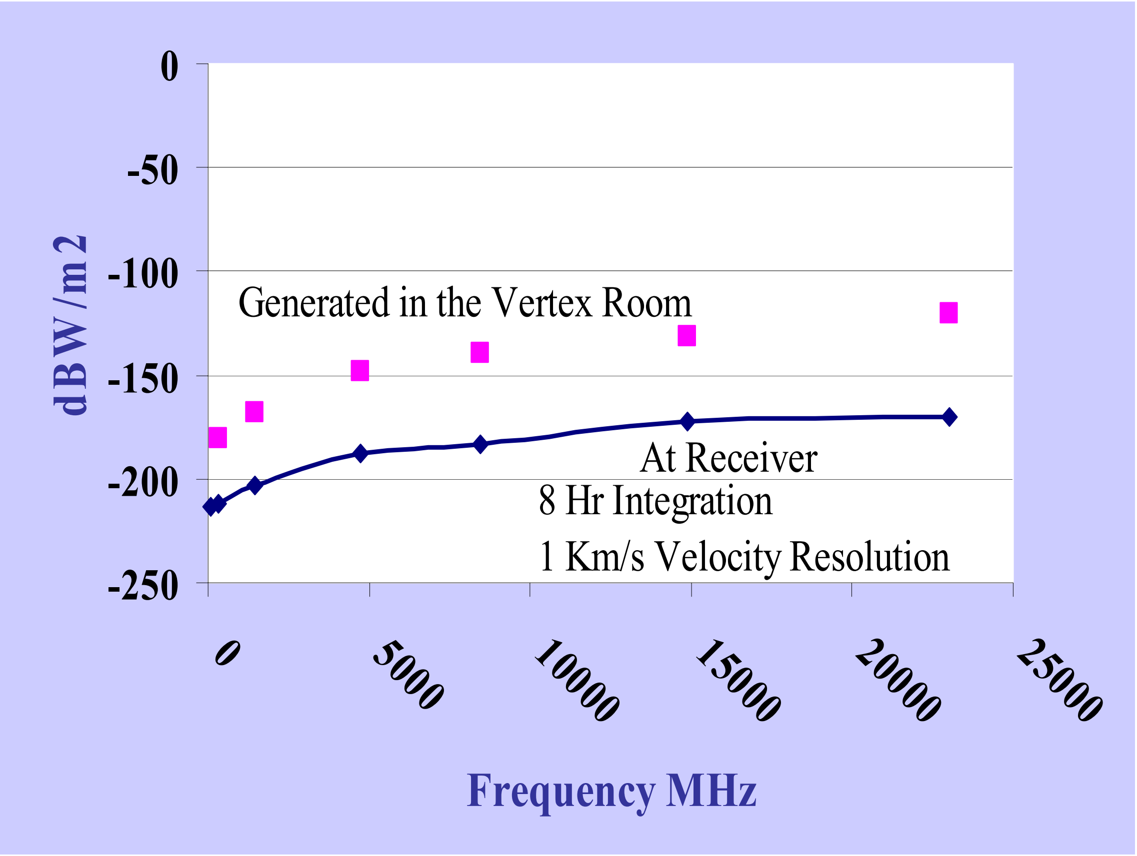
RFI Suppression Progress

- To keep internal RFI below these established standards, we must:
  - Design for low emissions (lower power, slower transitions)
  - Provide shielding at the module/rack/room levels to keep radiation low.
  - Utilize RF absorbing material to lower RFI power density.
- Tests show shielding better than 110 dB – we expect this will be sufficient to meet ITU standards.

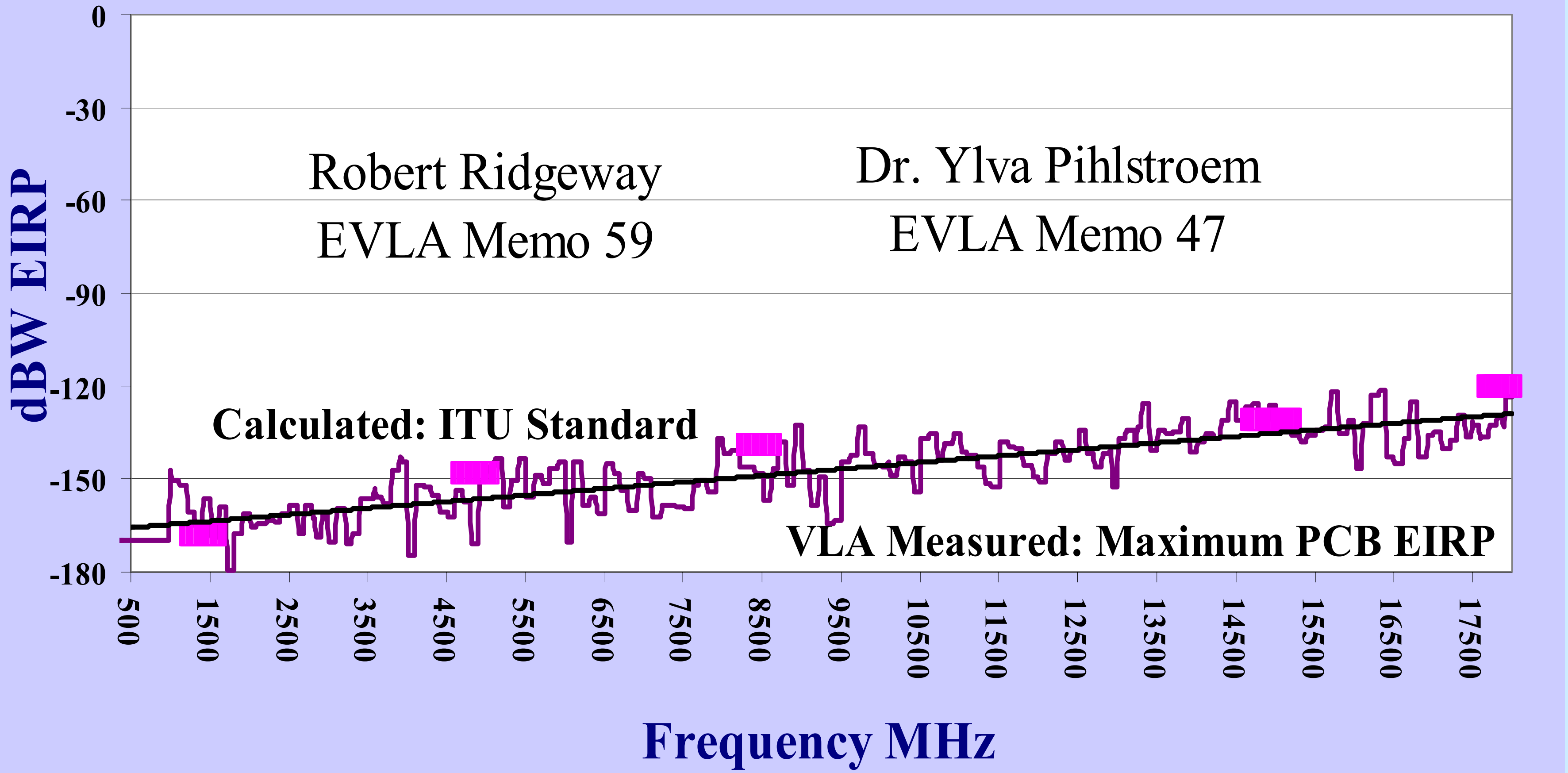
ITU Calculated Maximum Power Flux Density

- VLA antenna
- 18 m Distance

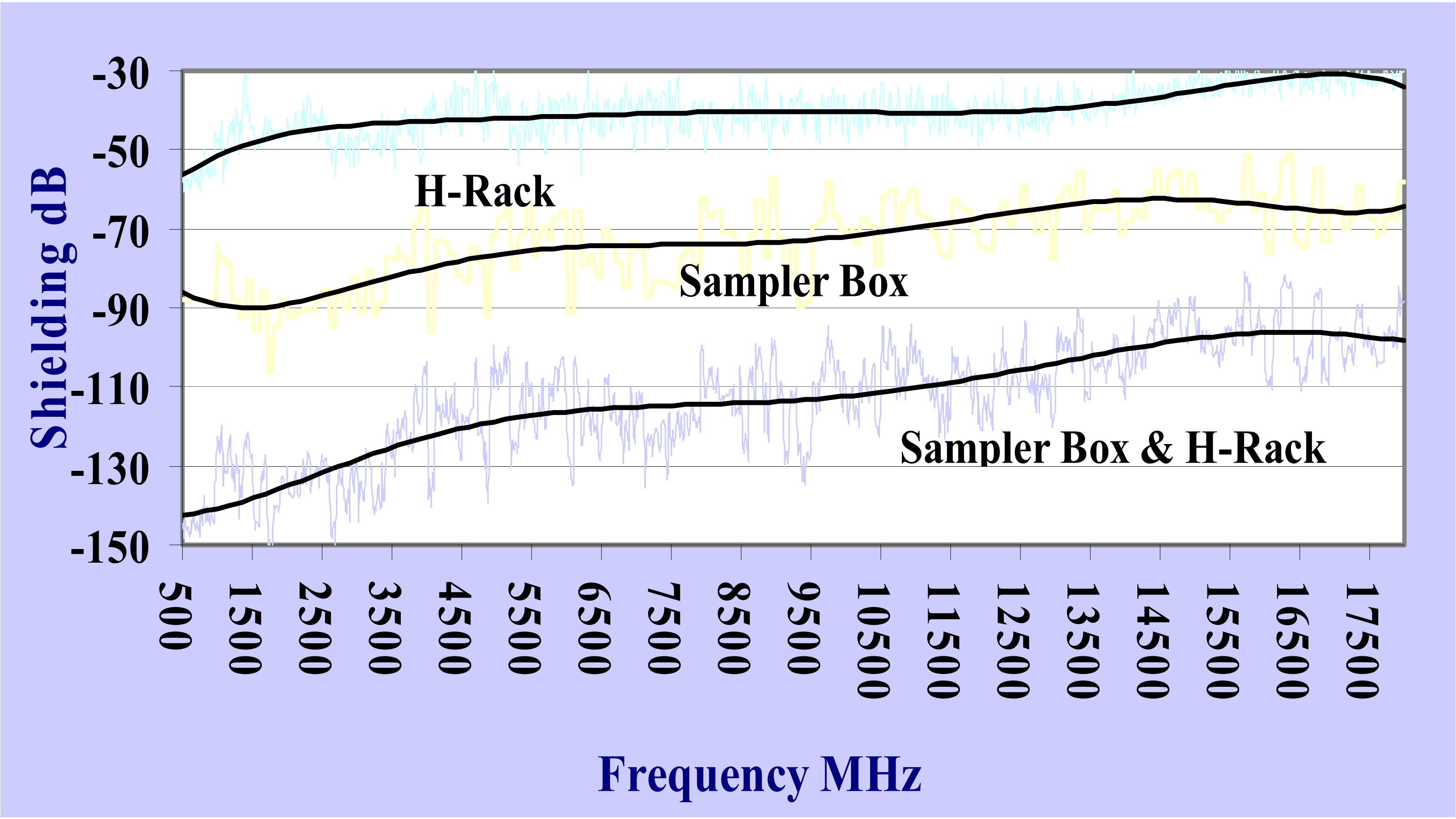
- 10% reflection off sub-reflector



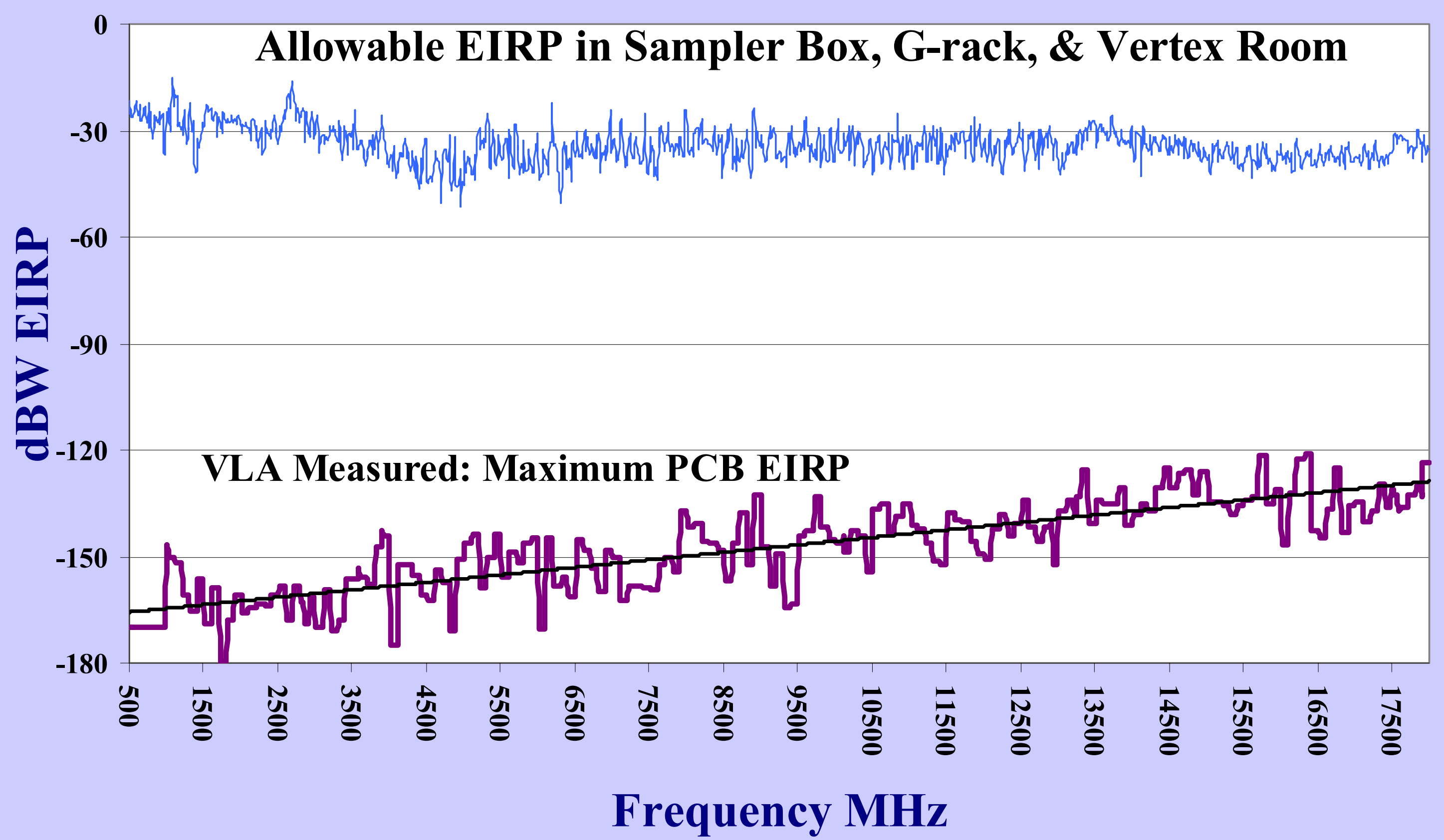
Measured Harmful EIRP from Vertex Room



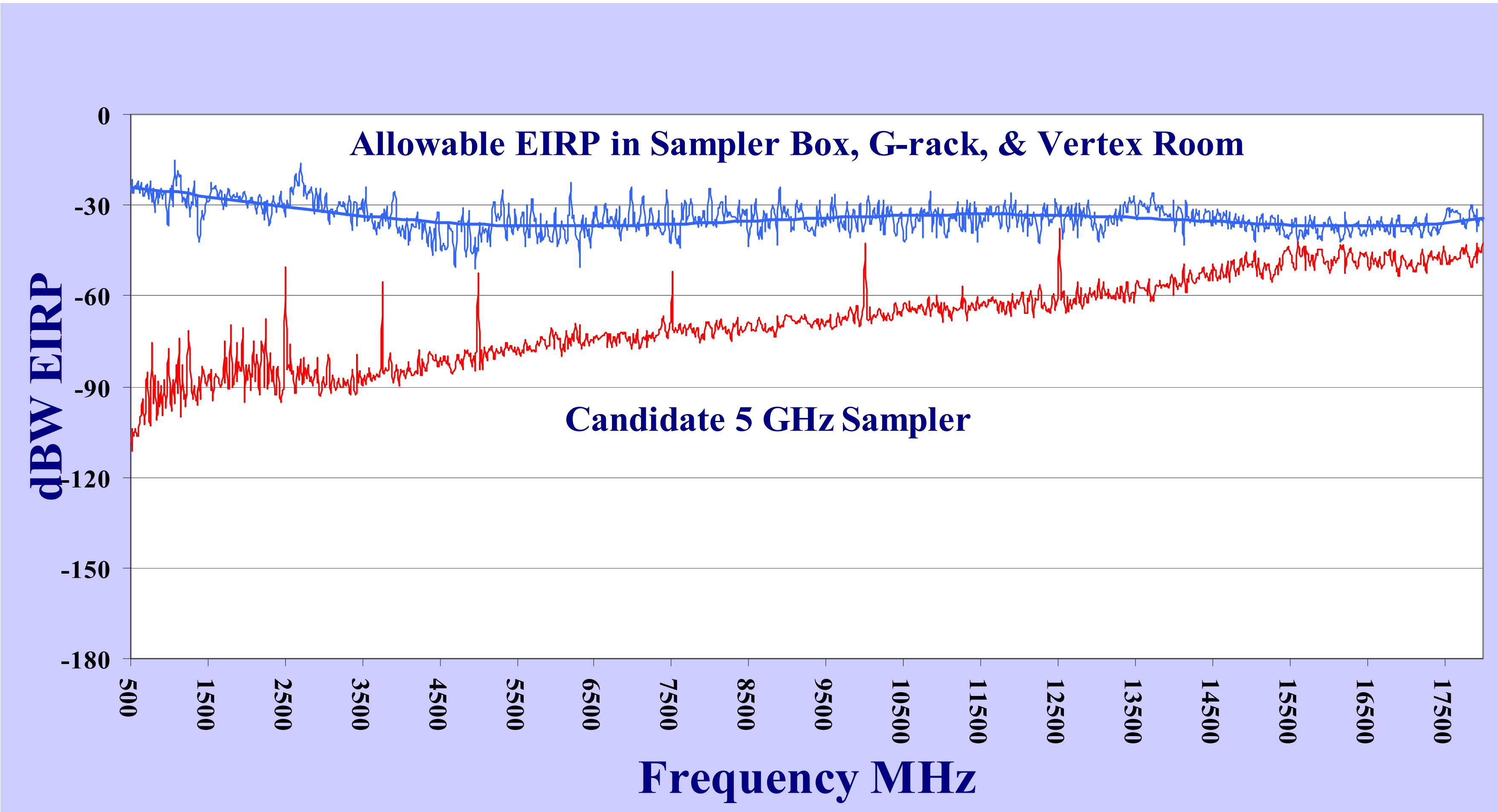
Sampler Box & H-Rack Shielding



Estimated Effect of Shielding



Circuit Comparison

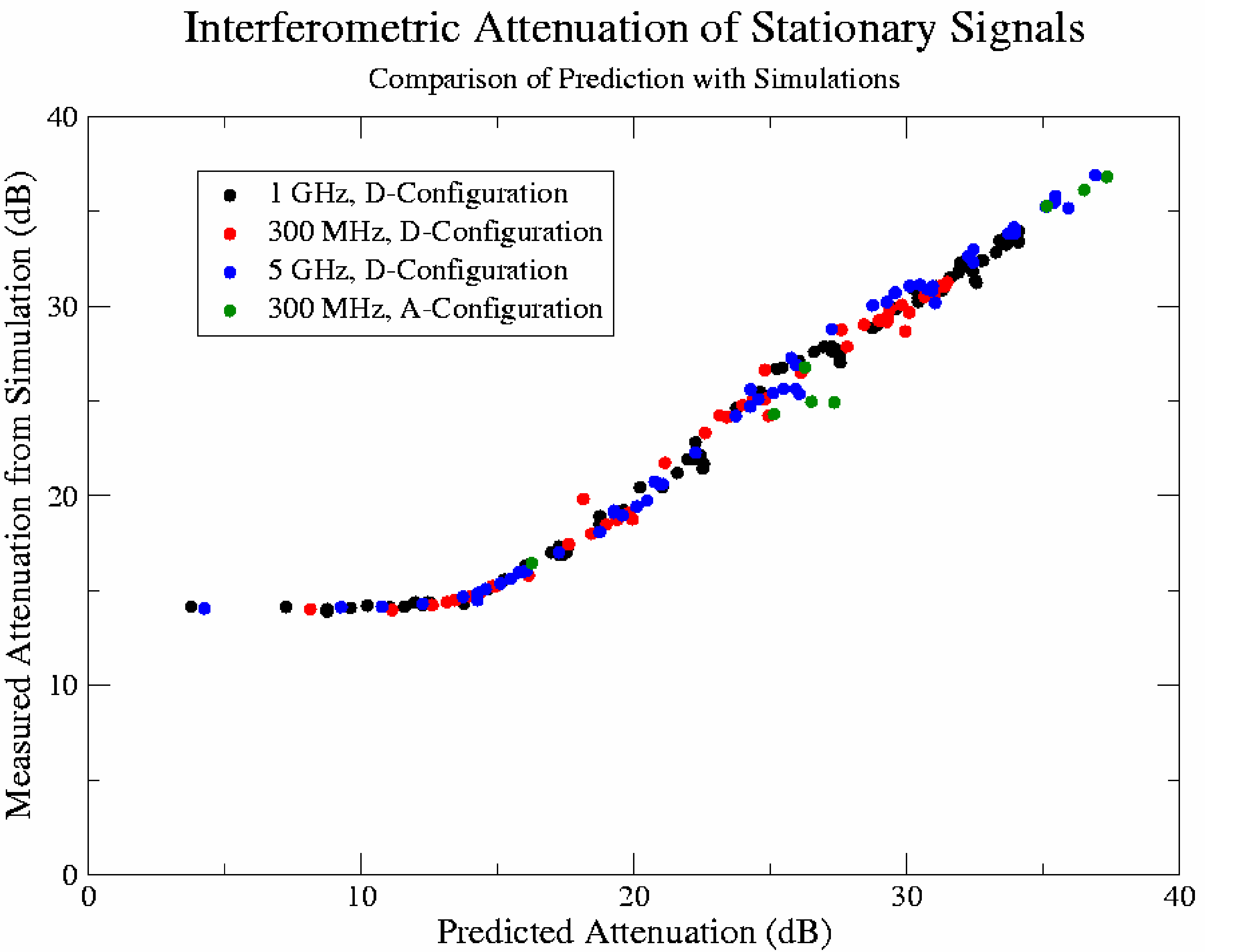


Direct Effects of RFI

- An interferometer has an inherent advantage over a 'total power' single dish:
  - Interfering signals have a phase and phase rate.
  - Over time, coherent averaging reduces signal strength – provides 15 to >60 dB isolation. From Memo #49:

$$A \approx \frac{2.5}{\sqrt{t_s \upsilon_M B_{\max} \cos\delta}}$$

- Phase and phase rate also be used to identify and remove unwanted emission.



Interferometric Attenuation of Stationary Signals
Comparison of Prediction with Simulations
Measured Attenuation from Simulation (dB)
Predicted Attenuation (dB)
1 GHz, D-Configuration
300 MHz, D-Configuration
5 GHz, D-Configuration
300 MHz, A-Configuration
0
10
20
30
40

Example: GPS signals

- Each GPS satellite has (on-axis) SPFD of about 10^6 Jy.
- If a satellite traverses a 0 dBi sidelobe, we obtain about 50 dB attenuation: Apparent SPFD is now 10 Jy.
- In traversing the entire sky (about an hour?), fringe winding will give about 30 dB further attenuation in D-configuration. Much more in larger configurations. Apparent SPFD is now about 10 mJy (comparable to noise in 1 km/sec channel width)
- If in continuum mode, the 1 MHz BW of the GPS signal is diluted by a further 30 dB (in the 1 GHz FE bandwidth). Signal is now about 10 μJy in effective strength (comparable to noise in full BW).
- But GPS is the most benign of all transmissions.

Post-Correlation Excision – Removing what we don't like

- For signals that enter the correlator (and which don't cause saturation or non-linear behavior), we have an 'ultimate' weapon: Post-Correlation Excision.
- This technique recognizes that RFI is not essentially different than an unwanted background astronomical source.
  - RFI 'closes' -- even for multipath! (Provided it is sampled quickly enough, and modulation or motion doesn't shift frequencies around.)
  - RFI is spatially unresolved, so its antenna-based phase and amplitude characteristics can be `easily' determined.
  - One can, in principle, then solve for, and remove, the unwanted signal.

Suggested Procedure

- Sample fast! (And preferably with narrow channelwidth).
  - N.B. This is an expensive combination!
- Phase rotate affected data to ‘stop’ fringe-winding of RFI.
  - Easy if the RFI is stationary (same rate as NCP).
- Use ‘CALIB-like’ program to solve for RFI phase and gain for every affected frequency channel.
  - Better: Solve for source and RFI at same time, allowing different gains for each.
- Subtract RFI from each affected channel, using gains.
- De-rotate data back to phase center, and integrate to reduce volume.

How Fast, How Big?

- For the VLA, with SNR = 100, we find, in **milliseconds:**

Config.	90cm	20cm	6cm	2cm	0.7cm
E	3860	860	260	85	30
D	960	210	65	20	7.5
C	300	70	20	6.8	2.4
B	95	20	6.5	2.2	.75
A	30	6.8	2.0	.70	.25
NMA	3.0	.70	.20	.070	.025

- These are very short times, leading to very large databases.
  - At 100 msec, the total rate > 1 GB/second for 16384 channels.
  - The red zone lies beyond the WIDAR correlator – but natural fringe winding provides 25 dB attenuation in 1 second!

Progress

- This method is similar to AT approach, but does not require a separated pointed antenna.
- Other approaches being developed elsewhere appear to be similar.
- We have no demonstrated examples yet. (Hard to find somebody to work on this).
- Considerable development is required – an interesting problem for a suitable person.

Final Level: Blanking

- The strongest signals are generally pulsed.
- The 8-bit sampling at L and S bands will have the capability to alert the correlator when a voltage level above a certain threshold is met.
- The correlator will then blank all computations using that frame.
- An adjustment to the correlation coefficient will be needed. (Thought to be small).
- Will extend to 3-bit sampling.