The Next Generation of Receivers for Low Frequency Radio Astronomy:

Designing a Sky-Noise-Limited Receiver for LWA

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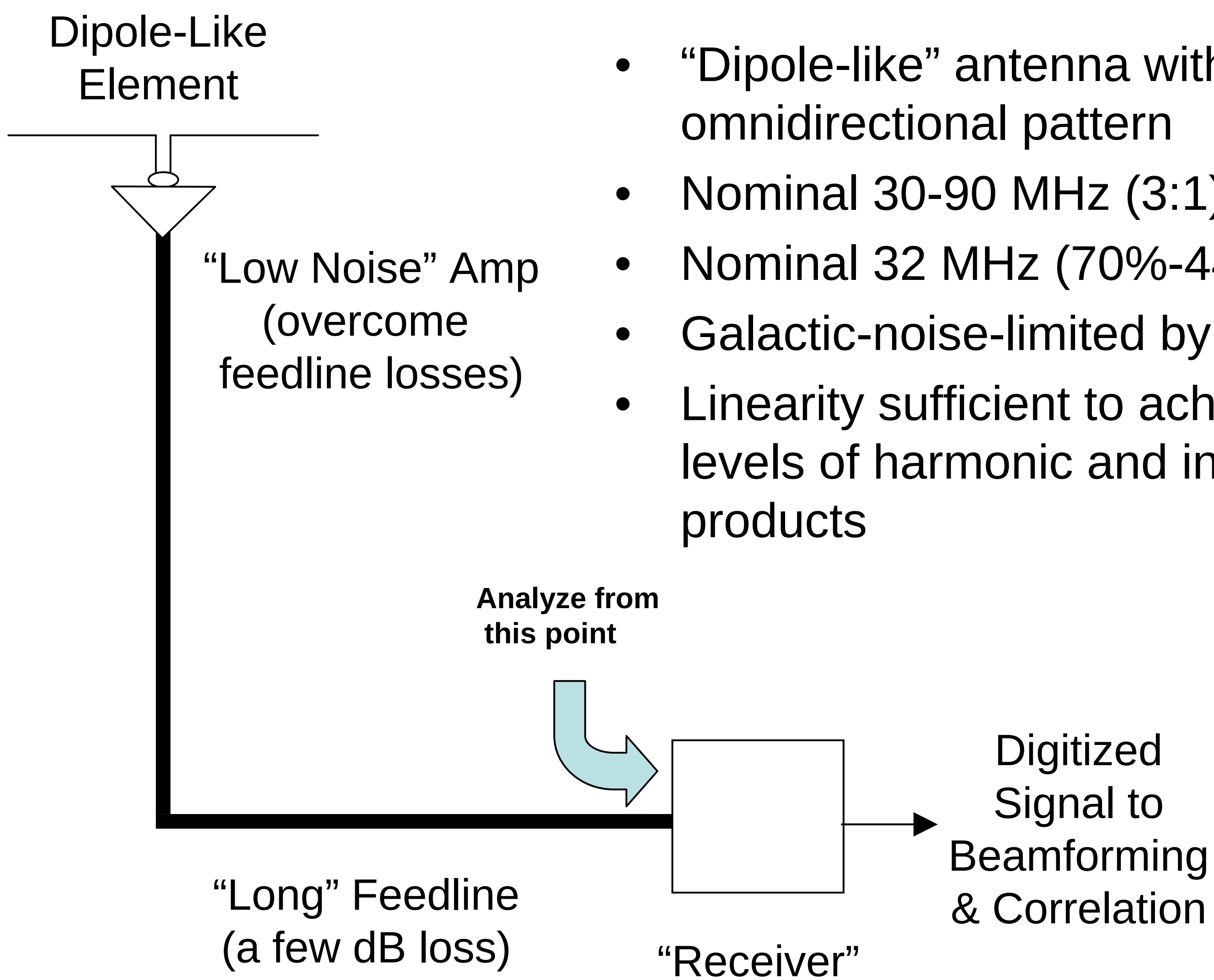
The LWA Receiver Design Problem

- “Dipole-like” antenna with roughly omnidirectional pattern
- Nominal 30-90 MHz (3:1) tuning range
- Nominal 32 MHz (70%-44%) BW
- Galactic-noise-limited by a factor of 10
- Linearity sufficient to achieve “acceptible” levels of harmonic and intermodulation products



Why This is (Relatively) Difficult

- **<u>Above 1 GHz</u>, achieving 3:1 tuning range and >10% BW is easy (in fact, routine).**
  - This is because receiver input is almost always noise limited under these conditions
  - RFI power is relatively small and does not significantly impact selection of receiver architecture
  - Popular solution: “upconvert-downconvert” architecture

- **What is different below 1 GHz?**
  - Impossible to avoid large, persistent RFI, which can easily dominate over noise.
  - Upconvert-downconvert architecture requires at least 2 mixers, which now have stringent linearity requirements. Becomes expensive and risky.
  - Strong motivation for direct sampling (no mixers)…

Antenna Considerations

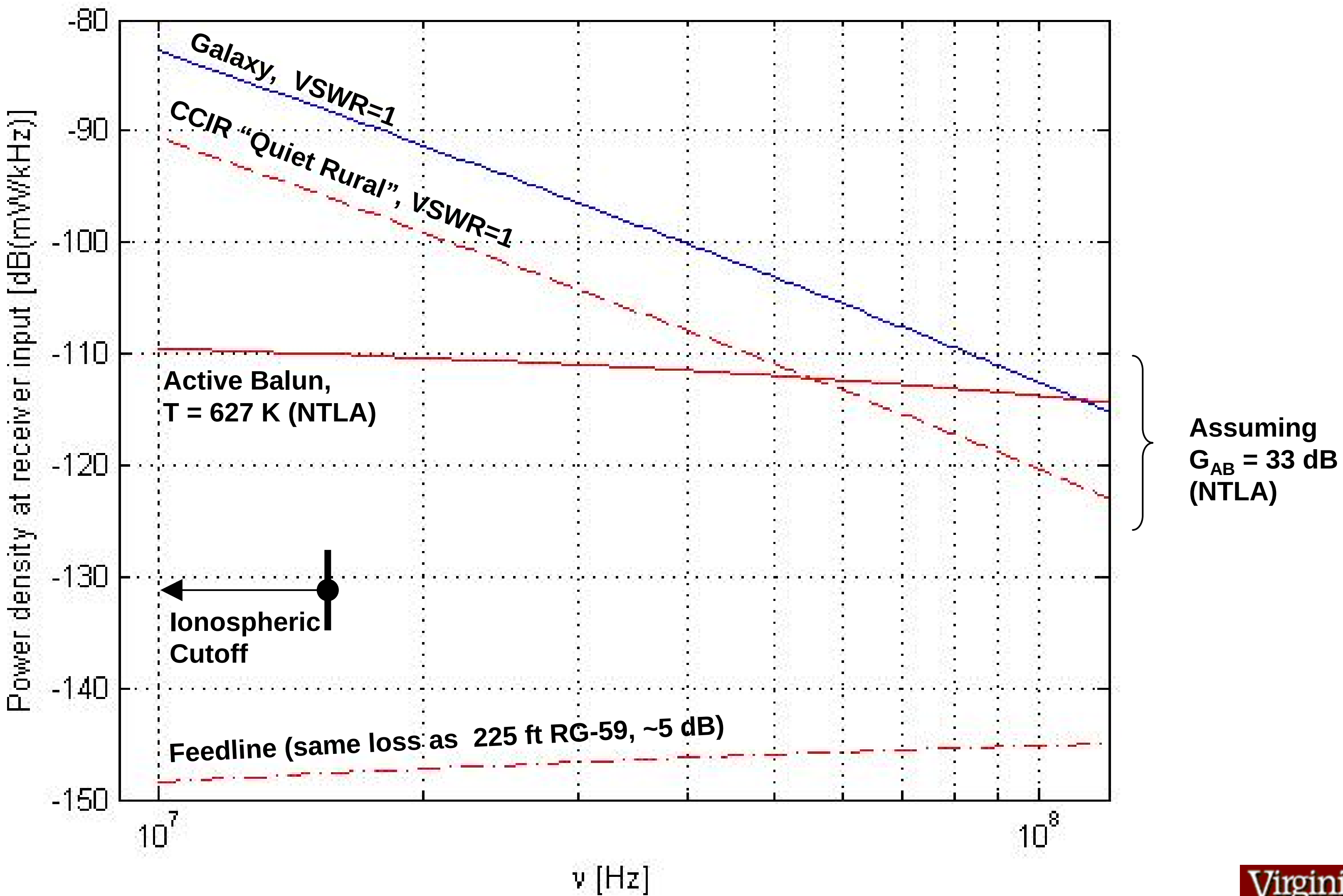
- Antennas using “dipole-like” elements are preferred for their relative simplicity and somewhat omnidirectional pattern.

- To maintain a nice pattern, such antennas cannot be used at frequencies > about 1.5 times resonance.

- As frequency drops below resonance, antenna impedance becomes overwhelmingly reactive – power transferred through antenna terminals quickly dwindles towards zero
  - “Fat” dipoles do better at this than “thin” dipoles
  - Certain types of “active antennas” have the potential to improve this, but for simplicity we will neglect this possibility here.

- As we will see, these issues upper-bound achievable antenna BW to about 3.5:1, and much less for thin dipoles

Power Densities at Input to Receiver, Perfectly-Matched (VSWR=1) Antenna



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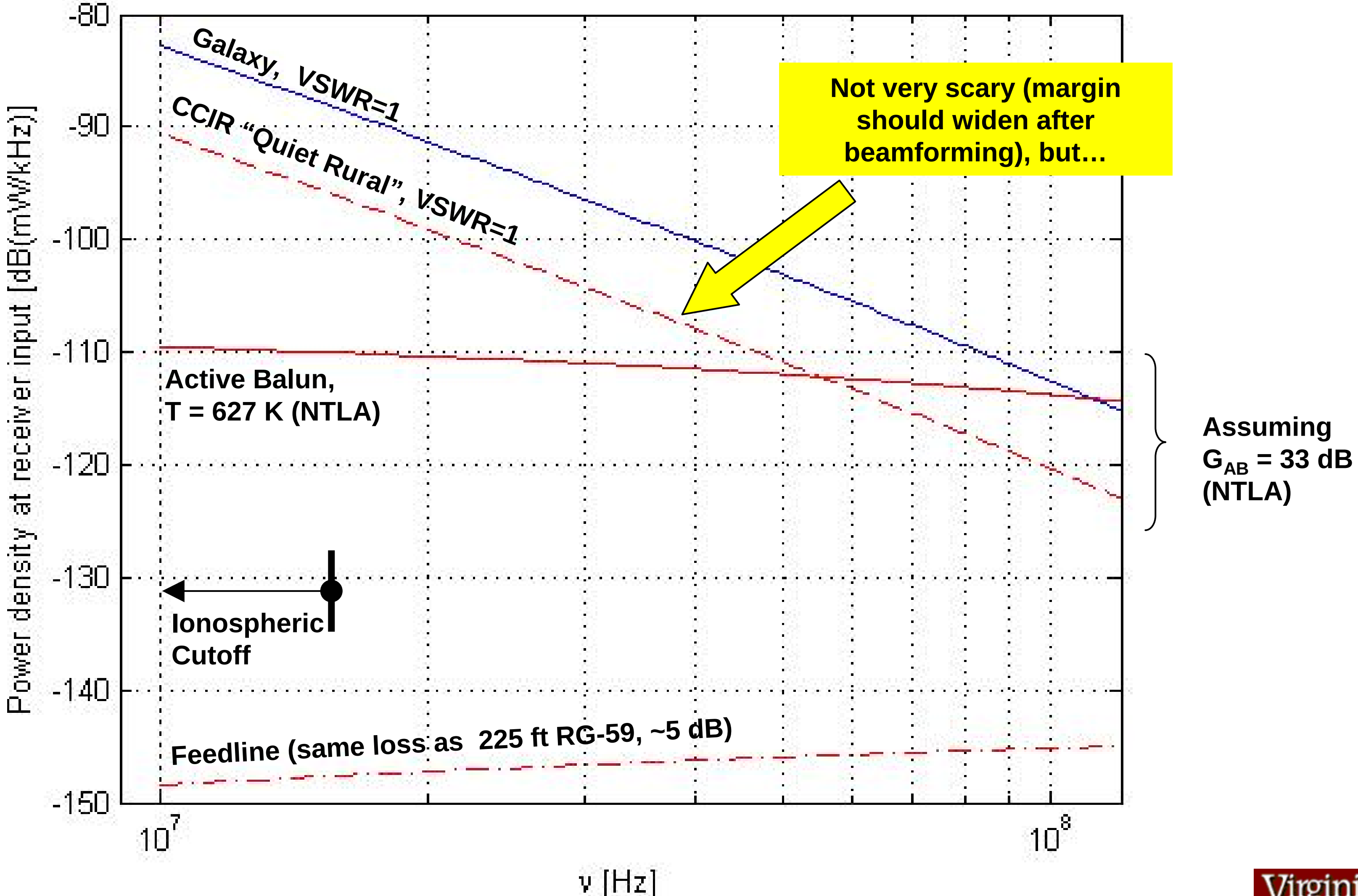


The Man-Made Noise Background

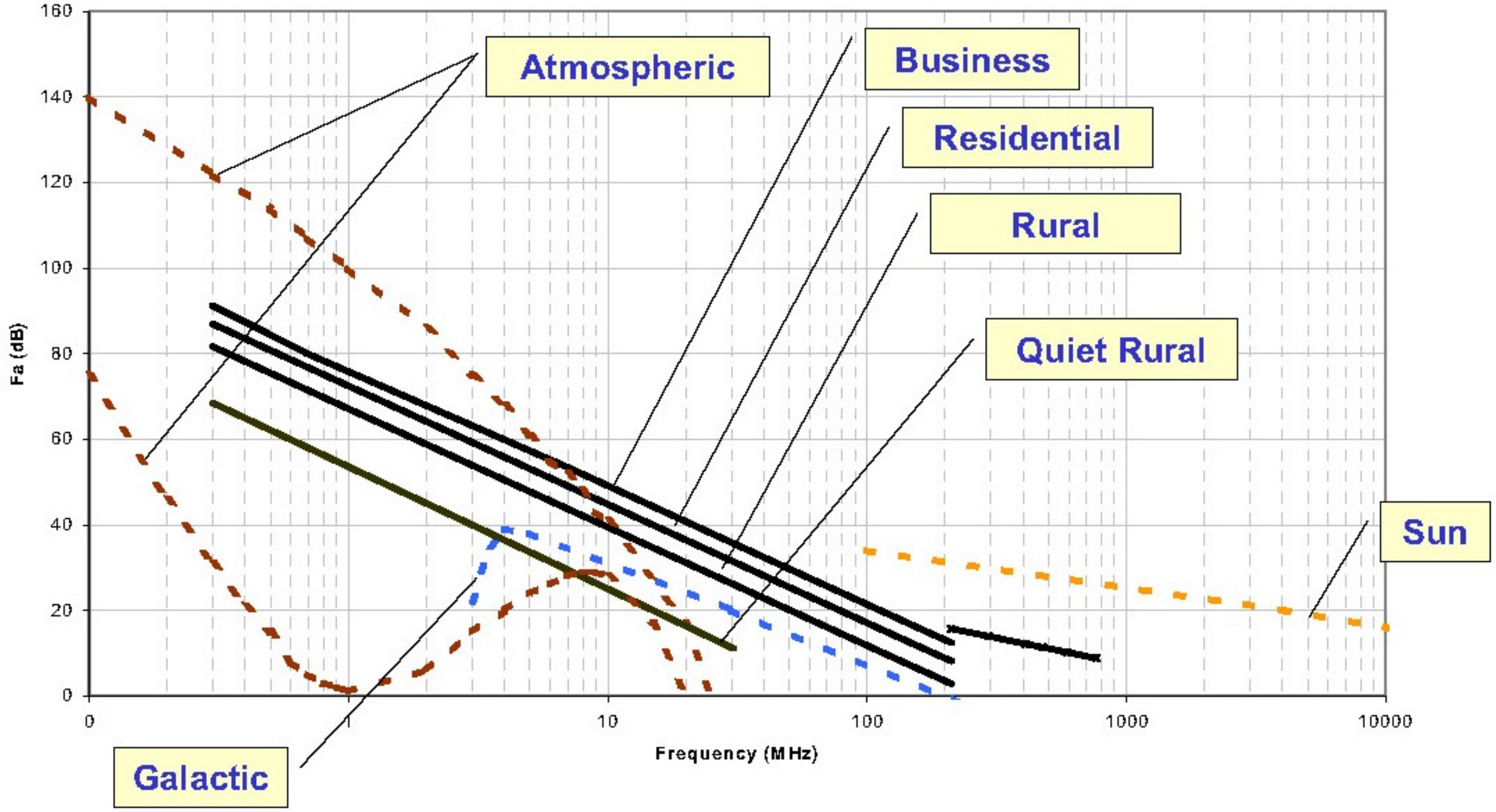
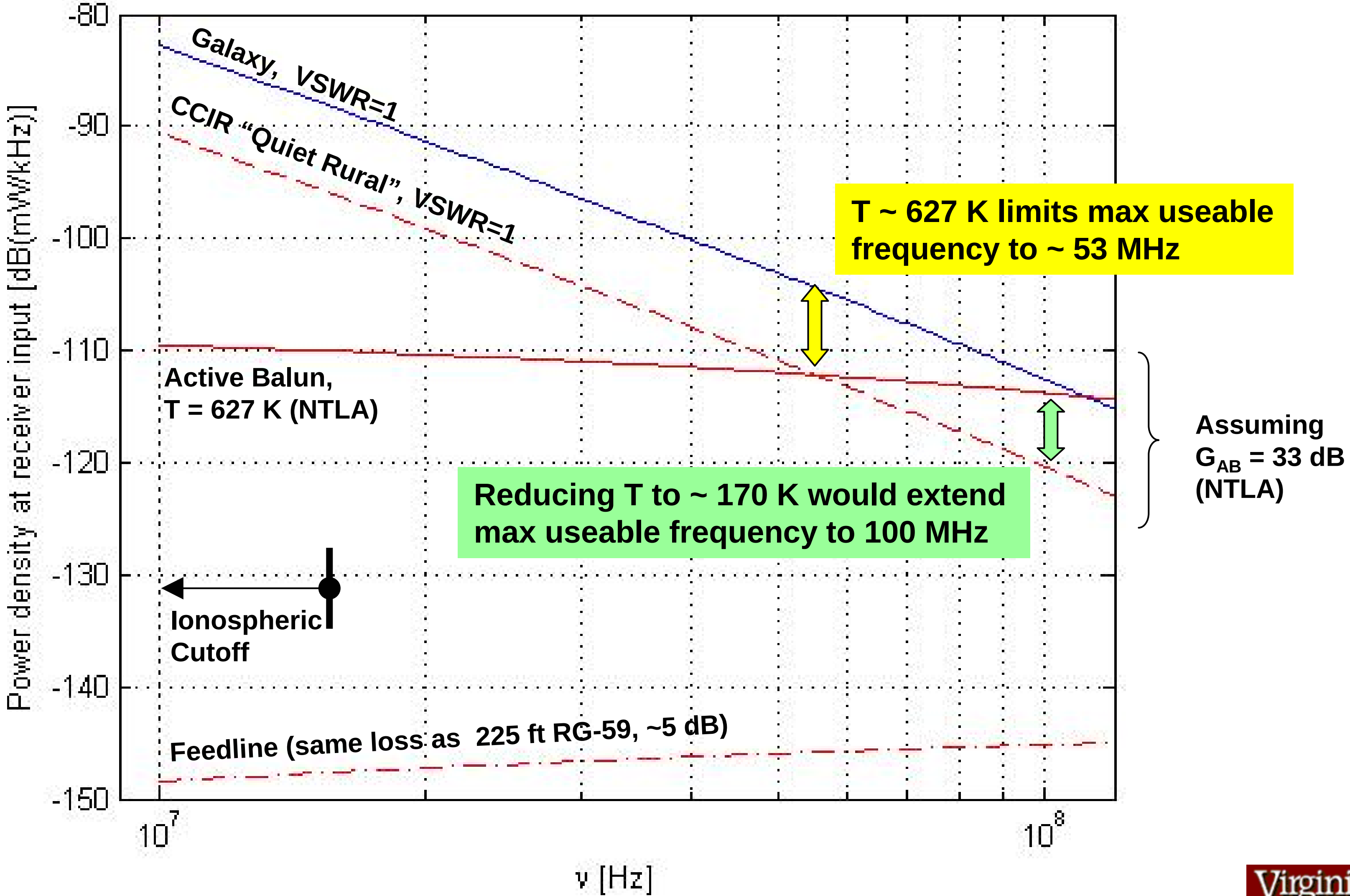


Figure 2 Noise distribution with Frequency

The levels in Figure 2 are taken from the ITU-R recommendation [P.372], which contains descriptions of the various types of electromagnetic noise.

LNA Noise Figure Constrains Upper Frequency Limit



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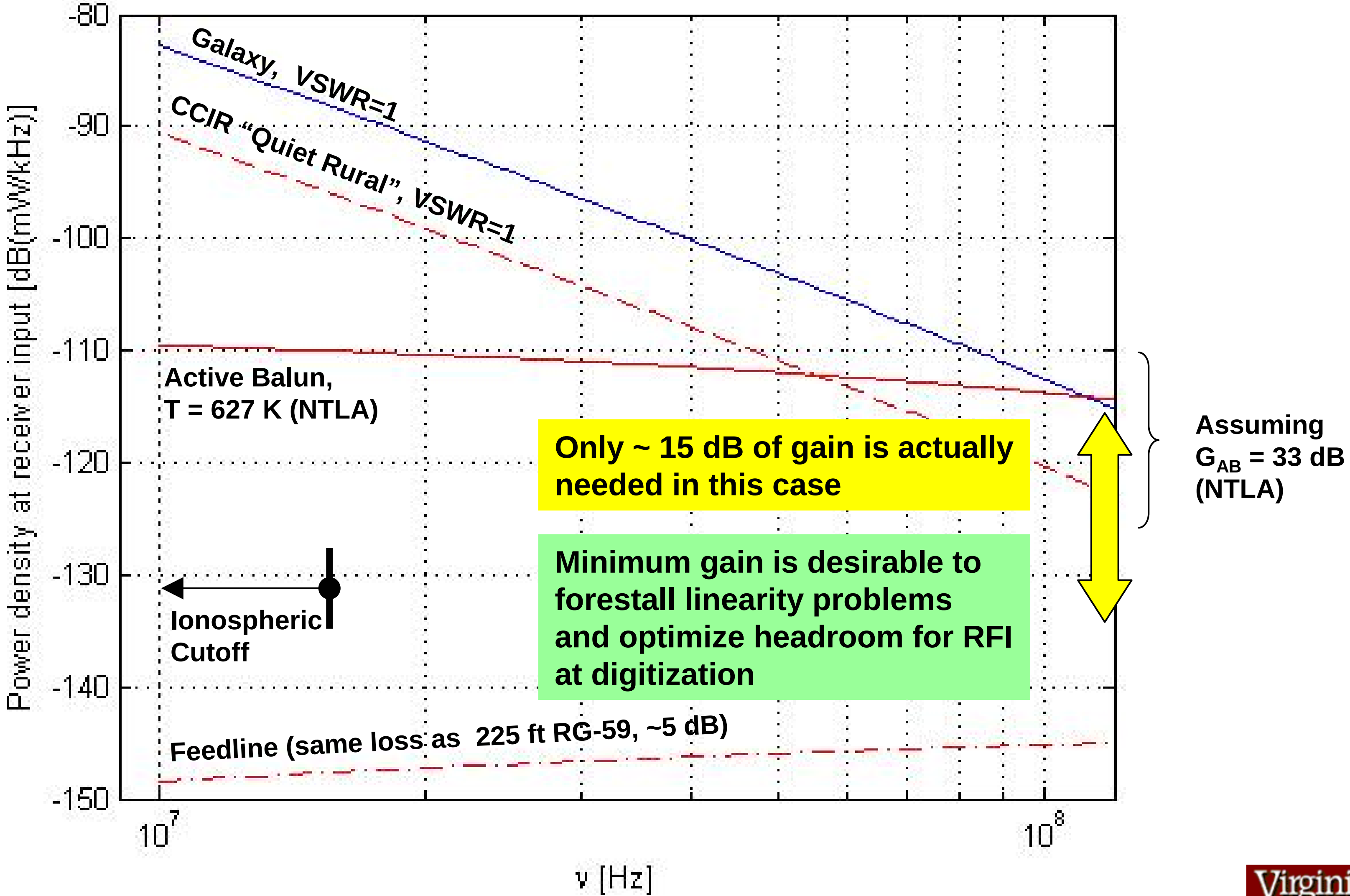
LNA Gain Should Be Minimized

(consistent with role of setting system temp)



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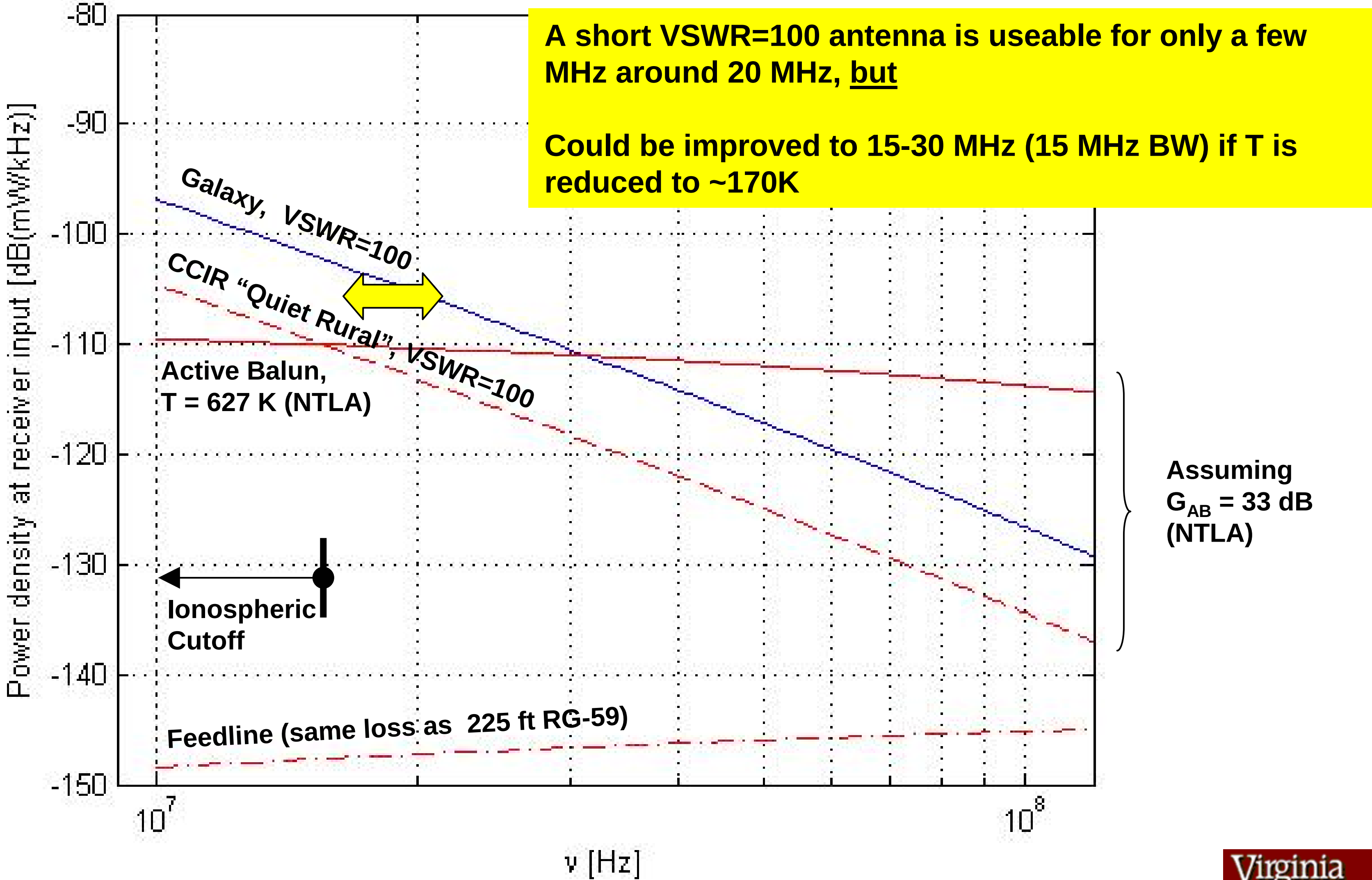
Power Densities At Input to Receiver, "Minimally Useful" (VSWR=100!) Antenna



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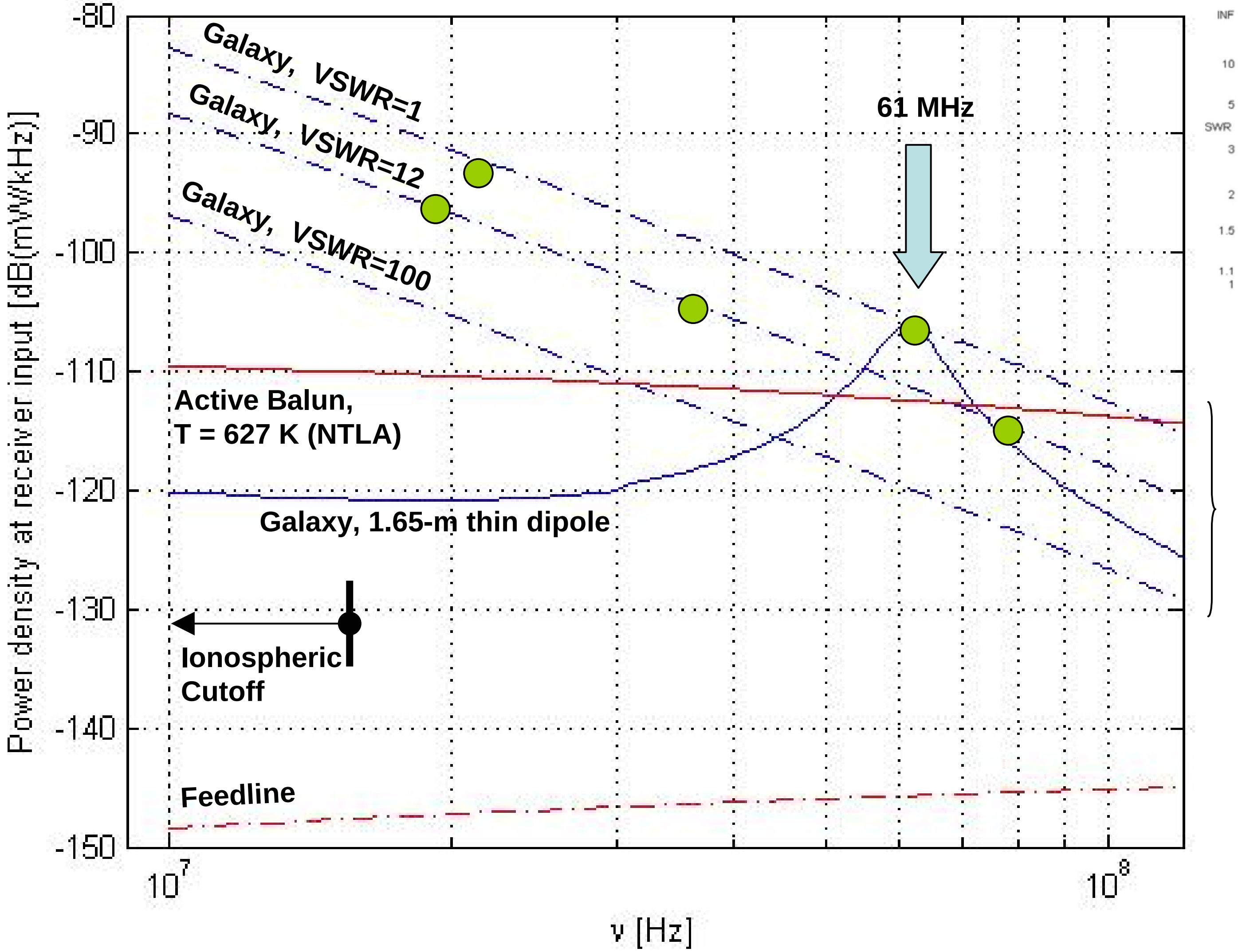
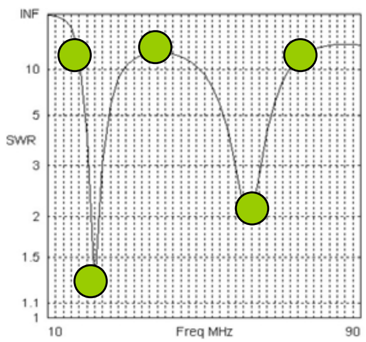
Why Fat Dipoles are a Good Choice: NTLA Fat Dipole vs. 1.65-m Thin Dipole





Assuming
G_{AB} = 33 dB
(NTLA)

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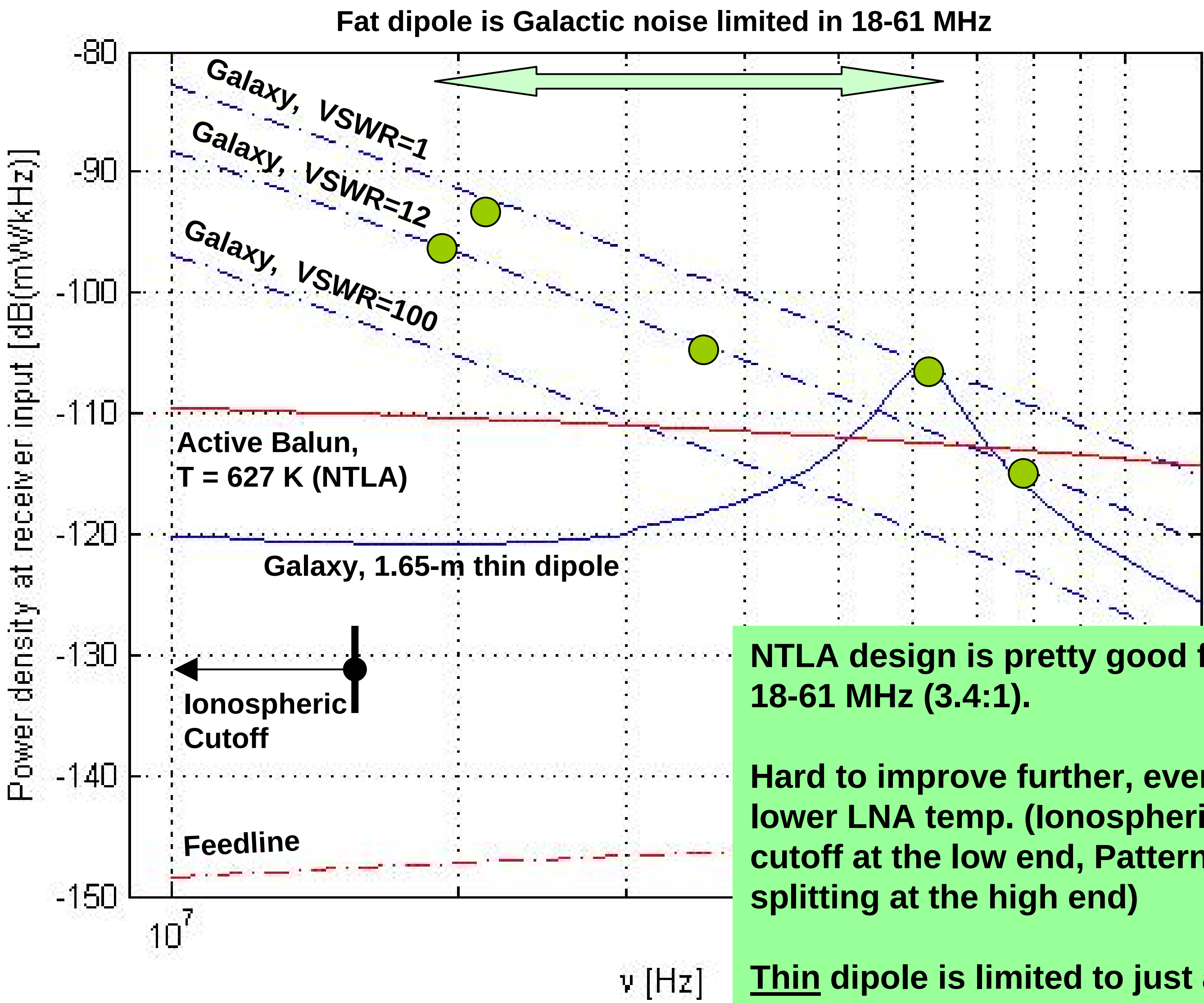
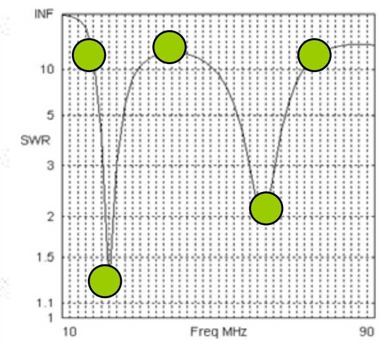




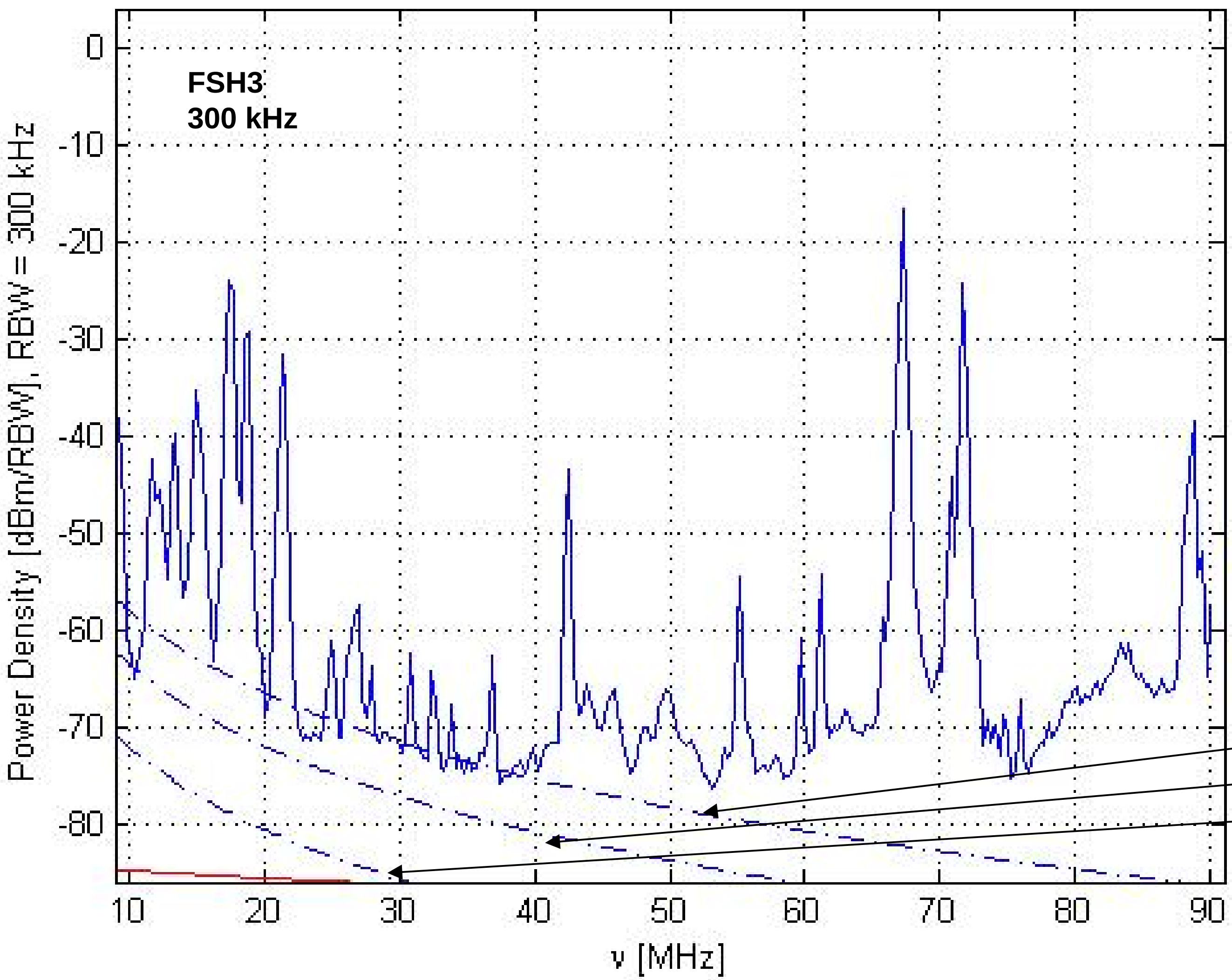
NTLA design is pretty good for 18-61 MHz (3.4:1).

Hard to improve further, even with lower LNA temp. (Ionospheric cutoff at the low end, Pattern splitting at the high end)

<u>Thin</u> dipole is limited to just a few MHz around resonance

A2b

Power Densities at Input to Receiver: NTLA Dipole+LNA+Feedline, *Measured*



Measurements taken at PLFM site @ PARI (Rosman, NC).

Spectrum analyzer ($\Delta\nu$=300 kHz) at end of feedline

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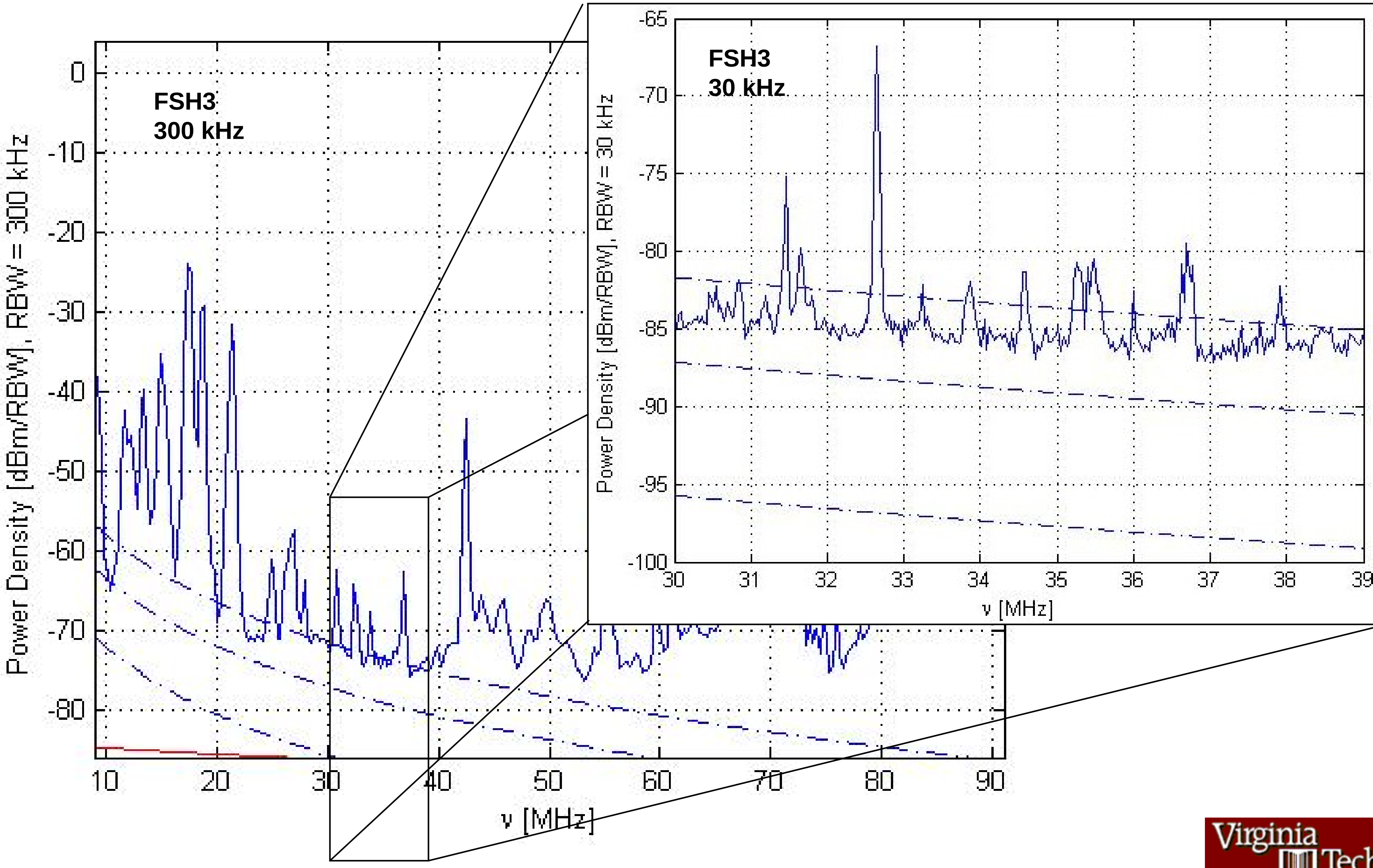
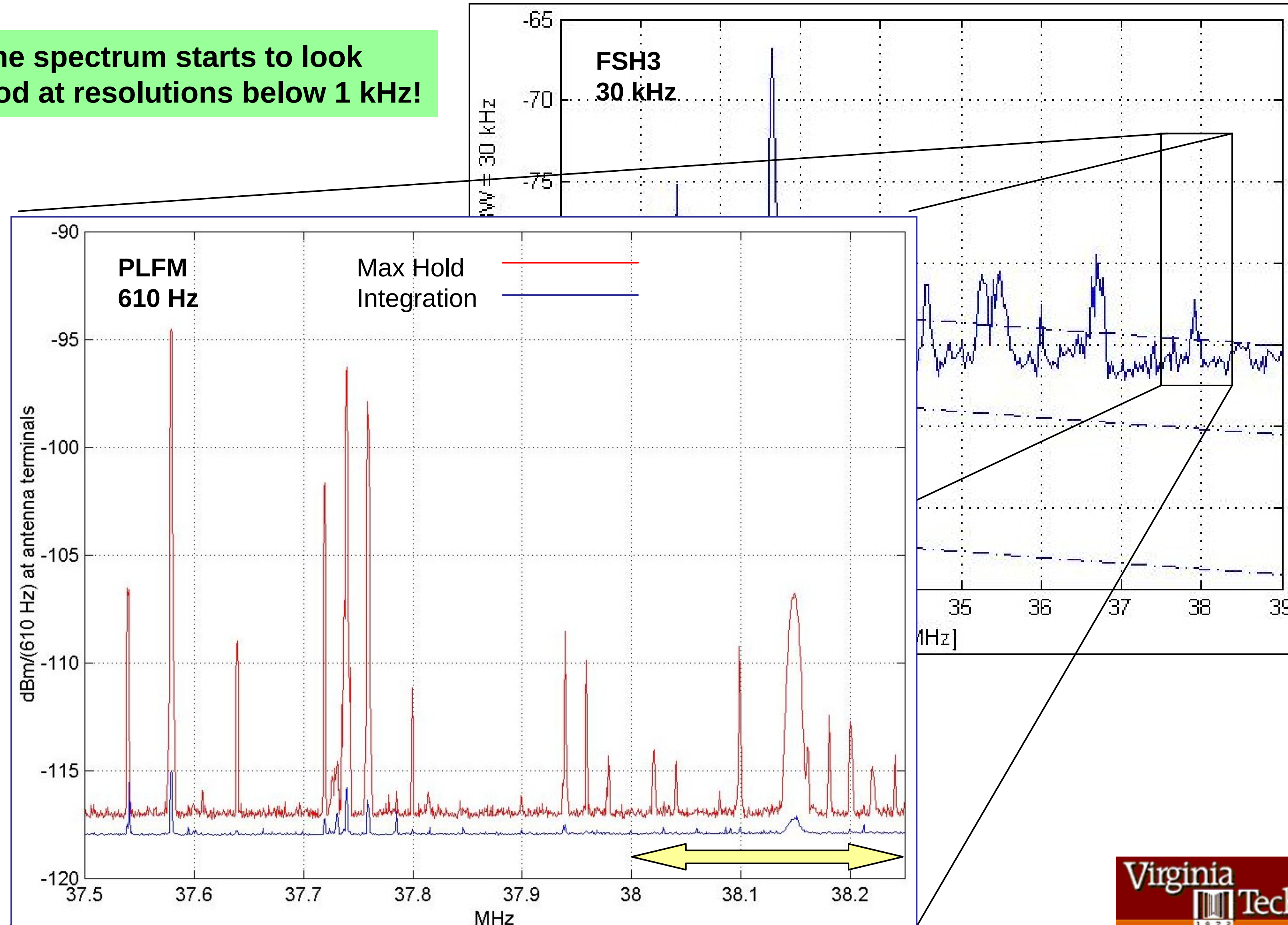


Power Densities At Input to Receiver: NTLA Dipole+LNA+Feedline, Measured

Most of the spectrum starts to look pretty good at resolutions below 1 kHz!



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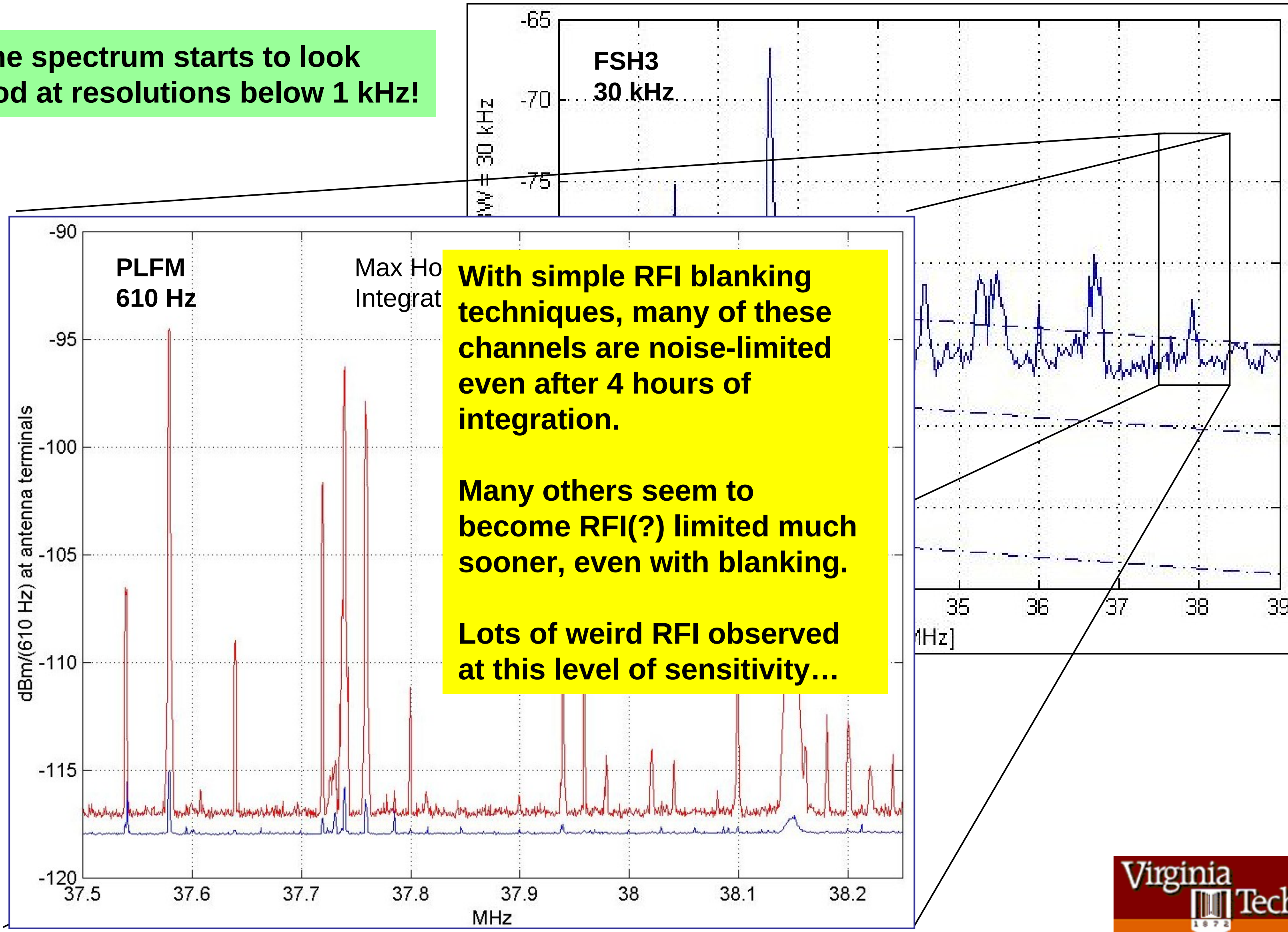
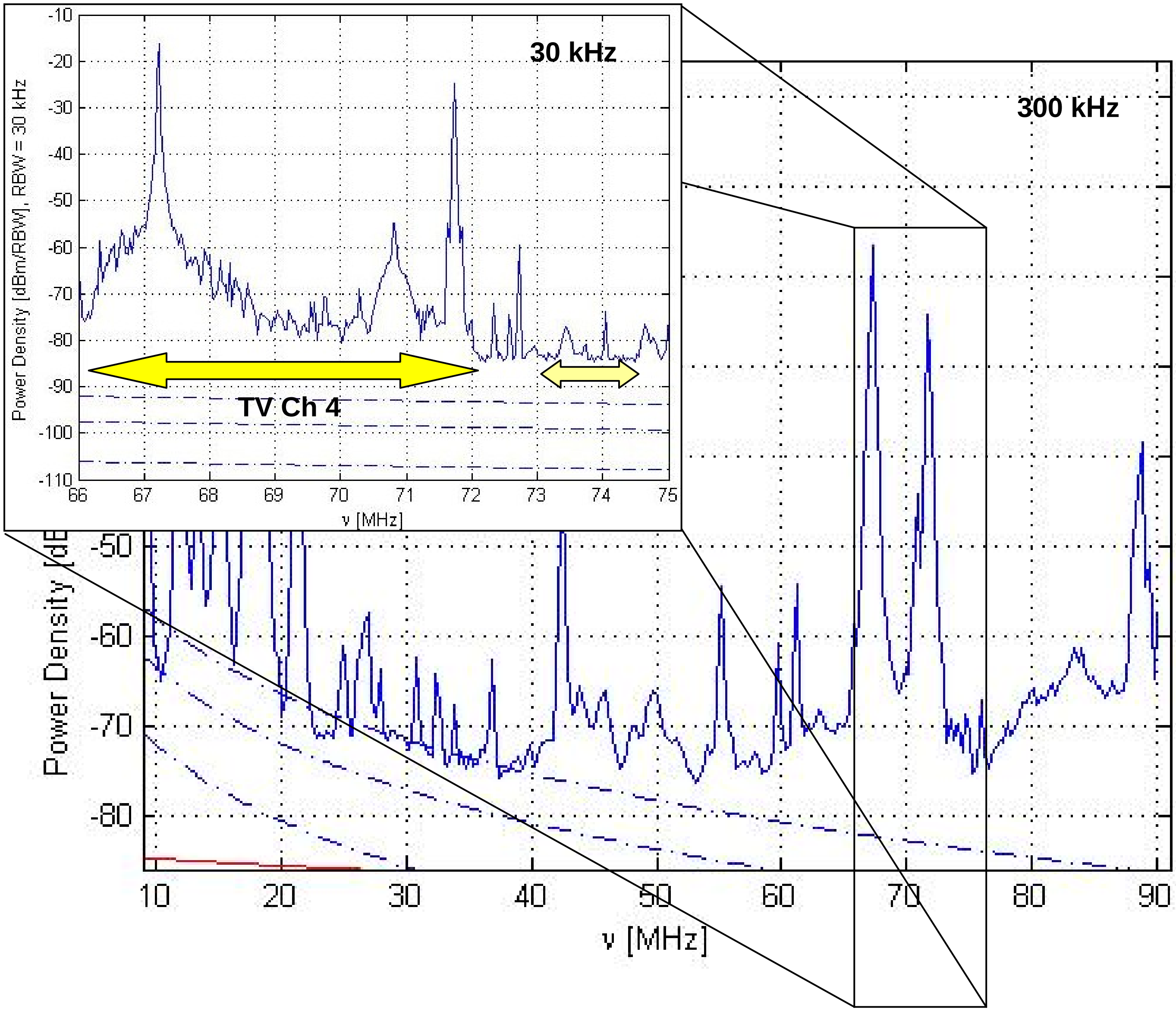


With simple RFI blanking techniques, many of these channels are noise-limited even after 4 hours of integration.

Many others seem to become RFI(?) limited much sooner, even with blanking.

Lots of weird RFI observed at this level of sensitivity…

Power Densities At Input to Receiver: NTLA Dipole+LNA+Feedline, Measured



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Spectrum analyzer ($\Delta\nu$=300 kHz) at end of feedline

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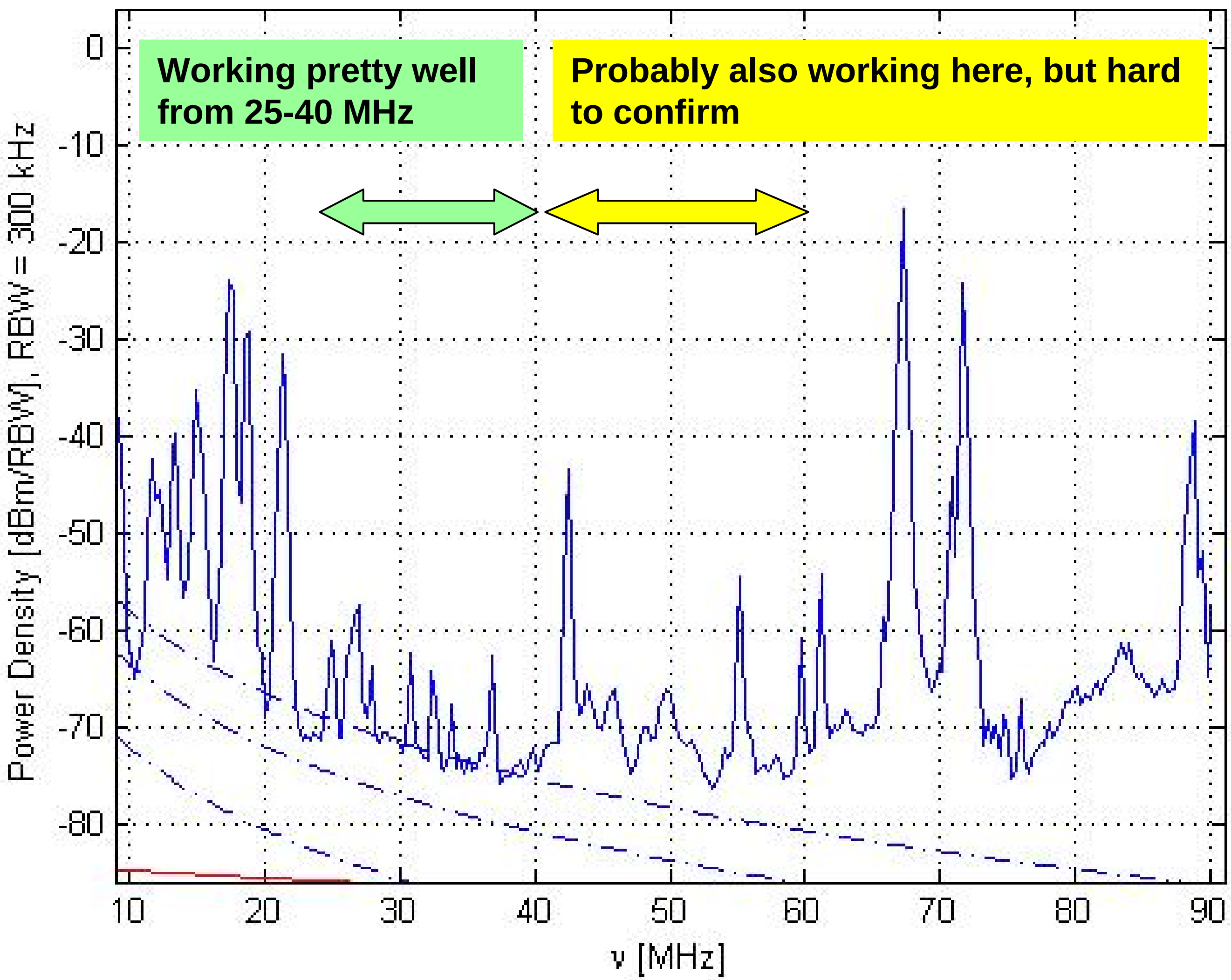

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PARI

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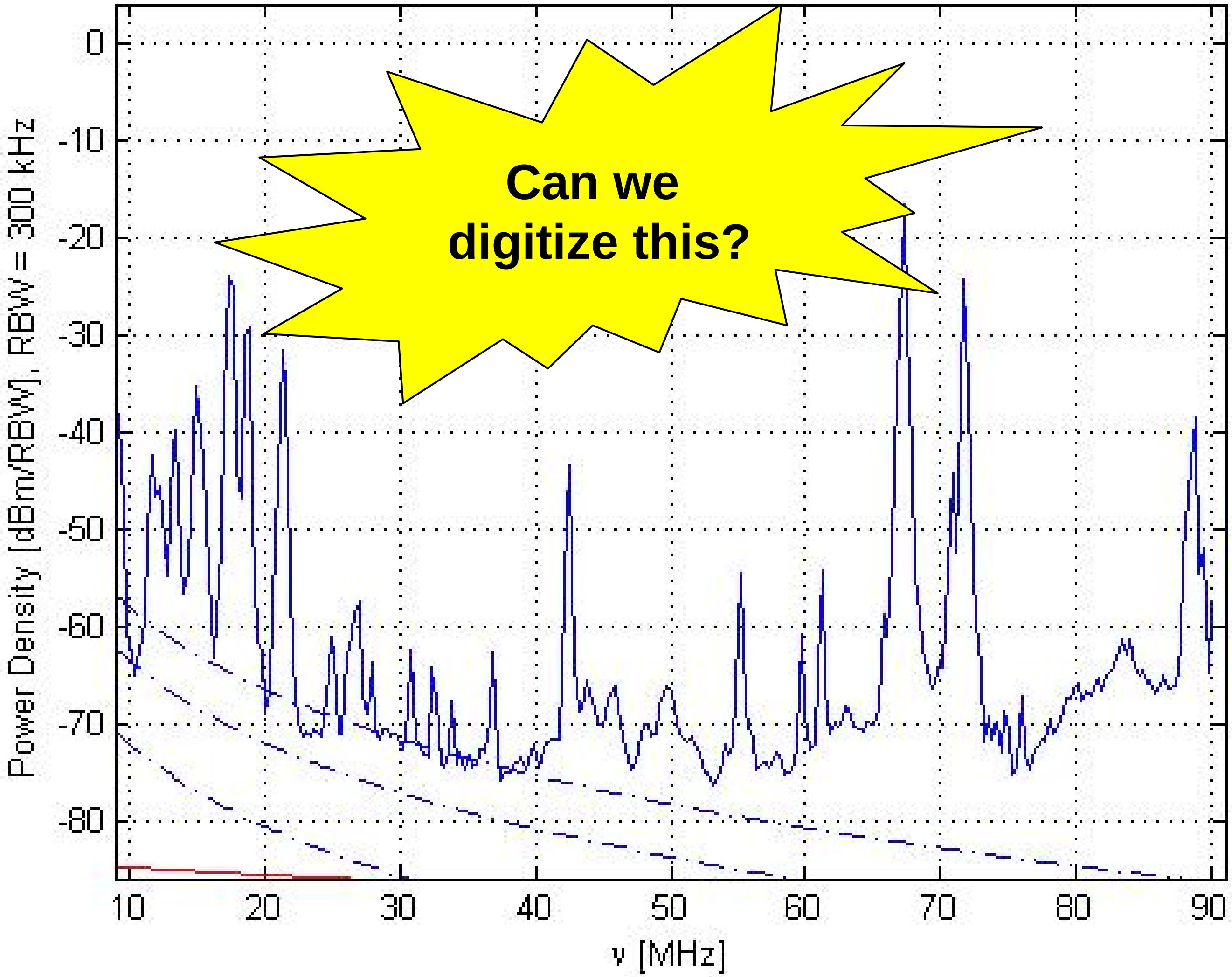

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Spectrum analyzer ($\Delta\nu$=300 kHz) at end of feedline

Digitizer Basics

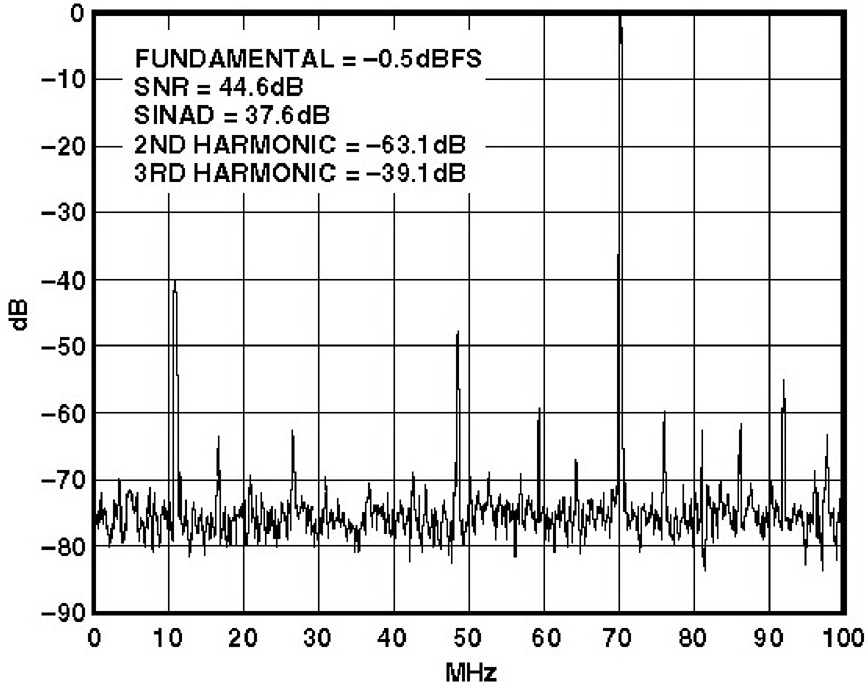
- ***Most "high speed" A/D circuits encode full scale at ~1 V_{pp} @ 50Ω***, and therefore clip around +10 dBm

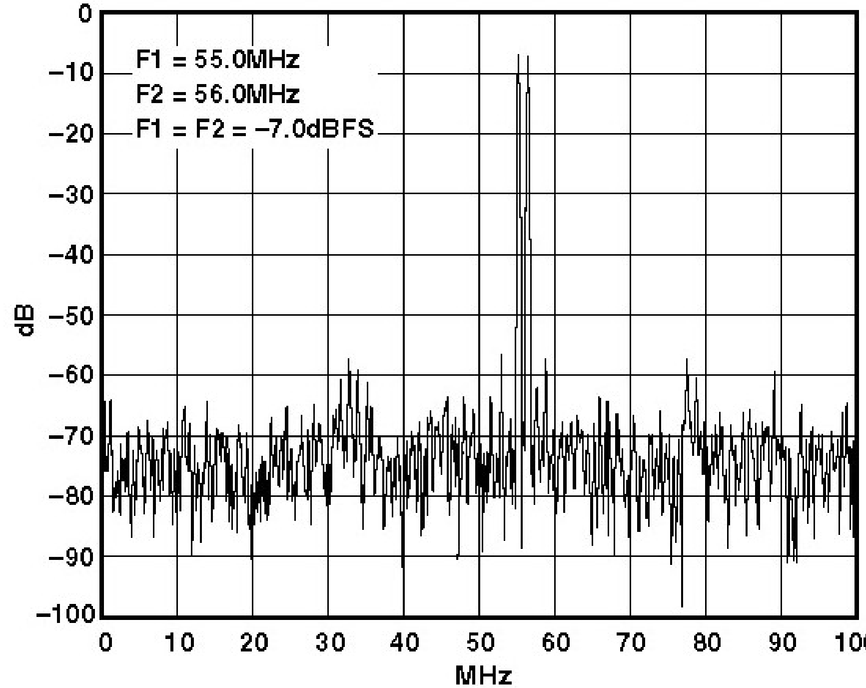
- ***Quantization noise power*** of about -6*N_b' dB (relative to input power) is generated, where N_b' is the number of bits actually exercised
  - Noise-like signals generate quantization noise which is spectrally white and uniformly distributed over one Nyquist bandwidth
  - However, RFI generates quantization noise which is *on average* spectrally white, but contain "sympathetic" spurious signals
  - All A/Ds generate a few extra dB of noise over the quantization noise due to analog imperfections (Sometimes combined with the above to define an "effective number of bits" (ENOB)).

- ***All A/Ds are slightly non-linear***, and so create additional spurious products, harmonics, and intermodulation. These often become a bigger problem than quantization noise for A/Ds wider than 8-10 bits.

Straight from the Datasheet: Analog Devices AD9054

(An 8-bit, 200 MSPS A/D)

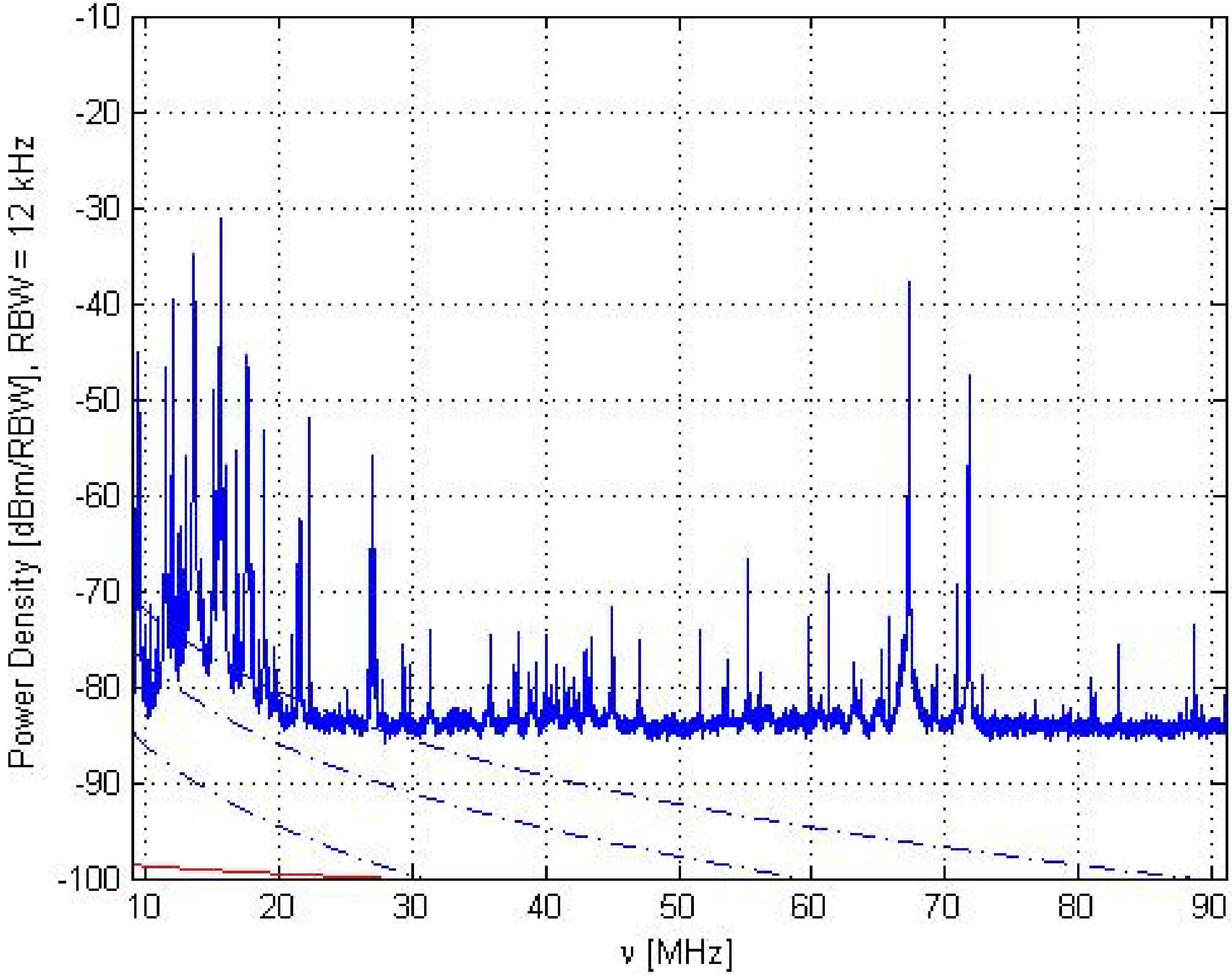


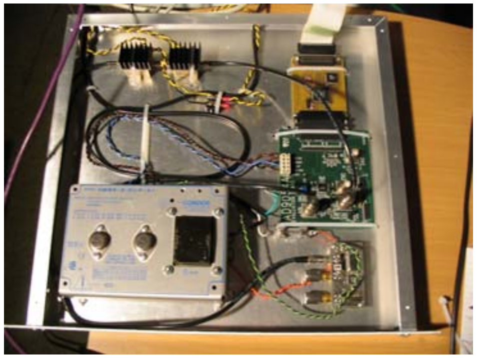


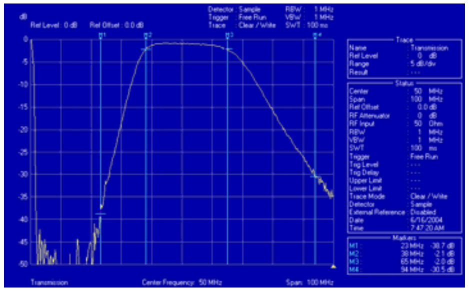
TPC 18. Spectrum: f_S = 200 MSPS, f_{IN} = 70.1 MHz

TPC 19. Two-Tone Intermodulation Distortion

Power Densities At Input to Receiver, Measured using an 8-bit, 200 MSPS A/D





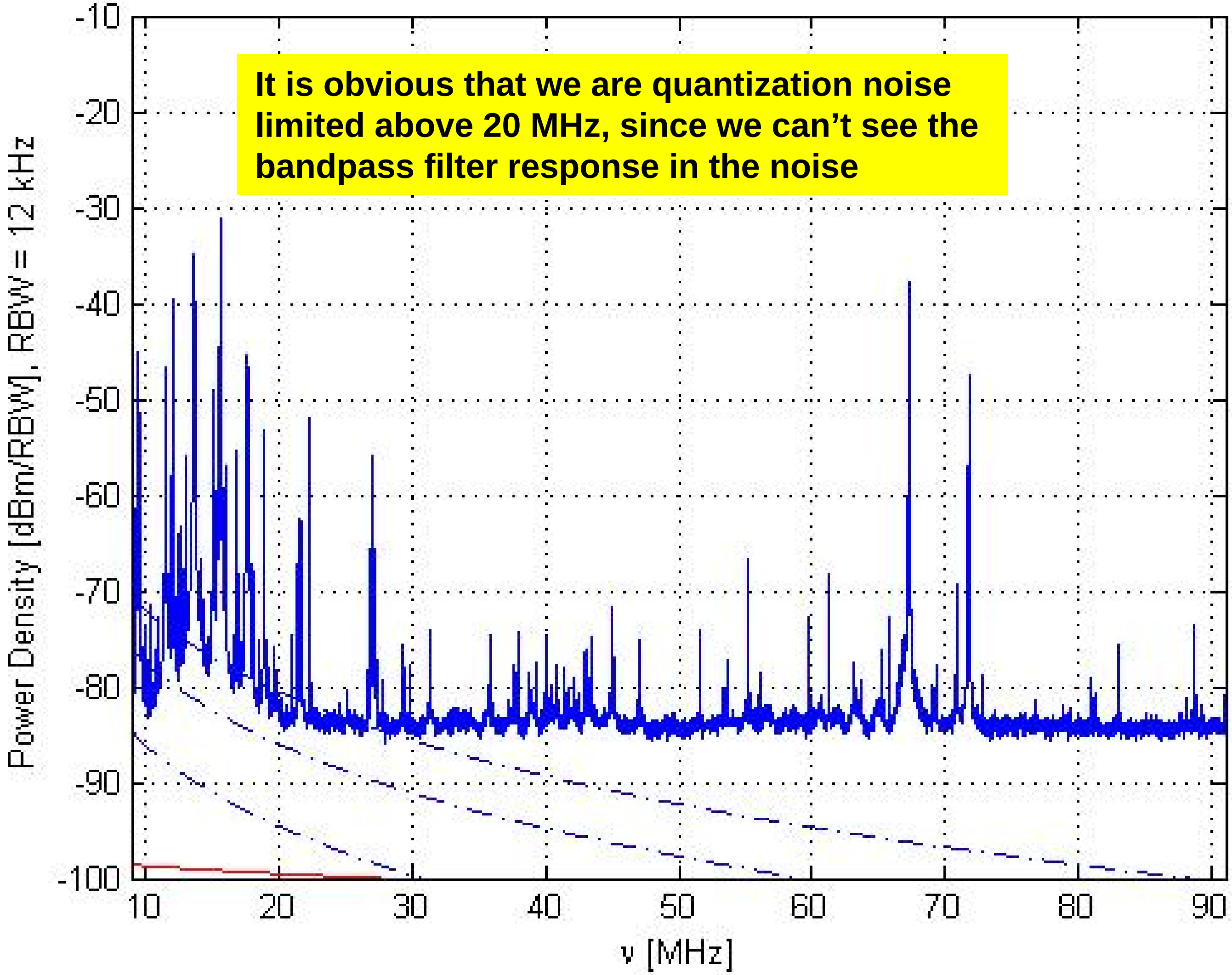


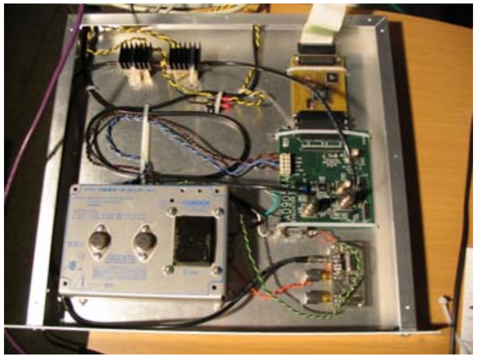
Analog Devices AD9054
8-bits, 200 MSPS

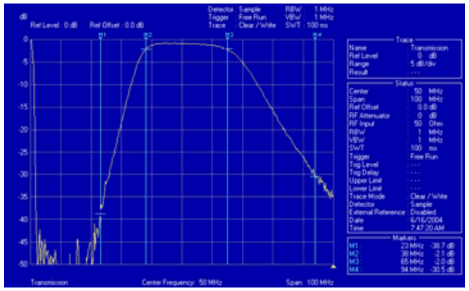
16K FIFO buffer to PC

A5a

Power Densities At Input to Receiver, Measured using an 8-bit, 200 MSPS A/D







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16K FIFO buffer to PC

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Power Densities At Input to Receiver, Measured using an 8-bit, 200 MSPS A/D

Check:

-15 dBm total power @ receiver input

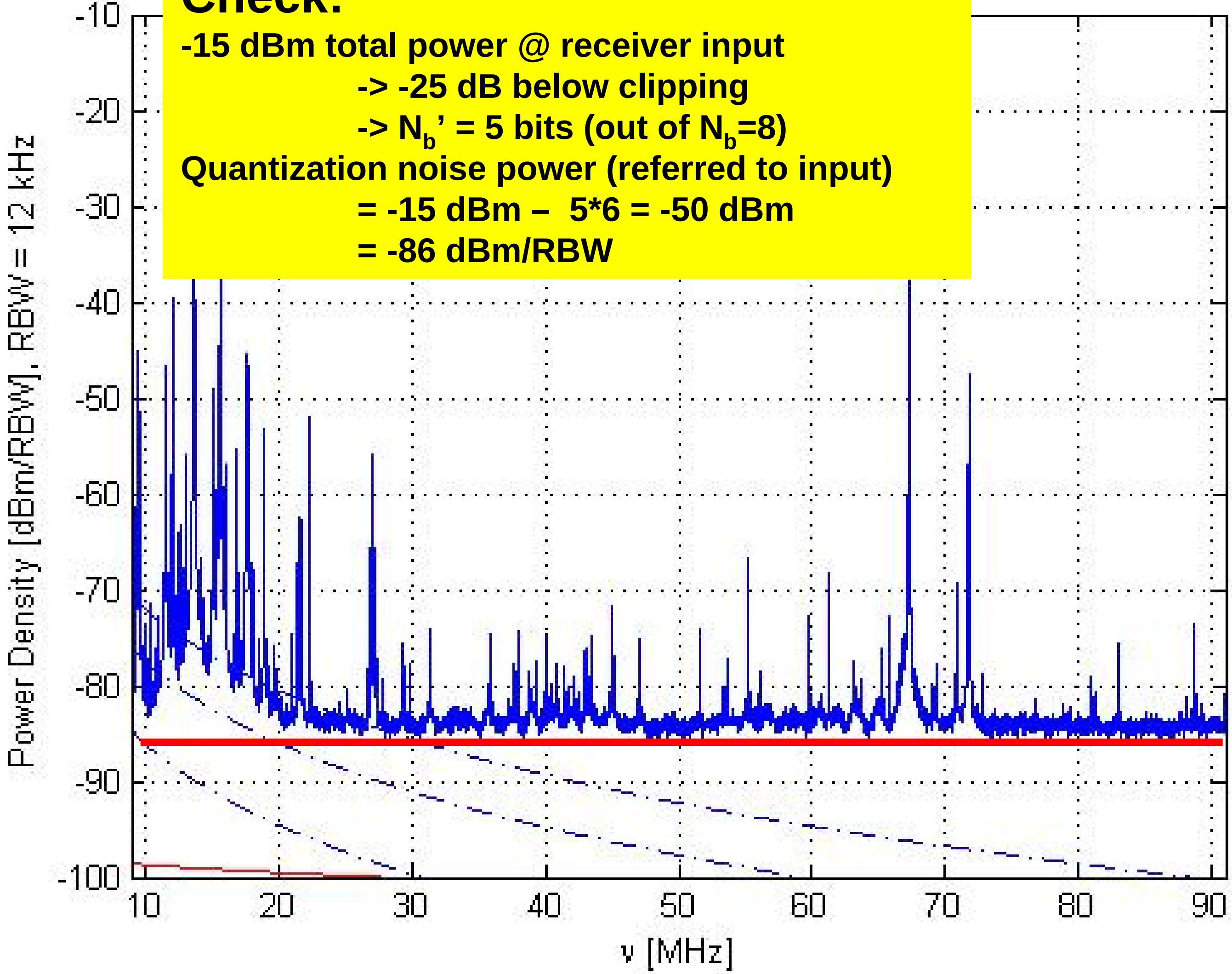
-> -25 dB below clipping

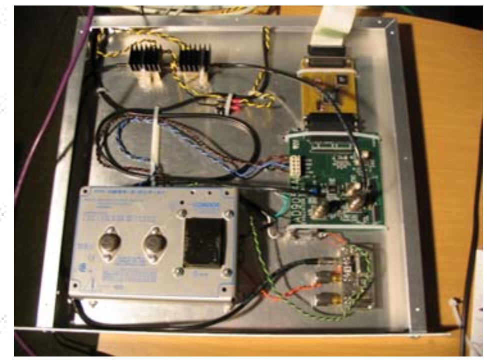
-> N_b' = 5 bits (out of N_b=8)

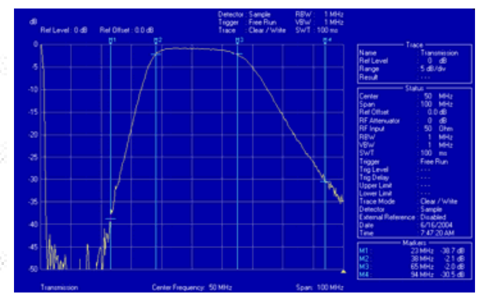
Quantization noise power (referred to input)

= -15 dBm – 5*6 = -50 dBm

= -86 dBm/RBW







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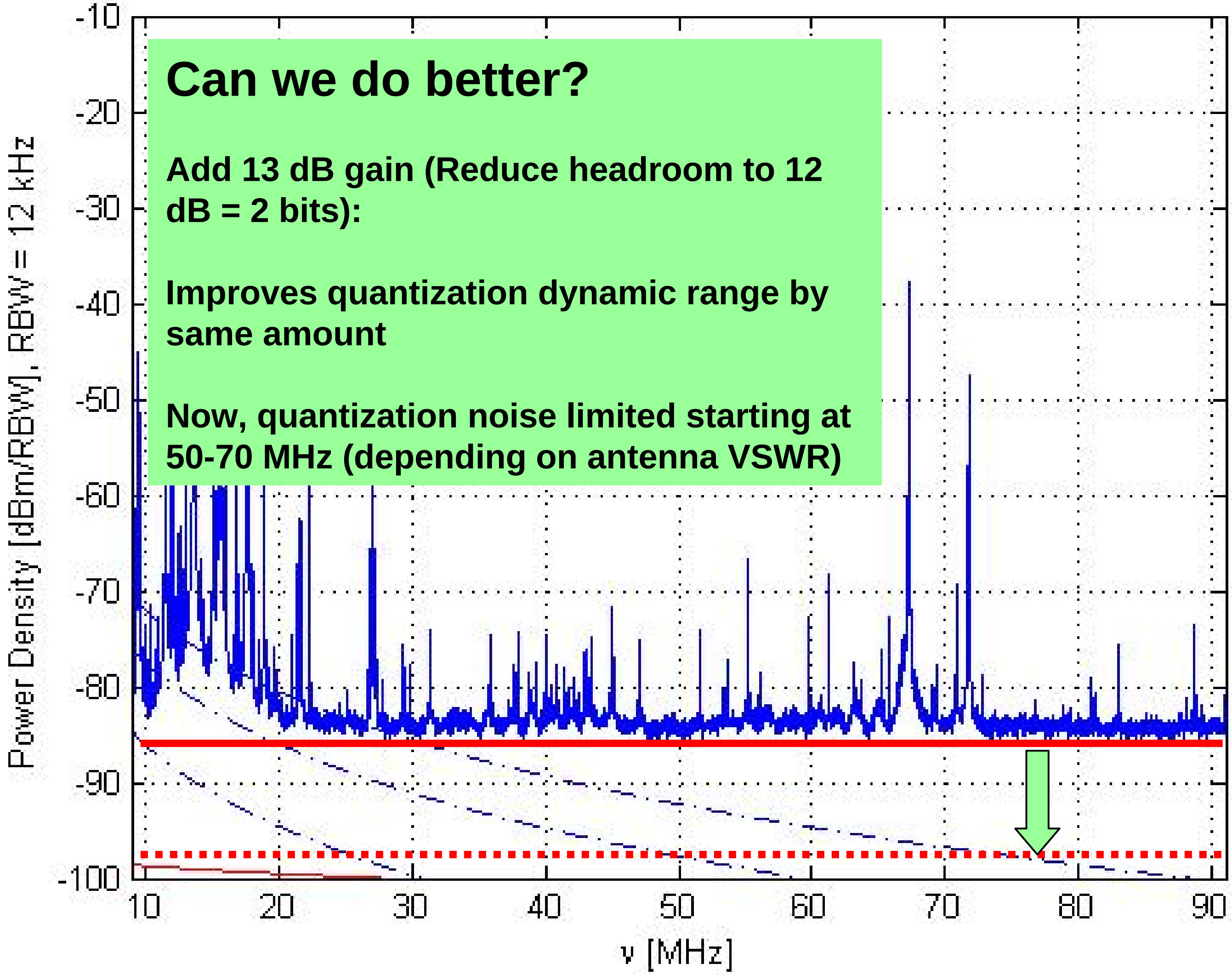
Power Densities At Input to Receiver, PLFM Configuration, 8-Bit Digitization

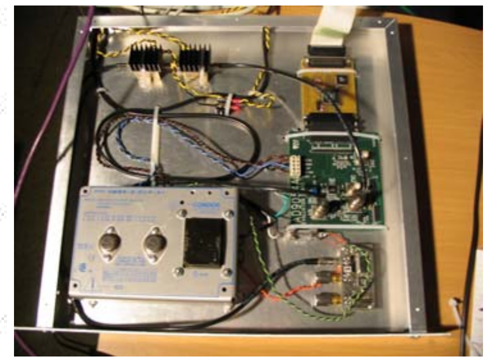


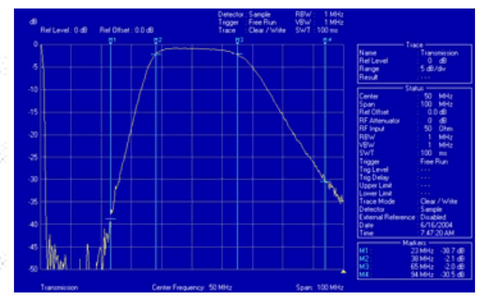
Can we do better?

Add 13 dB gain (Reduce headroom to 12 dB = 2 bits):

Improves quantization dynamic range by same amount

Now, quantization noise limited starting at 50-70 MHz (depending on antenna VSWR)





Analog Devices AD9054
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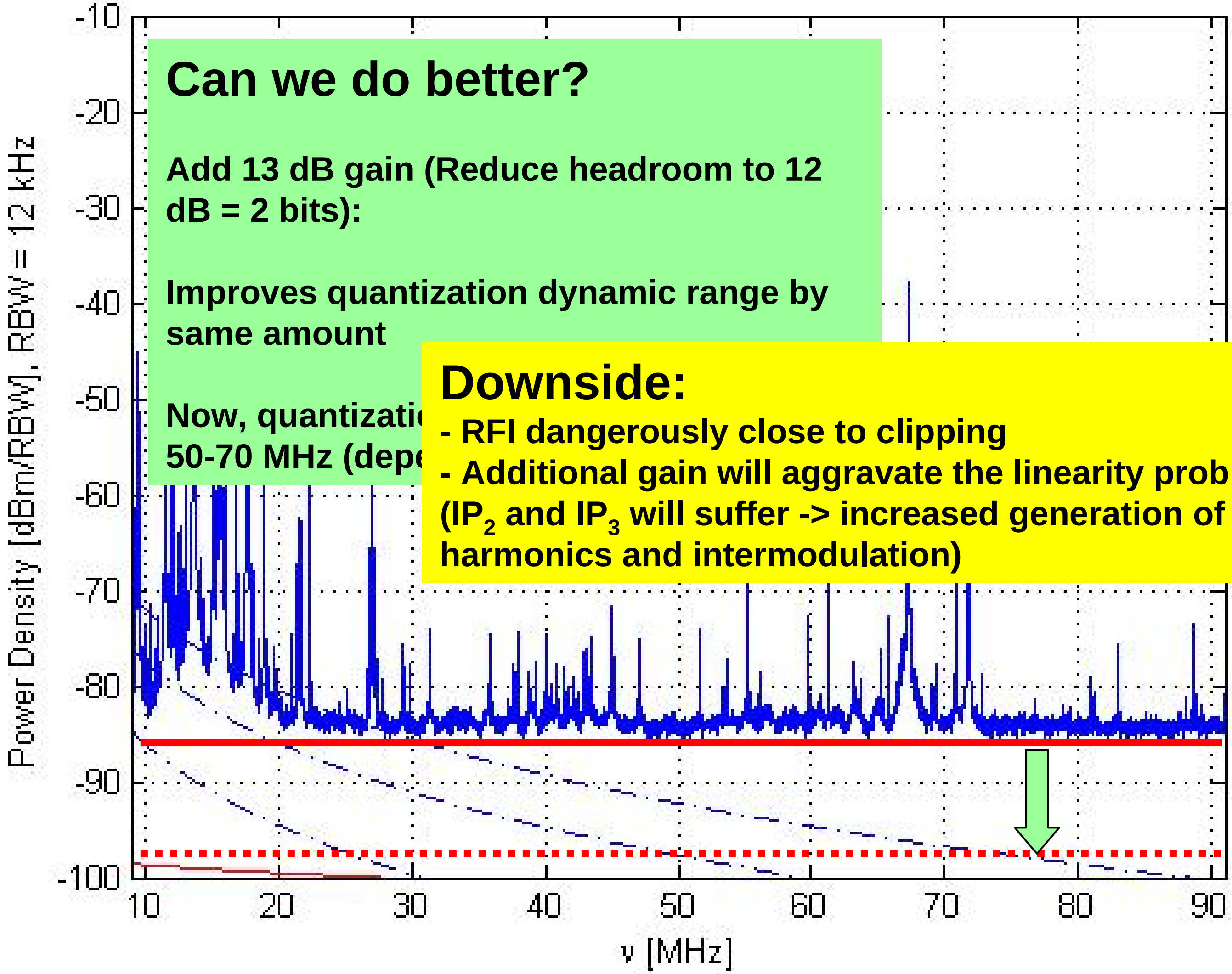
16K FIFO buffer to PC

Power Densities At Input to Receiver, PLFM Configuration, 8-Bit Digitization



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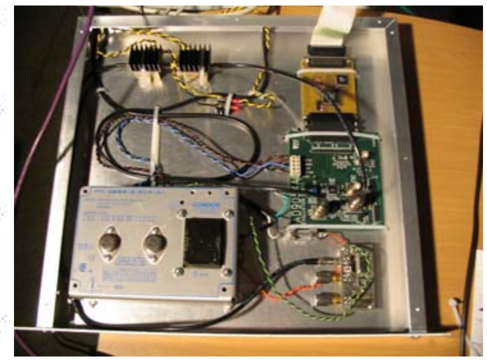
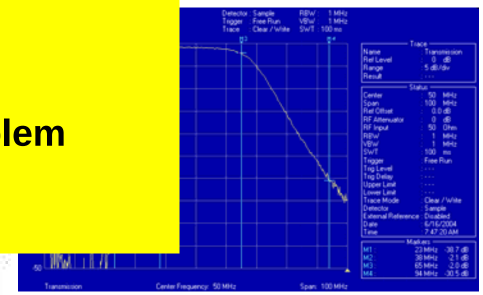
Now, quantizati... 50-70 MHz (depe...

Downside:

- RFI dangerously close to clipping

- Additional gain will aggravate the linearity problem (IP_2 and IP_3 will suffer -> increased generation of harmonics and intermodulation)





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8-bits, 200 MSPS

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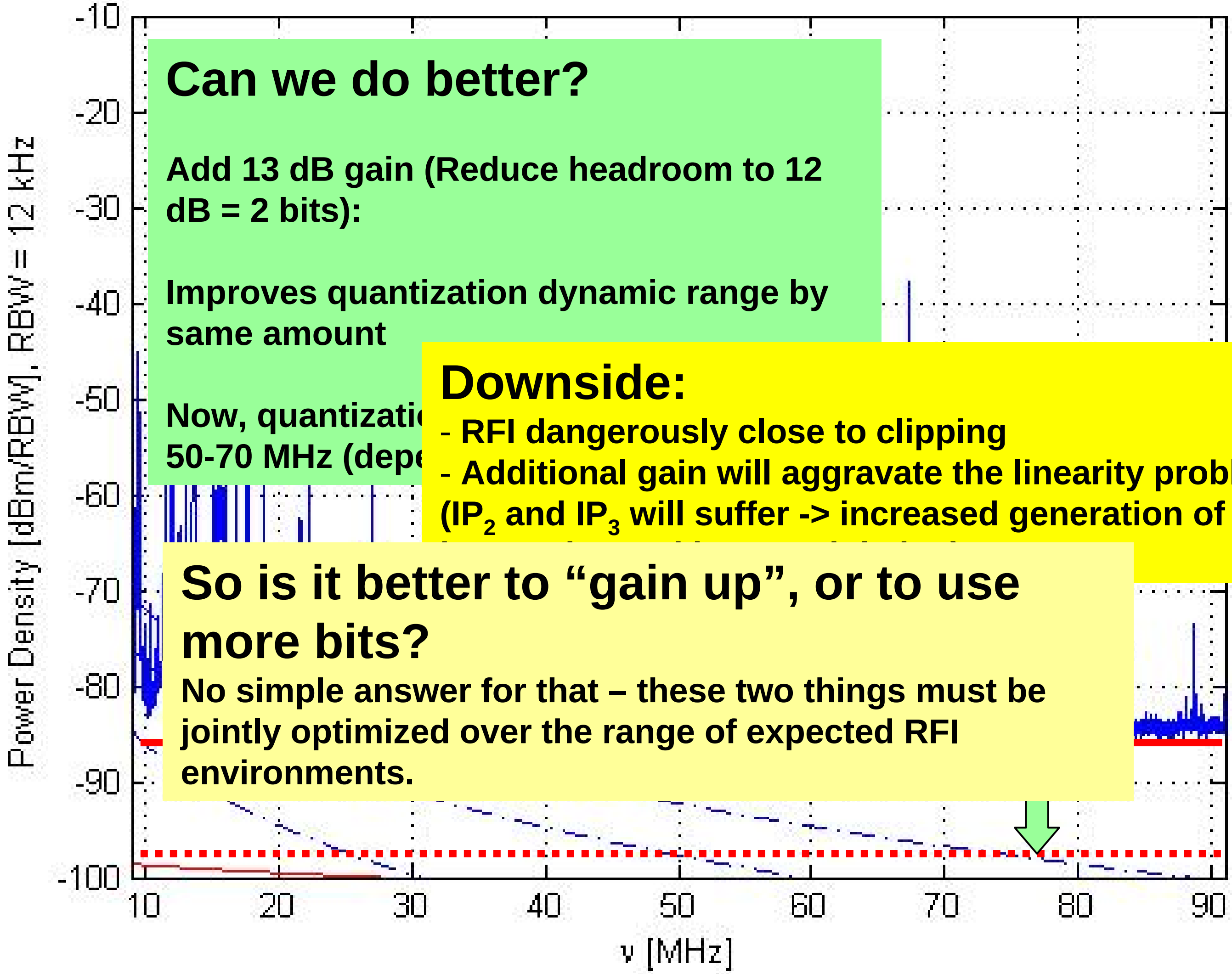
Power Densities At Input to Receiver, PLFM Configuration, 8-Bit Digitization



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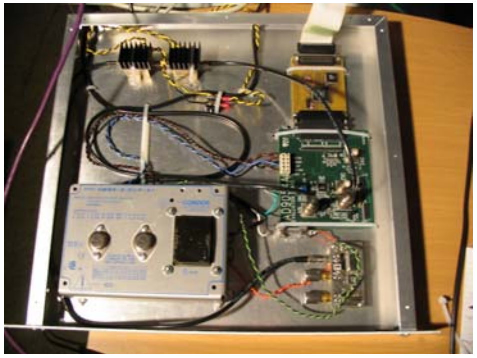
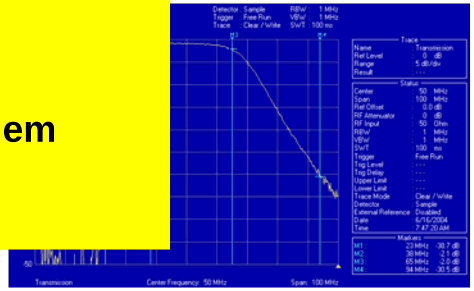
- **RFI dangerously close to clipping**
- **Additional gain will aggravate the linearity problem**

(IP_2 and IP_3 will suffer -> increased generation of

So is it better to "gain up", or to use more bits?

No simple answer for that – these two things must be jointly optimized over the range of expected RFI environments.



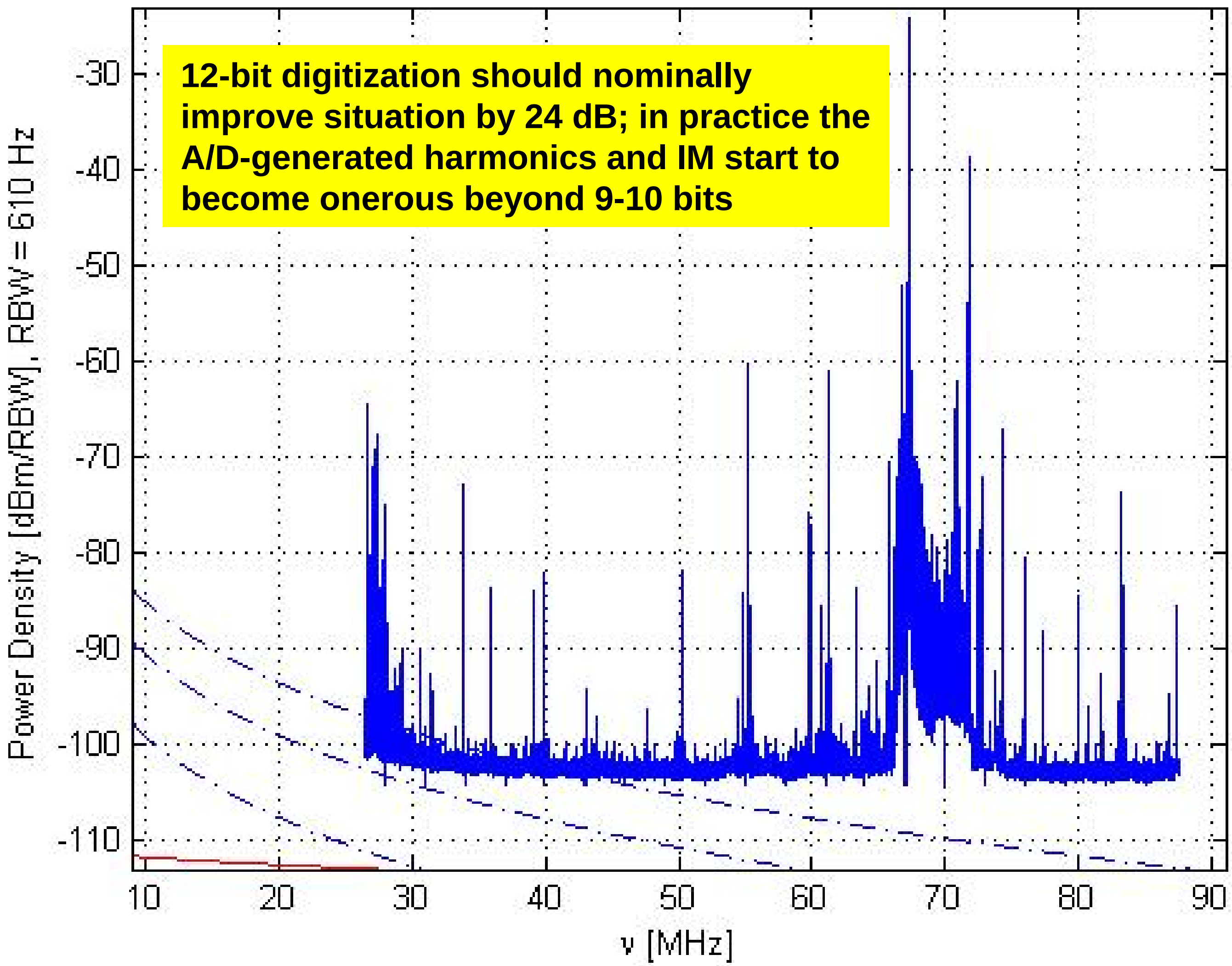


Analog Devices AD9054
8-bits, 200 MSPS

16K FIFO buffer to PC

A5a

More Bits is not a Magic Bullet



Measurements taken at PLFM site @ PARI (Rosman, NC).

PLFM Spectrometer

Unfortunately, Gain Won't Save You Either

- Linearity (IP_2, IP_3) will never be high enough to prevent generation of spurious products from being worrisome

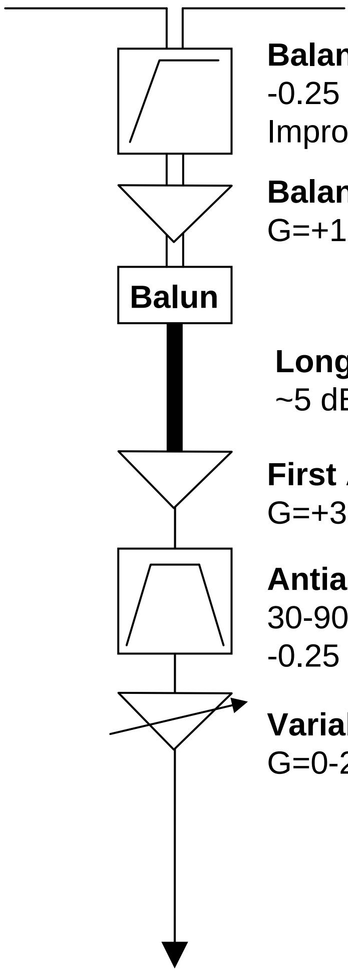
- Worse, these things become worse quickly with increasing gain.

- For details, see S.W. Ellingson, R. Ferris, and H. Hinterigger, "Station Processing for a Low Frequency Array in WA: Receivers & Beamforming", *Int'l Radio Quiet Array Meeting*, Kahuku, HI, Mar 2004. (Available via Haystack MWA website.)

- See also Tom Gaussiran's talk in this meeting.

Suggested LWA Design Concept

NTLA x 0.68



Balanced Filter
-0.25 dB/MHz below 50 MHz, IL ~ 0.5 dB
Improve match above 50 MHz

Balanced Amplifier
G=+17 dB, T=170K

The "front end"
i.e., the thing at the antenna

Long Cable
~5 dB loss

Analyze from this point (as before)

First Amplifier
G=+30 dB (minimum gain)

Antialiasing / RFI Rejection
30-90 MHz
-0.25 dB/MHz below 50 MHz

Variable Gain Amplifier
G=0-20 dB

The "receiver"
i.e., the thing at the other end of a long cable

A/D
10-12 bits @ 200 MSPS

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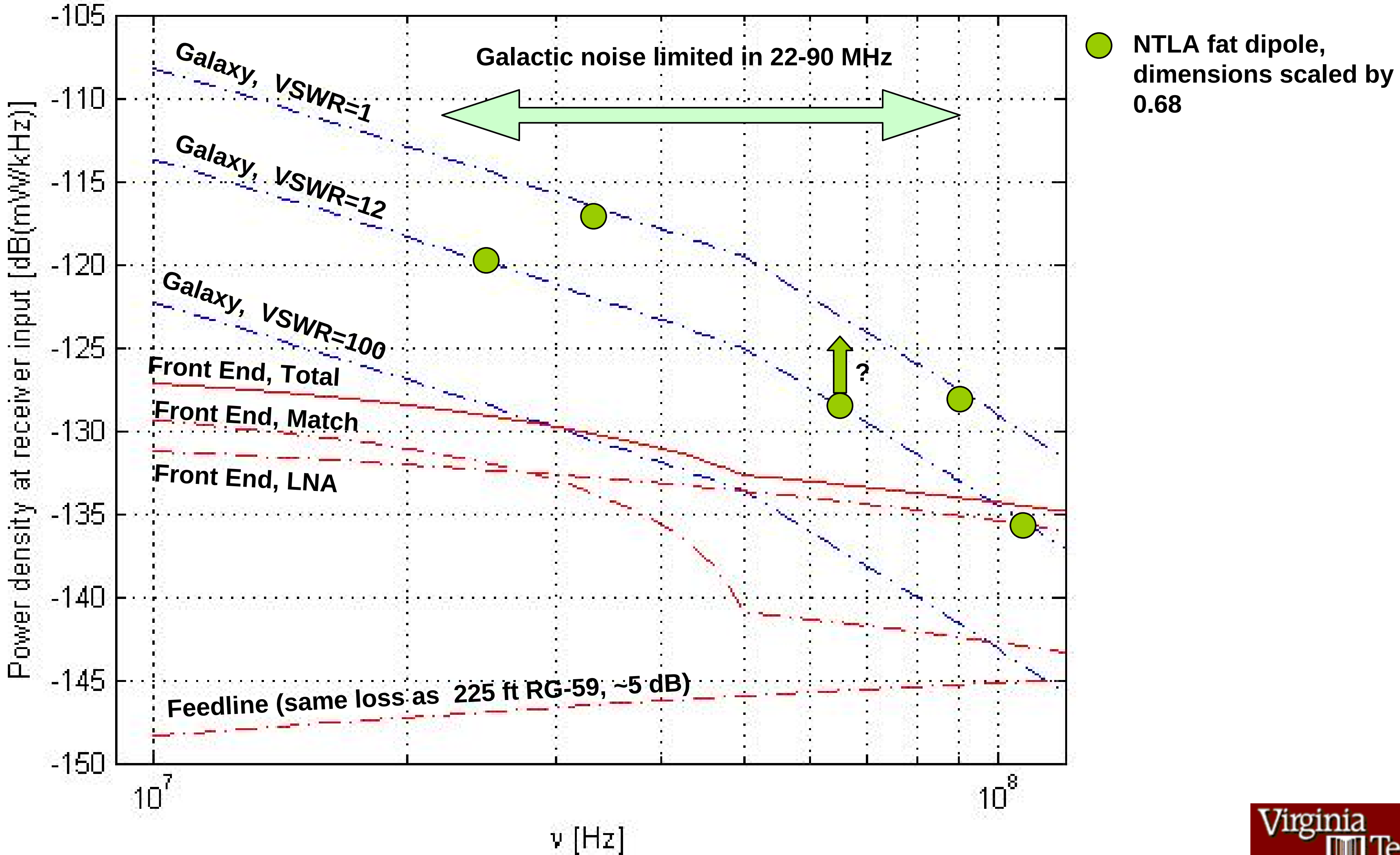
Power Density at Input of Receiver for Suggested LWA Design Concept



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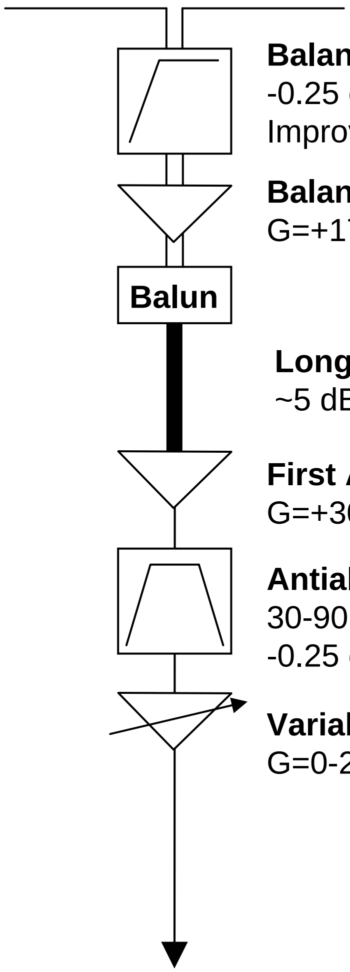

Balanced Filter
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Improve match above 50 MHz

Partially equalize Galactic background to prevent spectrum below 50 MHz from dominating system noise

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A/D
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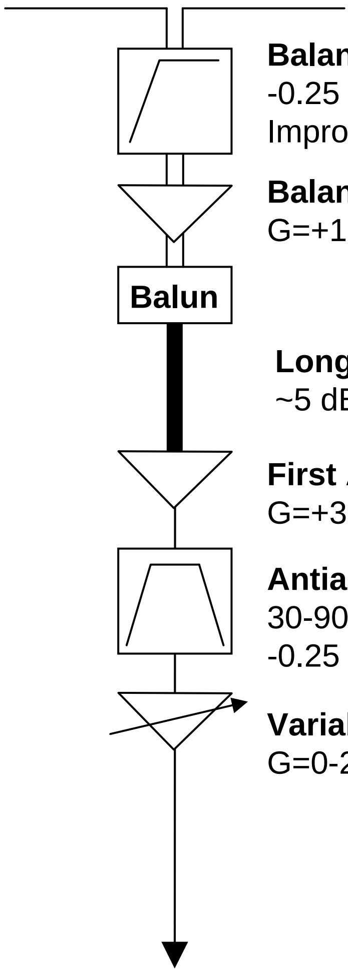

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May be able to improve mid-band VSWR slightly

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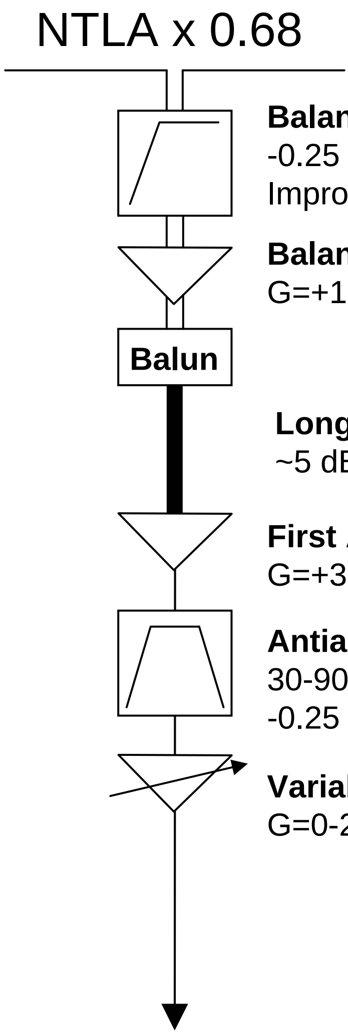

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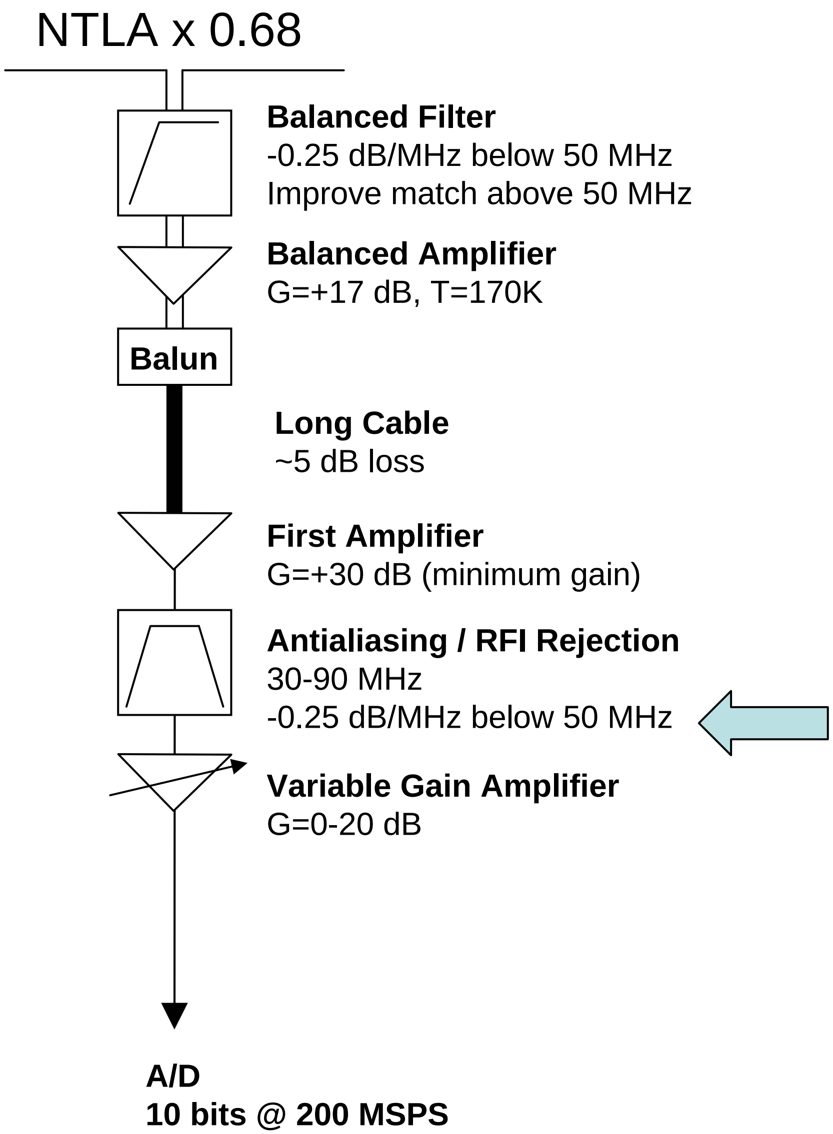
G=0-20 dB

A/D
10 bits @ 200 MSPS

This is minimum useful gain.

- Brings 30-90 MHz noise <u>due to RFI+Galaxy</u> (at PARI) to 0 dBm (dangerously close to clipping), and
- Brings 30-90 MHz noise <u>due to Galaxy</u> to -42 dBm, which is just 5 dB above 10-bit quantization noise for a realistic A/D

Suggested Design Concept

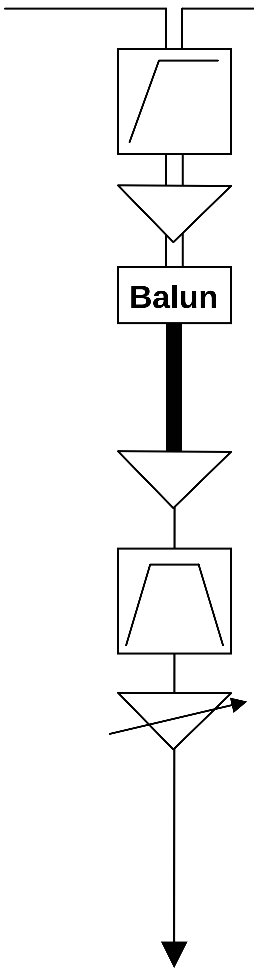


Finish equalization of Galactic background.

- Optimizes achievable quantization signal to noise ratio across bandwidth
- Additional (useful) de-emphasis of very bad RFI below 30 MHz

Suggested Design Concept

NTLA x 0.68



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A/D
10 bits @ 200 MSPS

Additional gain for improving margin over quantization noise

- 15 dB gain here puts the VSWR=12 Galaxy signal 10 dB above quantization noise of a realistic 10-bit A/D
- Need to be able to scale back gain to accommodate RFI and high levels of man-made radio noise

What Happens after Digitization: Channelization & Beamforming

- See S. Ellingson, R. Ferris, and H. Hinterigger, "Station Processing for a Low Frequency Array in WA: Receivers & Beamforming", *Int'l Radio Quiet Array Meeting*, Kahuku, HI, Mar 2004. (Available via Haystack MWA website.)

- Scheme for channelization and beamforming described there applies to LWA as well
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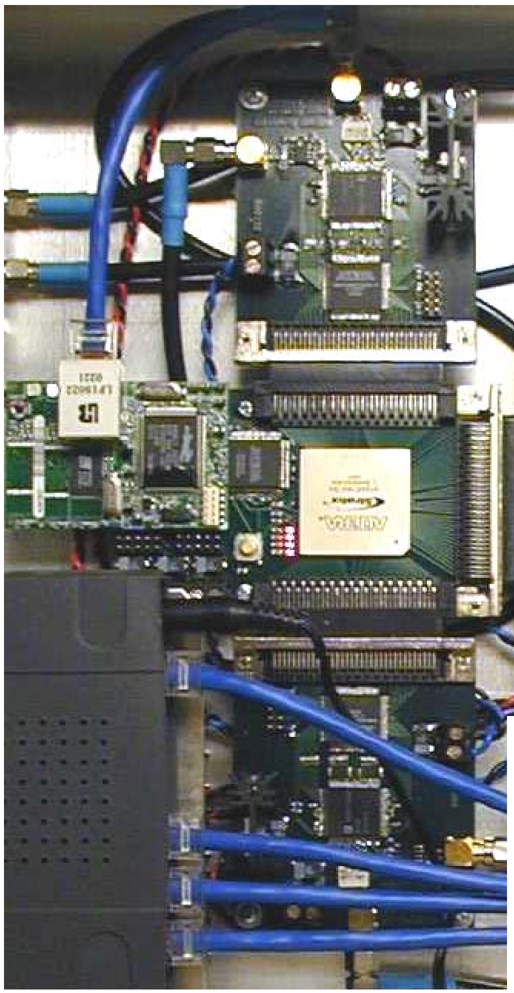
OSU/NASA "IIP" FFT Spectrometer

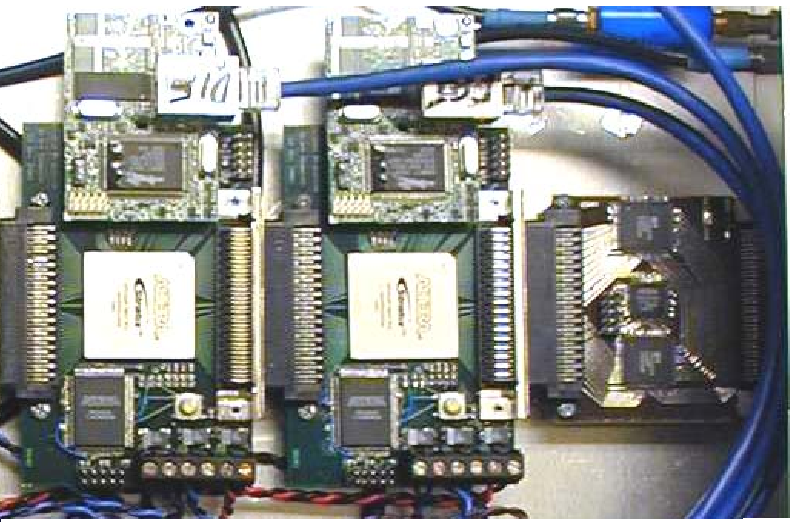
2 IF channels
10 bits @ 200 MSPS (~80 MHz) per channel
3 big FPGAs
~ US$1500 in Quantity=1
Year 2002 FPGA technology

ADC

DIF/
APB

ADC

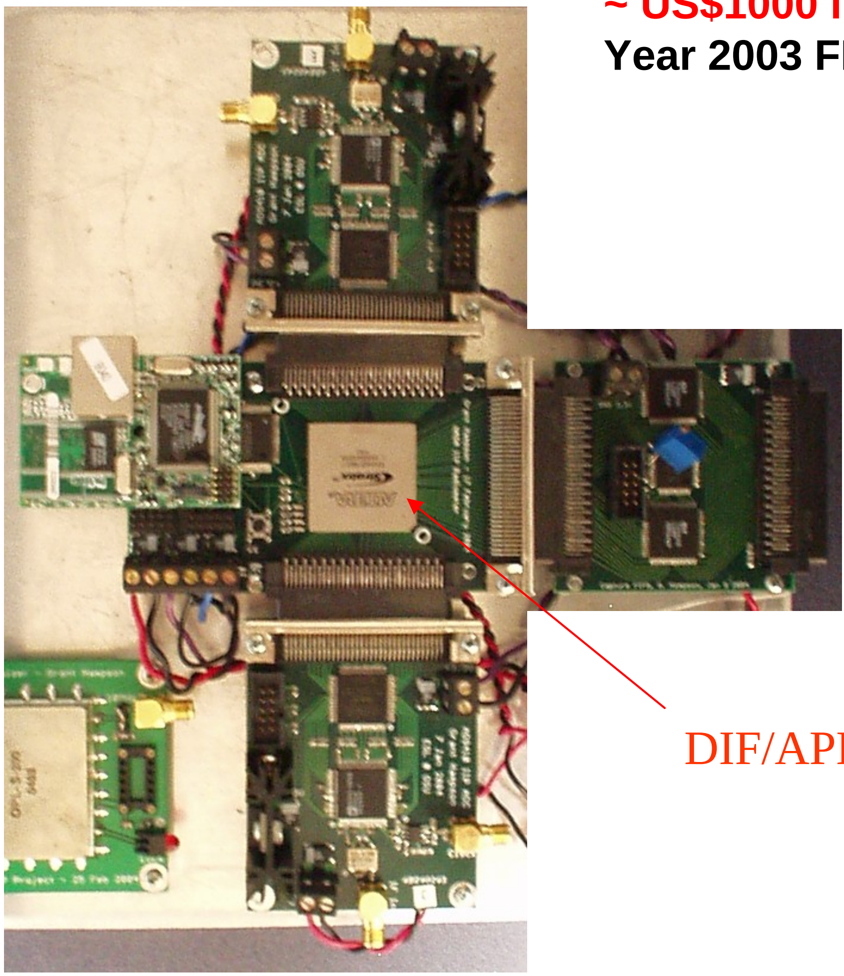




FFT SDP Capture

OSU/NOAA "CISR" FFT Spectrometer

2 Channels
10 bits @ 200 MSPS (~80 MHz) per channel
1 big FPGA
~ US$1000 in Quantity=1
Year 2003 FPGA technology



DIF/APB/FFT/SDP