HOW IMPORTANT ARE RECEIVER PERFORMANCE CRITERIA IN AN ERA OF SOFTWARE DEFINED RADIOS?

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Rev. 14 May 5, 2017

OUTLINE OF PRESENTATION

- Recent History of Receiver Performance Criteria
- Terminology
- Comparison of Legacy vs SDR Radio Architecture
- Performance Criteria For Legacy Radios
- Applicability of Traditional Criteria to SDR Radios
- Alternate Testing Criteria.

PRESENTATION PANEL

- Adam Farson – VA7OJ – Highly Respected for Receiver Performance and Analysis.
- David Jenni – W7CF. David is very knowledgeable with the science involved in SDR technology.
- Bill Trippett – W7VP. Bill has been active in developing policies relating to receiver performance.

RECENT HISTORY OF PERFORMANCE CRITERIA

- Sources of Performance Testing
    - ARRL
    - Rob Sherwood NC0B
    - Adam Farson VA7OJ
    - Other Qualified Technical Labs and Persons

ARRL LABS

Ed Hare W1RFI Lab Manager Bob Allison WB1GCM Product Review Engineer

SHERWOOD ENGINEERING INC.

Look in on part of SEI's Laboratory

Receiver Test Data

(Terms Explained: DOC PDF)

Sorted by Third-Order Dynamic Range Narrow Spaced - or- ARRL RMDR (Reciprocal Mixing Dynamic Range) if Phase Noise Limited

Updated 31 August 2016 added Apache ANAN-200D

Device Under Test	Noise Floor (dBm)	AGC Thrshld (uV)	dB	100kHz Blocking (dB)	Sensitivity (uV)	LO Noise (dBc/Hz)	Spacing kHz	Front End Selectivity	Filter Ultimate (dB)	Dynamic Range Wide Spaced (dB)	kHz	Dynamic Range Narrow Spaced (dB)	kHz
Added 9/29/14 FlexRadio Systems 6700 Hardware Updated	-118 -135[b2]	3.0 1.0[b2]	Var	130 preamp Off	2.0 0.25[b2]	145 155	10 50	B Band Pass	115	99	20&2	108[y]	20&2
Added 11/10/15 Elecraft K3S	-135 -138[b] -145[10]	1.5 0.45[b]	3	150	0.27 0.20[b] 0.08[10]	144 146	10 50	B Band Pass	110	107[q]	20	106[p] 106[q]	2
Added 02/23/15 Elecraft K3 (RX Gain Recal) New Synthesizer	-136 -139[bq]	1.0 0.3[b]	3	141	0.27 0.20[b]	145 147	10 50	B Band Pass	108	105[q]	20	107[p] 104[q]	2
Added 04/25/16 Icom	-123 -135[b]	8.5 1.85[b]	3	149	0.65 0.16[b]	148 153	10 50	A Trk Presel	100	110[aa]	20	105[aa]	2

SHERWOOD ENGINEERING INC.

- Note the Column Headings
- Note the Ranking is Based on 2 kHz Third Order IMDDR
- Note that Sherwood limits the 3rd Order IMDDR by Phase Noise
- We will talk about these terms

ADAM FARSON VA7OJ

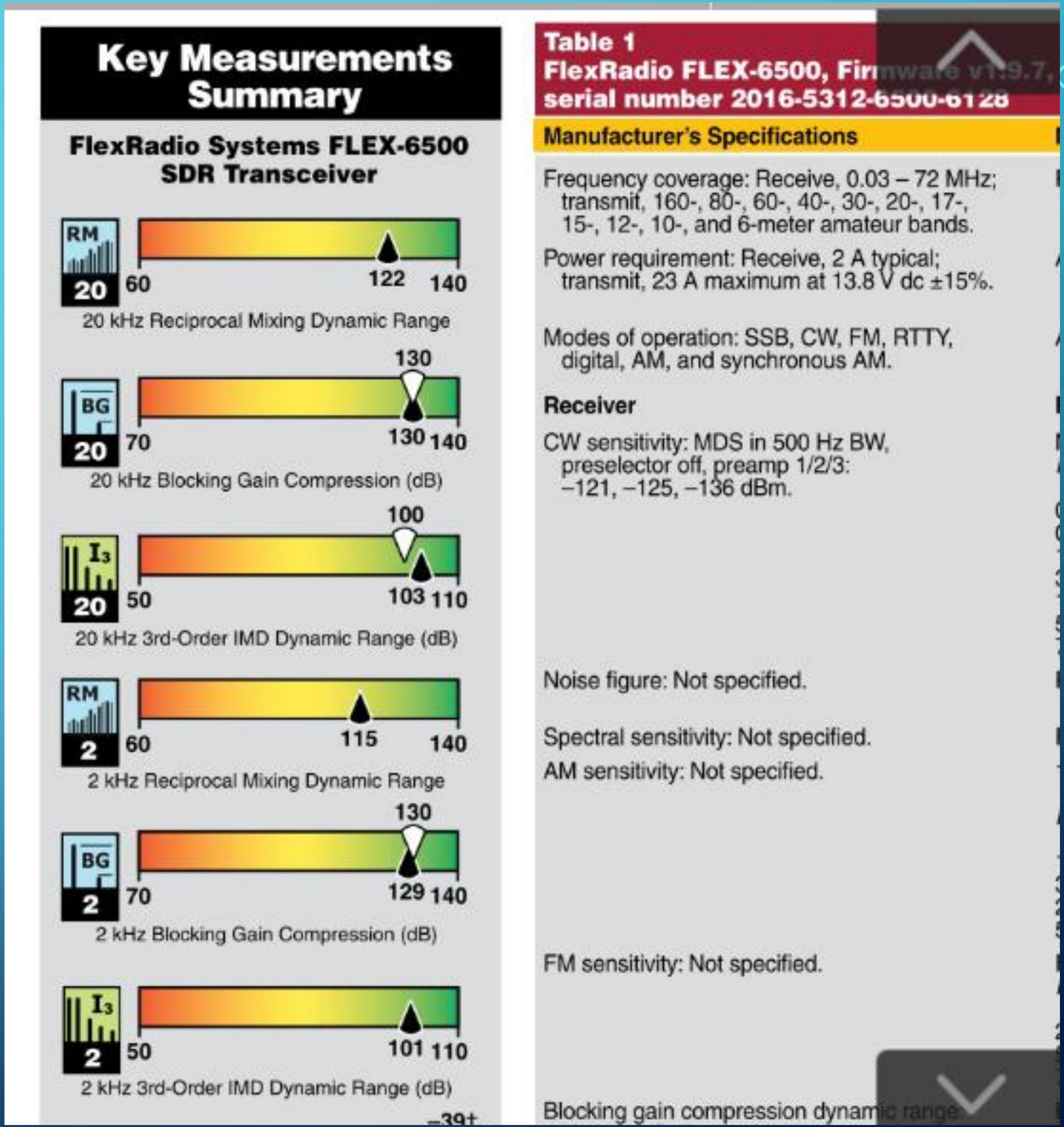
SELECTED PERFORMANCE TERMS

- AGC Threshold
  - The threshold is the signal level below which the receiver gain is basically running wide open.
- MDS (Minimum Discernible Signal) or Noise Floor
  - The RF input power required to raise the audio output level by 3 dB.
- Blocking Gain Compression
  - Blocking occurs when the radio is just beginning to overload from a signal outside the passband.
    - Example: Input power at a specified offset required to reduce by 1 dB the audio output from a 1 μV test signal.
    - Not applicable to a direct-sampling SDR, which does not block until ADC clips.

SELECTED PERFORMANCE TERMS

- Phase Noise
  - Old radios (Collins, Drake, Hammarlund, National) used a VFO or PTO and crystal oscillators to tune the bands. Any noise in the local oscillator (LO) chain was minimal. When synthesized radios came along in the 70s, the LO had noise on it. It is caused by phase jitter in the circuit, and puts significant noise sidebands on the LO.
- IMD Dynamic Range
  - Dynamic range is defined as the level in dB when two strong test signals make distortion in the radio equal to the noise floor. The radio thus can handle that range of signals before the strong signals just start to overload the radio. Can be either 3rd order or 2nd order or both.

ARRL GRAPHICAL PERFORMANCE REPRESENTATION



Key Measurements Summary

FlexRadio Systems FLEX-6500 SDR Transceiver

RM 20 — 60 — 122 — 140
20 kHz Reciprocal Mixing Dynamic Range

BG 20 — 70 — 130 — 130 — 140
20 kHz Blocking Gain Compression (dB)

I_3 20 — 50 — 100 — 103 — 110
20 kHz 3rd-Order IMD Dynamic Range (dB)

RM 2 — 60 — 115 — 140
2 kHz Reciprocal Mixing Dynamic Range

BG 2 — 70 — 130 — 129 — 140
2 kHz Blocking Gain Compression (dB)

I_3 2 — 50 — 101 — 110
2 kHz 3rd-Order IMD Dynamic Range (dB)

Table 1
FlexRadio FLEX-6500, Firmware v1.9.7,
serial number 2016-5312-6500-6128

Manufacturer's Specifications

Frequency coverage: Receive, 0.03 – 72 MHz; transmit, 160-, 80-, 60-, 40-, 30-, 20-, 17-, 15-, 12-, 10-, and 6-meter amateur bands.

Power requirement: Receive, 2 A typical; transmit, 23 A maximum at 13.8 V dc ±15%.

Modes of operation: SSB, CW, FM, RTTY, digital, AM, and synchronous AM.

Receiver

CW sensitivity: MDS in 500 Hz BW, preselector off, preamp 1/2/3: –121, –125, –136 dBm.

Noise figure: Not specified.

Spectral sensitivity: Not specified.

AM sensitivity: Not specified.

FM sensitivity: Not specified.

Blocking gain compression dynamic range:

COMPARISON OF LEGACY VS SDR RADIO ARCHITECTURE

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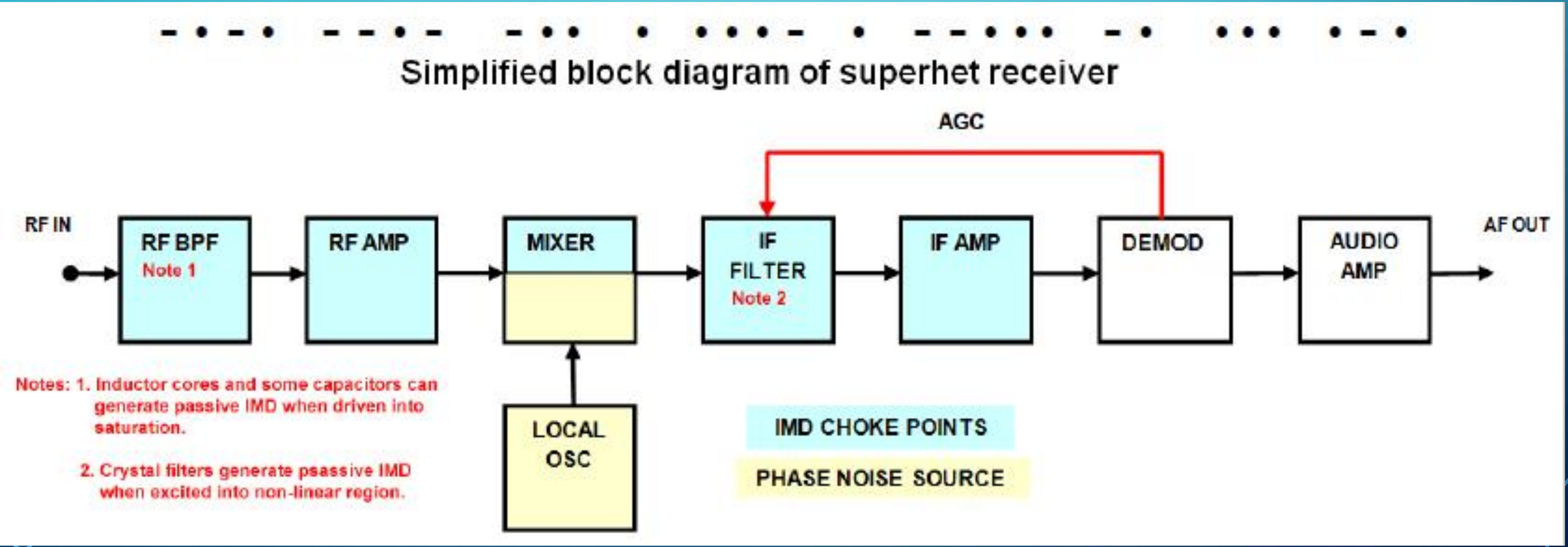
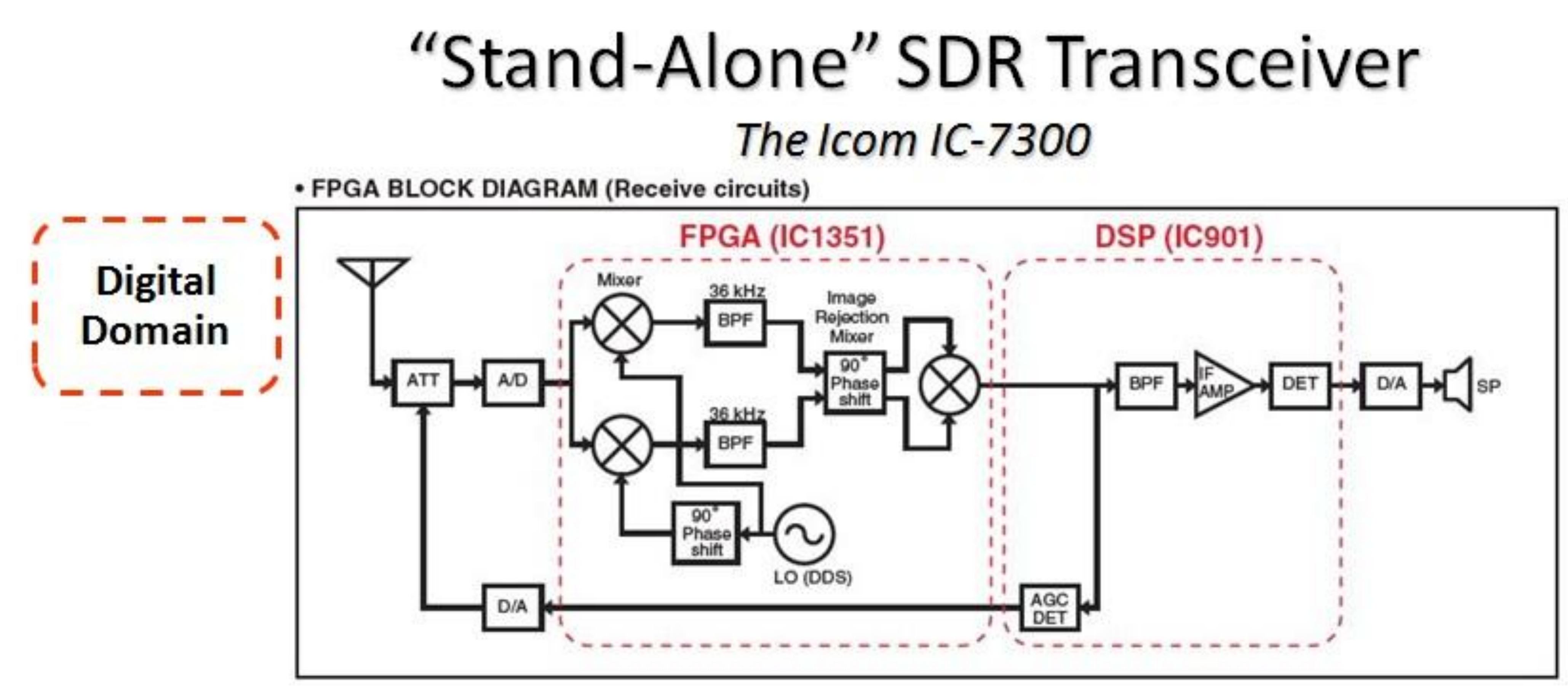


COMPARISON OF LEGACY VS SDR RADIO ARCHITECTURE



PERFORMANCE CRITERIA OF LEGACY RADIOS

Main HF Receiver Impairments

-.-. --.- -.. . ...- . --... -. ... .-.

- Intermodulation Distortion (IMD)
  - Odd-order IMD
  - Even-order IMD
  - IMD from multiple carriers approaches noise
- Reciprocal Mixing Noise
  - RF signal or noise mixes with LO phase noise
- Image Response, IF Leakage
  - RF signal or noise response at image freq. & IF
- Sensitivity/MDS is not an issue in modern receivers.
  - Below 21 MHz, the receiver noise floor is > 10 dB below band noise.

NOISE FLOOR, MDS AND LINEARITY

- Below 21 MHz, with preamp off, receiver noise floor is generally >10 dB below band noise. With preamp on, noise floor > 20 dB below band noise.
- The caveat is that in a quiet location, band noise can be sufficiently low to justify a -128 dBm (or better) MDS on and below 7 MHz.
- A combination of Norton-type "noiseless feedback" RF preamplifiers and a step-up transformer at the ADC input in a direct-sampling SDR can achieve optimum MDS without degrading noise figure or linearity.
- The IFSS curve shows the input level at which the receiver's transfer curve changes from 1st- to 3rd-order.

IMD Example

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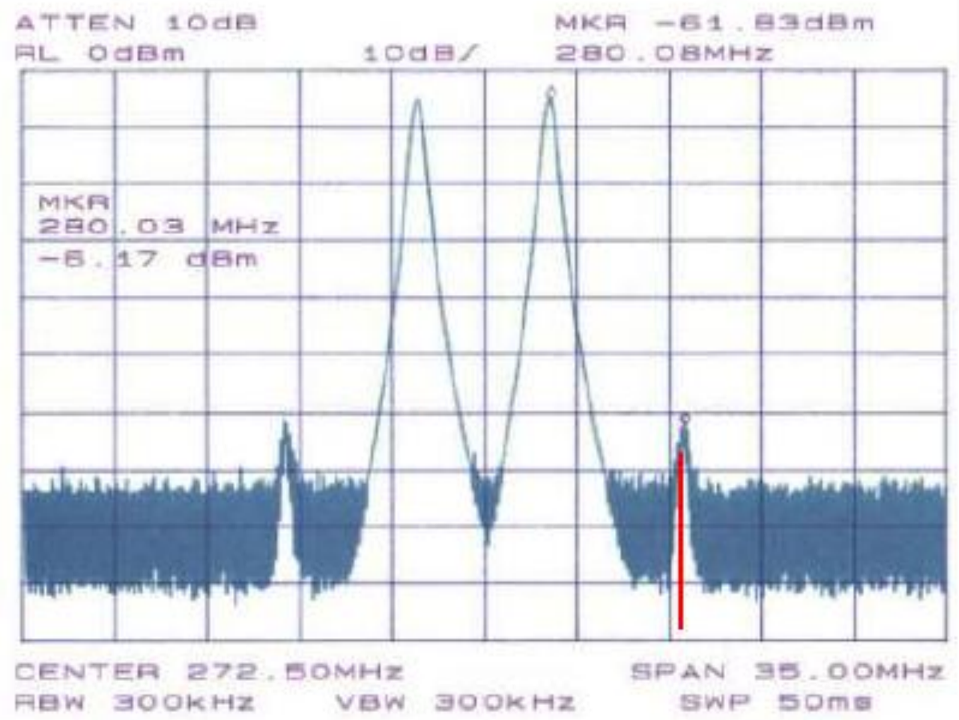
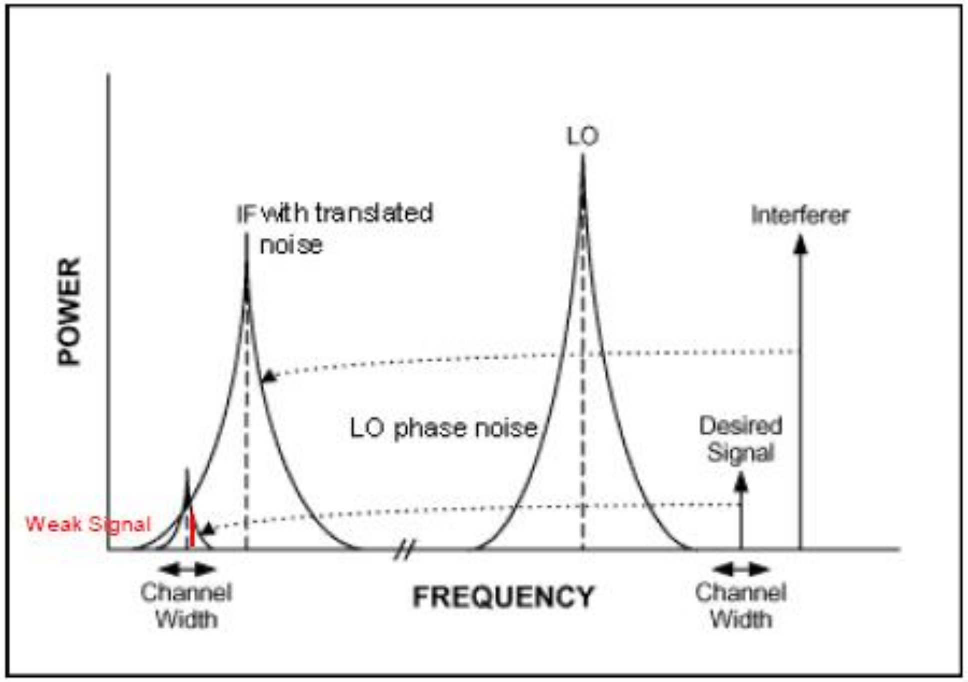


IMD Example: f_1 = 270 MHz, f_2 = 275 MHz.
IMD products at 265 and 280 MHz.
280 MHz IMD product masks weak signal.

PERFORMANCE CRITERIA OF LEGACY RADIOS

Reciprocal Mixing Noise



Strong interferer mixes with LO phase noise to "throw" noise into IF channel. If the interferer consists of wideband noise, the IF channel will be filled up with noise.

A typical synthesized LO divides its VCO down to cover lower frequencies. Thus, its phase noise will be worst at the top end of its tuning range than at the bottom end.

PERFORMANCE CRITERIA OF LEGACY RADIOS

Masking of weak signal

when reciprocal mixing exceeds IMD

nsarc NORTH SHORE AMATEUR RADIO CLUB

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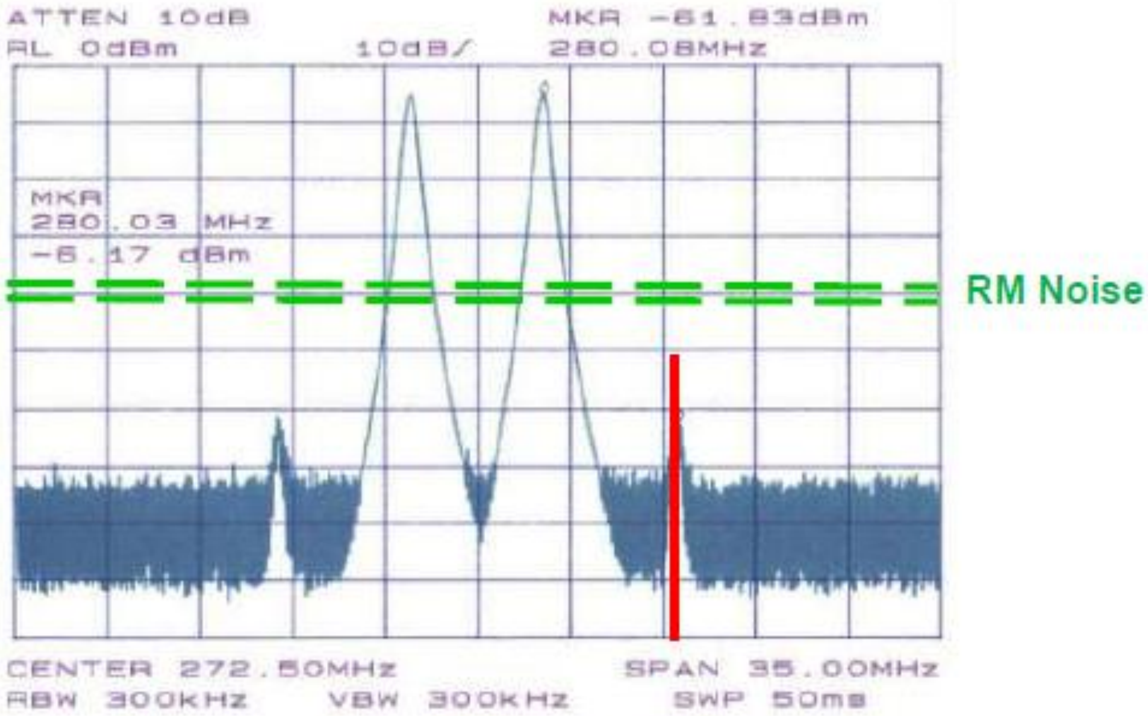

IMD Example: f_1 = 270 MHz, f_2 = 275 MHz.
IMD products at 265 and 280 MHz.
Reciprocal mixing noise masks weak signal.

APPLICABILITY OF TRADITIONAL CRITERIA TO SDR RADIOS

PHASE NOISE

- A precision crystal oscillator with ultra-low phase noise, or a calibrated low-noise RF signal generator, can be used as a test signal source for RMDR/phase noise measurements.
- As the ADC clock is the only significant phase-noise source, a very-low-noise crystal clock oscillator almost eliminates reciprocal mixing noise. Unlike a conventional LO, the ADC clock's phase noise is independent of the receive frequency.
- RMDR is usually very high (>> 100 dB).

APPLICABILITY OF TRADITIONAL CRITERIA TO SDR RADIOS

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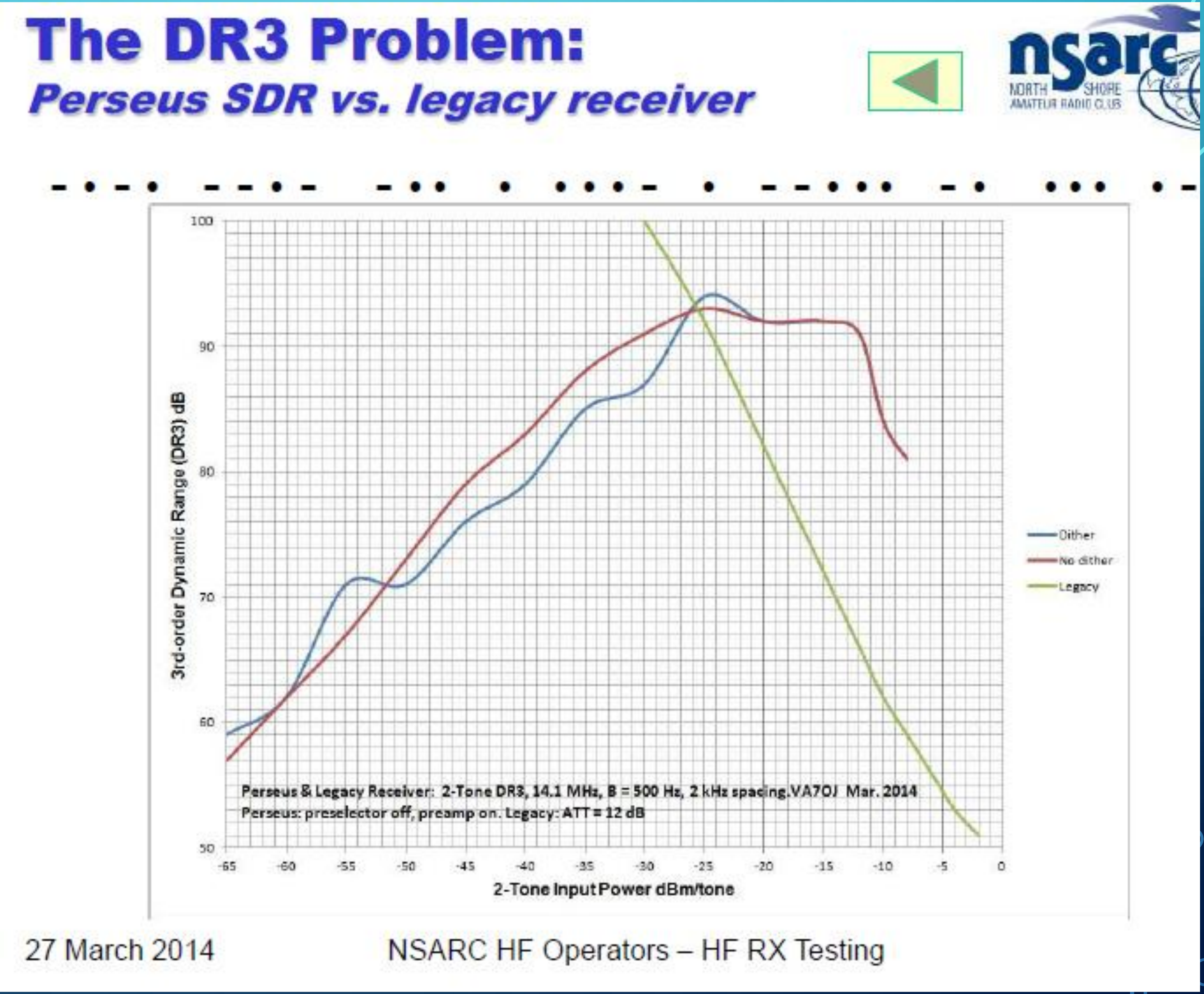
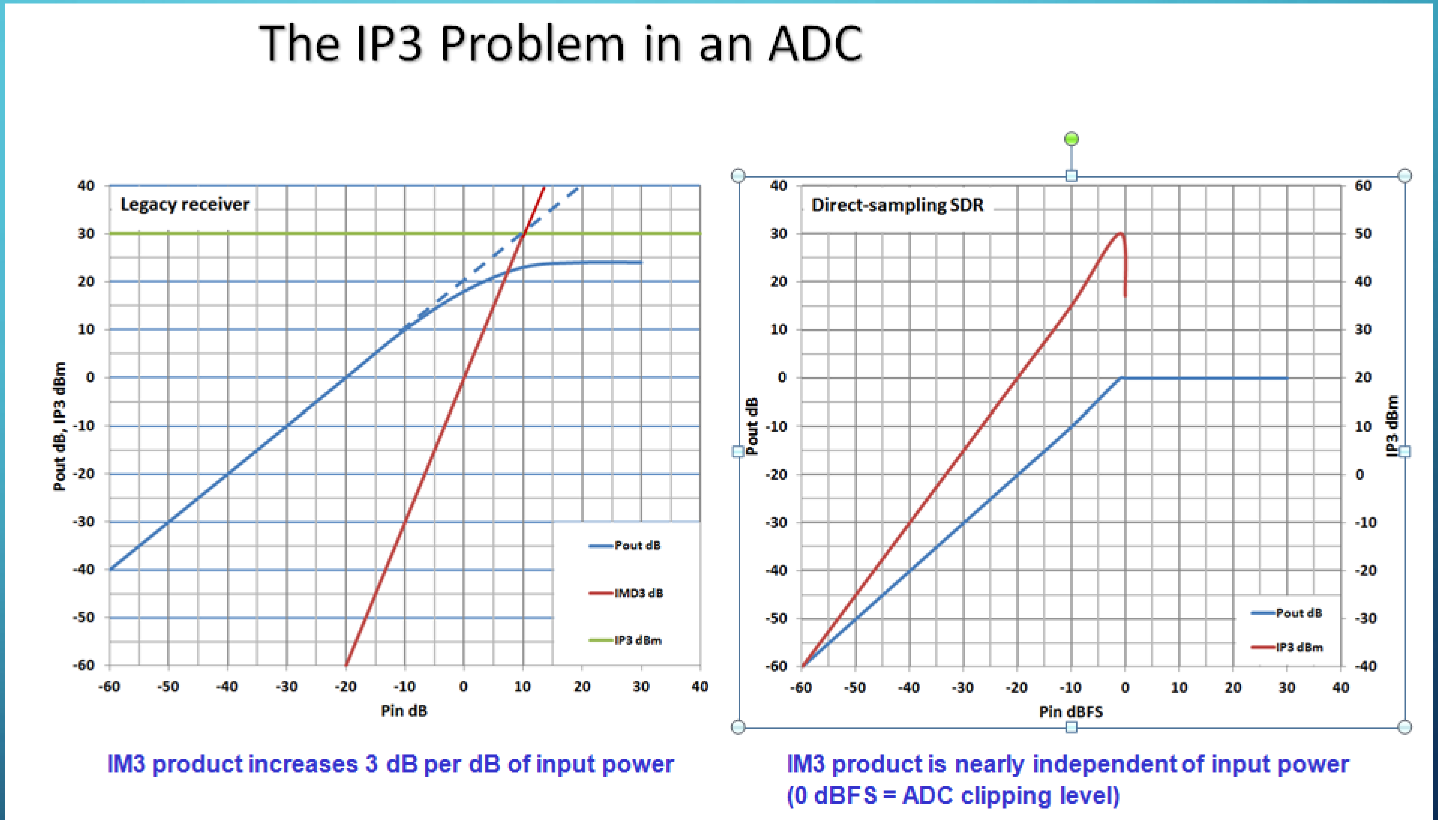


APPLICABILITY OF TRADITIONAL CRITERIA TO SDR RADIOS
DISCUSSION OF DR3 PROBLEM

- The chart shows that a classic DR3 measurement may not be applicable to a direct-sampling SDR receiver.
- DR3 increases with increasing input power, reaching a "sweet spot" at ≈ -10 dBFS, then falling off rapidly as 0 dBFS (ADC clip level) is approached.
  - By contrast, DR3 of the legacy receiver decreases with increasing input power.
- A new method for specifying receiver IMD is proposed: measure the absolute power of interferers (IMD products and spurs) against 2-tone input power, with the ITU-R P.372 band noise levels for typical urban and rural sites at the frequency of operation as datum lines. We term this IFSS (interference-free signal strength).
  - If the interferer is below the band noise at the user site, the band noise will mask it and it will not be heard. Note that the P.372 band noise levels are typical; the actual noise levels will be site-specific.

APPLICABILITY OF TRADITIONAL CRITERIA TO SDR RADIOS



SOURCES OF IMD IN AN SDR

- Preamps
- ADC input amplification and drivers
- ADC internal analog stages

These are commonly much better in IMD rejection than legacy radios due to elimination of analog mixer and roofing filters.

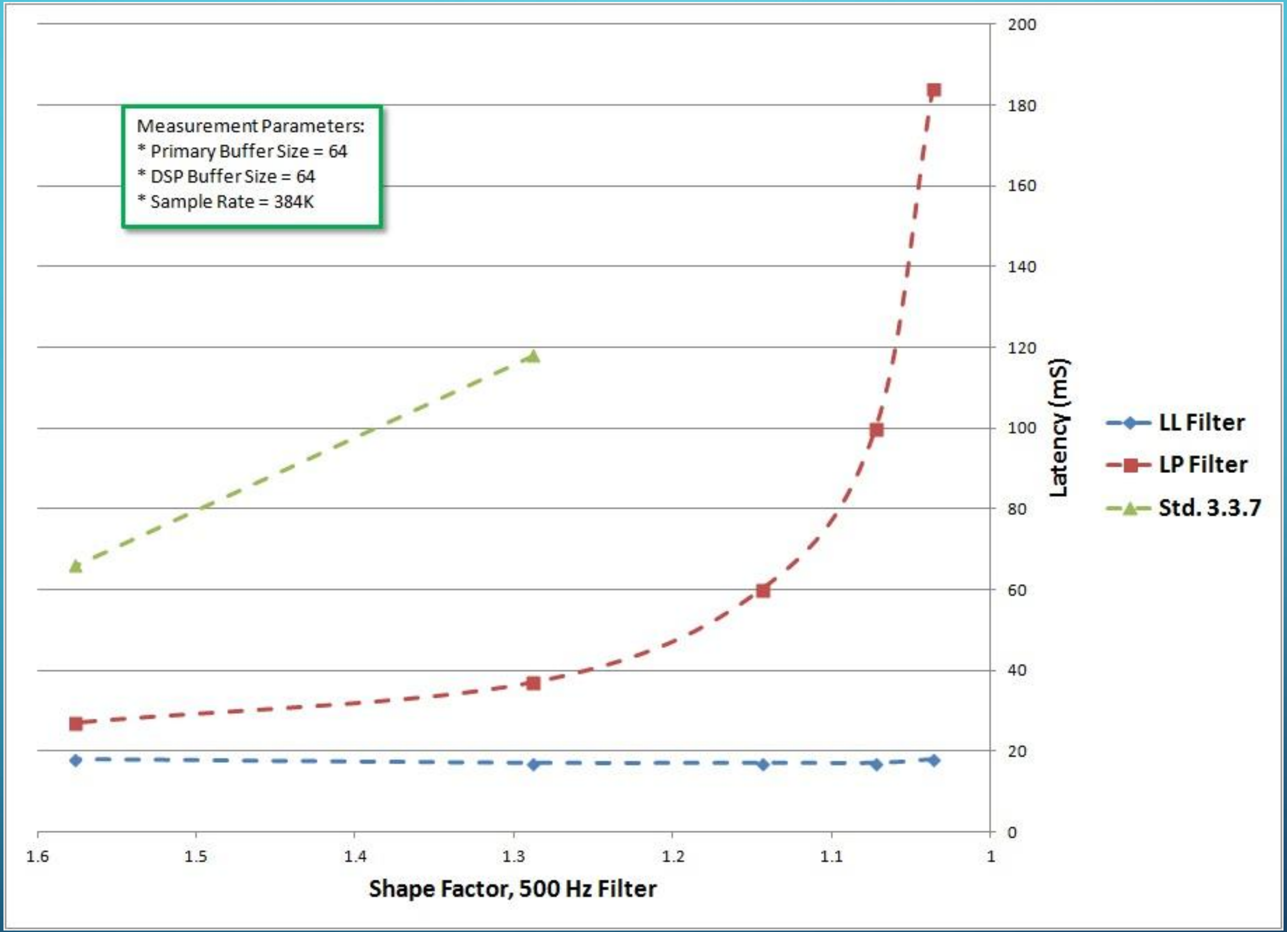
ISSUES RELATING ONLY TO SDRS

- Clipping – ADC Overflow
- Latency –This can happen in both SDRs and legacy radios with DSP if the DSP is slow or underpowered
- Aperture Jitter – This is an ADC phenomenon

LATENCY CONSIDERATIONS

- Poor filter design choices can cause unacceptable latency.
- One SDR OEM had as much as 163 ms latency, but has reduced it to 100 ms by degrading shape factors and can achieve 50 ms if shape factor > 2:1 is acceptable.
- Warren Pratt NRØV has achieved latency < 20 ms over a range of shape factors from 1.04:1 to 1.6:1 in the ANAN series SDR's *without degrading filter performance.*

TYPICAL FILTER SHAPE FACTOR/LATENCY CURVES
(ANAN SERIES, PSDR OPENHPSDR MRX V3.3.7)



LL: Low Latency. LP: Linear Phase. LP is provided as a user option. The basic V3.3.7 release does not have these options.

ALTERNATE TESTING CRITERIA

IFSS (Interference-free Signal Strength) IMD Power Measurement

in SDR's and legacy receivers

- We measure the absolute amplitude of each interferer (IMD product or spur) and draw a chart of interferer amplitude vs. per-tone test signal power at a 500 Hz detection or IF bandwidth.
  - The ITU-R P.372-2 band noise levels for ***typical*** urban and rural sites are shown as datum lines (-103 and -109 dB at 14 MHz, respectively.)
  - Test signal power should be varied in 1 dB steps, to capture large changes in IMD product amplitude with small changes in input power. (Example: Slide 34).
  - The IFSS curve clearly shows the transition from quasi-1st-order to 3rd-order behaviour as input power increases.
- If the interferer is below the band noise, it can be disregarded.
- The IFSS method eliminates the "sweet spot" problem in DR3 measurements on SDR's, and is valid for SDR and conventional receivers.

ALTERNATE TESTING CRITERIA

- IFSS (Interference-free Signal Strength) IMD Power Measurement *in SDR's and legacy receivers*
- The legacy receiver will often need front-end attenuation to bring its MDS into line with that of the SDR, which is ≈ 10 dB worse as a rule.)
- The IFSS test method allows us to compare the IMD vs. input power performance curves of a direct-sampling SDR and a legacy receiver on a common chart.
- A smooth, relatively monotonic IFSS curve will still yield a useful classic DR3 reading.

ALTERNATE TESTING CRITERIA

- "dBm from Heaven": how to exploit the band noise/noise floor margin for quieter reception.
- Insert attenuation to place RX MDS ≈ 10 dB below the band noise.
- With sufficient attenuation, AGC will respond to signal, ***not*** to band noise.
- ⚠ **DO NOT** activate preamp on 7 MHz or below unless band noise < S1 (-121 dBm) !
- In the IC-7300, the RF GAIN control manages front-end attenuation.

ALTERNATE TESTING CRITERIA

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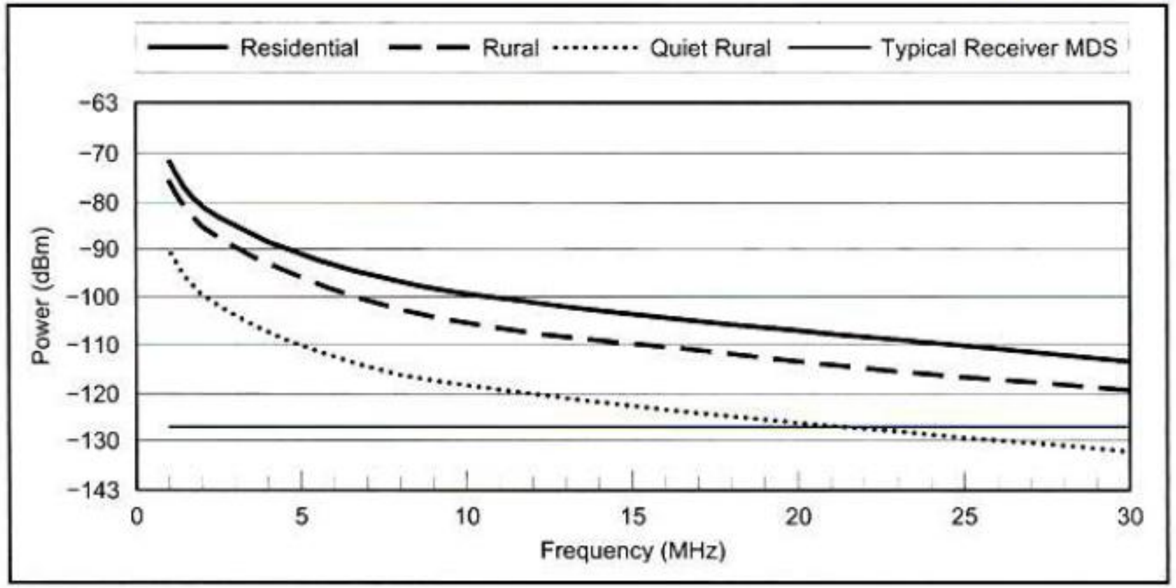
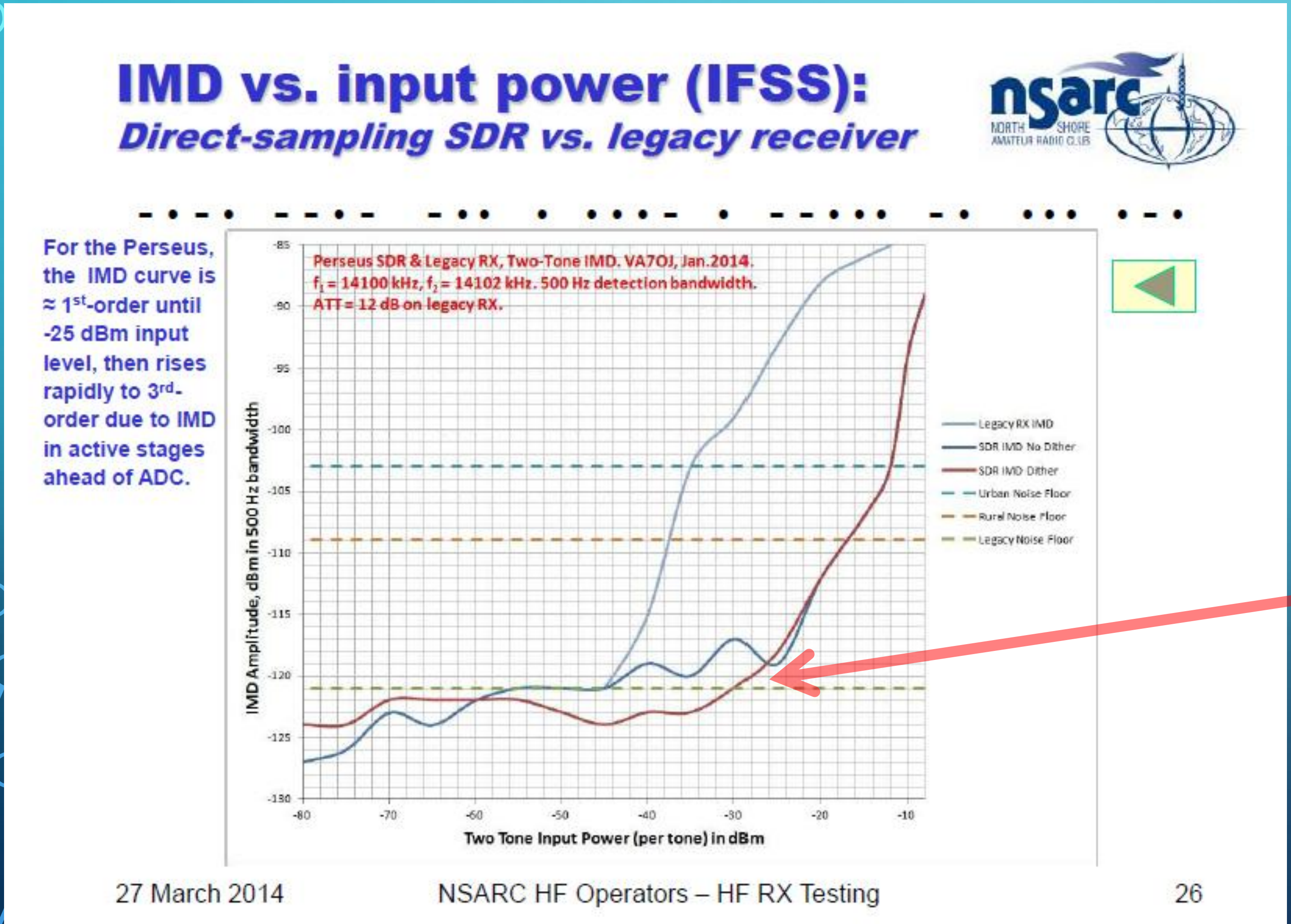
ITU-R band noise levels
(Courtesy ARRL)



Typical noise levels versus frequency for various environments.
(Man-made noise in a 500-Hz bandwidth, from Rec. ITU-R P.372.7, *Radio Noise*)

ALTERNATE TESTING CRITERIA

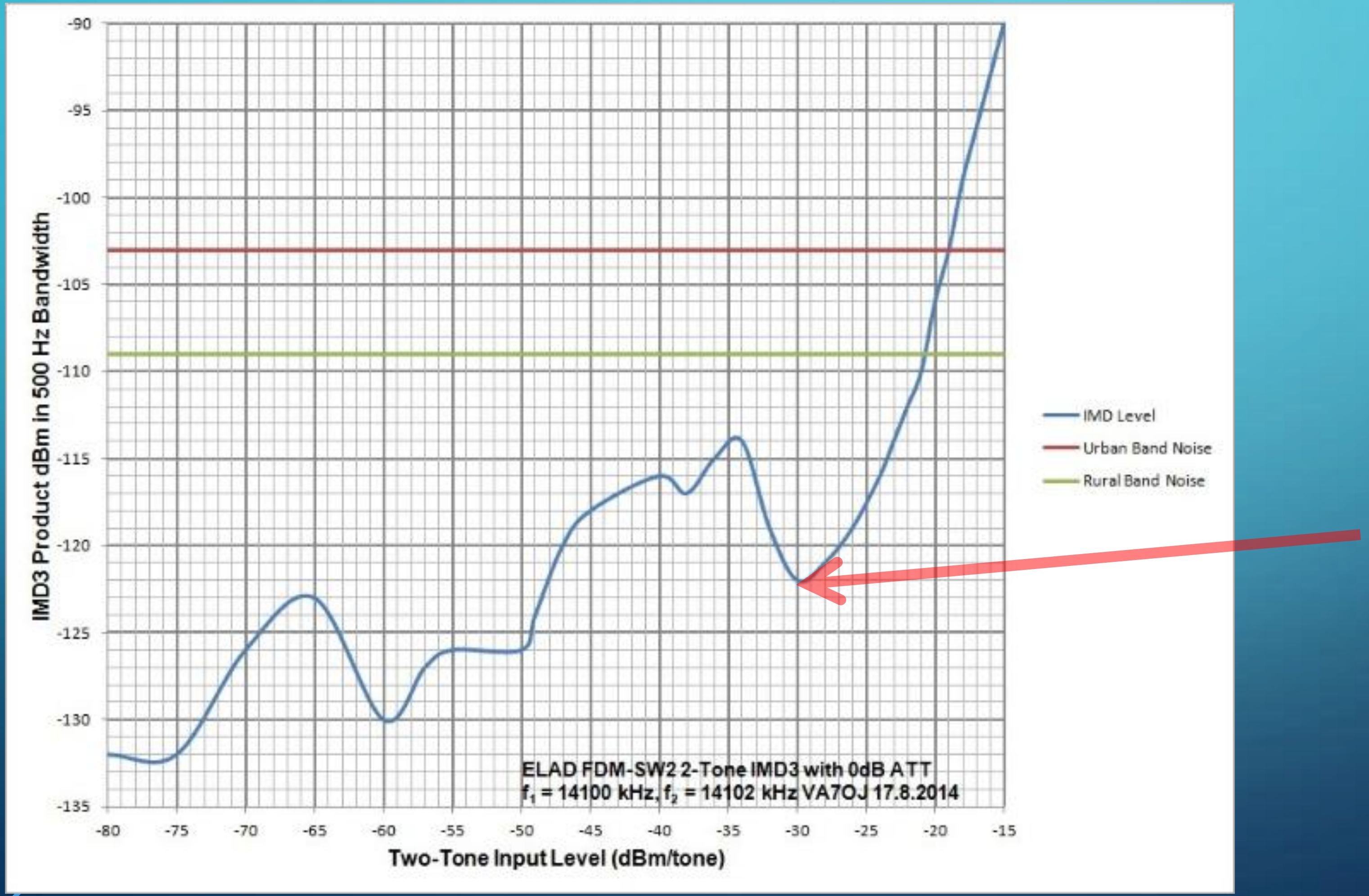
IFSS CHART: EXAMPLE 1: PERSEUS



Transition from first order to third order for strong signals (approximately 50 dB over S9)

ALTERNATE TESTING CRITERIA

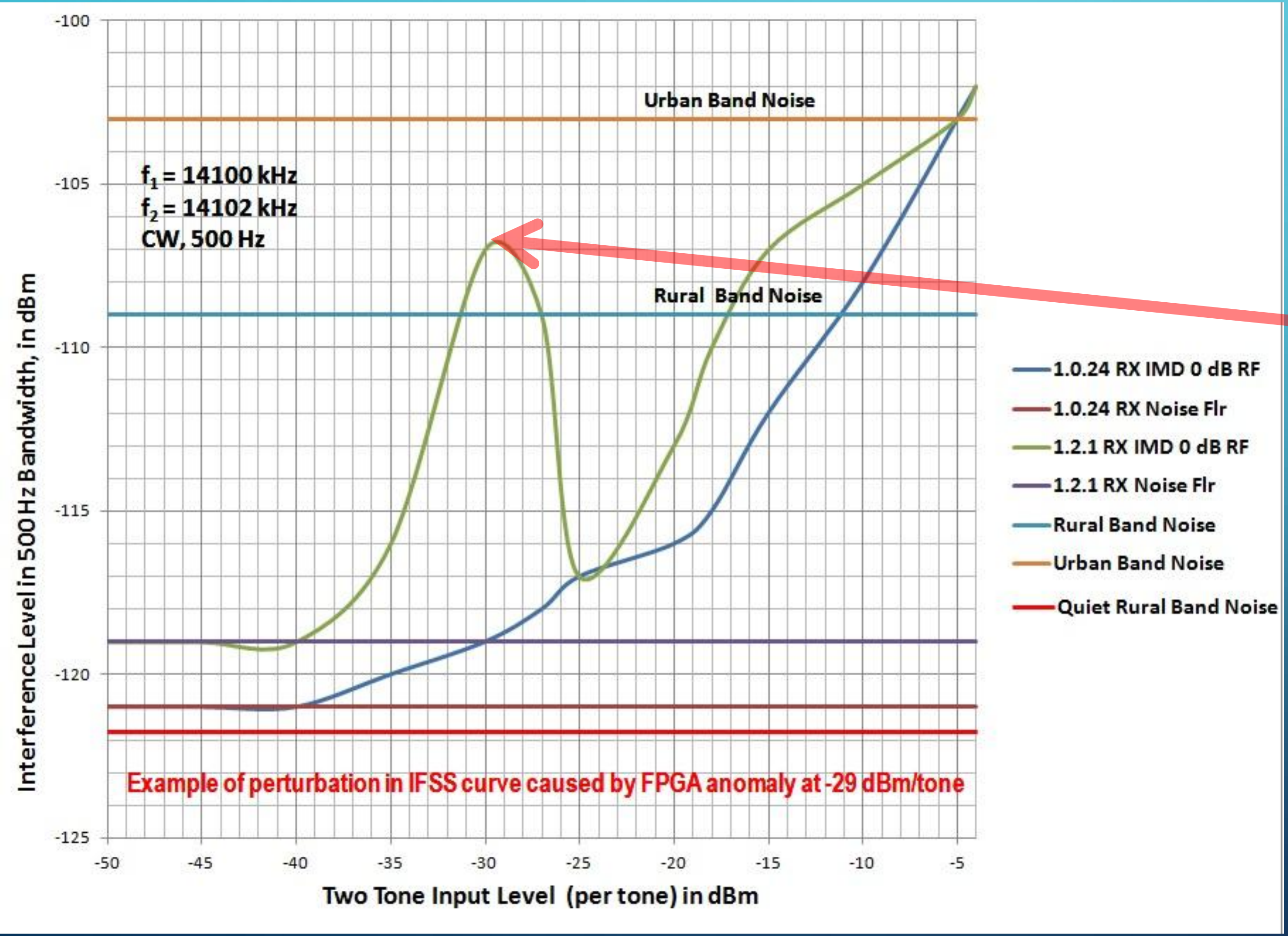
IFSS CHART: EXAMPLE 2



Transition from first order to third order for strong signals (approximately 40 dB over S9). Note irregularities in curve.

ALTERNATE TESTING CRITERIA

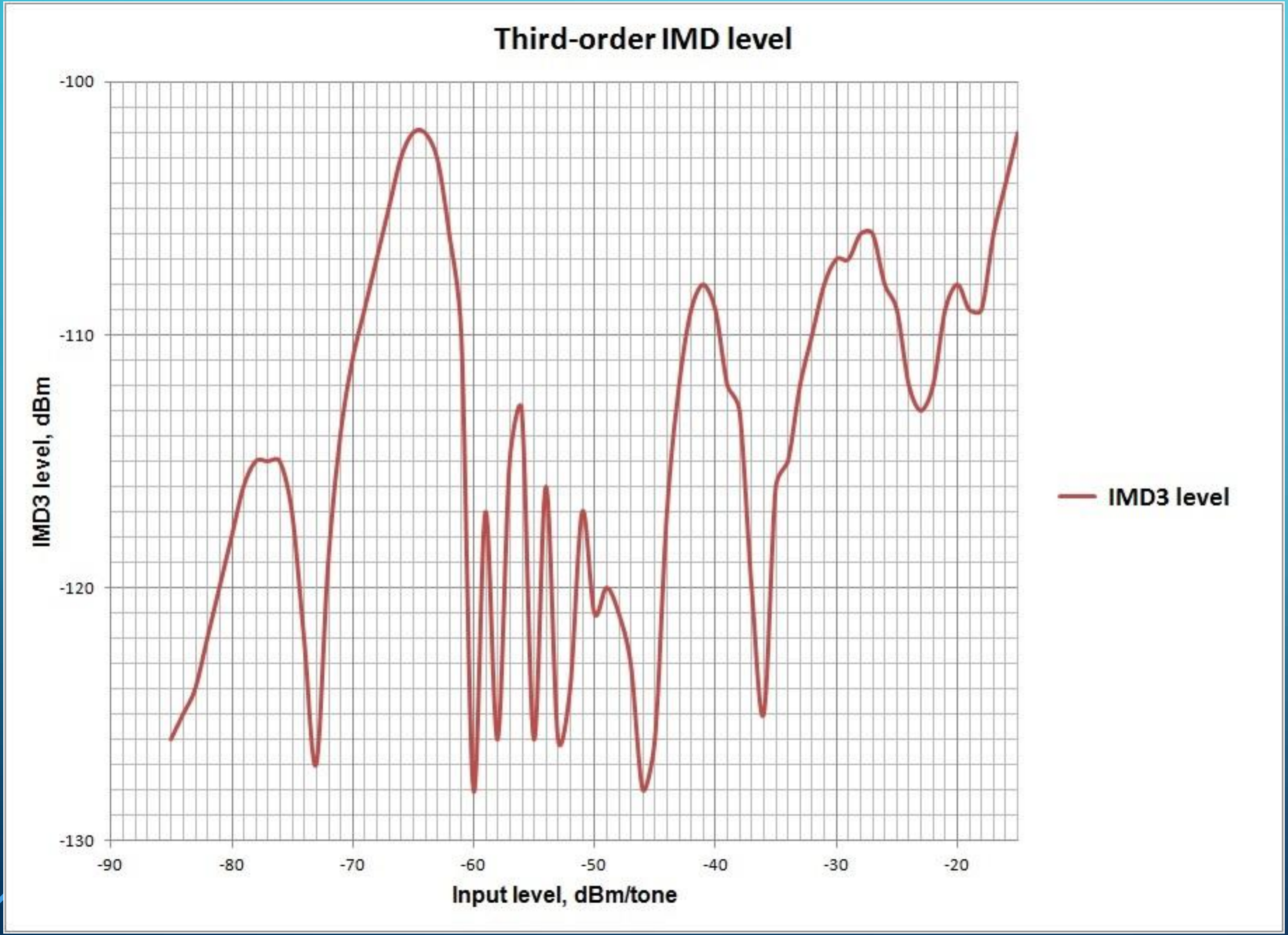
IFSS CHART: EXAMPLE 3



Note IMD amplitude spike at -29 dBm/tone input level, due to an FPGA processing anomaly.

ALTERNATE TESTING CRITERIA

IFSS CHART: EXAMPLE 4: EARLY DS-SDR RX (2007)



This direct-sampling SDR does post-ADC processing with discrete IC's (DDC, NCO) rather than an FPGA. The gross irregularity of the IFSS curve may be due to processing anomalies in this signal chain at specific input levels.

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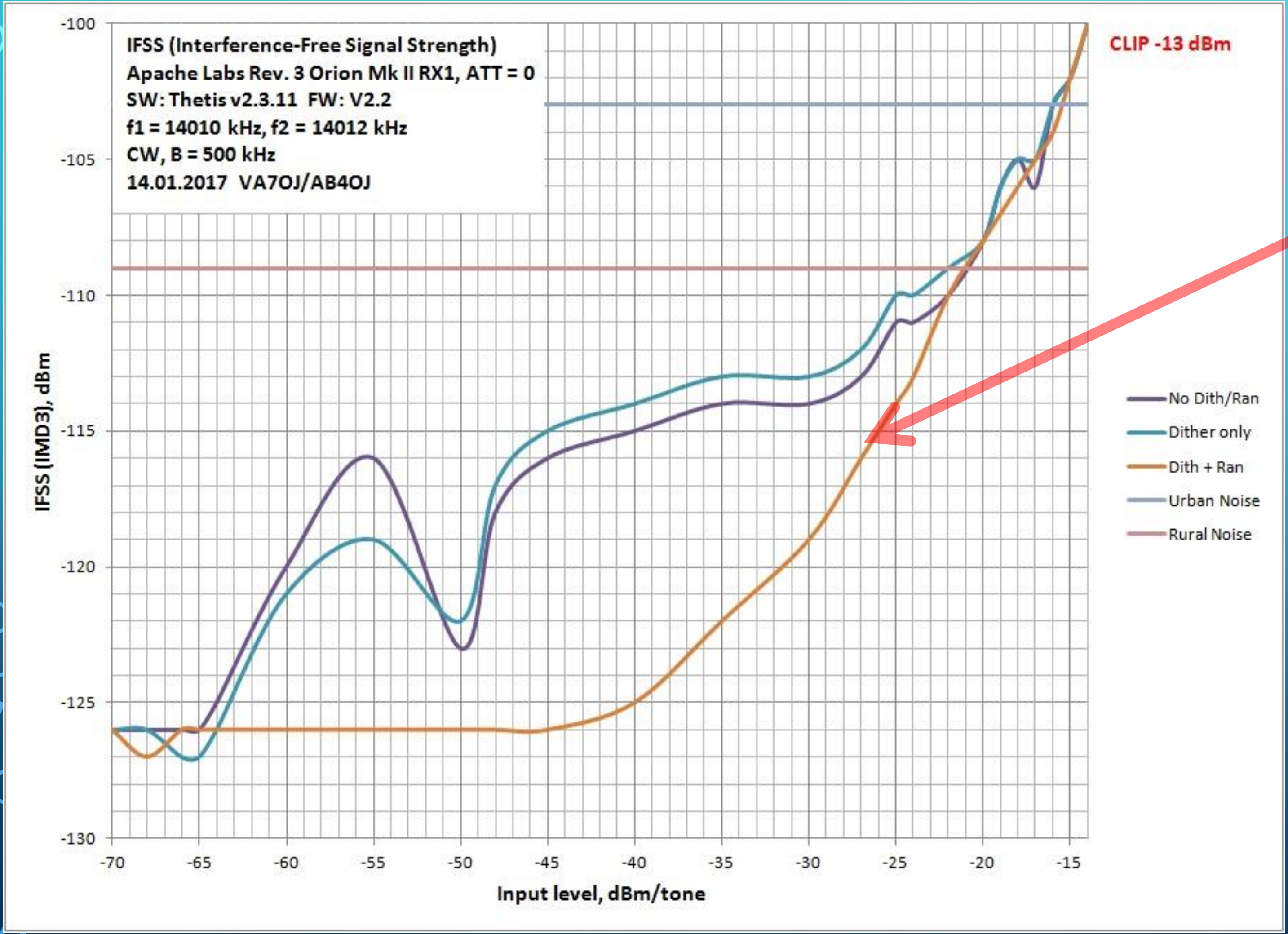
ALTERNATE TESTING CRITERIA

IFSS CHART: EXAMPLE 5: APACHE LABS ORION MK II (ANAN-8000DLE)

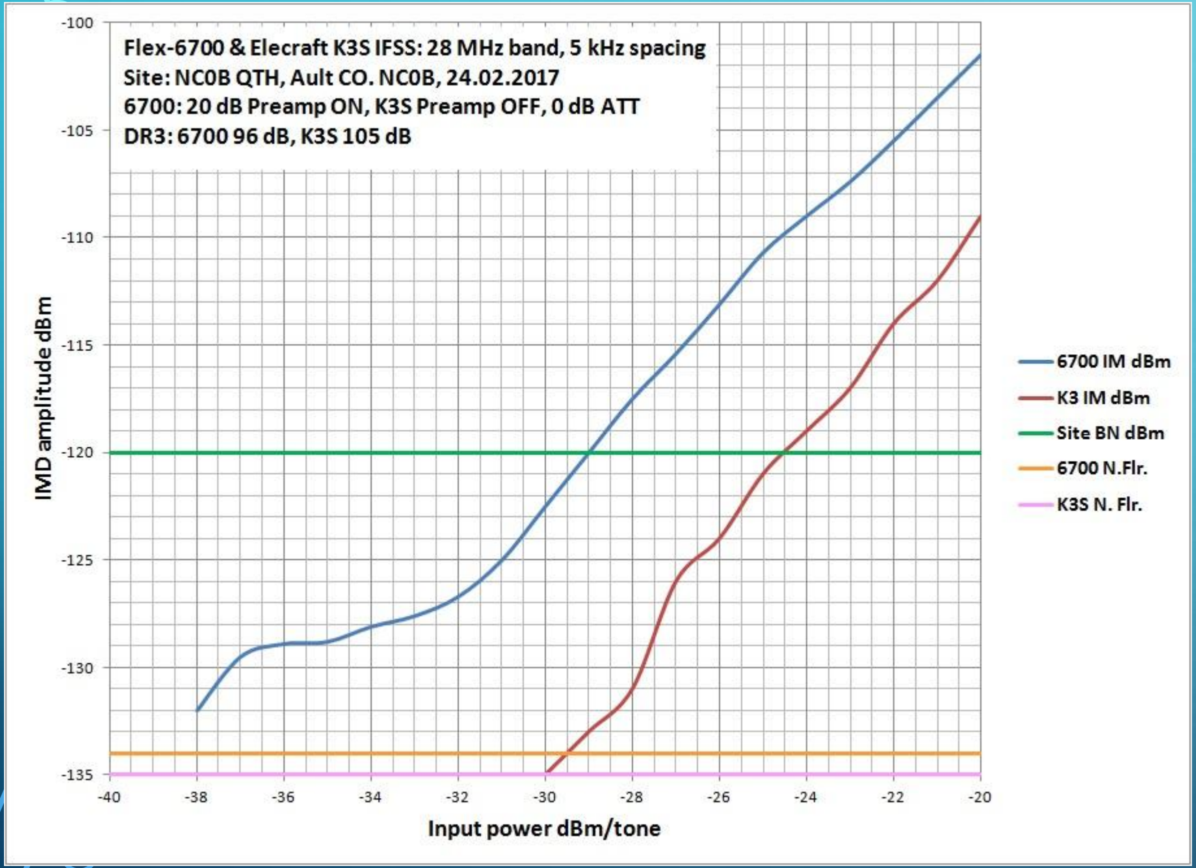


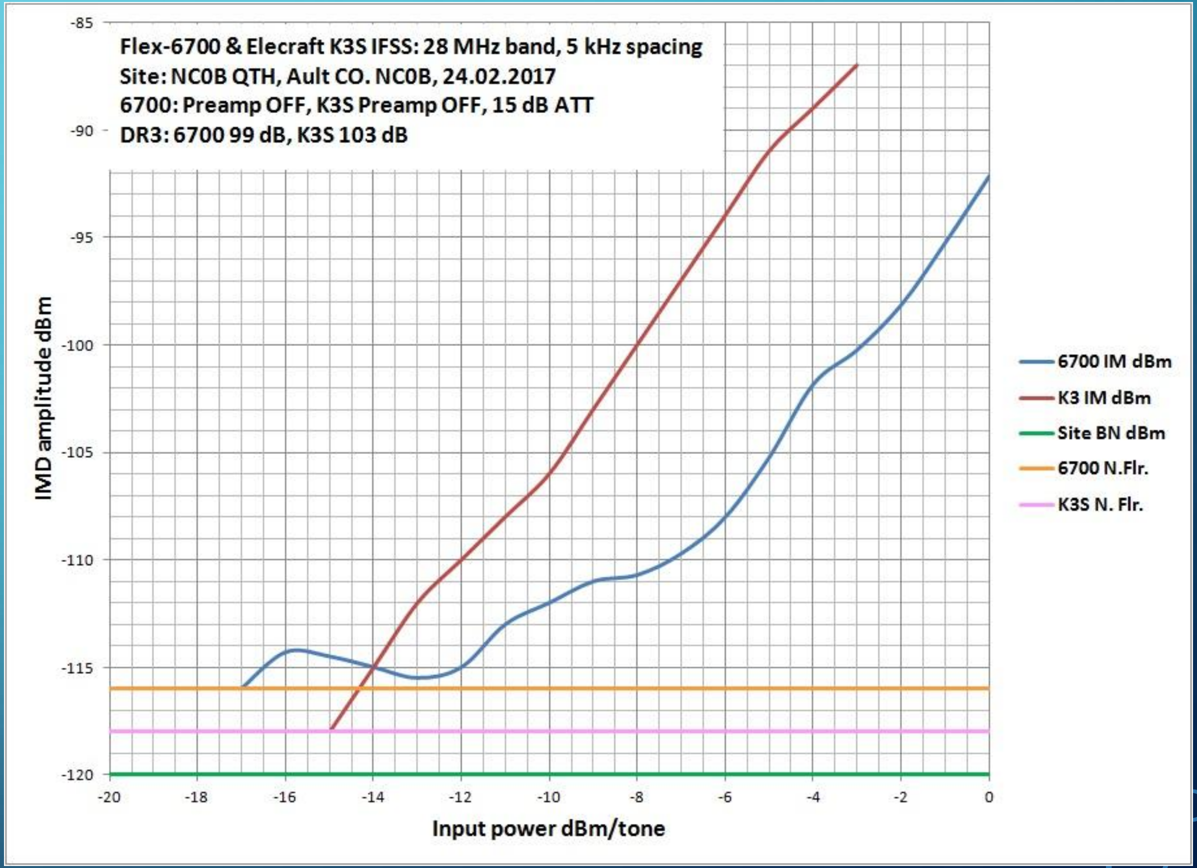
Monotonic IFSS curve with dither & randomization ON is "textbook".

ALTERNATE TESTING CRITERIA

IFSS CHART: EXAMPLE 6: FLEX-6700 VS. ELECRAFT K3S

BOTH THESE RADIOS ARE EXCELLENT, AND THE IFSS DIFFERENCE BETWEEN THEM IS INSIGNIFICANT (± 4 DB)





At -120 dBm† K3S IFSS ≈ -25 dBm, 6700 IFSS = -29 dBm

† -120 dBm = equiv. 10m rural band noise level (ITU-R P.372)

At -109 dBm* K3S IFSS ≈ -11 dBm, 6700 IFSS ≈ -7 dBm

** -109 dBm = equiv. 20m rural band noise level (ITU-R P.372)*

NOISE POWER RATIO (NPR) TESTING

LEGACY RX

- Wideband noise applied to RF IN from a noise generator will provoke IMD products at IMD choke points, and mix with LO phase noise to cause reciprocal mixing noise.
  - Steering diodes in RF/IF signal paths can also generate IMD.
  - Passive IMD can occur in RF BPF components and crystal or mechanical filters.
  - In addition to IMD and phase noise, image responses and IF leakage can arise if RF BPF is too wide to attenuate undesired signals at image frequency and IF.
  - All these products will appear in IF/AF chain as added noise.

NOISE POWER RATIO (NPR) TESTING

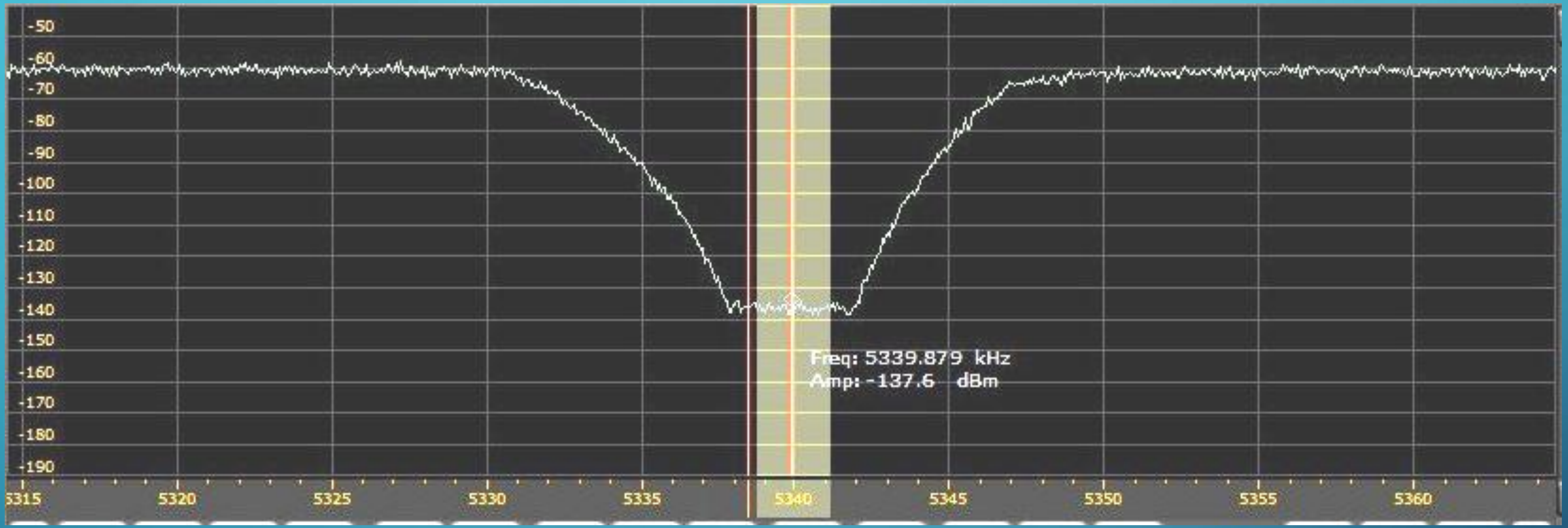
DIRECT-SAMPLING SDR RX

- Wideband noise applied to RF IN from a noise generator will provoke IMD products as below, and mix with ADC clock phase noise to cause reciprocal mixing noise.
  - Noise loading is applied 1 dB below ADC clip level.
  - RF preamp (if active) and ADC driver contribute IMD.
  - Steering diodes in RF signal paths can also generate IMD.
  - Passive IMD can occur in RF BPF components and wideband RF transformers.
  - All these products will appear in AF output as added noise.
  - NPR can be read directly off spectrum scope. *Deeper notch = better receiver.*

NOISE POWER RATIO (NPR) TESTING

- The applied *noise loading* provokes added noise in the receiver as described above.
  - Less added noise = better receiver. *A perfect receiver will add no noise at all*. The added noise is a measure of RX performance.
- We measure added noise power by creating an *idle channel* (a channel as free of noise as possible) in our applied noise band.
  - This is done by placing a deep notch (bandstop) filter just wider than the RX detection passband at the noise generator output. A band-limiting (bandpass) filter ahead of the notch filter defines applied noise BW.
  - The receiver is tuned to place the detection passband in the centre of the notch.
  - Ideally, only the added noise generated by the receiver's impairments will appear in the notch. This noise is termed *idle-channel noise (ICN)*.
- NPR = noise power in a channel equal in bandwidth to the idle channel, but outside the notch ÷ noise power in the idle channel.

TYPICAL SDR NPR TEST DATA:
DIRECT-SAMPLING SDR RECEIVER (PERSEUS)



- NPR = 73 dB, Preselector on, Dither on, Preamp on
- Measured NPR is very close to calculated theoretical value
- 60m filter pair: 5340 kHz Bandstop, 60-5600 kHz BPF

WHAT DOES IT MEAN

- Significant differences in receiver architecture lead to significant differences in methods of testing
- Receiver Performance has improved very much in the past few years.
- The critical Criterion for legacy radios has become phase noise – IMD has improved significantly.
  - Rob Sherwood notes when Phase Noise masks a weak signal before you ever get to IMD performance
  - ARRL uses a subtractive method that increases apparent IMD performance in an impractical way

WHAT DOES IT MEAN

- Sherwood says radios with dynamic range > 90dB are very good radios
  - "Never make the perfect the enemy of the good."
- SDR radios have some advantages in terms of traditional tests
- New policies need to be accepted to be able to make fair comparisons of legacy vs SDR radios.
- "What me worry?" There are many radios with performance criteria that are perfectly good radios even though they do not have the high numbers of some of the newer ones. Basing a purchase solely on very high IMD is silly.
- Reciprocal Mixing Noise is usually the most important criterion because of the significant effect it has with only one offending signal.

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SOFTWARE IMPACT ON PERFORMANCE

- It has become clear that as transceivers have become more and more dependent on software, the requirement for extremely competent programmers has become paramount.
- A competent programmer who lacks exposure to RF design may not fully grasp how software should function in a severe environment such as DXpeditions and CW contests.
- Other aspects of software performance may affect something as simple as AGC impulse response. A prime example of this problem is how poorly most receivers on the market today handle impulse noise.
- A spark in a light switch, or an electric fence, can capture the AGC of virtually all radios with a DSP back end.

DISCUSSION AND THANKS

- Discussion

Thanks to Rob Sherwood and Adam Farson

Thanks too to the Radio Club of Redmond and the members for the opportunity to make this presentation