HF Receiver Testing:

Issues & Advances

(also presented at APDXC 2014, Osaka, Japan, November 2014)

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HF Receiver Performance Specs
- what HF operators "shop" for

- Sensitivity
  - Test signal level for a given signal/noise ratio in a given bandwidth
  - Usually stated as Minimum Discernible Signal (MDS) or noise floor:
    - Input in dBm at 500 Hz bandwidth to raise audio output level by 3 dB
- Selectivity & shape factor
  - IF or detection bandwidth at -6 and -60 dB points on passband curve
- Reciprocal mixing dynamic range (RMDR)
  - Test signal level at a given offset from RX freq. to raise audio output by 3 dB, minus MDS
    - A function of local-oscillator phase noise
- 2-signal, 3rd-order IMD dynamic range (DR3)
  - Input power of each of two equal test signals at a given spacing and 500 Hz bandwidth to raise demodulated IMD product by 3 dB, minus MDS
- Blocking gain compression
  - Level of strong signal at a given offset from weak signal to reduce level of demodulated weak signal by 1 dB. RX tuned to weak signal; 500 Hz bandwidth.

More HF Receiver Specs

- also important in choosing a rig

- 2-signal, 2nd-order IMD dynamic range (DR2)
  - Input power of each of two equal test signals falling outside band under test at 500 Hz bandwidth to raise demodulated IMD product in band under test by 3 dB, minus MDS. Receiver tuned to band under test (typically 14 MHz).
    - Determines receiver's susceptibility to QRM from HF broadcasters
- Frequency stability
  - Drift measured in Hz or parts per million (ppm) over time, and over a temperature range if a variable-temperature test chamber is available
  - Not usually an issue with modern synthesized radios
- Inband IMD
  - Relative amplitude of either of two narrow-spaced test signals (typically spaced 200 Hz) and their associated IMD products, measured at audio output
    - Severe inband IMD causes listener fatigue
- Image & IF Rejection
  - An old problem returns in receivers with inband 1st IF

Main HF Receiver Impairments

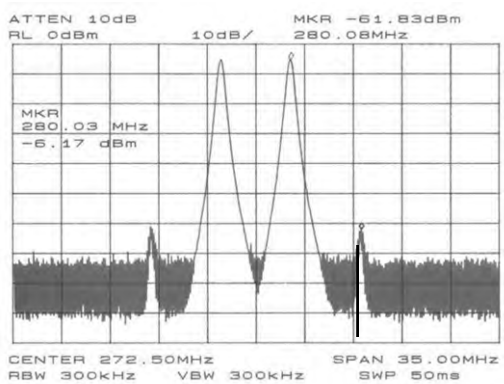
- Intermodulation Distortion (IMD)
  - Odd-order IMD
  - Even-order IMD
  - IMD from multiple carriers approaches noise
- Reciprocal Mixing Noise
  - RF signal or noise mixes with LO phase noise
- Image Response, IF Leakage
  - RF signal or noise response at image freq. & IF
- Sensitivity/MDS is not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

IMD:

intermodulation distortion

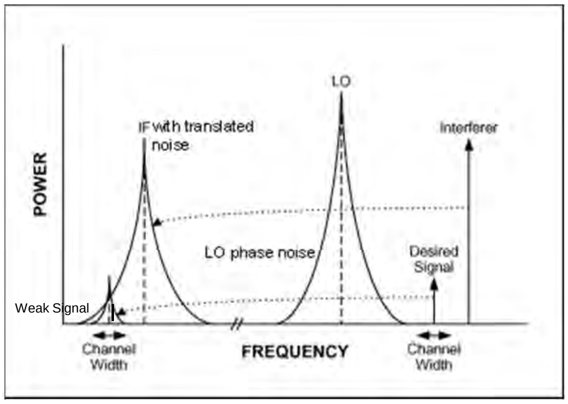
- Odd-order IMD
  - IMD products usually in same band as received signals f_1, f_2
  - 3rd-order IMD products: $2f_1 - f_2$, $2 f_2 - f_1$
    - Example: f_1 = 7010 kHz, f_2 = 7015 kHz. Products: 7005, 7020 kHz
- Even-order IMD
  - IMD products not in same band as f_1, f_2.
  - 2nd-order IMD product: $f_1 + f_2$
    - Example: f_1 = 8025 kHz, f_2 = 6010 kHz. Product: 14035 kHz
- On a crowded band, multiple carriers generate a large number of IMD products
  - Limiting case is where spectrum of IMD products approaches Gaussian noise

IMD Example



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

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.

Image Response, IF Leakage

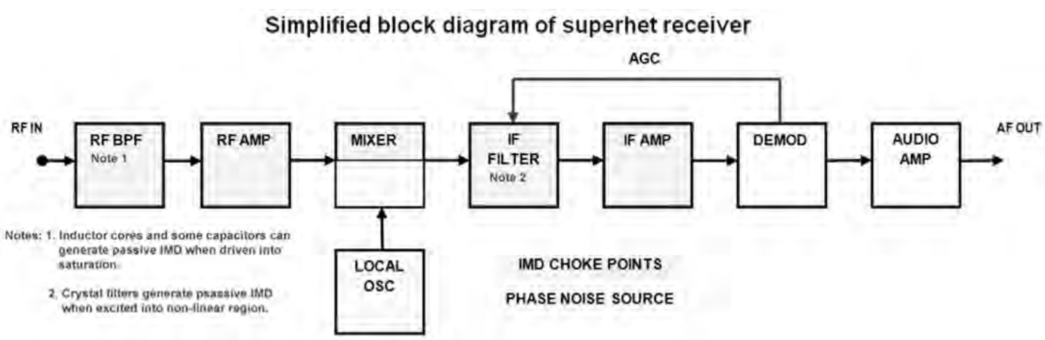
- Image response:
  - Acceptance of signals at $f_0 \pm 2 * IF$ (f_0 = signal freq.)
    - Example: f_0 = 10455 kHz, IF = 455 kHz. Image: 10000 or 10910 kHz.
  - In modern receivers with high 1st IF, RF preselector suppresses image response almost completely.
- IF leakage:
  - Acceptance of signals at or close to 1st IF.
    - Example: 1st IF = 9 MHz. On 30m band, preselector may be sufficiently wide to pass some energy at 9 MHz. This will enter the IF chain and interfere with desired signals.
  - This is not a problem in receivers whose 1st IF is above the highest operating frequency.

Blocking and overload

- Blocking: degradation of receiver sensitivity in the presence of a much stronger (blocking) signal.
- Blocking gain compression occurs when the interferer drives the first active RF stage to its compression point, thus causing desensing.
- Blocking gain compression is the difference in dB between the level of an incoming signal which will cause 1 dB of gain compression, and the level of the noise floor.
- Note that in a *direct-sampling SDR receiver,* no blocking occurs until the ADC is driven into saturation (clipping).

Typical Superhet Receiver

showing impairment areas



- Multiple signals or wideband noise applied to RF IN 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, spurs etc.

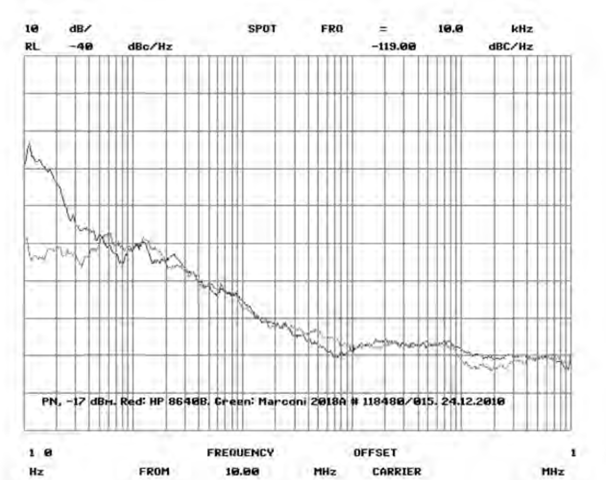
Issues in standard receiver test methods:

instrument limitations

- Synthesized RF signal generators used for MDS, reciprocal mixing, blocking and IMD testing can have moderate to severe phase noise. This will degrade measurement accuracy.
  - A solution: ultra-low-noise crystal oscillators. These are costly and not frequency-agile. A vacuum-tube LC-type generator is also usable, but has poor frequency stability/accuracy.
  - Synthesized generators with excellent phase-noise performance are available, but are somewhat costly.
- Spectrum analyzers are frequently used for phase noise measurements.
  - Many high-end analyzer models support phase noise measurement software.
  - The limitation here is that the lowest phase noise value the instrument can display is that of its own internal phase noise.

Sig Gen Phase Noise Example

HP 8640B & Marconi 2018A



Ultra-Low-Noise Crystal Oscillator

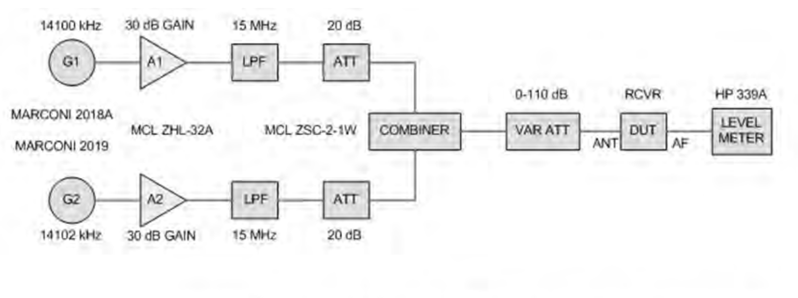
TYPICAL SPECS:

OUTPUT
Frequency
5 MHz
Level
+13 dBm ±2dBm into 50 ohms
STABILITY
Aging
1×10^{-9} per day
after 30 days operating, typical
Phase Noise L (f)

1 Hz	-115 dBc/Hz
10 Hz	-145 dBc/Hz
100 Hz	-165 dBc/Hz
1 kHz	-176 dBc/Hz

Temperature Stability
$\pm 5 \times 10^{-8}$, 0° to +60°C (Ref +25°C)

Typical 2-Tone IMD Test Setup:
also used for blocking tests (see p. 17)



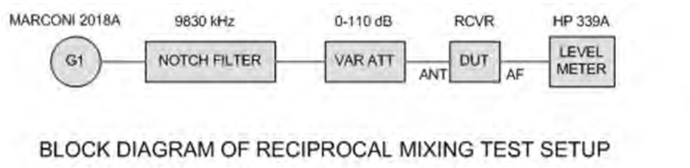
BLOCK DIAGRAM OF TYPICAL TWO-TONE RECEIVER TEST SETUP

Test signal power is adjusted for 3 dB increase in level meter reading. DR3 = test signal power – MDS.

Amplifiers A1, A2 buffer the signal generators G1 and G2 to block RF sneak paths across the combiner. This prevents mixing in the generators' output stages (a cause of IMD).

Improved RMDR Test Method

using notch filter to improve accuracy



- Notch filter (notch at f_0, depth > 80 dB) between sig. gen. and DUT.
- f_0 = freq. of max. attenuation. Δf = offset.
- DUT tuned to f_0. Sig. gen. tuned to f_0 + Δf; input power to raise audio output by 3 dB is noted.
- Notch filter suppresses sig. gen. phase noise at f_0, thus improving measurement accuracy.
- RMDR = input power – filter passband insertion loss – MDS.

Issues in 2-tone 3rd-order IMD dynamic range (DR3) testing:

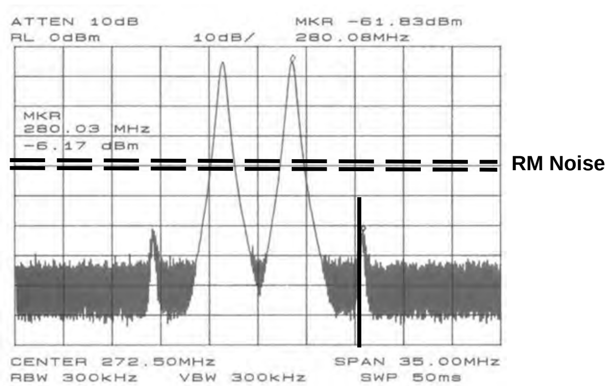
subtractive test method

- ARRL uses subtractive DR3 test method (ITU-R SM.1837 Sec.2).
  - IMD product amplitude is measured at audio output using signal analyzer with 1Hz or 3Hz RBW, to subtract out the noise contribution.
  - The DR3 value obtained via this method is *meaningless* unless RMDR is measured and the result presented alongside DR3.
  - ARRL are now presenting RMDR alongside DR3 in their QST Product Reviews.
- A “100 dB” radio with 85 dB RMDR is *not* a 100 dB radio; it is an *85 dB radio!* To claim otherwise is deceptive advertising.
- If RMDR < DR3, reciprocal mixing noise will mask that “weak one” long before IMD product does.
- In a practical on-air operating environment, artifacts and splatter from distant transmitters will mask weak signals much more often than will IMD in the local receiver.
- This is more an operational and regulatory problem than a technical one.

Issues in 2-tone 3rd-order IMD dynamic range (DR3) testing:
classical test method

- In the DR3 test method outlined on p. 14, the IMD + noise amplitude is measured at the audio output using an RMS level meter such as the HP 3400 or 339A.
- The test engineer ***must*** measure RMDR *and* DR3. If RMDR > DR3, the test result is DR3. If RMDR < DR3, we are reading RMDR.
- To check, turn off f_1 and f_2 in turn. If audio output drops by less than 3 dB when either f_1 or f_2 is switched off, the test result is RMDR, not DR3.
- This is acceptable; the test will reveal whether IMD or reciprocal mixing is the receiver's *dominant impairment*.
- In on-air operating, reciprocal mixing (RM) can arise more often than IMD, as only *one* undesired signal will produce RM whereas two are required for IMD to occur.

Masking of weak signal
when reciprocal mixing exceeds IMD



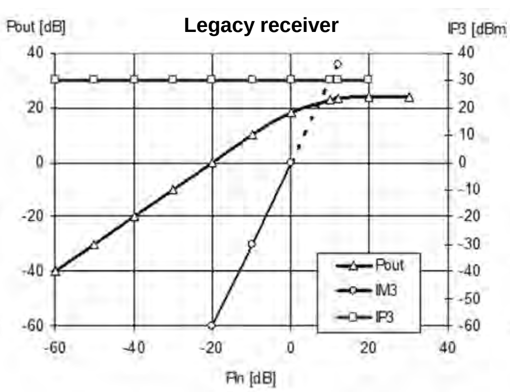
IMD Example: f_1 = 270 MHz, f_2 = 275 MHz.
IMD products at 265 and 280 MHz.
Reciprocal mixing noise masks weak signal.

Issues in SDR testing:

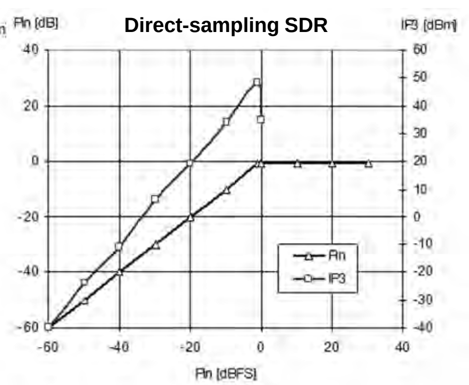
direct-sampling SDR characterization

- With the advent of fast, cost-effective ADCs, the direct-sampling SDR has eclipsed its QSD (quadrature-mixer) predecessors.
- This architecture poses new challenges to the test engineer:
- DR3 and RMDR have no relevance as performance metrics.
  - DR3 increases with increasing test-signal power, reaches a peak at ~ -10 dBFS (10 dB below ADC clipping) and then drops rapidly.
- IP3 (3rd-order intercept) is meaningless here, as IMD in an ADC follows a quasi-1st-order rather than a 3rd-order law.
  - The transfer and IMD curves diverge, and never intersect. In a conventional receiver, IP3 is the convergence point of the transfer and IMD curves.
- As the ADC clock is the only significant phase-noise source, a very-low-noise crystal clock oscillator almost eliminates reciprocal mixing noise.
  - RMDR is so high (>> 100 dB) that even the very best crystal oscillators as test signal sources can degrade the measurement.

The IP3 Problem in an ADC



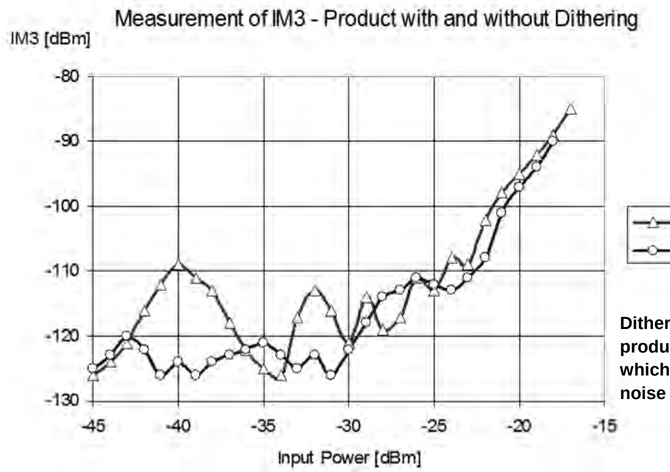
IM3 product increases 3 dB per dB of input power



IM3 product is nearly independent of input power (0 dBFS = ADC clipping level)

The effect of dither on IMD

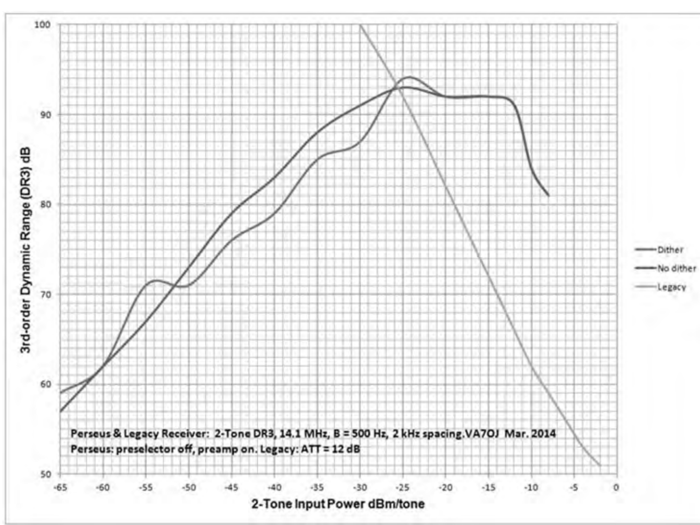
Try this with your old rig!



Dither breaks up IMD products into noise which degrades RX noise floor by ≈ 3 dB.

The DR3 Problem:

Perseus SDR vs. legacy receiver



The DR3 Problem:
discussion

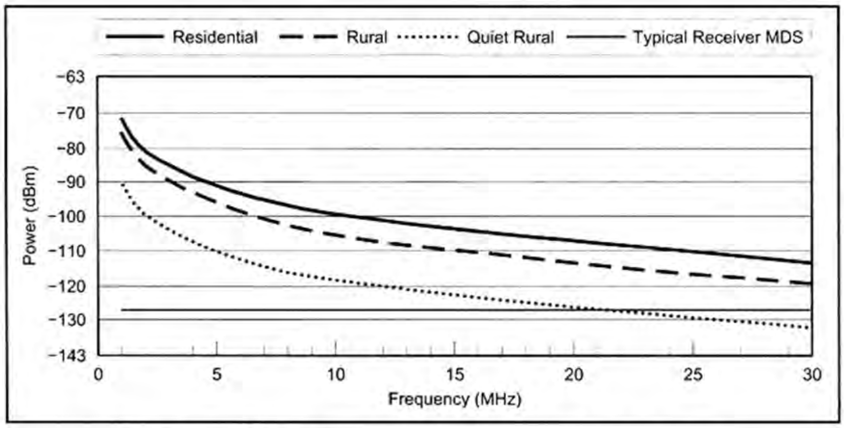
- The chart (see previous page) shows that the DR3 of a direct-sampling receiver is unusable as a predictor of dynamic performance.
- DR3 increases with increasing input power, reaching a “sweet spot” at ≈ -10 dBFS, then falling off rapidly as 0 dBFS (ADC clip level) is approached.
  - By contrast, DR3 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.
- The IFSS method allows *comparison* of SDR and legacy receivers.

IFSS 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 rural and urban sites (see next page) are shown as datum lines (-103 and -109 dB at 14 MHz, respectively.)
- 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.
- 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 as shown on p. 26.

ITU-R band noise levels

(Courtesy ARRL)

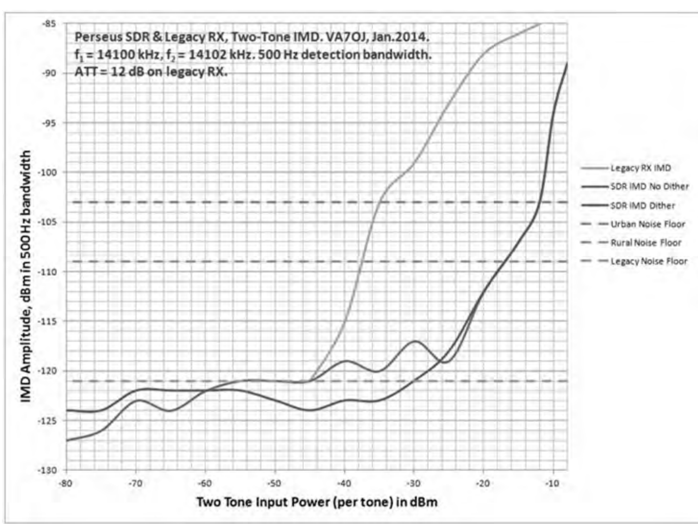


Typical noise levels versus frequency for various environments.
(Man-made noise in a 500-Hz bandwidth, from Rec. ITU-R P.372.7, *Radio Noise*)

IMD vs. input power (IFSS):

Direct-sampling SDR vs. legacy receiver

For the Perseus, the IMD curve is ≈ 1st-order until -25 dBm input level, then rises rapidly to 3rd-order due to IMD in active stages ahead of ADC.



Measuring dynamic range is easy
but how do we measure absolute interferer levels?

- On a direct-sampling SDR, we can read the observed IMD product and interferer levels directly off the S-meter or spectrum scope.
  - The scope and S-meter level calibration should be checked before taking these readings.
  - A preamp ahead of the ADC will degrade IMD.
- On a legacy receiver, the procedure is more complex.
  - Read recovered audio level of IMD product or interferer on level meter.
  - Next, apply a single-tone test signal to the DUT RF input and adjust input power to obtain same level-meter reading. (AGC must be on.)
- IMD product/interferer levels can also be read off a legacy receiver's *calibrated* signal-strength meter.

Other considerations for HF receiver testing

- The measurement of second-order IMD dynamic range (DR2) is still useful in SDR testing, as 2nd-order mixes in active stages ahead of the ADC can cause HF BCI.
  - Example: 41m BCI on the 40m amateur band in Region 1.
- Image rejection and IF leakage measurements are not applicable to direct-sampling SDR's.
- The **noise-power ratio (NPR)** test is a useful tool for identifying impairments in SDR and conventional receivers.
  - If a complete NPR test set (noise generator and noise receiver) is available, it can be used also for testing 2-port networks (amplifiers, filters etc.)
- **http://www.nsarc.ca/hf/npr.pdf**

References for further study

1. http://www.itu.int/rec/R-REC-P.372/en
2. http://tinyurl.com/testproc2011 *(ARRL Test Procedure Manual, 2011)*
3. http://www.nsarc.ca/hf/npr.pdf
4. http://www.ab4oj.com/test/docs/npr_test.pdf