Very High Performance Image Rejecting Direct Conversion Receivers

Or how can an 11 ma receiver out perform the world’s best ham transceivers?

Dan Tayloe, N7VE
NC2030 20m Prototype

- SCAF Tune
- CW Speed
- Volume
- Keyer Program

- Main Tuning
- Frequency Read-Out
- RIT
- Spot Switch
- Keyer Input
- Headphone Jack
NC2030 Receiver Specs

- MDS (3db S+N/N): -135 dbm (0.1 uV)
- Receiver Bandwidth (-6db): 350-800 Hz
- IP3 DR: 93db (2KHz), 105 db (5 KHz), 109 db (10 KHz)
- BDR: 119db (2 KHz), 128.5db (5 KHz), 139db (10 KHz), 142db (20 KHz)
- Image rejection: ~ >45 db over the band
- Receiver current drain: ~11 ma at 12v
NC2030 at full sensitivity, ranks among the best rigs which were measured with their RF pre-amps off.

Note: With the RF pre-amp on, the K2 suffers a 7 db degradation in blocking.

Even at only 2 KHz, the NC2030 performs at least as well as all but two rigs measured at 5 KHz.
Blocking DR: A comparison (vs. K2)

NC2030 Blocking DR does not plateau
- Rejection keeps improving

K2 plateau shows IF amp saturation
- Signals on the other side of the band (300+ KHz away) can still cause blocking

=> NC2030 blocking is a bit worse close in, much better further out

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<th>High Side</th>
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<td>20</td>
<td>142</td>
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</tbody>
</table>

*Extracted from QST K2 expanded report*
IP3DR: A comparison – 5 KHz

NC2030 at **5 KHz** is **13 db** better than the best.

NC2030 at **2 KHz** is still better than all the rest at **5 KHz**.

Not a true apple-to-apples comparison since NC2030 is at **full sensitivity** while other rigs have **pre-amps off**.
IP3 DR: A comparison (vs. K2)

IP3DR is *noticeably better* than the best radios available (K2/Orion)

NC2030 appears *17 db* better 2 KHz away (93 db vs. 76 db)

NC2030 appears *18 db* better 5 KHz away (105 db vs. 87 db)

*Extracted from QST K2 expanded report*
Typical Superhet Front End

• This is a simplified view, but represents many superhet receiver front ends

• The *large signal performance* is set in the sections *before* the radio “brick wall” filtering (Xtal filter)
Superhet Front End Bandwidth

- RF preamp, first mixer, and first IF amp sees *all signals* in the *entire band* all at the same time.
- Wide front end bandwidth is the main reason *preamps are turned off* and *attenuators are kicked* in during a contest.
Phasing DC Front End

- The narrow bandwidth direct conversion detector allows few signals to get to the audio preamps.
- The audio preamps also has a narrow bandwidth, thus off frequency signals are attenuated even further prior to the receiver “brick wall” audio filter.
Band View: Superhet Vs. DC RCVR

- **Superhet RF preamp/Mixer/IF Amp** sees all signals at full strength
  - Must remain linear with the *sum of all the signals on the band*
  - *This is hard!* RF pre-amp on/off, Attenuators, Variable IF amp gain
  - Requires a lot of power to stay linear; IF amp often uses **50 to 100 ma**

- **DC receiver** sees only a fraction of the band
  - Must remain linear over *just a few* of the many signals on the band
  - Only the close in signals are problems; **-16 db, 5 KHz away, -40 db at 20 KHz**
  - *A much easier problem!*
Superhet RF/IF Preamps

- RF and IF amps are typically 50 ohm in, and low Z out
  - These are both *power* amplifiers
- Wide band, high signal linearity amps require *lots of power*
- RF pre-amps are not normally designed to survive large in band signals
  - Which is why they are *useless* and *get turned off* in a contest
  - First mixer can only handle so much power out of RF preamp anyway
  - Superhet performance measured with *RF Preamp off* for a reason
DC Receiver Detector/AF Preamps

- Detector has \( \sim 0.9 \text{ db} \) of conversion loss rather than the typical high performance superhet 6 to 8 db mixer loss
  - Thus, RF preamp not needed to overcome first mixer loss
  - Allows receiver to have both high sensitivity & large signal performance
- AF Pre-amp is low Z in, high Z out, voltage amplifier
  - Voltage amplification takes less power than power amplification
- Detector/AF preamp rolls off relatively quickly
  - 16 db down at 5 KHz, 27 db at 10 KHz, 39 db at 20 KHz
Superhet “Brick Wall” Filters

- RF preamps and IF amps must have power limits because of crystal filter limitations

- Crystals used in xtal filters typically **10 mW**
  - ~1.4v RF limit, blocking limit of ~140 db BDR

- Crystal power limitations may contribute to close in IP3 problems

- **FT243 crystals might make superior filters**
  - Old FT243 crystals handle much higher power levels
DC Receiver “Brick Wall” Filters

• NC2030 8 pole low pass filter
• High voltage, very high dynamic range “brick wall” RC filters are easily constructed
  – Caps typically 50v
  – 1/2w resistors common
  – Op amps typically +/- 18v (36v)

• R/C filters: Lots of Rs and Cs!
• With a 3v receiver chain, NC2030 has ~13 db better IP3DR and similar BDR to the best available rigs
  – And this is at full sensitivity, not “RF Pre-amp off”!
Superhets can be simple

However, this is not a high performance superhet
DC Receivers can be simple also

“49er” Receiver Schematics

RF Preamp & Detector (NE602)

“Brick Wall” L/C filter (no AF preamp)

However, this is not a high performance DC Rcvr
A High Performance Phasing DC Receiver (NC2030) has a Price

**Lots of parts, with many Rs and Cs!**
- ~280 out of 360 total parts are Rs and Cs

- **175 Capacitors**
- **108 Resistors**
- 25 Inductors
- 19 ICs
  - 5 op amps, 5 LDO voltage regulators, 5 digital ICs, 2 uPs, 1 SCAF, and 1 switching regulator

- 17 Transistors
- 17 diodes
- 2 crystals

⇒ *High performance DC Receiver (NC2030) is more complex than a typical superhet*
  - *But higher performance and less power!*
 Broadband RX Diplexer

90 Degree Phase Delay Network

Quadrature (Q) Leg

In Phase (I) Leg

Guadrature Detector

Detector Preamps

Detectors and Phase Delay Network

1% Tolerance resistors: 100, 1k, 1.5k, 3.3k

Mem (NDC)

Keyer Speed

Keyer

Amplifier

Counter Audio (1/2)

Sidetone Level

Butterworth 9 Pole 800 Hz LPF

Tchebycheff 3 Pole 400 Hz Hi Pass

Variable SCAF Lowpass Filter

Audio Amp

Audio Limiter & Audio Mute

Headphone Amplifier (+0 db)

Norcal 2030 - Image Rejection 20 or 30M XCVR
Page # 1 Rx Strip LSB 14.0-14.070 or 10.1-10.150 Mhz

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Quadrature Detector

- Clocks route RF input to 1 of four Detector Caps at a 4x rate
- Each det. cap. averages ¼ cycle of RF – **Audio**!
- Four blade ceiling fan w/ strobe light analogy

**RF Input**
- 50 ohm
- 0-3v max

**Audio Outputs**
- 270° Audio out
- 90° Audio out
- 180° Audio out
- 0° Audio out

**Notes**
- One 50 ohm input, **Four** 200 ohm outputs
- No power gain
- Output ~0.9x Input due to integration on detector caps
- ~0.9 db loss
- Diode mixer: 6 db of conversion loss typical

**Diagram**
Quadrature Detector Outputs

- Note that 0º & 180º and 90º & 270º outputs are mirror images of each other.
- These pairs (such as 0º & 180º) are summed differentially via + & - inputs of op-amps
NC2030 5 KHz Blocking Calculations

- The simple RC roll off of the Detector and AF preamp is somewhat gradual, but 16 db of attenuation greatly helps BDR (and IP3DR also)

- AF Preamp has 66x of voltage gain (36 db)
- 16 db roll off at 5 KHz leaves 20 db of gain (10x)
- With 3v pk-pk max audio output, RF input blocks at 0.3v (-6 dbm) 5 KHz away
- Using -135 dbm sensitivity, BDR = 135 – 6 = 129 db
- Actual measured result 128.5 db BDR at 5 KHz
- Need to switch to each of four outputs every RF cycle, ¼ cycle dwell time on each detector output
- Two phase clock used to get four output states
Detector Clock Drive Circuit A

- **4x frequency source** used with digital dividers
- Advantage: Accurate clocks, *excellent opposite sideband rejection* over a very wide range
- Disadvantage: Dividers are a bit *power hungry*
Clock Drive Circuit B (NC2030)

- 1x frequency source used with L/C delay section
- Advantage: *Uses much less power* than dividers
- Disadvantage: Bandwidth limited, *USB rejection good over a limited range* (i.e., CW portion of band)
I – Q USB and LSB Outputs

- I (0°, 180°) and Q (90°, 270°) are 90 degrees apart
- USB/LSB depends on which leads the other

**USB I,Q**

**LSB I,Q**
90º Shift Phasing Network

- Two stage R/C phase shift network
- Both sides cause phase shift
  - One side starts first
  - 2\textsuperscript{nd} trails 1\textsuperscript{st} by 90º
- Limited sideband rejection range
- Rejection range optimized for CW bandwidth (500 Hz)
Phasing – How to Get 90° Shift

- One side starts falling in phase after the other
- *The late side is adjusted to be exactly 90° late*
- The 90° difference is good for a *limited range*
USB After 90° Phase Shift

After phase shifting, I & Q opposites of each other
Phasing outputs sum to zero – USB suppressed

- After phase shifting, I & Q opposites of each other
- Phasing outputs sum to zero – **USB suppressed**
- USB rejection **varies** across audio bandpass

- Smallest USB rejection at 150 & 650 Hz, ~ **55 db** down

- Filtering improves high & low frequency rejection

- Rejection shown is best case
  - LO clock uses L/C phasing
  - *Causes USB rejection to vary across band*
  
  > **45 db** across the band typical
- After phase shifting, I & Q are in phase
- Phasing outputs sum to 2x – LSB enhanced
LSB Audio Response Plot
SCAF LPF not included

- 6db at 350 & 800 Hz; 60 db at 50 Hz & 1.6 KHz
- Does not include the additional 40 db of variable SCAF LPF attenuation
- Main RC filter designed for low audio ringing
LSB Audio Response Plot

*Actual Band Noise – 30m*

- High side audio roll off is very step
- SCAF cleans up high frequency roll off even when “wide open”
- SCAF very good at removing a high side interferer when needed
- Noise below 100 Hz is a sound card issue
DC Receiver Pwr Consumption

• Quadrature detector *voltage* driven not *power* driven as required by diode mixers.
  – 74CBTLV3253 is a dual 4:1 analog bus switch

• First low noise audio preamplifier outputs are *voltage* outputs, not *power*, as needed by superhets

• *3v* receiver powered by a 3v & 5v switching supply, giving a *3x power savings* over simple linear regulation from 12v
DC Receiver Pwr Consumption

- VFO and VXO; 3 ma
- LO mixer; 1.6 ma
- LO filter amp; 9.5 ma
- LO squaring & detector driver (74AHC00); 0.8 ma
- Quadrature detector (“Tayloe Mixer”); 4.4 ma
- First audio LNA & phase shift network; 7.8 ma
- High and low pass RC filters and headphone drivers; 2 ma
- SCAF variable audio low pass filter; 1 ma

=> Roughly 30 ma total receiver drain at 3v supply
   - 14 ma for the LO subsystem, 16 ma for the receiver line up

=> 11 ma at 12v into the 3v & 5v switching supply
Conclusions

DC receivers have a performance advantage over superhets because:

1. **DC quadrature det has lower loss (1 vs. 6 db)**
   - DC does not need an RF amp for high sensitivity

2. **DC detector has a limited ~1.5 KHz bandwidth**
   - The superhet mixer can be 100’s of MHz wide

3. **DC AF amp also has ~1.5 KHz bandwidth**
   - The superhet has a wide bandwidth IF amp (>1 MHz?)

4. **DC receiver uses R/C active filters, not crystals**
   - Superhet good to ~2v pk-pk because of its crystal filter
   - DC filter is good to 36v pk-pk signal
   - DC can have superior large signal capabilities (20+ db higher than current 3v NC2030)