A COMPETITION-GRADE NDB RECEIVER

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Over the years I've used a wide variety of NDB receiving apparatus. There were European car radios, regens, all manner of military, maritime, aviation, commercial, consumer, hobby and ham radio receivers, converters, direction finders, selective voltmeters, even an R-27/ARC-5; so many receivers I can't remember them all. Not one was completely satisfactory, each suffering from one or more of the usual problems—poor selectivity, poor sensitivity, frequency drift, screeching sidetones, difficulty in jumping from frequency to frequency, AC operated and therefore not portable, poor tuning rate, wrong sideband in CW mode, AGC and so on. Consequently, I was always dreaming about building a receiver optimized for NDB DXing.

A New Receiver

During listening sessions as I battled these various handicaps, my mind invariably wandered to the subject of dream receivers, and over a period of several years I sketched out countless paper designs. I wanted good frequency agility, something that tuned in 1 kHz steps to make band scans less tedious. In addition I wanted my dream receiver to have 1 Hz tuning steps so I wouldn't have to use an audio filter for fine tuning; more of a one-knob approach. Along with this I wanted crystal-quality stability.

The other big deficiency I wanted to correct was IF bandwidth. My narrowest receiver IF was only 100 Hz, necessitating the use of an audio filter. Not that audio filters are bad, but such a wide IF allows carriers to get into the second detector.

NCO Tuning

Finally the enabling technology appeared—the author of a construction article in a ham magazine was offering kits for an NCO (numerically controlled oscillator), custom programmed for the frequency coverage of my choice. I immediately ordered one cut for 2.0 MHz to 2.5 MHz. This placed the IF at 2 MHz, high enough to be out of the AM broadcast band yet low enough to get good filtering performance with crystals.

The NCO had selectable tuning steps and was driven by a 50 MHz clock oscillator, thereby achieving my tuning goals: frequency agility and crystal-like stability.

Initial Construction

In the development phase I began piecing together the receiver, first driving an MC1496 Gilbert multiplier-type mixer with the NCO, followed by a stage of filtering and fed into a ham receiver serving as a fixed IF and second detector. It sounded good, but it seemed a little deaf. I dropped the '1496 in favor of a simple diode ring mixer which provided a better noise figure, and the receiver livened up.

After I was satisfied with the front end, I built up the entire IF and second detector and finished it off with an LM386 audio amplifier.

The various subsections of the receiver were attached to a piece of cardboard with clothespins and used for the latter half of the 2003-2004 NDB season with great success. I even heard David Curry's Burbank, CA beacon PLI at sunrise from the parking lot of the Livermore, CA flea market, a distance of some 300 miles, using an active whip on the bumper of my car.

The Circuit

The circuit shown in the schematic is exactly as built. It comprises the NCO, a mixer, a 2 MHz IF amplifier with distributed filtering, crystal-controlled BFO and LM386 audio output stage. The NCO includes an LCD display and rotary encoder for input/output. It also includes an output amplifier which drives the mixer directly.

Mixer

The input mixer is homebrew. You could use a Mini-Circuits mixer, but they are easy to build from scratch. I dug deep in my junk box and pulled out an 8-diode ring given to me long ago by Brooke Clarke, LAH. This ring was mounted on a piece of perf board and had been used in a variety of experiments over the years. I had been very careful with it, so it was still viable. I wound up two trifilar transformers with junk box ferrite toroids to complete the mixer. (The schematic shows a homebrew mixer you can build.)

Although the NCO board has a buffer amplifier, the ring's recommended +20 dBm LO drive was a bit of a stretch. I found that the mixer's performance (intermods and insertion loss) was not compromised by using less drive. I put a 47 ohm resistor in series with the NCO output to provide termination for the mixer. The output of the mixer is terminated with a 51 ohm resistor. Thus, the mixer is properly terminated at all frequencies except for a narrow region at 2 MHz.

The IF Amplifier

A distributed filtering technique is used in the 2 MHz IF, resulting in an outstanding bandwidth of less than 20 Hz after passing through 5 crystals. There is no need to sort, characterize or match crystals as is necessary in conventional filter designs; each crystal is independently and non-interactively tuned. The crystals are specified for parallel-mode operation on 2 MHz with 20 pF correlation capacitance.

To simplify the design I used common-base amplifiers and low cost, readily-available AM broadcast receiver oscillator coils as IF coupling transformers. The coils are self-resonant just above 2 MHz. In addition to the transistor collector capacitance, they need only 10-20 pF padding to center the tuning range on 2 MHz. This figure may vary +/- 10 pF for other broadcast LO coils. Tuning the coils varies the amplifier gain but has little to do with IF bandwidth.

You'll notice three different values for the IF transformer capacitors. The third stage is 12 pF because my junk box yielded only two 10 pF capacitors. The fourth stage needed more capacitance because the transistor's collector capacitance is no longer a factor. In retrospect, 15 pF would probably have sufficed for all four stages.

The IF is capable of more gain than needed; the last stage is set up for a low gain. You can configure it for high gain like the other three stages, but much care in construction is needed to maintain stability.

The coil connections flip-flop from stage to stage for physical reasons in the way I built it, not electrical. You can connect the collectors of the first 3 stages to pin 1 or pin 3 and take the output from 4 or 6—it doesn't matter. Again, the fourth stage is set up for low gain by driving pin 2 of the transformer primary.

I had some trouble with big signals clipping in the last (4^{th}) IF stage, so I moved the base bias down to allow for more collector swing. My choice of emitter resistor in stage 4 is a little light on current; the 2.7 kohm resistor should be about 1.5 kohms. Each stage should be biased to a value of 1-2 mA.

Second Detector

The product detector was slapped together last and in a hurry. I used a single-balanced mixer driven by a crystal-controlled BFO, a good topology but a sub-optimal implementation. The IF strip can probably overdrive the bottom transistor. This will be the subject of future investigation and rework.

The output transformer is a surplus unit whose specifications are 25 kohm CT: 600 ohm CT. Mouser's 42TM017 is identical, impedance-wise. The high impedance primary is coarsely resonated with a 200 nF capacitor and a couple of RF-bypass capacitors. The capacitance needed to achieve resonance depends on the primary inductance and the desired frequency. The exact value is not especially critical but it does eliminate any broadband noise.

BFO

The up-converting topology inverts the sidebands of the incoming signal. Thus the BFO frequency is situated just above 2 MHz in order to produce upper sideband detection. To assist in moving the BFO off 2 MHz I used a series-resonant crystal and some added tuning.

Audio Stage

My whole audio amplifier was a small pre-assembled circuit board—a flea market purchase and a pull possibly from a child's phonograph or other consumer product. It even included two large power supply bypass electrolytic capacitors and a volume control with bushing and hardware.

I set up the LM386 for a gain of 20. This gives the best performance with tolerable noise and low distortion. When I use sensitive headphones I find the output noise is objectionable-- in this case the output should be padded with 100 ohms or so to reduce the zero-signal output level. Bypass this resistor when a loudspeaker is used.

If you like loud audio in 8 ohm speakers, you may want to remove the 10 ohm resistor in the LM386's supply line.

Local Oscillator

For more information on the NCO I used, contact:

Jim Hagerty
64 Nonquit Lane
Tiverton, RI 02878
WA1FFL@arrl.net

I ordered a frequency range of 2.000 MHz to 2.500 MHz from Jim Hagerty. He programs the frequency range in a control processor that is included on the NCO board. Also on-board are the NCO chip, a 5V regulator, clock oscillator, some glue logic, and the output buffer amplifier. Off-board are an optical shaft encoder and LCD display panel.

As designed, the NCO runs on 12V at approximately 100 mA, reads a rotary optical encoder, displays the 6-digit frequency on a 2 x 16 LCD panel, and drives a 50 ohm load. A single switch closure (available on some rotary encoders) steps through the tuning rate selections (100 kHz, 10 kHz, 1 kHz, 100 Hz, 10 Hz and 1 Hz). I suggest using a cheap keyboard pushbutton for this purpose to save wear and tear on the encoder's switch.

The NCO has an enable input—this begs use as a mute or synchronous noise blanker. I haven't experimented with this feature so I can't comment on pops or other side effects.

NCO Problems

Before jumping to conclusions about the NCO, it should be recognized that no digital synthesis technique is perfect, and the aforementioned NCO is no exception. It is loaded with birdies and weird places where the noise floor rises and falls away.

For example, a birdie is heard when tuned to 70 kHz. This means the NCO is putting out 2.070 MHz as the primary LO signal, but a weaker output on 2.000 MHz also appears and enters the IF, covering up weak signals.

Fortunately, most of the birdies occur on round numbers, like 70 kHz or 400 kHz. Few are significantly loud, and they tune away rapidly so that in almost every case, they're gone with only a few Hertz of offset. Thus they aren't a significant issue when DXing NDBs.

Eliminating Birdies

I haven't done anything to cut down the birdies beyond the natural rejection offered by the balanced mixer-- they just haven't been an impediment to NDB DXing. If you build this receiver and want to make improvements, there are several ways to reduce the spurious content of the NCO.

One way is filtering, but this is hard to do when you're trying to separate 2 MHz from, say, 2.07 MHz. Another method is to notch 2 MHz out of the NCO output, using a crystal. Unfortunately the conflicting requirements of low impedance drive, high level output and medium-wide tuning range make this difficult to implement in practice. It may be possible to apply this technique within the NCO circuitry, something I haven't investigated.

My mixer uses well in excess of +10 dBm LO drive; using a smaller +7 dBm single-level mixer would produce a corresponding suppression of the birdies.

Of course for demanding applications the NCO could be replaced with a PTO; the GRC-19/T-195 PTO pulls (available from Fair Radio) would make an excellent LO for this receiver, but then you'd lose the frequency agility and the PTO's tuning rate is rather high. A 10 dB preamp could be added in front of the mixer. In principle this cuts down the effect of LO birdies by a factor of 10 dB, eliminating a large number from contention.

A perfectly-balanced mixer completely rejects the LO. Parasitics and mismatches in the diodes, transformers and circuit layout reduce the ideal performance to the 30 dB range. Trims could be added to null some of the non-idealities.

One last idea is to filter the NCO output with a phase locked loop. A low-noise, L/C-based VFO could be used as the LO, the NCO serving as a reference oscillator in a 1:1 PLL with no frequency dividers or other noise-generating digital circuits, save one phase comparator. I've never seen this done but it seems like a viable, if complicated, birdie-eliminating solution.

Alignment

The heart of the receiver is really the 50 MHz reference oscillator in the NCO. This establishes the tuning slope and accuracy of the NCO output frequency. An inaccuracy of 250 Hz in the 50 MHz time base translates to an error of 10 Hz when tuned to 0 Hz. Although this error is easily trimmed out by tuning the IF to, for example, 2.00001 MHz, the step size will err similarly, leading to an accumulated offset of 2.5 Hz at 500 kHz. To avoid these problems, the 50 MHz clock should be trimmed to frequency, so the alignment procedure starts here.

Lacking an electronically-tunable 50 MHz clock unit, I amassed several 50 MHz clock oscillators from various sources and simply selected the best of the group. Tune the NCO to an indicated frequency of 500.000 kHz (2.5 MHz actual output) and zero beat on any WWV frequency, or measure with an accurate frequency counter.

Next, the NCO should be disconnected from the mixer and replaced with a 51 ohm resistor. Similarly terminate the RF input port. Tune the NCO to an indicated 000.000 kHz, and couple a tiny amount of NCO output into the mixer (proximity should work) until a corresponding tone is heard in the audio output. The NCO serves as a precision 2 MHz signal source to which the IF is aligned.

Peak each IF crystal trimmer capacitor, then peak the IF transformers. Make a final pass through the trimmer caps, and alignment is done. As the IF is tuned up, gradually reduce the NCO coupling to maintain a weak signal. Use an oscilloscope or AC voltmeter to facilitate peaking as desired.

Last, tune the BFO for the desired side tone pitch. There should be no problem adjusting the offset to as little as 100 Hz as long as the BFO circuit is kept clear of the first one or two IF stages.

In Use

The variable-rate tuning is nothing less than a revelation. I can set the frequency to an offset of, say, 25 Hz, then tune in 1 kHz steps up and down the band at a fast pace, without the need for tedious fine tuning in an effort to re-center the beacon idents. Or better yet, I can offset the tuning by 400 Hz and rapidly scan up and down the band for 400 Hz Canadians, skipping carriers and 1 kHz NDB idents.

There are, of course, beacons with offsets of 10 Hz or 40 Hz, or other non-1020Hz values, and to find these I must fine-tune appropriately.

The sub-20 Hz IF bandwidth makes listening comfortable and stress-free. I can move easily and confidently to any target frequency with the adjustment of a single knob. Carriers cease to be a factor, even on the lower sideband. At night I occasionally tune to the frequency of a target NDB and turn the volume down to a low murmur; if the signal fades up in the middle of the night, I'll sometimes awaken from my deep slumber to hear it, then the catch is logged in the morning.

Because the front end is wide open, I use preselection under certain circumstances, such as when I'm listening with my random-wire antenna. No preselection is needed when I'm using a tuned loop or tuned active whip—preselection is inherent in their design. If I'm using my broadband wire coupler I put a 500 kHz low pass filter between it and the receiver.

One item I do keep in front of the receiver is a rotary step attenuator with a 0-60 dB range. It was a $1.00 flea market purchase, actually designed for 75 ohms. There are three stages—10, 20, 30 dB, driven by cams on a common shaft with a knob that stops at 40 dB. Much to my delight I found that by removing the stop in the shaft mechanism the knob continued to rotate and the cams continued the sequence to cover 50 and 60 dB. I kick in 20 or 30 dB of attenuation to prevent overload of the IF on loud signals like 60 kHz WWVB.

Other Comments:

1) There are no receiver kits or parts available from me.
2) I cannot provide technical assistance to help you get your project running if you encounter trouble. If you have never before built a receiver, don't start with this one.
3) As has always been my preference, there is no AGC. I like using a step attenuator in front of the mixer for an RF gain control. You can try adding AGC, or perhaps an "RF" gain control as part of the first IF stage, if you're partial to AGC.
4) The IF bandwidth is less than 20 Hz wide. It is designed for serious NDB DXing and is likely to be irritating, if not useless, for any other purpose.
5) The IF has quite a bit of gain, and will readily oscillate if you're not careful with layout. I built mine on a strip about 8 inches long with the mixer at one end and the product detector at the other end. Note that the last stage doesn't really have much gain; this stage is present just for the sake of getting one more crystal in-line. You could configure it for gain and then resistively load each stage to bring the gain back to an acceptable level.
6) The IF amplifier transistors are not low-noise types. Noise figure is broadly optimized in the 1-2 mA range according to the manufacturer's curves. If you have access to better devices, start by replacing the first IF transistor. Even so, using 2N3904's didn't stop me from getting –137 dBM MDS. Noted LF DXer Steve Ratzlaff built one, and achieved an impressive –141 dBm MDS.
7) If you're really into filters, you can do some interesting things with the IF. First, you can stagger-tune each stage to synthesize various alignments. Second, you can experiment with varying the gains in each stage to achieve more complex alignments. As for me, I just synchronously tuned them.
8) It is prudent and smart to add a diode in series with the 12V supply, thereby guarding against mistakes with reverse polarity. The NCO board already has a diode of its own, where a mistake could be very costly.
9) The receiver can be configured for other IF frequencies to suit readily available crystals. The NCO frequency range must be ordered accordingly. The IF transformers I used won't go any higher in frequency, but they would easily cover the popular crystal frequencies of 1 MHz and 1.843 MHz with padding. Still, placing the IF below 1.7 MHz is foolish as you may be plagued with break-through from the AM broadcast band stations.

   For higher frequencies, the IF transformers must be replaced. They could be hand-wound or commercially-available units. Common frequencies are 4.5 MHz (TV sound IF) and 10.7 MHz (FM IF). These are easily padded and tuned to cover from 2 MHz, where AM radio oscillator coils run out of range, to 11.059 MHz, a popular baud rate generator crystal frequency. Note the higher the crystal frequency, the wider the final bandwidth.

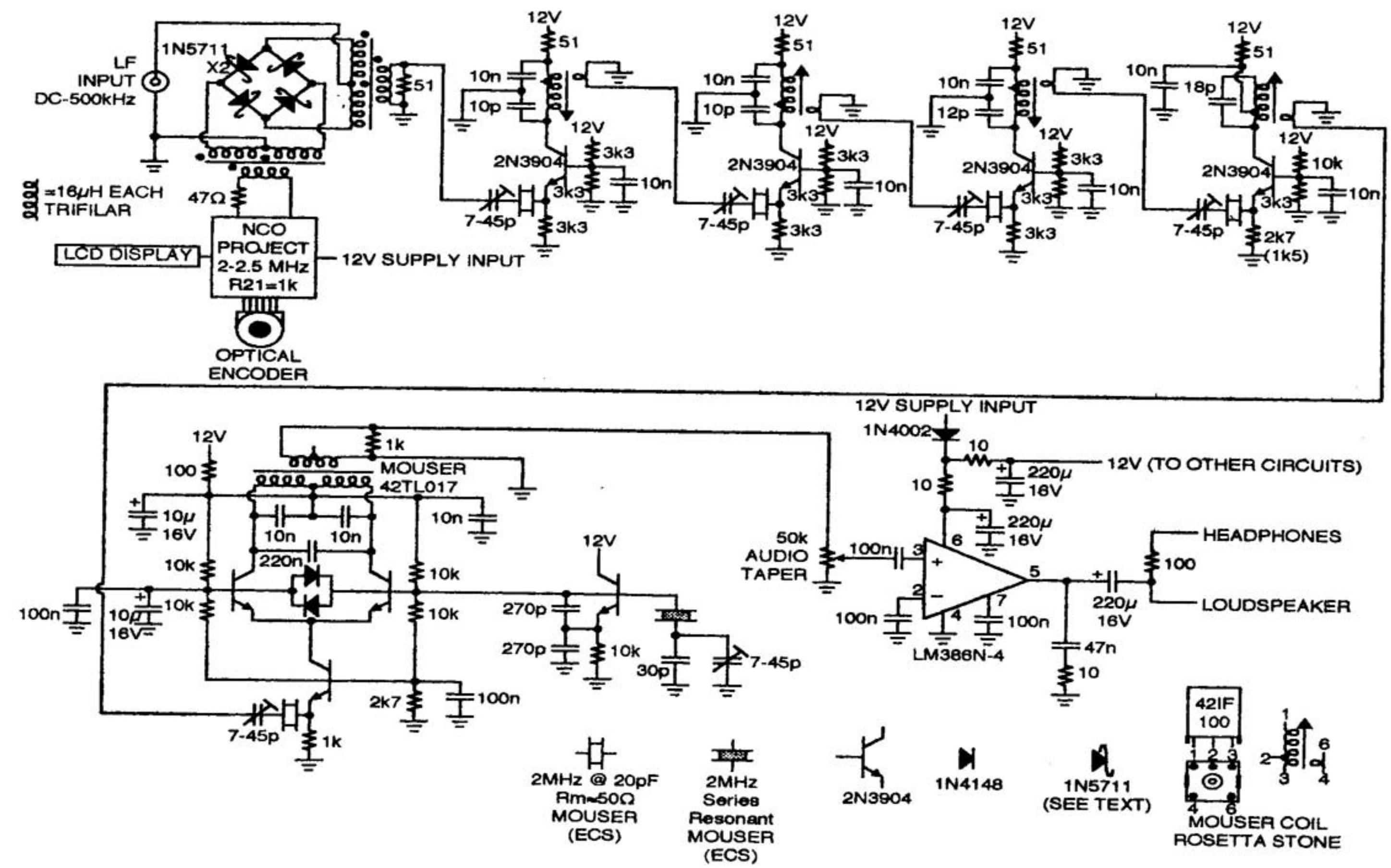
10) As a sidelight, while experimenting with this receiver in the breadboard stage, I caught UNID NOJ on approximately 213.416 kHz, running an uncommon DA3ID format, weak and just in the noise at sunrise. I heard it two mornings in a row, then nothing. I completed the receiver mid-season and began using it regularly.
In April I heard NOJ again, much stronger than before, yet something about the dashes didn't sound right; they seemed weaker than the ident and slightly off-frequency.

What gave it away was the rapid fading I noticed. I went downstairs and did some quick math on my pocket calculator. I fired up a shortwave radio and tuned to 8640.25 kHz, finding what I predicted—Coast Guard shore station NOJ. The third harmonic of my LO was converting 8640.25 kHz to 2 MHz. Returning upstairs, I verified my discovery by noting that NOJ tuned backwards, compared to legitimate longwave signals.

It seemed strange that NOJ could get through a pre selector which so effectively knocked out powerful AMBC stations at a much lower frequency. Disconnecting the coax feed to my pre selector, NOJ disappeared, reappearing with only the coax shield connected. Clearly, I had a giant ground loop antenna, completed by the ground on my power supply. A jumper between coax ground and power supply ground completely suppressed this effect and proved that lack of shielding in the IF was not at fault.

Conclusion

To summarize, this receiver offers new conveniences in tuning and a surprising level of IF filtering performance, without the need for expensive mechanical or crystal filters and with complete freedom from interactive alignment adjustments. Perfect 1 Hz resolution is realized with one-knob tuning and zero drift, coupled with a sub-20 Hz receiver bandwidth optimized for NDB reception. Further bandwidth reduction to 5 Hz or less is possible with the addition of an audio filter, and is supported by the narrow IF and low BFO offset.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X2
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NCO
PROJECT
2-2.5 MHz
R21=1k
12V SUPPLY INPUT
OPTICAL
ENCODER
12V
10n
10p
12p
18p
2N3904
3k3
10k
2k7
(1k5)
7-45p
12V SUPPLY INPUT
1N4002
12V (TO OTHER CIRCUITS)
220μ
16V
MOUSER
42TL017
1k
100
10μ
16V
220n
270p
30p
100n
50k
AUDIO
TAPER
LM386N-4
47n
HEADPHONES
LOUDSPEAKER
2MHz @ 20pF
Rm≈50Ω
MOUSER
(ECS)
2MHz
Series
Resonant
MOUSER
(ECS)
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(SEE TEXT)
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MOUSER COIL
ROSETTA STONE