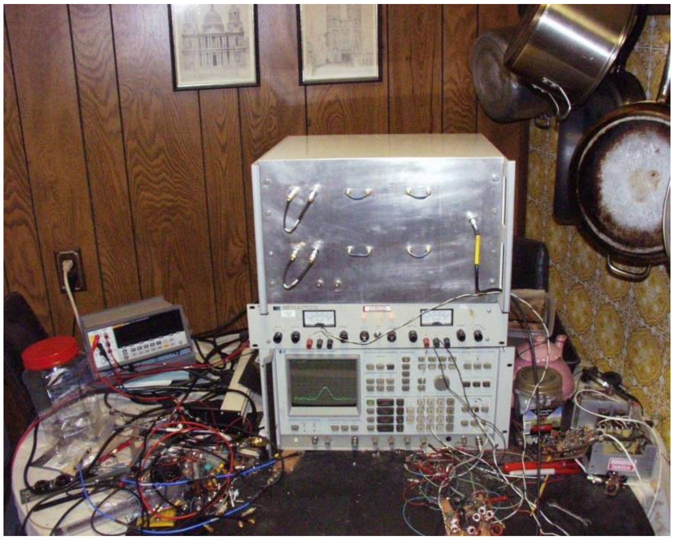


IMD and Phase Noise Test Instrument

Trials and tribulations of building a state-of-the-art Intermodulation Distortion (IMD) test instrument.

By Doug Ronald, W6DSR

I have always had an interest in building high-performance receivers and transmitters for HF. An expected performance metric for receivers is dynamic range. The receiver should not add noise of its own for weak signal reception, and at the same time, remain linear with a high amplitude signal in the receive information bandwidth. A transmit linear amplifier needs to be linear so that in-channel signals are free of distortion, and out-of-channel signals are not radiated.

All devices in the signal chain will become nonlinear at some power level, even innocent passive components as I will relate later in my quest to construct a decent IMD test instrument. The described instrument allows me to characterize a Device Under Test (DUT), be it active or passive, to a level of ~63 dBm IP3. The 63 dBm level is dictated by my spectrum analyzer (SA), which is an HP-3585A, and not the tester itself. In order to measure the testers IMD without a DUT present with my present SA, I would need to null-out the primary carriers so the SA sees only the sidebands. I see no need to characterize the tester further as my testing requirements are limited to IP3s in the low 60's.

The recognized parameter for characterizing linearity in a system is intercept point (IP). The third-order products are usually most significant because sidebands from those products are most likely to appear in the information bandwidth.

Measurement techniques

The DUT is presented with two identical amplitude carriers, very near in frequency, and the output from the DUT is displayed on a SA. The distortion products due to the third-order response of the DUT appear at four frequencies with the following relationship: Given F1 and F2, two equal amplitude carriers, the third-order sidebands are at: 2F1 + F2, 2F1 – F2, 2F2 + F1, and 2F2 – F1. The SA will display the two carriers and the difference sidebands will be close by in frequency. See Figure 1 for a typical result.

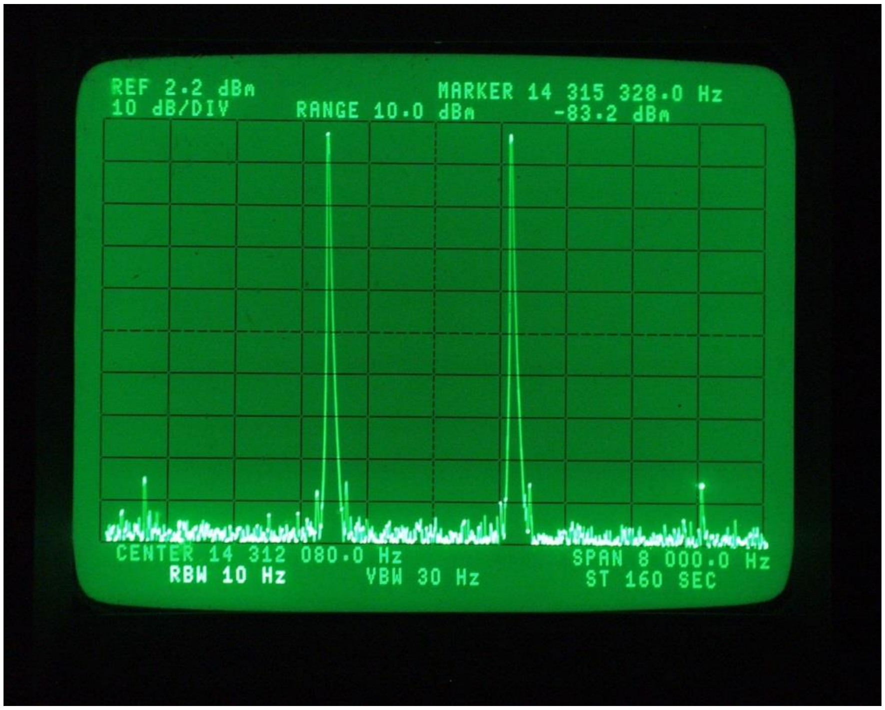
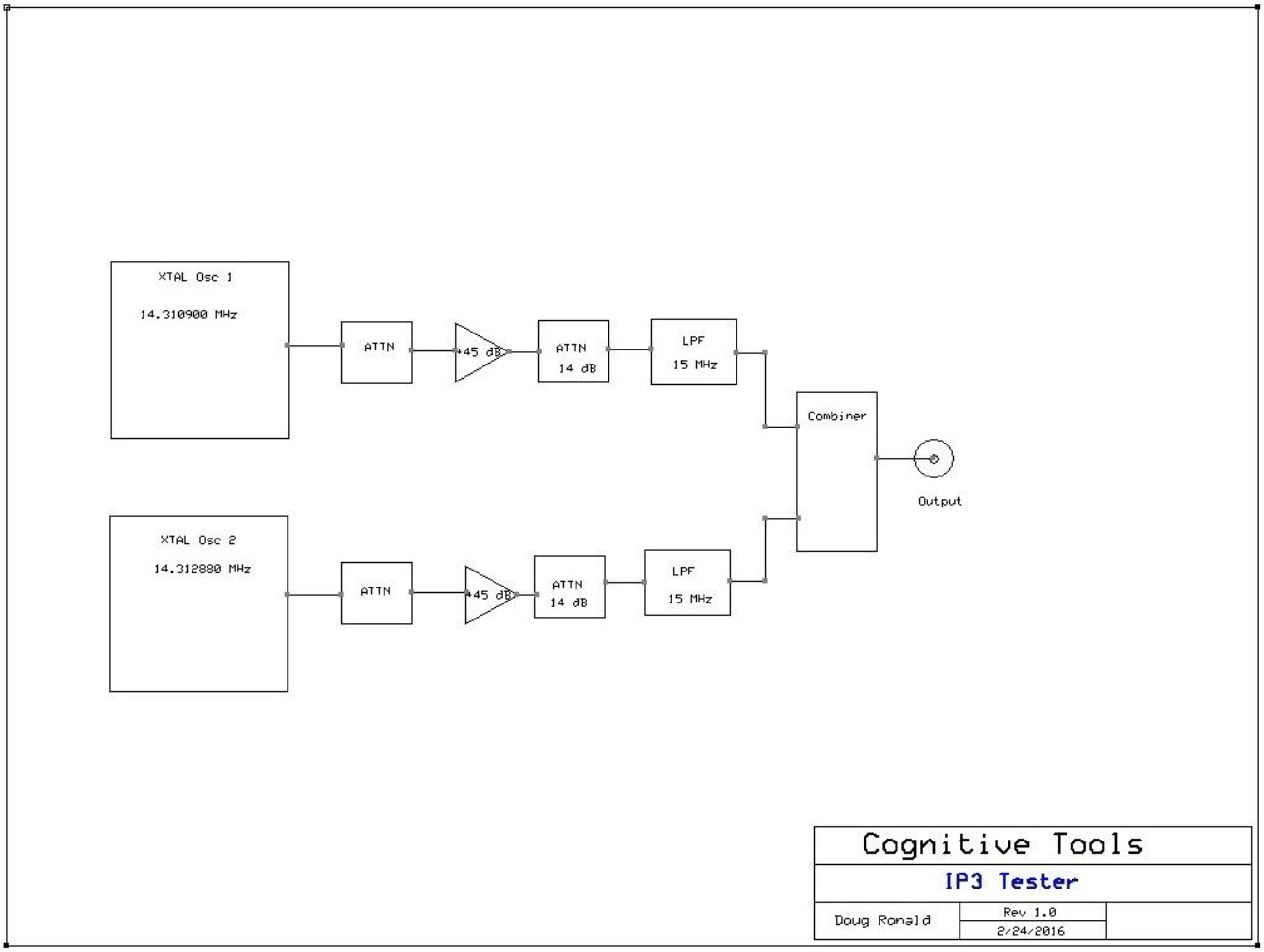


Figure 1: Typical IMD3 Spectrum – A low noise amplifier (LNA) under test. The carriers are 8.2 dBm and the upper sideband (marker) is -83.2 dBm for a calculated OIP3 of 53.9 dBm.

To calculate the IP3, measure one carrier's power, the weaker one if they are not identical, and call it Pc. Measure the power of one of the sidebands, call it Ps, then output intercept power third-order (OIP3) is: OIP3 = Pc + (Pc – Ps)/2. The input intercept point third-order (IIP3) is the OIP3 – Gdut, where Gdut is the DUT's gain. The OIP3 is simply a number used to assess the linearity of some component or subsystem. The device is not expected to actually output a power level represented by its OIP3. See reference 1 for an excellent, description of Third Order Intercept Measurements.

IMD tester block diagram



IMD tester component description

The sources are both crystal oscillators in the 20 meter band. I purchased from a local electronic junk store, ten 14.31818 MHz crystals, which are 4x the now obsolete NTSC television modulation scheme's color subcarrier frequency at 3.579545 MHz. Five were of one distinct type, and five of another, probably different manufacturers. One type had a plastic wrap coating them, the others did not. As expected, in the same Butler oscillator, the two different manufacturer's crystal's frequencies' clustered at different points. I found around a 2 kHz difference, which was great in that the two frequencies would lie within the normal information bandwidth of an HF communications receiver. The Butler circuit I cribbed was from John B. Stephensen's ATR-2000 Transceiver described in the Mar/Apr 2000 issue of QEX magazine. In his Appendix A, he describes the oscillator he used for phase noise measurements. I used the oscillator and filter portions from his schematic. I selected three crystals of each type, one for the oscillator, and the other two for the narrow-band filter following the oscillator. The crystals are pushed pretty hard in the oscillator in order to minimize the phase noise, and they drift around a bit with temperature. I leave the sources powered all the time to minimize the drift.

Following the oscillators is an attenuator and a narrow bandpass filter to minimize the phase noise and harmonics. The 3 dB points of the filter give it about a 1.5 kHz bandpass. The trimmer allows the center frequency to be tweaked a bit to match the oscillator's frequency. The final output level from the sources is around 0 dBm. I swept the crystals with a VNA to get matching devices, but discovered that this is unnecessary as any two at random would have produced good results.

The oscillator/filters are built into shielded modules made from die-cast aluminum boxes. An unregulated 24 VDC power supply is down-regulated in the module box with 7815 regulators, which do not need heat sinking.

The amplifiers are Mini-Circuits ZHL-5W-1A. These are expensive from Mini-Circuits; however there are some at a more reasonable price available on e-Bay. I also have several extras already mounted on heat sinks I will never use. They need to be on heat sinks and, even with reasonable size sinks, require a fan. They draw over 3 Amps at their supply voltage of 24 VDC. With 45 dB of gain, and 5 Watts output, they have tremendous reverse isolation, necessary to keep the two carriers from mixing in non-linear components, and ruining the overall IP3 of the tester. I follow the amplifiers with 14 dB, 5Watt attenuators made from lumped elements, and then a low-pass filter primarily to get rid of the second harmonic from the amplifiers.

The combiner easily handles 10 Watts with no sign of non-linearity, and the overall output from the combiner are the two carriers at a level of 20 dBm each. Of course this power level can be attenuated down for testing LNAs, mixers, and subsystems, or left at 20 dBm for passive components.

The power supply for the crystal sources is a simple 24 VDC, 250 mA linear supply from my junk box. As mentioned earlier, the unregulated 24 VDC is down-regulated to 15 VDC in the oscillator modules. The amplifiers each have their own 24 VDC linear supplies housed in a separate chassis because of problems encountered with magnetic coupling to the oscillators when I tried to house them in the main chassis enclosure. Naturally I used SMPSs for the initial bread-boarding of the tester, but couldn't no matter how hard I tried, get rid of the switching detritus in the sidebands of the oscillators, even with the supplies located remotely (several feet away). I have the same problem with the linear supply, but at least the sidebands are at 180 Hz, and not further out.

Construction details

All of the modules interface with the front panel via SMA connectors in a logical order from the sources on the left side, through to the combiner output on the far right side. This allows me to patch various configurations for phase noise measurements using the sources, or even using the 5 Watt, 5 to 500 MHz amplifiers as linears for lab activities. See Figures 13 and 14 for photos of the front panel and inside plumbing. Figure 15 is a shot of one of the sources, and Figure 16 shows the combiner module. I used BNCs on this module because they fit the pre-drilled holes on the surplus boxes. All the components are mounted in the "dead" position for fast, easy construction. Figure 17 shows the interior of the amplifier's power supply cabinet. I don't profess to construct pretty projects, but I expect them to at least produce good results. The power supplies use two ferro-resonant power transformers from surplus disk drives. These are fed to a bridge rectifier, and then on to a choke-input filter. This yields two supplies with semi-regulated voltage of about 30 VDC which I then send to a pair of series regulators composed of 2N3773 TO-3s on a heat sink. This gets me a pair of regulated +24 VDC supplies with 4 Amps capacity which are metered for current and voltage with a front-panel selector switch and appropriate meters. These two supplies then feed the amplifiers in the companion chassis.

Technical hurdles

Along the road to developing this instrument, many technical hurdles were thrown my way prompting me to have a skeptical attitude toward all intuitively trusted signal components.

First up was at the source's power supply. In each crystal oscillator module, I have a linear regulator bypassed on the input and output plus a low-pass inductor filter to the 2N2222 oscillator transistor itself. There is a feed-through capacitor in the wall of the module through which the unregulated 24 VDC flows. When I fired up the prototype in this configuration without a DUT, I had only 48 dBm IP3 for the tester! The culprit turned out to be a minute amount of signal from one oscillator leaking into its companion through what I had thought was a well bypassed supply line. There is enough non-linearity in the crystal bandpass filter to cause the IP3 sideband products to appear. The fix was two more sections of low-pass filter on the unregulated 24 VDC to each oscillator module. I placed these lumped components external to the oscillator enclosures.

After solving the oscillator coupling problem, I found the amplifiers had the same problem when I had a single 24 VDC regulated switching supply. Rather than try to isolate the amplifier's supplies, I created two separate 24 VDC regulated supplies for the amplifiers. This was about the time when I decided to dump the SMPS's anyway because of their insuppressible noise.

By now, the tester itself, without a DUT was in the 50+ dBm IP3 range, but I was expecting much better performance. The combiner I was initially using was a commercial Merrimac HF module. I found I had to reduce the input power level to 0 dBm in order to get a decent (50+ dBm) IP3 from it. I removed it and rolled my own combiner using FT-87A-43C toroids. Sure, these are huge, and the combiner starts to roll-off at 45 MHz, but they handle 20 dBm with no measurable IP3 with my setup. The trimmer in the circuit for the combiner is adjusted at 20 meters for the best isolation between the output ports. Connect a source (one of the oscillator modules works well) at one of the input ports, a 50 Ohm terminator to the combined output port, and a terminated receiver (a SA works) at the other input port. Adjust the trimmer for minimum signal on the SA. I achieved 36 dB of isolation at 14 MHz.

During testing I found problems with not fully torqued down SMA connectors. I found it necessary to torque them to spec in the low-level signal paths and, most importantly, after the amplifiers where the power level is in the 37 dBm range. I guess this is referred to as Passive Intermodulation Distortion (PIM) in the cell phone technology vernacular.

I was using an HP-8494B variable attenuator during testing. This expensive 0-11 dB attenuator has low IP3 on the 3, 4, and 8 dB settings. All other attenuation settings are okay. Perhaps there is some corrosion on a contact internally, or a bad resistor, but no amount of rotating the attenuator dial back-and-forth changed the unacceptable IP3. I now use only in-line SMA attenuators, properly torqued of course, during testing. Figure 5 shows the spectrum with the HP-8494B set at 2 dB attenuation. Figure 6 shows the same setup with the attenuator set at 3 dB attenuation. The calculated OIP3 of the attenuator at 3 dB attenuation is a miserable 51 dBm! I was only feeding about 13 dBm into the attenuator, so I was well below its power rating.

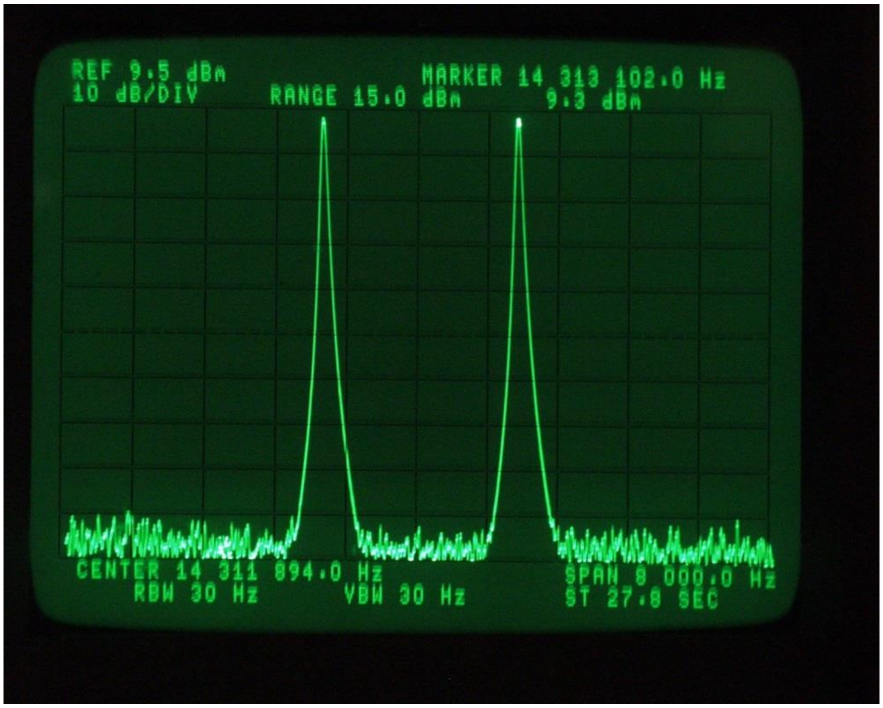


Figure 5: HP-8494B attenuator set at 2 dB attenuation – There are no discernable distortion sidebands.

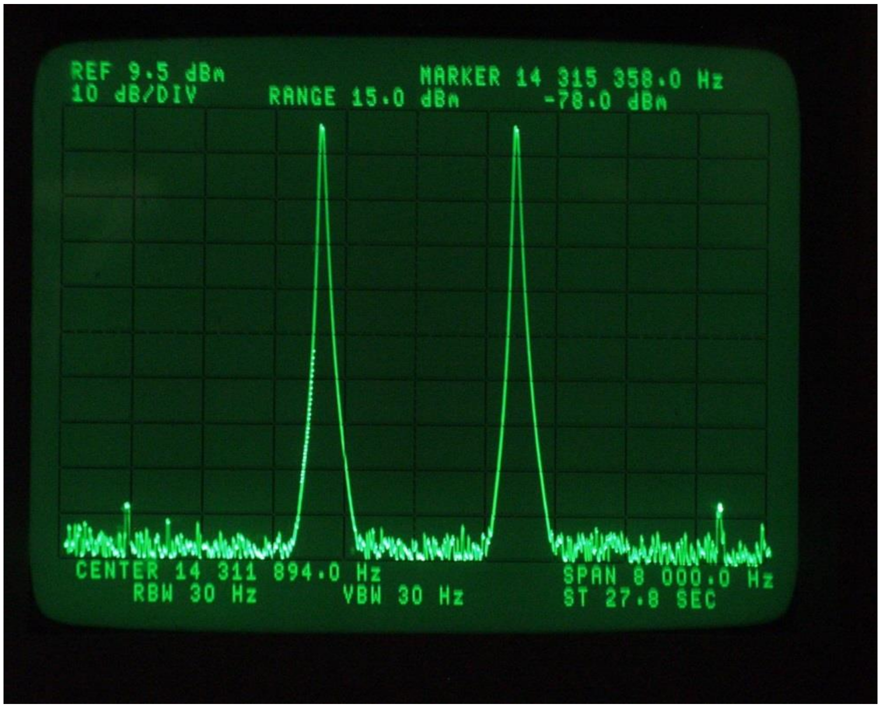


Figure 6: HP-8494B attenuator set at 3 dB attenuation – note the distortion sidebands!

This instrument was also intended to be used for phase noise measurements, and so the purity of the oscillators was important. By using a Butler oscillator, with lots of drive to the crystal, the phase noise is terrific; however, I have been plagued with 60 Hz related sidebands. The ripple on the power supply to the oscillators is undetectable on an oscilloscope; however the SA shows sidebands at 60 Hz about 87 dB down, sidebands at 80 Hz about 89 dB down and those at 180 Hz at 94 dB down. From the Fourier series of a square wave, it is easy to see how the third harmonic of the line frequency is created due to the bridge diodes conducting at the top of the sine wave. I was prepared for this effect to appear as ripple on the supply lines, but what I failed to appreciate initially, was the magnetic coupling from distant transformers, modulating the oscillators. My solution relies on the inverse square law – get the magnetics far away from the sensitive oscillators; however in the case of the fan, which cools the amplifiers, I would have had to run ducting from a remote fan to the cabinet to get the spatial isolation. Another solution I thought would be a DC fan, but the one I tried also generated sidebands due to the electronic commutation used in the motor. The solution was to keep the AC fan, but turn it off during phase noise measurements. The amplifier heat sinks can go about 15 minutes before they are too hot to touch, so I use that as a guide. The 60 Hz sidebands could probably be reduced with single-point grounding as I probably have some ground loops generating the offending sidebands. This would require too much effort in an electrical and mechanical redesign, so the sidebands are here to stay.

Figure 7 shows the higher frequency oscillator with the amplifiers' fan running, and Figure 8 without the fan running. The sweep is 500 Hz wide and the resolution bandwidth is 3 Hz to illustrate the close-in 60 Hz related sidebands.

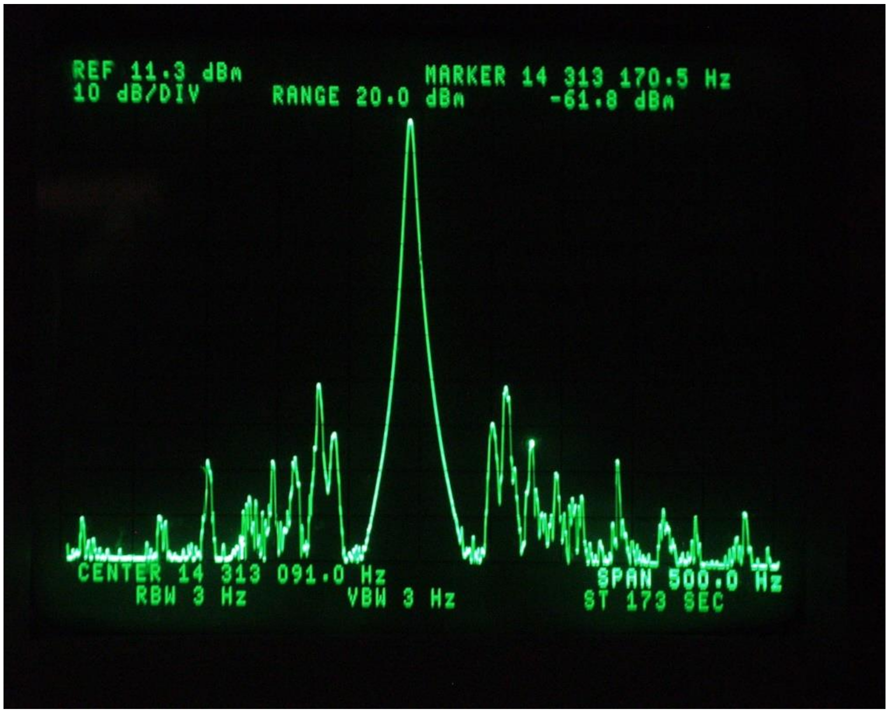


Figure 7: One oscillator with amplifier cooling fan operating.

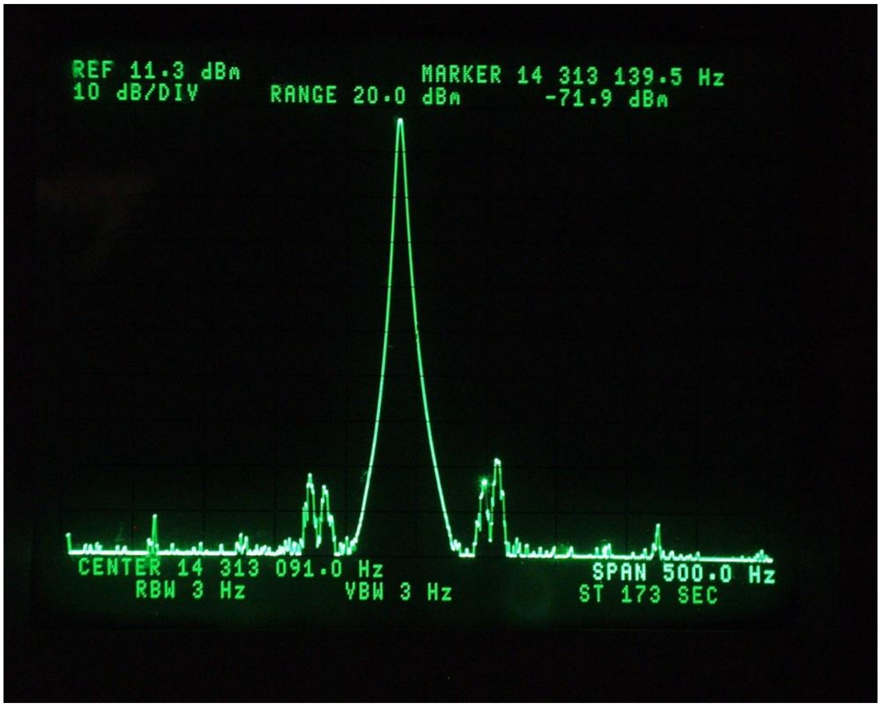


Figure 8: Same oscillator as Figure 7 with amplifier cooling fan off.

The added noise caused by the fan is caused by two phenomena. A lot of the 60 Hz, 120 Hz, and 180 Hz noise is due to magnetic coupling from the fan motor to the sensitive oscillator circuits. I know this from having the amplifiers' power supplies contained within the enclosure with the oscillators and amplifiers in the original configuration. The power transformer and input inductor were causing substantially more sidebands than the fan is now, and had to be moved to a separate enclosure.

The random wideband nature of the noise sidebands in the 120 Hz area is caused by microphonics. If I stall the fan, the noise sidebands are just the spikes at 60, 120, and 180 Hz with the wideband noise gone. Some of the noise appears to be windage induced microphonically.

The 60 Hz related sidebands with the fan off are due to magnetic coupling from the SA which is a couple rack chassis below the IMD tester. Moving the tester away from the bench solves this noise source.

I think in retrospect, I should have isolated the oscillators electrically, acoustically, magnetically, and pneumatically. Then I might have had my coherent noise sidebands 100 dB down. Three separate chassis for one piece of test equipment seemed a bit excessive, so it will stay as-is. This noise has no influence on the original IMD testing this unit was designed for.

Results

Figure 9 is a photo of the SA with no DUT connected. The carriers are at 11.3 dBm attenuated down from the nominal 20 dBm output of the IMD tester because the SA starts to go non-linear at higher input powers.

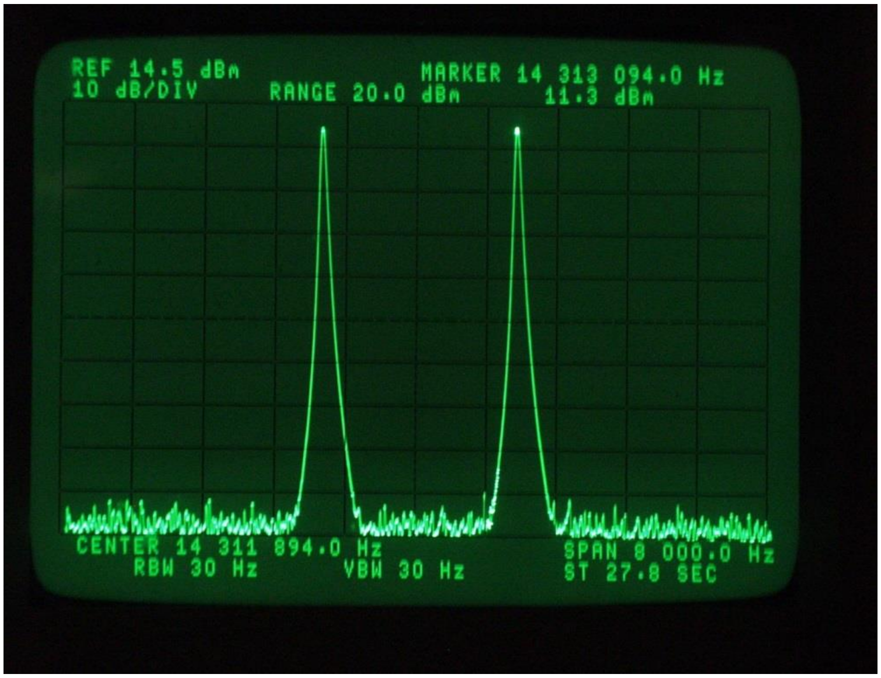


Figure 9: IMD Tester with no DUT.

Figure 10 is a photo of the SA with the two carriers present and the marker positioned where the upper third-order sideband would appear if it was above the noise level of the SA. One carrier is at 14.310,740 MHz, the other at 14.313,018 MHz, and the sideband at 14.315,298 MHz. There is a 6 dB attenuator between the tester and the SA to prevent the SA itself from generating significant IP3. The attenuator needs to be accounted for in the calculation of the DUTs IMP3. One carrier is at +14 dBm, and the sideband marker is reading -85.5 dBm (the noise level), so the calculated IP3 of the tester is in the high 60's dBm. Note that this number is the minimum the IP3 could be as the sideband is at the noise level, and there is no sign of any sideband even with a resolution bandwidth of 3 Hz. Without the 6 dB attenuator, the output of the DUT is 20 dBm, and the sideband could have been as high as -82 dBm.

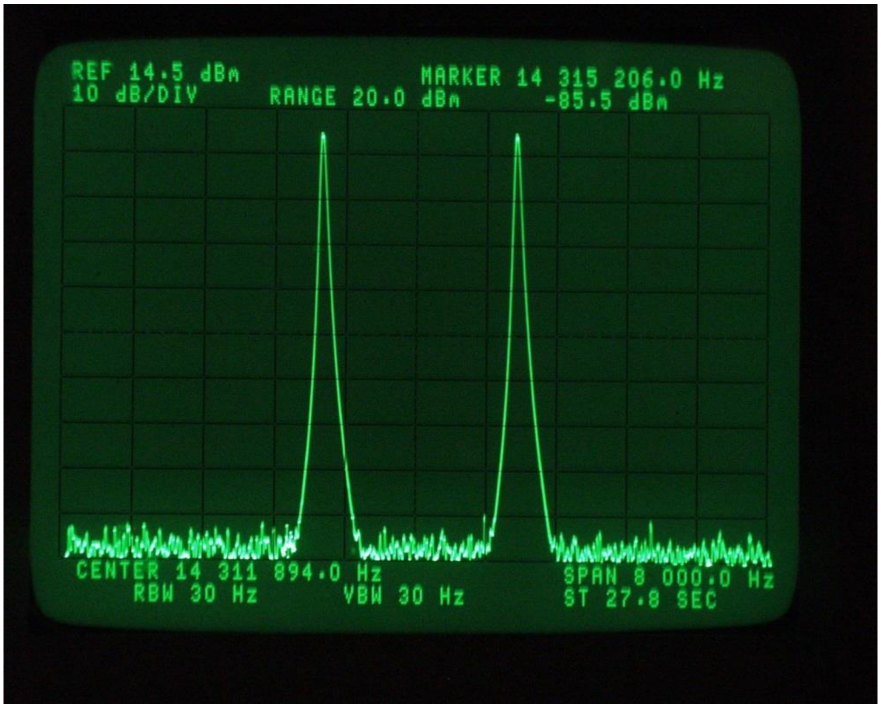


Figure 10: IMD tester with no DUT, marker at upper sideband's frequency.

Figure 11 displays the SA with a DUT present. I have designed an LNA for HF with a 3.1 dB noise figure (at 28 MHz – worst case), gain of 11.4 dB, and an optimized OIP3 in a design, which doesn't rely on a complicated technique to reduce the distortion like for example, a feed-forward amplifier. In this image, I have attenuated the IMD tester down to 0 dBm for input to the LNA, and have starved the LNA of DC power in order to generate some measurable distortion. The LNA is designed for +20.0 VDC, but in this photo, I am running it at 6 VDC. The OIP3 of the LNA is +52 dBm. At this low supply voltage, the noise figure also gets better, down to about 2.3 dB.

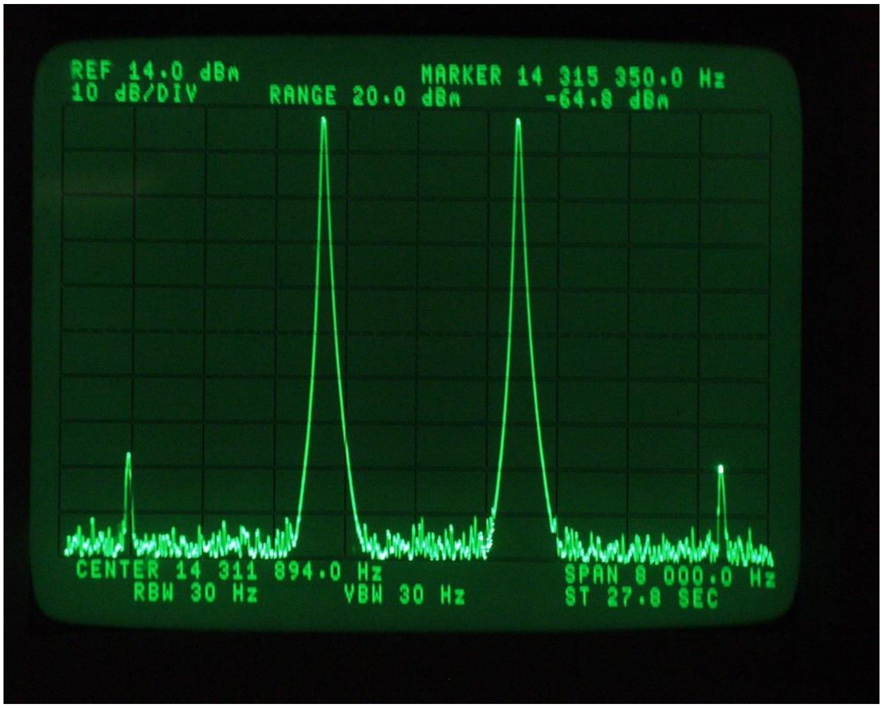


Figure 11: LNA test at 6 VDC. With 13 dBm carriers, OIP3 is about 52 dBm.

Figure 12 shows the same configuration as Figure 10, except the supply to the LNA has been increased to the design value of 20.0 VDC. The upper sideband is difficult to see, and is very close to the noise, so the IP3 calculation needs to compensate for the displayed S+N/N number. I calculate the OIP3 at 61.3 dBm.

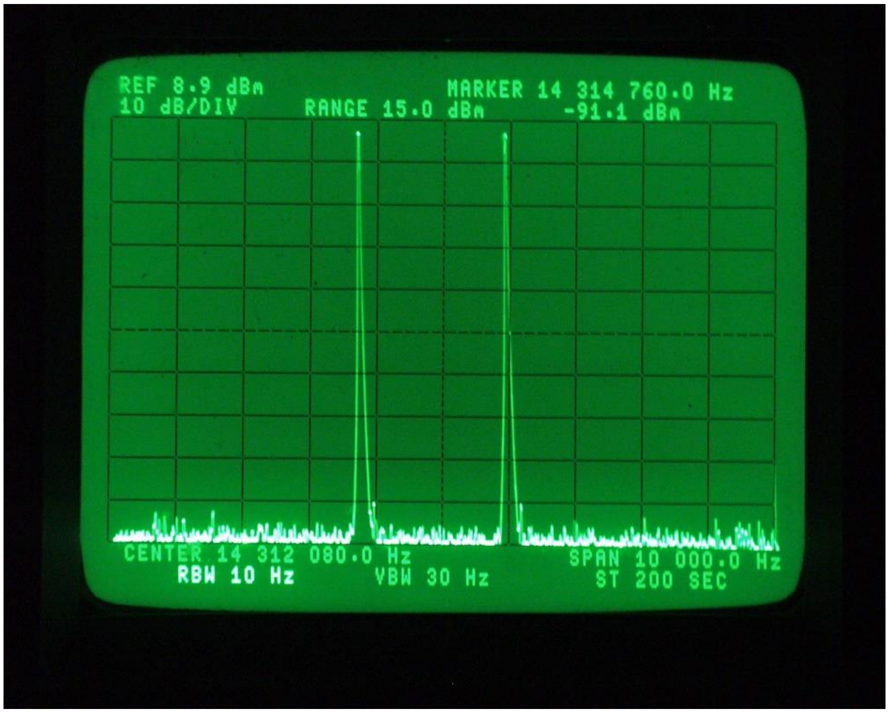


Figure 12: LNA test at 20 VDC. Marker is at the upper sideband's location.

Conclusion

The described IMD test instrument is certainly overkill for most ham projects, but once I got started on it, I couldn't resist running-down the distortion sources, and correcting them as best I could. The resulting tester is more than sufficient for any project I might undertake, and its design is general enough that I can use it for other projects.

Pictures of Unit's Internals

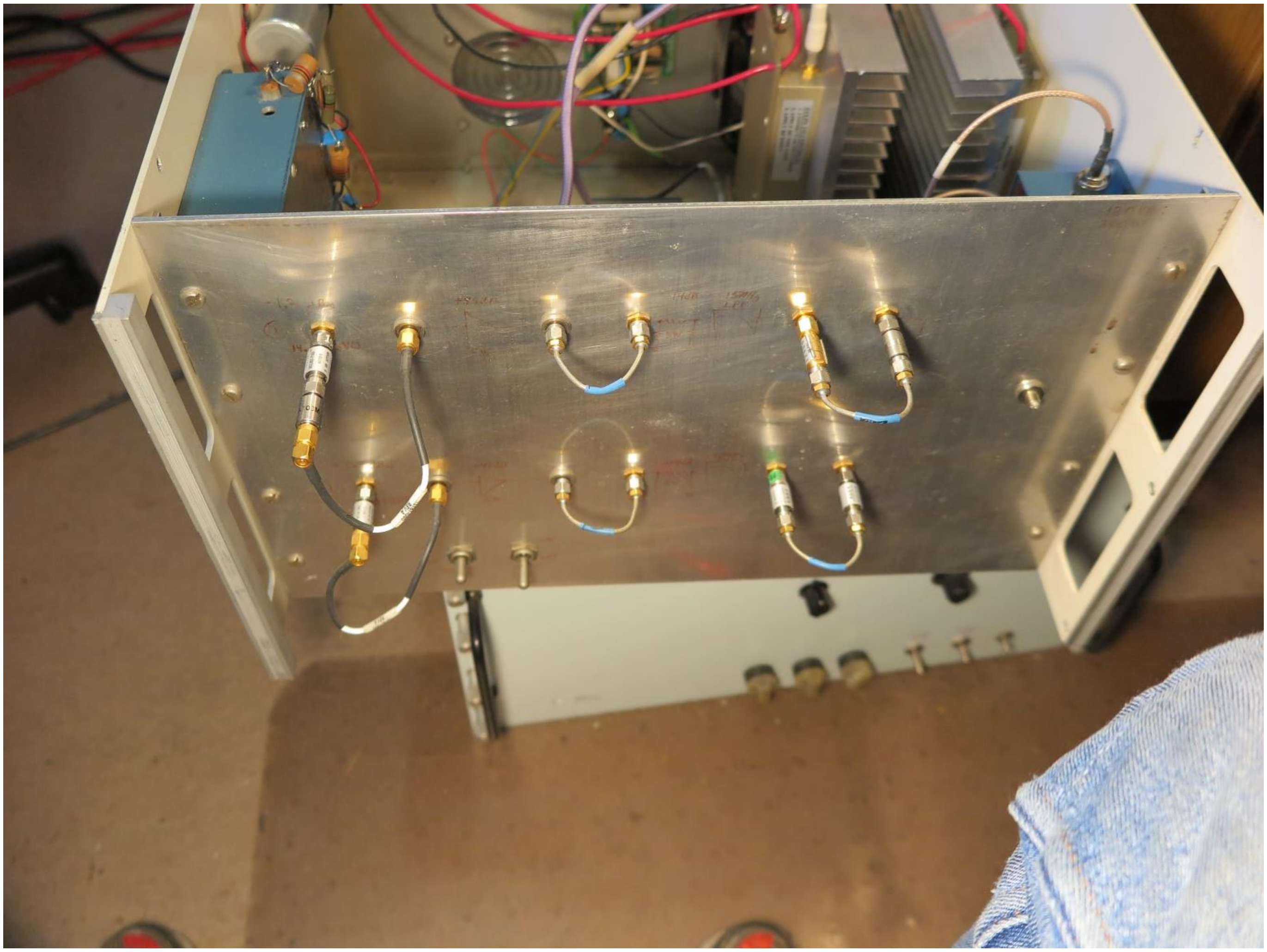


Figure 13: Front panel with oscillators on left, and SMA output on right all sitting on the dual power supply.

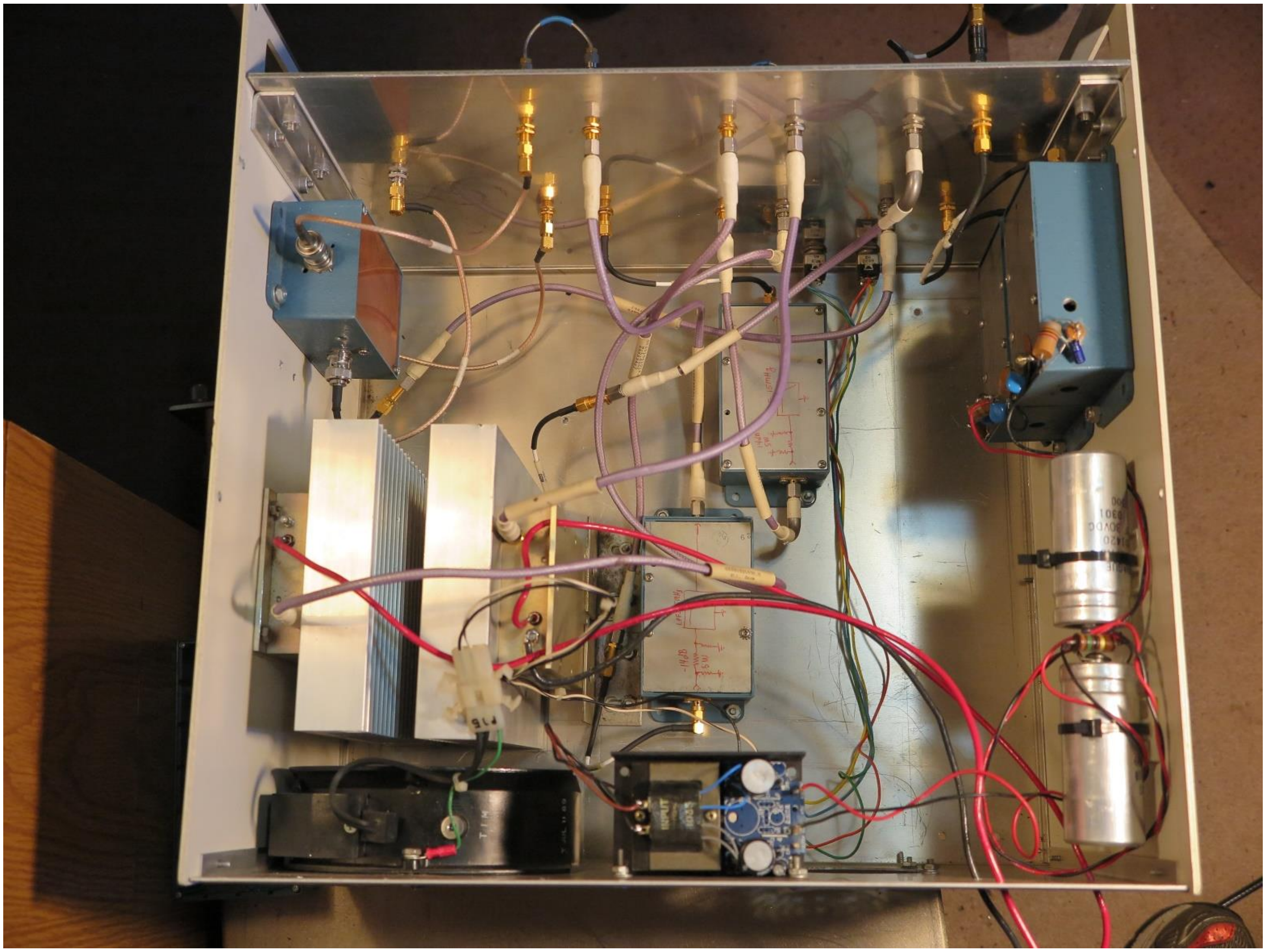


Figure 14: Amplifiers are lower left, combiner upper left, 14 dB attenuators on bottom shelf, and oscillators on the upper right side. Linear supply on back wall is for the xtal oscillators.

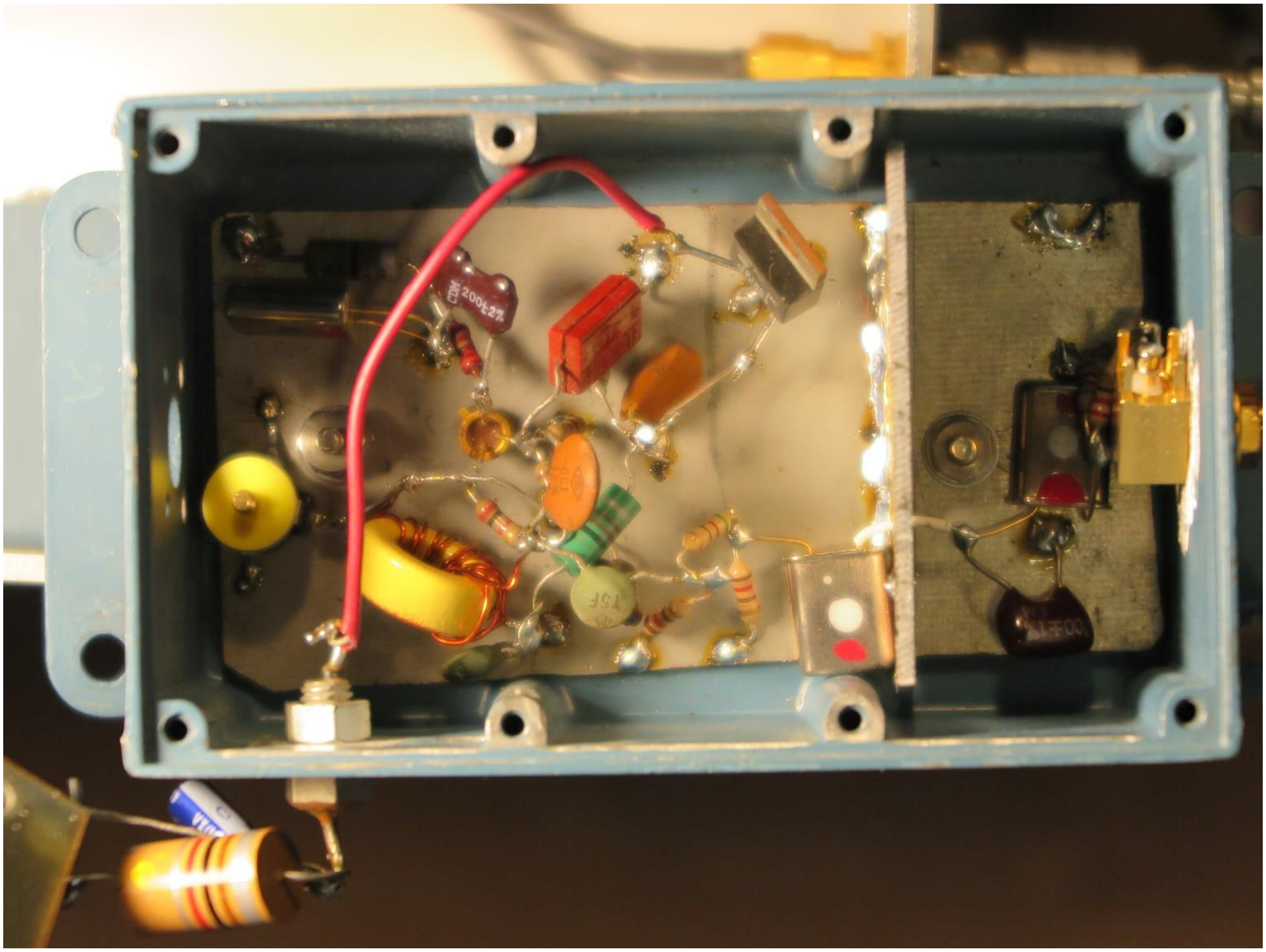


Figure 15: One xtal oscillator box. Butler oscillator to left with bandpass filter to the right.

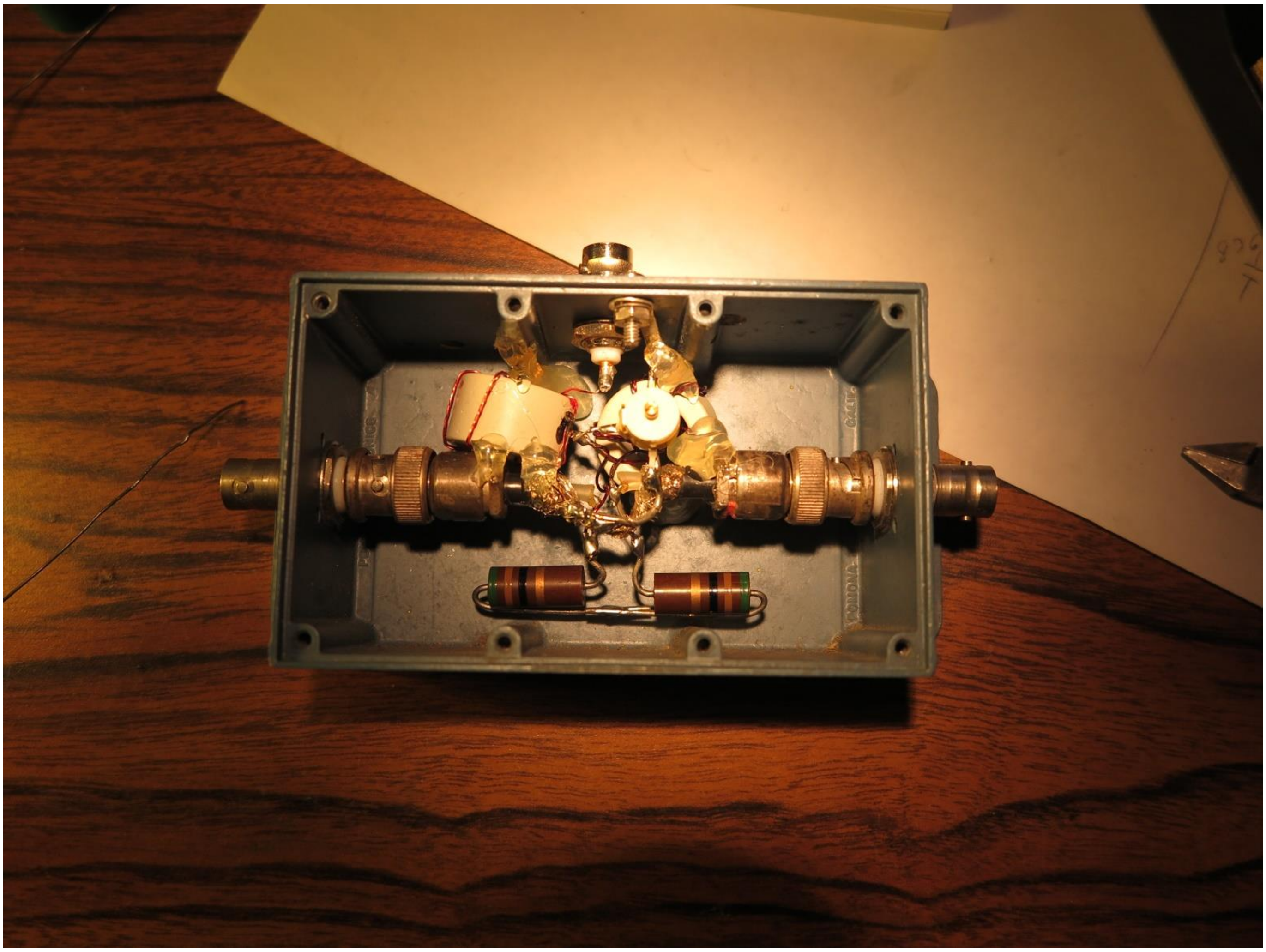


Figure 16: Power combiner box.

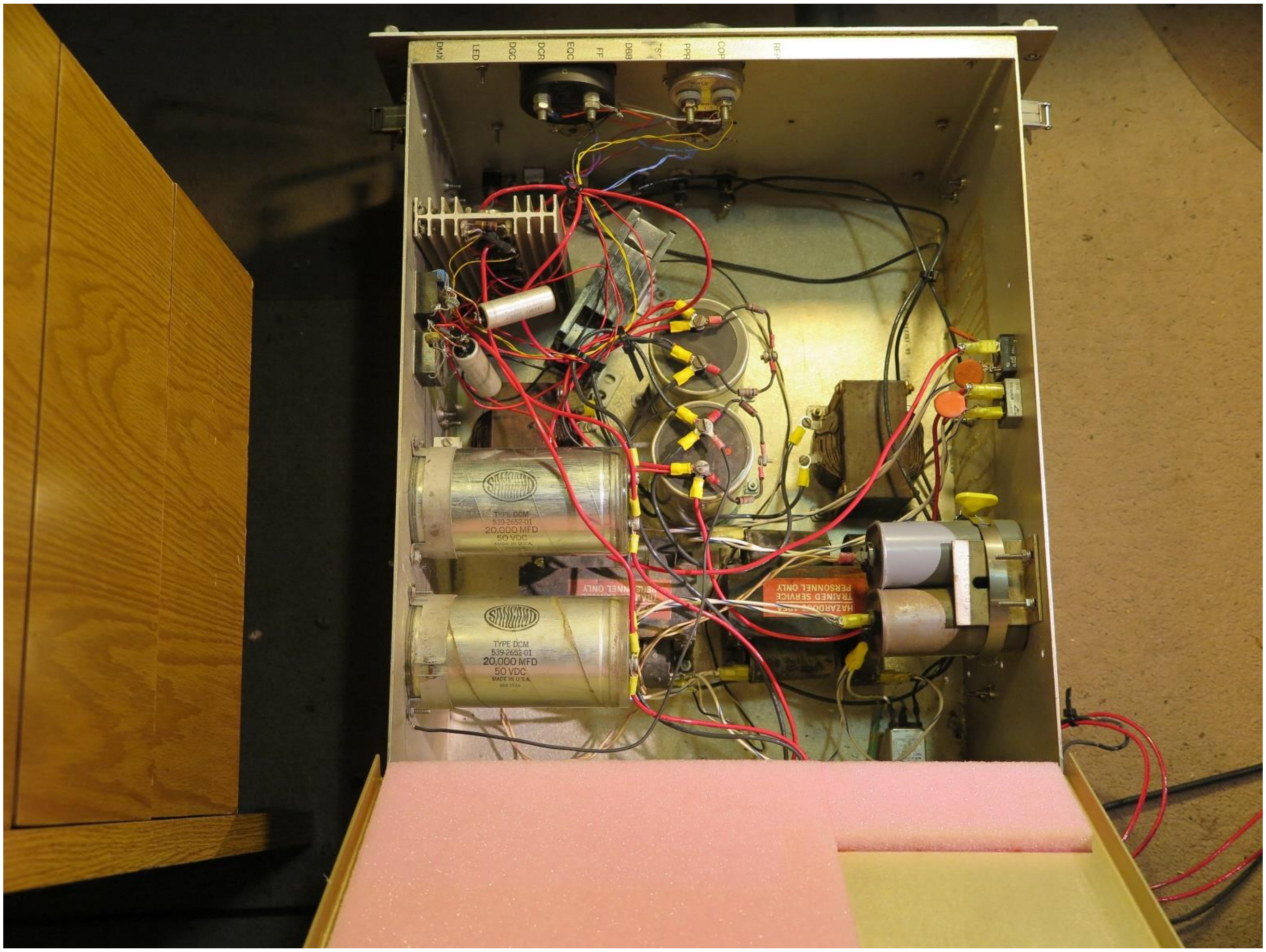


Figure 17: Dual 24 VDC, 4 Amp regulated power supplies.

Reference

1) Intermodulation Distortion Measurements on Modern Spectrum Analyzers

Application Note: Rohde & Schwarz

http://cdn.rohde-schwarz.com/pws/dl_downloads/dl_application/application_notes/1ef79/1EF79_1E.pdf