

A Spectrum Analyzer for the Radio Amateur

Good tools are priceless when you need them. Here's a piece of test equipment you've always wanted for your workbench. Now you can have it—without spending a fortune.

By Wes Hayward, W7ZOI, and Terry White, K7TAU



Among the many measurement tools sought by the amateur experimenter, the most desired—but generally considered the least accessible—is the *radio-frequency spectrum analyzer* or SA. This need not be. Simple and easily duplicated, this home-built analyzer is capable of useful measurements in the 50 kHz to 70 MHz region. The design can be extended easily into the VHF and UHF region with methods outlined later. The instrument is configured to be self-calibrating, or capable of calibration with simple home-built test gear. [1]

We often read and hear about "simple designs." Simplicity implies that something is eliminated to make the equipment easier to build, use or afford. Unlike designs that sacrifice performance for cost and simplicity, this one sacrifices only convenience, while retaining the capabilities needed for accurate measurements.

Modern technology eases the construction of this spectrum analyzer. The logarithmic amplifier uses an IF amplifier IC found in cellular telephones and includes a *received signal strength indicator* (RSSI) function. Hybrid and monolithic IC building blocks are employed extensively. These include mixers, amplifiers and VCOs—all vital elements in an analyzer. Finally, it is a rare devoted experimenter today who does not own an oscilloscope. With good basic 'scopes available for about the price of a hand-held FM transceiver, every experimenter should have one. Our spectrum analyzer uses a 'scope as the display. There are no special requirements for 'scope performance other than an X-Y mode with dc coupling in the X and Y axes.

Some Spectrum-Analysis Basics

The RF spectrum analyzer is essentially a swept receiver with a visual display. The display shows the strength of all signals within a user-defined frequency span. Each signal is represented by a line or blip that rises out of a background noise, much like the action of an S meter. Commercial analyzers are calibrated for signal power, with all signals referred to a reference level at the top of the screen. Our analyzer is designed for a basic reference level of -30 dBm, a common value in commercial analyzers. [2]

Signal levels are read from the display by noting that power drops by 10 dB for each major division on the 'scope. You can change the reference level. Adding gain to the analyzer moves the reference to lower levels; introducing attenuation ahead of the instrument moves the reference to higher power levels.

Circuit Overview

Figure 1 is a block diagram of our spectrum analyzer. A double-conversion superheterodyne, it begins with a step attenuator, followed by a low-pass filter and the first mixer, where incoming signals are upconverted to a 110 MHz first IF. After some gain and

band-pass filtering, a second conversion moves the signals to a 10 MHz IF. The resolution bandwidths available are 30 kHz and 300 kHz. A video filter smooths or averages noise. The available frequency spans range from a per-division maximum of 7 MHz to about 50 kHz. The center frequency can be adjusted over the entire 70 MHz range. An uncalibrated SPAN control allows expansion of the display about the screen center. An uncalibrated SWEEP RATE control allows the sweep to be controlled and matched to a given span while avoiding excessively fast scans that could introduce errors.

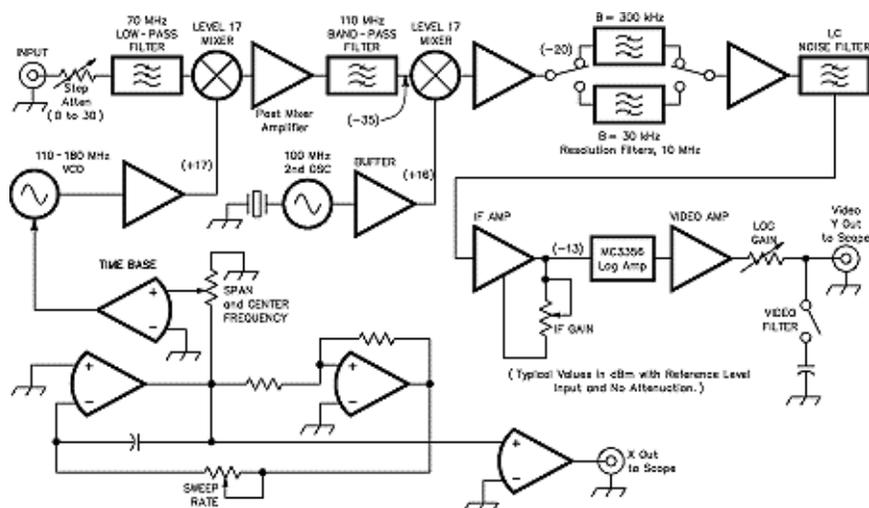


Figure 1—Block diagram of the spectrum analyzer. The circuit is a double-conversion superheterodyne design with intermediate frequencies of 110 and 10 MHz.

Ideally, a receiver's first IF should be greater than twice the highest input frequency, a design rule that we bend in this application. The input tuning range includes all HF amateur bands and 6 meters. (We'll discuss higher tuning ranges later.) We picked the 10 MHz second IF because surplus-crystal filters and LC filters for this frequency are easily built. You can easily adapt the design's IF to 10.7 MHz, or other close, convenient values.

The swept LO tunes from 110 to 180 MHz with a commercial VCO module. The VCO output is amplified to drive a high-level-input mixer. The commercial VCO is a recent modification to a design that started with a homebrew oscillator. [3]

Amplifiers are included at the 10 and 110 MHz IFs. These establish signal levels that properly match the log-amplifier window, while preserving system dynamic range. The proper distribution of gain, selectivity and signal-handling capability (intercepts) of the amplifiers and mixers is vital to achieving good performance in a spectrum analyzer, and indeed, any receiver. A proper design will have the same number of stages as a poor one, but will probably use different components and consume more current.

The analyzer uses a ± 15 V power supply. The positive supply delivers about 0.5 A. The negative supply current drain is under 50 mA.

Following sections present the circuit blocks in greater detail, in the order that they should be built. The partial but growing system can then be used to test the other sections as they are built, turned on and integrated. We *strongly discourage* building the entire analyzer before testing specific sections. Such an approach may work for casual kits, but is *not suitable* when careful control of signal levels is required. That approach also robs you (the builder) of the excitement of the process: the learning that comes from detailed examination.

Before jumping into the circuit details, we reemphasize that this analyzer—although simple—is intended for *serious* measurements. This means that a normal maximum span display contains no spurious signals. When clean (well-filtered, harmonic-free) signals are applied to the analyzer, there should be *no* extra products as long as the signal level is kept on screen. This performance goal applies for a single tone, or for two equal signals at the top of the screen.

Time Base

Figure 2 shows the analyzer time base, designed for basic functionality without frills; the result is a circuit using only a handful of op amps. [4] U401A and U401B form a free-running sawtooth generator, a circuit commonly found in function generators. U401A operates as an integrator; current is pulled from the inverting input through a 56-k Ω resistor connected to the SWEEP RATE control.

This current must flow through the capacitor (C401), creating a linearly changing op-amp output voltage. This ramp is applied to U401B, a regenerative comparator, which provides a reset signal to the integrator. The sawtooth waveform (pin 1 of U401A) is asymmetrical: The positive-going ramp grows with a slope determined by the front-panel-mounted SWEEP RATE pot, while the negative-going, faster reset ramp is determined by fixed-value components.

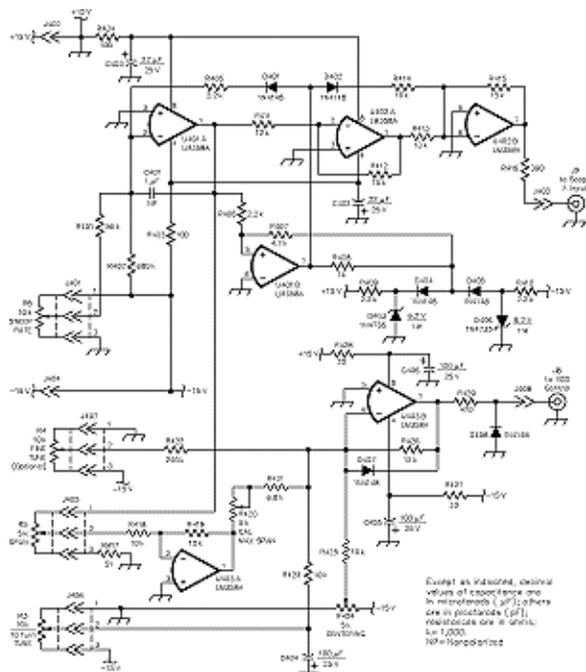


Figure 2—Time base for the spectrum analyzer. Refer to the text for a discussion of the various circuit functions. Front-panel controls include SWEEP RATE, SPAN and TUNE. Unless otherwise specified, resistors are 1/4 W, 5% tolerance carbon-composition or film units. Equivalent parts can be substituted.

U401, U402, U403—LM358 op amp

D403, D406—6.2 V Zener diodes, 1 W

C401—Metal film or Mylar, 1.0 µF capacitor

R420, R423—PC-mount trim pots, 5 kΩ or 10 kΩ suitable

R3, R4, R5, R6—Panel-mounted linear control, 5 kΩ or 10 kΩ suitable. If a 10 turn pot is used for R3, R4 is not needed.

The U401 ramp is used twice. U402A and B process the ramp to generate a signal that drives the 'scope's X axis. The signal has a 0 V-centered range with just over a 10 V total swing. Some of the "square wave" from the basic time base (U401B, pin 7) is added to the input of U402B to cause the sweep to reset quickly, even though the return sweep for the VCO occurs in a more stable, smooth way. A slight overscan is generated for the X axis, serving to hide an aberration occurring near the sweep beginning.

The sweep also generates the signal that controls the VCO. The sweep signal (U401A pin 1) is applied to a SPAN control. When the analyzer is set for maximum span, the VCO voltage (about 2 to 10 V) generates a sweep from 110 to 180 MHz. The VCO uses only positive sweep voltages, so the output of U403B is diode-clamped to prevent negative output. The center frequency TUNE, FINE TUNE and a MAX SPAN calibration pot set up the proper sweep for maximum span. As the span is reduced with the SPAN control, the sweep expands on (or zeroes in on) whatever appears at the center of the screen, determined by the tuning. The center frequency must be set for 35 MHz at maximum span, which coincides with having the zero signal, or "zero spur" at the left edge of the screen.

Setting up the time-base function is generally straightforward. The 'scope can be used to debug, check and study the circuits. The X-axis signal is a ramp ranging from -6 to +6 V with a reset to -15 V during the retrace. A similar ramp appears (without a reset pulse) at the VCO output, but with an amplitude dependent on the SPAN control setting.

Although the op amps are carefully bypassed, and the signal that tunes the VCO is shielded, most circuits are noncritical. Normal op-amp circuit precautions are taken with resistors injecting signals into inverting inputs positioned close to the op-amps. [5]

A 10-turn front-panel-mounted pot is used for the TUNE control (any value from 5 kΩ to 50 kΩ is suitable). A single-turn pot can be substituted if a 10-turn pot is not available. A fine-tuning function is included in this design, but may be omitted if a 10-turn pot is used for the main tuning.

Log Amplifier and Detector

Central to any spectrum analyzer is a *logarithmic amplifier*. The need for logarithmic processing becomes clear if we consider the range of signals we want to measure: At the low end, we may want to look at submicrovolt levels: under -107 dBm in a 50-Ω system. At the other extreme, we may want to measure the output of small transmitters, perhaps up to a power of 1 W, or +30 dBm. The difference between the two levels is 137 dB. The human ear is capable of handling linear ranges well over 60 dB. [6] This is a wide dynamic range world and linear displays, such as our screen, are inadequate unless some form of data compression or logarithmic processing is used.

The circuit element we use for this processing is the log amplifier. [7] The term is a misnomer, for the usual log-amp IC is both a logarithmic processor (amplifier) and a detector. The chips provide a dc output voltage that increases in proportion to the logarithm of the input amplitude. The central sensitivity specification for a log amp is a voltage slope that is equal to the voltage change (per decade or per decibel) of input-voltage-amplitude change.

An experimental log amp is shown in **Figure 3**. We breadboarded and tested this circuit to evaluate the log IC. To produce the MC3356 curve shown in **Figure 4**, the 10 MHz output of an HP-8654 signal generator was applied through HP-355 step attenuators. Exact dc output levels are insignificant, for they can be adjusted with dc voltage gain in a following amplifier. The salient detail that we observe is the dynamic input window. The MC3356, with a 50-Ω input termination, produces a nearly straight-line output voltage versus input power for inputs in the -80 to -10 dBm range. Hence, the analyzer log amp should operate with an input signal of -10 dBm for signals at the top of the screen.

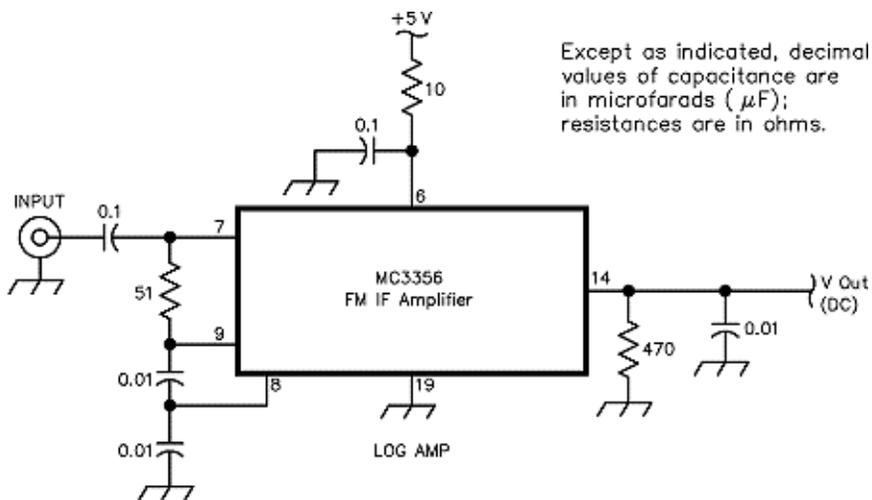
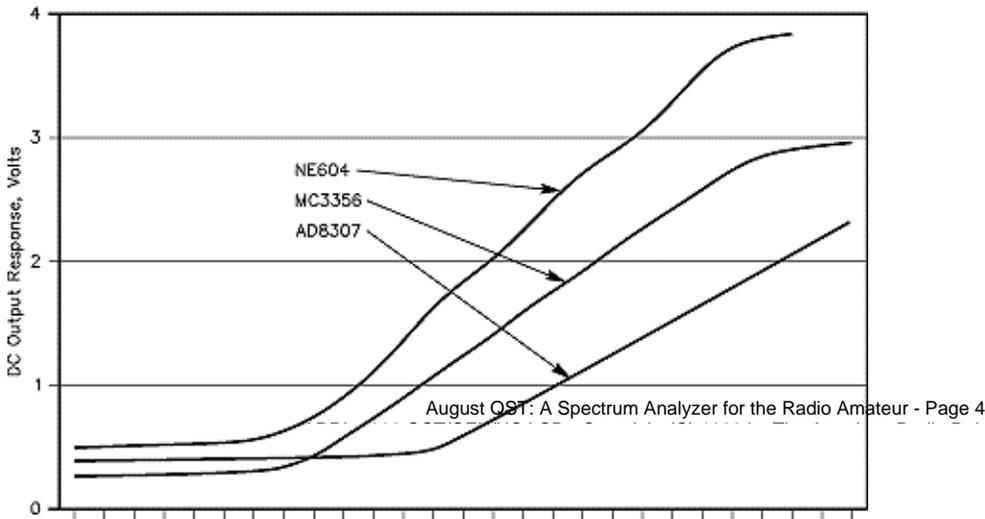


Figure 3—An experimental logarithmic amplifier breadboarded to evaluate performance prior to analyzer construction. You may want to duplicate this circuit and analyze its performance if you decide to use other log-amp ICs.



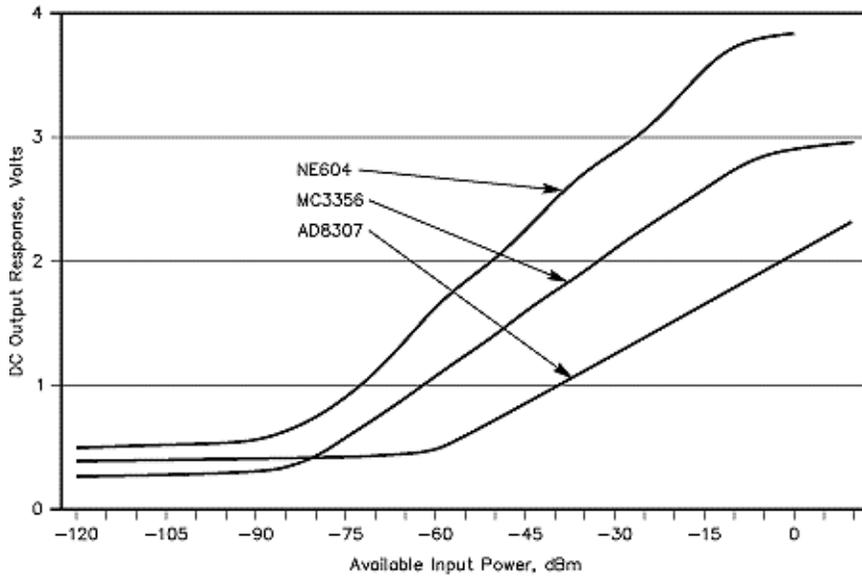


Figure 4—Transfer characteristics for three different logarithmic amplifier ICs. Although the MC3356 is used in our analyzers, use of the AD8307, shown in the lower curve, is recommended. Some curves have been linearly scaled to ease comparison.

We evaluated two other ICs. One, the commonly available NE/SA604, shows considerable ripple. The best performance offered came from a recently introduced chip from Analog Devices: the AD8307. This IC is designed specifically for measurement applications and offers outstanding logarithmic accuracy, a dynamic range exceeding 90 dB and better temperature stability than found with the usual cellular-receiver chips. The AD8307 requires a high drive level, so it must be preceded with higher-power amplifiers or impedance-transforming networks. The bandwidth of the AD8307 is about 500 MHz, so care is required in its use.

Our analyzer uses the inexpensive and readily available MC3356 log amp shown in **Figure 5**. [8] An op amp, U303, used to increase the signal output to 0.5 V per division, follows the log chip, U301. The 0 V level corresponds to the bottom of the screen; a signal of 4 V brings the response to the top of the screen. The op-amp output is slightly higher than this, but is then attenuated with a LOG AMP CAL control, R2. This pot should be accessible from the outside of the instrument.

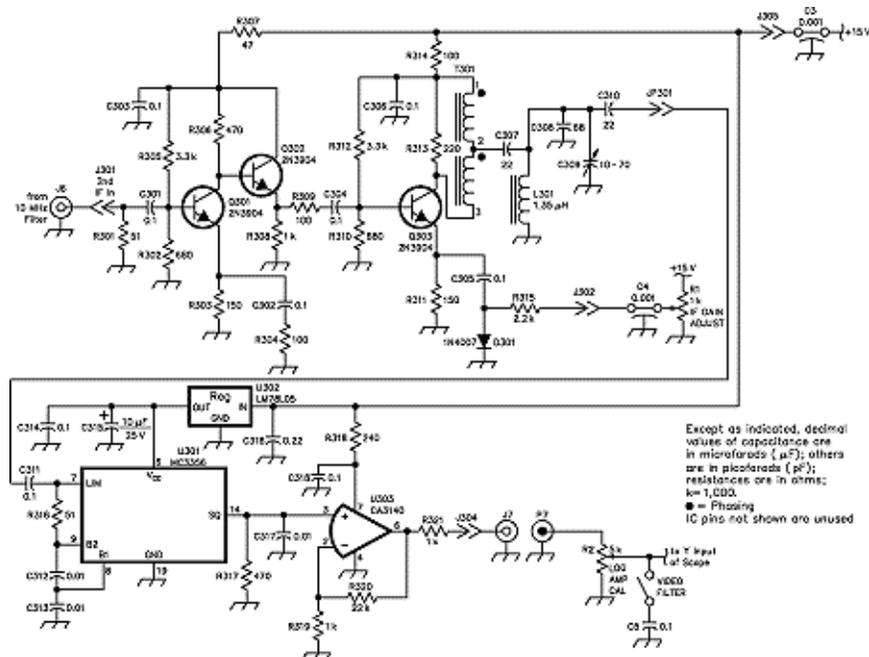


Figure 5—The 10 MHz IF amplifier and log amplifier used in the analyzer. Refer to the text for adjustment details. Unless otherwise specified, resistors are 1/4 W, 5% tolerance carbon-composition or film units. Equivalent parts can be substituted.

C309—Plastic dielectric trim cap (Sprague-Goodman GYD65000)

C307, C308, C310—Silver mica or NP0 ceramic capacitors, 10% tolerance

C316—0.22 μF ceramic

D301—PIN diode; 1N4007 used

L301—1.35 H, 18 turns #24 enameled wire on T-44-6 core, Q >150

Q301, Q302, Q303—2N3904

R1—Panel-mount, 1 kΩ linear

R2—Panel-mount, 5 kΩ linear

U301—Motorola MC3356

U302—78L05 +5 V regulator

U303—CA3140 op amp

The log amp is preceded by an IF amplifier, Q301 through Q303. These stages are biased for relatively high-current operation to preserve linearity. Gain is controlled through variable emitter degeneration in the form of a PIN diode, D301. Most common 1N4000-series power rectifiers work well for gain control. The IF GAIN ADJ control (R1) should be available from the exterior of the RF-tight amplifier box. We have placed it on the front panel of our analyzers.

Calibration of the IF and log amplifier is straightforward. First, set the 'scope's Y axis to 0.5 V/division and short it. Set the now-working time base to drive the X axis and adjust the 'scope's vertical position control to place the horizontal line at the bottom of the screen. Inject a -10 dBm signal from a signal generator into the log amplifier input, remove the short circuit and adjust R2, LOG AMP CAL, for a full-screen (reference level) response. The input level is next reduced in 10 dB steps. The horizontal sweep line should drop down one major division for each 10 dB reduction over a 60 dB range. If this does not happen, repeat the procedure with a slightly different drive level. In our analyzers, a typical drive level of -13 dBm produced good accuracy.

Now, attach the IF amplifier to the log amplifier and drive them with an input level of -23 dBm. Peak the IF output filter for maximum response and set R1, IF GAIN ADJ, for a full-screen response. A true filter peak can be confirmed by varying the generator frequency. There is considerable extra range in the IF GAIN ADJ, providing extra flexibility during use.

Resolution Filters

Continuing the backward progression through the system, we encounter the resolution-bandwidth-determining filters. Our analyzer uses bandwidths of 30 and 300 kHz, provided by crystal and LC filters, respectively. The 300 kHz LC filter, the crystal filter and the relay circuitry for bandwidth switching are shown in **Figure 6**. Although shown as individual modules, they can be incorporated into one. The PC board for the filter includes the LC filter and switching relays with room for a user-selected crystal filter. Builders may want to implement their own scheme here. We reasoned that builders would want to implement their own ideas. Maintain reasonable shielding for this part of the system. Additional attenuator pads can be inserted in line with one filter or the other to approximately equalize filter loss in the two paths.

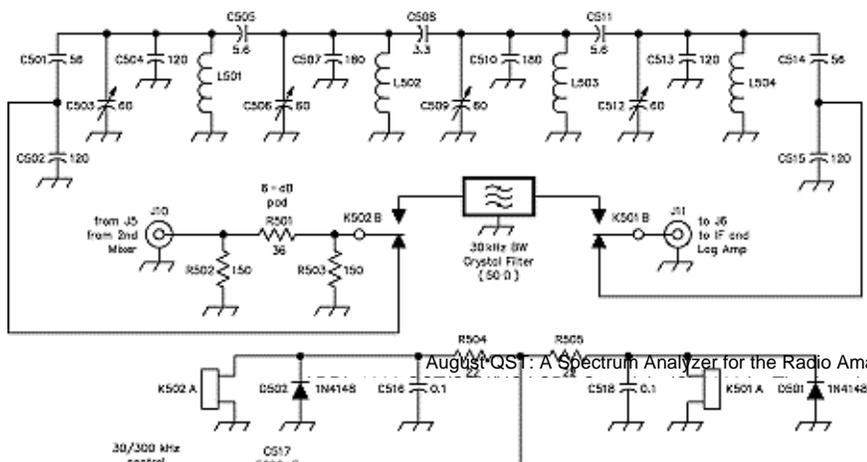


Figure 7—Second mixer and second LO. L203 in the output of U202 consists of 17 turns of #28 enameled wire on a T-30-6 toroid. The actual value is not critical and a molded RF choke can be used in place of the toroid. Unless otherwise specified, resistors are 1/4 W, 5% tolerance carbon-composition or film units. Equivalent parts can be substituted.

C201, C202—470 pF ceramic

C203, C206—15 pF NP0 ceramic or silver mica

C204, C207—82 pF NP0 ceramic or silver mica

C205—65 pF plastic dielectric trim cap (Sprague-Goodman GYD65000)

C211—120 pF, silver mica or NP0 ceramic

L201—57 nH; 5 turns of #22 wire wound on a 6-32 machine screw. Remove the screw before installing the coil.

L202—1 μH molded RFC; any value from 100 nH to 2.7 μH is okay

L203—0.3 μH; 9 turns #24 enameled wire on a T-30-6 core

Q201—2N5179

Q202—2N5109, 2N3866, 2SC1252, etc

U201—Mini-Circuits MAV-11

U202—Mini-Circuits TUF-1H mixer

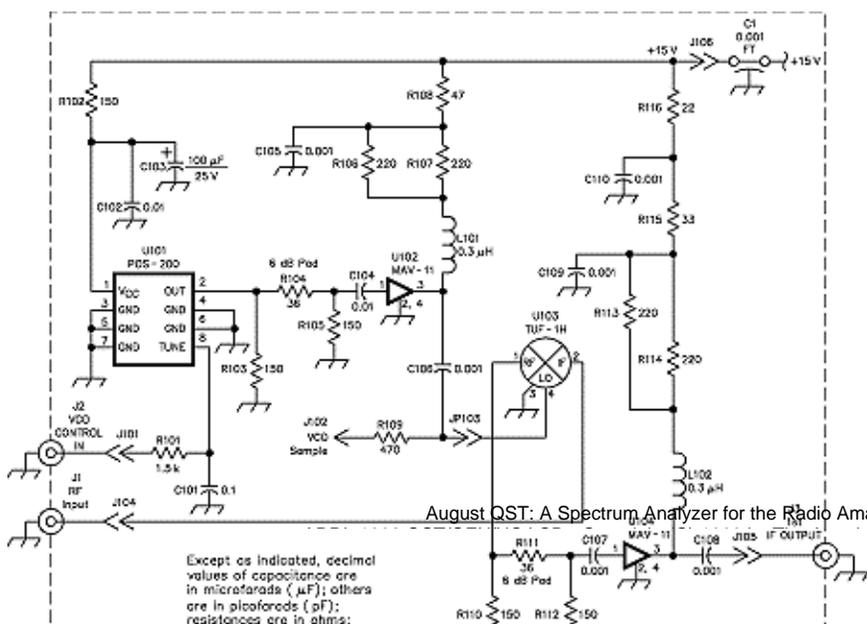
T201—10 bifilar turns #28 on FT-37-43 ferrite toroid

The second LO begins with a 100 MHz, fifth-overtone crystal oscillator (Q201), followed by a pad and a power amplifier. The oscillator inductor, L201, in Q201's collector is made of five turns of #22 wire wound on a 6-32 machine screw. (Remove the screw before installing the coil.) Here's an excellent way to align the oscillator: Temporarily replace the crystal, Y201, with a 51 Ω resistor. Adjust the tuned circuit until oscillation occurs at the desired 100 MHz frequency. Then, replace the 51 Ω resistor with the 100 MHz crystal; no further tuning is required. Measure the oscillator's output with a power meter before applying it to U202. Adjust the pad attenuation (R205, R206, R207) to realize the specified LO drive level.

After the second LO is operating, attach it to the second mixer and the rest of the analyzer. With a second mixer input of -35 dBm at 110 MHz, you should obtain a reference-level response.

Voltage-Controlled Local Oscillator and First Mixer

Figure 8 shows the analyzer's swept LO. The foundation for this module is a Mini-Circuits POS-200 VCO module, U101. Similar VCOs are available from many vendors. [10] The VCO output is about +10 dBm, too low a level for the high-level mixer. A MAV-11 amplifier, U102, preceded by a pad to provide level adjustment, increases the signal level. Confirm the output power level before applying it to the mixer, U103.



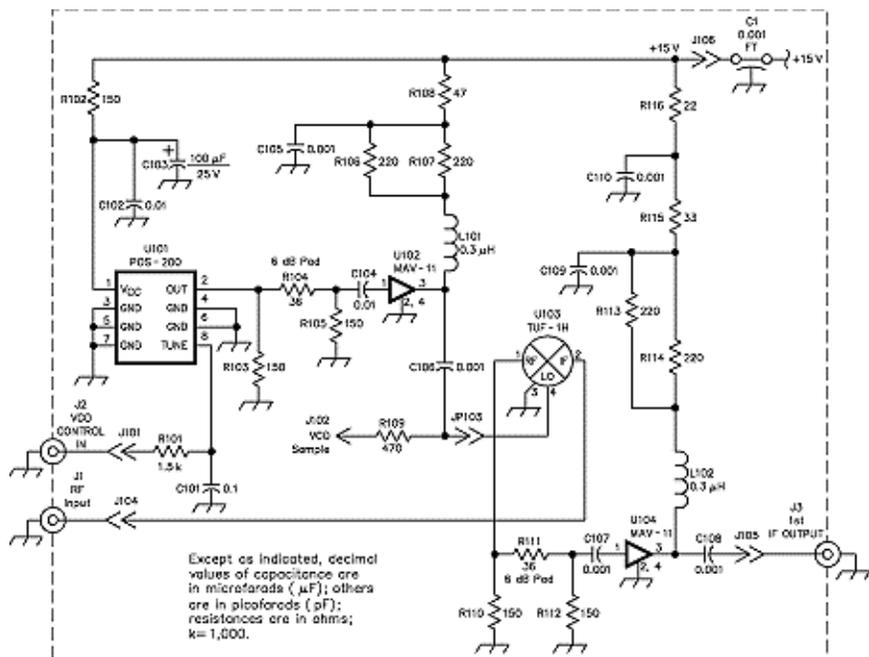


Figure 8—Front-end for the spectrum analyzer. The LO drive level is set to between +16 and +18 dBm by trimming the pad attenuation. The 1 μH inductors used in the MAV-11 outputs can be molded RF chokes or made of 17 turns of #28 enameled wire wound on T-30-6 toroids. Unless otherwise specified, resistors are $\frac{1}{4}$ W, 5% tolerance carbon-composition or film units. Equivalent parts can be substituted.

L101, L102—1 μH molded RFC; any value between 100 nH to 2.7 μH suitable

U101—Mini-Circuits POS-200 VCO

U102, U104—Mini-Circuits MAV-11

U103—Mini-Circuits TUF-1H

Once the VCO output level is adjusted and confirmed, calibrate its frequency against the VCO control voltage. If a VHF counter is not available, you can obtain a few points by tuning the VCO to hit local FM broadcast signals of known frequency. Calibrating the VCO is useful if the module is used later as a signal source for alignment of the 110 MHz band-pass filter.

Figure 8 also shows the input mixer, U103, another Mini-Circuits TUF-1H, terminated in a 6 dB pad. Although the pad degrades the noise figure, it presents a solid output termination for the mixer. This termination is reflected, helping to provide a good mixer-input impedance match, important in a measurement instrument. The pad is followed by a Mini-Circuits MAV-11 IF amplifier (U104) that restores the gain lost in the mixer and pad.

The mixer application differs from a normal diode ring: The RF input is now attached to the dc-coupled port. This allows input frequencies as low as 50 kHz to be converted to the first IF. The low frequency end is limited by mixer LO to RF isolation, which determines the LO energy that reaches the first IF. The related on-screen response is often termed the *zero spur*, a familiar "feature" in most RF spectrum analyzers.

This module (VCO and first mixer) is contained in a shielded enclosure with coaxial inputs and outputs, including coaxial routing of the VCO control voltage. The front end is susceptible to any VHF and UHF signals reaching it, making shielding and decoupling especially important.

The 110-MHz IF Band-Pass Filter

One of the more-critical blocks in the analyzer is the filter that establishes the bandwidth of the VHF IF. The bandwidth must be at least as wide as the widest 10 MHz filter, but must be narrow enough to reject the 90 MHz second-conversion images by 80 dB or more. This performance is only available with a three-pole or higher-order filter. The best double-tuned circuits we built (or computer simulated) came close, but just didn't cut it.

We described double-tuned circuits in detail in a 1991 QST tutorial paper. [11] Those methods have recently been extended to three-resonator filters. [12] One of the methods presented in the later paper is a sequential approach that begins with a double-tuned circuit (DTC). First, a DTC is built for the desired 3 dB bandwidth and has its performance confirmed with a wideband sweep (a vital requirement!) Then, a third resonator is inserted between the original two. Coupling elements similar to the one that produced the required DTC bandwidth are repeated in the triple-tuned circuit, but end-section loading is not changed. The center frequency of the three resonators is aligned to complete the filter.

The schematic for the 110 MHz triple-tuned circuit is shown in Figure 9. The inductors, 100 nH, are made by winding 5 turns of #18 wire on the shank of a 1/4-inch drill bit. These inductors typically have an unloaded Q of just over 200 at 110 MHz. Larger-diameter inductors would have produced higher unloaded Q with the attendant lower insertion loss. However, the stray coupling between coils would have increased, which would have necessitated shields between filter sections. The smaller (10 nH) end-matching inductors are one-inch lengths of #18 wire. The triple-tuned filter, and its parent DTC, have bandwidths of 2 to 3 MHz.

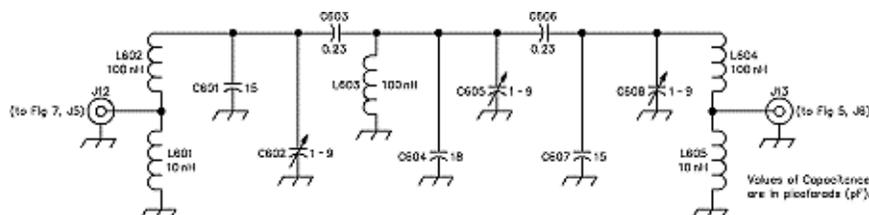


Figure 9—VHF band-pass filter used in the 110 MHz IF.

The filter alignment and experimentation is usually done with a sensitive power meter, a step attenuator and a signal source. [13] As mentioned earlier, the VCO can serve the role of signal generator, if one is not available.

The second-conversion image rejection is easily measured with a finished analyzer. Apply a 40 MHz signal to the analyzer and adjust it for a reference-level response. Don't touch the analyzer tuning, but move the signal generator to 60 MHz. An image signal may appear at the same point on screen as the original 40 MHz signal. The rejection was only 66 dB with a DTC used for some experiments. The triple-tuned filter produced 90-dB rejection. The slight extra effort of the triple-tuned circuit is easily justified. No PC board is available for the IF filter.

Input Low-Pass Filter

A 70 MHz low-pass filter is shown in Figure 10. This circuit and a step attenuator are housed in separate shielded enclosures in one of our analyzers. In the other, the filter and the attenuator remain outboard elements. Integral components are more convenient for routine analyzer applications, but incorporation removes them from the equipment pool available for other experiments. Also, operation without an outboard low-pass filter allows the instrument to be used well into the low UHF area by operating the mixer with VCO harmonics. (No circuit boards are available for this filter.)

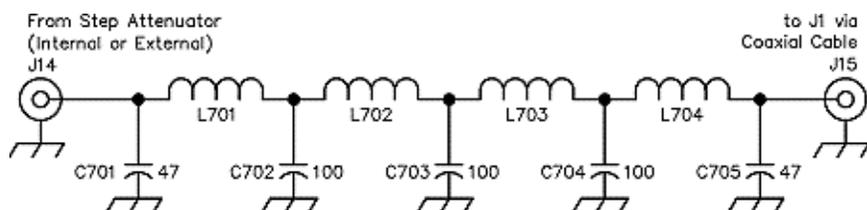


Figure 10—Input 70 MHz low-pass filter. The filter started as a ninth-order Chebyshev design, but was modified through computer manipulation to use equal-value inductors and standard-value capacitors. The inductors each consist of 8 turns of #22 wire. The wire is wound on the threads a 1/4-20 bolt as a form; remove the bolt after winding the inductor. See text.

C701-C705—NP0 ceramic, 5% tolerance.

L701-L704—8 turns #22 bare wire wound in 1/4-20 bolt threads; see text.

Construction and Adjustment Hints

The spectrum analyzer can be built using a number of RF techniques. Our analyzers are collections of small boxes using coaxial-cable interconnections. Power supplies reach the interior of RF modules through feedthrough capacitors. The only open boards in the system are the time base and (in one instrument) the log amp, both constrained to low frequencies. The 110 MHz IF filter and all RF circuit boards are designed to fit in Hammond 1590B diecast aluminum alloy boxes.

The sensitivity of such RF measurement equipment justifies the extensive shielding. Spurious responses are readily seen on the display. While a few can be tolerated, they seriously detract from a measurement when, for example, spurious transmitter products are being examined.

Most of the adjustment has already been discussed. Indeed, by the time the analyzer is finished, there is little alignment left! The block diagram (**Figure 1**) has typical signal levels shown in parentheses.

The finished analyzer is set up with a -30 dBm signal from a stable-impedance source. Adjust the IF gain to establish the reference level. If the 10 dB per division tracking is not quite correct, change the log amp gain, followed by a readjustment of the IF gain until tracking is correct. IF gain is adjusted to the reference level whenever the analyzer is used.

Next month, we'll present methods to extend the analyzer to higher frequencies. We'll discuss simple test equipment that can be used in alignment and present some typical examples of spectrum-analyzer use.

Wes Hayward, W7ZOI, and Terry White, K7TAU, are not strangers to *QST*. This is also not the first *QST* project on which they've worked together. The first, "The Mountaineer—An Ultraportable CW Station," described a QRP transceiver and appeared in the August 1972 issue. At the time this spectrum-analyzer project evolved, the authors worked together in the Advanced Circuits section of the Receiver Group at TriQuint Semiconductor in Hillsboro, Oregon. Over the years, Wes has provided readers of *QST*, *The Handbook* and other ARRL publications with a wealth of projects and technological know-how. You can contact Wes at 7700 SW Danielle Ave, Beaverton, OR 97008; e-mail w7zoi@teleport.com. Terry can be reached at 9480 S Gribble Rd, Canby, OR 97013; e-mail twhite@tqs.com.

A Spectrum Analyzer for the Radio Amateur—Part 2

Here are some examples of procedures you can use to become familiar with your new spectrum analyzer.

By Wes Hayward, W7ZOI, and Terry White, K7TAU

In Part 1 [14] we described the design and construction of a simple, yet useful spectrum analyzer. This installment presents some applications and methods that extend the underlying concepts.

Amplifier Gain Evaluation

One use for a spectrum analyzer is amplifier evaluation. We can illustrate this with a small amplifier from the test-equipment drawer—an old module that has been pressed into service for a variety of experiments. This circuit, shown in Figure 11, is used for illustration only and is not presented as an optimum design. It's a project that grew from available parts and may be familiar to some readers. The circuit uses four identical 2N5179 amplifier stages. A combination of emitter degeneration and parallel feedback provides the negative feedback needed to stabilize gain and impedance. (Ideally, construction and measurement of a single stage should precede construction of the complete amplifier.)

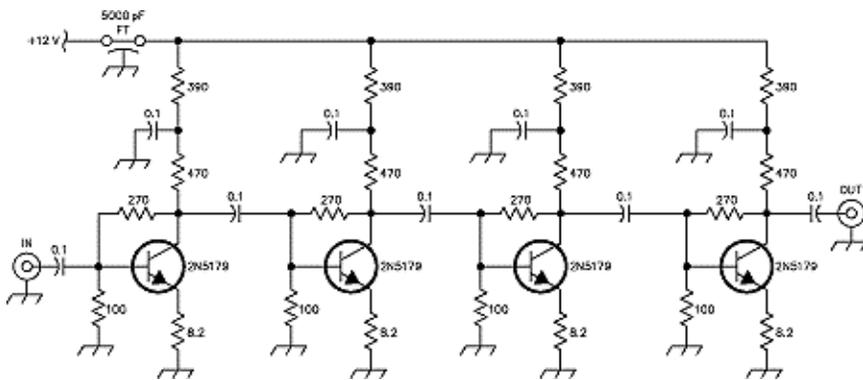


Figure 11—Sample wideband amplifier used to illustrate amplifier measurements.

We began the experiment by setting the signal generator at a known power level, -20 dBm. (If a good signal generator is unavailable, you can easily build a suitable substitute. [15] We used a surplus HP8654A for most of these experiments.) With the generator and spectrum analyzer connected to each other through 50-ohm coax cable, we set the generator to 14 MHz with 10-dB attenuation ahead of the analyzer. The amplifier was not yet connected. We adjusted the analyzer's **IF GAIN** control for a response at the top of the screen. Using a resolution bandwidth of 300 kHz allows for a fast sweep without distortion. In our case, the second harmonic was only 26 dB below the peak response. However, when we added a 15 MHz low-pass filter, the second harmonic dropped to -57 dBc. [16] The third harmonic is well into the noise. (It is not unusual for a signal generator to be moderately rich in harmonics.)

Next, we inserted the amplifier between the signal generator and the analyzer, keeping the low-pass filter in the generator output. The on-screen signal went well above the top as soon as the amplifier was turned on. Decreasing the signal generator output to -51 dBm produced the same -20 dBm analyzer signal that we saw before the amplifier was inserted. The gain measured 31 dB. [17] Increasing the analyzer attenuation by 10 dB (for a reference level of -10 dBm) and increasing the generator output to -41 dBm produced the same gain, but a growing harmonic output. The second-harmonic response was now at -43 dBc and a third harmonic appeared out of the noise at -60 dBc.

We continued the process—moving both step attenuators produced an amplifier output of 0 dBm with second and third harmonics at -28 and -36 dBc, respectively. The next 10-dB step, however, didn't work as well, producing gain compression. With a drive of -21 dBm, the output was only +4 dBm, a gain of only 25 dB instead of the small-signal value of 31 dB.

Amplifier Intermodulation Distortion

Next, we measured intermodulation distortion (IMD). The setup for these experiments is shown in **Figure 12**. Two crystal-controlled sources [18] at 14.04 and 14.32 MHz are combined in a 6 dB hybrid combiner (return-loss bridge), [19] applied to the 15 MHz low-pass filter and a step attenuator having 1 dB steps. This composite signal drove the amplifier, with its output routed to the spectrum analyzer. For this measurement, we dropped the resolution bandwidth to 30 kHz. (The video filter was turned on and the sweep rate reduced until the signal amplitude was stable.) The analyzer's attenuator, set for a reference level of -10 dBm at the top of the screen, was confirmed with a calibration signal from the signal generator. We adjusted the **IF GAIN** to compensate for changes in analyzer bandwidth and for log-amplifier drift.

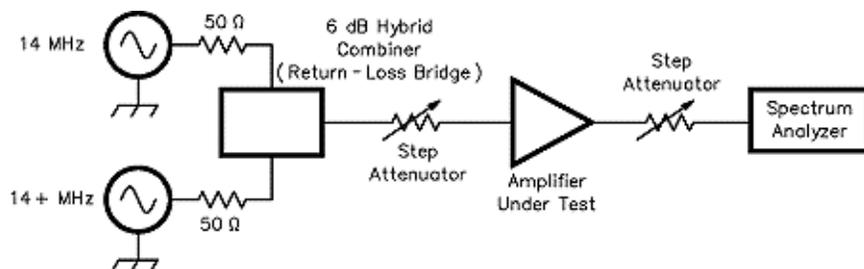


Figure 12—Equipment setup for evaluation of amplifier intermodulation distortion.

The output of the two-tone generator system was adjusted to produce a spectrum analyzer response of -10 dBm per tone. The IMD responses were readily seen, now 47 dB below the desired output tones. The output intercept is given by

$$IP3_{out} = P_{out} + \frac{IMDR}{2}$$

where P_{out} is the output power of each desired tone (-10 dBm) and IMDR is the intermodulation distortion ratio, here 47 dB. The output intercept for this amplifier measured $+13.5$ dBm. This is well in line with expectations for such a design.

When performing IMD measurements, it's a good idea to change the signal level while noting the resultant performance. Dropping the drive power by 2 dB should cause a -2 dB response in the desired tones, accompanied by a 6 dB drop in distortion-product tones. The output intercept should remain unchanged.

The IMD in the preceding example was 47 dB below the desired output tones, a value that we obtained by simply reading it from the face of the 'scope, possible because we use a log amplifier that has moderate log fidelity. If the log amplifier was not as accurate as it is, we could still get good measurements. In this example, you would note the location of the distortion products on the display. Then, using the step attenuator, decrease the desired tones until they are at the noted level. The result would be -47 dBc for the distortion level, a measurement that depends solely on the accuracy of the attenuator. This illustrates the profound utility of a good step attenuator, an instrument that can be the cornerstone of an excellent basement RF laboratory.

During the third-order output-intercept determination just described, we assumed that the distortion was a characteristic of the amplifier under test. This may not be true. It is important to determine the IMD characteristics of the spectrum analyzer used for the measurements before the amplifier measurements are fully validated. Specifically, for results to be valid, the input intercept of the analyzer should be much greater than the output intercept of the amplifier under test.

The spectrum analyzer input intercept is easily measured with the same equipment used to evaluate the amplifier. The two tones are applied to the analyzer input with no attenuation present at the analyzer front end. Then, the input tones are adjusted for a full-screen response. In this condition, there should be no trace of distortion. Although this is generally an adequate test, it does not establish a value for the input intercept. To do that, we must overdrive the analyzer, using signals that exceed the top of the screen.

The following steps were used to measure the analyzer input intercept

We calibrated the analyzer for a reference level of -30 dBm with a 30-kHz resolution.

Confirmed the lack of on-screen distortion with two tones at the reference level.

Increased the drive of each tone by 10 dB to provide a pair of -20 dBm tones to the analyzer. This higher-than-reference-level input produced distortion products 66 dB below the reference level, or -96 dBm. The input signals producing this were each -20 dBm, so the IMD ratio is $(-20) - (-96) = 76$ dB. Following the earlier equation, the input intercept was $+18$ dBm.

A 2-dB drive increase produced the expected 6-dB distortion increase. If this had not occurred, distortion measurements under overdrive would be suspect. The $+18$ -dBm value seems to be a good number. This analyzer generally seems happy with signals 20 dB above the top of the screen, but not much more.

The intercept for the analyzer with attenuation in place is the measured value with no pad plus the attenuation. Hence, with 20 dB of attenuation, the input intercept will be $+38$ dBm, and so forth.

Return-Loss Measurements

The next amplifier characteristic that we measured was the input impedance match, or return loss, performed with the setup shown in **Figure 13**. With the signal generator set for a 14-MHz output of about -30 dBm, we set the analyzer for full-scale response with the **LOAD** port of the return-loss bridge open circuited. Placing a 50- termination momentarily on the **LOAD** port, produced a 38-dB signal drop. This is a measure of the bridge directivity. A 38-dB directivity is more than adequate for casual measurements.

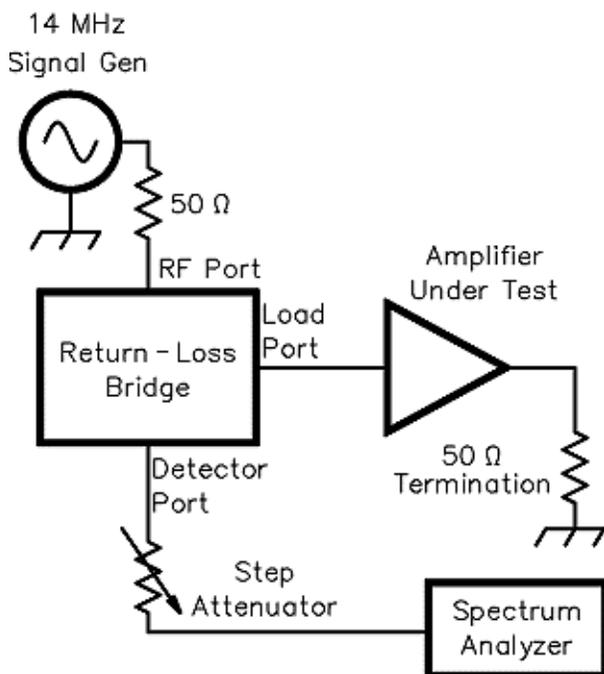


Figure 13—Test setup for impedance-match measurements with return-loss bridge.

Then, we removed the termination from the bridge and placed it on the amplifier output. A short length of cable connected the bridge load port to the amplifier input with power applied to the amplifier. The result was a response 20 dB below the top of the display; 20 dB is the return loss for the amplifier input, an excellent match for a general-purpose amplifier. [20] The match improved slightly when the output load was removed, an unusual situation.

The next variation measured the output match for the amplifier. The load was transferred to the amplifier input and the cable from the bridge **LOAD** port was moved to the amplifier output, producing a reading 15 dB below the screen top. This match was virtually unchanged when the input termination was removed. The weak dependence of both amplifier return losses is the result of a four-stage design. A single-stage feedback amplifier will have port impedances that depend strongly on the termination at the opposite port.

The -30 dBm drive from the generator provides an available power of -36 dBm from the bridge **LOAD** port. This is low enough that the amplifier is not over-driven. The match measurements should be done at a level low enough that the amplifier remains linear. In this case, we saw no difference in the results with drive that was 10 dB higher.

When performing return-loss measurements—and indeed, most spectrum-analyzer measurements—it is wise to place at least 10 dB of attenuation ahead of the spectrum-analyzer mixer. When this attenuation is switched in, the reference level changes from the top of the screen to a point down screen a bit. Return loss is then measured as a decibel difference with regard to the new reference.

Antenna Measurements

It is interesting to look at some other impedance values while the return-loss bridge is attached to the signal generator and spectrum analyzer. The obvious choice is the station antenna system, especially if it is connected through a Transmatch. Playing with the tuning will readily demonstrate that the return-loss bridge and sensitive detection system will allow adjustments to accuracy unheard of with traditional diode detector systems. Although such tuning accuracy is not needed in a normal antenna installation, it is interesting to see what can be measured when the need does arise.

Transmitter Evaluation

Another obvious application for a spectrum analyzer is in transmitter evaluation. **Figure 14** shows the output of a typical QRP transceiver kit. The 1-W plus output at 7 MHz is the dominant signal, with all others being transmitter spurious outputs. All spurs are more than 40 dB down, which meets current FCC specifications. On the other hand, significantly better performance is easily obtained, especially if the builder has the facilities to measure them. **Figure 15** is a photograph of a simpler QRP rig with two measurable spurious responses. One is the 3.5-MHz feedthrough from the VFO at -64 dBc; the second is a harmonic at -44 dBc.

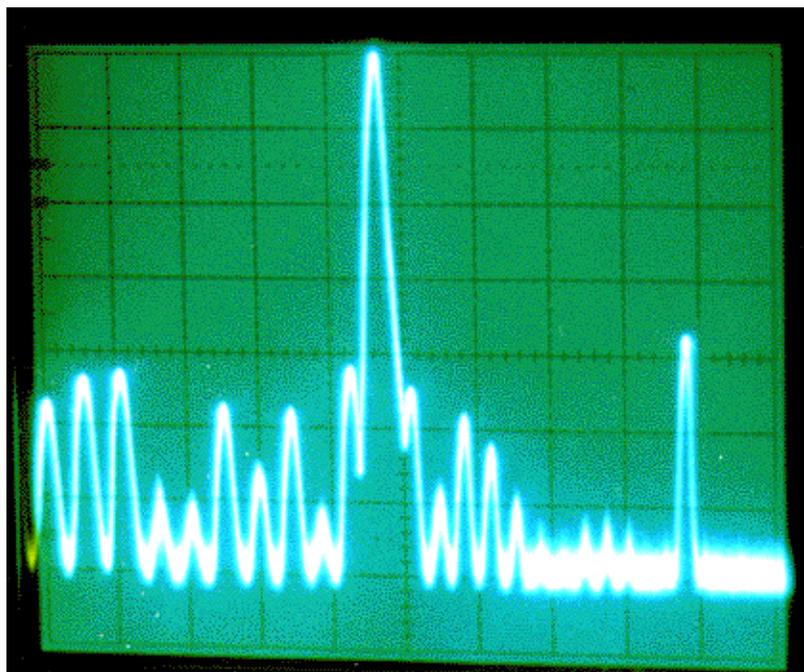
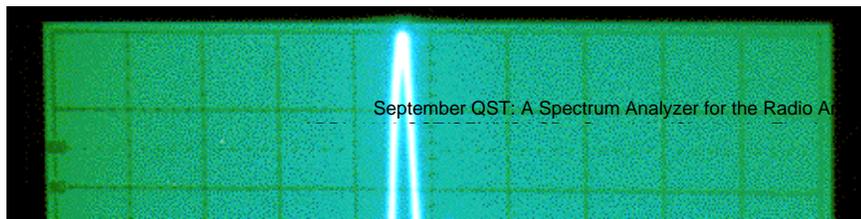


Figure 14—Output of a typical QRP transceiver kit. The 1-W plus output at 7 MHz is the dominant signal; all others are spurious outputs more than 40 dB down, currently meeting FCC specifications.



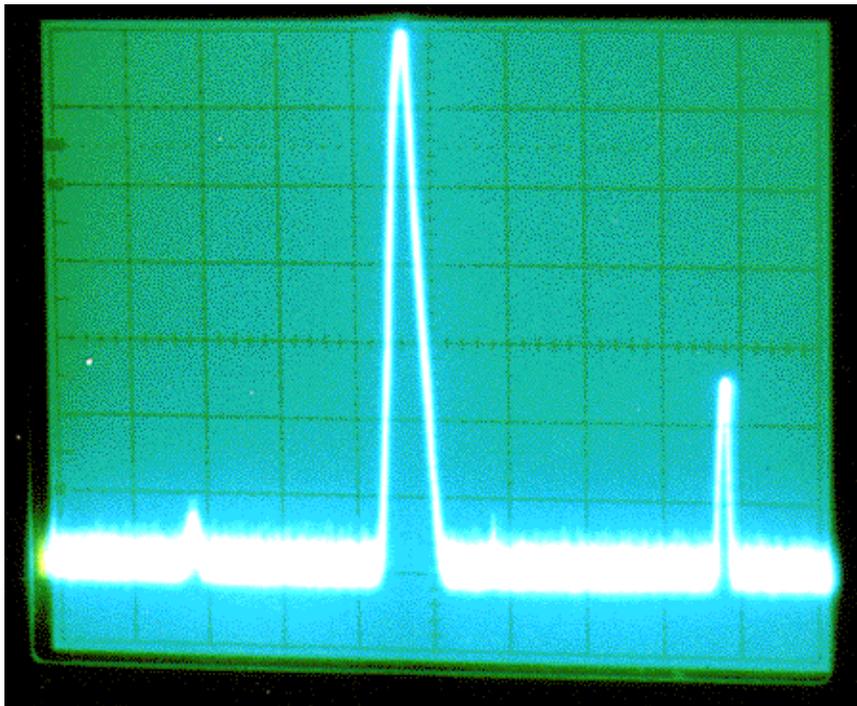


Figure 15—Output of a simple homemade QRP rig. The desired signal is the large pip at the center of the trace. Two measurable spurious responses exist, one to the left and one to the right of the main signal. The response to the left is 3.5 MHz feedthrough from the VFO at -64 dBc; the response to the right of the desired signal is a second harmonic at -44 dBc.

The output available from a typical QRP rig (and certainly higher power rigs) is enough to damage the spectrum-analyzer input circuits. Attenuators that we generally build are capable of handling 0.5 to 1 W input without damage, while commercial attenuators are rated at from 0.5 to 2 W input. The mixers used in this analyzer can be damaged with as little as 50 to 100 mW signals. Two methods can be employed to view the output of a high-power transmitter without causing damage to the spectrum analyzer. In one, the transmitter output is run through a directional coupler with weak coupling to the sampling port—perhaps -20 to -30 dB. The majority of the output is dissipated in a dummy load. The second method uses a fixed, high-power attenuator. **Figure 16** shows an attenuator that will handle about 20 W while providing 20-dB attenuation. The design is not symmetrical.

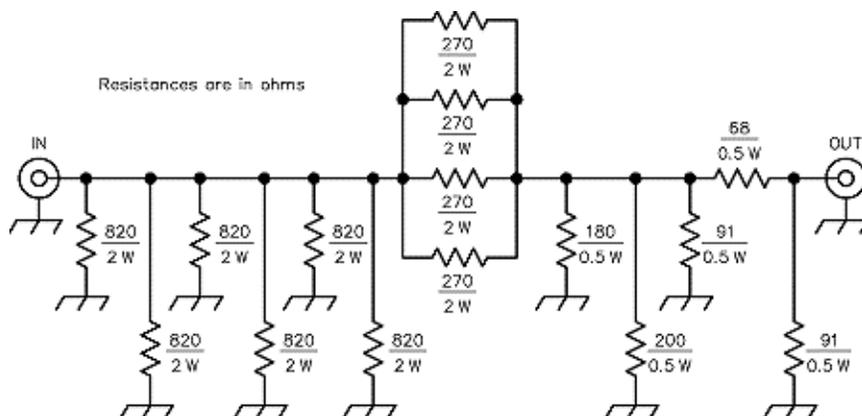


Figure 16—A 20-W, 20-dB attenuator for transmitter measurements.

Spectrum Analysis at Higher Frequencies

Although the 70-MHz spectrum analyzer is extremely useful, we constantly wish that it covered higher frequencies. Not only do we want to experiment on the VHF and UHF bands, but we need to examine higher-order harmonics of HF gear. One method we can use with a regular receiver is a converter, usually crystal controlled. The same can be done with a spectrum analyzer, although crystal control is not needed. We can build a simple block converter, consisting of nothing more than a 100 to 200 MHz VCO (just like that used in the analyzer) and a diode ring mixer. A Mini-Circuits POS-200 VCO with a 3 dB pad will directly drive a Mini-Circuits SBL-1 or TUF-1 mixer to produce a block converter with a nominal loss of 10 dB. (One of the spectrum analyzer front-end boards could be used, with slight modification, for the block converter.)

This block converter allows analysis of much of the VHF spectrum. With the converter VCO set at 100 MHz, frequencies from 100 to 170 MHz are easily studied. The 70 to 100-MHz image is also available—it can also lead to confusion, as a few minutes with a signal generator will demonstrate. With the converter VCO up at 200 MHz, the 200 to 270 MHz spectrum is also available. Clearly, there is nothing special about the particular VCO used in the converter. All that is required to convert other portions of the low UHF spectrum to the analyzer range is a different VCO, and perhaps, a higher-frequency mixer. We will soon build similar block converters to allow analysis of the 432-MHz area. One of the popular little UHF frequency counters is quite useful with these converters. The block converters should be well shielded and decoupled from the power supply.

Even without the analyzer, the block converter is a useful tool. For example, it can be used with a 10 MHz LC band-pass filter and an amplifier to directly drive a 50-terminated oscilloscope. This can serve as a sensitive detector for the alignment of a 110-MHz filter.

As useful as the block downconverter is, it has image-response problems that can greatly confuse the results. The preferred way to get to the higher frequencies is with a spectrum analyzer—just like the one we have described—but having higher-frequency oscillators and front-end filters. If you're careful, you can build helical resonator filters for the 500-MHz region, or higher, with sufficiently narrow selectivity to allow a second conversion to 10 MHz. A more practical route uses a third IF. Such a triple-conversion analyzer is shown in **Figure 17**, where a 1 to 1.8 GHz VCO moves signals in the 0 to 800-MHz spectrum to a 1 GHz IF. This signal is still easily amplified with available monolithic amplifiers. Building a 1 GHz filter should not be too difficult, for a narrow bandwidth is not required. A bandwidth of 20 or 30 MHz with a three-resonator filter would be adequate. The resulting signal is then heterodyned to a VHF IF (such as 110 MHz) where the remaining circuitry is now familiar.

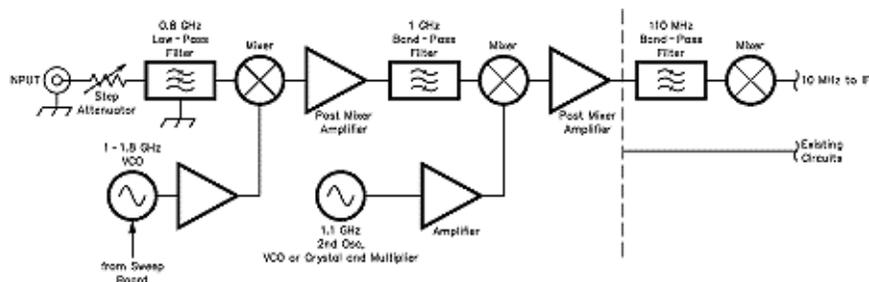
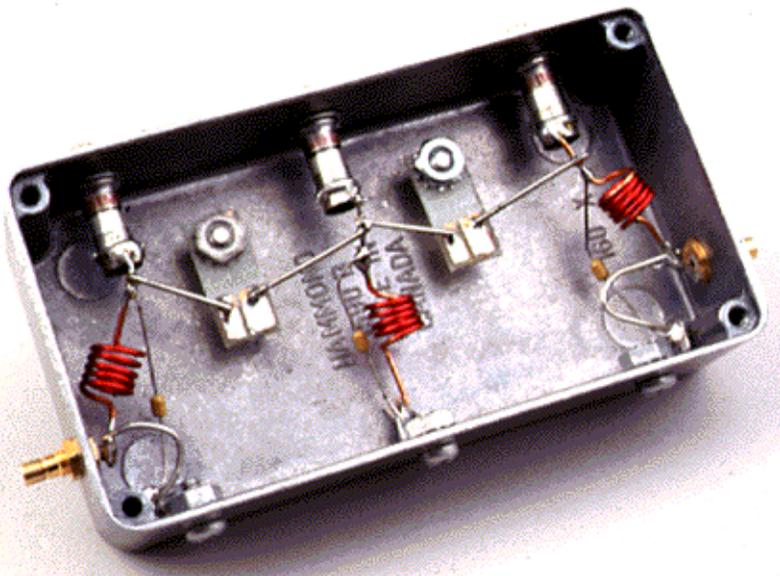


Figure 17—Block diagram for a version of this analyzer that will function into the VHF and low-UHF regions.

Clearly, there are several ways to attack the project. Recent technology offers some help in the way of interesting band-pass filter structures, as well as high-performance, low-noise VCOs. Time spent with some catalogs and a Web browser could be very productive in this regard. Just as important is the experience that the lower-frequency analyzer will provide. Not only is it the tool (perhaps supplemented with block converters) that is needed to build a higher-frequency spectrum analyzer, but it is the vehicle to provide the confidence needed to tackle such a chore.





An inside view of a prototype VHF band-pass filter. See Figure 7.

Summary

This analyzer has been a useful tool for over 10 years now. It was a wonderful experience and fun to build HF and VHF CW and SSB gear with the "right" test equipment available. We have built special, narrow-tuning-range analyzers to examine transmitter sideband suppression and distortion. The equipment uses the same concepts presented.

There are many ways that this instrument can grow. One builder has already breadboarded a tracking generator. (Let's see that in QST!—Ed.) Many builders will want to interface the analyzer with a computer instead of an oscilloscope. A recent **QST network analyzer paper (part 1)(part 2)** suggests circuits that may provide such a solution. [21]

A recent **QST summary of WRC97 (also Technical Correspondence, Unwanted Emissions Comments) [22]** outlines new specifications regarding spurious emissions from amateur transmitters. Generally, the casual specifications that we have enjoyed for many years are being replaced by new ones that are more stringent—and more realistic in safeguarding the spectral environment and reflecting the sound designs that we all strive to achieve. Equipment such as the spectrum analyzer described here can provide the basic tool needed to meet this new challenge.

Acknowledgments

Many experimenters had a hand in this project and we owe them our gratitude. Jeff Damm, WA7MLH, and Kurt Knoblock, WK7Q, built versions of the analyzer and have garnered several years of use with them. Their experiences have been of great value in our efforts. Barrie Gilbert of Analog Devices Northwest Labs suggested the AD8307 log amplifier and provided samples and early data needed for evaluation measurements. Many of our colleagues within the Wireless Communications Division at TriQuint Semiconductor have helped us with filter measurements. Thanks go to George Steen and to Don Knotts, W7HJS. Finally, special thanks go to our colleague in the receiver group at TriQuint, Rick Campbell, KK7B, who provided numerous enlightening discussions and suggestions regarding the preparation of the paper and the role of measurements in amateur experiments.