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May/June 2015

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QEX

A Forum for Communications Experimenters

Issue No. 290

VK5FE designed this Tricorder to serve three important functions on an Amateur Radio test bench. His version of a hand-held tool provides a 500 MHz RF signal generator, a low power meter and a scalar network analyzer.

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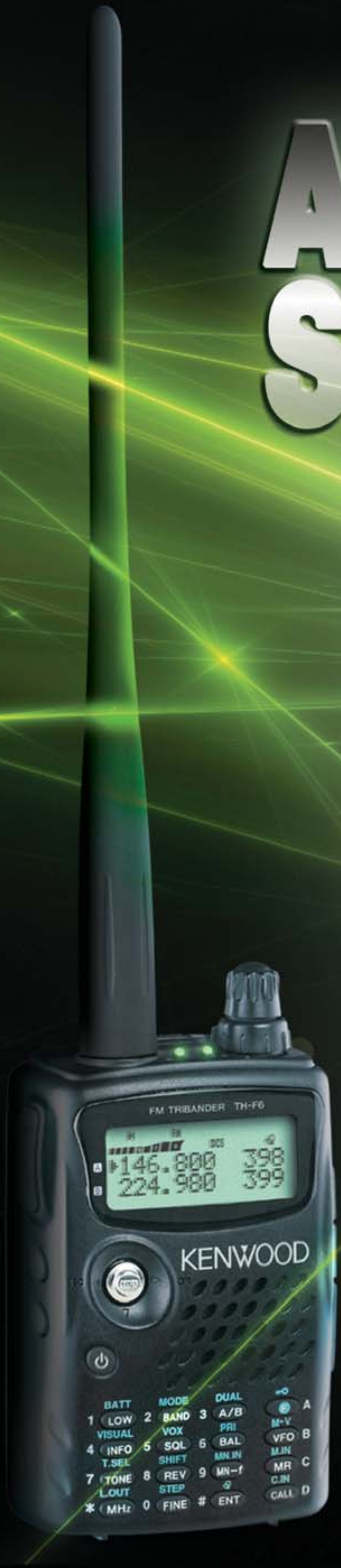
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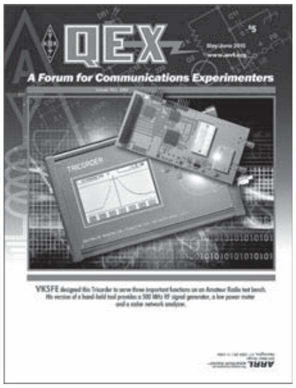
May/June 2015

About the Cover

Rubens Fernandes, VK5FE, built his own version of a Tricorder. His hand-held tool serves three important functions: it includes a 2 kHz to 500 MHz, –130 to +8 dBm RF generator, a 150 kHz to 500 MHz, –65 to +8 dBm power meter, and a 150 kHz to 500 MHz scalar network analyzer. A TFT touch screen provides input control and data display capabilities.



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The purpose of *QEX* is to:

1) provide a medium for the exchange of ideas and information among Amateur Radio experimenters,

2) document advanced technical work in the Amateur Radio field, and

3) support efforts to advance the state of the Amateur Radio art.

All correspondence concerning *QEX* should be addressed to the American Radio Relay League, 225 Main Street, Newington, CT 06111 USA. Envelopes containing manuscripts and letters for publication in *QEX* should be marked Editor, *QEX*.

Both theoretical and practical technical articles are welcomed. Manuscripts should be submitted in word-processor format, if possible. We can redraw any figures as long as their content is clear.
Photos should be glossy, color or black-and-white prints of at least the size they are to appear in *QEX* or high-resolution digital images (300 dots per inch or higher at the printed size). Further information for authors can be found on the Web at **www.arrl.org/qex/** or by e-mail to **qex@arrl.org**.

Larry Wolfgang, WR1B

Empirical Outlook

Changes for QEX

By the time you turn to this page, you will have noticed some fairly radical changes to the way your magazine looks. With this issue, we have switched to a lighter paper stock, and have used that same stock for the cover. With this change, the entire magazine, including the cover, can be printed on the same press, rather than requiring a different press, and a different set-up for the heavy, glossy cover stock we were using.

Over the years, *QEX* has undergone a quite a few changes, both to the overall magazine style as well as to the printing and the paper type used. In 1981, Paul Rinaldo, W4RI, had published a short newsletter as an experimenter's idea exchange. At first it was just a few pages of photocopied paper, stapled together. With the December 1981 issue of that newsletter, *QEX* was born! That issue had 14 pages — 7 sheets of 11 × 17 paper, folded and stapled in the middle — with a promise to publish an issue every other month, at least until a suitable flow of articles had been established.

Over the first few months of 1982 the magazine grew to 18 and then 20 pages. By May 1982 *QEX* changed to a monthly publication schedule. Each issue was 10 or 12 pages over the next several years. In March 1986 we switched to a glossy paper cover, although it was still only black and white.

In October 1986 *QEX* included the *AMSAT Satellite Journal*, and that partnership lasted until June 1989. During that time, most issues were about 20 pages, and the glossy cover stock added some color in the design, although the photos were all black and white. The June 1989 issue of *QEX* no longer included the *AMSAT Satellite Journal*, and with the July issue that year, the magazine switched back to a plain paper cover. The page count remained a fairly steady 20 pages.

With the January 1994 issue, *QEX* came with a glossy black and white cover stock. Over the next several years *QEX* published 20 to 24 pages in each issue. For the January/February 1998 issue, we changed to an every other month publication schedule and added color to the glossy cover stock, this time with color photos as well. That issue also began a run of 64 page issues.

Another significant change occurred with the Nov/Dec 2000 issue. CQ Communications published a technical magazine named *Communications Quarterly* from the Fall 1990 through Winter 1999 issues. Most issues had a bit more than 100 pages. No doubt it was mostly an economic move for CQ Communications to stop publishing *Communications Quarterly*, but it had a small following of highly technical readers, and a steady stream of excellent articles. ARRL purchased the rights to this magazine and added it into *QEX* for the last issue of 2000. The cover of QEX said "*QEX* Including *Communications Quarterly*" through the January/February 2006 issue.

We dropped the *Communications Quarterly* tag on the March/April 2006 issue. No doubt many authors who would have submitted their articles to *Communications Quarterly* over that time were sending them to *QEX* instead. (The March/April 2006 issue of *QEX* was also my first as Managing Editor.)

Throughout its history, *QEX* has remained "A Forum for Communications Experimenters." Radio Amateurs from around the world know that if they have some technical topic to write about or a project they want to share, *QEX* is the place to do it. Readers also know that if they want the best coverage of technical topics in Amateur Radio communications and electronics, there is only one place to turn.

While reviewing the changes *QEX* has gone through over the years, it is clear that economics has driven many of those changes. Of course ARRL wants *QEX* to be the best technical magazine that it can be, and we love printing on that heavy paper stock, and those glossy color covers that our Graphics Supervisor, Sue Fagan, KB1OKW, designs for each issue never fail to grab our attention! The reality, however, is that the heavy paper and cover stock comes at a price. We have seen our paper costs rise significantly, and mailing costs have also risen considerably. Those trends are not going to reverse any time soon, if ever. Meanwhile, the subscription rate for *QEX* has remained the same since the July/August 2001 issue!

Something had to change to maintain *QEX* as a strong technical publication. ARRL management has been looking at various options, and the decision to switch to a less expensive paper, including the cover stock, seemed like the most cost effective way to go. The lighter paper is less expensive, and that will also significantly reduce mailing costs. Those savings will allow us to continue publishing *QEX* for the foreseeable future.

We're glad you are along for the ride. Thank you for your continued interest in *QEX*. Tell your friends what they are missing if they are not reading *QEX* regularly. Of course we also need you to continue sending us the best technical articles, because that is an important part of a strong magazine!

As we were finalizing this issue, we received information about the ARRL/TAPR Digital Communications Conference for this year. The DCC will be held October 9, 10 and 11 2015 at DoubleTree by Hilton — Chicago, 75 West Algonquin Road, Arlington Heights, IL 60005. More details will be posted on the TAPR website (**www.tapr.org/conferences.html**) by the time you read this. Make plans now to attend!

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The Tricorder — A Self-Contained and Integrated 500 MHz RF Signal Generator, Power Meter and Network Analyzer

Here is a 2 kHz to 500 MHz, –130 to +8 dBm RF generator, 150 kHz to 500 MHz, –65 to +8 dBm power meter, 150 kHz to 500 MHz scalar network analyzer, touch screen, external reference option and more.

I have always wanted to build an RF generator. I have been looking through the Amateur Radio literature for a long time, especially old ARRL *Handbooks*, trying to find something that could cover at least the HF bands, but the available designs had restricted coverage and didn't have an accurate level and frequency control, which was a feature I wanted.

Then designs based on direct digital synthesis (DDS) ICs started to pop up in the literature, but spurs were something that appeared to be part of its wild nature, and in the next years great effort was made to tame this beast. The fact is that those devices were fantastic, an engine that could generate frequencies in a broad range, requiring just a reference oscillator and a controller.

Three facts definitively convinced me that it was time to design the generator, even considering that over the years I had gathered enough courage to buy a good commercial unit: a request from a friend, some excellent QEX articles written by Thomas Alldread, VA7TA, and Jim Koehler, VE5FP, along with the performance of modern DDS families.[1, 2]

During the initial phase of my project, while collecting information for the block diagram, I realized that if I had an accurate generator and power meter, I could also have a scalar network analyzer, which is an extremely useful tool.

I wanted to reach 500 MHz, to cover the 70 cm band, but the recommended maximum frequency for the particular DDS IC I was looking at was 400 MHz. To achieve that I had to include an extension board, using a solution that we will see in detail in the next sections. I also wanted a compact unit that didn't have to be hooked up to a computer.

I confess that my main intention was not to design something friendly from the point of view of replication, but instead, something that could reach the performance I wanted, independently of the assembly technique required. The consequence is that this is far from an easy weekend project; it uses components with tight pitches and concealed exposed pads, requiring advanced soldering skills. Nevertheless, it can be replicated and I will try to make available some surplus boards for purchase for those interested, along with fully functional firmware, in hex format, which can be downloaded from the ARRL *QEX* files website.[3]

I believe I have attained my goals with this project. It was a long development, grown practically from scratch: I spent many, many hours developing and testing hardware and software, and convincing them to talk to each other nicely.

A Word About Power Meters, Network Analyzers and Generators

Initially, let's consolidate some concepts. First of all, "network analysis," in this context, has nothing to do with computers. I am always referring to electronic circuits, or more precisely, RF circuits.

When the expression "network analyzer" comes up, normally the first thought is that it is related to an instrument that measures the scattering parameters (S parameters). Actually, this is correct, in the sense that a "full" network analyzer (vector network analyzer or VNA) measures magnitude and phase of the transmitted and reflected wave. In fact, in many applications the phase plays a very important role, and modern, dedicated, professional network analyzers are mostly VNAs. In many applications, however, scalar measurements (no phase) are perfectly satisfactory, and in those cases scalar network analyzers (SNAs) can be used, with the advantage of lower price and a simpler initial calibration.

VNAs and SNAs are selective devices, except when for some reason broadband

[1]Notes appear on page 22.

detection has to be used. Narrowing the measuring window will limit the noise, improving the dynamic range (in short, dynamic range here is the maximum power than can be measured less the noise floor). True VNAs and SNAs are normally specialized instruments.

Nevertheless, there are other ways of making scalar measurements. One of them is the use of a spectrum analyzer / tracking generator pair. This is a cost-effective solution, as spectrum analyzers can be used in a variety of applications. One disadvantage is the fact that a spectrum analyzer can only make transmission measurements, but this can be overcome with the use of an accessory called a return loss bridge (more about this later).

Another point is that because a spectrum analyzer is a selective instrument, we don't necessarily need a high quality harmonic free tracking generator. In fact, the generator doesn't even have to be perfectly flat across the entire frequency range. The level variations will be compensated when a pre-calibration, called "normalization," is done. Spectrum analyzers combined with tracking generators measure the insertion loss of a device under test (DUT). With the help of a return loss bridge, they can also measure the return loss.

At this point, for the sake of technical coherence, we must say that for the same measuring configuration, the magnitude of the S21 (or S12) parameter and insertion loss, even having different definitions, will be represented by the same number, but with different signs (both expressed in dB). The same can be said in relation to the S11 (or S22) parameter and return loss. Notice that, for passive structures, return loss and insertion loss are positive numbers. They are all usually expressed in dB.

Professional power meters, on the other hand, are essentially broadband devices and normally very accurate, but won't have a dynamic range comparable to the selective measuring devices. So, care must be exercised when comparing the measurement of power using power meters and, for example, spectrum analyzers (fundamental) – the result will tend to be the same when the signal tends to be a perfect unmodulated sinusoid having an adequate level.

Another way of making scalar measurements is using a high quality RF generator and a power meter. This configuration has been suggested lately by manufacturers with both instruments externally controlled by a PC and dedicated

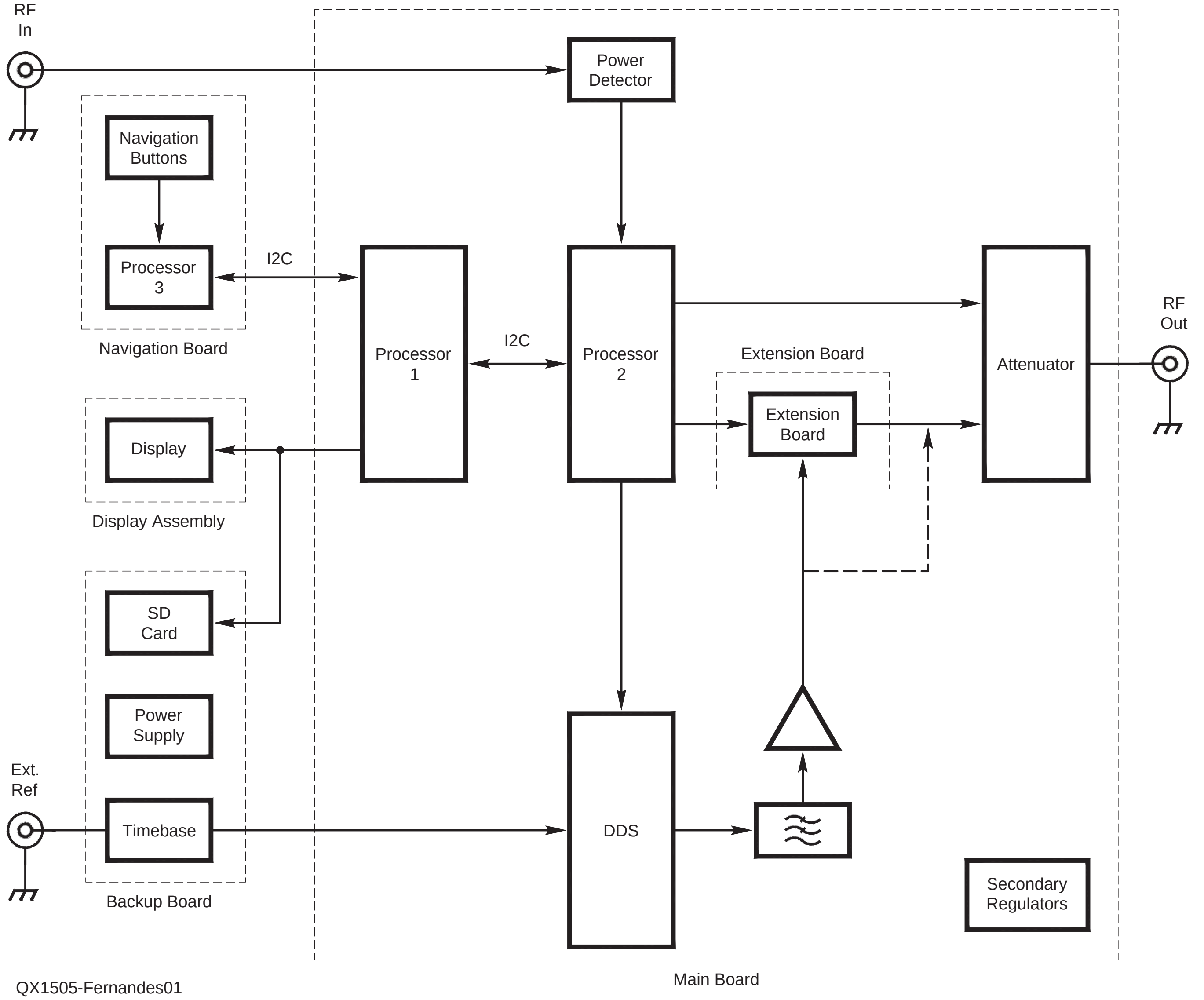


Figure 1 — This block diagram shows the basic architecture of the Tricorder.

software, as a form of extending the use of existing instrumentation.

The term "network analyzer" or "network analysis" has been used lately in a more relaxed way; calling the spectrum analyzer/tracking generator pair or RF generator/power meter pair a scalar network analyzer has been considered normal even by manufacturers of professional equipment.

The Tricorder uses this last concept in its scalar network analyzer— an RF generator and a power meter, combined to show in its display the insertion loss and return loss curves of a device under test (the latter with the help of an external return loss bridge). The advantage here is that we have three fairly accurate instruments in one, and the device is portable, which makes it a flexible device for the amateur experimenter.

Architecture

Figure 1 is the Tricorder block diagram. Figure 2A is a picture of the various circuit boards and Figure 2B shows a close-up of the assembled unit. Practically all interconnections are made directly with circuit board connectors, except the connection with the Navigation Board and the ON/OFF switch. RF connections are made with coaxial cables with UFL connectors.

Most of the flexibility of the Tricorder resides mainly in two Analog Devices ICs — the amazing AD9910 and the well known AD8307. They are supported by three processors from Microchip, which communicate with each other through an I2C interface.

One processor (the master) is responsible for controlling the display, the SD card, and also checks the consistency of the input data. The second processor controls the DDS, the extension board, and processes the information coming from the power detector. These processors are both 16 bit units. There is a third tiny 8-bit processor responsible for the navigation buttons — it sends the button status to the master when requested.

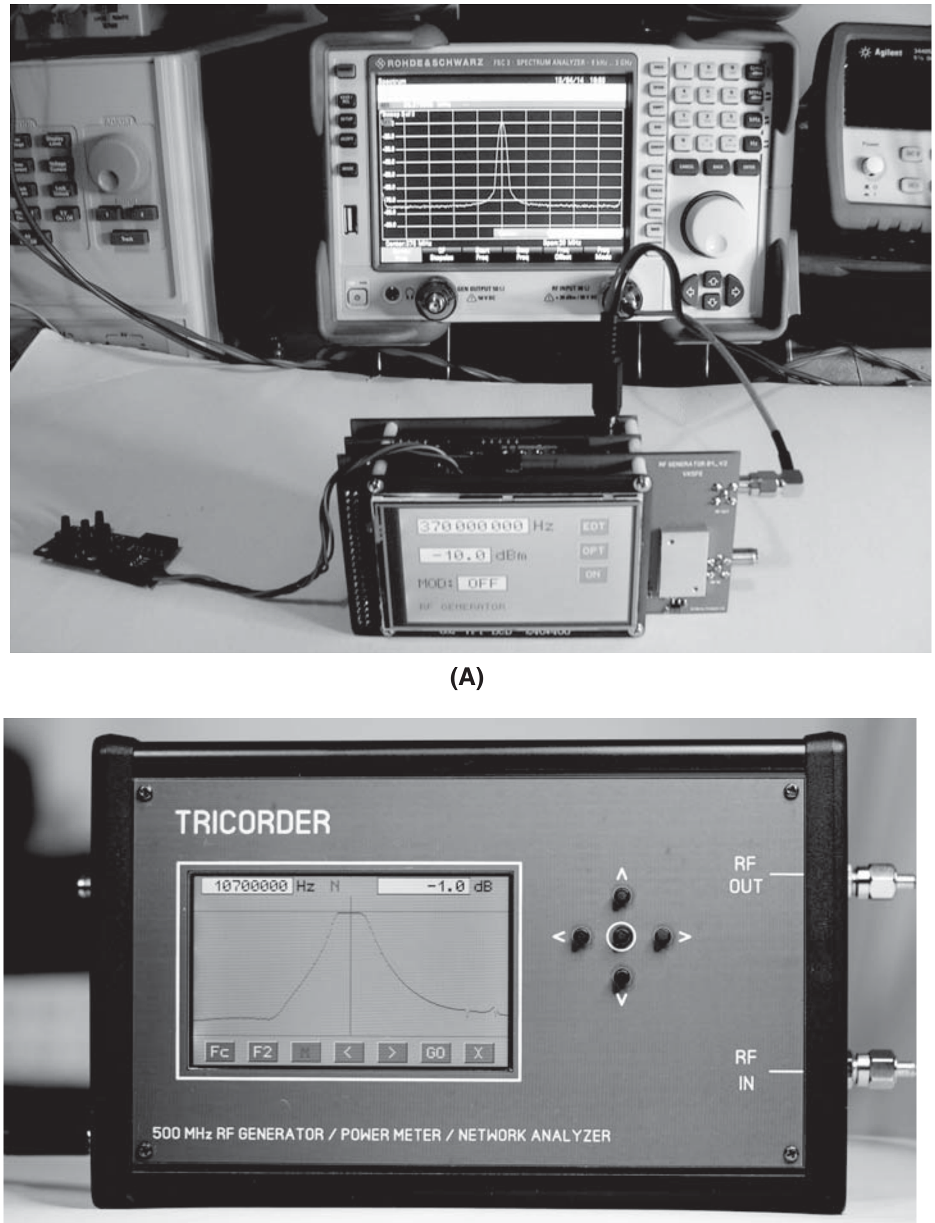
There are four circuit boards, as the block diagram shows. The Main Board includes the master processor, the DDS IC and associated circuitry. The Backup Board includes the main power supply, the internal time base, and the SD card connector. The Navigation Board is very small, accommodating the navigation buttons and the respective processor. The Extension Board is optional: if used, the frequency range of the device is expanded from 400 MHz to 500 MHz.

The Tricorder is very accurate for a homebrew device, typically about 0.5 dB across the entire range, and there are two main reasons that explain this performance: first, the DDS output level does not have discontinuities in the range, making it predictable and relatively easy to be compensated in software, and second, a different approach was used for measuring power, as we will see later.

The internal levels in the attenuator region of the circuit board, when they are at their limits, are very low. The Mini-Circuits chips have a tiny DG983-1 package, and the circuit board tracks have to be very thin, especially when they are used in tandem. This is the reason why I used only two chips. I found that when levels below about –110 dBm are needed, the best option was to use external coaxial attenuators to maintain the output impedance and output level accuracy.

During the initial calculations, I saw that power dissipation could be a problem in such a compact device. I always start from a 12 to 13.8 V external power supply, and most of the chips work with 3.3 V dc, the others with 5 V dc. A careful power distribution scheme had to be used; the DDS has the necessity of different low noise sources of supply for different internal circuits, if you want to attain the datasheet performance. So, the best thing to do would be to have a reliable 5 V dc source and then distribute power with individual low noise regulators. Looking carefully at the schematics, you will notice that I followed this strategy.

The whole unit draws about 950 mA at 5 V dc, and this would be a serious problem



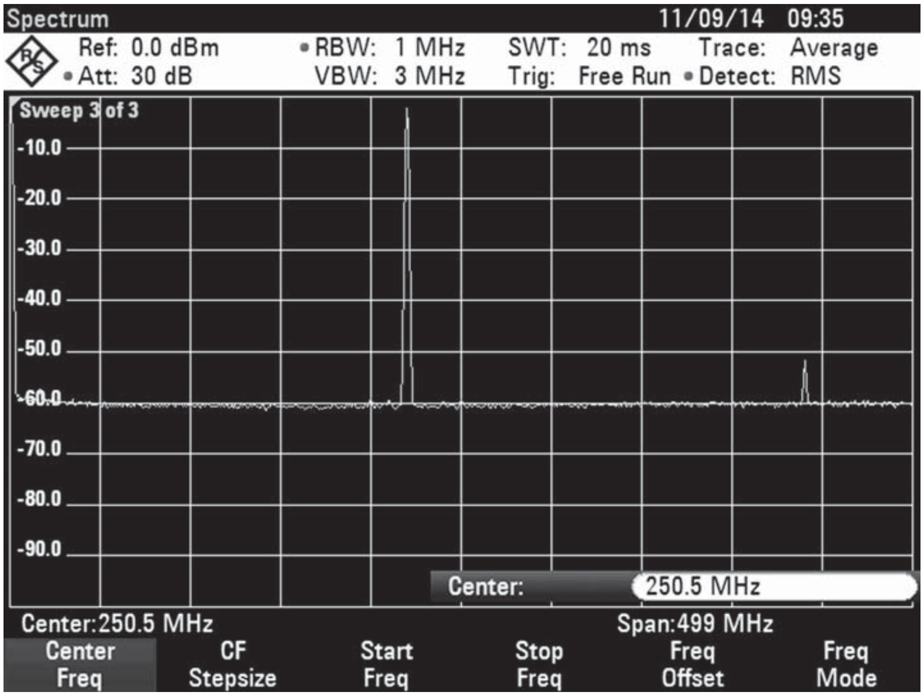
(A)

(B)

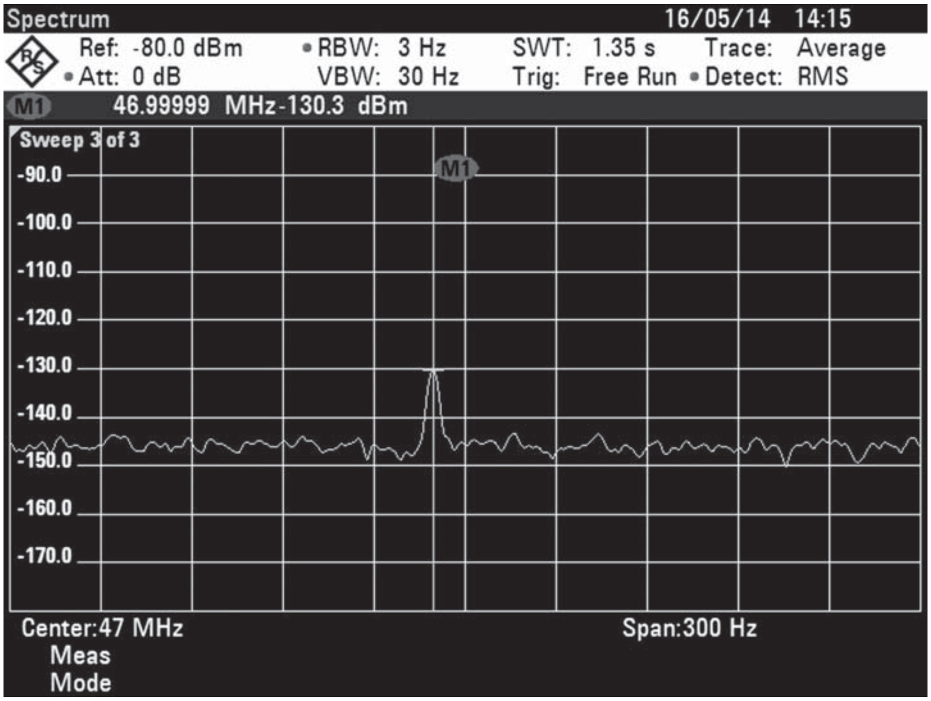
Figure 2 — Part A shows the "sandwich" of Tricorder circuit boards before the unit was packaged into a box. Here the unit is connected to a Rohde & Schwarz spectrum analyzer, for comparative measurements. Part B shows the packaged Tricorder, ready for use.

if I had used a series regulator to bring the external supply down to 5 V dc, because a difference of up to 8.8 V dc would be present in the series transistor, meaning that more than 8 W would have to be dissipated. This would have significantly increased the internal temperature of the Tricorder and would practically kill my intention of designing a portable device. The solution was to include a high efficiency buck converter from Texas Instruments, and take the correct precautions for not allowing its internal oscillator to spread noise to other parts of the Tricorder.

Shielding of some internal regions of the Tricorder is mandatory. Shielding was applied to the buck converter, to the internal time base, to the attenuator and to the power detector. In the case of the power detector, more than 10 dB of dynamic range would be lost without this precaution.



(A)



(B)

Figure 3 — Photo A shows the Rohde & Schwarz spectrum analyzer screen for the measurement of a 0 dBm, 220 MHz signal from the Tricorder RF generator. Note the second harmonic of the main signal near the right edge of the screen. Photo B is the R&S spectrum analyzer display for a –130 dBm, 47 MHz signal. An external 30 dB of attenuation was used to obtain this signal level from the generator.

Although some sort of keyboard was a necessity, I didn't want to use those clumsy units on the front panel, since that would defeat my goal of keeping the device small and portable. The solution was to implement the keyboard in software and to use a touch screen display. The consequence is a clean front panel, with just five small direction buttons. All of the other controlling functions were implemented in software.

The RF Signal Generator

There are some important things that have to be taken into account when designing a general purpose analog RF signal generator: the spurs, the harmonics (not considered spurs, in this context), output level and frequency accuracy, phase noise and modulation capabilities, among others.

Thanks to its digital nature, the result of using a DDS as its heart and a voltage controlled, temperature controlled crystal oscillator (VCTCXO) time base reference, the frequency accuracy in the Tricorder is not a concern. Level accuracy, as said before, was achieved by the predictable nature of the DDS, calibration and software-corrected levels across the range.

In the Tricorder, the DDS programming was based on a 1 GHz system frequency, and since this was to be a general purpose portable device, I decided to use a 10 MHz, low phase noise time base. The consequence is that the internal DDS PLL has to provide a frequency multiplication of 100, theoretically increasing the phase noise by 40 dB (20 Log 100). Unfortunately, I don't have resources for measuring low phase noise levels, but inspecting and comparing the phase noise using a spectrum analyzer (not the right tool in this case, I must say), it seems that that the Tricorder noise is what we could expect on a DDS based device.

Even so, to add more flexibility in the case of demanding applications, I included in the circuit layout and in the software, the possibility of using an external high performance time base of 10 MHz and also 100 MHz and 1 GHz, the last two being injected directly into the DDS. Notice that for 100 MHz, the PLL loop filter will have to be redesigned.

The other point is related to spurs. This is, certainly, the major concern about the use of direct digital synthesizers in Amateur Radio communications. Nevertheless, the AD9910 behaved well — there are a couple of known spurs (as is the case even with professional equipment) but DDS-generated spurs can be kept, in general, as low as –60 dBc with adequate use of external attenuators — very good, in my opinion, for a homebrew device (still better in the case of narrowband spurs). Figure 3A shows a 0 dBm, 220 MHz CW signal in the 1 MHz to 500 MHz range, and we can see its second harmonic near the right edge of the display.

Harmonics are very low, and in general can be neglected; they increase a bit for high output levels, but in this case they are not generated in the DDS, but instead in the level amplifiers.

The output level is controlled using the internal attenuation capabilities of the AD9910 and two adjustable Microchip attenuators — the combined action can set the output level from +8 dBm (depending on the frequency) down to –110 dBm. With an additional external 30 dB attenuator, the level can reach –130 dBm; enough for general receiver sensitivity tests. Figure 3B shows a –130 dBm carrier at 47 MHz. For higher frequencies, more external attenuation may be needed to keep the general accuracy of about 0.5 dBm. See Table 1 for a listing of measured values compared to the output setting.

When using the extension board, the internal attenuator of the AD9910 can't be used — the reason is that the doubler needs a high input level, so the output level can only be controlled with the two Mini-Circuits attenuators. Nevertheless, an additional 30 dB attenuator can be added to the output. The software allows the input of external attenuator values, so the display will always show the correct output level.

The Tricorder offers amplitude modulation (AM) and frequency modulation (FM). Phase modulation (PM) is still to be implemented. Both modulating frequency and modulation index can be changed — all this is implemented in software, thanks to the great flexibility of the AD9910. Figure 4A (time domain) and Figure 4B (frequency domain) show the good quality of the amplitude modulation. Figure 5 shows the frequency domain display of a 147 MHz carrier that is frequency modulated by a 1 kHz modulating frequency. The modulation index in this case is 2.405, corresponding to the first Bessel null. The AD9910 has amazing waveform generation capabilities.

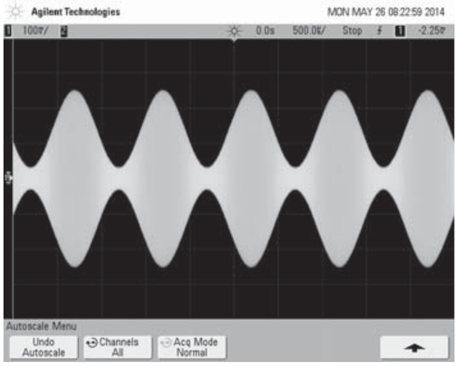
The frequency range of the generator, as you may have noticed, is broader than the range of the power meter and scalar network analyzer. The low frequency limit was extended to 2 kHz.

The Power Meter

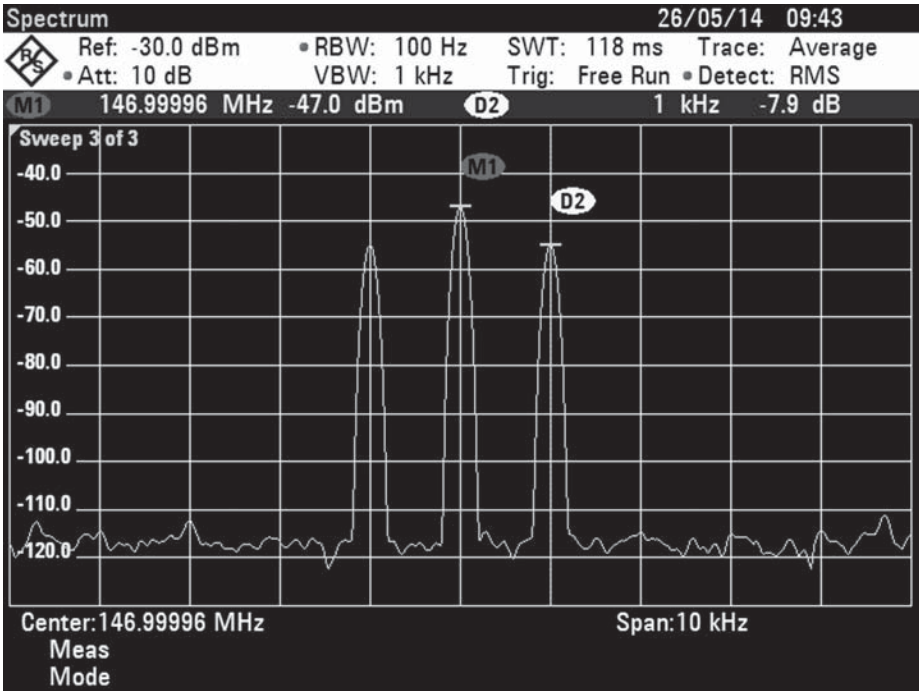
The AD8307 has been used extensively in Amateur Radio projects, since it appeared in a June 2001 *QST* article written by Wes Hayard, W7ZOI, and Bob Larking, W7PUA.[4] This chip has pretty good linearity, wide dynamic range, and consistent repeatability, as confirmed in a Jan/Feb 2014 *QEX* article

Table 1
RF Generator Settings Versus Measured Output

Frequency (MHz)						*Measured Output Power (dBm)*											
Setting	*+8*	*+5*	*0*	*–5*	*–10*	*–20*	*–30*	*–40*	*–50*	*–60*	*–70*	*–80*	*–90*	*–100*	*–110*	*–120*	*–130*
Measured Values																	
0.002	-	-	-	–5.5	–10.4	–20.4	–30.4	–40.4	–50.3	–60.4	–70.4	–80.3	–90.3	–99.7	–110.3	–120.3	–130.3
0.005	-	-	–0.2	–4.9	–9.9	–19.8	–29.8	–39.8	–49.9	–59.8	–69.9	–79.8	–89.9	–99.8	–109.9	–119.9	–129.9
0.010	-	-	–0.2	–4.9	–9.9	–19.8	–29.8	–39.8	–49.8	–59.8	–69.8	–79.8	–89.8	–100.4	–109.8	–119.8	–129.8
0.050	-	-	–0.5	–5.5	–10.3	–20.3	–30.3	–40.3	–50.2	–59.9	–69.9	–79.9	–90.3	–100.0	–110.3	–120.3	–130.3
0.100	-	-	–0.5	–5.4	–10.2	–20.2	–30.2	–40.4	–50.3	–60.0	–70.0	–80.2	–90.3	–100.4	–110.3	–120.3	–130.3
0.150	-	-	–0.5	–5.4	–10.2	–20.1	–30.3	–40.3	–50.2	–60.2	–69.9	–80.0	–90.0	–99.7	–110.0	–120.0	–130.0
0.200	-	-	–0.4	–5.4	–10.2	–20.1	–30.2	–40.2	–50.2	–59.9	–69.9	–80.0	–90.1	–100.1	–110.1	–120.1	–130.1
0.500	-	-	–0.3	–5.3	–10.0	–20.1	–30.3	–40.2	–50.2	–60.2	–70.0	–80.1	–90.1	–100.1	–110.4	–120.3	–130.2
1.000	-	-	–0.3	–5.3	–10.2	–20.2	–30.3	–40.3	–50.2	–60.2	–70.1	–80.2	–90.2	–100.2	–110.5	–120.3	–129.9
5.000	7.4	4.6	–0.3	–5.4	–10.3	–20.3	–30.4	–40.4	–50.3	–60.3	–70.3	–80.4	–90.4	–100.4	–110.5	–120.3	–130.3
10.000	7.5	4.7	–0.3	–5.2	–10.3	–20.2	–30.3	–40.3	–50.3	–60.3	–70.3	–80.4	–90.4	–100.4	–110.4	–120.4	–130.2
50.000	7.9	5.1	0.2	–4.7	–9.8	–19.8	–29.7	–39.8	–49.9	–59.8	–69.9	–80.0	–89.9	–98.9	–109.9	–119.8	–130.0
100.000	7.7	4.8	–0.1	–5.1	–10.2	–20.2	–30.2	–40.1	–50.2	–60.2	–70.2	–80.1	–90.0	–100.0	–110.1	–120.0	–129.6
150.000	7.6	4.8	–0.2	–5.2	–10.2	–20.2	–30.2	–40.3	–50.2	–60.2	–70.4	–80.1	–90.2	–100.3	–110.2	–120.1	–130.0
200.000	7.8	5.0	0.0	5.0	–10.0	–20.1	–30.0	–40.1	–50.1	–60.2	–70.2	–80.2	–90.2	–100.3	–109.7	–120.0	–130.4
250.000	7.7	5.0	0.0	–5.0	–10.1	–20.1	–30.0	–40.1	–50.3	–60.1	–69.8	–79.1	–89.8	–100.5	–110.3	–120.4	–130.7
300.000	7.2	4.4	–0.6	–5.6	–10.6	–20.6	–30.5	–40.5	–50.3	–60.3	–70.2	–80.3	–90.4	–100.4	–110.4	–120.3	–130.4
350.000	7.3	4.5	–0.4	–5.4	–10.4	–20.4	–30.5	–40.7	–50.2	–60.2	–70.5	–80.2	–90.3	–100.5	–110.3	–120.3	–130.5
400.000	-	-	-	–4.9	–10.0	–20.1	–29.8	–39.8	–50.0	–59.8	–69.9	–80.1	–90.0	–99.5	–110.0	–119.6	–129.8
450.000	-	-	-	–4.8	–9.5	–19.6	–29.6	–39.7	–49.6	–59.7	–69.8	–79.7	–89.5	–99.7	–109.6	–119.7	–129.5
500.000	-	-	-	–5.4	–10.3	–20.4	–30.1	–49.5	–50.5	–60.5	–70.6	–80.7	–90.5	–100.6	–111.0	–120.6	–130.5



(A)


Spectrum 26/05/14 09:43

Ref: -30.0 dBm • RBW: 100 Hz SWT: 118 ms Trace: Average

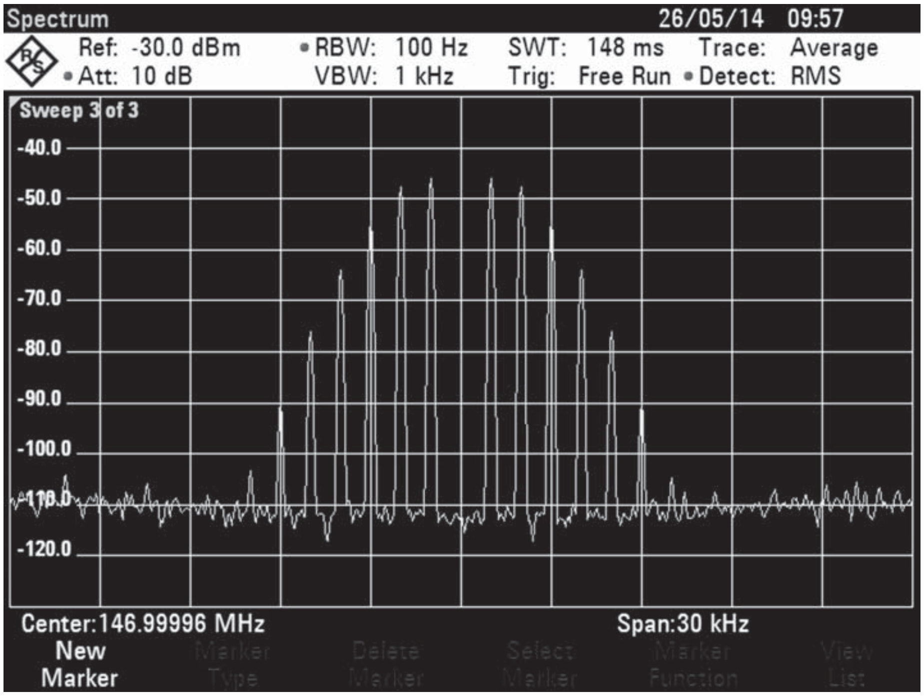
• Att: 10 dB VBW: 1 kHz Trig: Free Run • Detect: RMS

M1 146.99996 MHz -47.0 dBm D2 1 kHz -7.9 dB

Center: 146.99996 MHz Span: 10 kHz

(B)

Figure 4 — Part A shows the time domain display of a 147 MHz carrier with 1 kHz internal amplitude modulation, and Part B shows the frequency domain display from the R&S spectrum analyzer of the same signal.


Spectrum 26/05/14 09:57

Ref: -30.0 dBm • RBW: 100 Hz SWT: 148 ms Trace: Average

• Att: 10 dB VBW: 1 kHz Trig: Free Run • Detect: RMS

Center: 146.99996 MHz Span: 30 kHz

Figure 5 — This photo shows the R&S spectrum analyzer display of the 147 MHz carrier with 1 kHz internal frequency modulation. The modulation index is 2.405, corresponding with the first Bessel null.

by Sam Green, WØPCE.[5]

The problem is that for absolute measurements, some kind of correction has to be applied, if we want to use it across the entire frequency range with higher accuracy. Actually, for CW or even frequency modulated signals in the linear region of the chip, the solution is quite simple: in the majority of cases, we know beforehand the frequency of the signal we are going to measure, so if we apply a careful calibration, all we have to do is provide some way to include the frequency with the measurement. This is exactly how it is used in the Tricorder — we input the frequency when making absolute power measurements and the device "knows" the frequency when operating in the network analyzer mode. Actually, even some professional high-cost power sensors offer this possibility, especially those that can be connected directly to a computer. The difference is that with professional power sensors this information is used for slight corrections (in general not even needed), but here we are comparing $5,000 power sensors with a $15 chip.

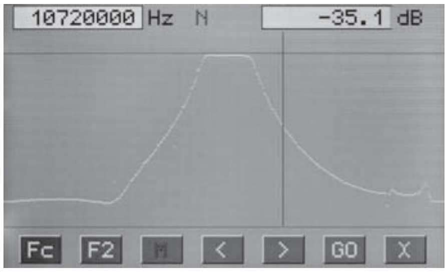

10720000 Hz N -35.1 dB

Figure 6 — Here is the scalar network analyzer measurement for a 10.7 MHz band-pass filter.

In Table 2 we can see the response of the calibrated power meter in comparison to the SMC100A Rohde & Schwarz signal generator (this is a *pretty accurate* generator). From –60 to +5 dBm, it has an overall accuracy of 0.5 dB, but we can see that it can be used, with care, from –65 to +8 dBm.

The Scalar Network Analyzer

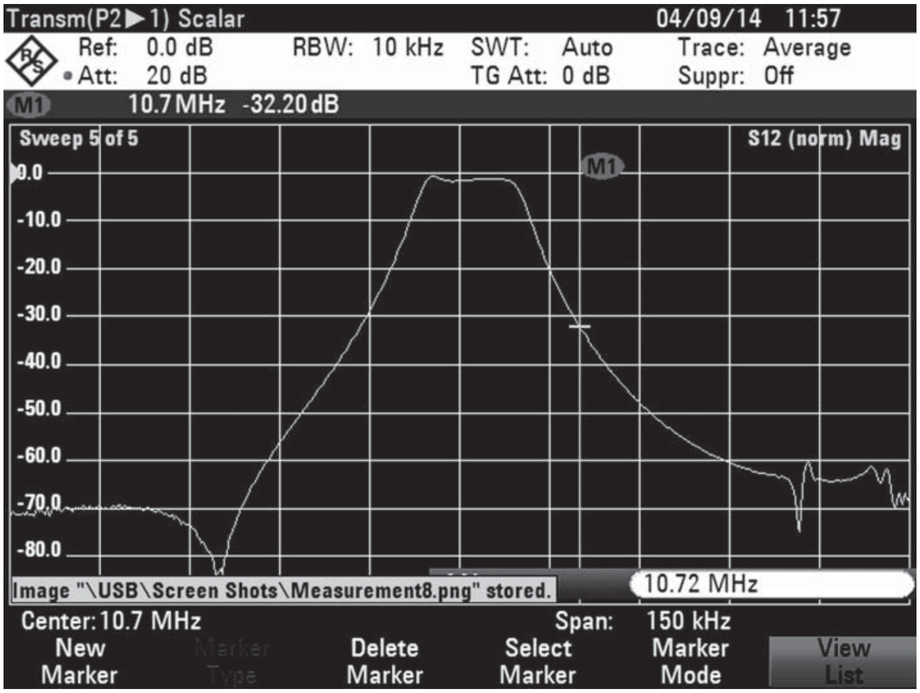
In this mode, the RF generator and power meter work together to plot the insertion loss of a device under test — with the help of a return loss bridge it will also show the return loss of this same DUT.

Its operation is similar to the tracking generator/spectrum analyzer way of measuring transmission loss, but instead it uses the power meter at the reception end. The curves are shown in a 400 × 240 TFT color display, and although not being

Table 2

Calibrated Power Meter Measurements Compared to the SMC100A Rohde & Schwarz Signal Generator Settings

R&S Setting	*+8 dBm*	*+5 dBm*	*0 dBm*	*–10 dBm*	*–20 dBm*	*–30 dBm*	*–40 dBm*	*–50 dBm*	*–60 dBm*	*–65 dBm*
Frequency (MHz)			*Power Meter Measurements*							
0.15	7.4	4.6	0.0	–10.1	–20.2	–30.1	–39.9	–50.0	–60.5	–66.3
0.2	7.3	4.5	0.0	–10.1	–20.2	–30.1	–40.0	–50.0	–60.2	–65.5
0.5	7.3	4.5	0.0	–10.2	–20.2	–30.1	–40.0	–49.9	–59.9	–64.7
1.00	7.3	4.5	0.0	–10.1	–20.2	–30.1	–40.0	–50.0	–59.8	–64.6
10.00	7.2	4.4	–0.1	–10.3	–20.4	–30.3	–40.2	–50.2	–60.2	–65.0
50.00	7.5	4.5	0.0	–10.2	–20.4	–30.1	–40.1	–50.2	–60.1	–65.0
100.00	8.1	5.0	0.2	–10.0	–20.1	–30.0	–40.0	–50.0	–60.0	–64.9
150.00	8.1	5.0	0.1	–10.1	–20.2	–29.9	–39.9	–49.8	–59.5	–64.3
200.00	8.1	5.2	0.2	–10.2	–20.4	–30.1	–40.1	–50.2	–60.4	–65.4
250.00	7.9	5.1	0.4	–10.0	–20.0	–29.9	–39.8	–50.0	–60.3	–65.3
300.00	7.8	5.0	0.4	–9.9	–19.9	–29.6	–39.5	–49.7	–60.0	–64.9
350.00	7.4	4.7	0.2	–10.2	–20.3	–30.1	–40.0	–50.0	–60.2	–65.0
400.00	7.8	4.8	0.5	–9.7	–19.8	–29.9	–39.8	–49.8	–59.6	–64.3
450.00	8.8	4.9	0.5	–9.5	–19.4	–29.4	–39.5	–49.4	–59.3	–63.8
500.00	9.3	4.8	0.4	–9.5	–19.7	–29.6	–39.8	–50.3	–60.5	–65.0



Transm(P2▶1) Scalar 04/09/14 11:57

Ref: 0.0 dB RBW: 10 kHz SWT: Auto Trace: Average

Att: 20 dB TG Att: 0 dB Suppr: Off

M1 10.7 MHz -32.20 dB

Sweep 5 of 5 S12 (norm) Mag

Image "\USB\Screen Shots\Measurement8.png" stored.

10.72 MHz

Center: 10.7 MHz Span: 150 kHz

Figure 7 — This screen shot shows the R&S spectrum analyzer sweep of the 10.7 MHz filter measured by the scalar network analyzer in Figure 6.

-35.47 dBm

Figure 8 — This screen is a measurement of the signal through the 10.7 MHz filter that was measured in Figures 6 and 7, using a professional broadband power meter.

a giant display, we can inspect the curves comfortably. TFT displays are reasonably priced, probably thanks to the Arduino fever. As we will see in the "Operation" section, the network analyzer has some software facilities to make its operation easier.

Figure 6 shows the sweep of a 10.7 MHz filter with the Tricorder, and Figure 7 shows the same filter plot on a spectrum analyzer. Notice the measured levels at the marker frequencies. Figure 8 shows the measured level using a high precision professional broadband power meter.

When the extension board is present it will be used, meaning that we can sweep from 150 kHz to 500 MHz, and the board's switching is transparent to the user. In Figures 9A and 9B we can see the response for a Mini-Circuits 300 MHz low pass filter. This filter is pretty sensitive to the generator impedance, so a 6 dB attenuator was used at the generator output, before making the normalization (for both instruments).

The sweep speed is fixed. It is not so low that it would put us to sleep, but not so fast that it would introduce distortion.

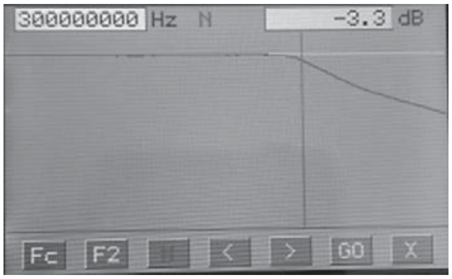
Hardware Implementation

Main Board

The assembled Main Board can be seen in Figures 10A and 10B. Figure 11 is the schematic diagram of the Main Board. The DAT-31R5-SP Mini-Circuits attenuators can be digitally controlled in steps of 0.5 dB. This is an important feature when the Extension Board is used. Notice the polarization of the ERA2 amplifier — the BFG31 is a 5 GHz transistor, and its collector will provide high impedance in the frequency range and so will not disturb the 50 Ω amplifier output impedance; remember that the DDS range is 2 kHz to 400 MHz.

Although I considered the importance of the input impedance of the power meter, I did not dedicate special attention to the frequency compensation of the circuit in the upper range, because it could be done in software.

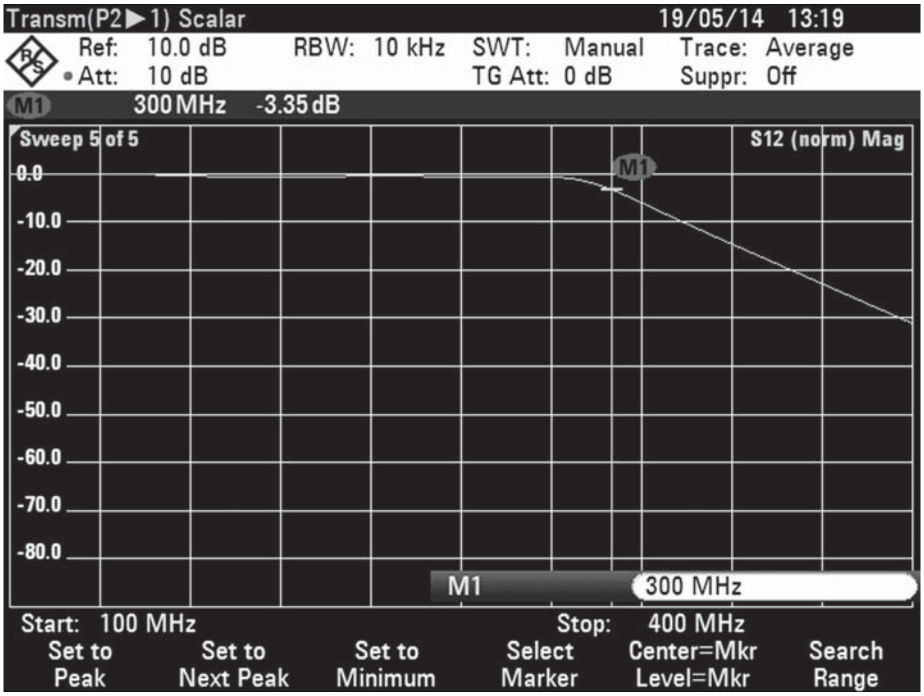
The solitary LED on the circuit board indicates when the internal PLL of the DDS is locked. This will be very useful when testing the board, and also if the loop filter is modified for some reason. The voltage regulators are all low noise type. I used ferrite beads (FB) in some places to limit



300000000 Hz N -3.3 dB

(A)

Figure 9 — Part A is the Tricorder sweep from 150 kHz through 500 MHz of the insertion loss for a 300 MHz Mini-Circuits low pass filter. Part B is the R&S spectrum analyzer measurement of the same filter insertion loss.



Transm(P2▶1) Scalar 19/05/14 13:19

Ref: 10.0 dB RBW: 10 kHz SWT: Manual Trace: Average

Att: 10 dB TG Att: 0 dB Suppr: Off

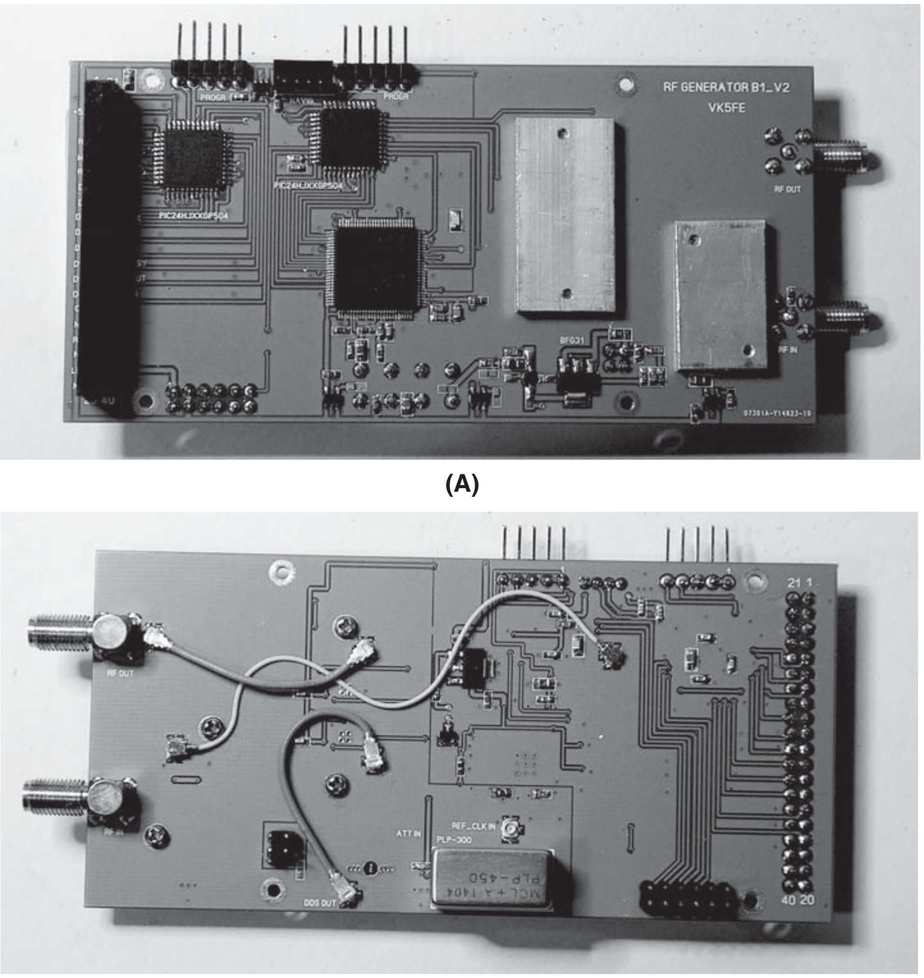
M1 300 MHz -3.35 dB

Sweep 5 of 5 S12 (norm) Mag

M1 300 MHz

Start: 100 MHz Stop: 400 MHz

(B)



(A)

(B)

Figure 10 — Part A is the top side of the Tricorder Main Board and Part B is the bottom.

the number of voltage regulators used, but always trying to not compromise DDS power supply requirements.

When the Extension Board is not used, the output of the ERA-2 amplifier is connected directly to the input of the attenuator; otherwise it is connected to the input of the Extension Board. The RF connections are made with mini coaxial cables.

Both the attenuators and power detector circuits are shielded — I used 3 mm (about 0.12 inch) thick aluminum profile, milled to accommodate the components. See one of them in Figure 12. They are held in place with 2 mm screws. This low profile shielding allowed me to keep a convenient separation between boards, important when we intend to design a compact device.

Backup Board

Figure 13A shows the schematic diagram and Figure 13B is a photo of the Backup Board. The Backup Board includes the main power supply, the internal time base and the SD card connector.

The internal time base is switched off (output and power supply) when the external time base option is selected — the switching is done by the 74HC4066 (a quad analog switch IC). The Schmitt Trigger inverter and 33 Ω resistor provides adequate signal conditioning (especially when an external time base is used) and also a stable 50 Ω source impedance for the 10 MHz elliptic low pass filter. This filter was used to avoid the harmonics reaching other circuit sections of the Tricorder, as was the shielding of the whole time base circuitry. The 20 dB pad adjusts the output to the level required by the DDS.

The reason for using a step-down dc-dc converter was explained in the “Architecture” section — it was shielded to confine eventual harmonics coming from the 1.6 MHz internal oscillator. The dc input circuitry of the board provides protection against short circuits, polarity inversion and overvoltage; the 78L09 feeds the polarization circuit of the ERA-2 amplifier on the Main Board.

The LM317L provides about 3.1 V dc for the TFT display backlight. I used a REG113 regulator exclusively for the SD card — the card can drain a considerable current under some circumstances.

Extension Board

This board is optional: it extends the upper range of the Tricorder from 400 MHz to 500 MHz. Figure 14A is the schematic diagram of the Extension Board. It consists of a frequency doubler and two filters from Mini-Circuits. Switching is achieved with two 3 GHz switches from Macom (MASWSS0143). Notice that I did not include a pad to adjust the level — it’s all done in software. Figure 14B is a photo of the Extension Board.

When using frequency multipliers, it’s important to carefully analyze the products generated. Table 3 shows the expected level of the fundamental and harmonics appearing at the output (Total), and the attenuation contribution from the frequency doubler and filters (in our case, we want just the second harmonic). Working on a restricted range (about 400 to 500 MHz) makes this task easier. The only limitations are the maximum output level of the Tricorder (–3 dBm maximum) and the fact that modulation is not allowed.

One of the microprocessors in the Main Board senses the presence of the Extension Board, and the frequency limits, level correction and board switching are all automatically managed.

Navigation Board

The Navigation Board is a very small board. Figure 15 is a photo of the board. Figure 16 is the schematic diagram.

The structure formed by the six resistors (R1 to R6) is in fact five different voltage dividers; each tactile switch selects one of the dividers and the respective voltage is routed to one analog-to-digital port of the microprocessor. Depending upon the voltage, the processor “knows” which button was pressed. This is a simple way of sensing buttons, and saves on the number of microprocessor ports required.

The processor, when requested, sends the button code to the master processor on the Main Board, through the I2C interface.

Operation

Navigation is done with five hardware buttons (tactile switches) and software buttons. We can move from field to field using the hardware buttons (sequential move – up and down arrows) or with a plastic stylus (random move) on the touch screen. We can just use a finger, but I found the stylus more comfortable and it avoids fingerprints.

When a field is selected (highlighted), a red rectangle will be drawn around the field. The touch screen is quite sensitive, so there is no need to use excessive pressure.

The action of the hardware buttons will depend on the particular screen shown. In this description, I will always consider the first button or field to be the one at the top. The EDT software button will normally take us to a software keyboard and the GEN button will always take us to the main (GENerator) screen.

The software buttons can be chosen/activated only with the stylus, with the exception of the small buttons on the network analyzer screen, as we will see.

Welcome Screen

Figure 17A shows the screen that will appear when the Tricorder is turned on. This screen shows the firmware version.

Main Screen

Figure 17B shows the initial Main Screen. The first field is frequency; to input a new frequency, tap the EDT button, which will take you to the keyboard shown in Figure 17C. We can input the frequency in Hz, kHz or MHz.

The second field is power level; again, the EDT button will present another keyboard (Figure 17D), where we can input the level in dBm, mV or µV. Notice that the level displayed in the main window will always be shown in dBm.

When one of the fields above is highlighted, if we press the central hardware button the field will enter in a different and useful edit mode: a small triangle will appear below the last character and with the up/down buttons we can change the number at the pointer triangle. With the right/left buttons we can change the position of the triangle. See Figure 17E. In the frequency field, for example, this will allow us to modify the frequency in steps of Hz, tens of Hz, hundreds of Hz and so on. When we press the central button again, we will leave this mode.

The third field is related to modulation. With the lateral buttons we see the modulation options and tapping the EDT button will take us to a new screen, related to the particular modulation type shown. The modulation screens are similar, and in Figure 17F you can see the one related to amplitude modulation (AM). There are two fields and with the help of the keyboard (EDT) we can edit the modulation frequency and modulation index. When we choose a modulation type in the main screen and press the hardware central button, it will be effective with the stored parameters — selecting OFF will remove any modulation.

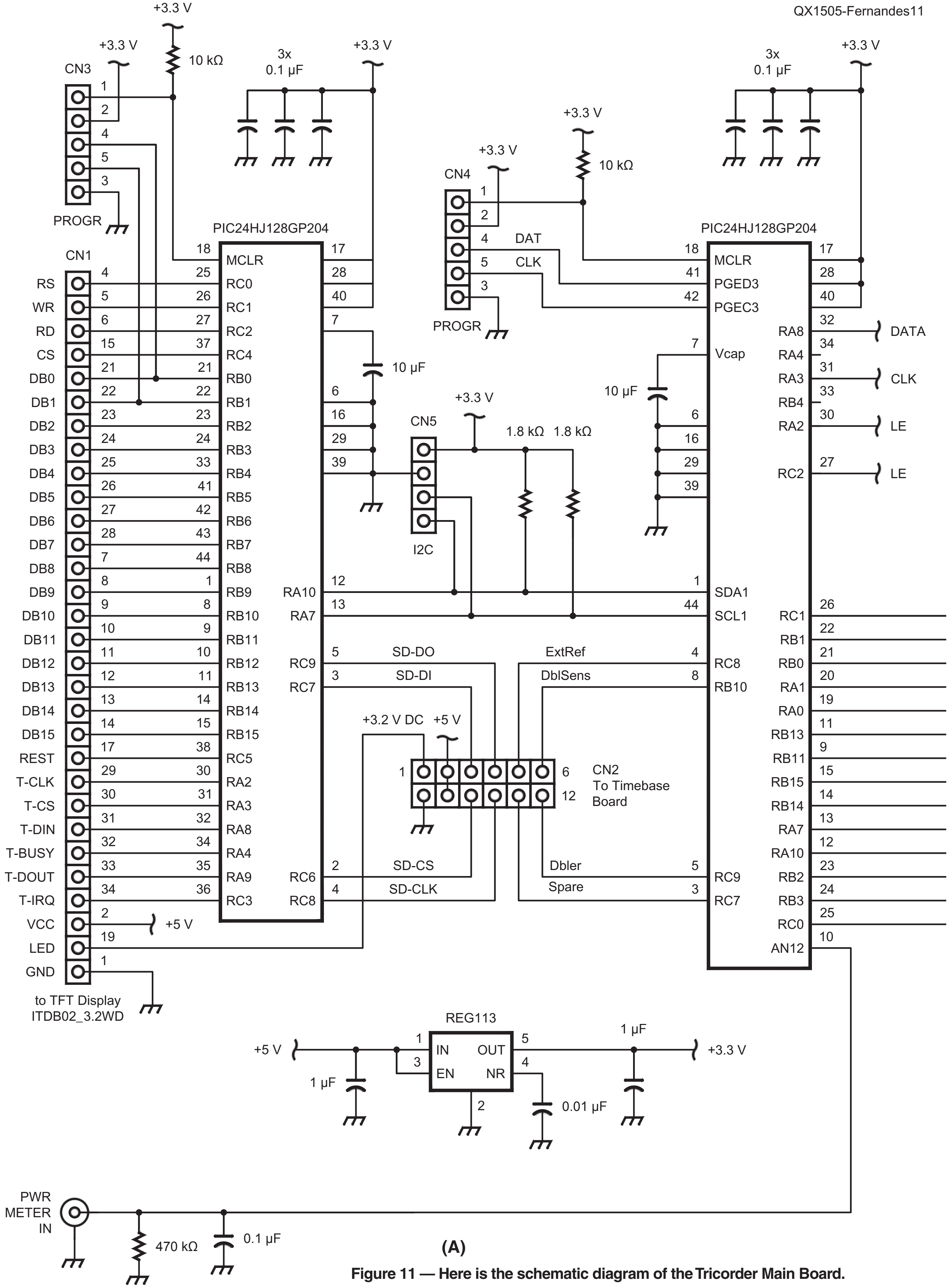
The second button will lead us to the Options Screen. Toggling the third software button will turn the generator output off or on.

Options Screen

Figure 17G shows the Options Screen, which is just a “connection box” to other functions of the Tricorder. When we tap the first button, the power meter mode is selected, the second button selects the network analyzer, the third button will show the Configuration Screen, and when we tap the last one, we return to the generator mode.

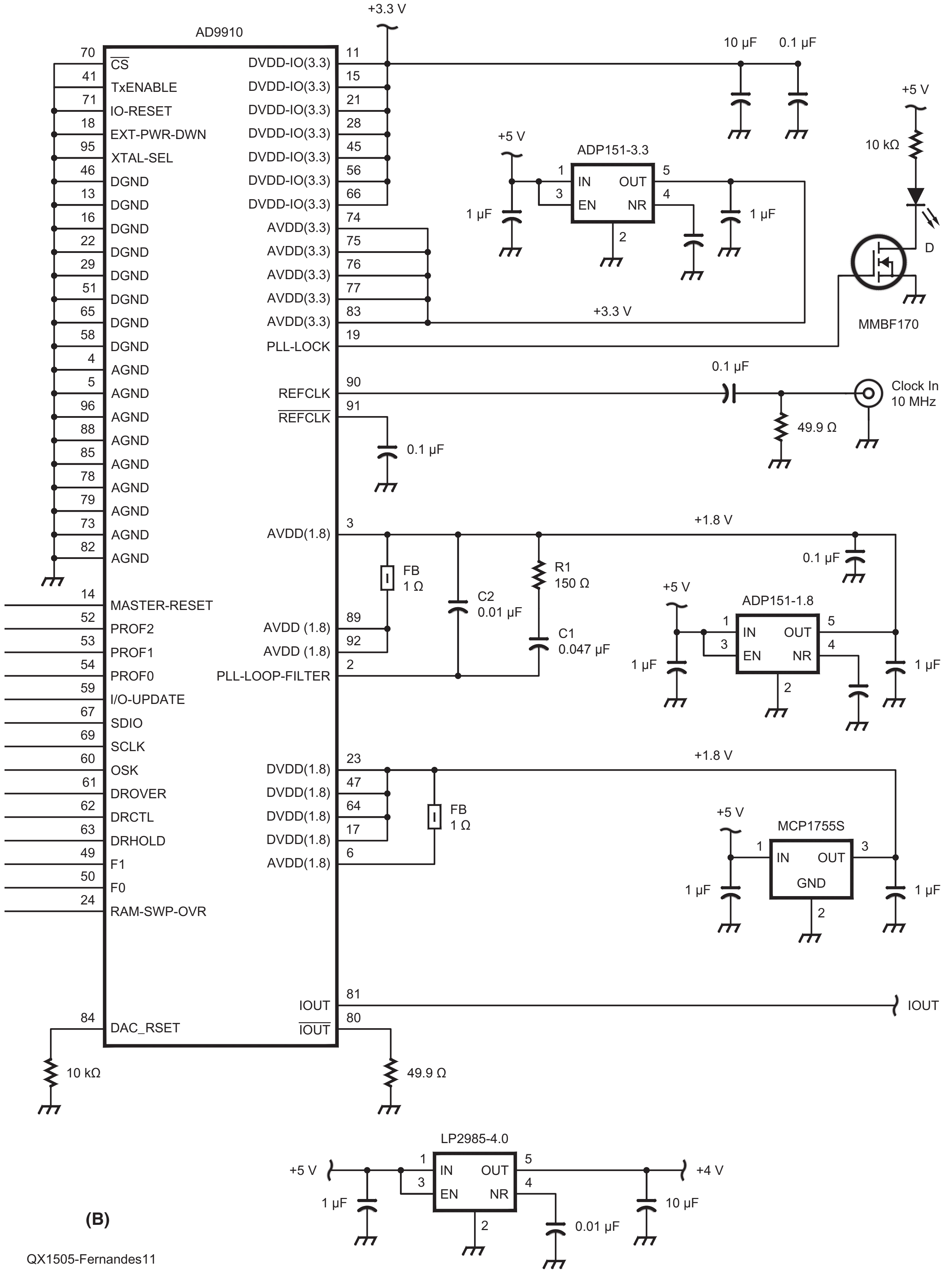
Configuration Screen

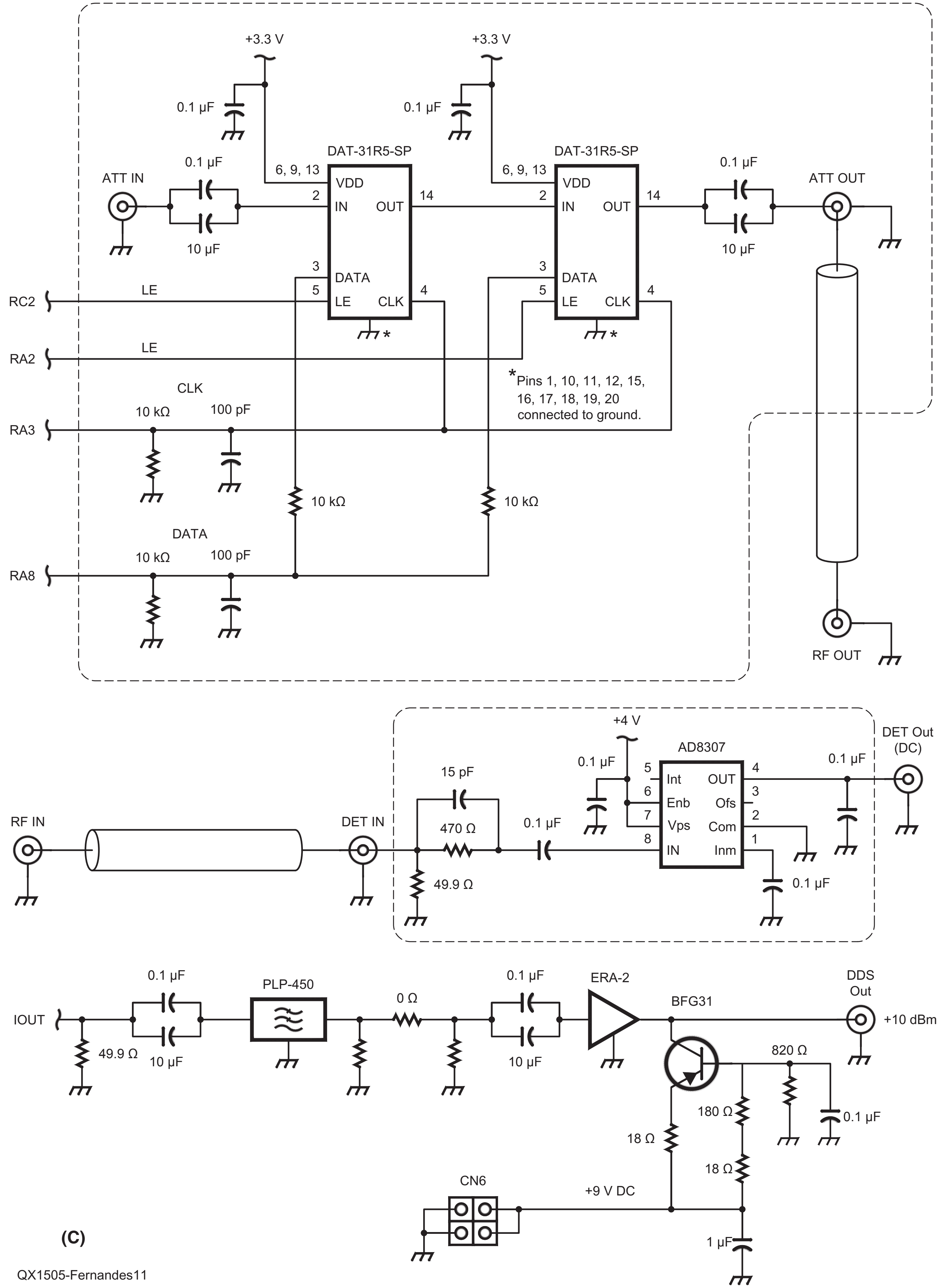
Figure 17H shows the Configuration Screen, which displays three fields. The first one is the frequency reference field. We can choose one of the following possibilities: internal reference (10 MHz) or external



(A)

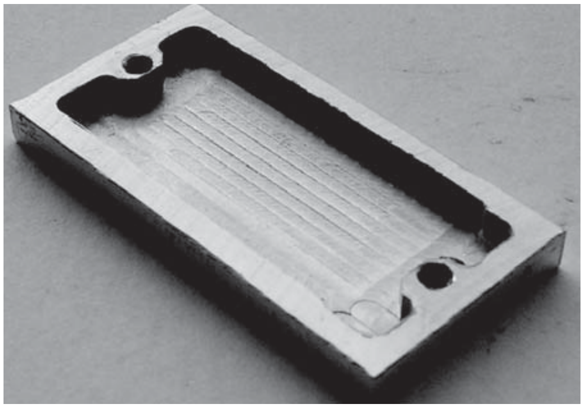
Figure 11 — Here is the schematic diagram of the Tricorder Main Board.

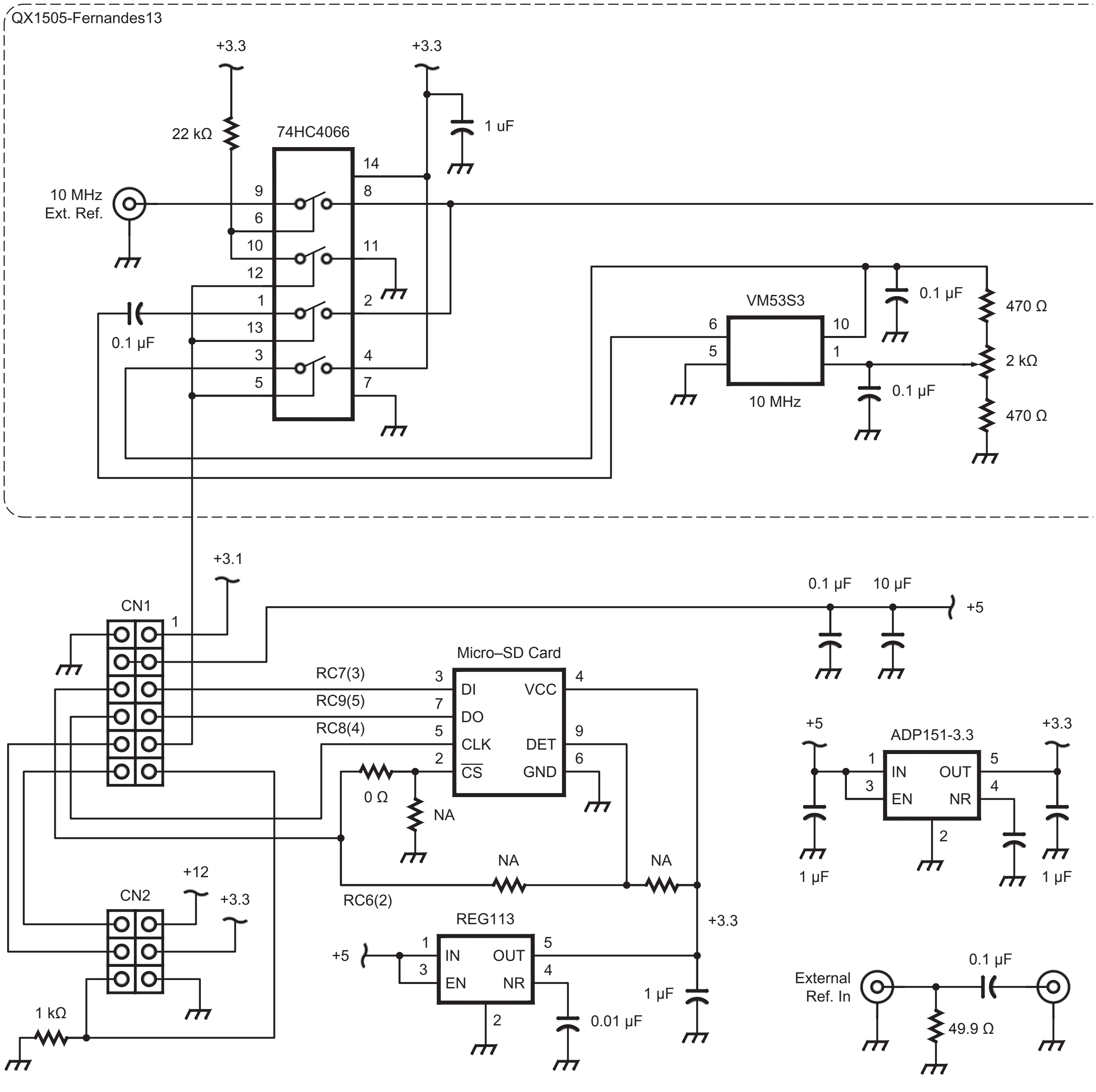

+3.3 V
AD9910
10 µF
0.1 µF
+5 V
10 kΩ
70 CS
41 TxENABLE
71 IO-RESET
18 EXT-PWR-DWN
95 XTAL-SEL
46 DGND
13 DGND
16 DGND
22 DGND
29 DGND
51 DGND
65 DGND
58 DGND
4 AGND
5 AGND
96 AGND
88 AGND
85 AGND
78 AGND
79 AGND
73 AGND
82 AGND
14 MASTER-RESET
52 PROF2
53 PROF1
54 PROF0
59 I/O-UPDATE
67 SDIO
69 SCLK
60 OSK
61 DROVER
62 DRCTL
63 DRHOLD
49 F1
50 F0
24 RAM-SWP-OVR
84 DAC_RSET
DVDD-IO(3.3) 11
DVDD-IO(3.3) 15
DVDD-IO(3.3) 21
DVDD-IO(3.3) 28
DVDD-IO(3.3) 45
DVDD-IO(3.3) 56
DVDD-IO(3.3) 66
AVDD(3.3) 74
AVDD(3.3) 75
AVDD(3.3) 76
AVDD(3.3) 77
AVDD(3.3) 83
PLL-LOCK 19
REFCLK 90
REFCLK 91
AVDD(1.8) 3
AVDD (1.8) 89
AVDD (1.8) 92
PLL-LOOP-FILTER 2
DVDD(1.8) 23
DVDD(1.8) 47
DVDD(1.8) 64
DVDD(1.8) 17
AVDD(1.8) 6
IOUT 81
IOUT 80
+5 V
ADP151-3.3
1 IN
3 EN
OUT 5
NR 4
2
1 µF
1 µF
+3.3 V
D
MMBF170
0.1 µF
Clock In
10 MHz
49.9 Ω
0.1 µF
+1.8 V
FB
1 Ω
C2
0.01 µF
R1
150 Ω
C1
0.047 µF
0.1 µF
+5 V
ADP151-1.8
1 IN
3 EN
OUT 5
NR 4
2
1 µF
1 µF
+1.8 V
FB
1 Ω
+5 V
MCP1755S
1 IN
OUT 3
GND
2
1 µF
1 µF
IOUT
10 kΩ
49.9 Ω
LP2985-4.0
+5 V
1 IN
3 EN
OUT 5
NR 4
2
+4 V
1 µF
0.01 µF
10 µF
(B)
QX1505-Fernandes11

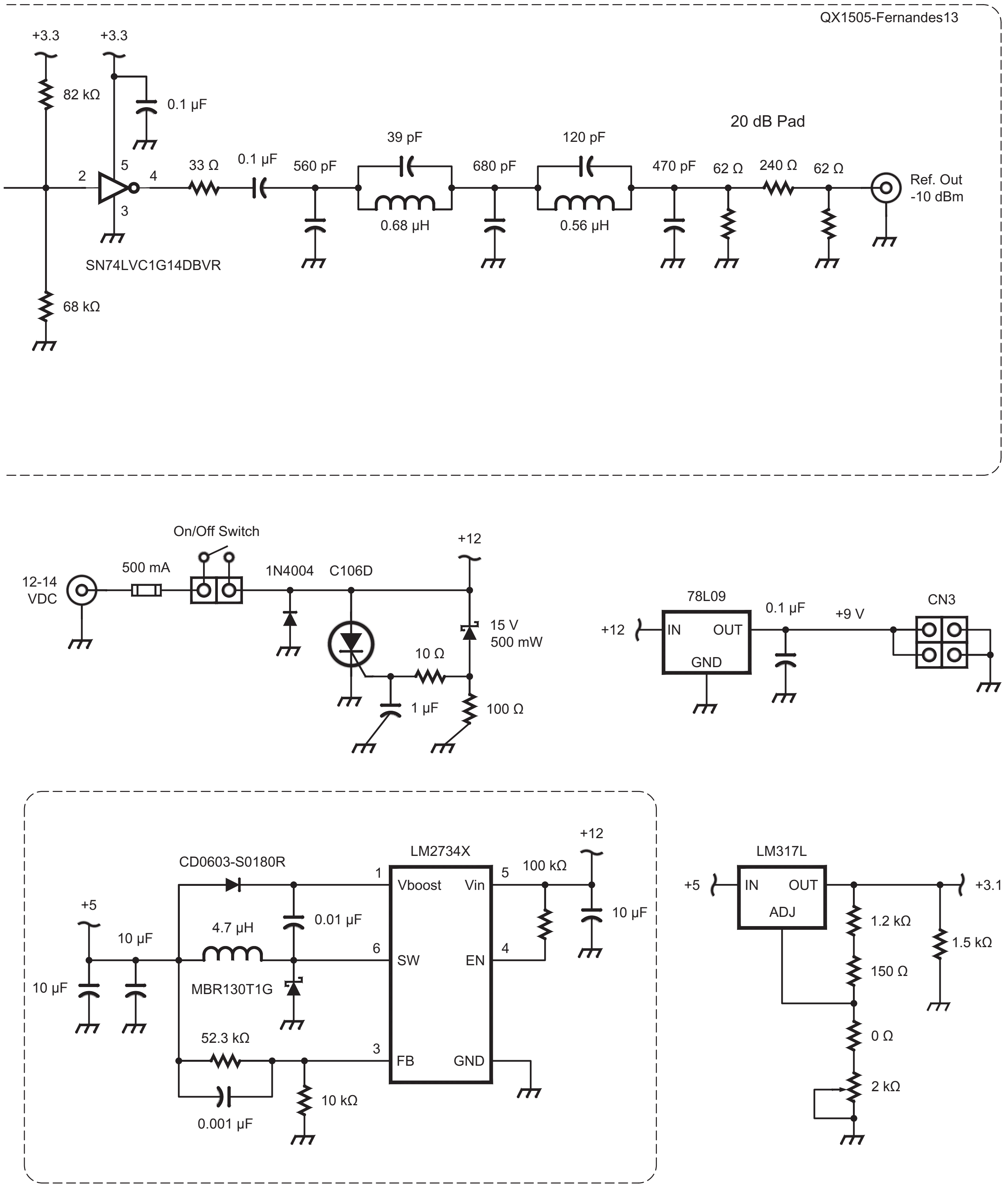


QX1505-Fernandes11

Figure 12 — This photo shows one of the milled aluminum shields used in some parts of the Tricorder circuitry to avoid noise-related problems.

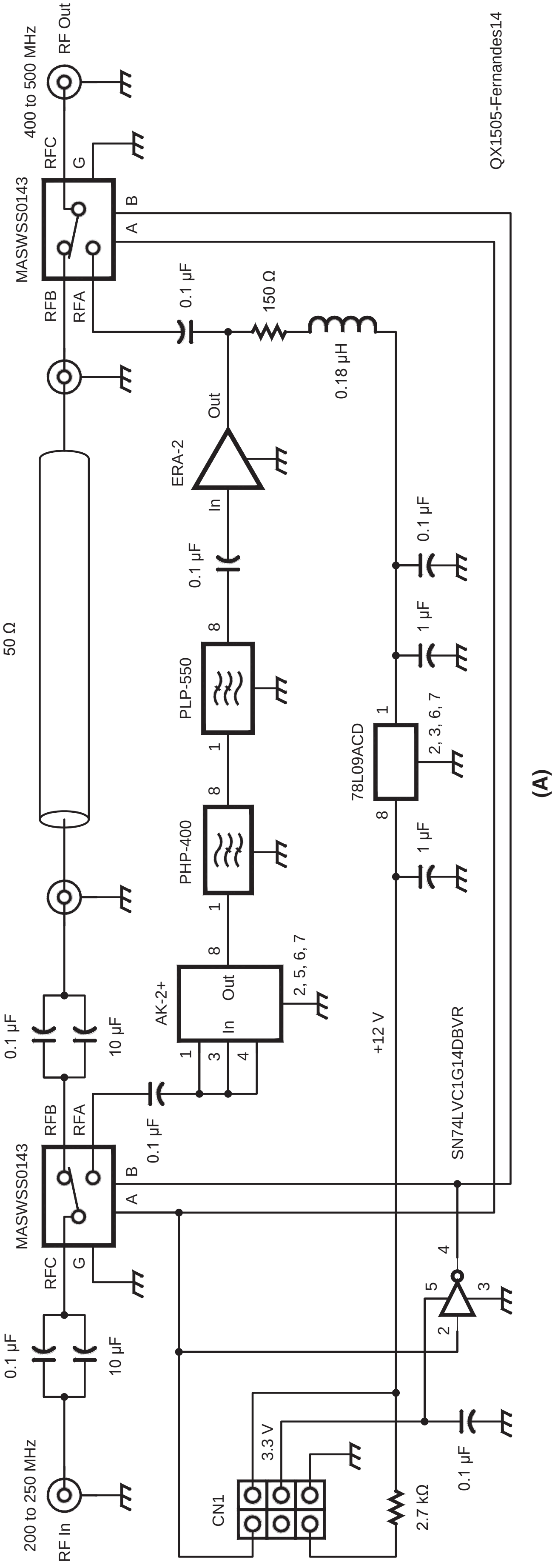




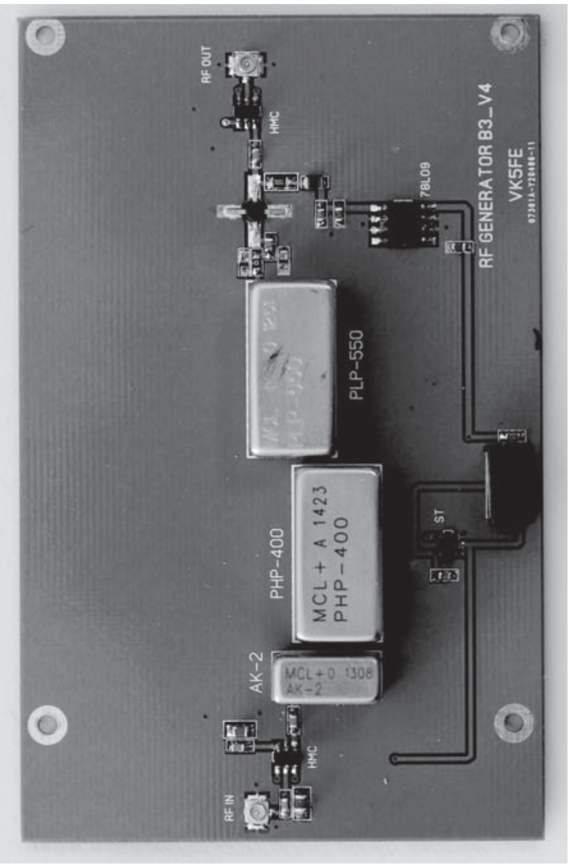


(A)

Figure 13 — Part A is the schematic diagram of the Backup Board.

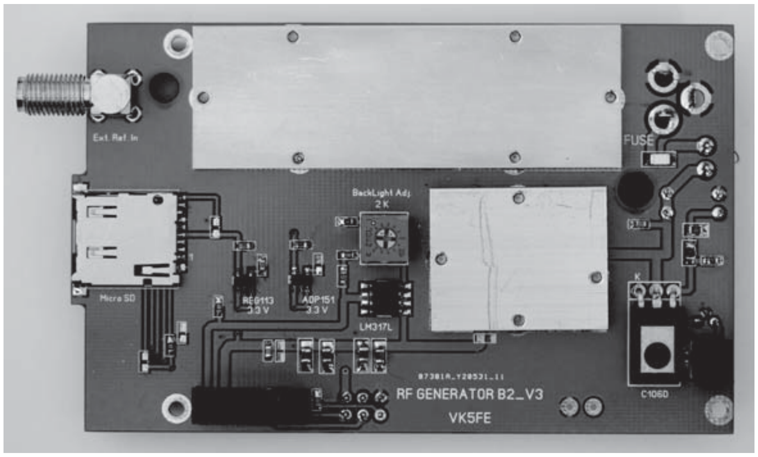


(A)



(B)

Figure 14 — Part A is the schematic diagram of the Extension Board. Part B is a photo of the completed circuit board.



(B)

Figure 13 — Part B is a photo of the completed circuit board.

Table 3
Expected Attenuation of the Funamental and Harmonics in the Doubler Circuitry

F1(MHz)	*F2(MHz)*	*F1(MHz)*	*F3(MHz)*	*F4(MHz)*	*F5(MHz)*	*AK–2+ (dBc)*	*PHP–400 (dBc)*	*PLP–550 (dBc)*	*TOTAL (dBc)*
200	400					–12			
200		200				–33	–50		–83
200			600			–50		–5	–55
200				800		–20		–40	–60
200					1000	–10		–62	–72
250	500					–12.5			
250		250				–34	–37		–71
250			750			–51			
250				1000		–21		–62	–83
250					1250	–10		–68	–78

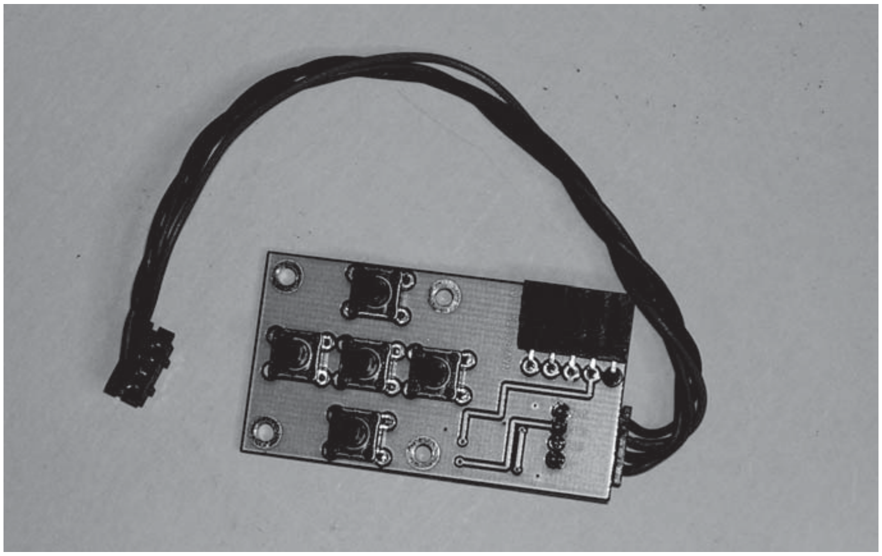


Figure 15 — Here is the Navigation Board. The five push-button switches control various features of the Tricorder, depending upon which menu option you select.

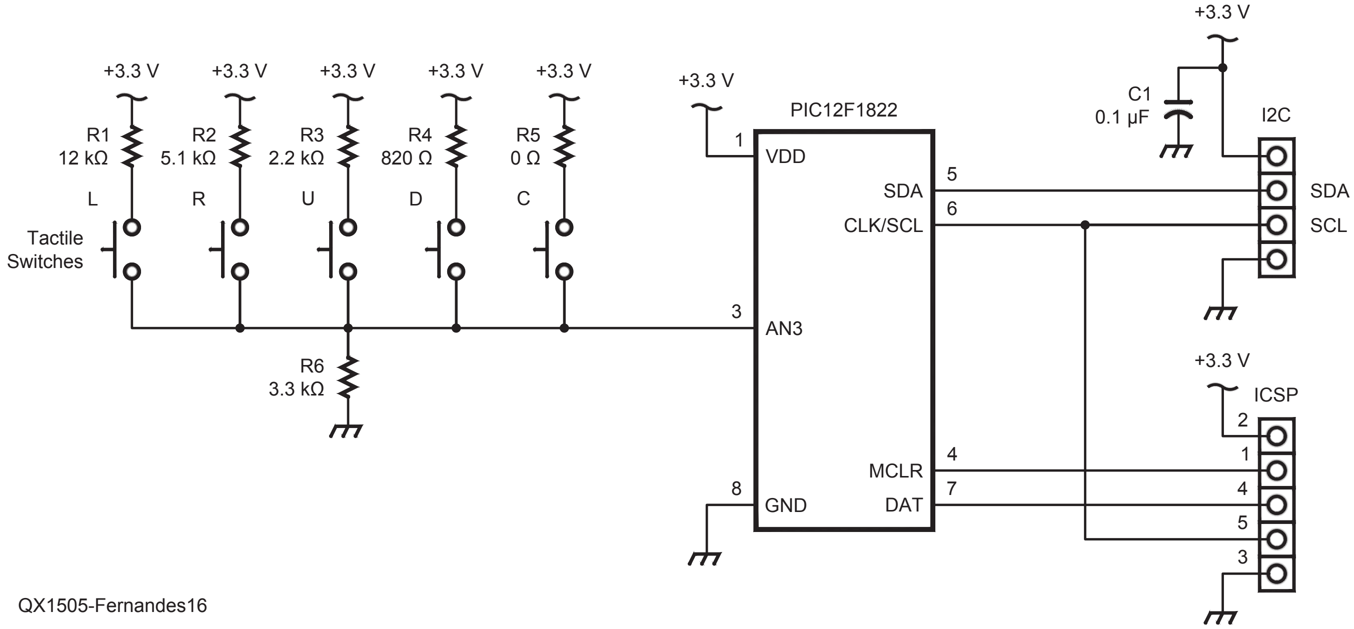


Figure 16 — This schematic diagram shows the Navigation Board circuit.

reference of 10 MHz, 100 MHz or 1 GHz. When the external 10 MHz reference is chosen, the internal signal conditioning circuits of the internal reference are also used (squarer and filter). The 100 MHz reference requires a new dimensioning of the DDS loop filter components. When using the 100 MHz and 1 GHz external reference, the reference frequency input connector has to be connected directly to the DDS, using mini coaxial cables.

Use the second field if you are connecting an external attenuator to the generator output (10 to 90 dB in steps of 10 dB). When one attenuator value is selected, the software will correct the output power level shown in the main window, in such a way as to always show the generator level after the attenuator. Coaxial attenuators connected to the output are important to improve the output level accuracy for low levels/high frequencies, to improve the generator output impedance for demanding measurements and also to reduce fixed-level spurs.

The third field shows the internal attenuator options (10, 20, 30, 40, 50, and 60 dB) that will be connected to the power meter input; again, the power meter level shown will be corrected. This is an important feature if we want to use the power meter for high power measurements. For instance, with the RF power tap suggested by Wes Hayward and Bob Larkin in their article (see Note 4), plus a precise low power attenuator of 10 dB connected to the tap port, we could measure powers of about 100 W.

Power Meter Screen

Two fields are shown in Figure 17I, but only the frequency can be edited, which you can do by pressing the FREQ button. As I said before, the full accuracy of the power meter is achieved only when we inform the software about the frequency of the signal to be measured.

The second field shows the power being measured. It can show the power in dBm, Watts or Vrms (50 Ω), depending on the status of the third software button to the right of the screen. Each time we tap that button, the unit changes, in a circular menu.

With the second button we can choose the measurement style: automatic or manual. In the manual mode, each time we press the central hardware button, the power meter takes a new measurement. In the automatic mode, it takes sequential measurements.

When the power meter is not operating in normal conditions, the data in field one or two is written in red: for instance if the frequency has not been set, there is an overload, or other conditions.

Scalar Network Analyzer (SNA) Screen

Figure 17J shows the Scalar Network Analyzer screen. This is a more complex screen, but you will become familiar with its operation after using it for a couple of minutes. There are two fields at the top that will show different data, depending on the operating mode. You cannot edit the data in these fields. There are two always-present lines, one at the top of the screen (0 dB) and the other at the bottom (–85 dB). The screen, in general, will show the magnitude of S21 (or the magnitude of S11, when used with a return loss bridge).

The power level used at the transmission side will be the one defined in the Main Screen (signal generator) and it will be rescaled to 0 dB, meaning that the network analyzer works with relative levels.

The small function buttons are shown at the bottom of the screen; the first is the one to the left. We can highlight (select — it will show up with red characters on the screen) the buttons sequentially with the left/right hardware buttons or by tapping the selected function on the screen with the stylus. The first, second, third and sixth buttons are two-function buttons — when we hold for a few seconds, a new selection screen will appear. The following text describes the function buttons across the bottom of the screen.

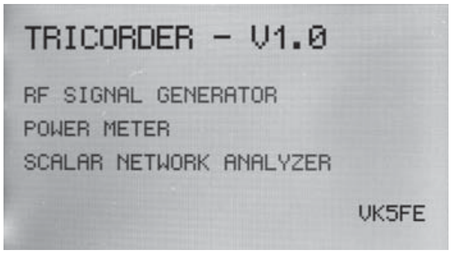
- Fc Button — frequency/span button — this button is mostly used for band-pass filters. When tapped, the first field (at the top left of the screen) will show the center frequency, and the second field will show the span. When held, a new screen (Figure 17K) will appear. In this screen we can see two fields, the center frequency and the span, which can be edited (tap the Edit button) with the help of a keyboard. The Scrn button will take us back to the main SNA screen.
- F2 Button — start/end frequency button — this is similar to the Fc button, but in this case the first field is the start frequency and in the second field is the end frequency. This is normally used to set up the frequency sweep for low pass or high pass filters.
- M Button — markers button — the network analyzer has two markers that are shown simultaneously in the main window. When we tap this button, we toggle between markers, and the selected marker will be represented by a vertical red line (the other marker will be shown as a blue line). The upper fields will show different information, depending on the marker mode (more on this later). When this button is held for a few seconds, the screen of Figure 17L will be shown. The first field has the Marker 1 frequency and the second has the Marker 2 frequency, and both can be edited. The third soft button changes the marker mode. In the Split mode (normal mode), the upper left field in the SNA window will show the selected marker frequency and the other the selected marker level. In the Differential mode, the left field will show the frequency difference between markers and the other the level difference. This will be useful for measuring, for instance, the pass band or stop band of band-pass filters. A red D character will appear between the two upper fields in the main SNA screen and will disappear when the Split mode is chosen.
- < Button — when tapped, this button will make the marker move to the left 1/400 of the SNA window range. If kept pressed, the marker line will move continuously.
- > Button — when tapped, this button will make the marker move to the right 1/400 of the SNA window range. If kept pressed, the marker line will move continuously.
- GO Button — when tapped, the frequency sweep will begin, using the range selected — for each sweep, the color of the trace will toggle between blue and white. When held for a few seconds, the screen of Figure 17M will be shown. The first soft button will start the normalization procedure. The normalization is a precalibration of the test setup. The generator and power meter have to be connected to each other through the test setup. After the normalization is done, the character N will appear in red between the two fields in the SNA main screen, and will disappear when a new frequency range is defined. (This is the screen displayed in Figure 6.) The second button will toggle between manual and automatic operation. In the manual operation, there will be just one sweep every time the GO button is tapped, and in the automatic operation it will sweep continuously. This will be important, for example, when we are adjusting a filter.
- X Button — the network analyzer mode will be abandoned and the Tricorder will return to the RF generator mode.

Applications

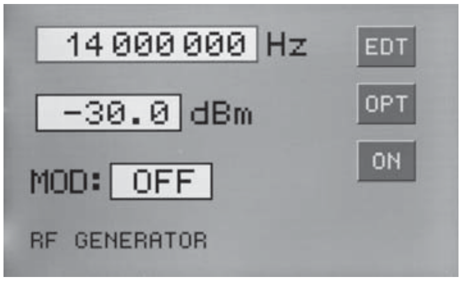
The RF signal generator and power meter find many uses around an Amateur Radio station, especially for testing receiver and transmitters. For those who like to design, assemble or test radios or other circuits (especially filters), the scalar network analyzer is a valuable tool, although it is not a common piece of test equipment in many workshops. In the next few paragraphs, I will describe its functionality, with two case studies.

Case Study 1 — A 10.7 MHz Band-Pass Filter

This filter was proposed many years ago by Fred Holler, W2EKB, and Jack Glandon, WB4RNO, as an alternative for one of the resolution filters of the spectrum analyzer designed by Wes Hayward, W7ZOI, and Terry White, K7TAU, which became a reference for other experimenters.[6] The


TRICORDER – V1.0
RF SIGNAL GENERATOR
POWER METER
SCALAR NETWORK ANALYZER
VK5FE

(A)


14 000 000 Hz
-30.0 dBm
MOD: OFF
RF GENERATOR

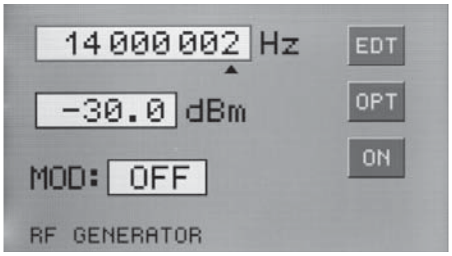
(B)


14

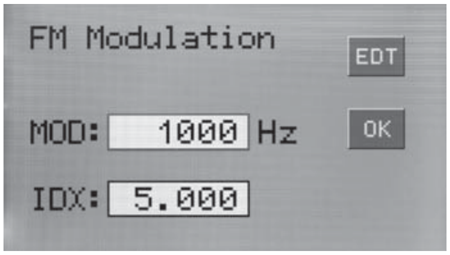
(C)


-3

(D)

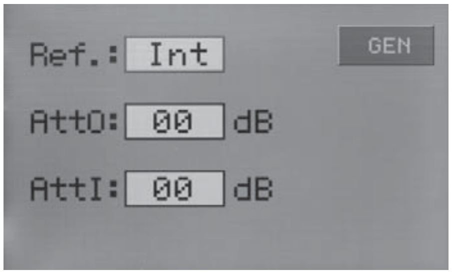

14 000 002 Hz
-30.0 dBm
MOD: OFF
RF GENERATOR

(E)


FM Modulation
MOD: 1000 Hz
IDX: 5.000

(F)

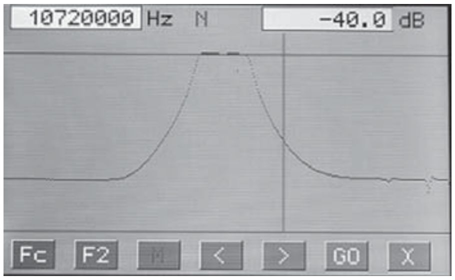
(G)


Ref.: Int
AttO: 00 dB
AttI: 00 dB

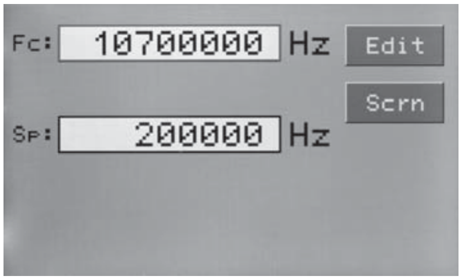
(H)


0 Hz
-75.5 dBm
POWER METER

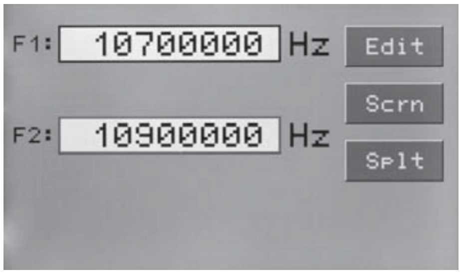
(I)


10720000 Hz N -40.0 dB

(J)


Fc: 10700000 Hz
Sp: 200000 Hz

(K)


F1: 10700000 Hz
F2: 10900000 Hz

(L)


Normalizing...

(M)

Figure 17 — Parts A through M show various control and measurement screens for the Tricorder. See the text for detailed explanations of each screen.

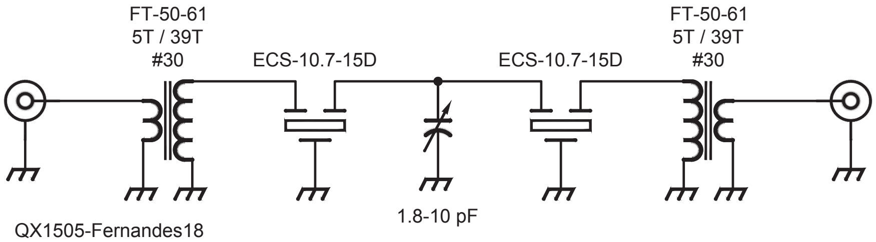


Figure 18 — This schematic diagram gives the circuit for a 10.7 MHz band-pass filter.

schematic of this filter is given in Figure 18. I have implemented this filter in the version shown in Figure 19.

First, using the buttons and respective screens, I set up the Tricorder with a center frequency of 10.7 MHz, a span of 150 kHz, and a marker on 10.7 MHz. I connected the signal generator RF output and the SNA RF input using a short cable, and the normalization was done. Then I connected the filter between the generator RF output and the SNA RF input and made the measurement. The result is shown in Figure 20A. Notice the insertion loss of 0.8 dB at 10.7 MHz.

Then I changed the span to 100 kHz and did a new normalization. Using the two markers, and alternating between split and differential modes, I positioned the markers in such a way so as to show the –3 dB pass band, as shown in Figure 20B.

At this point I wanted to check the input impedance of the filter, and for this I used the tiny homebrew return loss bridge shown in Figure 21. First, I defined again a span of 150 kHz. Then I connected the return loss bridge using two short cables, one from the RF output to the generator port of the bridge and the other from the detector port of the bridge to the RF input — the reference port was terminated with 50 Ω and the unknown impedance port (Zx) was left open, and the normalization procedure was done.

After normalization, I wanted to check if this bridge was really adequate for the measurement. The Zx port was terminated with 50 Ω and I ran a new sweep. The result is shown in Figure 22A. This is the directivity of the bridge in this range, about 50 dB, which is exceptionally good.

Then I removed the 50 Ω termination of the Zx port, connected to the filter input, and terminated the filter with 50 Ω. The result is the graph in Figure 22B. At 10.7 MHz we see that the return loss is 34 dB, corresponding to an SWR of about 1:1.04. Again, this is very good.

Case Study 2 — Multiband Antenna

For this example, I connected the return loss bridge, now normalized for the range of 5 MHz to 35 MHz (6 meter resonance not shown), to the 50 Ω coaxial cable that goes from the shack to my 8-band vertical antenna. The result of this measurement is shown in Figure 23A. The marker is on the 7 MHz dip.

Next I changed the range to 6 to 8 MHz and did a new normalization. The new sweep is shown in Figure 23B. Notice that the 40 meter band resonance is a bit low. Then I inserted the antenna tuner and tuned for the lower segment of the band. Measuring at the tuner input port, a new graph was drawn (Figure 23C), and we can see the correction made by the tuner.

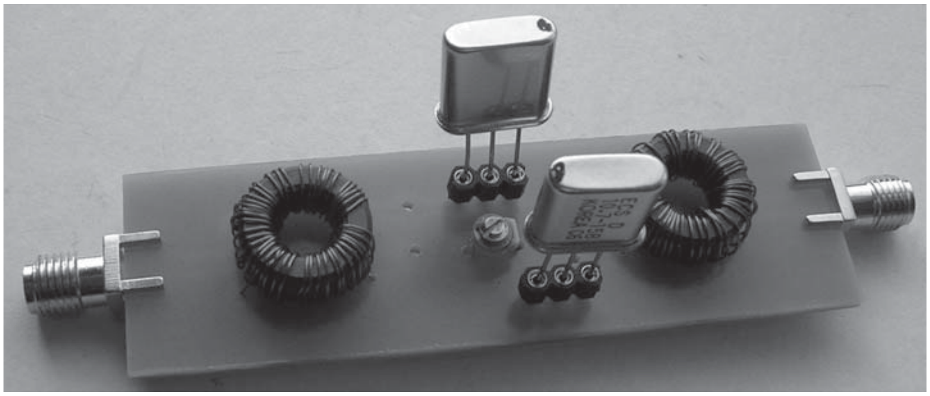
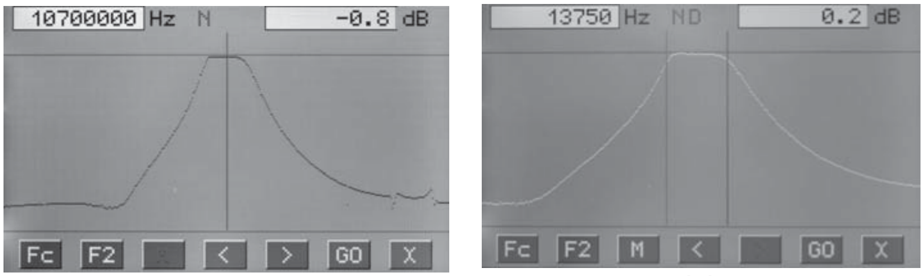


Figure 19 — Here is a photo of the 10.7 MHz band-pass filter circuit board.



10700000 Hz N -0.8 dB

13750 Hz ND 0.2 dB

(A)

(B)

Figure 20 — Part A is a screen shot from the scalar network analyzer measurement of the 10.7 MHz filter response. Note that the insertion loss is 0.8 dB. In Part B, the sweep span was changed and the marker were moved to indicate the –3 dB response, shown here as 13.75 kHz.

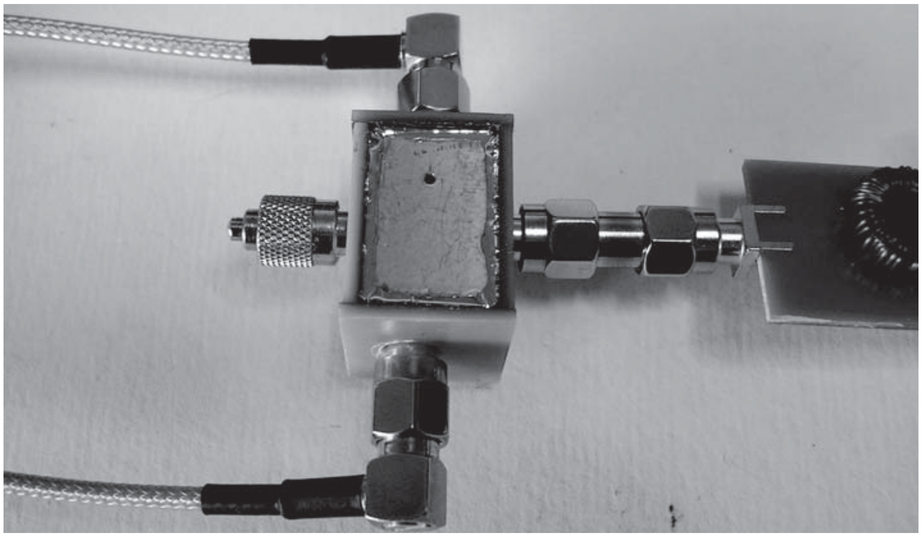
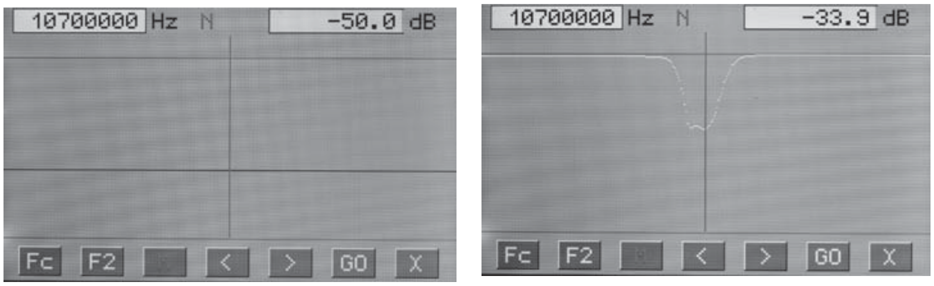


Figure 21 — Here is my homebrew return loss bridge.



10700000 Hz N -50.0 dB

10700000 Hz N -33.9 dB

(A)

(B)

Figure 22 — Part A shows the measured response when the Zx port of the return loss bridge was terminated in 50 Ω. You can see that the response is very flat, at 50 dB. Part B shows the measured response of the filter, with the filter connected to the Zx port and the filter output terminated in 50 Ω.

(A) (B) (C)

Figure 23 — Part A shows the sweep of the coaxial cable going to my 8 band HF vertical antenna. The marker is set on the 7 MHz dip. In Part B, I changed the sweep range to 6 to 8 MHz, to zoom in on the 40 meter response. You can see that the antenna resonance is a bit low, at 6.91 MHz. For Part C, I placed my antenna tuner in line with the coax, and tuned for 7.015 MHz. With the tuner, the return loss is 20.4 dB.

Final Words

There is still room for some improvement, at the time of preparation of this article. The internal attenuator layout is one point, to make the device less dependent on external attenuators. Also, as you may have noticed, the hardware is prepared for SD cards, but nothing was said about this. An SD card would be a very convenient way of recording the screen with a known graphics file format, to be printed afterwards using a computer. Unfortunately, the software routines I had didn't work, so I have more work to do, debugging them and getting the routines working. These two points will be the next steps of the development.

The other improvement will be to create a new set of fonts for the TFT screen. This will be a time-consuming task and before starting, since this is an embellishment detail, I will have to gather the needed motivation.

And finally, many of you certainly linked the name I gave to this device to the old and famous TV series, Star Trek. Well, you are right; it's a tribute to the original series, which many of us were so fond of and, since this is a triple instrument, I couldn't resist. I apologize for not having enough competence to implement the teleportation feature — the designers of the original Tricorder were very good indeed.

Rubens Ramos Fernandes earned a BS in Electrical Engineering in 1970 and worked for about 31 years in the telecommunications industry in research, design and production. He retired in 2004. He has been a licensed Amateur Radio operator since 1979 and held the call signs PY2FXJ and PY2QE while living in Brazil and VK5FE since September 2010 in Australia. Rubens is a CW enthusiast. He now dedicates his spare time to home brewing small transceivers and test equipment. He has a small workshop that includes mechanical, electrical and software facilities.

www.vk5fe.com

Notes

[1] Thomas M. Alldread, VA7TA, "NimbleSig III — Part 1" *QEX*, Jan/Feb 2009, pp 3 – 20. Part 2, *QEX*, Mar/Apr 2009, pp 16 – 24.

[2] Jim Koehler, VE5FP, "A DDS-Based Signal Generator," *QEX*, Nov/Dec 2009, pp 3 – 13.

[3] The circuit board and firmware files associated with this article are available for download from the ARRL *QEX* files website. Go to **www.arrl.org/qexfiles** and look for the file **5x15_Fernandes.zip**.

[4] Sam Green, WØPCE, "An Extremely Wideband QRP SWR Meter," *QEX*, Jan/Feb 2014, pp 15 – 23.

[5] Wes Hayward, W7ZOI, and Bob Larkin, W7PUA, "Simple RF-Power Measurement," *QST*, Jun 2001, pp 38 – 43.

[6] Wes Hayward, W7ZOI, and Terry White, K7TAU, "A Spectrum Analyzer for the Radio Amateur," *QST*, Aug 1998, pp 35 – 43.

Scotty Cowling, WA2DFI and Chris Testa, KD2BMH

At the direction of the TAPR Board of Directors; **taproffice@tapr.org**

TAPR Looks to Advance the Work of John Stephenson, KD6OZH

The Amateur Radio community lost a valuable contributor on July 27, 2014 with the passing of John Stephensen, KD6OZH. John was born and raised in Fresno, California, and graduated from McLane High School in 1970. He studied electrical engineering at the University of California, Santa Barbara.

John developed his interest in Amateur Radio and electrical engineering at an early age, after discovering his father's shortwave radio. John pursued these interests as a hobby and a profession throughout his life.

He was a gifted engineer and independently designed an early desktop computer in 1972, while working as an electrical technician at MiniCar Corporation in Goleta, California. He then started one of the first personal computer companies, PolyMorphic Systems, with two partners, Brian Wilcox and Richard Petersen. John was the principal product designer. John later worked as an engineer at CompuCorp in Santa Monica, where he was Director of Systems Engineering. In 1985 he co-founded the ISO-based network communications company Retix in Santa Monica, where he was Vice President of Technology Development. In 1993 John joined another Santa Monica-based computer company, ISOCOR, where he became Vice President for Technology.

John returned to Fresno in 2007, and started Millenium Radio to develop technology for software defined radio applications for use on wireless networks. He was working on the technology when he died.

John was the author of many technical publications concerning computer, digital radio and related technologies. He was a participant in the development of standards for computer network and internet communication protocols, working with industry groups and the US National Institute of Standards and Technology (NIST).

John Stephenson, KD6OZH

John was a member of the ARRL High-Speed Multimedia (HSMM) Working Group, and volunteered to develop an RF modem to augment IEEE 802.11 (WiFi) equipment to provide longer-distance communications links. He developed numerous prototypes of both direct conversion and quadrature sampled Software Defined Radios. The prototypes were designed in CadSoft *Eagle*, and manufactured at his home RF lab in Fresno, California.[1] He stated in an e-mail that they "have been tested over distances of up to 8 miles on 70 cm in a 1 MHz channel with 50 W PEP, using one mobile antenna at 10 feet and one base antenna at 25 feet."

An orthogonal frequency division multiplexing (OFDM) modem was the core of John's work, and his goal was high: to cover the San Joaquin Valley and surrounding mountains with a high-speed mesh network. John used two layers of error-correcting codes (dual-ECC) in his modem to ensure the reliable transfer of data. The inner code minimizes the SNR required by the data link and the outer code compensates for fading. The radio functions as a multi-hop bridge, similar to 802.11s, but uses multiple channels to allow multiple simultaneous data transfers, minimizing contention in ad-hoc and mesh networks. One channel is the control channel and multiple data channels may be used.

John wanted to support point-to-point packet communications, as well as broadcast voice chats with the new modem. He noted that the dual-ECC is especially important for broadcast and multicast data, where it would be very inefficient for all of the recipients to transmit acknowledgements. Source multi-point relays (S-MPR) are employed to select a minimal set of relay stations that still ensure complete coverage of all stations in the network. He dubbed the protocol the Advanced Wireless Mesh Protocol (AWMP) and optimized it for broadcast, multicast, and unicast routing.[2]

The modem is built on top of a custom designed processor named the CPU16F. It's a 16-bit Reduced Instruction Set Computing (RISC) machine implemented as a soft core in a Xilinx Field Programmable Gate Array (FPGA). The processor is described in his 2010 Digital Communications Conference paper titled "An FPGA-Based Transceiver Module."[3] John coded a custom assembler in *Delphi*, and all of the radio's software was written in this format.

The CPU16F processor itself was

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[1] Notes appear on page 24.

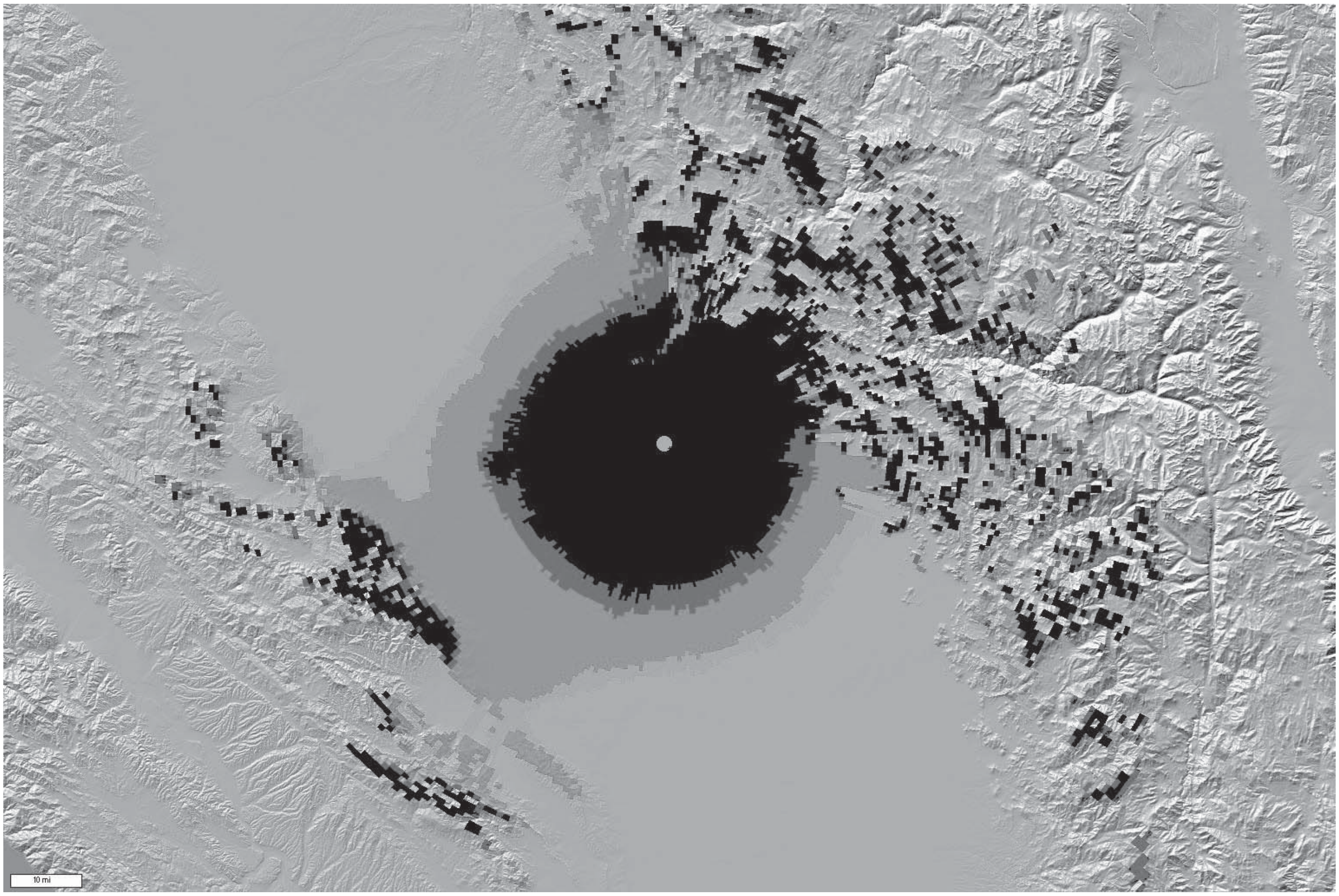

Figure 1 — This map, centered on Fresno, California, shows the 70 cm coverage of John Stephensen's orthogonal frequency division multiplexing (OFDM) modem. The map shows an analysis using the Radio Mobile software package for a 12 dBi antenna at 90 feet, and transmitter powers of 5 W, 10 W, 100 W, and 200 W.

designed and written in *Verilog*, as were the many coprocessors necessary to support the wideband OFDM modes. For example, trellis-coded differential 8-PSK modulation with a rate-2/3 inner error correcting code (ECC) is implemented within the FPGA fabric and accessed from the soft core processor via I/O instructions.

The prototypes were manufactured by hand at his home. The setup consisted of quality rework equipment, including a hot air bath and solder paste dispenser. A home-brewed vacuum placement tool allowed him to work with small surface-mount packages including leadless integrated circuits (ICs) right at his desk.

Towards the end of his life, John was working on an OFDM modem for 1.8 Mbps links. He assessed setting up networks with different power levels (from 1 to 100 W) and antenna heights (45 and 90 foot towers) on the 70 cm and 23 cm Amateur Radio bands. See Figure 1. The work was analyzed using the *Radio Mobile* software package.[4]

John donated his fully operational desk to TAPR. His *Windows XP* computer was set up with two DCP-6 prototypes connected via an RF combiner, demonstrating the OFDM modem. The last written notes we have describe how to turn on and load the prototype demonstration. It has been carefully wrapped up and photographed for further analysis. John donated a cash sum plus all of his research documentation and hardware to TAPR so that interested parties may build upon his work.

John's legacy includes many well-documented DSP functions written in *Verilog*. While this code can be used as part of John's SDR, it also forms a basis for building new DSP functions in *Verilog* without starting from scratch. Well-written, documented, reusable DSP modules are also an excellent learning tool, both for DSP and *Verilog*. TAPR intends to make all of John's code available on its servers for interested developers to use as they see fit. While TAPR is still working to determine the best way to achieve the maximum benefit to the community from John's work and generosity, we welcome proposals from interested parties interested in building upon John's research. Did you know John? Did you work with him? TAPR would like to hear from you! John left us way too soon and way too abruptly. John, we will miss you!

You can contact TAPR via e-mail at: **taproffice@tapr.org**, call the office at 972-671-8277 or write to: TAPR, PO Box 852754, Richardson, TX 75085-2754.

Notes

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[1] CadSoft *Eagle* is available from **cadsoftusa.com**.

[2] John B Stephensen, KD6OZH, "A Software Defined Radio for Mesh Networks," 2013 ARRL/TAPR Digital Communications Conference. This paper is available for download from: **www.tapr.org/pdf/DCC2013-SDR-Mesh-KD6OZH.pdf**.

[3] John B. Stephensen, "An FPGA-Based Transceiver Module," 2010 ARRL/TAPR Digital Communications Conference. This paper is available for download from: **www.tapr.org/pdf/DCC2010-FPGA-BasedTransceiver-KD6OZH.pdf**.

[4] The *Radio Mobile* software package is available from: **www.cplus.org/rmw/english1.html**.

[5] The colorized version of Figure 1 is available for download from The ARRL *QEX* files website. Go to **www.arrl.org/qexfiles** and look for the file **5x15 Stephensen-Fig-1.zip.**

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A High Performance 45 MHz IF Amplifier for an Up-Conversion HF/LF Receiver

The author describes the design process for a high performance IF Amplifier.

The July/August 2013 edition of *QEX* contained an article about the design of the HF7070 up-conversion HF/LF receiver, which has a 45 MHz first IF. A key building block in this receiver was the IF amplifier, which was a 45 MHz version of the amplifier that uses four J310 junction FETs with source/gate feedback, originally designed by Bill Carver, W7AAZ, for use with down conversion receivers. At 45 MHz, it has a noise figure of 1.3 dB, a gain of 10 dB, a third order intercept point (IP3) output of 40 dBm, and a nominal 50 Ω input and output impedance. In the HF7070 *QEX* article, Table 1 showed the use of this amplifier in the signal path. The gain distribution in the IF strip was such that from a linearity point of view nothing was pushed to the limit.

In the HF7070 there is no preamplifier before the first H-Mode mixer, so it is essential that the first IF amplifier has a low noise figure and a high output IP3 in order to have a sensitive receiver that is also highly linear for close-in signals. It would have simplified the circuitry if an MMIC could have been used in place of the 4 × J310 amplifier, but at the time none were available with the performance of the 4 × J310 amplifier. A low noise figure and a high output IP3 were two conflicting requirements in the available MMICs. However recently Mini-Circuits have introduced the PHA-1+ and the dual matched version the PHA-11+. Unlike most MMICs designed for microwave applications the noise figure and IP3 out are at their best between 40 and 100 MHz, making them suitable for use as IF amplifiers in up-conversion receivers.

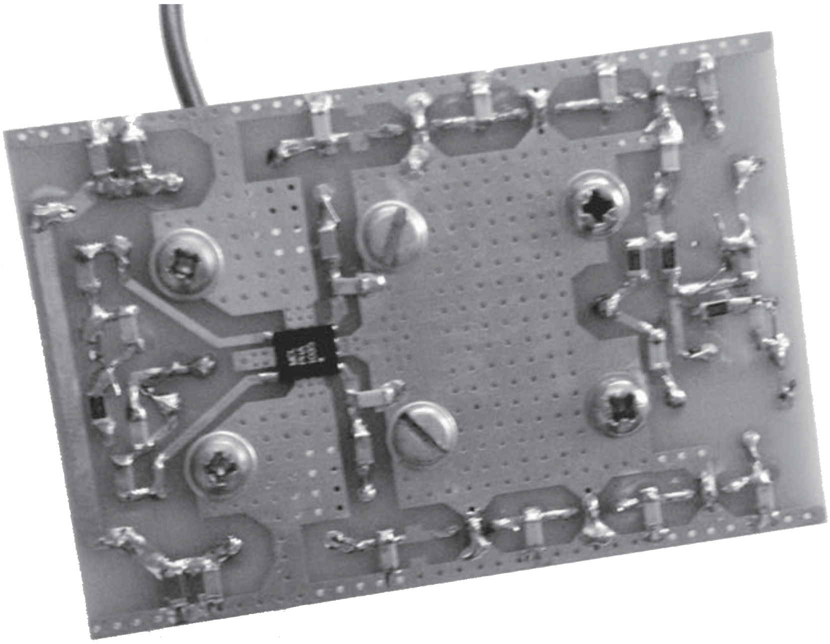


Photo A — Here is the circuit board/wiring side or the completed 45 MHz IF amplifier. The PHA-11 MMIC amplifier IC is to the left of center, near the RF output side of the amplifier. The wire connecting to the top of the board is the 5 V supply.

Unlike the 4 × J310 amplifier, however, the PHA-1+ has too much gain to drop it into the existing HF7070 IF strip. In addition its reverse isolation is not adequate for the output to directly drive a crystal filter like the 4 × J310 amplifier. This deficiency can be overcome by following the PHA-1+ with an 8 dB attenuator before the 4 pole crystal filter to smooth any reactance from the crystal filter and also make the PHA-1 output impedance nearer 50 Ω for the L match to the crystal filter. Fitting the 8 dB attenuator raises the input in-band IP3 of the crystal filter (26 dBm) to 34 dbm. This is still

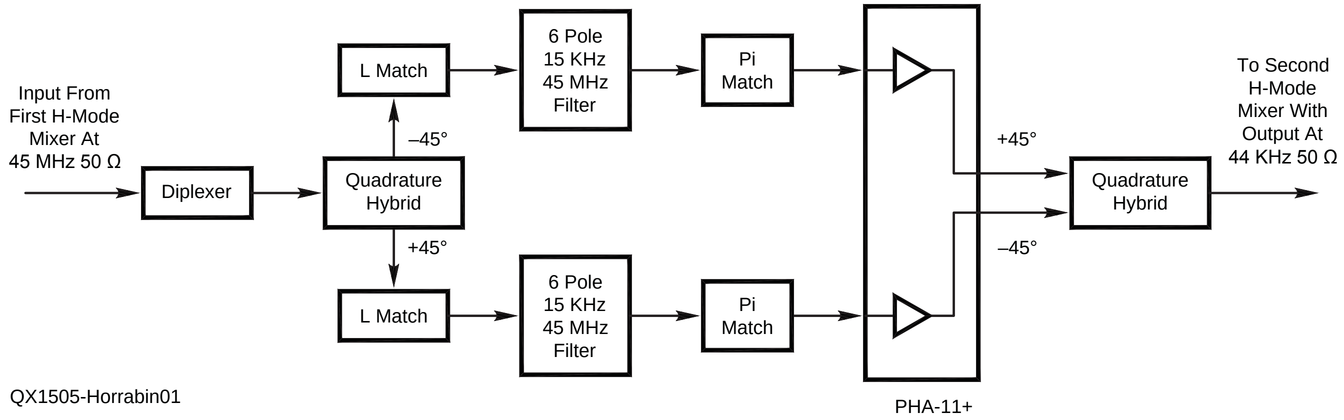


Figure 1 — This block diagram shows the improved architecture for the HF7070 45 MHz IF amplifier, using the PHA-11 MMIC. Note that it is necessary to have at least 110 dB of stop band attenuation at the second mixer image frequency. The 6 pole filter is made from three discrete 2 pole filters.

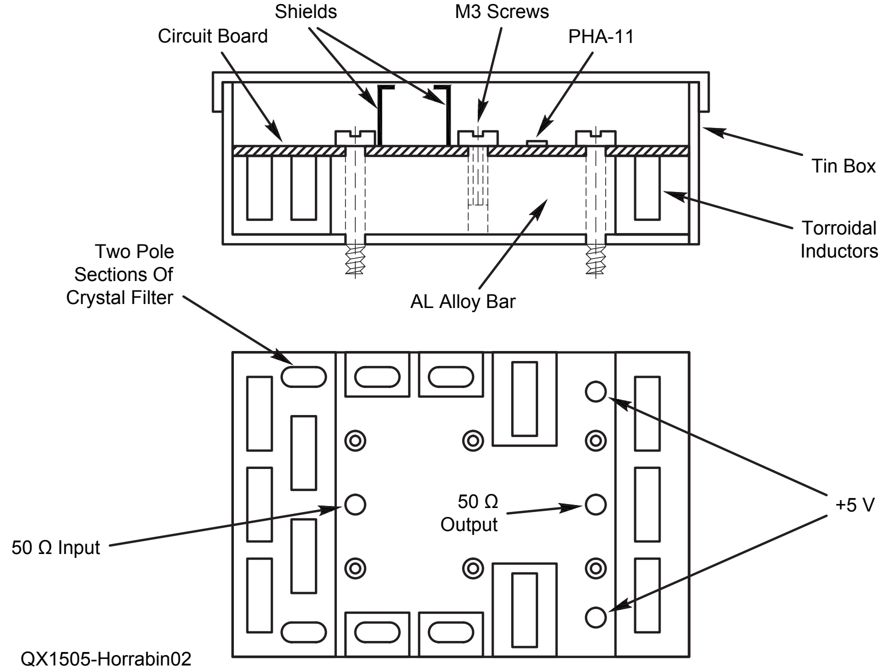


Figure 2 — This diagram shows the mechanical details of the PHA-11 amplifier.

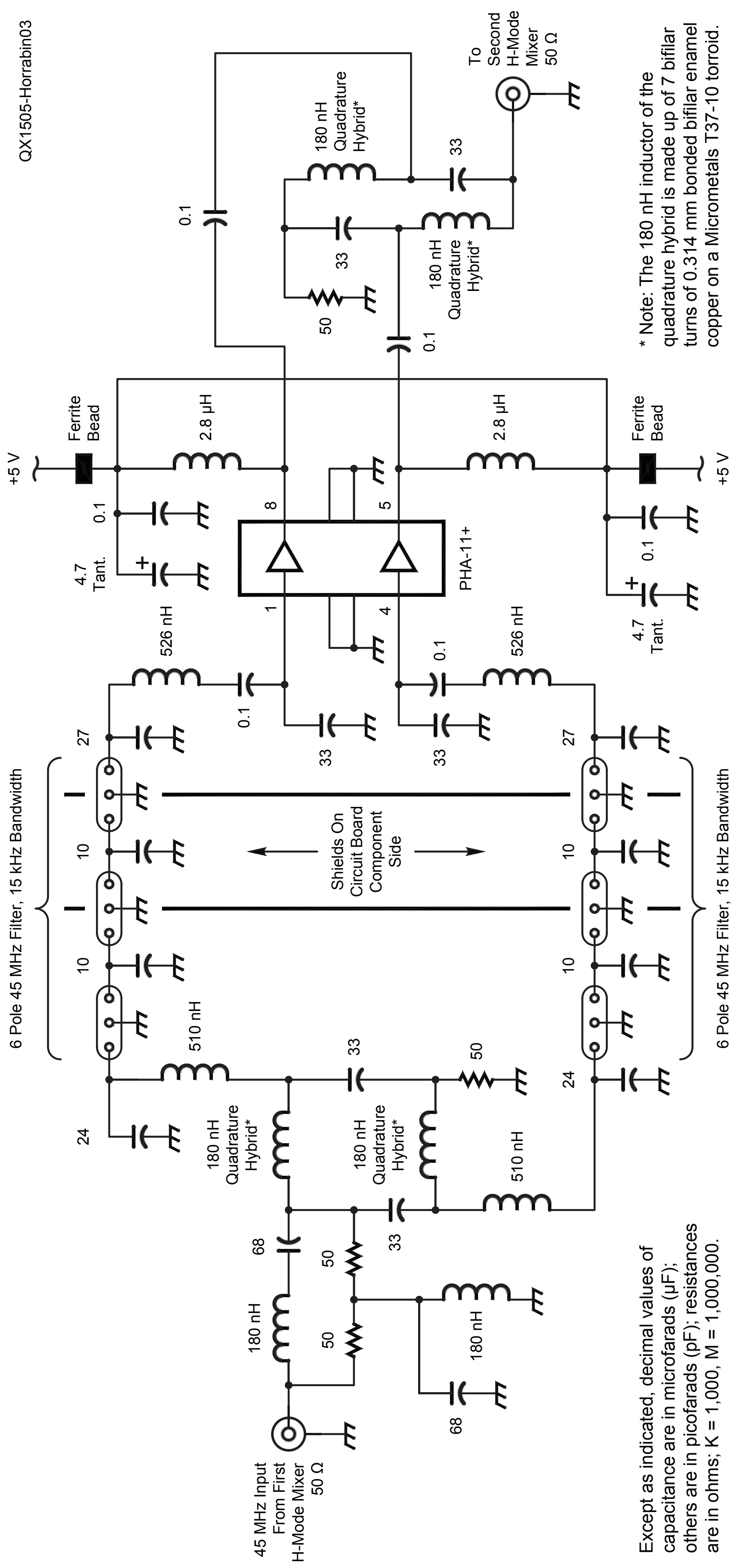
well below the PHA-1 output IP3 of 42 dBm.

To see if the PHA-1+ would be suitable in a practical design Dave Roberts, G8KBB, first measured its input impedance at 45 MHz using his N2PK vector network analyser (VNA). It was 80 Ω in parallel with 25 pF. Dave then measured the noise figure (NF) at 45 MHz from a 50 Ω source impedance, which was 2.2 dB. In one proposed use of this chip it would see an 80 Ω source impedance, so an L match was fitted to match its 80 Ω plus 25 pF input impedance to 50 Ω. When the chip saw an 80 Ω source impedance its NF was raised from 2.2 to 2.7 dB, which is quite a bit higher than the 1.3 dB of the 4 × J310 amplifier. The PHA-1+ has a gain at 45 MHz of 18 dB, however, and the higher gain could reduce the NF contribution from following stages.

In the present HF7070 45 MHz IF design the optimum gain block at 45 MHz is 20 dB and this is made up of two 4 × J310 amplifiers separated by a 4 pole roofing filter. Also the in-band IP3 of the receiver is ultimately determined by the in-band IP3 of the 4 pole crystal roofing filter that follows the first 4 × J310 amplifier. The 15 kHz bandwidth roofing filters at 45 MHz need to have six poles to get at least 110 dB attenuation at the second H-Mode mixer image frequency. In the existing design there are two poles of quadrature hybrid connected 45 MHz, 15 kHz bandwidth crystal filters after the first mixer. There is then a 4 × J310 amplifier and then a 4 pole filter followed by another 4 × J310 amplifier and then the second H-Mode mixer, to give a 44 kHz output frequency for the 25 bit audio ADC.

Because the PHA-1+ has 18 dB gain, a different IF architecture offered a simplification of the circuit and the possibility of a significant improvement of in-band IP3 and a better out of band IP3 at 20 kHz spacing. See Figure 1. The penalty would be a 2 dB increase in receiver noise figure. If necessary, a preamplifier for use above 7 MHz could be used, based on the push pull MRF 581A amplifier originally designed by Jacob Makhinson, N6NWP, that was presented in *QST*. The MRF 581A is still available, and an 8.8 dB gain with a noise figure of 2.5 dB and an IP3 out of 57 dBm should be possible. The use of this amplifier would not significantly affect the receiver dynamic range, and it would only really be needed to provide extra sensitivity of the receiver for reception of signals above 7 MHz.

In the new IF architecture described using the PHA-11+ MMIC, all six poles of roofing filter are in one place so that careful shielding from input to output is needed. See Figure 2. This has been achieved by machining a 12 mm thick piece of aluminium bar fitted inside a tin box of dimensions 50 × 75 × 25 mm. The aluminium bar also doubles as a heat sink to the PHA-11+ MMIC used in the design, which is the dual matched version of the PHA-1+. One of my neighbors, Alan Heywood — whose brother is a radio



* Note: The 180 nH inductor of the quadrature hybrid is made up of 7 bifilar turns of 0.314 mm bonded bifilar enamel copper on a Micrometals T37-10 toroid.

Except as indicated, decimal values of capacitance are in microfarads (µF); others are in picofarads (pF); resistances are in ohms; K = 1,000, M = 1,000,000.

amateur — builds model steam engines for a hobby, and has a good mechanical workshop. He offered to do all the mechanical work. The circuit shown in Figure 3 was constructed on a commercially made, double sided circuit board with plated through holes. Figure 4 shows the circuit board pattern. The circuit board has thermal vias to conduct heat from the chip to the aluminium bar. It was essential to keep the chip temperature down to get the best noise figure and with a dissipation of about 1.25 W, the chip temperature was only 34°C.

All of the inductors in the unit were wound on T37-10 powdered iron torriods because it was convenient to do so for the prototype. In a commercial design, surface mount inductors could be used to replace all the torriods, except for the two that form part of a quadrature hybrid. In the HF7070 radio most of the RF inductors were surface mount shielded chokes manufactured by Vishay.

Construction

I designed the circuit of the 45 MHz amplifier, the circuit board layout, and also drew up the mechanical side of the job. The commercially made printed circuit boards were made by Fischer in Germany. George Fare, G3OGQ, used a software circuit board design package to generate the necessary files for commercial manufacture from my free-hand graph paper layout. Martein Bakker, PA3AKE, arranged the manufacture of the circuit boards with the German company, and also paid for them as his personal contribution to this project.

A few PHA-11+ MMICs were supplied by John-Paul Newbold of Mini-Circuits Europe and two of these chips were reflow soldered onto the commercially made circuit boards in the electronics workshop at Daresbury Laboratory. The mechanical drawing of Figure 2 shows that the circuit board is secured to the aluminium bar by six M3 screws. The outer four screws project from the base of the tin box, so that the completed IF strip could be mounted to a motherboard. Before any of the passive components were soldered to the circuit board, the board was loosely screwed to the machined aluminium bar and this was placed into the tin box to see if there were any tolerance issues. There wasn't, so the six M3 screws were fully tightened, securing the circuit board to the aluminium block. The circuit board and aluminium block were then

Figure 3 — This schematic diagram shows the 45 MHz IF amplifier circuit. Note that the 180 nH inductor of the quadrature hybrid is made with 7 bifilar turns of 0.314 mm bonded bifilar enamel copper wire on a Micrometals T37-10 powdered iron toroid.

gripped in a small vice so that the surface mount capacitors and 50 Ω resistors could be fitted. Unlike George and Dave, I had never done any serious surface mount assembly before, but by using a special pair of tweezers I found it easy to do (or as we British would say "A piece of cake").

All of the inductors in the design were wound on Micrometals T37–10 toroids. What made the winding of the toroids easy to do was the use of the capacitance and inductance measuring box from Almost All Digital Electronics USA (**www.aade.com**). The result was that the first time the amplifier was switched on it worked straight away and only minor adjustments were needed to remove a 1 dB dip in the passband. After the initial performance tests the edges of the circuit board were soldered to the tin box and two internal shields were fitted to improve the stop band of the unit at 45 MHz minus 90 kHz, the second H-mode mixer image frequency.

Performance Tests

The design team met at Dave Roberts' house one evening with the prototype 45 MHz IF amplifier. Although the unit was designed to mount on a motherboard, two SMA sockets were fitted to the unit for testing, and a shield fitted between them. Using an N2PK vector network analyzer (VNA), its transmission characteristics were plotted. See the graphs of Figure 5. Also the circuit noise figure (NF) and gain were measured using Dave's NF measuring gear. See Figure 6.

The noise figure was measured as 6 dB, and this was what it should be, remembering that the insertion loss of the 6 pole crystal filter forms part of this circuit and should account for about 3.5 dB. Overall circuit gain was 14 dB. What was disappointing was that the stop band was only 80 dB, although at that point the internal shields had not yet been fitted. It was nowhere near the 110 dB desired, however. Two internal shields were then fitted inside the tin box and its transmission characteristics measured again. See Figure 7. The stop band was improved by around 20 dB, but some more work is needed to further improve this.

Next, I visited the RF lab at Daresbury Laboratory to measure the in-band and out of band IP3 of the circuit. Two visits were required due to problems with the first set of measurements. I discussed the first set of results with Martein Bakker, PA3AKE, and set out the next time with a definite strategy in mind. The next IP3 results are shown in Table 1. The big surprise has been the significant improvement in out of band IP3.

The two amplifiers in the PHA-11 have their outputs summed by the second

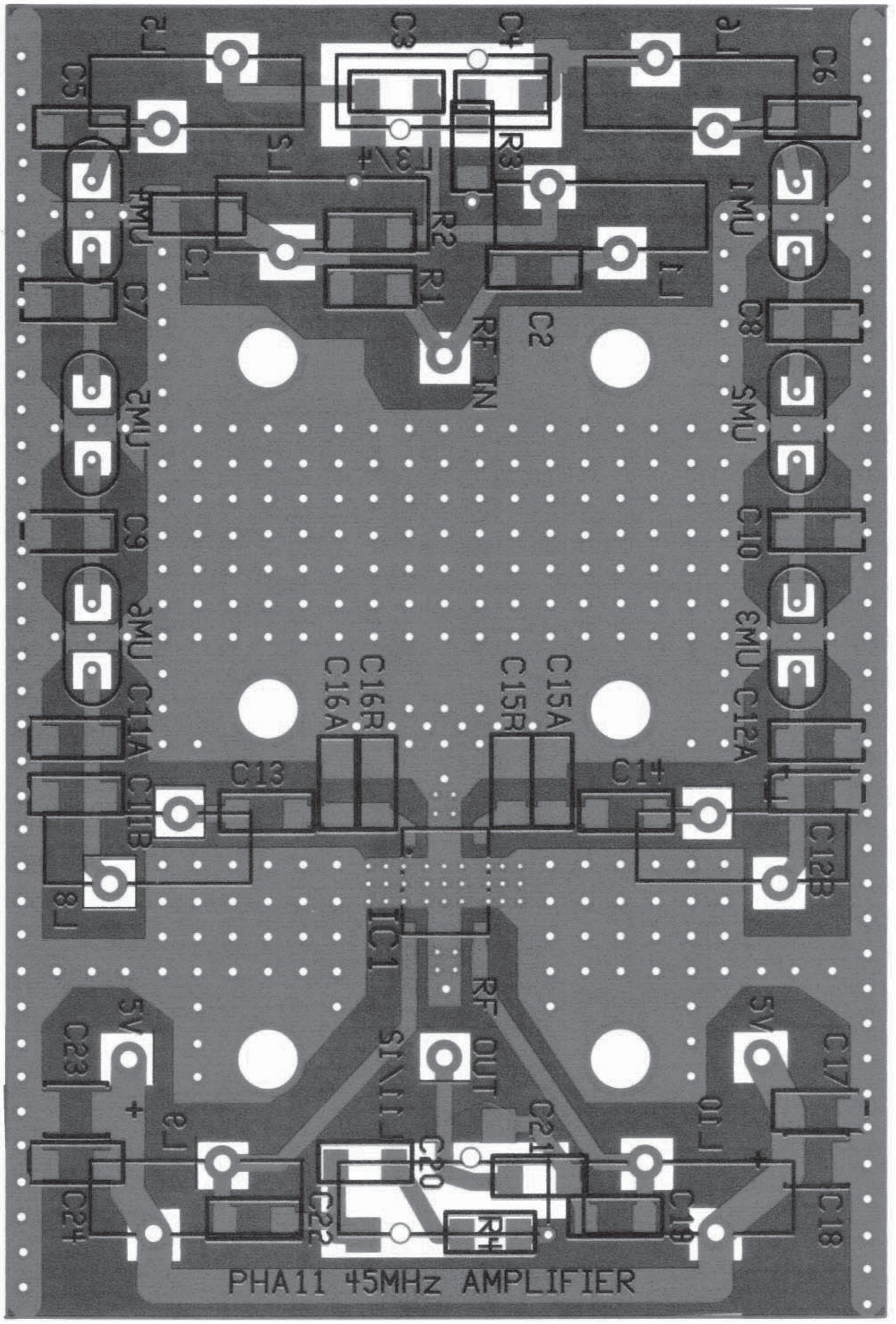
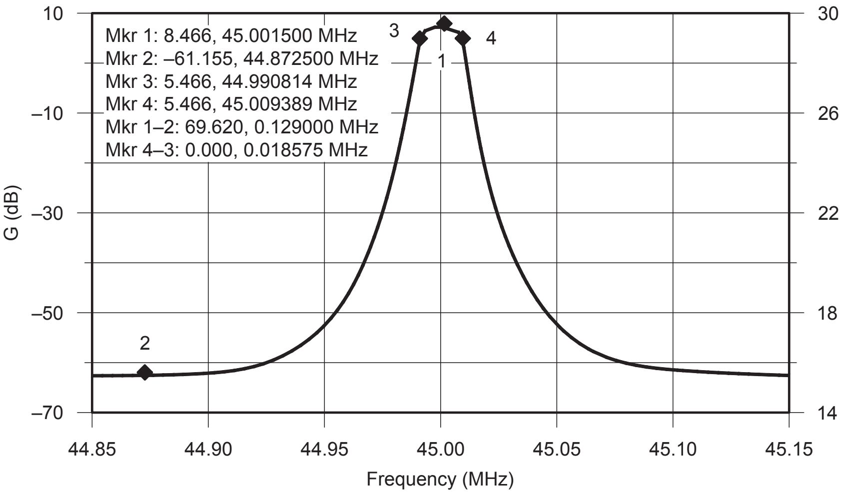


Figure 4 — Here is the circuit board etching pattern for the 45 MHz IF amplifier. This is not to scale. The actual circuit board files are available for download from the ARRL QEX files website. Go to www.arrl.org/qexfiles and look for the file 5x15_Horrabin.zip.

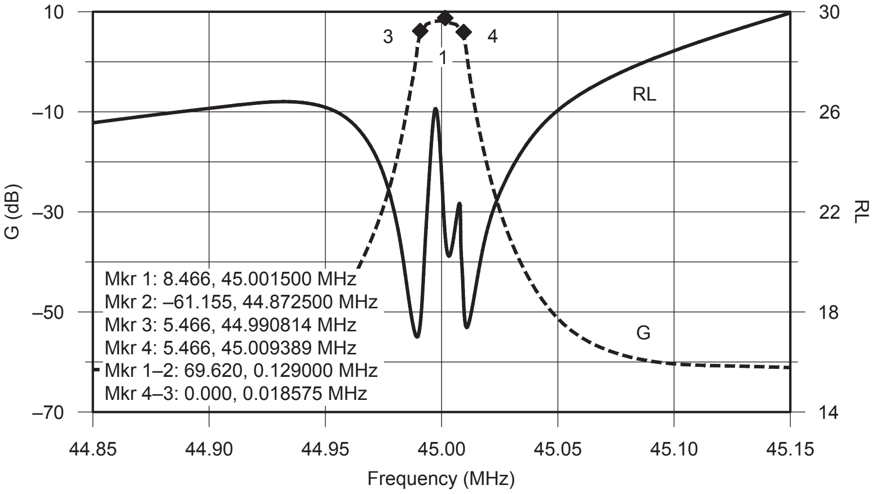
Table 1
Measured Performance of the IF Amplifier

Test Tone	*IP3 Product*	*Output IP3*	*Input Ip3*	*RX IP3*
(kHz)	*(dBm)*	*(dBm)*	*(dBm)*	*(dBm)*
2	–75	37.5	23.5	30.5
5	–96	48	34	41
10	–92 (–75)	46 (52.5)	32 (38.5)	39 (45.5)
20	–126 (–89)	63 (59.5)	49 (45.5)	56 (52.5)
40	–130 (–98)	65 (64)	51 (50)	58 (57)
80	–115	57.5	43.5	50.5



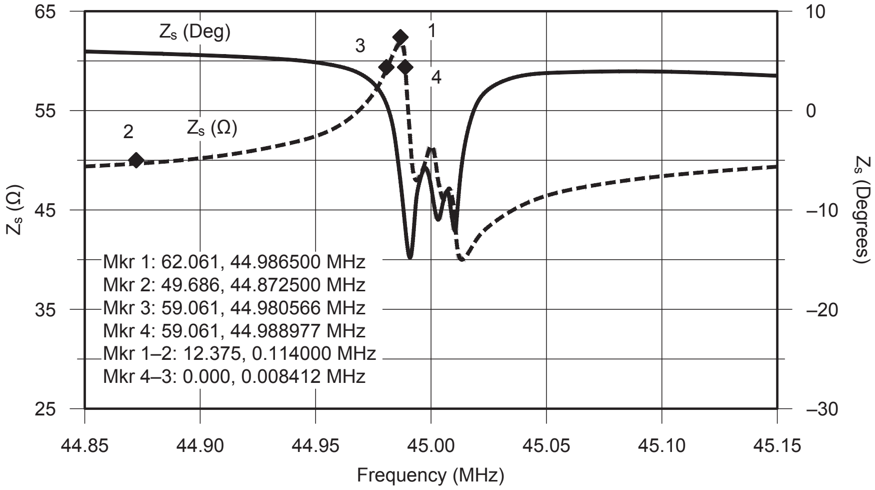
QX1505-Horrabin05a

(A)



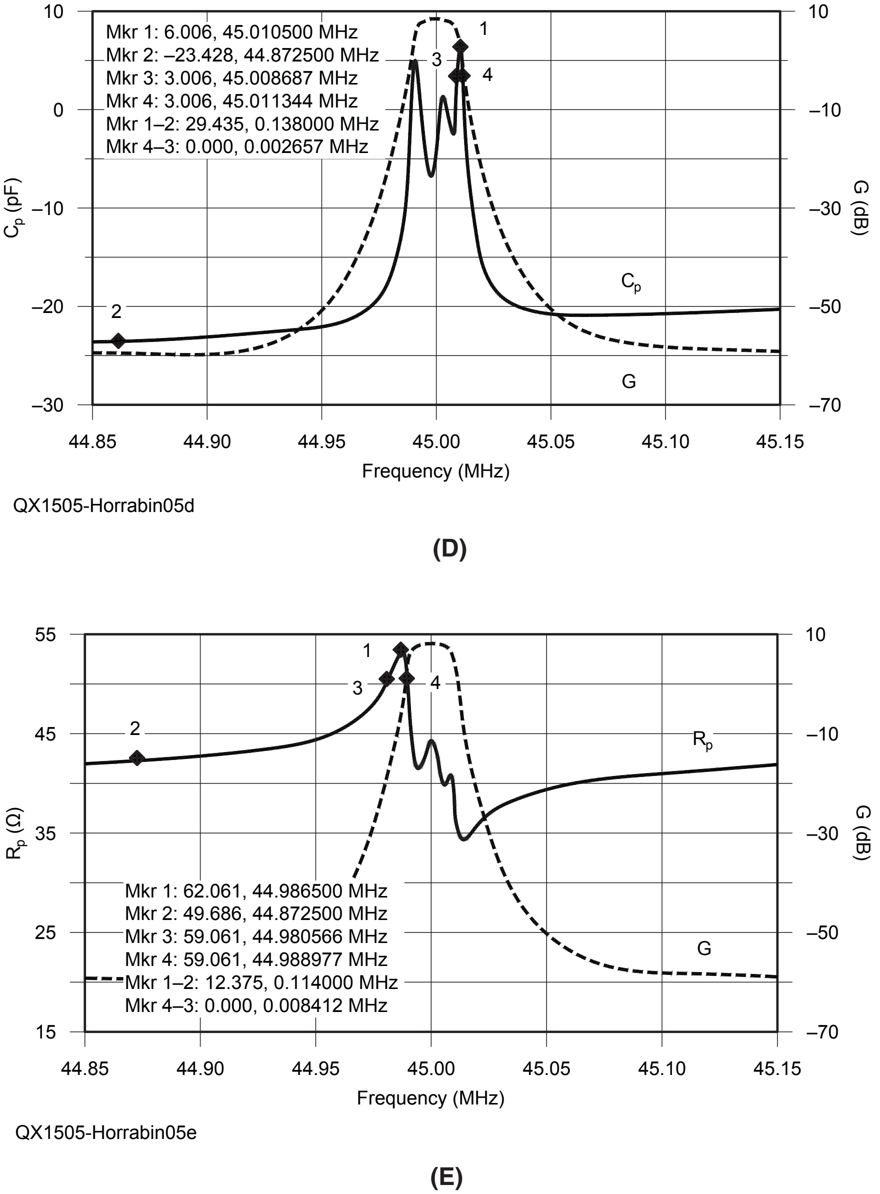
QX1505-Horrabin05b

(B)



QX1505-Horrabin05c

(C)



QX1505-Horrabin05d

QX1505-Horrabin05e

Figure 5 — These graphs are the performance measurements made by Dave Roberts using his N2PK vector network analyzer.

quadrature hybrid. For an amplifier output level of 0 dBm, each amplifier has an output of –3 dBm. Because it has a gain of 18 dB, the amplifier input level and the 6 pole crystal filter output level is –21 dBm. This gives an input level to the crystal filter of –17 dBm, and an input level to the complete amplifier of –14 dBm. This ties in with the measured performance of the unit as a gain block with a gain of 14 dB and a noise figure of 6 dB.

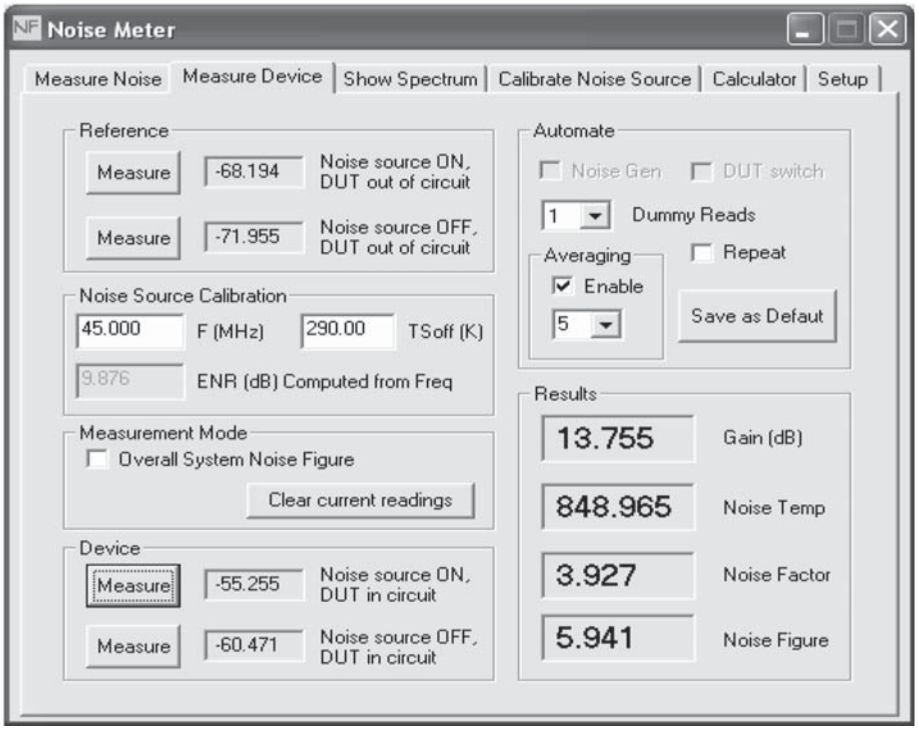
The main measurements of in band and out of band IP3 were made at an amplifier output level of 0 dBm. A few out of band measurements were made at a 10 dBm output level (shown in parentheses in the table) to give some idea of the linearity of the unit with signal amplitude. The projected IP3 of a receiver using this amplifier assumes a 5 dB mixer loss and 2 dB loss due to its input low pass filter. So effectively, the input intercept of the 45 MHz amplifier module has 7 dB added to its input IP3 to calculate the receiver performance. This presumes that the amplifier is used with the HF7070 front end. It is unlikely that the out of band IP3 of such a receiver will exceed 45 dBm, but Table 1 does show that the IP3 performance of the radio will not be limited by the IP3 of the roofing filters.

Figure 8 is a screen shot from the spectrum analyzer, with the test tones 2 kHz apart but offset by a few hundred hertz. The offset is necessary to identify the third order product, because at this spacing of the signal generators there are spurious peaks from the signal generators on integer boundaries. For the out of band measurements, the signal generator frequencies again had to be offset slightly because there was a low level spurious peak from the signal generator at exactly 45 MHz.

Observations

Using this amplifier to replace the 45 MHz IF amplifier in the HF7070 receiver makes possible a receiver IP3 performance of 50 dBm at 20 kHz tone spacing, for a receiver noise figure of 13.5 dB. In addition, the in-band dynamic range is also significantly improved and that was the real reason for constructing this IF strip using the PHA-11+ MMIC. In fact for in-band signals it is now the IP3 performance of the ADC that is the limiting factor. Improve the ADC and an in-band IP3 of over 30 dBm at 100 Hz spacing is possible for an up-conversion radio. The MMIC has gain at 3 GHz, and fortunately there has been no sign whatsoever of any instability with the circuit during testing. The circuit board layout and the Pi match capacitors close to the input of the chip have probably helped in this regard.

It is very unlikely that John Thorpe will incorporate this prototype amplifier into one of the HF7070 prototypes, to test it as part of a real radio receiver. With John, you never can tell, however!


Noise Meter

Measure Noise | Measure Device | Show Spectrum | Calibrate Noise Source | Calculator | Setup

Reference
Measure -68.194 Noise source ON, DUT out of circuit
Measure -71.955 Noise source OFF, DUT out of circuit

Noise Source Calibration
45.000 F (MHz) 290.00 TSoff (K)
9.876 ENR (dB) Computed from Freq

Measurement Mode
☐ Overall System Noise Figure
Clear current readings

Device
Measure -55.255 Noise source ON, DUT in circuit
Measure -60.471 Noise source OFF, DUT in circuit

Automate
☐ Noise Gen ☐ DUT switch
1 Dummy Reads
Averaging
☑ Enable
5
☐ Repeat
Save as Defaut

Results
13.755 Gain (dB)
848.965 Noise Temp
3.927 Noise Factor
5.941 Noise Figure

Figure 6 — This screen shot shows the results of the noise figure and gain measurement made by Dave Roberts.

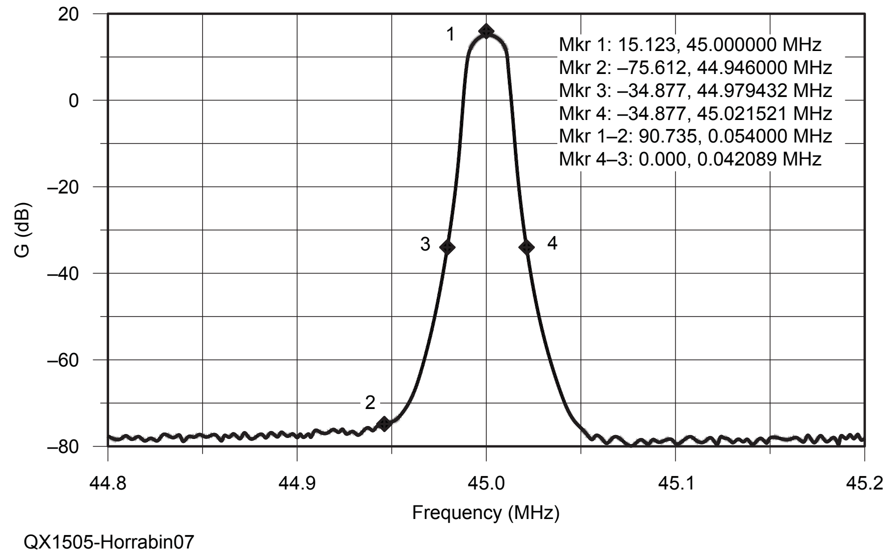


Figure 7 — This graph is the result of a second measurement of the circuit transmission characteristics made with Dave Roberts' vector network analyzer, after internal shields were installed between sections of the circuit.

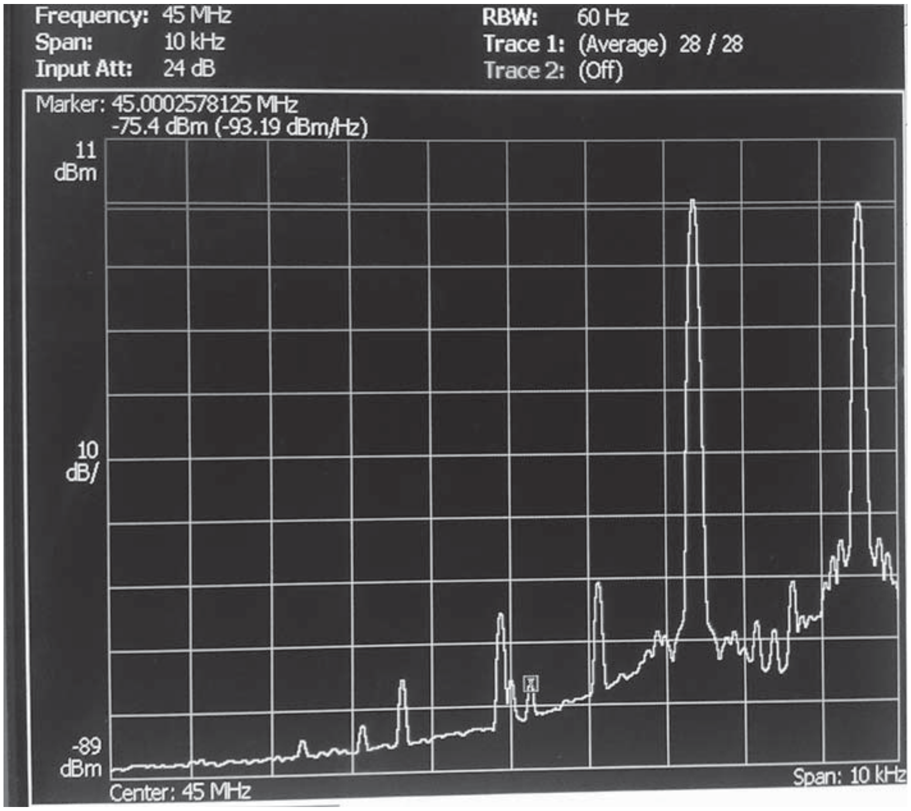
The PHA-1+ / PHA-11+ MIMC is unsuitable for application in down conversion receivers for the amateur bands but could be used to give state of the art performance in an up-conversion radio with simple circuitry. If you are interested in a state of the art receiver for the amateur bands then PA3AKE's holy grail version of the CDG2000 transceiver is definitely the way to go. By publishing details of this 45 MHz MMIC IF amplifier, perhaps it might be incorporated into some shortwave radio transceivers. In principle the result could be a state of the art up-conversion receiver at a budget price. Mini-Circuits now supply the PHA-22+ MMIC. It looks like a 1.5 GHz version of the PHA-11+ so it should be of lower cost and a drop-in part for this application.

The noise figure of the MMIC chip used in the amplifier adds directly to the receiver noise figure. Mini-Circuits do make chips with 0.5 dB noise figures, but in most of these their performance below 100 MHz is unsuitable. Those that have a very low noise figure below 100 MHz have too much gain. In fact the PHA-1/PHA-11 appears to be the ultimate part made by Mini-Circuits for this sort of application at the present time.

This amplifier has been built into a tin box to get a good stop band and also so that a complete IF module could be mounted onto a circuit board motherboard. It is likely any potential manufacturer of a transceiver would want it to be part of the main circuit board. The 45 MHz monolithic crystal filters used in the HF7070 proto 2 receiver were obtained from the British company Total Frequency Control (TFC). The 6 pole filters used in this prototype 45 MHz amplifier were made up by splitting 4 pole pairs. Total Frequency Control's Japanese supplier does in fact make a 6 pole, 15 kHz bandwidth, 45 MHz monolithic crystal filter in one can. This has a poor stop band, however. They have been asked if they can produce a 6 pole filter with a 110 dB stop band at ±90 kHz. They could probably achieve this by constructing it in a larger can.

One problem with the HF7070 receiver was coupling between the two toriods used as part of a quadrature hybrid. Mini-Circuits makes a shielded quadrature hybrid centered on 45 MHz. So it may be possible to build this circuit on the main circuit board and get a 110 dB stop band at the second mixer image frequency.

I sent a copy of the circuit and the IP3 measurements to several American friends for their comments. Wes Hayward, W7ZOI, was amused that we have spent so much time and effort and our own money on this project because it is only of use to an "appliance" manufacturer and not for normal Amateur Radio projects. The *QEX* article on the HF7070 receiver showed



Frequency: 45 MHz
Span: 10 kHz
Input Att: 24 dB
RBW: 60 Hz
Trace 1: (Average) 28 / 28
Trace 2: (Off)
Marker: 45.0002578125 MHz
-75.4 dBm (-93.19 dBm/Hz)

Figure 8 — This screen shot is the spectrum analyzer two-tone test measurements the author made at Daresbury Laboratory. The input tones were 2 kHz apart. The analyzer is set to a center frequency a few hundred hertz offset from the center of the tones.

that it should be possible for main stream "appliance" manufacturers to make a good up-conversion receiver that will outperform most commercial down conversion receivers. The application of the PHA-11+ in a 45 MHz IF amplifier can further improve the IP3 performance of an up-conversion radio like the HF7070, and also simplifies the circuit in that only one chip is required in the 45 MHZ IF amplifier.

Acknowledgements

This project needed the use of machine tools, and I would particularly like to thank my neighbor, Alan Heywood, for doing all the mechanical work.

Our friend Martein Bakker, PA3AKE, ordered and generously paid for the commercial circuit board with its thermal vias, and checked the circuit board files before they were sent to Fischer in Germany for manufacture.

Since Dave Roberts has an N2PK VNA and the capability to measure noise figure, it was only necessary to visit Daresbury Laboratory to measure IP3. As usual, my former colleagues were most helpful even though they were particularly busy at the time. I want to single out the help given by Andy Moss in the RF group, and Nigel Lightbown, who did the reflow soldering of the PHA-11+ chips onto the circuit board in the electronic workshop.

There was a problem in getting samples of the Mini-Circuits PHA-11 + MMIC from the US, because they wanted to sell only the minimum reel size, which came to about $300. John-Paul Newbold of Minicircuits Europe supplied us with some he bought on his own budget, however. He obviously realized the potential of this application of the chip in up-conversion radio receivers when others didn't.

Mark Sumner of MWS Technical Services provided the 45 MHz crystal filters that were made by Hertz Technology in Japan for use in the amplifier. Although these filters are no longer commercially available, those supplied by the British firm TFC Ltd have similar IP3 performance, and they were fitted in the HF7070 proto 2 receiver on which the technical performance measurements were made. Those measurements are presented on Martein Bakker's website.

Finally, although most consumer electronic products these days originate in the far east, it is still American companies that drive fundamental technological advances, of which the Mini-Circuits PHA-11+ is one such example. It remains to be seen how long it will be before it is used in commercial Amateur Radio equipment designs.

Appendix A: Variations on a Theme

In the present circuit, the output of each arm of the six poles of crystal filter went to one of the amplifiers in the PHA-11 and the outputs of the two amplifiers were combined by the second quadrature hybrid.

Two other circuits were considered that used a single device. In both these circuits the outputs of the two arms of the six poles of crystal filter were combined by the second quadrature hybrid before a single amplifying device. The devices considered for this were two Mini-Circuits MMICs: the PHA-1+ and the very low noise PGA-103+.

There were two main reasons for the present architecture. The first being that the quadrature hybrid input network seen by a MMIC is effectively a "floating" circuit. Because the MMICs have gain at 3 GHz we thought that the series inductance and parallel capacitance to ground of a Pi network at the input to the MMIC in the present architecture would give less chance of instability. Also the output IP3 would be increased by 3 dB and the output quadrature hybrid would present a good match to the second H-mode mixer.

If a single PHA-1+ MMIC is used in the alternative architecture at 45 MHz, the noise figure (NF) of the chip would be around

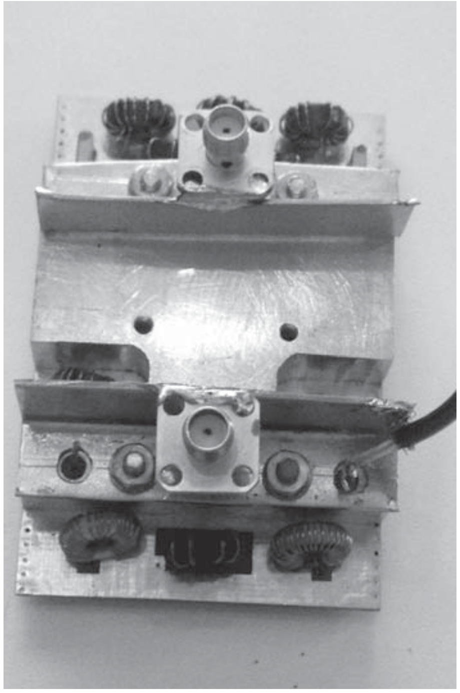


Photo B — This photo shows the component side of the completed 45 MHz IF amplifier circuit board, attached to the aluminum bar shield/heat sink. The SMA connector at the top of the photo is the RF input and the one at the bottom is the RF output. The length of small coaxial cable brings the 5 V supply to the circuit board.

2 dB, with a gain of 18 dB, an IP3 out of 43 dBm, and the output IP3 of the hybrid connected filters would be about 27 dbm for in-band signals. Putting these figures in John Thorpe's spreadsheet gives a receiver NF of 13.6 dB, an IP3 of 26.3 dBm, and a dynamic range in a 2.4 kHz bandwidth of 101.8 dB for close-in signals. The loss because of the six poles of crystal filter and two hybrids is around 4 dB.

The PGA-103+ at 45 MHz has a very low noise figure of 0.5 dB a gain of 26 dB and an output IP3 of 37 dBm. Putting these figures into the spreadsheet gives a receiver performance of NF of 11.6 dB, an IP3 of 20.3 dBm, and a 99 dB dynamic range in a 2.4 kHz bandwidth. This is close to the performance of the HF7070 receiver using the 4 × J310 amplifiers. The other difference would be that the out of band IP3 from 20 kHz outwards would be superior to the present HF7070 receiver.

In both of these circuits the gain of the HF7070 in the spreadsheet for the 44 kHz balanced amplifier was changed so that the total gain from antenna to the 25 bit audio ADC was the same, at 22 dB.

Commercial design can be all about compromise, so the use of the PGA-103+ could be the chosen option to avoid the use of a preamplifier with the receiver above 7 MHz. Where the present architecture will score (and also if a single PHA-1 is used) is that it will have a much better IP3 in the crystal filter transition region for test tones from 5 kHz to 20 kHz than if a PGA-103 + was used. This all presupposes that the MMICs will not become unstable when driven by the output from a quadrature hybrid.

Having demonstrated the use of the PHA-11+ MMIC in this type of 45 MHz IF amplifier, I will leave it to others to try the other options described, to see if these circuits remain stable when driven directly from a quadrature hybrid.

Colin Horrabin, G3SBI, was born in 1941. His father provided him with a World War II BC348 radio receiver for his 12th birthday, followed by a copy of the ARRL Handbook *for Christmas. After years building various projects using government surplus equipment, he obtained his Amateur Radio license in 1963. He has a degree in electrical engineering and a degree equivalent qualification in mechanical engineering. Following an apprenticeship with the British Aircraft Corporation in the early 1960s, he spent over 30 years working at Daresbury Laboratory as an electronic engineer. Colin is interested in small DX antennas for the LF bands, and intends to do some work on small multi turn spiral wound loops that are self resonant, containing ¼ wavelengths of wire, which are suitable for transmitting.*

Reference Material

See the Mini-Circuits website for data on the PHA-1+ / PHA-11+ / PHA-22+ and the PGA-103+ MMICs and other interesting parts: **www.minicircuits.com**.

Reed Fisher, W2CQH, "Twisted-Wire Quadrature Hybrid Directional Couplers," *QST*, Jan 1978, pp 21 – 23. Note that better results at VHF can be achieved by using bonded bifilar wire with the added practical advantage that each wire has a different colored enamel. Such wire is available from the Scientific wire Company (**www.wires.co.uk**).

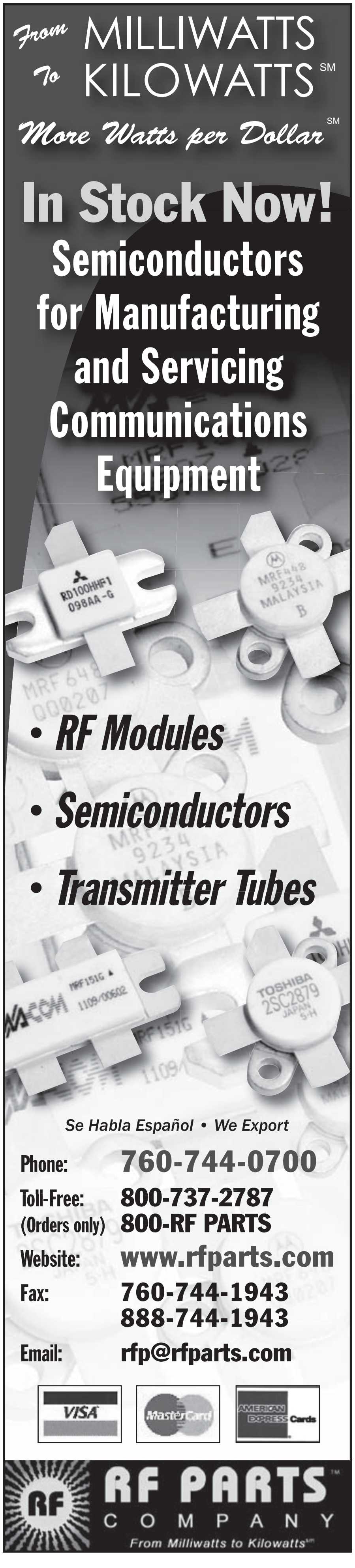
The "Instruction Manual" for the L/C Meter IIB from Almost all Digital Electronics, USA: **www.aade.com**.

Data on Micrometals T37-10 powdered iron RF toroids is available on the Micrometals website: **www.micrometals.com/rfparts/rftoroid3.html** and various vendor websites.

G R Jessop, G6JP, *Radio Data Reference Book*, Fifth Edition, 1985 (RSGB Publication) page 58, "Pi and L-Pi Network Couplers — Improved Design Methods" (about lower impedance ratio matching circuits).

The N2PK VNA by Paul Kiciak, N2PK, (**http://n2pk.com/**) with modifications by Ivan Makarov, VE3IVM, (**www.makarov.ca/vna.htm**) and a USB interface and *Windows* application software by Dave Roberts, G8KBB (**www.g8kbb.co.uk/**).

Dave Roberts, G8KBB, "The measurement of Noise," *RadCom*, Jan 2007 pp 70 – 80. This is an article about Dave's noise figure measuring system.



Jeff Wadsworth, KI5WL

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$25 10 GHz Signal Generator

Do you need a way to verify that your 10 GHz receiver is working?
Do you need an inexpensive signal source for other microwave testing?
This project may be the easiest answer you will find.

Microwave Amateur Radio is interesting and quite educational. New commercial microwave test equipment is expensive, though. For example, a new Keysight analog signal generator starts at $25,825 as typically configured.[1] That is why we go to hamfests and read articles like this!

To build a complete 10 GHz signal source we will use an inexpensive miniature motion sensor module, the ST Electronics HB100.[2] All we are going to do is add power, run a coax line from the transmit feed network in the HB100 to an SMA connector and put it all in a plastic box. Then adjust the frequency and we're done!

Joe Theobald, AC7JD, originally wondered whether the HB100 could be used as a test source while he was building his 10 GHz station. He noticed that the HB100 is widely available and essentially a 10 GHz Doppler radar transceiver. We bought several for about $3.50 apiece on eBay.[3] (I have seen others advertised from $1.50 on eBay to $10.00 on Amazon.[4]) I began to think that I could use a 10 GHz signal source that I could put in my shirt pocket for around $25. This article describes that inexpensive, simple 10 GHz signal source.

Requirements

I wanted a signal generator for rover use, to determine if my rig was working. Joe, AC7JD, suggested this could also be used as a source for testing cable loss. (Testing an X Band radio's cables is a really good idea before you go into the field!) This led to my requirements for an HB100 based source:

- Low cost — goal of less than $25 for the whole signal generator.
- Generates a signal between 10.368 and 10.370 GHz (most amateurs operate here and this is where my transverter is designed to work).
- Radiates to free space.
- SMA output for lab tests.
- Small and portable.
- Can run off a 9 V battery or 12 V supply.
- Fits in my shirt pocket.

Table 1
HB100 Characteristics

Parameter	*Minimum*	*Typical*	*Maximum*
Frequency (GHz)	10.520	10.525	10.530
Radiated Power (dBm)	12	15	20
Supply Voltage (V dc)	4.74	5.00	5.25
Current (mA)		30	40

Table 2
Parts List

Item No.	*Reference*	*Description*	*Source*	*Notes*	*Cost*
1	V1	9 V battery			
2	S1	Miniature push button switch	Flea Market		$1.00
3	PW1	LM7805	RadioShack		$1.99
4	RF1	HB100	eBay	Motion sensor module	$5.50
5	J1	SMA socket	RF Parts		$3.95
6		Enclosure	Radio Shack	3x2x1 project box	$3.49
7		Front panel	Lowes	Acrylic sheet, 8x10, smaller if you can find it	$4.24
8		9V battery connector	RadioShack		$2.99
				Total Parts Cost	**$23.16**

[1] Notes appear on page 38.

Design

The heart of this project is the microwave sensor module. Key characteristics of the HB100 are shown in Table 1.

This module is designed to be used in a short range motion detector. It uses a dielectric resonator oscillator (DRO) as the internal signal generator. This acts as both the transmit signal, which goes to the two transmit patch antennas, and as the local oscillator signal for the receive mixer. That mixer is fed a signal from the two receive patch antennas. Because the same signal is used for both transmit and receive, it can wander around and still work quite well in the Doppler radar front end configuration of the HB100.

The DRO is an inexpensive way to get X band energy if its performance meets the system needs. It does for a motion detector and for the requirements of this project. I wouldn't recommend a DRO as a general replacement for an oven-controlled crystal oscillator (OXCO), however. The HB100 sold for use in the United States is tuned 10.525 GHz, just above the US Amateur Radio band, but can easily be retuned to 10.369 GHz.

In his online paper, Walter Clark describes how to make a short range transceiver using an HB100 and a commercial FM radio receiver to find the signal on receive.[5] The radio has a range of "a few blocks" but illustrates another opinion that there is X band power here that can be used.

After studying the data sheet I decided the module already had everything needed for these requirements except a power source, an output for an SMA connector and an enclosure.[6] This design adds that power source and taps the DRO feed line to the transmit antennas for an SMA connector output.

The schematic for the 10 GHz source is shown in Figure 1. The parts list is given in Table 2.

Build and Tune

Figure 2A shows the DRO side of my HB100 circuit board, with the metal cover removed. The white cylinder in the upper left is the DRO. Figure 2B shows the reverse side, where you can see the four elegant patch antennas. Two are located on each end of the board. The HB100 circuit board also has four pairs of two-hole connection points. These are labeled and are located on each corner. The end of the board with the "IF" and "+5V" labels is the transmit end. The holes at the other two corners are both labeled "GND." The pen tip points to a platted through hole that connects to the patch antennas with two symmetric etch runs. This hole is the point where you attach the coax center conductor to pick off the 10 GHz signal to feed the SMA connector. The shield is soldered to the ground plane. Both need to be cleaned of insulation before soldering.

DC Power

Note that in Figure 2B the word "DEAD" is written on my SN1 unit next to the receive antennas. This is because I did not pay careful attention to the data sheet that states that +5.25 V dc is the maximum supply voltage. These units die quickly with too high a supply voltage. I suggest you buy a spare HB100 when you build this project.

A simple LM7805 or similar three terminal regulator works fine to bring a 9 V battery, a 12 V battery or power supply to 5 V. You can add capacitors for input and output filtering but I agree with the TI data sheet for the regulator, and did not.[7]

The power connections are made to the corners of the HB100 board. These are labeled "+5V" and "GND" on the antenna side of the board. The RF and power connections are shown in Figure 3.

RF Connections

To test whether or not your X-band rig can hear, this project is a good source of radiated RF, and the antenna structure and

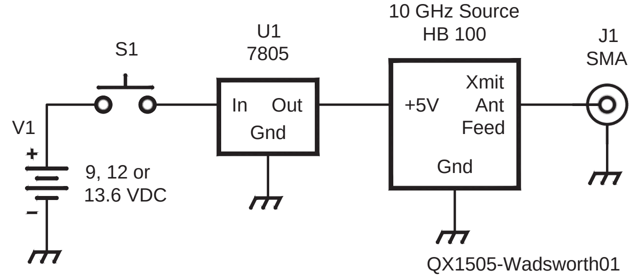
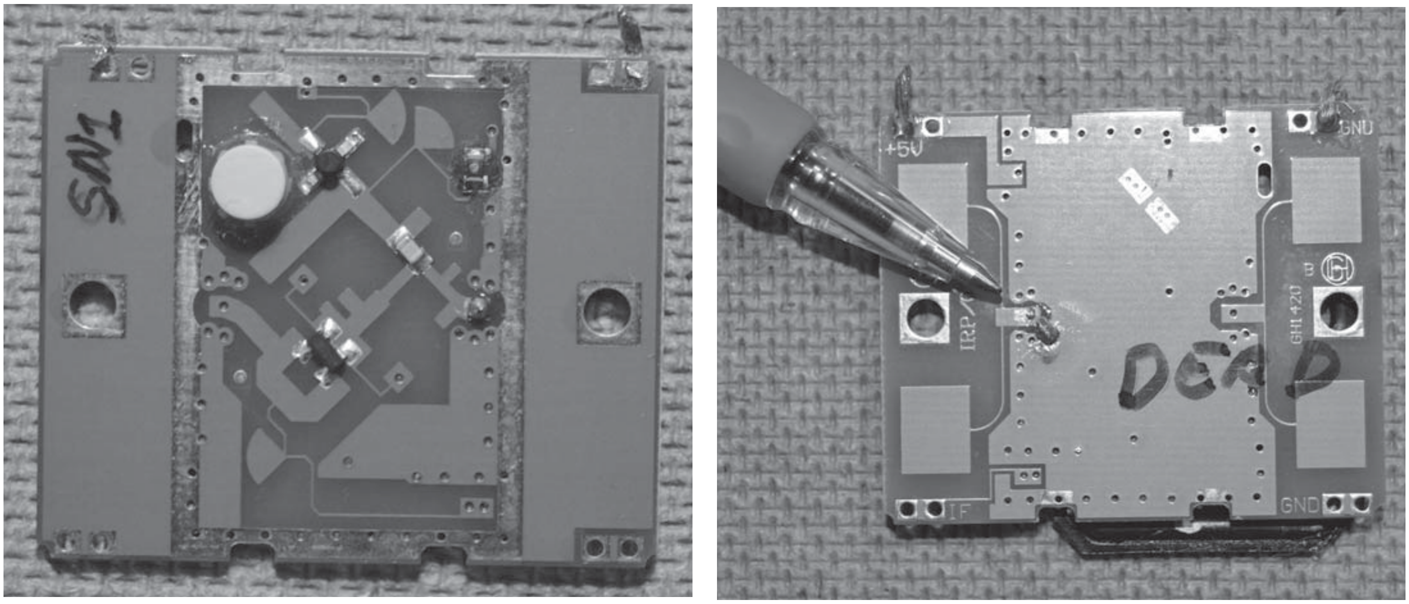


Figure 1 — Here is the schematic diagram of the $25 X-band source.



(A) (B)

Figure 2 — Part A is the component side of my HB100 circuit board, with the metal cover removed. The white cylinder at the upper left side is the dielectric resonator oscillator (DRO). Part B shows the reverse or antenna side of the HB100 board, with the coax attachment point at the tip of the pen. The HB100 is sensitive to V_{CC} overvoltage, which is how this one came to be labeled "DEAD."

feed line is already on the board. Make sure the transmit antennas face outward in your box, or whatever package you use.

For the RF tap to feed the SMA connector, use a short piece of small diameter coax. Don't ask your friends if you can use coax at microwave frequencies; you can. Ideally it should be short in length (a few inches). I used RGS-178 because I had it, but the exact type of coax is not critical. If it's longer you lose more power. You could use semi-rigid cable, but it's harder to work with in this design.

Carefully scrape the green insulation off both sides of the connection point on the HB100. This point is a plated through hole where the two feed lines split off for the two transmit antennas. (These are patch antennas and look like solid rectangles.) Figure 2B shows this point on the antenna side of the board. Note the pen is pointing to the plated through hole for the center connection of the coax. The coax shield gets soldered to the ground plane. It is probably easier to solder the center wire of the coaxial cable on the other side of the board.

Frequency Tuning

Now — hopefully — you have a functioning X-band source. To test and tune it you will need a detector of some type. If you already have a 10 GHz Amateur Radio rig, that will work fine. A power meter that covers X band connected through a 10.368 GHz filter will also work. If you don't tune it at all the frequency will probably be where the manufacturer said it would be, between 10.52 and 10.53 GHz.

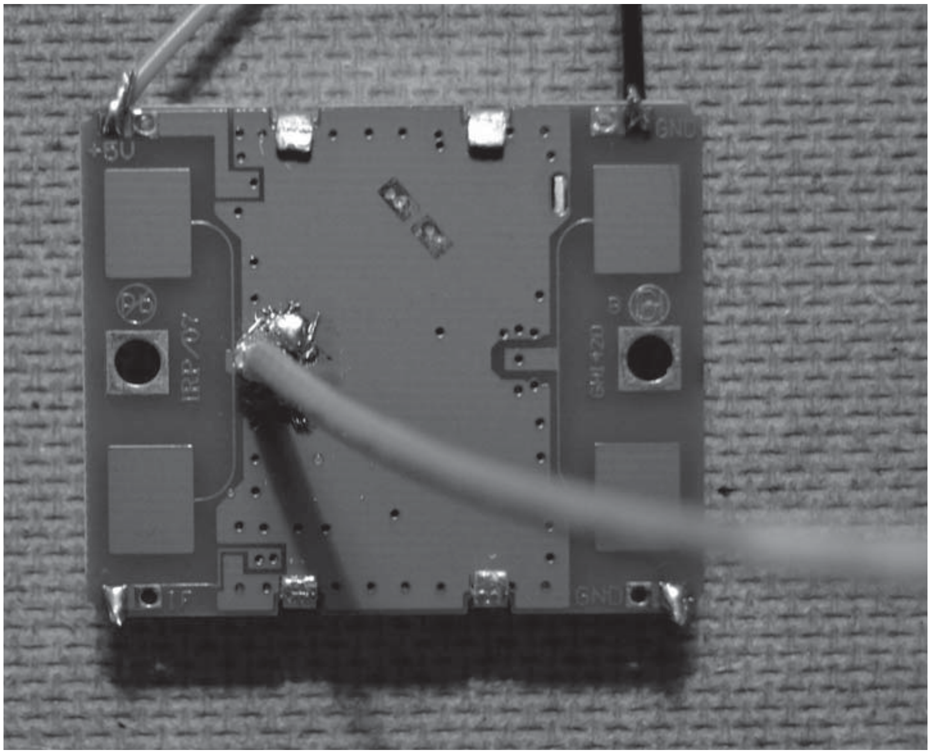


Figure 3 — Here you can see the coax, +5 V dc power, and ground leads attached to the HB100 board.

Tuning is accomplished by turning a set screw in the metal cover on the HB100. If you have a new HB100, the set screw is probably covered by a paper sticker marked "QC." In Figure 4 the pen is pointing to the set screw. Tune your rig to about 10.369 GHz and turn the screw slowly until you detect the signal. It will sound like noise. For future reference note how it sounds in your rig.

Packaging

The package is up to you. I built one unit for bench use without a power supply or enclosure. The unit I use in the field is shown in Figure 5. The board is housed in a plastic box and mounted to the clear plastic lid with

4-40 machine screws and nuts. The 9 V battery is duct-taped to the back.

Using the 10 GHz Source

When packed in a small box the source is quite handy. The only control is the on/off button. My main use is to confirm that the rover rig is receiving signals. Press the ON button and you should hear a noise-like signal. In Figure 6 I am testing my X-band roving dish antenna using the signal radiated by the patch antennas. It's a good idea to run this at home and hear what the source sounds like before you take it to the field.

I have also used the SMA output on this source with a power meter to measure loss in multiple cables, an attenuator, and to check the SWR of two X-band antennas.

Results Compared to Requirements

- $25 cost: The parts cost as listed in Table 2 is $23.16. This buys the parts new. You can cut this below $18 if you already have a project box and a piece of scrap acrylic sheet, or similar material.
- Outputs a signal between 10.368 and 10.370 GHz: Yes, but with only a little more than a milliwatt of power. This worked well for me in field tests during the 2014 10 GHz and Up contest.
- Radiates to free space: Yes.
- SMA output for lab tests: Yes, but the acrylic panel I mounted it on is a little fragile. The side of the project box may be a better choice.
- Small and portable
- Can run off a 9 V battery or 12 V supply: Yes, the LM7805 will handle 8 to 18 V and more.
- Fits in my shirt pocket: Yes, it's snug but fits in mine. You will have to test your own shirt.

I compared the results I measured using the inexpensive 10 GHz source with measurements using my 10 GHz DB6NT G2 based transverter as a signal source. The power measurements were made with an HP 436A power meter and HP power sensor. All were outside their calibration period.

A 6 dB pad measured within about half a dB of its intended value with both sources. Individual cable readings were within 1 dB between the two sources.

I also measured the SWR of two antennas using both sources and a Narda X-band directional coupler. The antennas were a well-executed, homemade X-band horn I bought at the 2012 Microwave Update, and an E-System spiral covering 402 to 19502 MHz. I had never tested SWR on either antenna before.

The SWR results were more interesting than the cables and attenuator. Using either

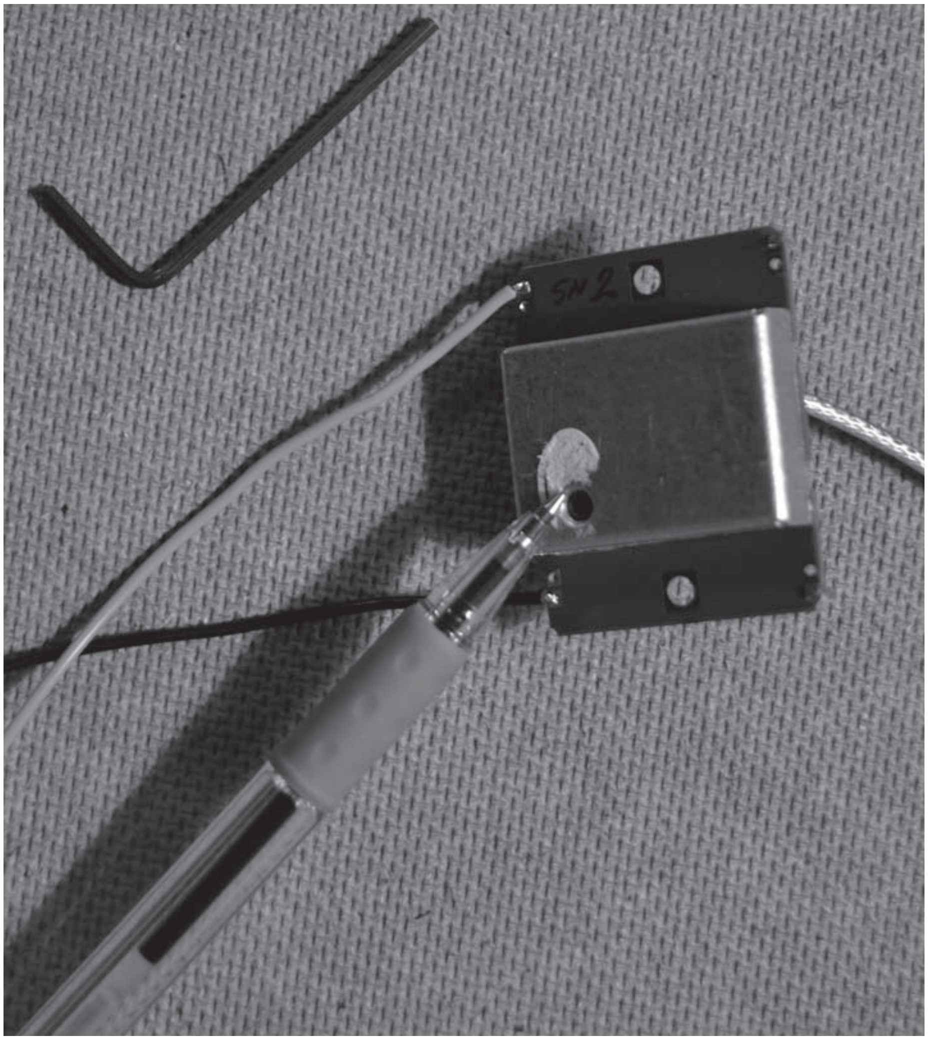


Figure 4 — The frequency tuning screw is shown at the tip of the pen. Use an Allen key to turn the screw. The white paper cover has been removed.

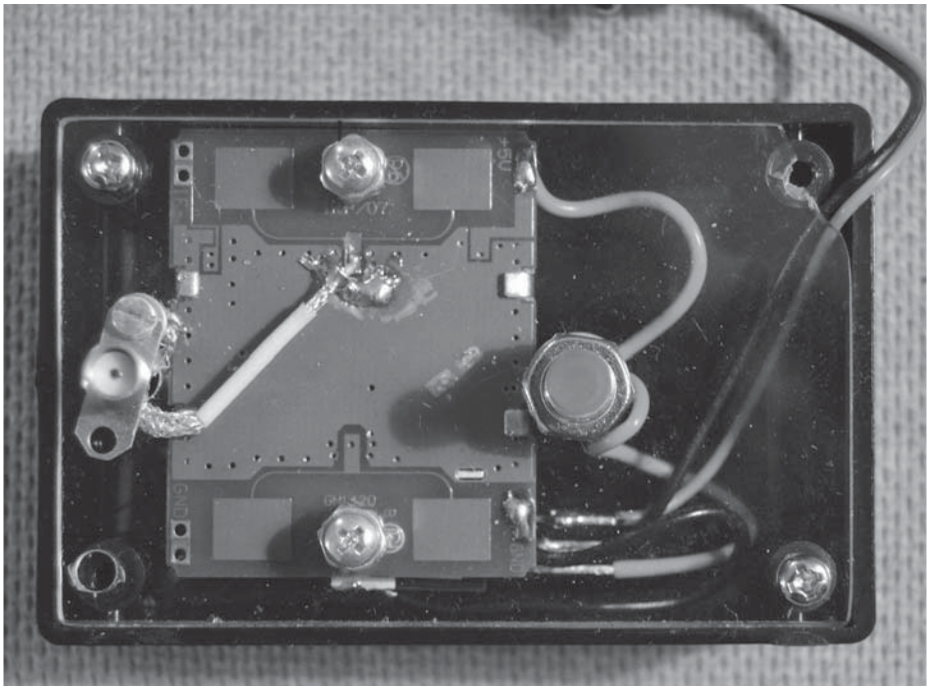


Figure 5 — Here is my 10 GHz source packaged in small plastic box.

Figure 6 — KI5WL testing his rover antenna with the HB100 based source.

source, both antennas looked pretty good. Using the HB100 based source, however, I had power level problems. My DB6NT transverter module puts out about 230 mW of power and my $25 source only puts out about a milliwatt. The Narda coupler port is 20 dB down. If the antenna under test has an SWR of 1.2 (about 21 dB return loss), then to use this source that means you need to be able to measure power levels of at least –41 dBm. That's getting low for my home lab set up.

Using the DB6NT source, the horn and spiral measured an SWR of 1.2 and 1.3 respectively. With the $25 source I could tell both had an SWR better than 2.2, but not how much better.

This source works well for me and is a very low cost unit. If you already have a project box, some scrap cable and a power supply, it can be a $10 unit. You are not going to confuse it with an excellent Keysight signal generator though.

Jeff Wadsworth, KI5WL, was first licensed about 1968 and currently holds an Amateur Extra Class license. He worked in the defense industry for the past 34 years as an electrical and systems engineer, doing RF and missile design. He also teaches systems engineering.

Jeff was a Senior Engineering Fellow and then a Program Director for Raytheon, and a Senior Member of the Technical Staff for Texas Instruments. He is an ARRL Member, a Life Member of the Association of Old Crows and the Society of Amateur Radio Astronomy. He is active in VHF/UHF and microwaves in southern Arizona. Be sure to contact him at ***ki5wl@arrl.net*** *if you want to launch some VHF+ photons and need another station to work!*

Notes

[1] Keysight signal generators are described at **www.keysight.com/en/pc-1000000524%3Aepsg%3Apgr/signal-generator-signal-source?pm=SC&nid=-536902260.0&cc=US&lc=eng**, downloaded September 23, 2014.

[2] For more information about the HB100, go to the manufacturer's website: www.agilsense.com.

[3] Search eBay for "HB100" in Electrical and Test Equipment at **www.ebay.com/** to see what is currently available. The units used in this project were purchased in March, 2014.

[4] Search for "HB100 Doppler sensor" at **www.amazon.com/** to see what is currently available.

[5] Walter Clark, "Inexpensive, Easy to Build Microwave Transceiver," **www.ham-radio.com/sbms/presentations/Walt_Clark/DROplexer.pdf**, downloaded Sep 23, 2014.

[6] HB100 Microwave Sensor Module, ST Electronics, **https://www.openimpulse.com/blog/wp-content/uploads/wpsc/downloadables/HB100_Microwave_Sensor_Module_Datasheet.pdf**, downloaded Sep 23, 2014.

[7] See the second paragraph of the description on page 1 of the TI data sheet for a discussion of bypassing, "LM340-N/LM78XX Series 3-Terminal Positive Regulators," revised December 2013, Texas Instruments, **www.ti.com/lit/ds/symlink/lm340-n.pdf**.

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SDR Simplified

Step One towards a working SDR.

Beginning A Real Radio

We have looked at a lot of topics related to SDR and DSP over the past years. It is time to actually build a radio. The goal is to design a VLF/LF/MF/HF radio that puts the transmitter and receiver as close as possible to the antenna. The first step is to create a desktop radio that handles SSB voice, CW, and AM, and covers the frequency range from 10 kHz to 30 MHz. We will take the system step by step and assemble a complete working transceiver.

Human Factors in Device Design

Perhaps I am old school, but I believe that radios should be radios and computers should be computers. From a human factors perspective, controlling a radio with a computer means you have multiple interconnect and control interfaces to manage, so the system does neither very well, especially when you want to use the computer as a computer! A single device that encapsulates the entire user interface is much simpler to manage as a user. The worst interface I have seen in a tool was an early computer controlled Hewlett-Packard oscilloscope. There was one adjust knob and one select button. Everything else was done with menus on a screen. It was impossible to make a set of measurements without constantly taking your eyes off your work. I was lucky I didn't fry more circuits from having the probe slip. I quickly went back to a much older analog scope because it was easier to use by feel alone.

There are a number of radios currently on the market that I believe share a similar failure of human factors. One hand-held radio has three levels of menus with each of the 16 buttons on the panel having at least three different mode-specific functions. You have to look directly at the radio in order to control just about every function, and you will also need the manual at hand in order to navigate the menu structure for even simple top-level functions. For me, if I cannot do the basic control functions within two minutes of walking up to a radio for the first time, the interface has failed.

Especially in a mobile radio, it is important that we be able to control the common functions with a small number of dedicated knobs and buttons. At the top level of control, we need an on/off button, volume control, a frequency control, and probably band select. These functions need to be discernable without looking at the radio! The next level, which also needs dedicated buttons, would include things such as noise blanking, selectivity, A/B band selection, and transmission mode. These might need a quick glance at the screen for confirmation, but should never require visual engagement to perform the function. Each time one changes frequency (either band change or tuning within a band) the radio should give a clear indication on the screen of both the frequency and mode with nothing more than a quick glance. A desktop radio can be slightly more complicated because we can devote our entire attention to the user interface. The user interface should not be so complicated, however, that it gets in the way of the primary function of the radio, which is to communicate!

Figure 1 shows the front panel design of my proposed desktop radio. The central feature is the 7 inch TFT display, which provides 800 × 480 pixels.[1] The industry calls this WVGA resolution (Wide VGA). My first design for a radio used a 4.3 inch WQVGA resolution screen (Wide-Quarter VGA) which is 480 × 272 pixels because the displays were inexpensive and a large number of manufacturers make equivalent devices. The size and resolution became popular because it was used in the Playstation Portable game system. Now, smart phones are our friend. The proliferation of smart phones has pushed resolution to WVGA in both 5 inch and 7 inch sizes from the same manufacturers and at reasonable prices.

The button and knob usage and layout is inspired by any number of analog radios I have used over the years. The main difference is that the tuning knob is moved

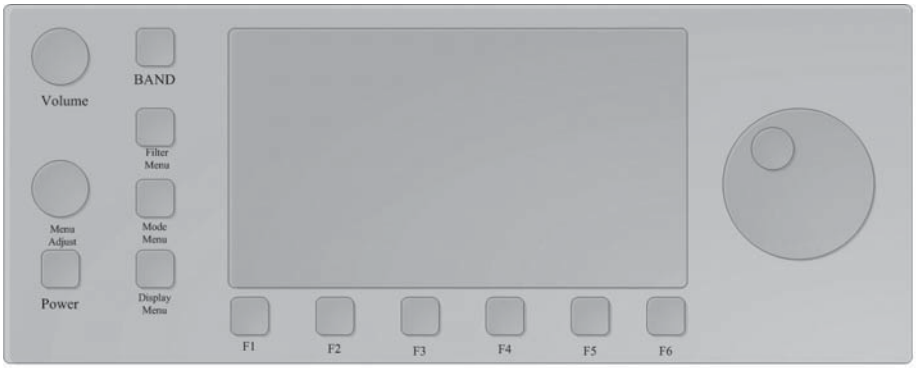

Figure 1 — Here is my proposed front panel layout for a self contained SDR. The display panel has 800 × 480 pixels, to give a full color internal computer display of control functions and data. The menu keys along the left have dedicated functions and the keys along the bottom are soft function keys.

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[1] Notes appear on page 44.

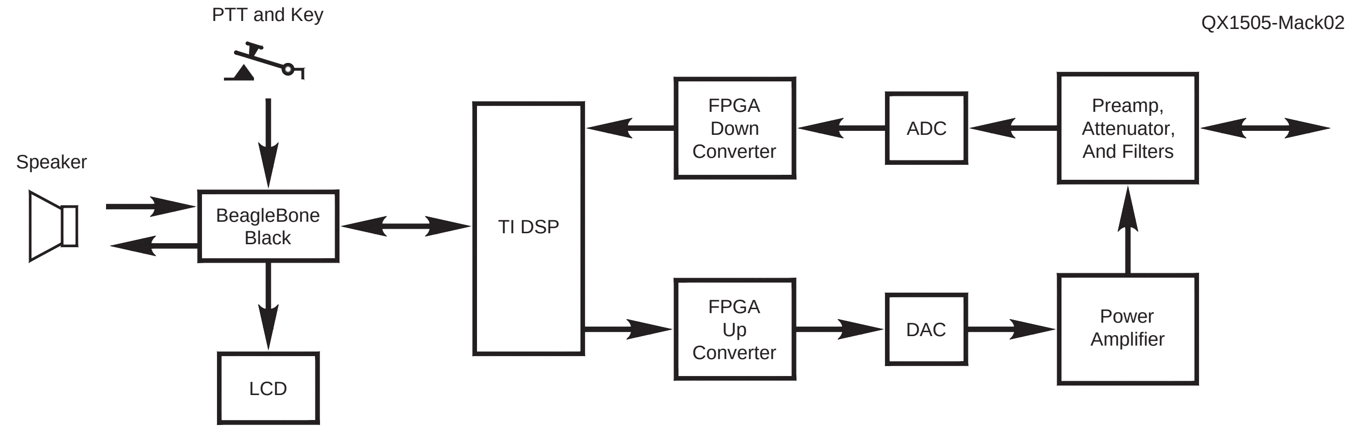


Figure 2 — A block diagram of the proposed transceiver. There are three main processing elements: the BeagleBone Black *Linux* computer, the Analog Devices DSP, and the FPGA hardware accelerator.

to the right side to accommodate the full size screen. Almost all analog desktop radios place the tuning knob in the center, with small readouts along the top of the panel. Feel free to comment on any aspects of the layout. The tuning knob is the focus of our laboratory exercise this time.

Top Level System Design

Figure 2 is the block diagram of the transceiver system. We are still going to want all of the graphics-intensive functions that we see on a computer controlled SDR, such as ones using *PowerSDR*, so we will need a computer that can run a modified version of one of those programs. The BeagleBone Black (just BeagleBone from here) is an inexpensive prototype computer that fits the bill for our needs. In fact, it is a complete *Linux* computer on a 2 × 3.5 inch circuit board. It is based on a 1 GHz Texas Instruments Sitarra AD3359 processor.

The AD3359 has internal support for TFT LCDs for the display, quadrature encoder support for our frequency control knob, and ADC support for our analog controls like volume. All of the normal peripheral interface buses such as USB, I2S, SPI, and I2C are available for the other devices we will need to control. Ethernet is available for debugging and other network uses. The McASP interface ports are actually enhanced I2S ports similar to those used for audio CODECs on sound cards. We will use at least one of those ports for receiving data for waterfall and spectrum displays from the main DSP portion of the radio.

Any computer that does more than the very basic bare metal control is going to need an operating system to help us manage the various software tasks in the system. Some systems such as our DSP portion need exact or very fast response to incoming data. These are called hard real time systems. Even a slip of a few milliseconds can cause problems for the system. Our user interface is less demanding. Our eyes and hands need feedback about 10 to 20 times per second in order for us to perceive that tasks are happening continuously. A difference of 10 to 50 ms will not change our perception of continuous control. These systems are called soft real time.

Windows is far from a real time operating system. It is not uncommon for the mouse pointer to pause noticeably as we move it across the screen. Modern *Linux* is a better system. It includes real time extensions that allow for implementing soft real time systems. Fortunately, the BeagleBone comes with *Linux* installed. *Linux* also provides us with the advantage that many of the SDR functions we will implement for the display are supported in the *Linux* versions of software like *PowerSDR*.

Using the Quadrature Encoder

We will use the quadrature encoder in the same way we use the wheel on the mouse for a PC. Turning one direction will increase the frequency and turning it the other way will decrease frequency. Figure 3 shows several quadrature optical encoders I have collected over the years. An optical encoder is made of an opaque disc with equally spaced slots that let light transmit from one or more LEDs on one side of the disk to two phototransistors on the other side of the disk. The phototransistors are arranged so that there is overlap of both the light phase and the dark phase. The transitions are arranged so that the square wave signals from the two phototransistors are 90° out of phase (hence quadrature encoding). The 90° offset allows the electronic hardware to determine the direction that the encoder is turning. This operation is shown in Figure 4. In our example, when the A signal goes low to high before the B signal goes low to high (and the A signal goes high to low before the B signal goes high to low), the shaft is rotating clockwise. The converse is true; when the B signal goes from low to high before the A signal, the shaft is rotating counterclockwise.

Of course, we can attach the A and B signals to GPIO pins (general purpose I/O) and watch their state every few milliseconds in software, but the load on a CPU to perform this relatively mundane operation is huge. Instead, the AM3359 provides up to three Enhanced Quadrature Encoder Pulse (eQEP) modules that can be used to gather motion data. The eQEP module is useful for both human interface encoders and electric motor feedback. For our purposes, we only need the A and B input pins to allow the module to count pulses up or down. The eQEP module contains the QPOSCNT register, which keeps a running tally of both clockwise and counterclockwise (the British refer to this as *anti-clockwise* in some documents).

The finest resolution optical encoder has 64 pulses per revolution, but those are likely too expensive for use in our radio. A cost effective one (CUI C14D32P-A3, $17.22 at Digi-Key) has 32 pulses per revolution. We can start the position counter register at half scale so that we almost never have to do the logic required to handle overflow or underflow of the register. Each time we read the register, we simply subtract the previous count from the present count to determine how many changes and the direction of the changes since we last read the register.

There is a timer that is part of the eQEP hardware. It is possible to set up the timer to capture the position counter every time the counter matches the compare value. The time for the capture and the position counter can be used to determine the rotation velocity

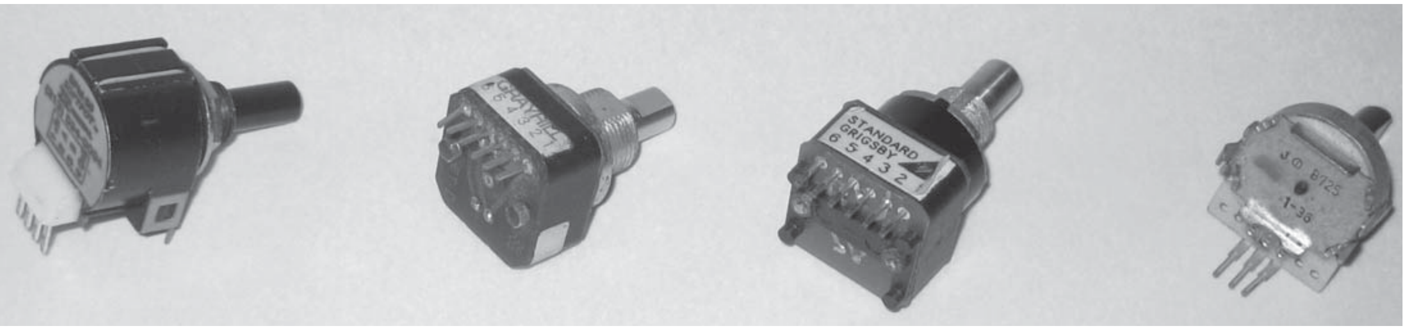


Figure 3 — This photo shows three optical encoders and a mechanical encoder. The two in the middle also contain a push button switch. One is Standard Grigsby and the other is Grayhill, but the traces on the circuit board appear identical.

of the encoder. We can use the velocity to modify our frequency change logic, to change the frequency faster if the velocity is higher. This could be a feature in a future version of the software. Many systems use this velocity mechanism to adapt the speed of change of a variable to the speed of the control knob.

Connecting the Encoder to Hardware

There are three eQEP blocks that show up on various pins depending on how the hardware is configured in software. We need to look at the pins that are available on P8 and P9 of the BeagleBone. We look at the tables on pages 70 and 72 of the BeagleBone user manual to see which pins are used, and their functions. The eQEP2 pins conflict with the eMMC1 pins, which are used for the SD card, and the eQEP1 pins conflict with the LCD. This leaves us with pins 27 and 42 on header P9 as available for eQEP0 operation. Page 71 of the manual indicates that pin 42 is connected to processor pin B12 *and* C18. In order to use this header pin for eQEP0, we need to set B12 for use as an eQEP input and C18 as a GPIO input. We could also make sure the pin is safe by removing the extra resistor as described in the user manual.

The BeagleBone has 3.3 V circuits, so my older 5 V encoders need some level adjustment. The circuit in Figure 5 shows the circuit that lowers the signal to 3.3 V. The user manual warns that using 5 V signals will damage the circuits. If you buy a brand new encoder, you will want to select a version that works at 3.3 V.

Linux Introduction

Linux is a computer operating system that has its roots in the *Unix* operating system from AT&T. If you have ever written a truly useful program, especially in *C*, you have run into bugs that have caused your program to "crash and burn." When you do that with an Arduino project or an SDR running on a dedicated DSP, there are no real consequences. You just debug to find your problem, edit, compile, and restart the debug process. On a computer such as a PC running *Windows* or *Linux*, however, your program could do real damage to things like the hard disk or burn up the CPU if your program crashes in the absence of some sort of protection. *Windows* 3.1 ran on top of *MS-DOS,* which did not have any protection mechanism, and crashing the system was a normal occurrence. The solution is a hardware/software mechanism called protected mode. *Linux* has always run in protected mode and *Windows*, starting with NT 3.1, now runs in protected mode.

The protection comes from special hardware inside the CPU, called the memory management unit and a bit in the status register called the supervisor bit. When the supervisor bit is turned "on," the system is in Supervisor Mode and all software has complete access to everything on the computer: all I/O ports and every memory location. This is what allows rogue software to do damage. When the supervisor bit is "off," the software is in User Mode and the software is very limited in what it can access. This restriction is forced by the memory management unit hardware. In general, a User Mode program cannot touch any I/O ports since those are considered essential to proper operation of the computer. The only resource a User Mode program can touch is a small amount of memory, which is just large enough to run the program. So, for example, you cannot directly toggle a bit on the parallel port or the modem control lines on a serial port from a program that you run from the command line.

So, how can we connect a new device like the quadrature optical encoder to the computer and use it for input in our SDR program? A protected mode operating system implements functions that are part of a device driver, to give us protected access to hardware. A device driver is responsible for collecting information from your User Mode program and then passing that information to the operating system. These are usually a call to read() or write(). Once the read or write call verifies that your information is not going to crash the system, it uses an operating system mechanism to shift the computer from User Mode to Supervisor Mode. The code inside the operating system, running in Supervisor Mode, now has permission to talk directly to the I/O ports of the hardware of the computer. It does the read or write from the hardware and then sends the requested information back up through the protection system and then changes the CPU back into User Mode. Now, you can access the data provided by the device driver. We will use a device driver to connect to the quadrature encoder.

The operating system has basically two functions: protect the computer hardware from defective programs, and allow multiple independent programs to run "simultaneously" on one CPU. On the BeagleBone, *Linux* creates the illusion of

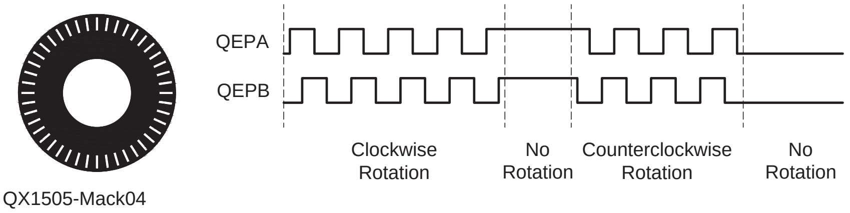


Figure 4 — An illustration of the waveforms for clockwise rotation. The circle shows what the optical disk looks like. Notice that the sensors need to be positioned near the inner part of the clear slot so that the light and dark areas are the same size.

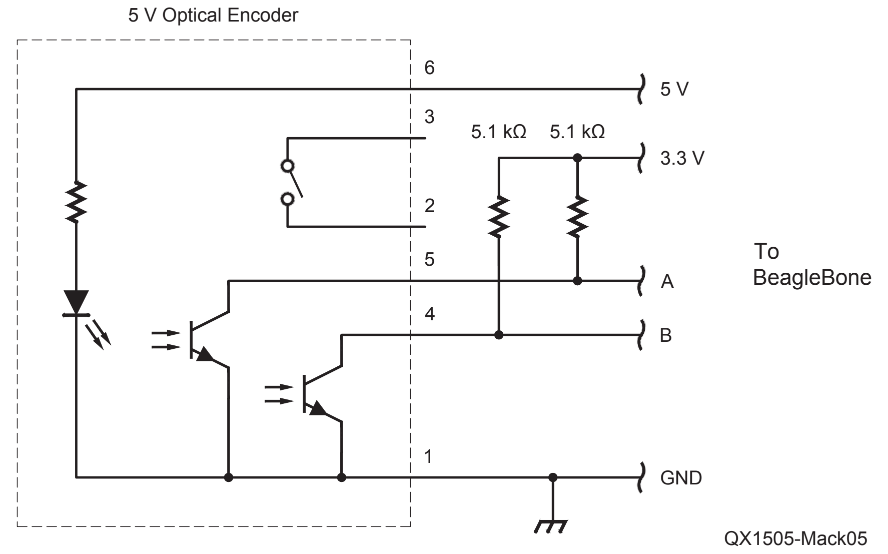


Figure 5 — The schematic of my level shifter to allow use of a 5 V optical encoder in the 3.3 V BeagleBone system.

simultaneous operation of multiple programs by time division multiplexing the operation of multiple user programs. This is easy because programs do not need the CPU while they are waiting on some piece of hardware. During the time one program is waiting, *Linux* runs another program that has work to do.

Linux comes in many different flavors including Debian, Gentoo, and Fedora. These are called distributions or "distros." If you have used desktop *Linux*, it is likely you have used Ubuntu, which is a version of Debian optimized for desktop use. The distribution shipped on the BeagleBone is Debian.

Connecting the Encoder to *Linux*

One of the nice features of *Linux* is that it has a mechanism to install a device driver into the kernel from the User Mode command line. Device drivers that are a part of a distribution are simply compiled into the kernel and are always present. Since a driver for the TI eQEP is not part of the distribution, we must design our own driver and install it from the command line.

A device driver must implement the init() and exit() functions as a minimal set. Of course, such a driver would not be especially useful. The read() and write() functions are required as the next level of operation to be useful. The write() function will simply return without any operation since there is no actual write that can occur. It is included so a call to the generic write() function from User Mode will not cause an error. There are two final functions needed to provide the mechanism to glue a User Mode program to our driver: open() and close().

Listing 1 shows the init() and exit() functions. The program listings and various other files associated with this article are available for download from the ARRL *QEX* files website.[2] The init() function must set up the hardware and do the other tasks to connect the hardware to the kernel. The exit() function can be trivial because we will have minimal resources to release or other cleanup to do. In fact, normal operation will never exit from the driver. So exit() only needs to disconnect the /proc/eqep file from the kernel and then exit. We put kprintf() calls in these two functions so we can see the results of installing or removing the driver on the console as a sanity check.

The init() function must connect our driver to a device file so we can open the file as a character device in a User Mode program. The first operation is to tell the kernel where to put the interface for the device file. It is convention that installable drivers are placed in the /proc directory. This is the location of the driver for User Mode program use; it is not where the actual binary file (eqep.o) is located. The kernel also needs us to connect our driver data and functions and tell it who owns the file. Next, the init function must set up the eQED hardware for use by the driver. We set the mode for the eQEP0 A and B input pins to MODE1 and then turn on the eQEP hardware.

We need to decide how to encode the data from the encoder into data that is read from the file. The easiest way is to simply encode the data as a signed 8 bit value. It is very unlikely that we can spin the knob fast enough to generate more than 127 pulses between reads of the device file. To that end, the read() function will read the position register and subtract the half value from the register. Then the value will be truncated to an 8 bit value. This makes the logic simple, as shown in Listing 2. For now, the write() function does nothing. If we decide later that it would be nice to set parameters of operation, we can extend the driver so writes to the device file affect its operation.

We compile and link the program and create a file called eqep.o. You can place it in any convenient directory. I prefer /root just because that is where I put things when using the QNX operating system. Change to /root and type the command:

```
insmod eqep.o
```

You should see the message from the init() function show up on the console. We will now be able to interact with the eQEP driver by opening and reading the file /proc/eqep.

An Example User Mode Program

Listing 3 is an example User Mode program that looks at the eQEP driver every 100ms and displays an absolute frequency that is adjusted by turning the encoder. We initialize the program to display 7100.00 kHz. Each position change of our encoder will adjust the frequency up or down by 0.01 kHz.

Making a Build Computer

It is possible to set up the BeagleBone to build the software we need, but it would require a USB hard disk and other accessories to make it a real computer. It is much easier to build using an existing computer (workstation) and transfer the drivers and programs to the BeagleBone (target). My suggestion is to set up a computer with a dual boot of *Windows* and Ubuntu *Linux*. The current version of "long term support" *Linux* is 14.04. Ubuntu is supported by Canonical which is a company in the United Kingdom. A lot of what makes Ubuntu a truly usable desktop solution is because of their efforts and support. You can find much information on the Internet for support of BeagleBone and Ubuntu.

I have both *Windows 7* and *Windows 8* systems that I have set up as dual boot. I recommend avoiding a *Windows 8* machine if you can. There are issues with getting the dual boot menu to populate correctly. My *Windows 8* machine requires that I power cycle and hit <esc> to force it into the BIOS mode, where I select <F9> to go to the boot menu. I can probably fix it at some point, but I prefer working on SDR projects.

The following is an abbreviated set of instructions for those who feel comfortable doing normal computer building operations. There are very detailed instructions, notes, and pointers to on-line resources in the zip file on the ARRL *QEX* files website site for this issue. See Note 2.

The first step is to make sure you are connected to the Internet for the whole process. There are numerous updates that must come from the Internet. You download the ISO image from the Ubuntu site and burn a DVD (since it is 900 MB of data, it won't fit on a CD). Ubuntu is free, but the $16 suggested donation is a small amount to help them maintain stable, working software. You will need to use the *Windows Disk Manager* utility to reduce the size of your hard disk for *Windows*, to make an unused partition. I set mine to 250 GB out of 750 GB, but about 100 MB should be enough. My system is almost fully set up, and uses 6 MB of space.

Now that you have an unused partition, you need to power cycle and boot from your DVD. If your system does not boot the DVD, start up in the BIOS configuration mode. This varies from computer to computer. It is always <esc>, <del>, or a function key. You need to make sure that your BIOS is set up to boot from the DVD as the first option. Your system will boot into a small program called GRUB that lets you select the operation to perform. You want to "install *Linux*" rather than "try *Linux*." The system will start up and prompt you for various actions. You want to install *Linux* beside *Windows*, so you can choose which way to boot each time. The system will prompt you to install in the newly created empty partition. Let the system complete the task and you will have a working *Linux* computer. Be sure to write down the password that you select! This is the administrator (root) password, which you will use very frequently. I also recommend that you select the "automatically log me in" option at that point. When the system re-boots, select *Linux* from the boot menu. When you are prompted to update Ubuntu, select yes, because we need the extra packages that get installed at this point.

The Ubuntu desktop looks similar to a *Windows* desktop, but has some unfamiliar characteristics. The "X" to kill a program is on the left rather than the right of each program window. There is a task bar, but it operates differently from *Windows*. Basically it is where programs are "pinned." The top left icon is the Ubuntu "search your computer" program. Click on that icon and type in "ClassicMenu." Double click the program icon that is displayed. That will place a small "Ubuntu icon" on the top right of the menu bar. Selecting that icon now gives you something much more like the *Windows* "Start Menu."

The next step is to click on the settings icon (the adjustable wrench on top of a gear) on the left bar. Double click on Appearance and change "Show the menus for a window" from "in the menu bar" to "in the window's title bar." This makes the menus look a lot more like *Windows*. The system still automatically hides the menu, but it stays on the window instead of the top of the display. Programs in Ubuntu do not typically have "Close" or "Exit" buttons. Changes take effect immediately in many cases. The other thing I found different is the lack of a scroll bar on windows. The scroll tool automatically hides. It is at the right side of each window and pops up if you hover the cursor above it. Once it displays, it operates similarly to a *Windows* scroll bar.

We use the command console for most software development tasks in *Linux*. This is a holdover from old *Unix* days. Select the ClassicMenu icon/Utilities/Terminal to bring up a command window. One really nice feature of the terminal is that it remembers your command history even across power cycles.

We need to install a lot of software developer programs at this point. First, we need the cross compiler, arm-linux-gnueabi-gcc, and associated tools. Ubuntu was installed with the native x86 version of the compiler, but we need the ARM version for the BeagleBone. The command to do this is:

```
sudo apt-get install gcc-arm-linux-gnueabi
```

You can think of "sudo" as meaning "do this command as super user." It changes your security permission from normal user to super user for the next 15 minutes. Only super users are allowed to do certain operations, such as install new software. This is another mechanism to keep you from accidentally killing your computer. After you type the command, the computer will ask you for your password.

Next, you need to get Eclipse, which is an IDE (integrated development environment) for building programs. This is the same IDE that we saw when we used Code Composer for the Texas Instruments DSP board. The command here is:

```
sudo apt-get install eclipse eclipse-cdt g++ gcc
```

This gets and installs the Eclipse IDE and the plugin for *C* development as well as updating the g++ and gcc compilers in case they are out of date. We need a few more utilities:

```
sudo apt-get install git build-essential lzop
u-boot-tools
```

Git is a configuration management tool that we need to use to retrieve files for the kernel from the public repository for the BeagleBone *Linux* distribution. The files are compressed so we need the lzop tool to decompress those files, and we might need the u-boot files for later operations. The next step is to create a build directory for the *Linux* kernel and other necessary software. I choose to call it bbb_linux, but you can pick any name you like. Do the following commands:

```
sudo mkdir /bbb_linux
sudo chown ray /bbb_linux
cd /bbb_linux
```

Of course, substitute your login name for "ray."

The last operation before we can actually do some work is to retrieve the kernel directory tree: git clone git://github.com/beaglebone/linux

This git command will create a new directory /bbb_linux/linux and store the *Linux* tree there. The next step is to build the kernel. We need to build the kernel and collect the necessary header files. The instructions for doing that are more complicated and not amenable to including here. Please download the files from the ARRL *QEX* files website for a truly detailed sequence. (See Note 2.) A big problem is that much of what you will find on the Internet is out of date or incomplete. My instructions capture the errors you can uncover and how to avoid them, at least at the time of this writing!

Quick Start for the BeagleBone

You will want to read the quick start instructions on the BeagleBone website.[3] The most important admonition at this point is to *always* use the power switch next to the Ethernet connector to shut down the BeagleBone. Failure to do so can leave the power controller IC in an indeterminate state. The first step is to plug your BeagleBone into the PC using just the USB cable. The BeagleBone will show up as a removable drive with various files for *Windows*. You will not be able to see the *Linux* file system, though. The next step is to install the USB driver that lets you connect to the BeagleBone with an IP address through USB. The IP address is always 192.168.7.2. You can connect to the BeagleBone through Chrome or Firefox (not Internet Explorer) by typing in the IP address.

The next steps install a new kernel image from the repository. Step one is to download the latest image from the beagleboard.org website. Store it someplace convenient like the desktop on the PC. Next, you need to get *7-zip* from its website and install it.[4] Use *7-zip* to convert the compressed .img.xz file on your desktop to a 4 GB uncompressed .img file. Get the program *Win32imager* from Ubuntu. Be very careful when you run *Win32imager*. It only lets you write removable media, but if you have multiple devices plugged in, you could accidentally kill the wrong device. Plug the micro-SD card into the adapter and plug that into your PC. Use *Win32imager* to write the image to the SD card.

Now is the time to connect the infrastructure for your BeagleBone. Turn off the BeagleBone. Disconnect the USB cable from the PC. Attach a micro-HDMI cable from the board to your monitor (you might need a HDMI to DVI adapter), a USB hub, a keyboard, a mouse, and a network cable. Insert the micro-SD card with the new image and a 5 V power supply. This is a place where the current instructions on the Internet are wrong. The image is not set up to automatically copy the new image from the SD card into the internal eMMC flash drive. You need to navigate to Applications/Accessories and double click on LXTerminal. You need to change to the /media/rootfs directory. Use the "sudo chown debian boot" command so you can save files in the directory. Now change to the boot directory and "sudo chown debian uEnv.txt" so you can edit the file. The easiest way is to navigate to the file using the file manager, right click, and select edit. Find the line that begins "#cmdline=init=/opt" and remove the "#". Save the file. Shutdown the BeagleBone and restart it. The new image should take hold of the boot process and you will see the various operations on the monitor. Once it finishes, the system will power off, so you know it is finished. The uEnv.txt file will be removed from the rootfs/boot directory so you do not have to worry about the process happening twice. You can see which install is active on your BeagleBone by the command "cat /opt/dogtag".

Plans for Next Time

My inspiration for the next step is the yearly scheduled transmissions from the Alexanderson alternator in Sweden, which transmits every year on the last Sunday in June or first Sunday in July (Alexanderson Day) on 17.2 kHz. I tried unsuccessfully to listen for it during a special transmission event on February 13, 2015. I am hoping to have a minimal SDR up and running to listen for it this summer. The system will use the BeagleBone, the LCD, and an audio codec. It should also be useful for listening to WWVB on 60 kHz. I was able to copy WWVB quite easily from the parking lot at work in Cedar Park, TX (an Austin suburb) using an old tube based test receiver.

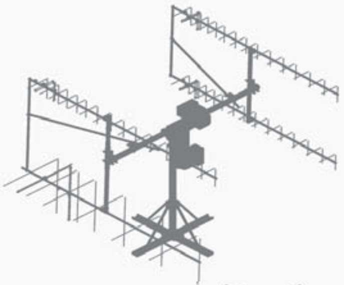
Notes

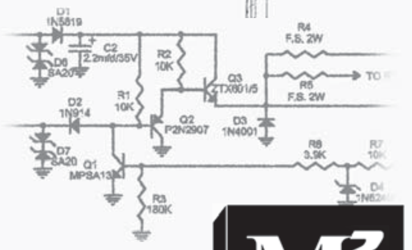
[1] Thin film transistor (TFT) is a special type of LCD in which each pixel of the display is controlled by an individual transistor deposited on the glass surface. All LCD TV screens use TFT glass. A consequence of the way TFT works is that it requires a constant refresh of the data to be displayed, a horizontal clock, a vertical clock, and a pixel clock. These clocks create a signal that is very similar to a standard analog TV signal. The Sitarra processors include internal hardware that produces these signals with no software involvement.

[2] The program listings and other various files associated with this article are available for download from the ARRL *QEX* files website. Go to **www.arrl.org/qexfiles/** and look for the file **5x15_Mack_SDR.zip**.

[3] The top level of support for the BeagleBone Black is found at **www.beagleboard.org**. The newest image for the BeagleBone is found at **www.beagleboard.org/latest-images**.

[4] You can find more information about the 7-Zip program, and download the program file at **www.7-zip.org**.

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Q3
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D6
SA20
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R1
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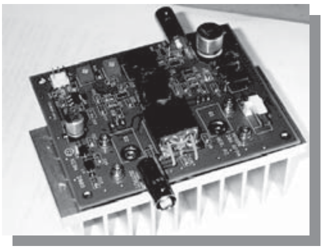

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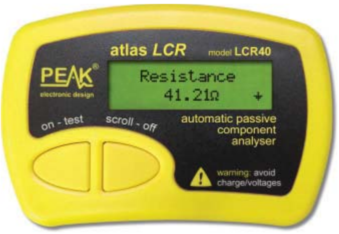

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Analyzes transistors, MOSFETs, JFETs, IGBTs, and more. Graphic display. Enhanced functionality with included PC software.

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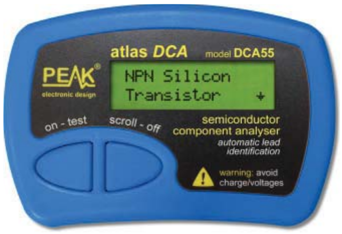
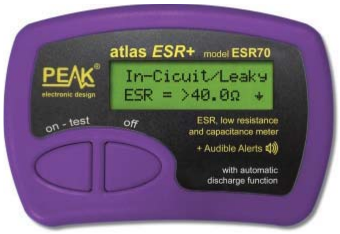


Analyzes transistors, MOSFETs, JFETs and more. Automatically determines component pinout.

Capacitance and ESR Meter



Analyzes capacitors, measures ESR.

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