TESTS OF 1 MHZ SIGNAL SOURCE
FOR SPECTRUM ANALYZER CALIBRATION

7/8/08

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(Updated 7/19/08 to delete sine wave output)

I constructed the 1 MHz square wave generator shown in the Appendix. This device is intended to produce a clean square wave with predictable levels of fundamental and harmonics. It also contains a "sine" wave output, which is a modestly filtered version of the square wave. The purpose of the device is calibration of Scotty's Modular Spectrum Analyzer, which would utilize the fundamental at 1 MHz. It is possible that the added power of the harmonics in the square wave may complicate calibration, in which case the sine wave output can be used. The sine wave will be 0.4 db below the fundamental in the square wave, which in turn is 0.3 db. A procedure is provided for calibrating the exact output level.

The square wave is produced by a 2 MHz oscillator, and divided by two to get a clean 50% duty cycle. This signal then drives two logic inverters, whose outputs are paralleled through a voltage divider to the output. The output impedance of each inverter is expected to be about 15 ohms. The predictability of the output level of the fundamental component of the square wave depends on having a near-50% duty cycle with flat tops and bottoms. It actually takes considerable distortion of the leading and falling edges to affect the fundamental value. The level of harmonics is much more sensitive to duty cycle, rise and fall times, and distortions such as overshoot. As will be seen below, the square wave produced by this device is very clean, with a duty cycle very close to 50%, rise/fall times below 2 ns, and only small amounts of distortion near the transition edges.

The output stage consists of two inverters driving a voltage divider consisting of 470 ohm resistors coming from each inverter to a 63 ohm grounded resistor. The load will be in parallel with the 63 ohm resistor. The output impedance seen by the load is 50 ohms, if we assume that the output impedance of each inverter is 15 ohms, which is an average value derived from the data sheets. Because the inverter output impedance is in series with 470 ohms, even deviations of 15 ohms in that output impedance have minimal impact on the accuracy of the device.

Calibration

The exact output level of the device depends on the exact value of the nominally 5 volt supply. There is a very simple way to determine the actual peak-to-peak output voltage, because that voltage will exactly equal the DC voltage that builds up at the output capacitor. The 5 volt supply, inverter output impedance, and 63 ohm shunt resistor at the output can all be reduced to a Thevenin equivalent circuit consisting of a voltage source of approximately 1.03 volts feeding a source resistance of 50 ohms, as shown in the following diagram:

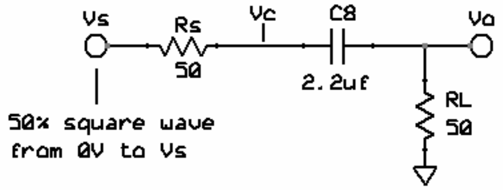

Diagram 1—Equivalent Circuit of Output Stage

To determine the DC component of V_C, the voltage at the output capacitor C8, consider this: that DC voltage (call it V_{DC}) will adjust until the current through R_S to the capacitor during the square wave High equals the current going the other way during the square wave Low. Because the duty cycle is 50%, this means

$$\mathbf{V_{DC}=V_S/2}$$

Note that the value of V_{DC} is independent of the values of R_S and R_L. The AC component of V_C (call it V_{AC}) is determined by the voltage divider consisting of R_S and R_L. Because they are equal,

$$\mathbf{V_{AC}=V_S/2}$$

So,

$$\mathbf{V_{AC}= V_{DC}}$$

Therefore, the peak-to-peak square wave output is equal to the DC voltage at the output capacitor, which is very easy to measure. With a good voltmeter, it can be measured directly. To allow for not-so-good voltmeters, voltage reference is contained on-board that is close to the expected DC value, so the target voltage can be measured against that reference. For small deviations from the reference (approx. 0.5V), even a 5% error in the deviation is a small percentage of the total voltage level. In case the voltmeter may give a faulty DC reading because it is also receiving an AC signal, a short-circuit load can be presented to the device. As noted above, V_{DC} is independent of the load impedance.

Oscilloscope and Spectrum Analyzer Views

The following series of photos show views of the outputs on an oscilloscope, and their spectra on an HP8568B spectrum analyzer. Note that on the spectrum analyzer views, the fundamental at 1 MHz sometimes has a marker, which does not always show exactly 1 MHz. My spectrum analyzer accurately shows the frequency only at low resolution bandwidths.

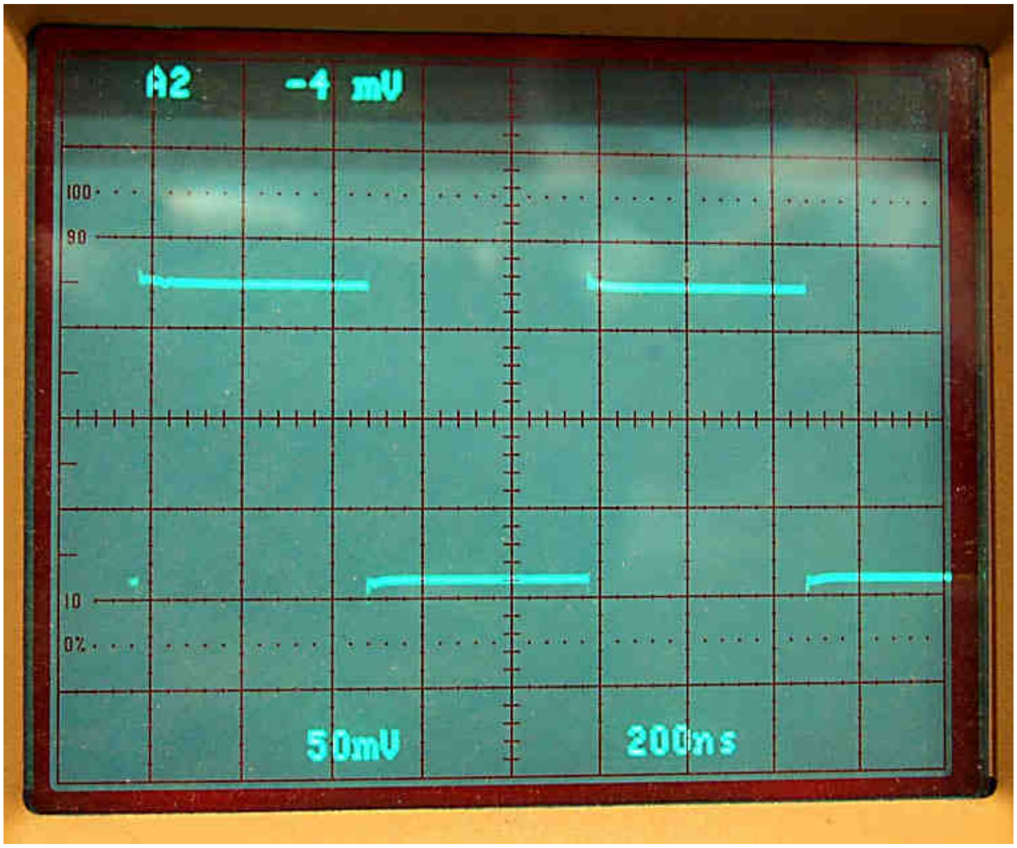

Figure 1—Two cycles of 1 MHz square wave. Very flat and square except for a small portion at leading and trailing edges. Due to an attenuator on the scope input, the absolute voltage levels are meaningless.

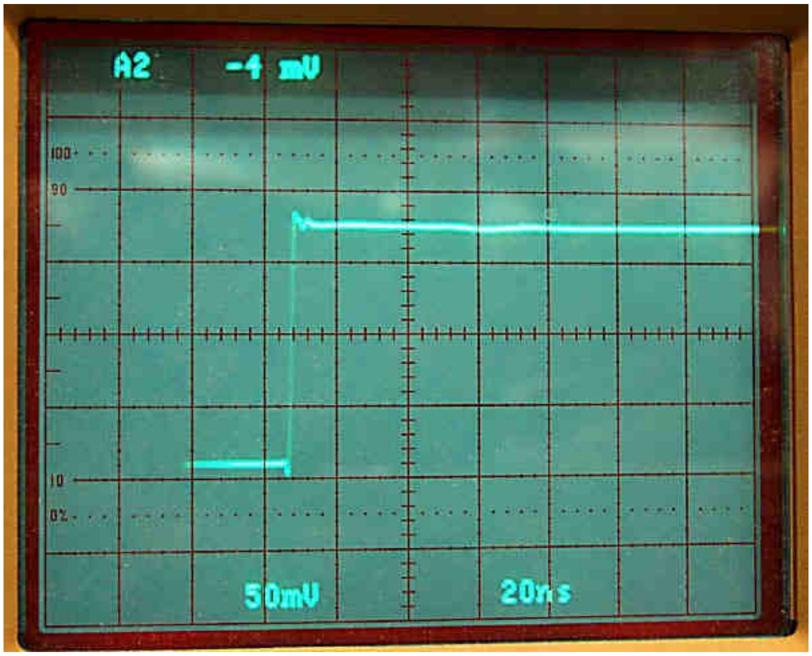

Figure 2—Expanded view of leading edge. Small ripple in first 5 ns. A more expanded view showed rise/fall times of about 1.5 ns.

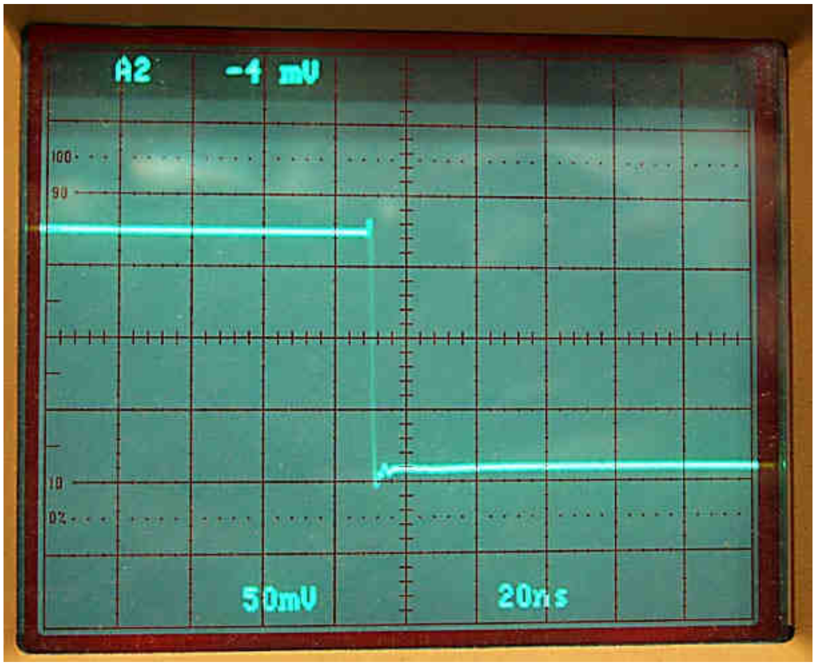

Figure 3—Expanded view of trailing edge. Tiny glitch at start of transition, and 5 ns of ripple after transition.

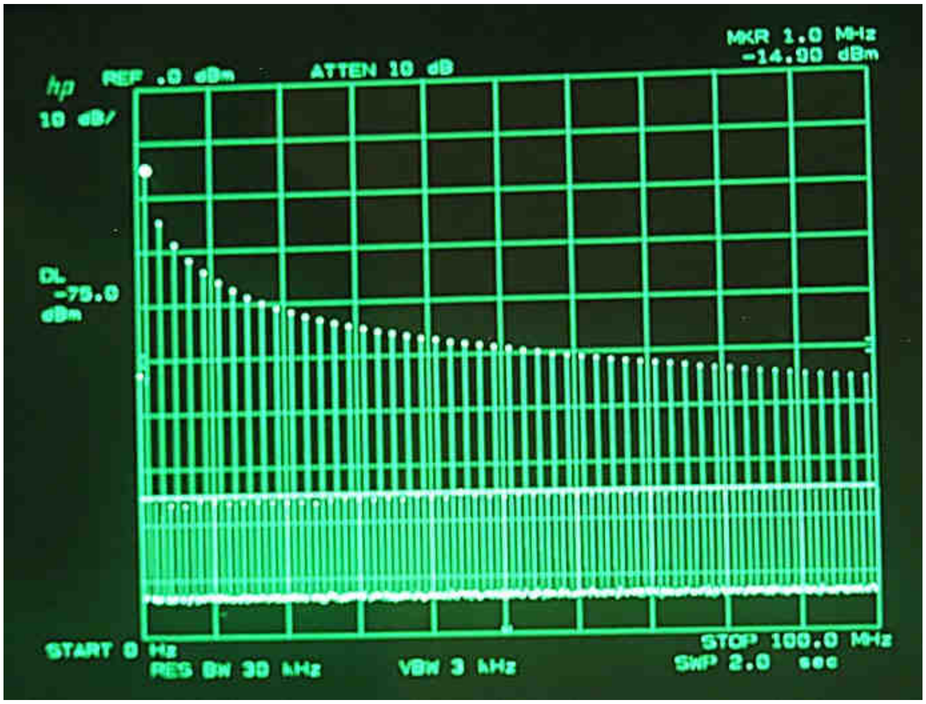

Figure 4—Spectrum of 1 MHz square wave. Even harmonics are consistently more than 60 db below the fundamental. Odd harmonics show a steady decline. Due to an attenuator on the spectrum analyzer, the absolute signal levels are meaningless. Here we care about relative levels.

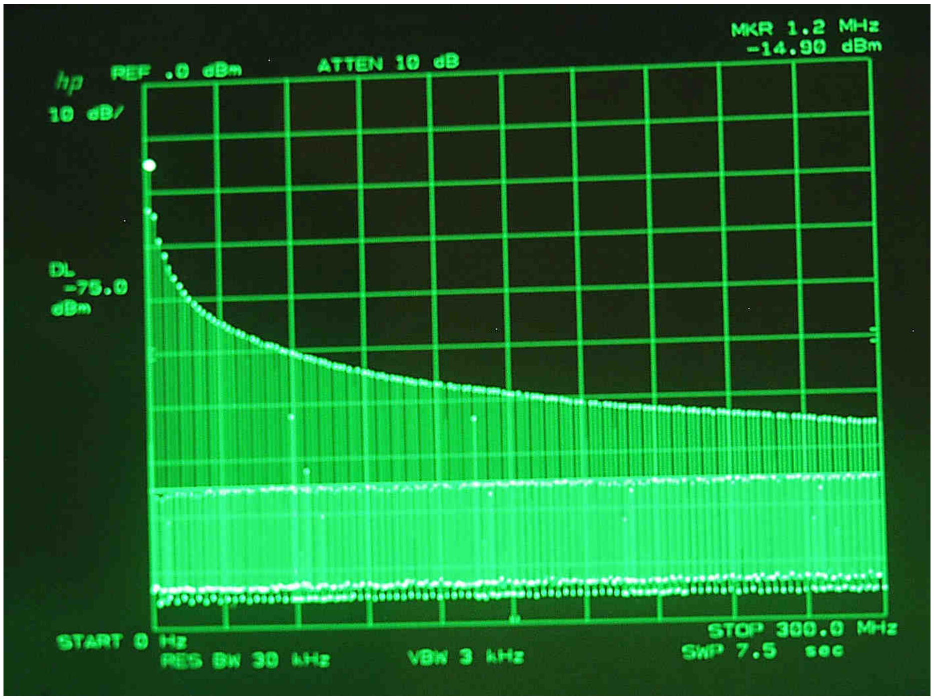

Figure 5—Spectrum from 0 to 300 MHz. Same steady trend as Figure 4. The minor glitches are artifacts from the close spacing of the peaks, and went away in a view with more limited span.

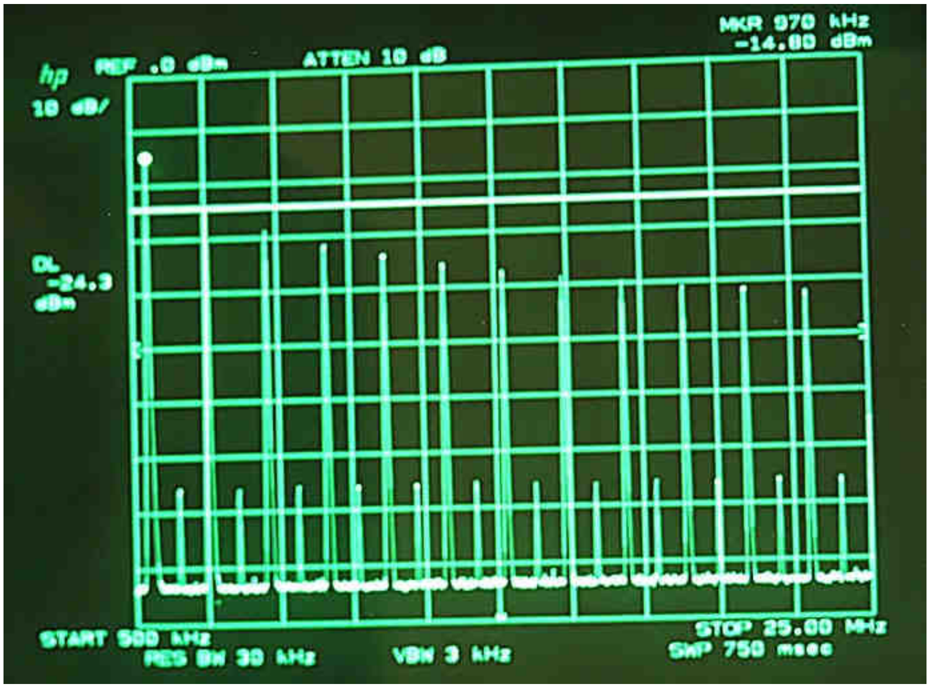

Figure 6—Spectrum from 0 to 25 MHz, showing the most important harmonics. Marker at fundamental and display line show third harmonic is 9.5 db below the fundamental, exactly as it should be. The frequency shown for the marker is not quite accurate. Long story.

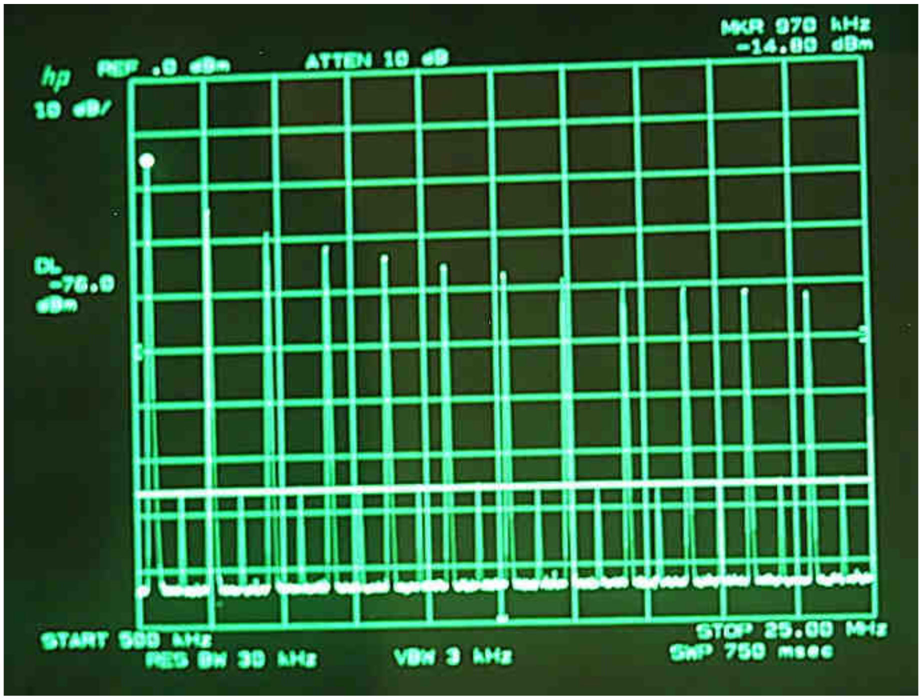

Figure 7—Spectrum from 0 to 25 MHz. The display line shows even harmonics to be steady and approx. 60 db below fundamental.

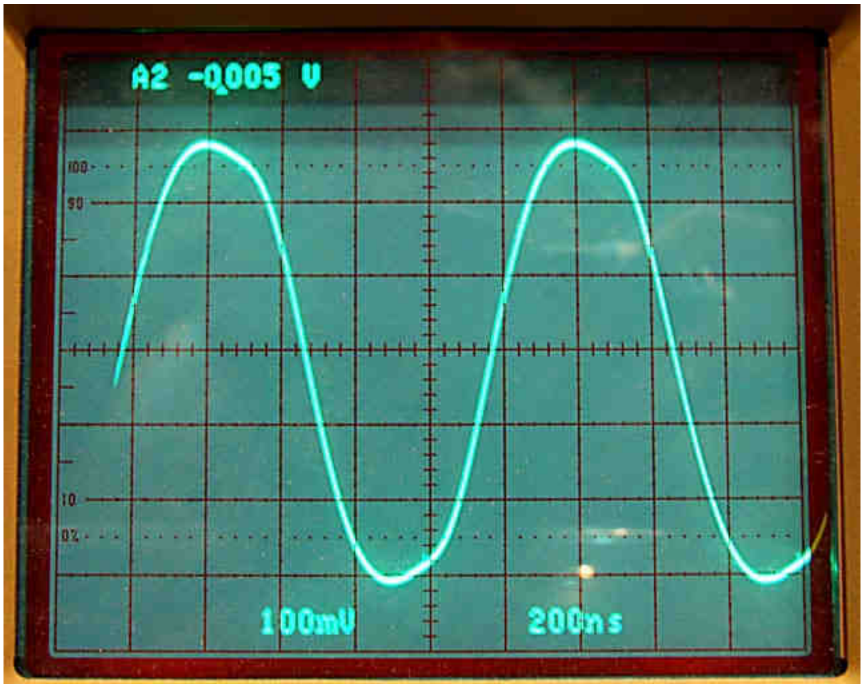

Figure 8—Sine wave output. There is just enough filtering to be sure that the total power in the harmonics is a minor portion of the fundamental power, but not enough filtering to make the filter loss excessively unpredictable.
(Note: Sine wave output deleted 7/19/08)

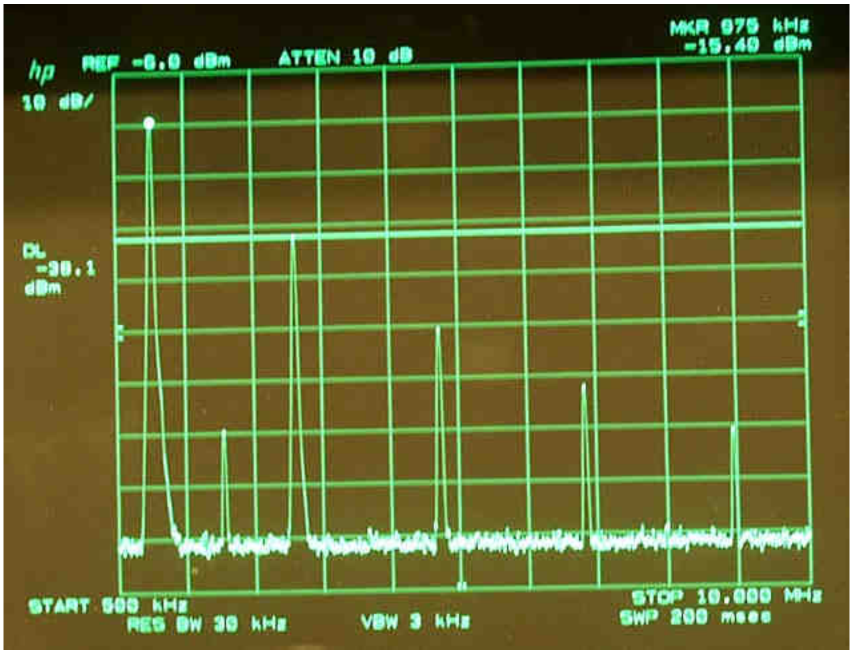

Figure 9—Spectrum from 0 to 10 MHz of the sine wave output. Compared to Figure 6, the harmonic power diminishes very rapidly. The third is now about 23 db below the fundamental, and the fifth is nearly 20 db below that. The net result is that at least 99% of the signal power is in the fundamental.

Precise Measurement of Signal Levels

Visually, the power levels in the fundamental and harmonics look much as they should. I made more precise measurements by comparing the various signal levels to the output of a trustworthy signal generator, an HP3336C which I believe to be accurate within 0.1db or better. This is more accurate than my spectrum analyzer. The fundamental level of the square wave was measured at 0.3 dbm, exactly as predicted. The fundamental level at the sine wave output was -0.1 dbm, also exactly as predicted. Figure 10 shows a graph of the levels of the various harmonics up to 21 MHz, comparing predicted and actual levels. (The voltage level of the Nth harmonic of a perfect square wave would be 1/N the voltage of the fundamental. In terms of power, the Nth harmonic is 20*Log(N) below the fundamental level.)

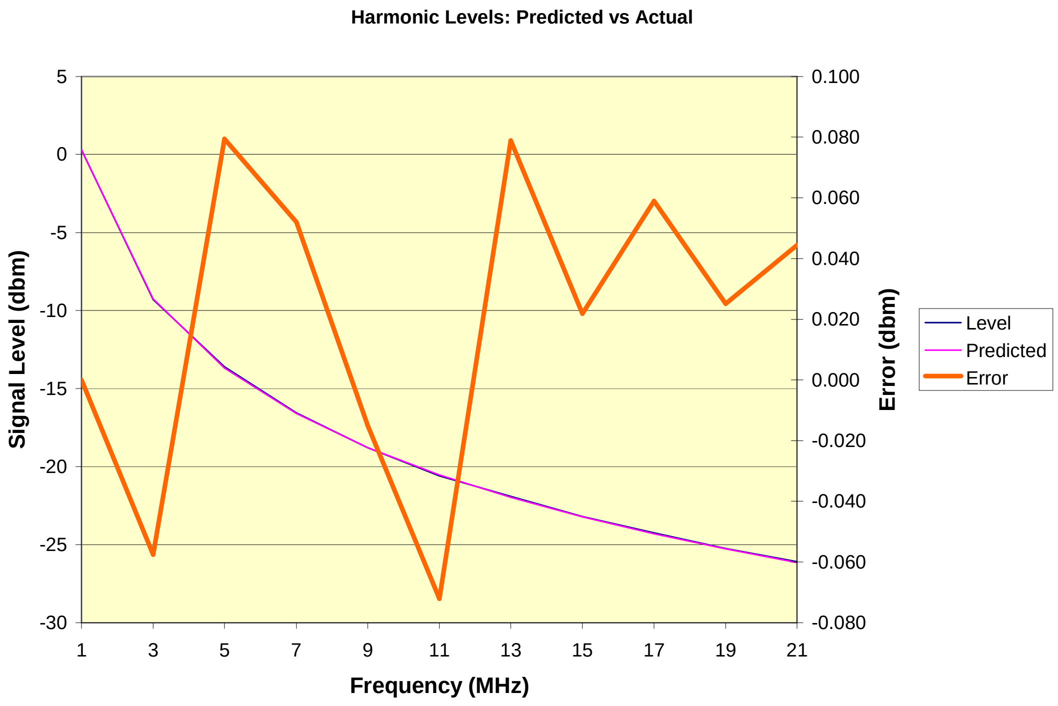

Figure 10—Predicted vs. Actual Harmonic Levels.
The small error is an indication that the square wave is very square.

Higher Frequency Tests

The 2 MHz oscillator was replaced by a 10 MHz oscillator, and then by 20 MHz. The 10 MHz oscillator produced a 5MHz square wave whose fundamental and third harmonic were within 0.05 db of that predicted from the DC voltage, which was unchanged. The 20 MHz oscillator produced a 10 MHz square wave whose fundamental was within 0.1 db of that predicted from the DC voltage. At 10 MHz output, the fundamental output was the same as at lower frequencies, but the DC voltage increased 2 mV, probably due to fact that overshoot became a more prominent proportion of the output. The shape of the leading and trailing edges of the square wave did not change noticeably with change in frequency.

Conclusion

The device shown in the Appendix provides a method of producing a square wave with very predictable levels for total power, fundamental power, and power of a large number of odd harmonics. This will make a good source for calibration of Scotty’s Modular Spectrum Analyzer. In theory, the fundamental level is predictable within 0.05 db, that error being derived from the on-board voltage reference and errors in the voltmeter used for calibration (assumed 5% + 1mV; but the 5% applies only to the difference between DC output and the voltage reference). Square wave distortions can add additional error, so I state the overall error as +/- 0.1db. However, the good performance at 10 MHz convinces me that square wave distortions will have minimal impact at 1 MHz, where the accuracy is likely to be 0.05 db, which accuracy is beyond my ability to test.

APPENDIX—SCHEMATIC

(Updated 7/19/08 to delete sine wave output)

Calibration Procedure (Use any voltmeter with 5% or better accuracy and 1 mV resolution.)

Determine the DC voltage at Vo by measuring the difference between the voltage reference and Vo. Call that voltage Vdc. Vdc will also turn out to be the peak-to-peak square wave voltage for a 50-ohm load. The stated output levels assume Vdc=0.5155V. Determine the deviation of your Vdc from 0.5155V in millivolts. For each millivolt of deviation adjust all the output values stated in dbm by 0.017 dbm. (This is accurate for deviations of a few percent.)

The adjustment is positive if Vdc>0.5155; otherwise it is negative. Round results to nearest 0.1 dbm.

As a precaution against the possibility that a voltmeter may give an inaccurate DC reading due to the presence of an AC signal, the output can be shorted at the right side of C8.