SIGNAL GENERATORS and OSCILLOSCOPE CALIBRATION

By Lannes S. Purnell

FLUKE CORPORATION

This paper shows how standard signal generators can be used as leveled sine wave sources for calibrating oscilloscopes. To do so, it is necessary to show that signal generator specifications match, or can be made to match, oscilloscope calibration requirements. Assume that oscilloscope calibration equipment is currently in place and performs adequately, including leveled sine wave performance up to 500 Mhz. Also assume a need to increase the frequency capability of the leveled sine wave source for new, higher frequency, oscilloscopes. A good place to start looking at performance requirements for a signal generator is the performance of existing calibration equipment. The Tektronix SG 5030 is a commonly used leveled sine wave generator.

SG 5030 specifications

Frequency
0.1 Hz to 550 MHz
Frequency accuracy
+/- 3 ppm
Amplitude Range
4.5 mvpp to 5.5 Vpp
Amplitude accuracy
from 0.1 Hz to 50 kHz --- +/- 1.5 % of setting
Flatness (relative to 50 kHz amplitude)
+/- 1.5 % from 50 kHz to 100 Mhz
+/- 3 % from 100 Mhz to 250 Mhz
+/- 4 % from 250 Mhz to 550 Mhz
VSWR
< 1.2:1
Harmonic distortion
all </= -50 dBc from 0.1 Hz to 49.999 kHz
2nd Harmonic </= -30 dBc from 50 kHz to 550 Mhz
all other Harmonics </= -35 dBc from 50 kHz to 550 Mhz
all Non-Harmonics </= -40 dBc from 50 kHz to 550 Mhz

On the other side of the coin are the capabilities of available signal generators. HP, Rhode & Schwarz, Anritsu, and many others are happy to provide signal generators. If we limit the search to the lower price range ($5K to $15K), there are available frequency and level characteristics as below:

Maximum Level @ Frequency
+ 10 dBm to + 20 dBm @ 1 GHz (or 1.9 to 6.26 Vpp)
+ 7 + 19 2 (or 1.25 to 5.57 Vpp)
Frequency stability
</= +/- 3ppm
Level accuracy @ Frequency
+/- 0.5 dB to +/- 1.5 dB to 1 GHz (or 5 to 20 %)
0.9 1.5 2 (or 11 to 20 %)
Harmonic distortion
</= -30 dBc (all) specs are below levels from +4 to +10 dBm or 1 to 1.9 Vpp
Sub-Harmonic distortion
</= - 40 dBc
Non-Harmonic distortion
</= - 50 dBc

SWR
<1.5:1 for frequency <2 GHz

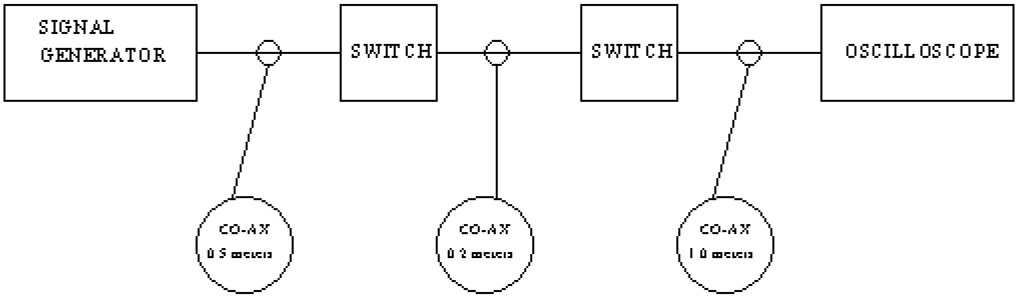
A quick look says that the signal generators may be marginal in maximum output capability, VSWR, and harmonics and are certainly not accurate enough in level. At least this is the case in comparison to the SG 5030. We need to go a step further and look at calibration procedure requirements. If we look in the procedures for digitizing oscilloscopes with high frequency capabilities in the 1 to 1.5 GHz range, we see another set of leveled sine wave requirements.

- Maximum Level @ Frequency
  - 600 mvpp @ 1 GHz
  - 1.2 Vpp @ 1.1 GHz
  - 500 mvpp @ 1.5 GHz
  - 1.2 Vpp @ 1.5 GHz
  - (plus optional tests to 5 Vpp @ 1 GHz)
- Accuracy -- Accuracy requirements are not specified in procedures but test equipment is. We need to look at the test equipment specs to determine the accuracy requirements.
  - Power meter with +/- 3% accuracy (to set levels)
  - Signal generator
    - Level available - + 19 dBm @ 1 GHz (5.6 Vpp)
    - Level accuracy - +/- 1.5 dB (+/- 20 %)
    - Harmonics - </= -30 dBc for levels </= + 10 dBm
    - Source impedance - nominal 50 ohms
    - VSWR -- </= 1.5:1 for frequency </= 2 GHz

In fact, these procedures call out a signal generator as the leveled sine wave source together with a power meter to provide the required level accuracy. Since the leveled sine wave source is used to determine the bandwidth (and flatness) of the oscilloscope, we are concerned with the signal generator specifications as they relate to level accuracy. We need to relate harmonics and source / load match effects to level accuracy.

Before continuing this path, we should look to see if there are other elements in the system which will contribute problems. The obvious one is that there needs to be a connection between the signal generator and the oscilloscope. This can be a very short cable in a simple test setup or can be considerable cable length together with switches in an automated factory, or calibration lab, test set. Fig. 1 shows a typical interconnection.

Fig 1



Good quality Co-axial cable will show attenuation of approximately 0.3 dB / meter at 1 GHz. In the ideal case, we have no other losses and no VSWR problems. Fig. 2 shows the loss vs frequency characteristic of this example.

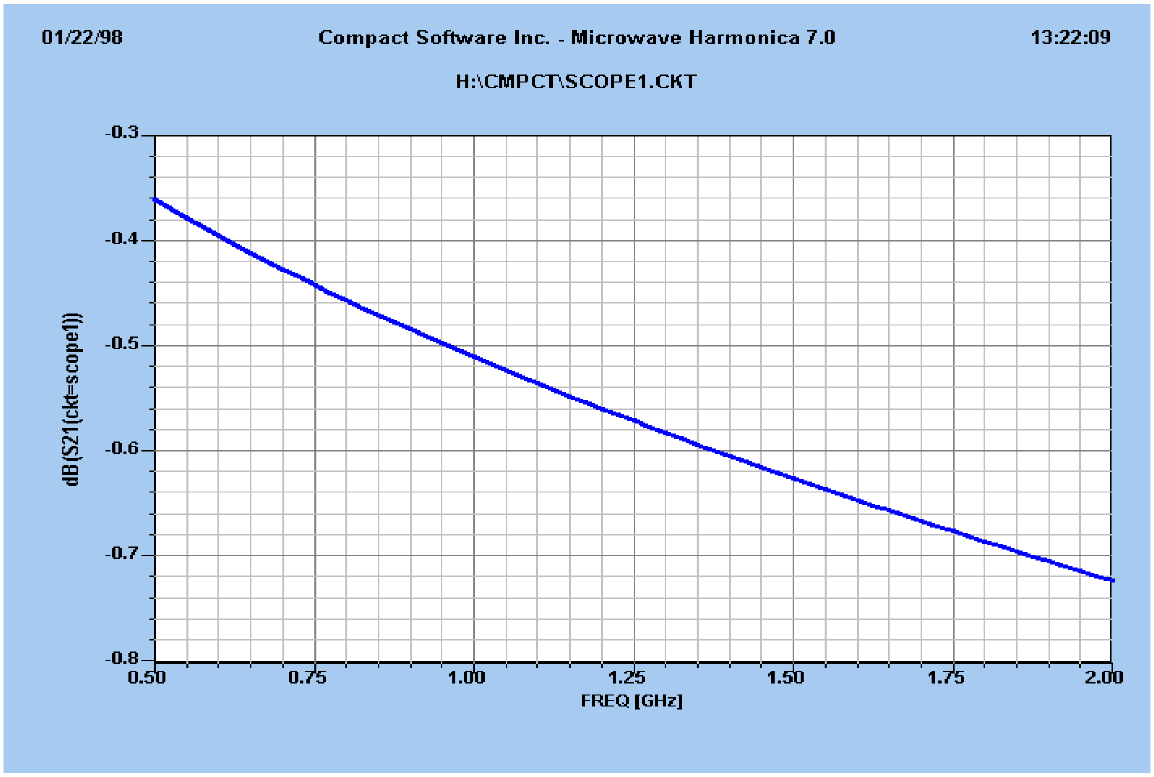


Fig. 2

Add in some typical loss, impedance, and VSWR numbers.

switch -- 0.3 dB loss and 1.3:1 VSWR @ 2 GHz
Co-ax -- 0.3 dB per meter loss @ 1 GHz and impedance from 49 to 51 ohms
Signal generator -- Output SWR of 1.5:1

This yields the loss vs frequency characteristic shown in Fig. 3.

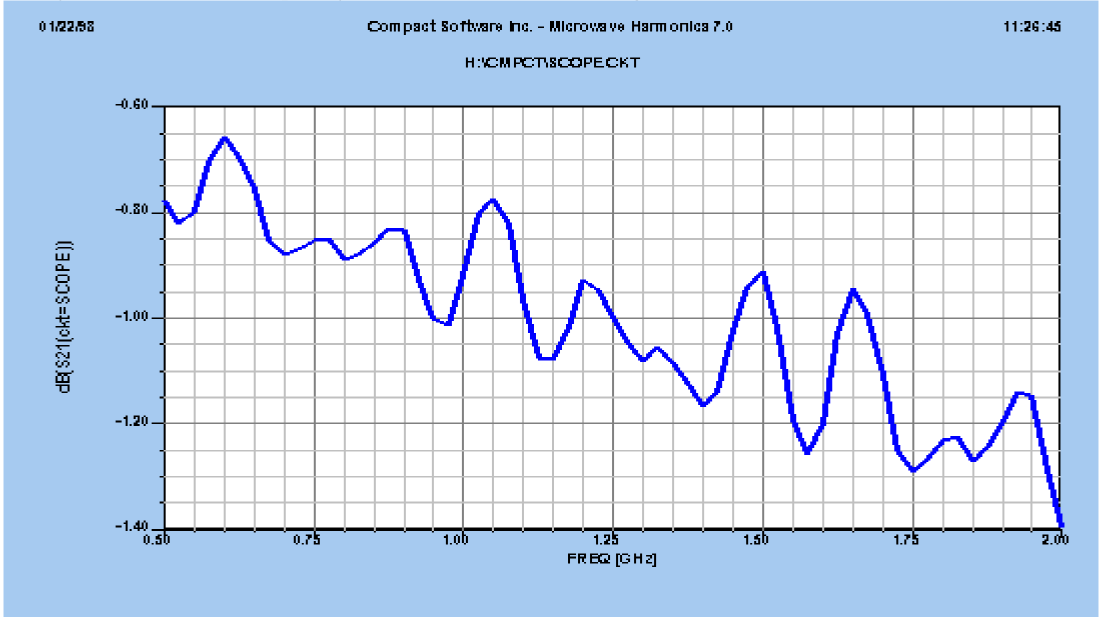


Fig. 3

This error, maximum of -1.4 dB at 2 GHz, is correctable if our chosen signal generator has sufficient extra power available. In order to examine some realistic numbers we use the HP 8648B in standard configuration. This unit provides + 13 dBm (2.8 Vpp) minimum. The highest requirement noted has been 1.2 Vpp (~ +6 dBm) at 1.5 GHz. To make a worst-case example, assume that the 1.2 Vpp requirement is at 2 GHz. In order to correct for the 1.4 dB loss, the signal generator needs to provide + 7.4 dBm (~ 1.5 Vpp). This is still within the capability of the HP 8648B. Now we can look at level correcting our test set in order to obtain the necessary level accuracy.

There are at least three methods available to accomplish automatic level correction. The oldest method is the analog leveling loop.

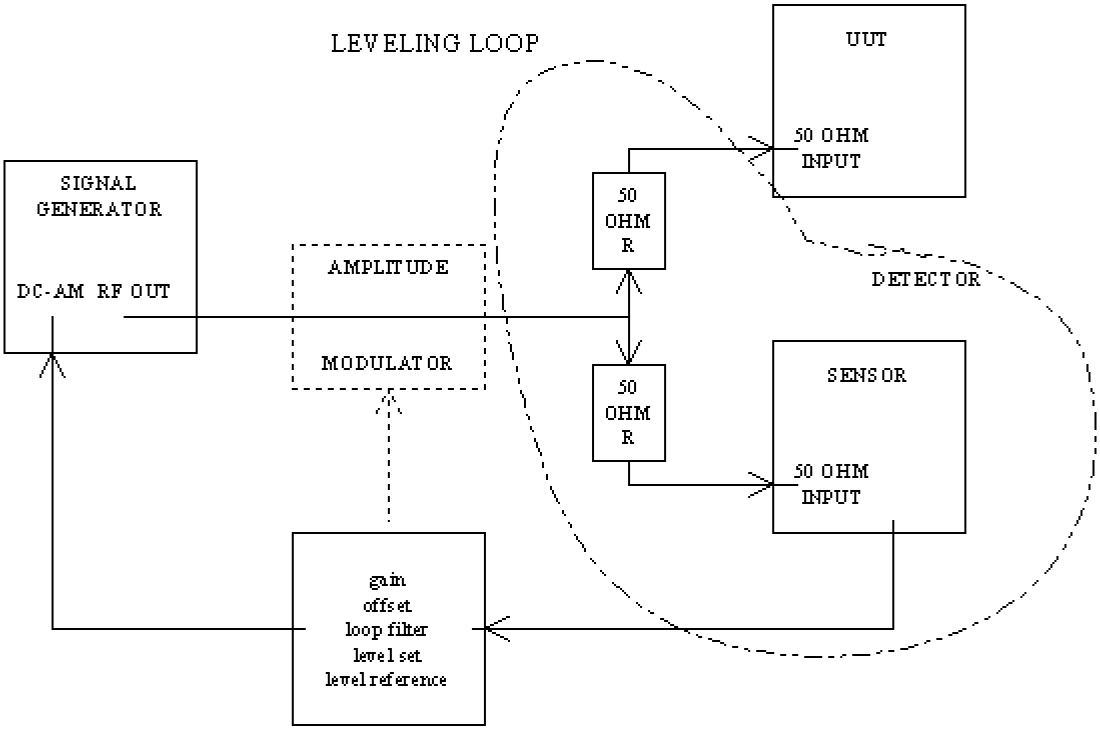


Fig. 4

This has the advantages of acceptance by tradition. The accuracy is as good as that of the detector used. The disadvantages include hardware (some custom), difficulty in applying calibration corrections, power loss (6 dB when using a 50 ohm splitter), and low level limitations due to detector and loop problems. In fact, our example will not work with this method. The 6 dB loss due to the splitter requires that the signal generator be capable of a + 14.4 dBm output level. An unequal power splitter or a signal generator with higher output level capability would be required.

Another method is to use the internal level correction capability of the signal generator. The signal generator service manual should detail the procedure. The advantages are that the end system requires no extra equipment, the power meter corrections (as from NIST) can be incorporated, and no additional loss is added to the system. The disadvantages are that the available internal correction range may not be adequate and that the correction points may be too few or not optimally placed for the application. Another possible problem would be if the signal generator manufacturer required a special test set to do the level correction. This method could likely be made to work with our example.

The most versatile method uses a computer to store and apply the corrections as external level commands. This allows corrections to be applied in whatever manner gives the best accuracy and allows the use of a factory standard signal generator. The disadvantage is that a computer is then required in order to run tests and oscilloscope calibration routines. In any automated system a computer is a part of the system and no penalty is accrued. The most simple and accurate way to use this capability is to make a correction list, or table, with all of the frequency/level points of interest and have test software use this table to provide the level corrected signals. A more general, but less accurate, method is to make a frequency/level array that covers all possible points of interest and use an interpolation routine to determine the correction values for points that fall between the calibration points in the array. This requires more knowledge of the signal generator architecture and performance. Internal switch points for attenuators and other circuit elements will affect the choice of calibration points for the correction array. The best starting point for this array is the internal level correction array. Calibration points can be added, changed, and subtracted as accuracy requires.

The accuracy which can be achieved by this technique depends on the accuracy of the power sensor calibration, the match between the source and the power sensor, and temperature sensitivity.

Power measurement uncertainties example
- Sensor calibration
  - +/- 1 %
- Source / power sensor match (source $p = .08$, sensor $p = .1$)
  - +/- .8 %
- Temperature
  - This will be added later as an overall measurement effect.

The RSS sum of these components gives an uncertainty of +/- 1.3 %. We can expect the level characterization of the source to be accurate within 1.3% at the measured points.

NOTE: The RSS sum is defined as the square root of the sum of the squares of the individual components.

The power level errors of the signal generator and the loss contributed by interconnecting hardware are both correctable errors. Considering only these factors, we can get performance as good as traceability and uncertainty allows. There are some factors that are not correctable, at least in a practical sense. These may be factors which are not directly specified in terms of level effects. In these cases, the effect on level must be derived. Some factors which may not be correctable include:

Harmonic distortion (can have large effect)
Temperature (effect should be small in calibration environment)
Amplitude modulation (should be small with a good signal generator)
Source and load match interactions (may be difficult to quantify and may be large)

Harmonic distortion can be a problem because it is a phase dependent contributor to peak/peak voltage and a phase independent contributor to power measurements. This means that a signal with a particular harmonic component can be viewed on a spectrum analyzer while the phase of the harmonic is changed and no change will be observed on the spectrum analyzer display. Performing this same experiment while applying this signal to a power sensor will likewise indicate no changes in power level. If the signal is applied to an oscilloscope and the phase of the harmonic is changed, there will be changes in the observed signal. The output level of the signal generator is being measured, and corrections determined, by a power meter. The measurements that are made using the signal generator are done with an oscilloscope. This leaves an error term which is due to harmonic components on the signal.

A general expression for a sinusoidal signal is:

$$\underset{\text{dc}}{A0} + \underset{\text{fundamental}}{A1 \sin (wt + z1)} + \underset{\text{2nd harmonic}}{A2 \sin (2wt + z2)} + \underset{\text{3rd harmonic}}{A3 \sin (3wt + z3)} + \dots$$

The effect of adding harmonic components to the fundamental can be seen by doing this mathematically and rotating the relative phase of the harmonic.

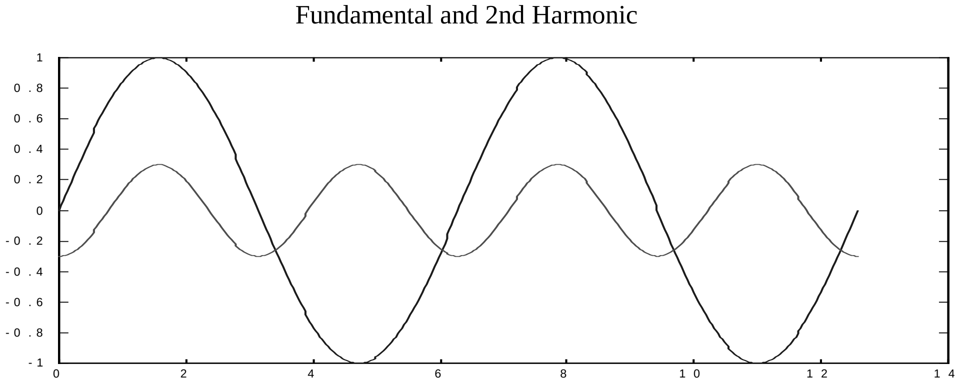

Fundamental and 2nd Harmonic

Fig. 5a

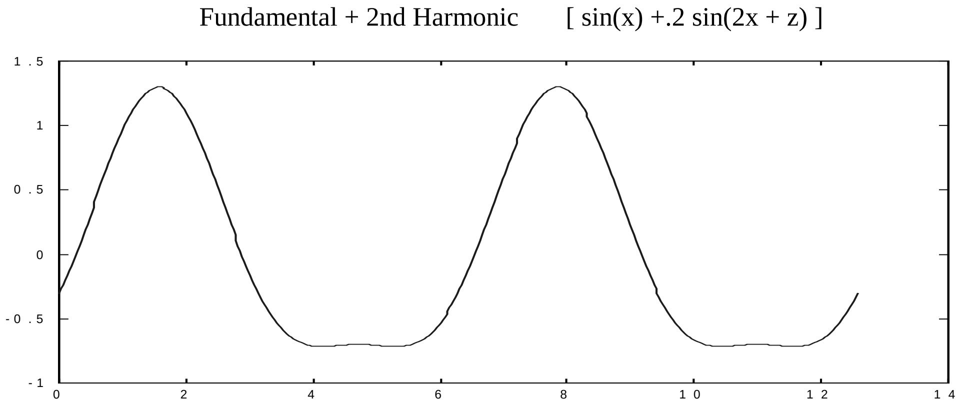

Fundamental + 2nd Harmonic [sin(x) +.2 sin(2x + z)]

Fig. 5b

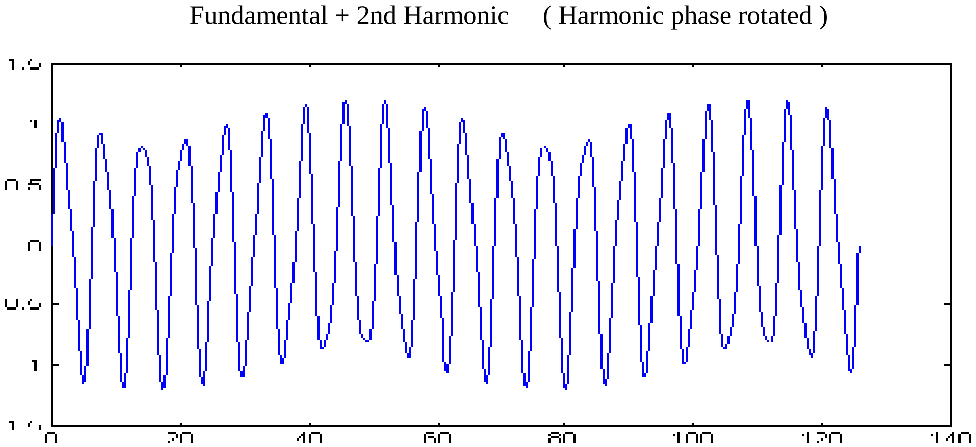

Fundamental + 2nd Harmonic (Harmonic phase rotated)

Fig. 5c

Notice that the peak/peak level does not change but a “dc” component is added.

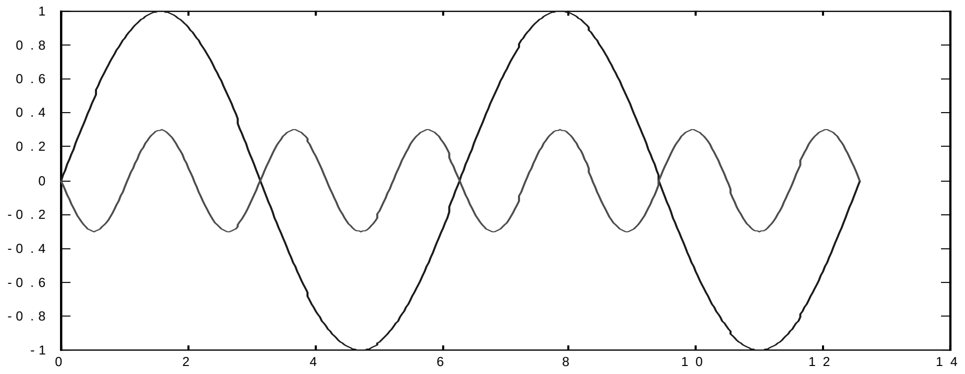

Fundamental and 3rd Harmonic

Fig. 6a

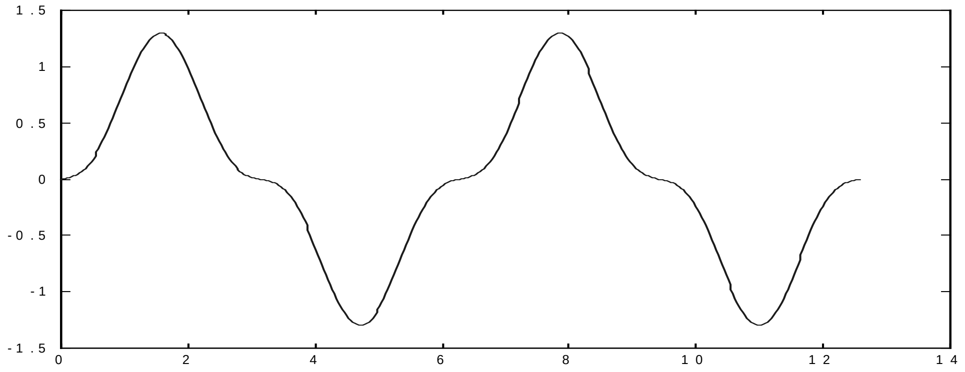

Fundamental + 3rd Harmonic [sin(x) + .2 sin(3x + y)]

Fig.6b

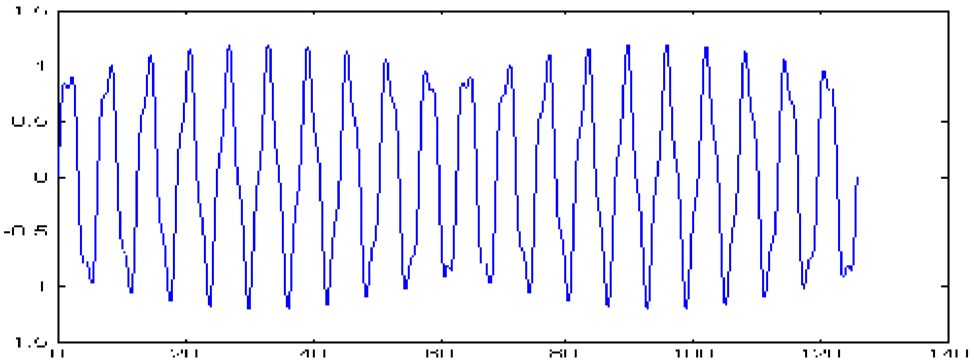

Fundamental + 3rd Harmonic (Harmonic phase rotated)

Fig. 6c

Notice the variation in the peak/peak level.

Some facts about harmonics:

1) Third harmonic is the most important when peak-to-peak voltage is the quantity of interest. The uncertainty due to the third harmonic is:
   +/- [10 exp (-dBc/20)] % example --- -30dBc > +/- 3 %
2) The second harmonic adds a similar dc component (uncertainty ?) which is usually not important.
3) Higher order harmonics and, in some cases sub-harmonics, have similar effects but are usually at much lower levels.

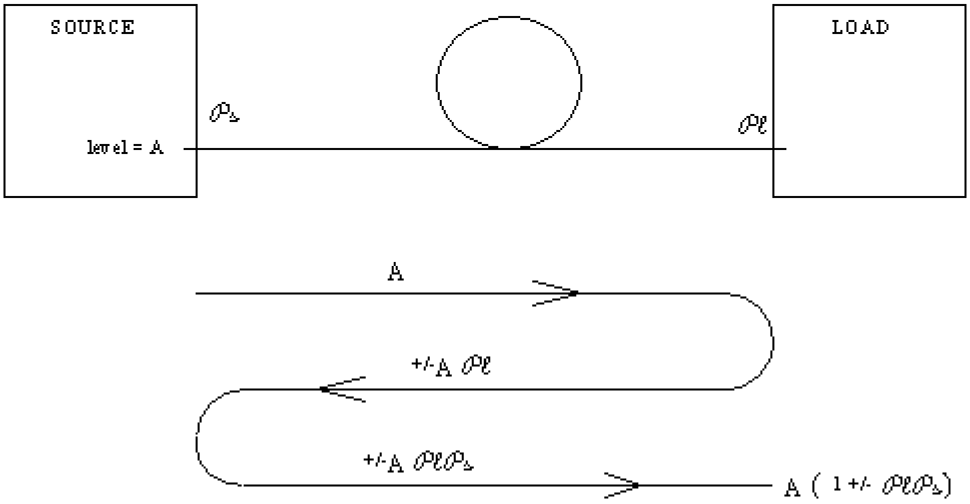
The effect of temperature on level accuracy is usually lumped into the overall level accuracy specification by the signal generator manufacturer and is not easy to extract. It is, luckily, a small contributor to the specification. Flatness and attenuator errors are the large contributors. Much of the signal generator error budget is tied up with very low level (1 mv and below) signals which are of no concern in an oscilloscope calibration application. Of course, the better the environment is controlled, the less this is of concern. Some reasonable numbers might be:

< +/- 1 % if the temperature is held to < +/- 2 deg C
< +/- 2 % < +/- 5 deg C

A poor (or broken) signal generator might have power line related amplitude modulation. This would likely first appear as a noisy signal until identified as power line frequency related. Normally, there should be no amplitude modulation related level errors.

Look at a picture to better understand the mismatch error problem.

Fig. 7



The error is +/- p1*p2 % example --- p1 = p2 = .1 (VSWR = 1.22) then error is +/- 1 %

Since we do not know actual numbers, only max allowable limits, we must use the max numbers to calculate the possible error and use this in our error budget. Our example scope has a VSWR of </= 1.5:1 from 500 Mhz to 1 GHz, or $p = .2$. Our example signal generator has a VSWR of </= 1.5:1 for frequency < 2 GHz, or $p = .2$. Our error from this source is then +/- 4 % maximum. We have no control over the oscilloscope input VSWR. The signal generator output match can be improved if there is excess signal power available after level correction. In that case, we can insert an attenuator pad in the system. This must be done prior to any level correction, of course. In our example we do have an excess and can insert a 4 dB pad and still maintain some headroom. This improves the signal generator output match to </= 1.17:1, or $p = .08$. The error is reduced to +/- 1.6 %. Improving the signal generator output match also reduces the mismatch error contribution in the level correction process.

Let us put all of these errors and uncertainties together and see the limits of our calibration process when we use a signal generator as the leveled sine wave source. First, use point-by-point corrections and a good source/load match (obtained by adding a pad to the system).

Level correction error	
Source / power meter mismatch	+/- 0.8 %
Certification uncertainty	+/- 1 %
Source resolution error (0.1 dB steps)	+/- 0.5 %
Harmonic error (use spec value of - 30 dBc 3rd harmonic)	+/- 3 %
Temperature effect error	+/- 1.5 %
Source / load (source / oscilloscope) mismatch error	+/- 1.6 %

The RSS error in this case is +/- 4 %.

As a second example, repeat this calculation but add an interpolation error of +/- 1 % (array method of level correction).

Level correction error	
Source / power meter mismatch	+/- 0.8 %
Certification uncertainty	+/- 1 %
Source resolution error (0.1 dB steps)	+/- 0.5 %
Harmonic error (use spec value of - 30 dBc 3rd harmonic)	+/- 3 %
Temperature effect error	+/- 1.5 %
Source / load (source / oscilloscope) mismatch error	+/- 1.6 %
Interpolation error	+/- 1 %
Linearity error	+/- 1 %

The RSS error in this case is +/- 4.2 %

As a final example, repeat the second calculation but increase the source/load mismatch error to 4 % by removing the pad.

Level correction error

Source / power meter mismatch	+/- 0.8 %
Certification uncertainty	+/- 1 %
Source resolution error (0.1 dB steps)	+/- 0.5 %
Harmonic error (use spec value of - 30 dBc 3rd harmonic)	+/- 3 %
Temperature effect error	+/- 1.5 %
Source / load (source / oscilloscope) mismatch error	+/- 4 %
Interpolation error	+/- 1 %
Linearity error	+/- 1 %

The RSS error in this case is +/- 5.6 %

As a point of comparison, the SG5030 yields an RSS error of 4.9% at 550 Mhz. The errors are distributed somewhat differently but they add up about the same. There appears to be no fundamental problem with using a signal generator as the leveled sine wave source for oscilloscope calibration