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Signal Generator APPLICATION NOTE

HP 8640A/B AN 170-1

OUTPUT LEVEL ACCURACY

1. INTRODUCTION

The HP 8640A and 8640B are signal generators which cover the frequency range of 450 kHz to 550 MHz, and can be extended to 1100 MHz with a frequency doubler. These generators provide AM, FM and pulse modulation. The 8640A has a mechanical dial; the 8640B has a built-in counter and phase lock synchronizer that locks the RF output frequency to the crystal time base used in the counter. Output level range of the 8640A/B is from +19 dBm to −145 dBm (2 volts to 0.013 μ volts into 50 ohms). This application note discusses output level accuracy considerations.

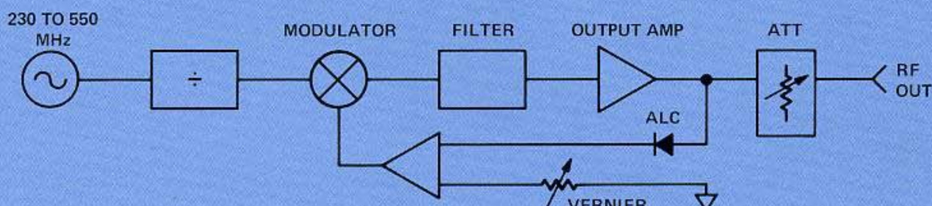

Figure 1. 8640A/B Simplified block diagram.

Objectives:

1. Describe two methods of achieving good output level accuracy in signal generators.
2. Explain the level accuracy specification of the 8640A/B.
3. Show how to operate the 8640A/B for best level accuracy.
4. Compare the absolute level accuracy of the 8640A/B AM/FM signal generator versus the earlier HP 608 series VHF signal generators.

Output level control is accomplished by the modulator, the ALC loop, the output vernier and step attenuator. The modulator acts as a current-controlled attenuator which varies the RF output level. The ALC loop is a conventional, negative feedback approach, where the RF output is sampled by the detector, and the output of the detector is compared with and made equal to the reference voltage from the vernier. The output of the summing amplifier is in turn applied to the modulator as correction signal. Thus, by controlling the reference voltage, the vernier controls the RF output level. The output step attenuator provides further control by attenuating the RF in fixed 10 dB increments. Amplitude and pulsed RF modulation are done in the ALC loop, however, throughout this note, we shall assume that the RF output is CW.

The output attenuator in the 8640A/B is a step attenuator type, rather than the waveguide-beyond-cutoff attenuator type used in most other HP signal generators. Referring to Figure 1, the circuitry to the left of the attenuator is used in most signal generators, whether a step attenuator or waveguide-beyond-cutoff attenuator is used. Let's look, therefore, at the properties of each type of output attenuator.

Waveguide-Beyond-Cutoff Attenuator

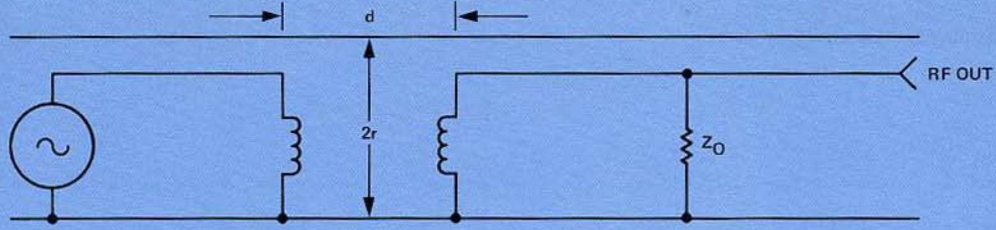

Figure 2. Waveguide-beyond-cutoff attenuator configuration.

The waveguide-beyond-cutoff attenuator has been around for quite some time. The physical phenomenon which produces attenuation is relatively simple and straightforward. We know from transmission line theory that when a waveguide is excited by a frequency lower than its cutoff frequency, the excitation energy dies away exponentially with distance from the point of excitation. Mathematically, this relationship is:

$$\alpha = \frac{54.6}{\lambda_c} \, d \sqrt{1 - \left(\frac{\lambda_c}{\lambda}\right)^2}$$

Where:

- α : attenuation in dB
- λ : free space wavelength
- λ_c : cutoff wavelength
- d : distance between the pick-up and excitation point

Note that λ_c is geometry-dependent and that the attenuation expression is independent of the frequency of excitation (as long as $\lambda_c << \lambda$), i.e.,

$$\alpha \cong \frac{54.6}{\lambda_c} \, d$$

Looking at circular waveguides, we know that the TE_{11} is the dominant mode and for this mode $\lambda_c = 3.42$ r were, r: waveguide radius.

Therefore attenuation of this TE_{11} mode, α, is:

$$\alpha = \frac{54.6}{3.42\ r} \, d = 15.9 \, \frac{d}{r}$$

For frequencies below 1 GHz, the attenuation in two inches of 0.25 inch radius waveguide is 127.2 dB ($15.9 \times \frac{2}{.25}$). Clearly, the closer we control the waveguide dimensions, the better the accuracy of attenuation. An accuracy of ±0.0005 inch which is typical for HP waveguide components gives less than ±0.127 dB incremental variation over the full 127.2 dB range. Most attenuation errors result from the mechanics of the pickup probe drive and dial system. Figure 3 shows a typical error function for waveguide-beyond-cutoff attenuators.

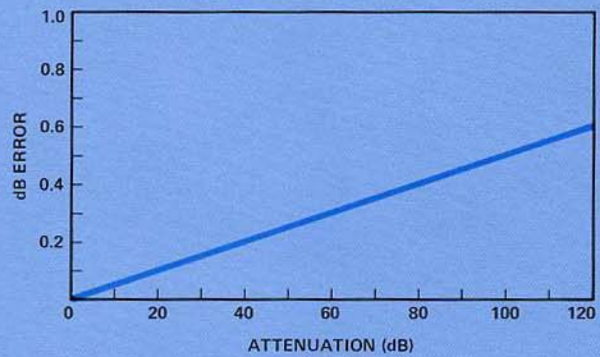

Figure 3. Typical error function of a waveguide-beyond-cutoff attenuator.

Summary of Waveguide-Beyond-Cutoff Attenuators Properties:

1. No frequency response variations except that of the pickup loop.
2. Excellent incremental and overall attenuation accuracy.
3. Continuously variable attenuation.
4. Large insertion loss (20 dB or larger), limits maximum available power.
5. Susceptible to positional and tracking errors between the pick-up probe and the dial indication. These errors have been greatly reduced in the HP signal generators due to precision control of the drive mechanism.

Step Attenuators

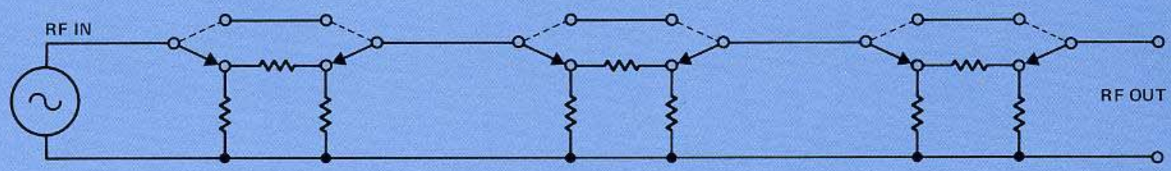

Figure 4. Typical step attenuator configuration.

The step attenuator consists of several resistive elements each with a fixed attenuation value and certain accuracy. These elements are selected in the right sequence and switched-in to provide 10 dB attenuation steps. In contrast to the waveguide-beyond-cutoff attenuator, the step attenuator has negligible insertion loss and is easily coupled into the RF output circuit of the signal generator.

The step attenuator has two main characteristics:

1. Cumulative attenuation errors.
2. Variation of insertion loss with frequency.

Attenuation error is cumulative, i.e., error is equal to the algebraic sum of the inaccuracies of the individual elements that have been switched-in to arrive at any attenuation setting. Figure 5 shows a typical error function for a step attenuator. Note the step increases in error. Frequency response variations simply add more errors, so unless a special design effort is made to correct these errors the signal generator may have a poor level accuracy. Such an effort was made in the 8640A/B design.

Two features have been incorporated in the design of the output stage of the 8640A/B generators which substantially reduce the errors contributed by the step attenuator. One feature is to adjust the meter reading at two levels to cancel the errors accumulated in the steps previous to each of the two levels. More will be said about this under Sources of Error, item E below.

The other feature is the design of the ALC loop itself. Figure 6 shows the frequency response of a typical step attenuator, where insertion loss increases at higher frequencies.

To compensate for the increased high frequency losses, the output voltage is shaped so that the power amplifier output increases with frequency. As a result the net power delivered at the generator output remains constant regardless of frequency as shown in Figure 7.

Thus, the step attenuator in the 8640A/B approaches the accuracy of the waveguide-beyond-cutoff attenuator. The user has good accuracy at low as well as high output levels.

Summary of Step Attenuators Properties:

1. Low insertion loss.
2. Cumulative errors.
3. Variations of insertion loss with frequency.

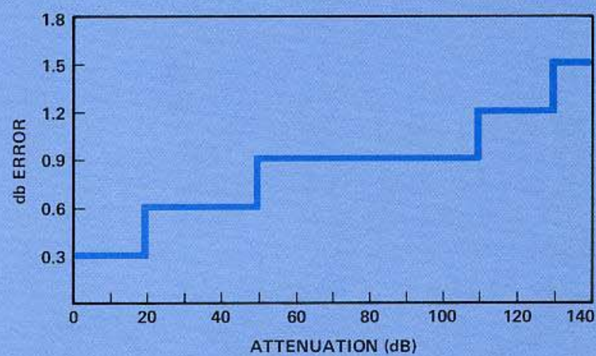

Figure 5. Typical error function of a step attenuator.

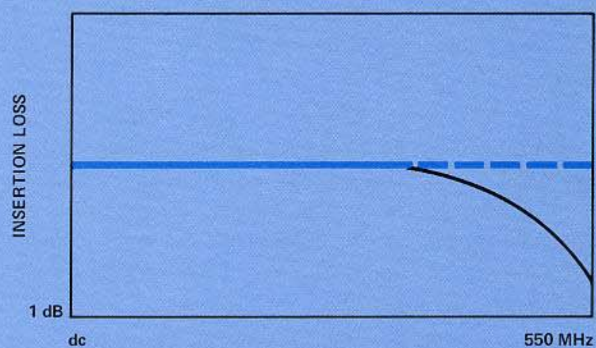

Figure 6. Typical frequency response of a step attenuator.

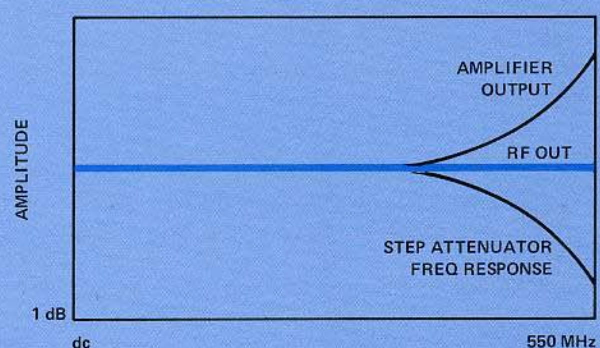

Figure 7. Flat RF output using a step attenuator.

2. SOURCES OF ERROR

The worst case absolute output level accuracy specifications for the 8640A/B are as follows:

	Using Top 10 dB of Vernier Range			Using Full Vernier Range
Output Level (dBm)	+19 to −7	−7 to −47	−47 to −137	+19 to −145
Accuracy as Indicated on Level Meter	±1.5 dB	±2.0 dB	±2.5 dB	Add ±0.5 dB

These specifications are not attenuator accuracies, they are the total comprehensive possible errors in the **absolute output level.** Let's look at all the sources of error, see when they come to play, and find how we can obtain substantially better level accuracies.

A. ±0.5 dB Level Flatness: This is a measure of how good the ALC loop is. It is a measure of the flatness of the insertion loss of the detector/attenuator from 0.5-512 MHz. Within any octave band, level flatness is much better than ±0.5 dB. Furthermore, at a fixed frequency, this error can be calibrated out, and level accuracy improved using a power meter.

B. ±0.2 Total Variation with Temperature: Within the 0 to 55°C operating range, temperature variations may produce up to ±0.2 dB change in output level. This is due primarily to changes in the sensitivity of the detector. This error can be eliminated by maintaining a relatively constant ambient temperature.

C. ±0.3 dB Detector and Meter Linearity: This refers to the tracking between the level which the detector sees and the level which the meter displays. For example, if the vernier is changed by 3 dB, the meter indication should change by 3 dB ±0.3 dB. This error can also be eliminated by calibrating the output level with a power meter at a fixed vernier setting.

D. <±0.4[1] dB Measurement Error: This refers to the uncertainty in the absolute level due to the system measurement error when the 8640A/B is calibrated. This uncertainty comes about mainly because of impedance mismatch between the 8640A/B and the thermistor or thermocouple detector used in the calibration set up. VSWR is the term used to express mismatch, and knowing the VSWR specifications of the 8640A/B and the thermistor thermocouple, we can calculate the maximum mismatch error using the following expression:

Maximum measurement error (dB) = 20 log $(1 \pm \rho_1 \rho_2)$

where: ρ_1 is the reflection coefficient of the 8640A/B and

ρ_2 is the reflection coefficient of the thermistor/thermocouple.

The 8640A/B VSWR is ≤2:1 for the top two positions of the Output Level Control (2 V and 1 V ranges, or +19 dBm to −7 dBm using full vernier range) and ≤1.3:1 for all other positions. Using the full VSWR specification of a standard power meter thermistor mount like the HP 432A/478A, the following mismatch uncertainty can occur:

Output Level	8640A/B VSWR	Thermistor VSWR	Worst Case Measurement Error
+19 dBm to −7 dBm	≤2	≤1.3	<±0.4 dB
−7 dBm to −145 dBm	≤1.3	≤1.3	<±0.15 dB

The ±0.4 dB and ±0.15 are worst case errors; the uncertainty encountered in calibrating the 8640A/B is much less. It is important to keep in mind that this uncertainty error is encountered when we calibrate the 8640A/B output power. It is Z_0 power (i.e., power delivered to a 50Ω load) and measurement error is Z_0 mismatch. A different set of errors must be applied if the receiver, filter, amplifier, etc., being tested has a different VSWR. However, in such a case, we can reduce the mismatch error as will be shown below.

There are three ways to reduce the mismatch error:

1. Actually verify the VSWR of the specific detector device used in the calibration. Thermocouple or thermistor mounts typically have VSWRs of 1.05 to 1.1 at frequencies below 1 GHz.
2. Insert a 6 dB or 10 dB fixed, highly accurate, calibrated attenuator between the 8640A/B and the thermistor or thermo-

[1] <±0.4 dB, +19 dBm to −7 dBm; <+0.15, +5 dBm to −145 dBm.

couple. Below 1 GHz, precision fixed attenuators have VSWRs in the order of 1.05.

3. Use slide screw tuners[2] to calculate the mismatch correction factor, both magnitude and phase.

Let's look at each of the first two methods more closely.

1. Known detector VSWR: The table below shows the new measurement error limits when the 8640A/B is calibrated with a power measurement system whose maximum VSWR is 1.05.

Output Level	8640A/B VSWR	8481A VSWR	Worst Case Measurement Error
+19 dBm to −7 dBm	≤2	≤1.05	≤±0.07 dB
−7 dBm to −145 dBm	≤1.3	≤1.05	≤±0.03 dB

2. Inserting a 6 dB or 10 dB attenuator between the 8640A/B and power detector as shown in Figure 8.

A 10 dB attenuator with an accuracy of ±0.05 dB and a VSWR of 1.05 is inserted as shown above. In this case, multiple mismatch results and total worst case error is ≤0.10 dB (±0.072 dB ±0.028 dB). Adding the accuracy of the attenuator, we have a worst case measurement error of ≤±0.15 dB. This compares to ≤±0.4 dB with the attenuator out, i.e., an improvement of ±0.25 dB.

Mismatch error is present in every measurement, we cannot completely eliminate it. The best we can do is to actually measure the reflection coefficient of the 8640A/B and the load, both magnitude and phase, and use slide screw tuners to calculate a correction factor, taking into account the tuner loss. This is not a one-time measurement, however, it must be repeated for every load.

E. ±1 dB Step Attenuator Error: The 8640A/B output level control is designed so that in the top two positions (2 V and 1 V ranges), the step attenuation elements are not in the RF output path. For these two positions, VSWR is ≤2. Starting with the third position, the step attenuator is in and VSWR improves to ≤1.3. Because of this feature, the step attenuator error does not affect output levels above −7 dBm. The attenuator itself consists of five step attenuators (10 dB, 2 each 20 dB, 30 dB and 60 dB elements) which are selected and summed in the correct sequence to yield a 10 dB to 140 dB of attenuation. Each of these elements is manufactured to an accuracy of ±0.3 dB or better. Thus, total cumulative error may be as much as ±1.5 dB.

We reduce the cumulative error to ≤±1 dB, however, by compensating the level meter at two output levels; once where the 60 dB element is first switched in and again where the 60 dB and 30 dB elements are switched in together for the first time. With the vernier at its uppermost position, the 60 dB element is switched in for the first time when the output level is a −67 dBm[3]. At this level a variable resistor is adjusted to reset the level meter and cancel the cumulative errors of the previous seven attenuation steps. Likewise, at −97 dBm[3] where the 60 dB and 30 dB elements are switched-in together for the first time (they remain switched-in for all levels below), another variable resistor is adjusted to reset the meter and cancel the previous cumulative attenuation errors. These adjustments are made at 50 MHz, but they can be made by the user at any frequency of his choice.

F. ±0.5 dB Output Level Vernier Error (only for lower 8 dB Vernier Range): The vernier has approximately 18 dB of range. In the top 10 dB (the thick white area indicated in the output level control), the vernier error contribution is negligible and is already included in item C above. In the lower 8 dB range, however, the vernier

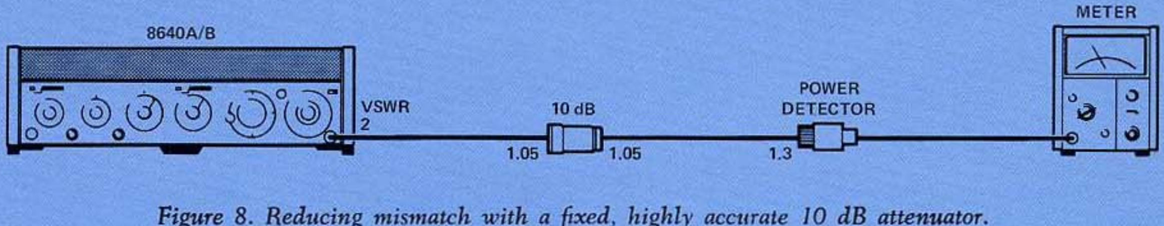

Figure 8. Reducing mismatch with a fixed, highly accurate 10 dB attenuator.

[2]See HP Application Note 64, pp 3-11 to 3-13.

[3]This level is measured with an accurate IF substitution technique.

may add up to ±0.5 dB to the overall accuracy. This additional 0.5 dB is due to slight deterioration in the detector linearity, a larger temperature coefficient and increased metering error. Thus, it is always recommended that the vernier only be used in the top 10 dB of its range and the step attenuator be used for greater attenuation. The top 10 dB range can be used to set all levels down to −137 dBm. From −137 dBm to −145 dBm, the lower 8 dB of the vernier must be used. Thus far, we have discussed the worst case specifications. Let's see how we can get the best level accuracy.

3. BEST LEVEL ACCURACY

We can obtain the best level accuracy by calibrating the RF output with a power meter at a **fixed frequency, fixed vernier setting** and a relatively constant ambient temperature. This approach eliminates four sources of error:

1. Flatness
2. Variations with temperature
3. Detector and meter linearity
4. Vernier error

However, the accuracy obtained depends on the VSWR of the thermistor/thermocouple and the absolute output level. This discussion assumes that we use a 1.05 VSWR[4] thermocouple.

In the top two positions of the Output Level Control, i.e., from +19 dBm to −7 dBm using all 18 dB vernier range, the best level accuracy we can obtain is ≤±0.07 dB. This error consists entirely of the measurement error (primarily from mismatch). From −7 dBm[5] to −145 dBm, the best level accuracy we can obtain is ≤±1 dB; this error, however, consists mostly of the step attenuator cumulative errors.

Calibration with a power meter is a very simple matter. From +19 dBm to −7 dBm, simply connect the 8640A/B directly to the power meter and set desired output level, as shown in Figure 9.

Likewise, from −7 dBm to −145 dBm, connect the 8640A/B directly to the thermocouple. Set the vernier in the top 10 dB of its range,[6] and set the Output Level Control to −10 dBm[7] and the power meter to the best resolution position. Adjust the vernier so that the power meter reads the least significant digit of the desired output level and attenuate the required number of steps. For example, if the desired output level is −73 dBm, adjust the vernier so the power meter reads −3 dBm, i.e., output level is −13 dBm; now leave the vernier in position and attenuate six steps to get −73 dBm ±1 dB. Likewise, if −128 dBm is desired, adjust the vernier so that the power meter reads −8 dBm.[8] Attenuate twelve steps to get −128 dBm ±1 dBm.

Within the range of −7 dBm to −145 dBm, output level accuracy after calibrating with a power meter is substantially that of the step attenuator. Typical attenuator accuracy is ≤+0.9 dB and mismatch error is ≤±0.03 dB.

Summary: By eliminating the above sources of error a useable accuracy of ±1 dB is achievable down to −145 dBm.

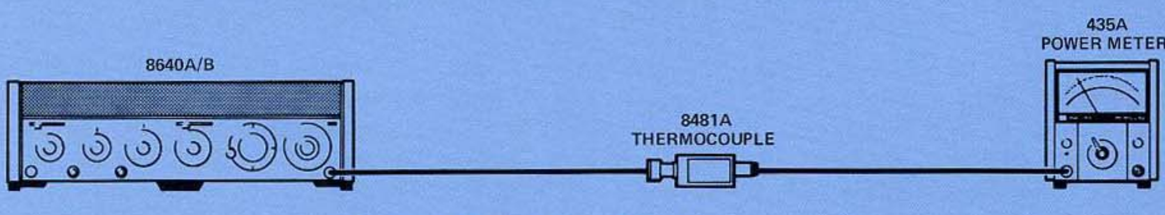

Figure 9. Calibration with a power meter.

[4]If detection element VSWR is 1.2 or more, use a precision 10 dB attenuator to reduce mismatch as described earlier.

[5]In the range overlap from +5 to −7 dBm, accuracy is better with step attenuator out of the signal path.

[6]Below −137 dBm, lower 8 dB must be used.

[7]Actual output level from −7 to −17 dBm.

[8]8640A/B level meter reads +2 dBm.

4. ACTUAL LEVEL ACCURACY DATA
8640A/B vs. 608

The 608 series VHF signal generators have been the standard in signal generators for many years. Even today, the 608 series is accepted for precision and accuracy. These generators use a waveguide-beyond-cutoff attenuator. The level accuracy of several 608F generators was measured and compared with the 8640A/B.

Figure 10 shows the typical level accuracy of the 8640A/B at two frequencies referenced to the specification values. Figure 11 shows the typical level accuracy of the 8640A/B versus the 608F. One can readily conclude that the 8640A/B approaches the 608 in level accuracy for most of its output range. Furthermore, the 8640A/B level accuracy specification is clearly very conservative.

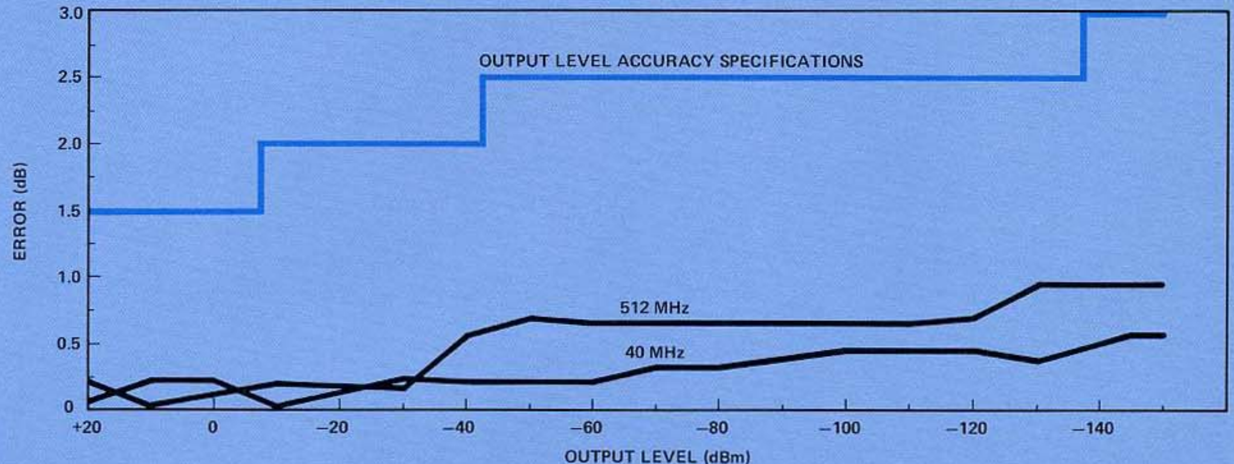

Figure 10. Typical level accuracy for the 8640A/B vs. specifications.

(Recorded data shows the worst of seven instruments).

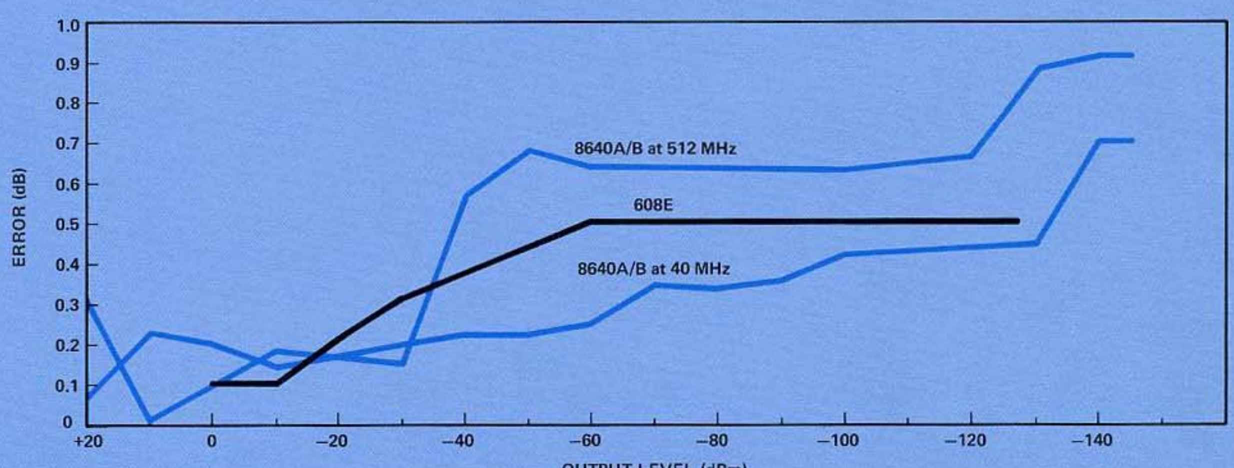

Figure 11. Typical level accuracy of the 8640A/B vs. the 608.

(Recorded data is the same as in Figure 10).

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