

Calibration of Precision Step Attenuators

Presenter and Author
Bill Bruce
Hewlett-Packard Company
Loveland, Colorado 80537
Fax: (970) 679-5263
E-mail: bill_bruce@hp.com

Abstract

This paper describes an automated parallel IF substitution system for precision attenuator calibration which has been in use for over 15 years and presents results of tests made on some very accurate attenuators.

The calibration system was originally developed to meet the calibration needs of a step attenuator in a new synthesizer. Years of data have shown this attenuator to have phenomenal accuracy. The system has been continually refined and is now used for high-accuracy calibration of several other types of step attenuators. The data presented establishes confidence in the accuracy of the system and the attenuators.

Introduction

During 1978, there was a need to verify the accuracy of an excellent attenuator in a new synthesizer product. The author attempted to calibrate one attenuator using the existing manual method and found it to be an exasperating process. The natural consequence was to develop an automated calibration system. The system has been in use since that time, and with some refinements over the years, it has been used to calibrate a large number of very accurate step attenuators. This paper describes the system and some of the considerations necessary for achieving high accuracy. One particular data set has become more or less standardized and many attenuators have been measured using this data set. Graphs and histograms of some of the data from approximately 90 attenuators are presented. The data demonstrates the capability of the system and also indicates that a well-designed attenuator can exhibit very small errors.

Description and Basic Operation of the System

The method chosen for the automatic calibration system is parallel IF substitution¹. This method has the capability to achieve excellent accuracy and fairly wide dynamic range. A programmable ratio transformer is used as the system standard. The system capability covers frequencies between approximately 0.3 MHz and 80 MHz, and attenuation between 0 dB and 100 dB. With some re-connection to a non-mixer configuration, 1 kHz is also a usable frequency.

Figure 1 shows a block diagram of the system. Its operation can be compared to a superheterodyne radio receiver which has a 1 kHz IF and has the capability to precisely measure changes in input signal level. A doubly balanced mixer is fed by two signals, one from a local oscillator at a fixed level, and one from an RF source, which is phase locked to the local oscillator. Figure 2 shows a photograph of the system.

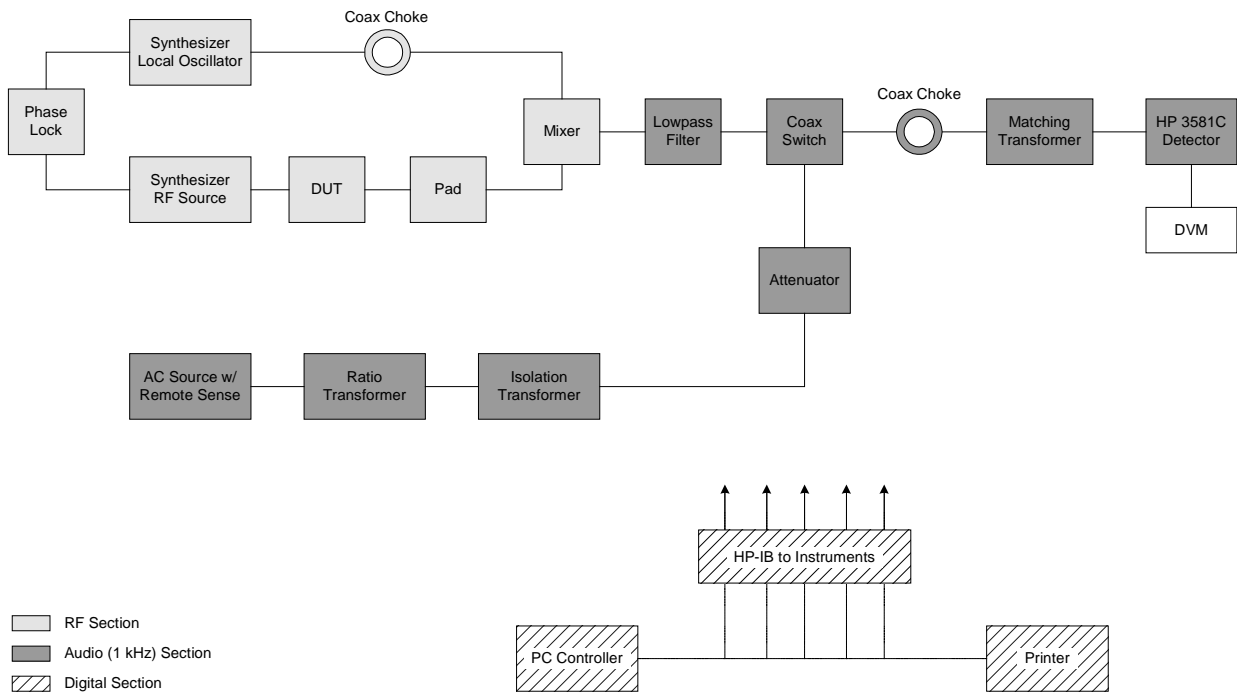


Figure 1. Block Diagram of System.



Figure 2. Photograph of System.

The signal from the RF source is passed through the attenuator under test before it goes into the mixer RF input. Appropriate padding in the signal path is used to minimize uncertainties due to impedance mismatch. The mixer output should be terminated in its characteristic impedance for all frequencies exiting the mixer. Also, some low-pass filtering is done on the mixer output to prevent LO feedthrough and unwanted mixer products from causing abnormal response by the detector. These two requirements are filled by a simple “constant Z” two-stage low-pass filter, with the first stage f_c at 32 MHz and the second stage at 32 kHz. Figure 3 shows the filter details.

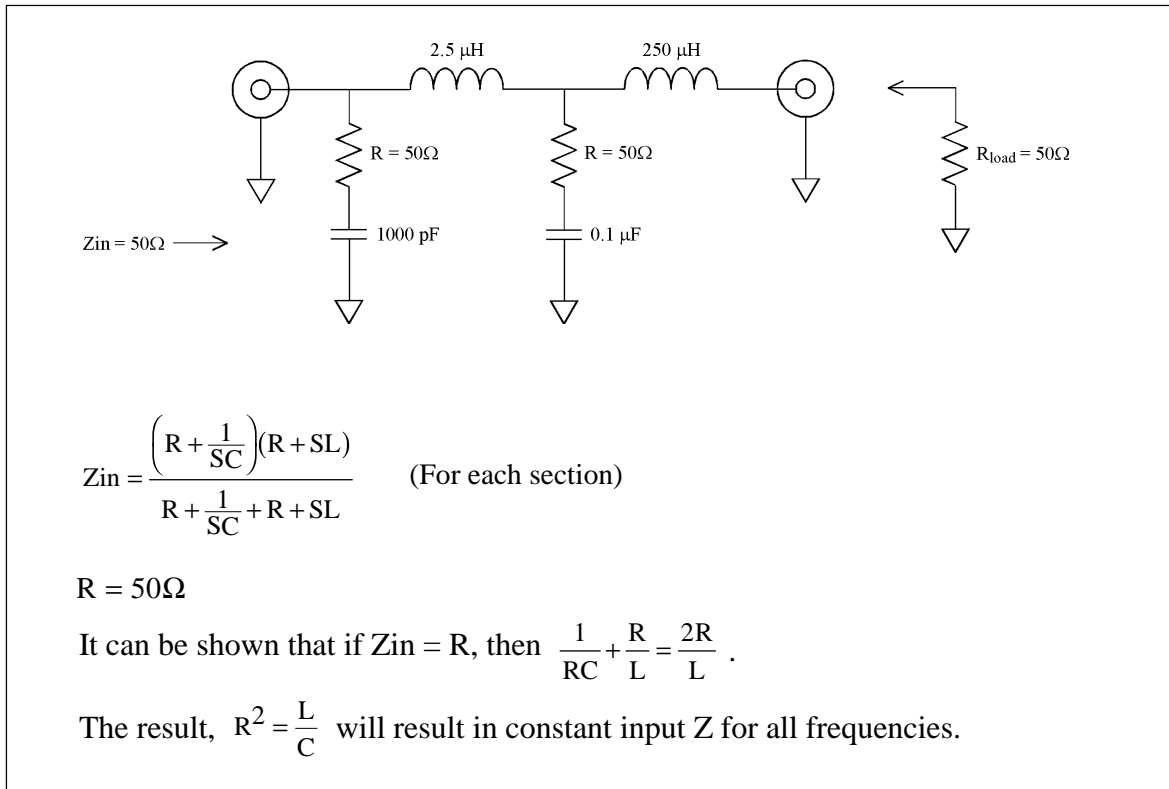


Figure 3. “Constant Z” Low-Pass Filter Design.

The detector input is routed through a switch that allows selection of either mixer IF output or output from the ratio transformer. The ratio transformer is driven by a stable AC voltage source at approximately 1 kHz, with remote sensing at the ratio transformer input. The load regulation of this AC source must be adequate to negate the effects of varying reflected load as the ratio of the transformer is changed. The burden on the output of the ratio transformer is a 100 kΩ to 50Ω resistive divider.

The general operation of the system is described by the following sequence. First, with the device under test (DUT) set at its reference position, the IF level is read by the detector. The reference setting is normally zero, but other settings can be accommodated. Next, the detector input is switched to the output of the ratio transformer and the ratio is adjusted to obtain the same detector reading, within a defined window. Then, with the DUT set at the first step to be tested (10 dB for example) the matching process is repeated and a second ratio is obtained. The attenuation is then $20 \log(\text{ratio}_2/\text{ratio}_1)$.

Note that the above sequence produces error data for the attenuator under test with the errors at each setting referenced to its zero (or other specified) setting. The actual value of its insertion loss when set at zero is not measured. If this were required, a reference would have to be set using a lossless “through” connection, then the test device connected and measured. The requirements for this system were to measure errors relative to the zero setting.

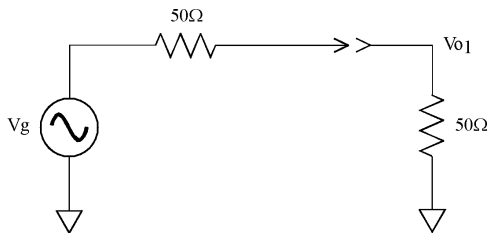
Additional System Considerations

The parallel IF system uses a programmable ratio transformer as its standard, operating at a frequency of approximately 1 kHz. The ratio transformer is the backbone standard of the system, in that all measurements are derived from settings of the ratio transformer. It must be periodically checked against a traceable standard. The practical range over which a six-decade ratio transformer may be used to match IF levels is determined by the desired resolution and the nominal ratio at which it is being used. For a resolution of 0.001 dB, a range of approximately 40 dB can be covered. In order for the system to calibrate DUT attenuator settings above 40 dB, it is necessary to set a second reference level using a step at or near 40 dB which has already been measured. This is accomplished by increasing the input signal to the DUT by 40 dB, which results in a detector level very close to that used for the first 0 dB reference. Note that for DUT settings of 40 dB to 80 dB, the detector and mixer are operating over the same range that was used to test 0 dB to 40 dB. The error of the second reference setting is then added to the measured errors of subsequent steps to reference them to the zero setting.

An additional 20 dB of DUT attenuation can be measured if the lowest detector signal is sufficiently above its noise floor to provide an acceptably small error contribution from the noise. With the system parameters used, this is possible, allowing a total range of 100 dB, with some degradation of uncertainty near 100 dB. To cover the 80 dB to 100 dB range, the AC calibrator driving the ratio transformer is switched down one range (20 dB). Normally, the uncertainty requirements for large values of attenuation are less stringent than for low values of attenuation and fortunately this fits well with the system’s performance.

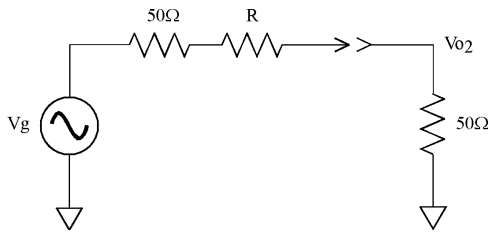
After all the steps have been tested using a reference, the reference level is measured again to determine if it has changed. Repeatability of the reference is part of the uncertainty budget, and it must be within acceptable limits. There are several possible causes for changes in the reference level, involving both the device-under-test and the system. Some of these are drift of the RF source, non-repeatability of switch contacts, either in the DUT or the system, change in connector resistance, and self-heating effects. The problem of non-repeatability of contact resistance is always present at some level in step attenuators. Figure 4 relates changes in contact resistance to change in attenuation. Once the system has been well characterized, the reference change is an excellent indicator of switch contact problems in the DUT.

In a perfect 50Ω system, the output will be exactly half the generator voltage.



$$V_{01} = V_g \frac{50}{50 + 50}$$

Now if a small resistance, R, is introduced in series with the generator, what is the relationship between its value and the change of the output (in dB)?



$$V_{02} = V_g \frac{50}{50 + 50 + R}$$

$$\frac{V_{01}}{V_{02}} = \frac{100 + R}{100}$$

$$\text{dB} = 20 \log \frac{100 + R}{100}$$

$$10^{\frac{\text{dB}}{20}} = \frac{100 + R}{100}$$

$$R = 100 \left(10^{\frac{\text{dB}}{20}} - 1 \right)$$

Results:

For .001 dB, R = .0115Ω

For .01 dB, R = .115Ω

For .1 dB, R = 1.16Ω

Figure 4. Analysis of Effect of Contact Resistance.

Switching of the detector between the IF and ratio transformer was initially accomplished by an expensive high-quality SMA coaxial relay with excellent isolation. It was found that although it had great isolation, the repeatability of the contact resistance of this device left something to be desired. Data was obtained on relay contact performance using a precision DMM to make four-terminal resistance measurements at its connectors. Since the IF frequency of 1 kHz does not really require 50 ohm geometry to be preserved, an inexpensive power relay with large contact area mounted in a shielded box was found to provide superior performance. Contact resistance repeatability was evaluated and the calculated switching uncertainty in a 50 ohm system was predicted to be well under .001 dB. Isolation was also found to be sufficient. Without sufficient isolation, either the IF or ratio transformer output signal appears at reduced level at the detector input when measuring the other and can cause problems.

The use of a 1 kHz IF frequency requires the use of high-quality synthesizers for the system. Unwanted sideband energy close to the carrier frequency caused by phase noise of the synthesizers must be at a low enough level to not cause adverse effects.

In order to minimize ground loop currents in the system, two coaxial chokes² are used. Each choke consists of about 16 turns of .141" semi-rigid coax wound on a toroidal form. The choke in the RF path between the DUT and the mixer has a powdered iron core and the choke in the IF path ahead of the detector has a high-permeability tape wound core. Another measure to protect against ground loop currents is a double-shielded isolation transformer that is inserted between the ratio transformer output and the IF-Ratio switch.

Ground loop currents in the outer conductor of the coaxial path between source and detector can cause errors in measured attenuation, particularly at low frequencies and large attenuation settings. Reference 3, page 218 has a discussion and analysis of this so-called "classical attenuator" problem. The same problem has also been observed as occurring within some step attenuators, probably due to some sort of internal grounding problem.

The detector used (HP 3581C) has automatic frequency control, which centers its IF passband on the incoming signal. This allows the IF and ratio transformer output frequencies to differ slightly without affecting detector performance. The detector has a selectable IF bandwidth, which is normally set at 30 Hz. Also, an audio transformer is used to improve power transfer to the high-impedance detector input from the 50 ohm system. Detector linearity has no effect on system accuracy because it is only required to measure two nearly identical levels, the IF and ratio transformer outputs. The system must be tailored so that the lowest level measured by the detector is sufficiently high such that its input noise (which RMS adds to the signal) is sufficiently below the input signal. The detector DC output is read by a DMM which sends its readings to the control computer via the HP-IB interface. The HP 3581C does not have a remote-controllable input attenuator, so some operator involvement is needed when level changes are made. A programmable 50 ohm step attenuator ahead of the matching transformer could be used to eliminate operator involvement, but it would decrease signal-to-noise ratio because the detector would always be set at maximum gain.

The main requirements placed on the detector are that it be repeatable (short-term stability), have sufficient resolution and sufficiently low noise, in addition to the AFC capability mentioned above. A possible way to improve the system would be to phase lock the AC source and synthesizers together and use some sort of lock-in amplifier as a detector.

Mixer non-linearity will contribute directly to system errors, and therefore the linearity of the mixer must be checked over the range where it will be used. Fortunately, this is possible using the ratio transformer and a step attenuator which only needs to exhibit excellent repeatability. The low-frequency limit of the system in IF mode is dictated by the ferrite core transformers inside the mixer.

Various step sizes can be used for linearity verification. The apparent attenuation of a given step is measured at many different input levels, spaced over the mixer dynamic range of interest. Differences in the apparent attenuation which exceed the attenuator's repeatability are attributed to mixer non-linearity. Again, the lowest level used must be sufficiently above the detector's noise. The high-end limitation of usable mixer dynamic range is due to compression. The maximum dynamic range over which the mixer is used in this system is slightly over 60 dB, and its linearity error is approximately .002 dB or less. The software must insure that the mixer is always used in the range over which it has been characterized. The uncertainty analysis assumes that the mixer linearity follows a pattern, which doubles its uncertainty for the second reference.

When each IF and ratio transformer output level is measured by the detector, at least 20 measurements are made and simple statistical methods are used to help assure data integrity.

Summary of Uncertainty Analysis

The following table summarizes the various contributions to the uncertainty budget for the system (not including mismatch effects). Each number represents approximately 2 standard deviations.

Range	0-40 dB	40-80 dB	80-90 dB	90-100 dB
	dB	dB	dB	dB
Ratio Transformer Output	negl.	negl.	.002	.002
Ratio-IF-Match	.0014	.002	.0028	.0028
Mixer Linearity	.002	.004	.008	.008
Reference Drift	.001	.001	.001	.001
Noise	.0006	.0006	.005	.03
RSS Sum	.0027	.0046	.0100	.031

Table 1. Summary of Uncertainty Analysis.

Analyzing the uncertainty of the system has not been straightforward because it is very difficult to separate and quantify each source of uncertainty. The system design approach and careful assessment of the system's various error mechanisms has resulted in an analysis of system uncertainty which seems to agree very well with practice.

Uncertainty Caused by Impedance Mismatch

After it has been calibrated on the system, the return loss of both ports of each DUT attenuator must be evaluated and an estimate made of the uncertainty in attenuation caused by impedance mismatch. Sometimes this uncertainty will be greater than that of the system. In this case, the uncertainty of the calibration must be increased to include the effects of mismatch. We have been assuming worst-case phase conditions for calculating mismatch uncertainty, although a less conservative approach seems to be acceptable. A practical and verifiable level of return loss for the input and output ports of most step attenuators seems to be somewhere around 40 dB. This is equivalent to a VSWR of 1.02 to 1. Modern network analyzers are easily able to verify this return loss (actually their capability is quite a bit better than this). With 40 dB return losses at both ports of the system and both ports of the device under test, and with the device under test set at zero, the worst case uncertainty due to mismatch is predicted to be about ± 0.005 dB using the equations presented in reference 4. Reference 5 describes a more aggressive approach to estimation of uncertainty due to mismatch.

Comparison With Another Method of Measuring Attenuation

A recent intercomparison was made with a different method of measuring attenuation to see if any systematic difference could be detected. The waveguide below cutoff attenuator is accepted as the standard for attenuation, and its behavior has been analyzed in detail.⁶

Measurements were made on a step attenuator using this parallel IF substitution system and the same attenuator was also measured at another Hewlett-Packard division by a waveguide below cutoff (WBCO) standard piston attenuator equipped with a laser interferometer to measure piston displacement. The following data indicates excellent agreement between these two entirely different ways of measuring attenuation. Each mean value in the table below is the average of 10 measurements.

Frequency: 30 MHz

Measured attenuation values (dB)

Step dB	IF Standard		WBCO Standard		Difference of Means
	Mean	2 Sigma of Mean	Mean	2 Sigma of Mean	
10	9.9858	.0004	9.9854	.001	.0004
20	19.9904	.0002	19.9897	.0006	.0007
30	30.0504	.0006	30.0516	.001	-.0012
40	40.0363	.0018	40.0367	.0006	-.0005
50	50.0393	.0020	50.0404	.0008	-.0011

Table 2. Comparison of Parallel IF Substitution and WBCO Standard.

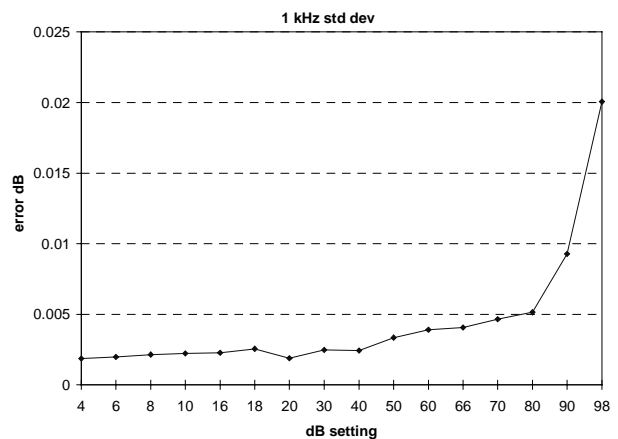
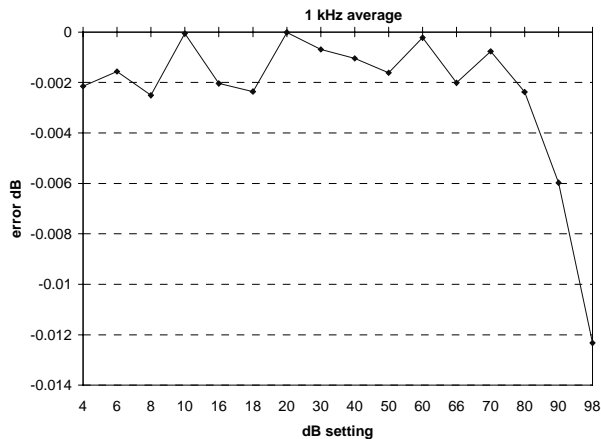
Connector Considerations

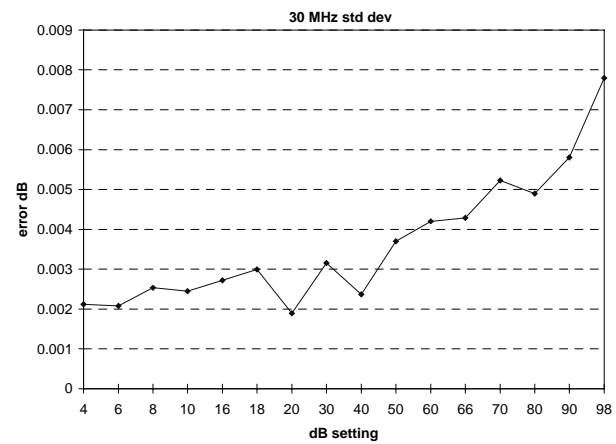
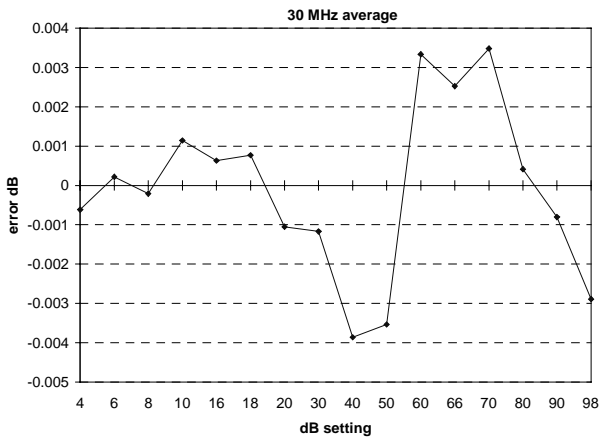
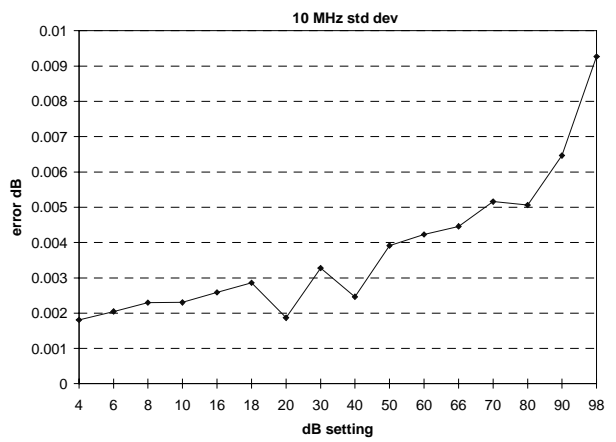
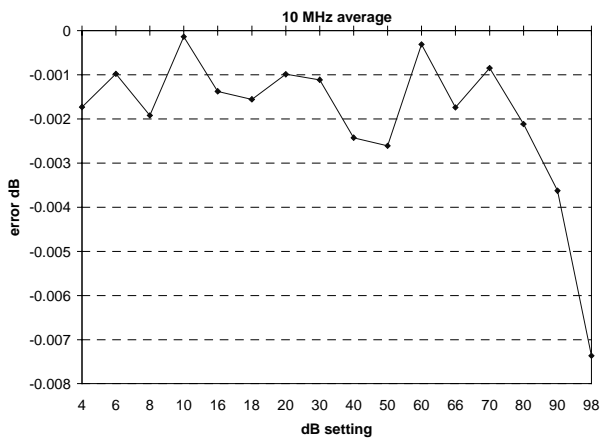
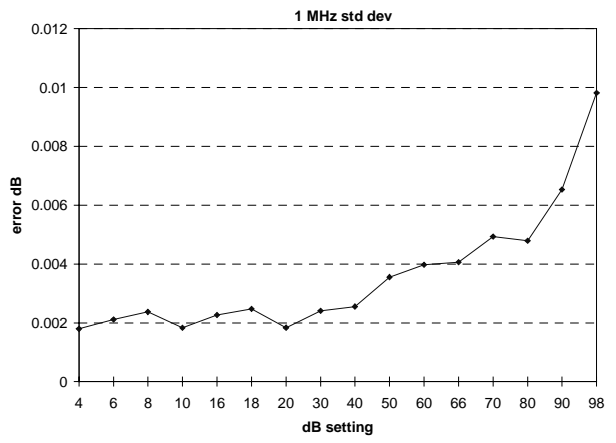
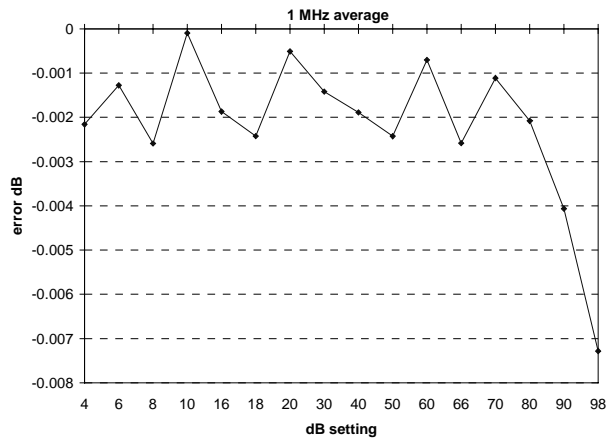
For precision attenuators, the requirements placed on the connectors become quite demanding. The analysis of contact resistance in Figure 4 applies to connector resistance variations just as it does to switch resistance variation. In addition, impedance “bumps” caused by connectors can degrade overall performance. Experience with different connector families has shown that some are not compatible with the low uncertainties that the system is capable of achieving. In particular, BNC connectors have been observed to cause as much as .01 dB variation in measured attenuation when wiggled. Their relatively loose mechanical tolerances and the wobbly joint that results may be responsible. SMA and type N connectors are far better in this regard. BNC connectors should be avoided when doing precision attenuation measurements.

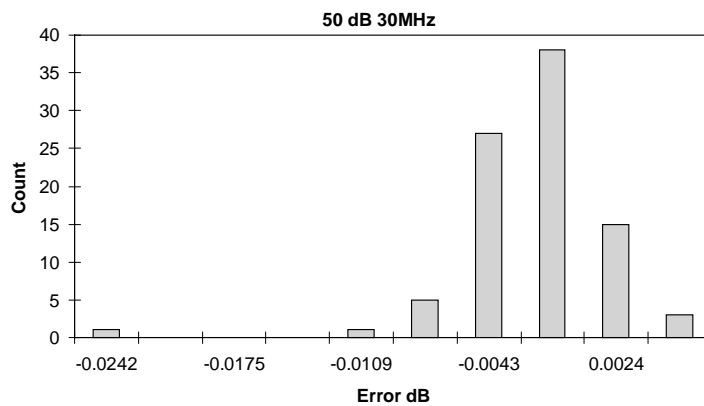
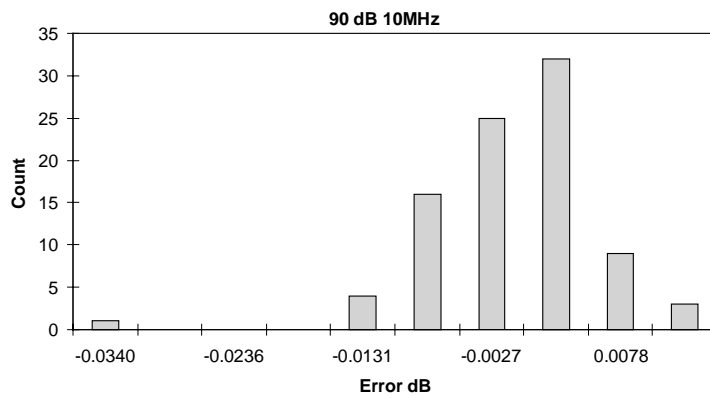
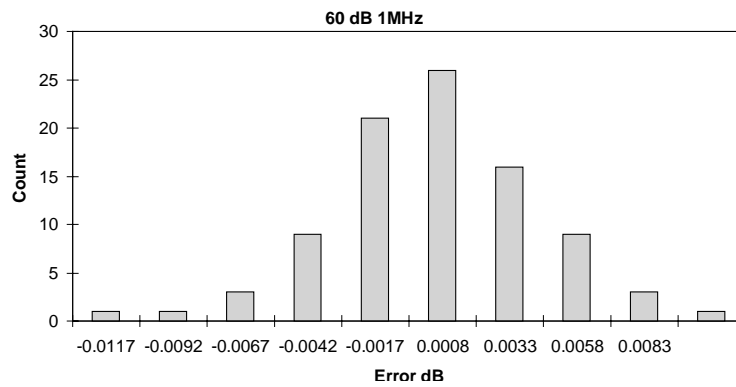
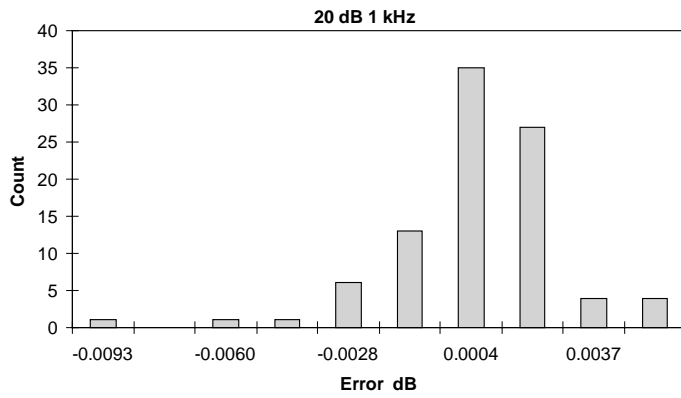
Summary of Data Obtained by the System

Following are some graphs showing average errors and standard deviation (for a single reading) as measured by the parallel IF substitution system at selected steps and frequencies. These plots demonstrate the performance capabilities of the system and the attenuators. They also indicate some error patterns in the attenuators at various steps and frequencies. Note that the data has been compiled over a period of time from routine calibrations of approximately 90 attenuators that have been in use in the field and has not been screened in any way. Also shown are some selected graphs and histograms of the data.

Graphs and Histograms







Conclusion

The creation and refinement of an automated parallel IF substitution system has resulted in a very useful measurement capability with state-of-the-art accuracy for evaluating the errors of step attenuators in the mid-RF frequency range. The system has been used over the years to calibrate a large number of precision step attenuators with impressive results. It has also been a valuable tool for precision characterization of other attenuators which exhibit good repeatability but have larger absolute errors.

References

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