RF Attenuation Measurement and Calibration
How to Improve Accuracy by Using Low SWR Masking Attenuators

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HOW TO IMPROVE ACCURACY BY USING LOW SWR MASKING ATTENUATORS.

Abstract.

Measurement of attenuation at microwave or any other frequencies is affected by a number of accuracy constraints. Chief among the basic requirements is traceability to a national standard. This brings with it a value of measurement uncertainty, but provides a common means of providing assurance of measurement integrity to all customers. In addition there are other issues that cloud the measurement accuracy picture, the largest and usually least under control being that due to mismatch. Short of adjusting the measurement results using the full reflection coefficients of the device under test and the insertion point source and load impedances, adequate results can be achieved by a careful choice of components used to provide the test port impedances. Care of the connectors is also a most important part.

Measurement Principles.

Reference 1 defines attenuation as follows:

"A general term used to denote a decrease in signal magnitude in transmission from one point to another."

It also defines an attenuator as follows:

"A device for reducing the amplitude of a signal without introducing appreciable distortion."

Measurement of attenuation is usually done by measuring insertion loss. This can be done using a variety of instruments such as power meters, scalar analyzers, vector network analyzers, stepped superheterodyne systems, and so on. A number of instrument manufacturers provide such systems.

The basic premise is to take a system reference with an insertion point closed, followed by a second measurement with the device under test connected into the circuit at the insertion point. Figure 1 shows a setup for performing such measurements. A signal generator provides a stimulus signal, whose level is measured by a superheterodyne receiver. The change in level at the receiver, when the device under test is inserted in at the insertion point, is the insertion loss.

Traceability.

There are a number of techniques that can be used to provide traceability to a national standard.

A national laboratory such as National Institute of Standards and Technology in the USA can accurately measure an attenuator or "golden standard," which can be used on a regular basis to verify the accuracy of a measurement system. The device is simply measured using the system and the results compared with those from the standards laboratory calibration. Such attenuators have special precision connectors that provide the best possible repeatability, and are treated with great care. The traceability is provided at the frequency of interest, but only over the fixed range of the device.

The frequency of 30 MHz has for a long time been a standard frequency, at which attenuation measurements can be made with high precision and over wide dynamic ranges. So called piston attenuators, more accurately styled "waveguide below cutoff attenuators," can be used to provide very accurate measurements over dynamic ranges in excess of 100 dB, and in any incremental value to four decimal places. Their accuracy comes from the theoretical performance of the circular waveguide being used below its cutoff frequency. It relies on very accurate machining of the cavity and very accurate measurements of its dimensions by standard dimensional techniques. The movement apart of the two antennae within the

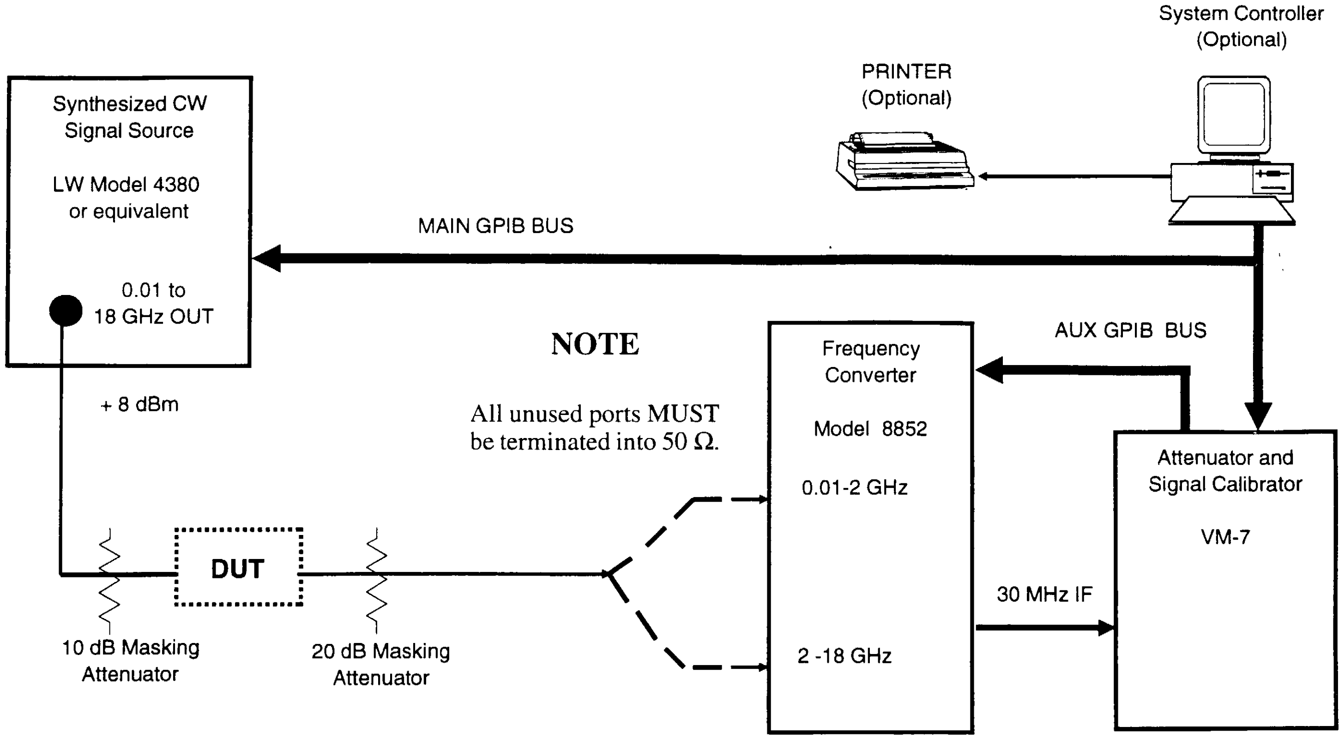

Figure 1. Highest Accuray System Configuration

cylinder can be very accurately measured using laser techniques. Such instruments are usually quite expensive, and are normally owned by standards laboratories themselves. They do not travel well.

Another device that can be used to provide a direct link to the standards laboratory is the "Voltage Doubler" (Reference 2). In this device two parallel paths are summed to provide an output signal. If one path is removed, and terminated, the output drops by 6.020 dB. The frequency of 1.25 MHz became a standard frequency in the early 1980's, and this instrument became the means of providing traceability. The excellent repeatability of the switches in the device allowed calibration to an accuracy in the order of 6 microbels, i.e. 0.00006 dB, over the 6.020 dB step. Performance at 30 MHz can also be calibrated, but at reduced accuracy.

The preceding two instruments are intended to provide traceable linearity accuracy at the IF of a superheterodyne receiver. There is a technique, which can be used at the frequency of interest, in the same fashion as the "golden standard." Figure 2 shows the system. A generator's output is caused to drop by 10 dB. The drop is measured by both a Power Standard, and the receiver under test. The results are then compared. The Power Standard is traceable through voltage and resistor standards, and can give accuracies to several thousandths of a dB in 10 dB.

System Errors.

When using any scalar system, such as that in Figure 1, there are a number of sources of error or, more correctly, uncertainty in the measurement. These are as follows:

System Stability
System Linearity
Connector Repeatability
Mismatch.

System stability or repeatability is a measure of the system's ability to hold the reference level constant. Stepped systems, e.g. the Lucas Weinschel Model 8850-02, can quote +/- 0.015 dB over several minutes.

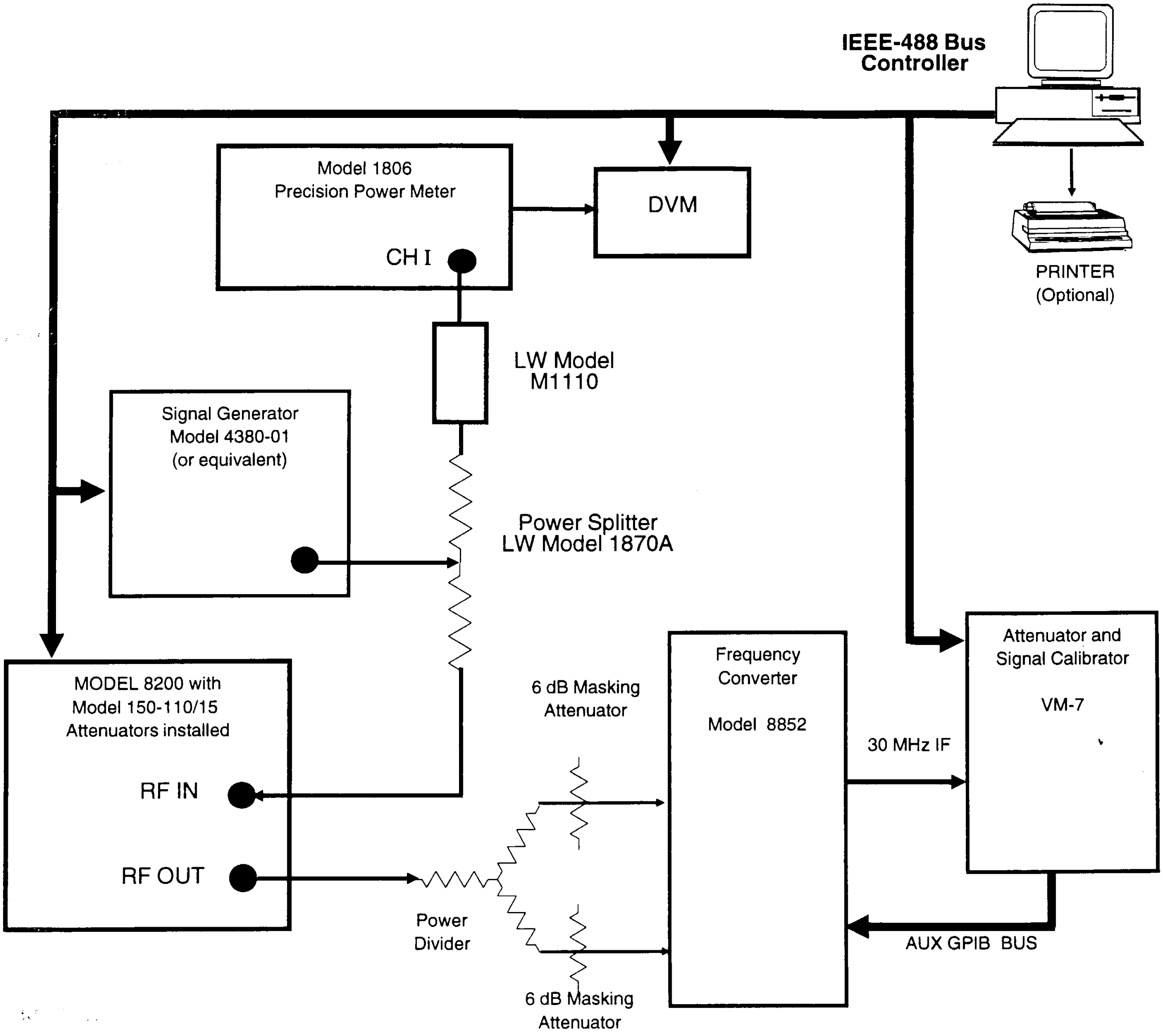

Figure 2. Linearity Verification Setup

This means that if a set of reference measurements is taken, and a second is taken a few minutes later, the difference betweeen the two sets is less than +/-0.015 dB. This assumes that the insertion point has not been touched.

System linearity is a measure of the difference between the actual power drop caused by the insertion of the device under test, and the drop as registered by the meter or display on the instrument. The best systems quote +/-0.005 dB per 10 dB of attenuation over a wide dynamic range. Such a system is the Lucas Weinschel Model 8850-02 as seen in Figure 1.

Connector repeatability is the variation in insertion loss given by the device, when the connections are remade. Normal precision "N" connectors give approximately +/- 0.01 or 0.02 dB maximum variation at 18 GHz on subsequent reconnection. This uncertainty is minimised by using precision connectors and tightening the connections to the correct torque. It is also necessary to keep the connectors clean and free from dirt.

SWR or mismatch errors are caused by the fact that neither the test point connections nor the device under test have perfect 50 Ohm impedances. The true insertion loss of the device by definition is the insertion loss it would give when inserted into a perfect 50 Ohm impedance setup. The uncertainty introduced when source and load are not perfect 50 Ohm impedances is termed mismatch uncertainty.

System Definition.

Figure 1 shows the Lucas Weinschel Model 8850-02 Attenution Measurement System. A signal generator produces a stimulus signal which is applied to the insertion point. The Model 8852 converts the input signal from the insertion point to a proportional signal at 30 MHz. This signal is then fed to the Model VM-7 Attenuator and Signal Calibrator.

The Model VM-7 was specifically designed to measure relative signal levels, in other words attenuation. Figure 3 shows a block schematic of the Model VM-7. A front end amplifier buffers the input attenuators, and provides low noise figure. The input attenuators provide approximately 50 dB in 10 dB steps. Following the attenuator is a phase locked loop providing tracking of the input signal, and producing an IF of 1.25 MHz. This IF is then translated to a 10 kHz IF, which is passed through a set of amplifiers, which provide gain to 50 dB in 10 dB steps. This signal is then detected using an analog to digital converter, running in an undersampled mode, with a clock at 8 kHz. (See Reference 3.)

The detection technique used in the Model VM-7 removes all dc offsets. In addition the linearity of the analog to digital converter is such that the instrument easily achieves a linearity accuracy of 0.005 dB per 10 dB, even when range changes are taken into account. This is also achieved without any special linearization calibration as is used on other instruments.

The actual attenuation and gains of the various stages are measured in a self calibration using the linearity of the analog to digital converter. Since the averaging, i.e., filtering, at the low level end is performed using digital techniques, the autoranging function has a wide bandwidth. This makes it extremely fast, giving a response time to a 100 dB drop in level in the tens of milliseconds.

The Model 8852 includes a synthesized local oscillator and mixers covering the 10 MHz to 18 GHz range in two bands. To avoid spurious problems the band below 100 MHz is first translated to a 150 MHz IF before being retranslated to the 30 MHz IF to send to the Model VM-7.

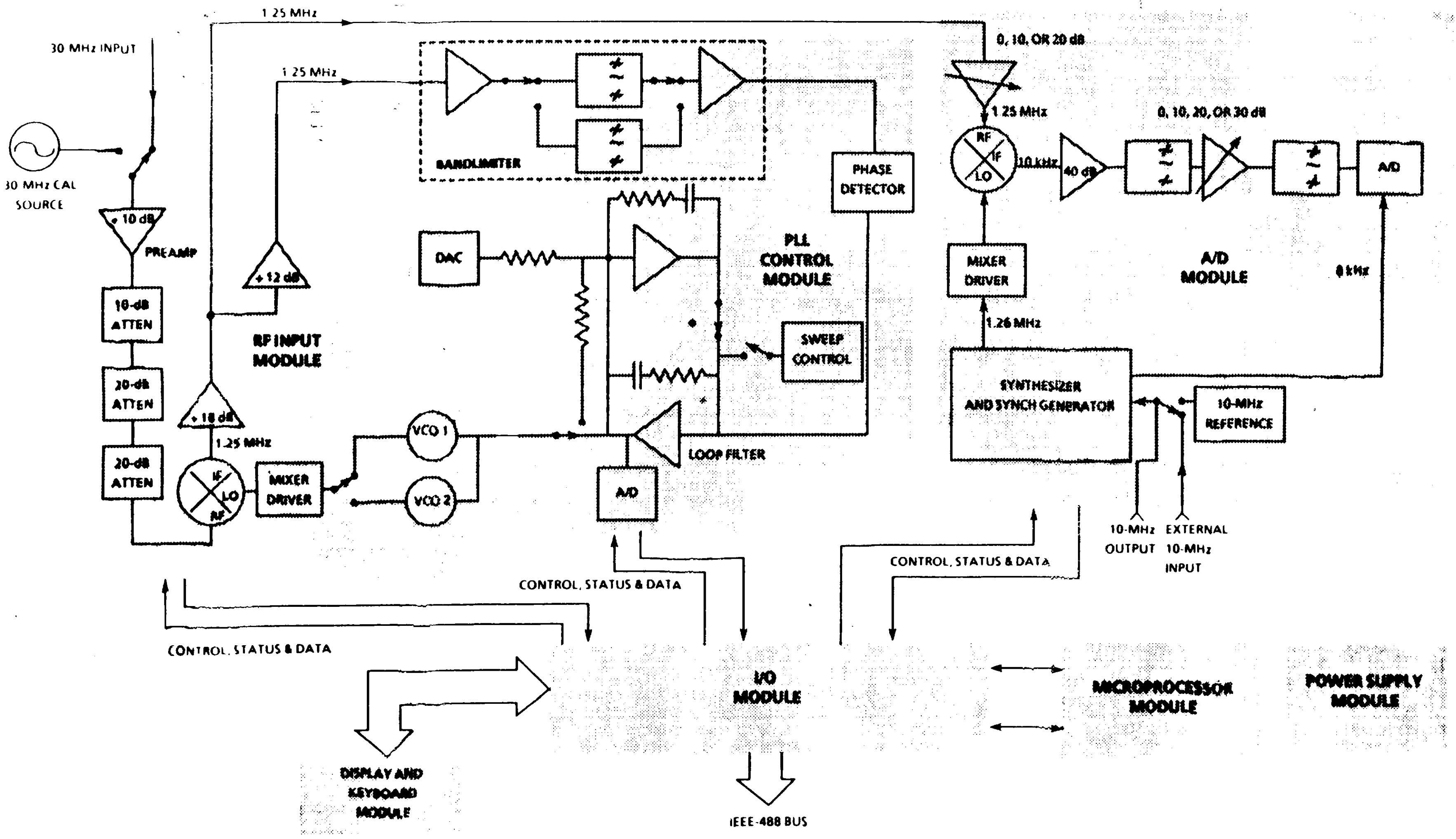

Figure 3. VM-7 Block Diagram

Total Measurement Uncertainties.

An example of an insertion loss measurement and its associated uncertainties is given below:

Mismatch Uncertainty	+/-0.480 dB
Linearity Accuracy	+/-0.040 dB
Reference Drift	+/-0.015 dB
Connector Repeatability	+/-0.010 dB
Worst Case Total	+/-0.545 dB.

This was calculated for an 80 dB, "N" type attenuator at 18 GHz, having maximum SWR of 1.5:1 at each port, and inserted between two Lucas Weinschel Model 44 Laboratory Standard coaxial attenuators. The two Model 44's thus define the test insertion point.

It can be seen that mismatch uncertainties are a large portion of the possible error in the measurement.

Mismatch Uncertainties.

The worst case mismatch uncertainty is calculated by the following:

The worst case uncertainty caused by mismatch is calculated by:

$$20 \log \left[1 \pm |\Gamma_G| \cdot |\Gamma_1| + |\Gamma_2| \cdot |\Gamma_L| + |\Gamma_G| \cdot |\Gamma_L|\right] \text{ dB}$$

or approximately

$$\pm 8.69 \left(|\Gamma_G| \cdot |\Gamma_1| + |\Gamma_2| \cdot |\Gamma_L| + |\Gamma_G| \cdot |\Gamma_L|\right) \text{ dB}$$

where,

Γ_G is the modulus of the source reflection coefficient,
Γ_L is the modulus of the load reflection coefficient,
Γ_1 is the modulus of the input reflection coefficient of the device under test with a 50 Ω termination on its output, and
Γ_2 is the modulus of the output reflection coefficient of the device under test with a 50 Ohm termination on its input.

The modulus of the reflection coefficient can be calculated from the SWR using the following:

$$|\Gamma| = \frac{S-1}{S+1}$$

where S is the SWR (Standing Wave Ratio).

The above holds true for a device having large enough insertion loss (20 dB) to mask input and output SWR effects from one another.

The first two terms in both equations are for the input and output interfaces of the DUT, respectively. The last term in each case is an error in the reference level taken before the insertion of the DUT, and is caused by the measurement being an insertion loss measurement. (See References 4, 5 and 6.)

The SWR figures used to generate the worst case mismatch error in the above section were the specified values. Assuming that their performance is within the specification, their actual SWR is lower. If these lower actual values are known, they can be inserted into the mathematics instead of the specified values.

Different Connector Types.

In the measurement setup shown in Figure 1, two masking attenuators are used to define the insertion point. Most microwave components, e.g., cables and instruments, have poor SWR performance. It is thus good practice to use masking attenuators, whose performance dominates the SWR performance at the insertion point, thereby improving it.

When the user needs to change to an alternative connector type, an adapter is usually placed at the insertion point. However, this is not good practice as the adapter will degrade the SWR performance at the insertion point. Even the combination of lab standard attenuator and precision adapter can change the worst case SWR from 1.25:1 to 1.38:1!

It is thus advisable to use masking attenuators of the same connector type as the device-under-test, with an adapter being used to mate these attenuators into the measurement system. The attenuators thus also mask the effects of the adapters.

Table 1 shows the SWR specifications of a number of the Lucas Weinschel precision attenuators suitable for use as masking attenuators.

TABLE 1. SWR Specifications for Four Lucas Weinschel Attenuators Suitable for Masking

MODEL	CONN TYPE	SWR AT FREQUENCY (GHz)				
		dc-4	4-8	8-12.4	12.4-18	18-26.5
44	N	1.15	1.20	1.20	1.25	-
17	GPC-7	1.10	1.15	115	1.20	-
55	TNC	1.15	1.20	1.25	1.35	-
56	3.5mm *	1.10	1.10	1.15	1.25	1.25
* (SMA Compatible)						

Lucas Weinschel Solution.

The Lucas Weinschel Model VM-7 was designed to replace the Model VM-3, which for many years has been an attenuation standard. It was designed for speed and accuracy, with self adapting averaging to replace the fixed time averaging in all other instruments. The use of the Confidence Factor gives the user an immediate answer, even at very low levels, and at the same time gives him/her a measure of the stability or quality of that answer. The need to wait several minutes to even see if the answer is in the right neighborhood has gone.

The digital detection technique gives the unit unsurpassed linearity accuracy as shown in Table 2.

The phase-locked-loop tracking system allows the receiver to hang onto the signal, even when the generator is unlocked. The narrow band mode, specifically designed for use with synthesized generators gives the VM-7 a potential sensitivity of -130 dBm at 30 MHz. The inbuilt algorithm to deduce and partially correct for errors due to noise in the phase-locked-loop at low levels gives the unit excellent linearity even at the full extent of its range.

Table 2. Measurement Accuracy

Attenuation level (dB)	LW VM-7	LW VM-7 / 8852
10	±0.005	±0.020
20	±0.010	±0.025
30	±0.015	±0.030
40	±0.020	±0.035
50	±0.025	±0.040
60	±0.030	±0.045
70	±0.035	±0.050
80	±0.040	±0.055
90	±0.045	±0.155
100	±0.055	±0.255
110	±0.075	-----
120	±0.155	-----

The VM-7 has a specified dynamic range of 127 dB, which it can traverse in a matter of milliseconds to give an answer. Even when mixers are added to the front end to provide wide frequency coverage, the dynamic range is still a solid 100 dB or greater.

Like any scalar system the Model 8850-02 has the ability to measure SWR using bridges, opens and/or shorts. Figure 4 shows such a setup. The measurement becomes one of measuring attenuation, which is effectively return loss. The system software can then perform the standard conversion to SWR.

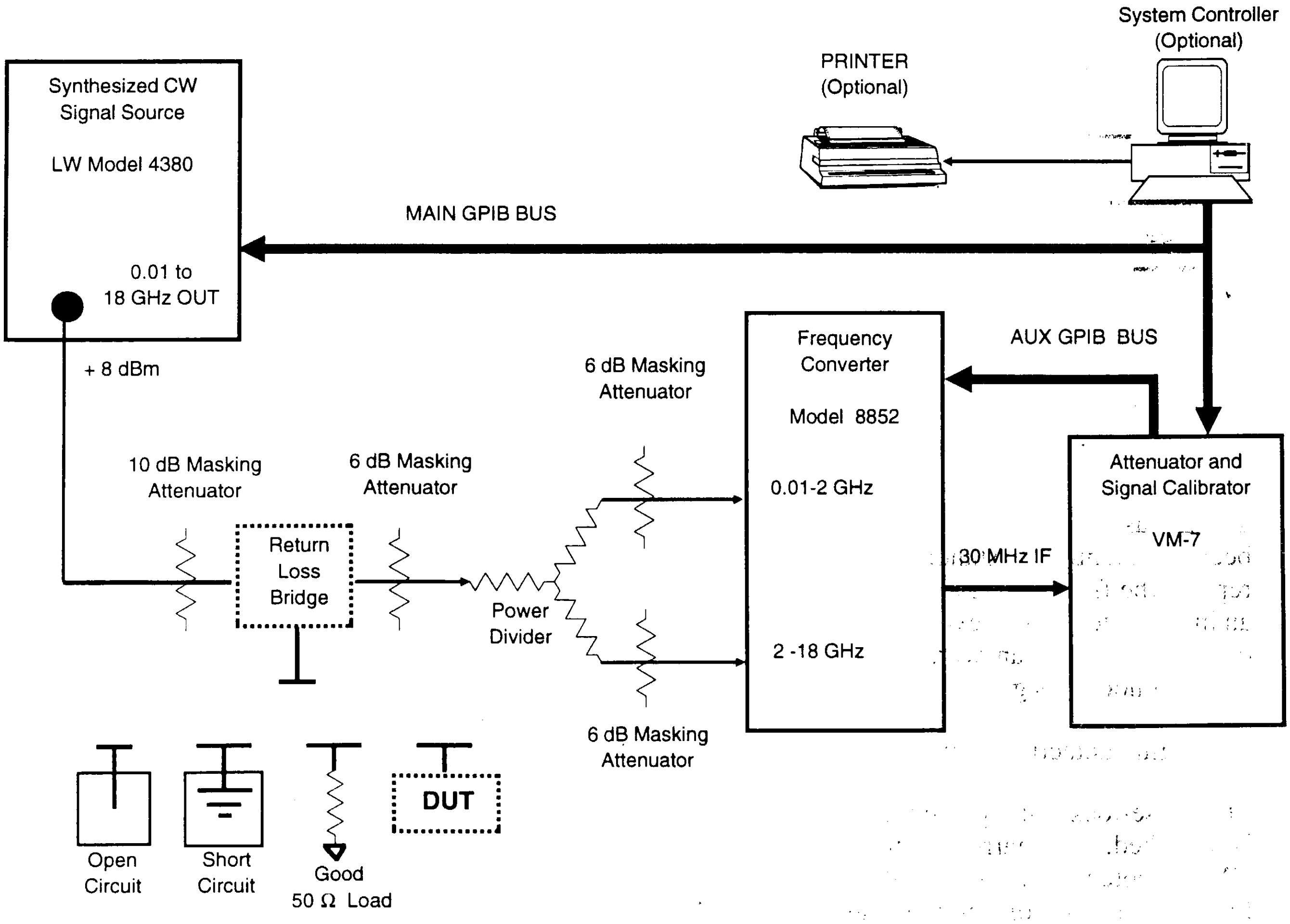

Figure 4. Return Loss Measurement Configuration

Conclusion.

When making attenuation measurements, it is of tremendous importance for maximum accuracy to have the lowest possible SWR performance at the insertion point. The potential measurement errors due to poor SWR at the insertion point far outweigh the performance limitations of modern measurement equipment (Vector Network Analyzers cannot fully compensate for SWR beyond an insertion loss of 30 dB). Given that SWR errors cannot be eliminated, it is essential to utilize the best available masking attenuators to minimize measurement errors, to determine the effects of these errors, and to account for them when presenting the accuracy of an attenuation measurement.

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