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# SWR/Return Loss Measurements Using System IIA

## SWR/Return Loss Defined

Both SWR and Return Loss are a measure of the divergence of a microwave device from a perfect impedance match, for example, 50 Ω. They are mathematically interchangeable and result from scalar measurements, which are required for a number of reasons. For instance, it is necessary to make sure that devices meet their specifications, one of which is SWR. Also, modern measurement practice dictates the calculation of a quantitative accuracy value, which is affected by SWR at the port of a microwave device.

## Scope and Purpose of App Note

This app note describes the use of a TEGAM System IIA Power Sensor Calibration System (Figure 1) for SWR/Return Loss measurements. System IIA is a scalar measurement system whose principal function is power sensor calibration. However, when combined with a return loss bridge, it can be used to characterize the SWR performance of passive devices or sensors. Thus, expanded use of System IIA eliminates the need to purchase separate equipment for SWR measurements.



**FIGURE 1. SYSTEM IIA POWER SENSOR CALIBRATION SYSTEM**

## System IIA Operating Principles

The System IIA functions by providing a precisely known source of power, which is then measured by the sensor under test. The ratio of the measured value of power to the known value is the calibration factor, $K_1$, of the sensor.

This is shown mathematically as follows:

$$K_1 = \frac{P_m}{P_{rf}}$$

where:

$P_m$ is the power indicated by the sensor/power meter, and

$P_{rf}$ is the actual power from the precision source.

The System IIA calibration system itself has to be calibrated against a common standard to provide consistency in measurements. This is termed traceability, and is provided by having a traveling standard, a terminating mount, calibrated by National Institute of Standards and Technology (NIST) or other calibration laboratory. This traveling standard is then used to measure the power emanating from the System IIA source. By this means the source itself is calibrated.

## Calibration and Mismatch Error

Every calibration has associated with it an uncertainty value, which takes into account the inaccuracy and drift of all the instruments and devices used in the calibration. Accuracy is affected by connector repeatability, temperature stability of the thermistor mount standard, etc. A major source of error in any transfer of power from one instrument to another is due to mismatch. This can cause large errors, especially at higher frequencies.

Modern measurement techniques require these uncertainties to be calculated for each calibration point, and the values inserted into a measurement results report. To do this, sources of measurement error must be defined quantitatively. Typically, calibration software is used to calculate uncertainty values using measurement data files, etc.
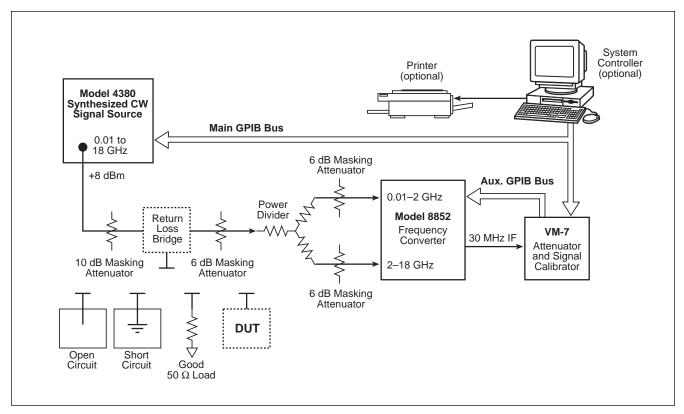
**FIGURE 2. MODEL 8850-02 SWR-MEASUREMENT CONFIGURATION**

The maximum error due to mismatch can be deduced from the SWR values of the two instruments or devices being connected together. The two devices in this case are the sensor being calibrated and the precision source, i.e., a TEGAM Feedthrough Mount. Each of these devices has a specified maximum SWR. Table 1 lists the SWR specifications for a sensor and a TEGAM Feedthrough Mount at various frequencies. The calculated maximum mismatch error induced in a transfer of power from one to the other is shown in the last column.

**TABLE I. SPECIFIED SWR VALUES VERSUS RESULTANT CALCULATED WORST CASE MISMATCH ERROR**

| Frequency Range | Specified Sensor SWR | Specified F1109 SWR | Maximum Mismatch Error |
|---|---|---|---|
| 10–30 MHz | 1.40 | 1.06 | 1.0% |
| 30–50 MHz | 1.18 | 1.06 | 0.5% |
| 50–2000 MHz | 1.10 | 1.06 | 0.3% |
| 2–8 GHz | 1.18 | 1.06 | 0.5% |
| 8–12.4 GHz | 1.18 | 1.10 | 0.8% |
| 12.4–18 GHz | 1.28 | 1.10 | 1.2% |

In general, maximum mismatch error, M, can be calculated from the following equation:

$$M = 1 - \frac{1}{(1 \pm |\Gamma_1| \cdot |\Gamma_2|)^2}$$

where $|\Gamma_1|$ and $|\Gamma_2|$ are the magnitudes of the reflection coefficients of the two impedances involved. $|\Gamma|$ is related to SWR by the following equation:

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

where S is the SWR.

From these equations it can be seen that the lower the reflection coefficient, and hence the SWR, the lower the potential mismatch error during power transfer from one device to the other. Since SWR is a scalar quantity, it can only be used to estimate the possible error in the transfer. If actual SWRs are not known, the devices' specified SWRs can be used in the equation, under the assumption that they meet their specifications. However, if the actual SWR of even one of the devices is known, then a (presumably) reduced value of estimated maximum mismatch error can be calculated.
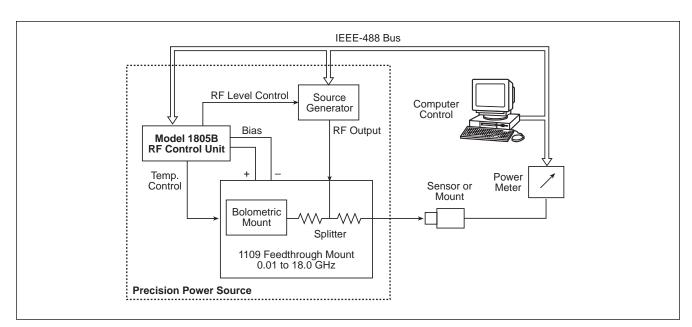
**FIGURE 3. SYSTEM IIA-SENSOR CALIBRATION CONFIGURATION**

Users of TEGAM System IIA power standards have full "S" parameter data in the form of a published report that comes with the system. The unknown should only be the SWR of the sensor under test.

## Basic SWR Measurement Techniques

The TEGAM Model 8850-02 shown in Figure 2 is one type of scalar system useful for measuring SWR. The open circuit, short circuit and matched impedance are connected to the test port (lower leg) of the SWR/Return Loss Bridge for calibration purposes, before measuring the device under test (DUT).

System IIA can be similarly employed. The measurement configuration is similar to that used for a sensor calibration. This is shown in Figure 3 for a terminating type sensor. Calculation of the sensor calibration factor, $K_1$, was described earlier in the section on System IIA Operating Principles.

Figure 4, shows the same setup, but with an SWR/Return Loss Bridge connected between the precision source output and the sensor being "calibrated." In this setup, two different "calibrations" are performed. First a short or open is connected to the test port of the SWR bridge. This has the effect of reflecting all of the power from the precision source through to the sensor. The DUT is then connected to the test port of the SWR bridge, and a second calibration of the sensor performed. In this case only a portion of the power is reflected from the

device under test through to the sensor. The ratio of the powers is the return loss of the device under test.

These results can be expressed mathematically as follows:

**Case 1.** Total power is reflected from the short/open.

$$K_{1r} = \frac{P_{mr}}{P_{rf}}$$

where $P_{rf}$ is the power emanating from the precision source, $P_{mr}$ is the power registered by the power meter attached to the terminating sensor, and $K_{1r}$ is the calibration factor of the sensor.

**Case 2.** The DUT is attached to the bridge test port.

$$K_{1t} = \frac{P_{mt}}{P_{rf}}$$

where $P_{mt}$ is the power as now registered by the power meter attached to the terminating sensor, and $K_{1t}$ is the equivalent calibration factor of the sensor. (The calibration factors are denoted by $K_1$ as this is the normal identification of the calibration factor of a terminating sensor.)

In this measurement sequence the so-called calibration factors have little relevance to the performance of the terminating sensor. If calibration measurements are being performed by hand, all that is needed is the power meter readings. However, the System IIA software gives results in terms of calibration factors. To cover a large number of measurement frequencies, it is more expedient to use the software to generate calibration factors.
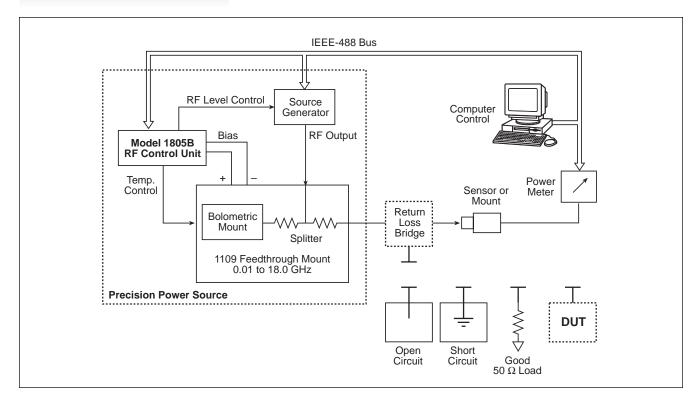
**FIGURE 4. SYSTEM IIA-SWR-MEASUREMENT CONFIGURATION**

It can be seen from the equations that a calibration factor is proportional to measured power, so the two can be used interchangeably. Therefore, the return loss of the DUT is the ratio of the so-called calibration factors, i.e.,

$$\frac{K_{1r}}{K_{1t}} \text{ in power ratio terms, or}$$

$$10 \log \frac{K_{1r}}{K_{1t}} \text{ in dB terms.}$$

System IIA Software Limitations — The System IIA software has been designed for calibrating sensors. This technique for measuring SWR makes use of that design. However, the software cannot automatically calculate the calibration factor ratios, or perform other math functions associated with SWR measurements. At present, this is a manual task.

However, the software can perform the averaging of the "Open" and "Short" reference measurements by calling up two runs, with a pause between the two, as required for testing connector repeatability. After the first run with an "Open" attached to the Return Loss Bridge, the software will wait while the "Short" is attached. The final set of results will be the average of the two measurements (Reference 3).

## Accuracy and Resolution Analysis

Table 2 shows actual data taken with the setup in Figure 4. The three columns show the calibration factor with a short, an open and unterminated 10 dB attenuator, resulting in a total return loss of about 20 dB. The Open and Short columns of Table 2 show that unlike normal calibration conditions, where a calibration factor close to 1.000 is expected, the SWR bridge has a starting point around 0.05.

**TABLE 2. ACTUAL SWR MEASUREMENTS @ 10 mW**

| Frequency | Short | Open | 10 dB Att. | Open/Short Average | Calc. SWR |
|---|---|---|---|---|---|
| 200 MHz | 0.0551 | 0.0498 | 0.0010 | 0.0525 | 1.32 |
| 400 MHz | 0.0538 | 0.0489 | 0.0009 | 0.0514 | 1.30 |
| 600 MHz | 0.0477 | 0.0508 | 0.0008 | 0.0493 | 1.29 |
| 800 MHz | 0.0471 | 0.0506 | 0.0007 | 0.0489 | 1.27 |
| 1000 MHz | 0.0448 | 0.0477 | 0.0005 | 0.0463 | 1.23 |
| 1200 MHz | 0.0427 | 0.0478 | 0.0005 | 0.0453 | 1.23 |

Bridges typically have around 6.5 dB of insertion loss on each transition, giving 13 dB total. This directly translates into a calibration factor around 1/20th of maximum, i.e., 0.05. Starting at 0.05 means that the practical return loss range is limited to about 20 dB, as shown by the unterminated 10 dB attenuator. In
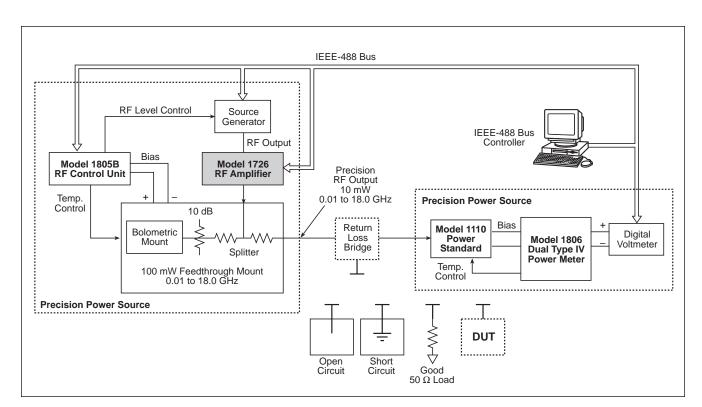
**FIGURE 5. 100 mW SWR MEASUREMENT CONFIGURATION**

SWR terms this is equivalent to 1.22:1. There are two factors that govern this range limitation: power range and measurement resolution.

Power Range — The most typical level at which to perform sensor calibrations with System IIA is 1 mW. This means that a calibration factor of 1.0000 at the power meter/sensor being calibrated represents 1mW. With the bridge in place, as in Figure 4, the working power at the terminating power sensor now starts at a reference level of 0.05 mW or –13 dBm. A DUT with a return loss of 20 dB is then equivalent to a measurement level of –33 dBm.

If the terminating power meter/sensor is a thermistor power standard, such as a TEGAM M1110 attached to a Model 1806 Dual Type IV Power Meter, substituted power is measured with a digital voltmeter (DVM) At a power level of –33 dBm, i.e., 0.5 μW, measurement results may not have a high level of accuracy, depending on DVM specifications.

Assuming that the inaccuracies of the Power Standard and Model 1806 are systematic, and are constant for all the power levels, the major source of inaccuracy is from the DVM (Reference 2). The catalog specification for a typical DVM measurement configuration is ±0.03% + 2 μW. This potential

error completely swamps measurements of the power levels mentioned above.

One way to improve matters is to raise the "calibration" power level. For example, if 10 mW were available, a 20 dB return loss would give measurements around –23 dBm, i.e., 5 μW. This is a tenfold increase in working levels. However, the calibration factors still start at approximately 0.05 as before.

Measurement Resolution — A printout from the System IIA software displays results with a maximum resolution of four decimal places. Therefore, starting with a reference of 0.0500, the 20 dB return loss gives a reading of approximately 0.0005, as shown for the unterminated 10 dB attenuator in Table 2. There is, however, a technique that can improve on this resolution limitation.

Figure 5 shows an arrangement whereby a terminating power standard has an attenuator between it and the splitter. This is the basis of the "H" series standards described in Reference 1. As described in the reference, the operating power of the standard itself is 10 dB less than the power emanating from the output port of the splitter. However, the "H" series mounts have calibration factors on the order of 0.1, so that with the bridge in place the starting point of the return loss exercise is still 0.05 as before.
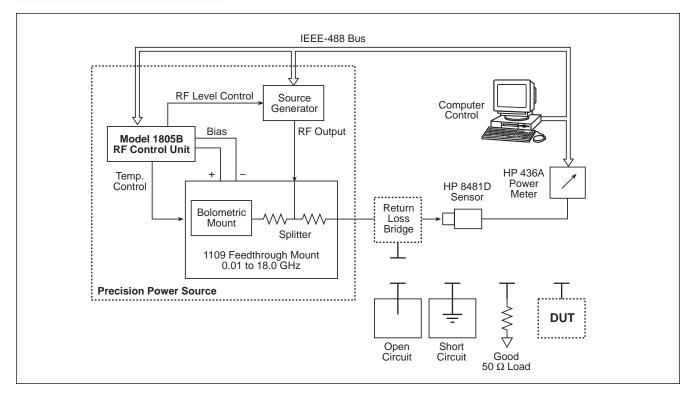
**FIGURE 6. SWR-MEASUREMENTS USING HP 8481D**

If, however, a series of calibration factors around 1.0 was assumed for the "H" series mount, the starting or reference point for the fully reflected power situation would now be approximately 0.5, a tenfold increase. This is because the output from the Precision Source is 10 dB higher than the $P_{rf}$ calculations would suggest, reducing the effect of the bridge to approximately 3 dB. A 20 dB return loss would now be equivalent to a measurement calibration factor of approximately 0.0050, and a 30 dB return loss would give a figure of approximately 0.0005. A return loss of 30 dB is equivalent to an SWR of 1.065, which now becomes the rough limit on the range.

This approach also has the advantage that the operating power is higher, as described earlier. In fact, operating power is now limited only by the available amplifier, which should provide at least 100 mW.

Since the power standard calibration factors drop out of the mathematics for the process, it is valid to use the calibration factors for any feedthrough mount. Thus the calibration factors for an F1109 could be used where the actual mount is an F1109H.

Using the setup shown in Figure 5, with an 1806 and standard DVM, and with the precision source output at 10 mW, the following is a typical uncertainty calculation:

Precision Output = 10 mW,
Loss through bridge = 13 dB,
Reference level from bridge = 0.5 mW, i.e. 500 µW,
Output for a 20 dB return loss = 5 µW
Accuracy of Model 1806 with typical DVM = ±0.03% ± 2 µW.
Resulting uncertainty at 500 µW = ±0.43%, and at 5 µW = ±40.03%.

Ignoring everything except the 40%, which is approximately equivalent to ±1.5 dB, this translates to an SWR reading between 1.18:1 and 1.27:1, or an actual computed value of 1.22:1. The same exercise for a 30 dB return loss yields an SWR range from 1.00:1 to 1.15:1, or an actual computed value of 1.065:1.

If the standard 6.5 digit DVM is replaced by, say, an eight digit DVM, the equivalent results for a 20 and 30 dB actual return loss are approximately 1.221:1 to 1.223:1 and 1.062:1 to 1.069:1, or actual computed values of 1.222:1 and 1.065:1 respectively.

The previous analysis totally neglects any effects due to the return loss bridge itself; i.e., the bridge is assumed to be perfect. In fact, a typical bridge might have a guaranteed directivity of only 35 dB. The directivity is a measure of the suppression of the incident signal at the output of the bridge. A 35 dB directivity is equivalent to an SWR of 1.036:1. This is the limit of the bridge's capability. If the DUT has a return loss of 30 dB, the directivity would possibly yield an answer as high as 1.075:1 instead of 1.065:1. Even with a bridge directivity of 40 dB the answer for an actual SWR of 1.065:1 could be 1.069:1.

With a high resolution DVM and higher power levels, bridge performance becomes the ultimate limitation on measurement accuracy.

## Alternative Solution

An alternative solution for precision SWR measurements requires a commercially available power meter and sensor, such as those made by Boonton, Hewlett Packard, Wavetek, et al. Over a 30 dB range the power meter/sensor must have adequate linearity and accuracy, and should be able to start measurements at –30 dBm. Figure 6 illustrates a possible setup using the HP436A power meter and HP8481D, a high sensitivity diode sensor.

A 20 dB attenuator is inserted between the bridge and the sensor. Normally these sensors are calibrated with a 1 mW precision output and 30 dB calibrated attenuator between the precision output and the sensor. Calibration can go ahead exactly as if this were the case. In operating the software, a data file for a calibrated 30 dB attenuator needs to be called up. As before, its use is merely to get the reference readings on scale.

The measurement range at the sensor is now approximately from –33 dBm to –63 dBm, which is well within its linear span. If needed, the attenuator can be reduced somewhat to raise the level, but the sensor should not go above –20 dBm.

## Conclusion

Clearly, the TEGAM System IIA can be used quite successfully to measure SWR. The system must be configured in a specific fashion, but can then measure to the limits of the available return loss bridges. With a Return Loss Bridge and System IIA, the user does not need access to another system. In addition, although the calculations have to be done manually at this time, the answers will automatically pertain to the correct frequencies, i.e., the NIST traceable frequencies needed by System IIA for uncertainty calculations.

To further simplify SWR measurements with the System IIA or Model 8850-02, TEGAM offers an SWR Measurements Kit (P/N 187-4003). This kit includes all the necessary components to perform measurements on devices containing Type N, GPC-7, and SMA connector types over the 0.01 to 18 GHz frequency range.

## References

1. "100 mW Feedthrough Power Standard," Application Note #212 from TEGAM.
2. "System IIA, Automatic Power Meter Calibration System," Manual IM-198, from TEGAM, section 3–10
3. "System IIA Software Operations," Manual IM-235, from TEGAM, section 2–3.5.1.

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