Application Note

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Assuring Accuracy in Aeroflex PXI RF Test Systems and Modules

This document explains how a combination of user measurements, corrections and adjustments are used to ensure accurate performance of Aeroflex PXI RF modules when used alone or within systems. The practical effects of mismatch errors due to the VSWR of the device under test are assessed and means of minimising the errors are outlined. These procedures and methods including the use of test system calibration to include the effects of external fixtures and pads are similar to those that apply to conventional GPIB instruments and rely on repeatability of performance, which for Aeroflex PXI RF modules is excellent.

Introduction

The Aeroflex 3000 Series modules undergo rigorous testing and calibration prior to leaving the factory. The calibration is performed using test equipment traceable to national standards via our UKAS accredited calibration laboratory to ensure specified performance is achieved with due allowance for measurement uncertainty, drift and the influence of temperature within the specified range of operation. This application note describes how the user calibration routines incorporated into the modules can be used to maintain and optimize performance during routine use. Additionally the application note looks at some of the calibration methods, which may be employed at a system level to ensure the best overall accuracy and repeatability is achieved. This application note applies in general terms to the Aeroflex family of PXI modules although specific details are provided for the 3010, 3020, 3030 and 3060 products.

User Selectable Calibrations

To supplement the factory calibration, the following user calibrations can be invoked to give further improvement in performance for the specific conditions of operation.

302X Series

The following also apply to the 3020A and 3025 except where stated.

IQ User Calibration

Factory calibration of the IQ modulator is used to calculate and store IQ modulator errors which are used in the 3020 to correct the I and Q data to optimize modulation accuracy. IQ user calibration is also available to give further improvement in performance for the specific conditions of operation and ensure that guaranteed specifications of carrier leak and image suppression are met. The module calibrates at the current frequency, or at a range of frequencies, and stores the results so that if you change frequency and return again, the calibration still applies. During the user calibration process the 3020 output is disabled. For optimum performance the user calibration should be done following a period of warm up and periodically if the operating temperature is expected to change by more than 5^{o}C.

The following types of user IQ calibration are available:

Cal Current Frequency calibrates the IQ modulator at the current frequency. Calibration is valid for frequencies within ±1 MHz of the current frequency. This user calibration gives improved performance at a spot frequency and is quicker than calibrating all bands. Multiple spot frequencies can be user calibrated and will be used in place of any other calibration data.

Cal All Bands calibrates the IQ modulator over the entire frequency range of the module and returns the instrument to its current state. The bands calibrated are given in table 1.

3020	3020A	3025
		76 MHz - 93.75 MHz
		93.75 MHz - 125 MHz
		125 MHz - 187.5 MHz
		187.5 MHz - 250 MHz
250 MHz - 375 MHz	250 MHz - 375 MHz	250 MHz - 375 MHz
375 MHz - 500 MHz	375 MHz - 500 MHz	375 MHz -500 MHz
500 MHz - 750 MHz	500 MHz - 750 MHz	500 MHz-750 MHz
750 MHz - 1000 MHz	750 MHz - 1000 MHz	750 MHz-1000 MHz
1000 MHz - 1500 MHz	1000 MHz - 1500 MHz	1000 MHz - 1500 MHz
1500 MHz - 2500 MHz	1500 MHz - 2700 MHz	1500 MHz - 2000 MHz
		2000 MHz - 3000 MHz
		3000 MHz - 4000 MHz
		4000 MHz - 4900 MHz
		4900 MHz - 6000 MHz

Table 1 302X IQ calibration bands

Cal Selected Band calibrates the IQ modulator over individual bands and returns the Instrument to its current state. This user calibration is quicker than calibrating all bands. Multiple bands can be calibrated.

A mixture of single point frequencies and selected bands can be calibrated to match user requirements. At any specific frequency the IQ calibration data used will be single frequency if calibrated, followed by user band or all bands calibration data, if calibrated, followed by factory calibration data.

Store Single Point/Banded to File lets you save calibrations using the standard Windows browser. Calibrations are saved as .ciq files.

Restore Single Point/Banded from File lets you restore .ciq calibrations using the standard Windows browser.

Detector Zero User Calibration

Detector Zero calibration is run in the factory and sets the levelling detector to zero to ensure that the module meets the level accuracy specified in the data sheet.

Detector Zero user calibration only needs to be run once e.g. on change of PXI rack, which may influence power supply voltages. Detector Zero is not required to cope with temperature changes since that is taken care of by temperature correction which happens automatically and transparently every 5 minutes. The temperature correction process does not affect the 3020 time to respond because the 3020 carries on using the old data until they have been updated.

IQ Bandwidth Correction

IQ bandwidth correction is normally off but can be set to manual using ***setIqBwCorrectionMode***. In the normal off mode, the module achieves its specified IQ bandwidth. Manual mode allows for correction to improve roll off beyond the specified performance. In manual mode the FPGA applies a filter to the I and Q data to compensate for the roll off (3 dB at 14 MHz) in the analog path as determined from a type tests. The correction results in a nominally flat response across 14 MHz.

In manual mode the FPGA also applies a flat gain correction selectable in the range 0 to -3 dB across the whole bandwidth as set by ***Function af3020_setIqBwCorrectionGain***.

To safely use the bandwidth correction it is recommended that the gain correction figure is determined by the signal bandwidth according to table 2.

I or Q bandwidth (MHz) (half occupied bandwidth)	IQ BW Correction gain value (dB)
14	-3.000
13	-2.500
12	-2.000
11	-1.950
10	-1.850
9	-1.600
8	-1.000
7	-0.875
6	-0.750
5	-0.625
4	-0.500
3	-0.375
2	-0.250
1	-0.125
0	0

Table 2 Recommended 3020 IQ BW correction gain values

The maximum available power from the module is reduced by the correction figure selected. The correction figure should be determined by the user from the bandwidth of the signal to prevent clipping of the signal. E.g. if a full-scale signal at 14 MHz is compensated for it will need a gain reduction of 3 dB to prevent clipping. A narrow band signal will need no gain reduction.

IQ bandwidth correction is not provided with the 3020A or 3025 in view of their much flatter IQ bandwidth.

303X Series

The following also apply to the 3030A and 3035.

Level Correction

Function af3030_getLevelCorrModule

This function passes back the level correction figure in dB. This correction figure is used in the Aeroflex FFT Spectrum Analyzer Suite supplied with the 3030 to calculate the signal power. This figure is only valid for the current hardware setting. (Equivalent level corrections can be applied for the RF down converter when used alone and for the IF input to the digitizer when used alone). It is recommended that the level correction figure is obtained every 5 minutes or whenever hardware settings are changed or the temperature correction has taken place. Returning the level correction figure takes about 1 ms.

The correction figure is also used in other Aeroflex Measurement Applications. If the user wishes to write custom measurement applications then the level correction figure can be used to calculate the absolute power associated with a captured IQ data pair the user as follows:

Power (in dBm) = 10log(I^2 + Q^2)+ level correction figure

To calculate the absolute power associated with a series of IF data, the RMS value of that series has to be calculated. Once this has been computed, power can be computed as follows:

Power (in dBm) = 10log(RMS value of IF data series/maxIFvalue) + level correction figure + 3 dB

Temperature Correction

Temperature correction in the 3030 takes place automatically and monitors the temperature of the module at regular intervals of 5 minutes then adjusts the correction figure for the current temperature. Reading the temperature and correction takes approximately 1 second. Once a data capture has started auto temperature measurement is held off. Hence the worst case effect is to delay re-arming the 3030 for capture when auto temperature occurs. If auto temperature optimization is likely to interfere with a time-critical measurement, the user can turn this off using *Set Temperature Optimization*.

Once the module has warmed up it should be unnecessary to correct for temperature more often than every hour which can be done in off mode using *Optimize Temperature Correction* which forces an immediate update. In auto mode *Optimize Temperature Correction* also forces an immediate update after which the timer starts a new interval.

Flatness Correction

The IF anti-alias filter flatness and RF slope are corrected automatically in real-time in the 3030 using factory calibration data. This automatic correction ensures that errors in level are typically less than 0.01 dB per MHz of offset from the IF centre frequency i.e. less than 0.1 dB for the maximum of 10 MHz from centre imposed by the 20 MHz IF bandwidth of the 3030. The RF slope correction is based on factory calibration at 2 GHz. Over the RF frequency range of 850 MHz -2.4 GHz additional errors due to changes in RF slope from the 2 GHz value are less than 0.002 dB/MHz or 0.02 dB for 10 MHz offset.

If the user wishes to provide additional correction for the change in slope of RF response from its 2 GHz value Auto Flatness Mode can be used in addition to the real-time correction described above. Default is that this additional auto flatness correction for the RF response is 'off'. The change in RF level due to RF response may not be significant for narrow-bandwidth measurements (less than 0.002 dB/MHz), which should be taken into account as auto flatness mode compensation may slow measurement time. The auto flatness correction with the latest drivers adds about 1 ms to the typically 2 ms to change frequency. Alternatively where speed and optimum accuracy are required, list mode in the 3030A pre-calculates and stores flatness correction to maintain frequency switching times of typically 250 us.

306X Series

Within test system software, the 306X combiner loss data can be re-called and used to add to the RF input power setting on the 3030, correct level on measurements performed by the 3030 and to add to the signal level called for on the 3020 to give accurate power measurement and generation at the sum port of the 3060X.

For the 3060, ***Function af3060_getCombinerLoss*** returns the losses, in dB at the specified frequency, for the following combiner paths.

Summing paths (A to Sum, B to Sum, and C to Sum)

Calibration paths (A to B, C to B)

The accuracy of the values returned is +/-0.2 dB plus temperature influence of 0.006 dB/deg.C for the summing paths and 0.002 dB/^{0}C for the calibration paths. Allowing +/-10 ^{0}C of influence for 23 ^{0}C +/- 5^{0}C for both factory test and user environment leads to a net accuracy of

+/-0.26 dB for the sum paths

+/-0.22 dB for the calibration paths.

Similarly for the 3065, calibration data are provided for its sum paths and calibration paths and the data are additionally temperature compensated using on board temperature sensing. For the 3065 the accuracy of the values returned for 23 ^{0}C +/-5 ^{0}C is as follows:

+/- 0.2 dB below 2.7 GHz

+/- 0.3 dB 2.7 GHz -5 GHz

+/- 0.4 dB 5 GHz -6 GHz

Mismatch Effects on Measurement Uncertainty

Uncertainty due to mismatch can be a significant contribution to measurement error when the VSWR or return loss of the UUT (unit under test) is taken into account. Accuracy quoted for a piece of test equipment includes measurement uncertainty which includes mismatch effects for the factory test equipment used to verify the performance. In use, overall accuracy will be degraded by mismatch uncertainty when the VSWR of the UUT is worse than the VSWR of a power meter used to calibrate and verify the performance of the test equipment. The examples given in Appendix 1 quantify typical contributions of mismatch to measurement uncertainty and show how a good test equipment VSWR contributes to accuracy. The same effect will occur with any test equipment and shows the importance of specifying a piece of test equipment with a low VSWR which for the Aeroflex PXI modules is better than or comparable with the best GPIB instruments.

Using a pad between the source and the UUT can reduce uncertainty due to mismatch at the expense of lowering power available at the UUT. A further advantage of using a pad is an increase in reverse power protection. The pad attenuates the reflected signals by twice the pad attenuation and masks the poor VSWR of the UUT. Pads can be obtained with a good VSWR of typically 1.1. Examples of the improvement in mismatch uncertainty are given in Appendix 1.

Improving System Accuracy

Within a test system, as noted earlier, the 3060 loss data can be recalled and used for level correction. The 3060 sum port has an excellent VSWR, which is comparable with the best radio test sets leading to low mismatch uncertainty. As with conventional instruments, improved system accuracy can be obtained by the addition of a pad between the 3060 sum port and the UUT to reduce mismatch uncertainty due to the VSWR of the UUT. This pad is best placed as close as possible to the UUT to avoid reflections in the RF cables connecting to the UUT. The reverse power handling of the 3060 is 27 dBm continuous so addition of a 6 dB pad will also increase reverse power protection to 33 dBm typical of maximum power output for some digital cellular mobile phones. As with conventional instruments, system calibration is also beneficial because the uncertainty in a single measurement for a system will be less that the sum of the uncertainties for individual components. The system calibration is more effective if carried out at the specific frequencies of use.

Test System Calibration

The accuracy of most parameters is underwritten by the calibration of the individual instrument modules. The only parameters which are affected by the losses in the test system are level accuracy and maximum and minimum power. As noted above, in common with conventional test systems, the test system is best calibrated as a whole for level accuracy. To maintain accuracy, system level calibration should be repeated after module replacement or after instrument replacement if conventional instruments are being used. If calibration is being performed at the interface to the UUT then calibration could beneficially be performed more often dependant upon wear on the interface to the UUT. The system calibration supplements the standard calibration procedure for individual PXI modules by providing a set of level correction data for RF inputs and RF outputs as appropriate to each port. The only equipment required for system calibration given in the examples in the next section is a power meter and calibrated power splitter.

Examples of System Calibration

Calibration of Signal Generator Paths

In this example the signal generator is switched to the 3060 sum port. A 6 dB pad is included to give improved VSWR at the interface to the UUT. The output power is measured using an external power sensor connected directly to the UUT interface as shown in figure 1. The signal generator should be set to deliver a power of -3 dBm at its output so that conditions correspond with those used for the factory calibration of the RF detector. Accuracy at other power levels then relies on the factory calibration of the 3020 module. Further improvement may be possible by system calibration at the specific power settings to be used in the test system. Correction data are calculated versus frequency and stored. Within the test system the correction data would be used to correct the level requested for the signal generator. The corrected performance can be verified similarly using an external power meter.

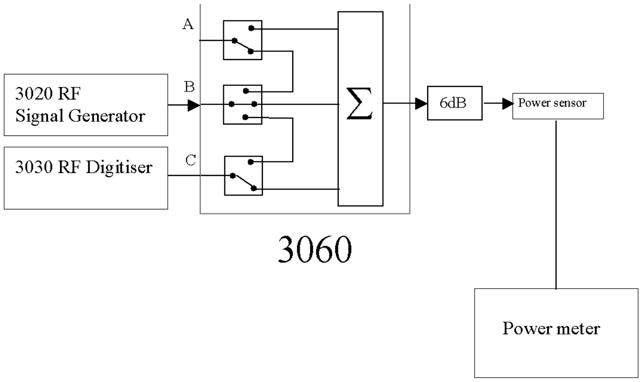

Figure 1 Calibration of Signal Generator Paths

Calibration of Signal Analyzer Paths

In the example in Figure 2 the RF digitizer input is routed to the sum port of the 3060. The signal generator is routed to port A of 3060 to generate a test signal which is fed to the sum port via an external calibrated splitter with a power sensor and power meter to measure the power input. The 3030 should be set to the same attenuator settings of 0 dB RF attenuation and 15 dB IF attenuation as used for the factory calibration. Accuracy at other attenuator settings then relies on the factory calibration of the 3030 module although further improvement may be possible by system calibration at the specific settings to be used in the test system. Correction data are calculated and stored versus frequency. Within the test system the correction data would be applied to set the 3030 target power and to correct the level measured. The corrected performance can be verified similarly using an external calibrated splitter and power meter.

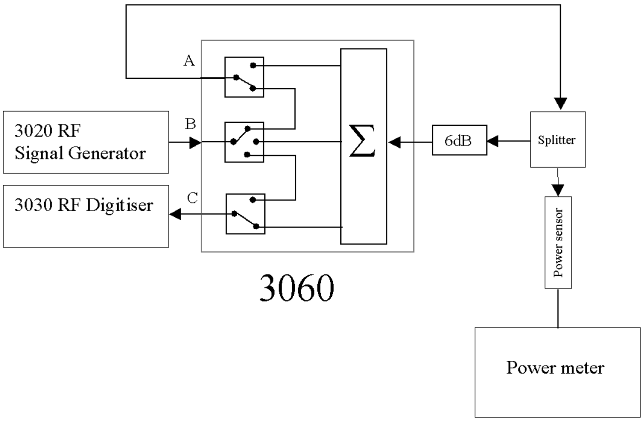

Figure 2 Calibration of Signal Analyzer paths

Conclusions

The performance of Aeroflex PXI modules is optimized by factory calibrations, which are used to correct or adjust resultant performance. This is backed up by factory measurements, which verify that the specified resultant performance has been achieved. Further improvements are available to the user through the use of user calibration functions. Level accuracy has been shown to depend on mismatch errors introduced by the VSWR of the UUT. The size of this mismatch error is minimized by the excellent VSWR performances of the 3020 and 3030, which are better than or comparable with the best GPIB instruments. For duplex connection the 3060 provides an output VSWR comparable with the best radio test sets. As with conventional GPIB instruments, further improvements can be achieved by adding a pad between the test system and the UUT to reduce mismatch uncertainty and by calibration to the test port including this pad and any test fixture. Under these circumstances the excellent signal to noise performance and repeatability of better than +/-0.05 dB for Aeroflex PXI modules is critical.

Appendix 1
Mismatch Uncertainty Examples

When a loss-less cable connects a RF source to a load, the VSWR or return loss of each device reflects incident signals and creates a standing wave in the cable. The standing wave results in the RF power transferred to the load being dependent on the phase of the reflections, the length of the cable and the RF frequency. Hence there is a measurement uncertainty due to mismatch.

Measurement uncertainty due to mismatch =20Log$_{10}$ (1± $\rho_s\rho_l$) dB

Where:

ρ_s = reflection coefficient for the source

ρ_l= reflection coefficient for the load

Return loss = -20Log$_{10}$(reflection coefficient)

And

VSWR source = (1+ ρ_s)/(1- ρ_s)

VSWR load = (1+ ρ_l)/(1- ρ_l)

Table 3 below shows uncertainty due to mismatch for the 3020 source VSWR of 1.3 and a range of loads.

Source VSWR (dB)	Load VSWR	Source return loss (dB)	Load return loss (dB)	Source reflection coefficient	Load reflection coefficient	+/-uncertainty due to mismatch (dB)
1.30	1.07	17.69	30	0.130	0.032	0.036 -0.036
1.30	1.07	17.69	29	0.130	0.035	0.040 -0.040
1.30	1.08	17.69	28	0.130	0.040	0.045 -0.045
1.30	1.09	17.69	27	0.130	0.045	0.050 -0.051
1.30	1.11	17.69	26	0.130	0.050	0.057 -0.057
1.30	1.12	17.69	25	0.130	0.056	0.063 -0.064
1.30	1.13	17.69	24	0.130	0.063	0.071 -0.072
1.30	1.15	17.69	23	0.130	0.071	0.080 -0.081
1.30	1.17	17.69	22	0.130	0.079	0.090 -0.090
1.30	1.20	17.69	21	0.130	0.089	0.100 -0.102
1.30	1.22	17.69	20	0.130	0.100	0.113 -0.114
1.30	1.25	17.69	19	0.130	0.112	0.126 -0.128
1.30	1.29	17.69	18	0.130	0.126	0.141 -0.144
1.30	1.33	17.69	17	0.130	0.141	0.159 -0.162
1.30	1.38	17.69	16	0.130	0.158	0.178 -0.181
1.30	1.43	17.69	15	0.130	0.178	0.199 -0.204
1.30	1.50	17.69	14	0.130	0.200	0.223 -0.229
1.30	1.58	17.69	13	0.130	0.224	0.250 -0.257
1.30	1.67	17.69	12	0.130	0.251	0.280 -0.289
1.30	1.78	17.69	11	0.130	0.282	0.314 -0.325
1.30	1.92	17.69	10	0.130	0.316	0.351 -0.366
1.30	2.10	17.69	9	0.130	0.355	0.393 -0.412
1.30	2.32	17.69	8	0.130	0.398	0.440 -0.463
1.30	2.61	17.69	7	0.130	0.447	0.492 -0.521
1.30	3.01	17.69	6	0.130	0.501	0.550 -0.587

Table 3 Effect of mismatch on measurement uncertainty

If the performance of the 3020 is verified with a power meter having a typical VSWR in the range of 1.15 to 1.2 and the 3020 has a VSWR of 1.3 it can be seen from table 3 above that the contribution of mismatch error to uncertainty is approximately 0.1 dB. This is quite reasonable in the overall context of the overall signal generator accuracy of 0.6 dB. The major factors contributing to quoted overall instrument accuracy are:

a) Variation in performance with settings unit to unit and any relevant drift

b) The influence of temperature and other environmental factors

c) Measurement uncertainty of the factory performance verification system which includes mismatch errors for the factory test equipment

If the 3020 is then used with a UUT having a typical VSWR of 1.92 or return loss of 10 dB it can be seen from table 2 above that the uncertainty due to mismatch is approximately +/-0.35 dB. This mismatch error is assumed independent of the 3020 uncertainty so it is added by r.s.s. (root sum of squares) to the 0.5 dB uncertainty (excluding the temperature influence of 0.1 dB, which is systematic). As a result overall accuracy worsens by 0.11 dB relative to the specified 0.6 dB accuracy for the 3020 resulting in an overall accuracy of 0.71 dB. The same effect will occur with any test equipment and shows the importance of specifying a piece of test equipment with a low VSWR which is excellent for the Aeroflex PXI modules and better than or comparable with the best GPIB instruments.

Figure 3 and Table 4 below show the uncertainty due to mismatch for the 3020 source VSWR of 1.3 for a 3060 combiner with a VSWR of 1.22, and for comparison the effect of a poorer test equipment VSWR of 1.5 and 1.7. The importance of a good test equipment VSWR can be seen.

Using a pad between the source and the UUT can reduce uncertainty due to mismatch at the expense of lowering power available at the UUT. The pad also has the benefit of increasing the reverse power handling of the test equipment. The pad attenuates the reflected signals by twice the pad attenuation and masks the poor VSWR of the UUT. Mismatch uncertainty due to the pad must also be included but typically pads can be obtained with a good VSWR of 1.1. Examples of the mismatch uncertainty for a typical pad VSWR are also shown in Figure 3 and Table 4. The effect on the 3020 mismatch uncertainty in a test system with a 6 dB pad is illustrated in Table 5 which shows an improvement from 0.35 dB to 0.14 dB.

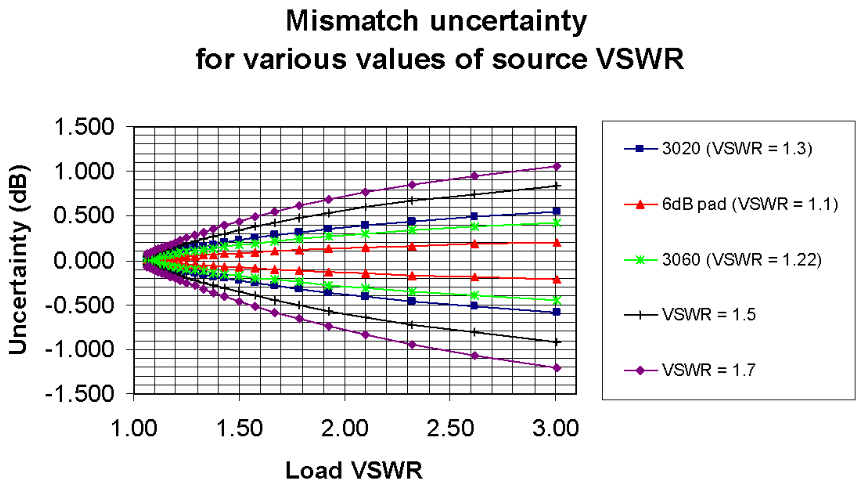

Figure 3 Examples of the effect of test equipment VSWR on mismatch uncertainty

Source VSWR	Load (UUT) VSWR	Source return loss (dB)	Load return loss (dB)	Source reflection coefficient	Load reflection coefficient	Mismatch uncertainty (dB)	
						+	-
1.30 (3020)	1.92	17.69	10.00	0.13	0.32	0.35	-0.37
1.10 (pad)	1.92	26.44	10.00	0.05	0.32	0.13	-0.13
1.22 (3060)	1.92	20.00	10.00	0.10	0.32	0.27	-0.28
1.50	1.92	13.98	10.00	0.20	0.32	0.53	-0.57
1.70	1.92	11.73	10.00	0.26	0.32	0.68	-0.74

Table 4 Examples of the effect of test equipment VSWR on mismatch uncertainty

	Source VSWR	Load UUT VSWR	Source return loss (dB)	Load return loss (dB)	+/- uncertainty due to mismatch (dB)	
3020 without pad	1.30	1.92	17.69	10	0.351	-0.366
3020 with effect of 6 dB attenuation	1.30	1.17	17.69	22	0.090	-0.090
3020 interface with 6 dB pad	1.30	1.10	17.69	26.44	0.054	-0.054
6 dB pad interface with UUT	1.10	1.92	26.44	10	0.130	-0.132
Net effect of r.s.s. addition of uncertainties					**0.141**	**-0.143**

Table 5 Example of the effect of a 6 dB pad on improving mismatch uncertainty for the 3020 PXI RF signal generator

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