A Novel Architecture Reduces Uncertainties of the Precision RF and Microwave Switched Attenuator.

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Abstract

Scale fidelity or log conformance calibration of high performance spectrum analysers and an increasing demand for linearity verification of power sensors are both strong motivators for reduced uncertainties in attenuation.

The achievable performance of a precision RF and microwave switched attenuator is typically compromised by its mismatch, and the source, the load and transmission line mismatch conditions around it. A novel signal levelling and switching architecture has significantly reduced mismatch and its potential impact. This paper presents the new architecture, integrated within a purpose designed RF Reference source and attenuator [1] along with results achieved and quantified benefits at import and export of calibration.

1. The Switched Attenuator in the Calibration Laboratory

The switched attenuator is an essential element within the RF and microwave calibration laboratory. It is used to reduce signal level, in precise steps, at the input of a measuring device or at the output of a sourcing device. It is the latter application that is of interest here, the attenuation of a calibrating RF reference signal source.

Unfortunately, the attenuator can also be one of the larger sources of error in a calibration system. Error arises not so much through inaccurate ratio of attenuation but typically from other sources in its traceability chain. The most significant of these are likely to be mis-match errors (poorly defined transmission line and termination impedances) that occur throughout an interconnection system and of course within the attenuator itself.

Take, for instance, a microwave signal generator and connect a bench top precision switched Attenuator [2] to its output; as in Figure 1.

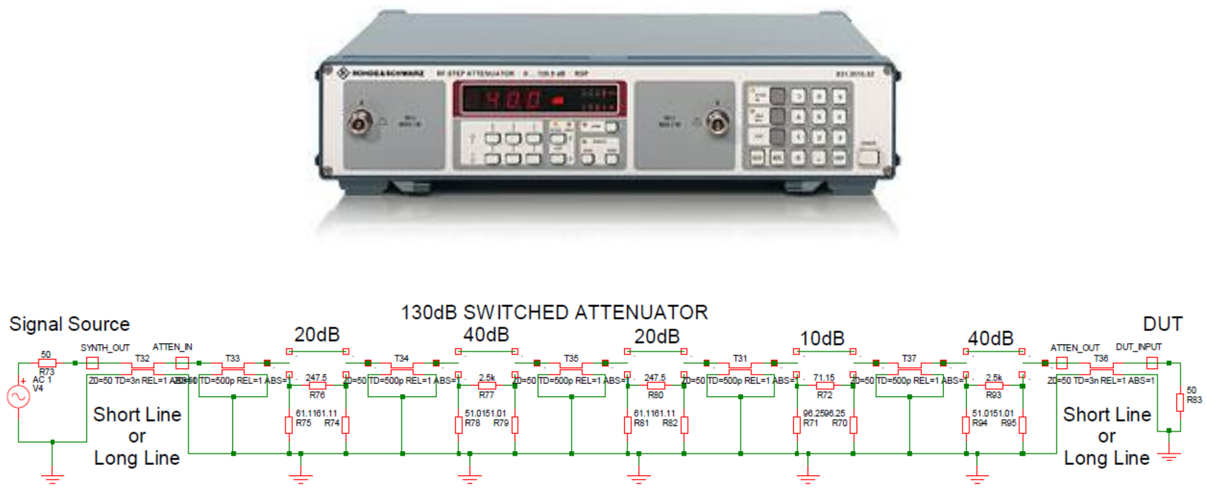

Figure 1: Possible use of a Signal Generator and a Precision Switched Attenuator [2]

At 50MHz, such an arrangement will support a relatively high attenuation reference level of 15 dBm, or 5 dBm if the first “masking” attenuation range is used to improve match.

Despite the quality of the example attenuator, the resulting output level could be subject to quite considerable and various errors at the Device Under Test (DUT) …

1) Relatively poor signal generator source match could “double reflect” mismatch reflections returning from the attenuator. Most notably, when 0 dB attenuation is selected the signal routes through all the attenuator bypass switches and interconnecting transmission lines without any “masking” of an intermediate attenuator. Resulting Attenuator mismatch could be significant and the DUT, connected at the attenuator output, could also have poor match and further add to the problem.
2) Signal generators are typically not accurately calibrated for output level, nor are they particularly stable over time, temperature or switch loss repeatability.
3) The interconnecting co-axial cables, connectors and the attenuator itself have flatness and roll-off errors that could need to be known and compensated. And even if these were measured and compensated, their repeatability with break-remake of connections, flexing of cables and temperature all inject a degree of uncertainty.
4) Were the switches to be electronic (perhaps GaAs or PIN devices) rather than electromechanical relays (or perhaps nowadays MEMs switches) additional and variable loss, distortion, linearity and injected noise could all add further uncertainty contributions.
5) At low signal levels, very deep attenuation, signal leaking from the signal source, or other interfering signals can leach into the coaxial cable connecting the attenuator to the DUT. The former causes flatness errors, possibly severe. The other interfering signals can be RFI or common mode currents circulating between grounded devices.

6) It is likely that all the elements in this system have been calibrated separately, possibly some not at all, or with data that has been lost or confused. Significant error can arise in the incomplete or erroneous combination of characteristics and corrections.

While it might be arguable that stepped attenuation ratio could be relatively accurately implemented at the DUT, absolute level accuracy and flatness are likely to be inadequate, and linearity of the signal generator between steps may not be well specified. The approach is generally un-suitable for Calibration.

Before considering improvements to this situation, notice that the output impedance of the attenuator will depend upon the transmission line paths back through the attenuator to an effective termination resistor. The path (one of the four shown in Figure 2.) will vary with attenuator setting. In other words, four different output impedances will be presented to the DUT by this example attenuator. As already mentioned, the most concerning of these will be the long un-attenuated path right back to the Signal generator. The latter will probably be rather poorly specified for match and so potentially contribute another significant error …

7) the changing source impedance will directly impact attenuation ratio, with a dependence upon DUT load impedance. The latter of course may not be accurate.

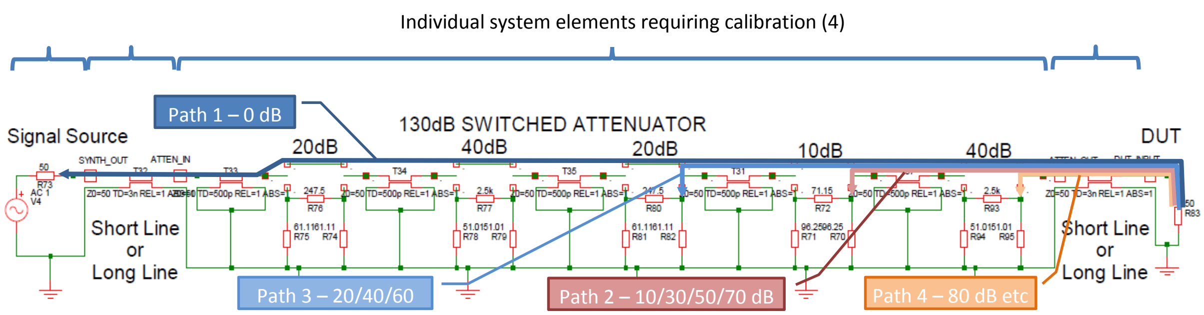

Figure 2: Source impedance paths presented to the DUT by a switched attenuator and the individual elements requiring calibration.

A bench precision switched attenuator can be very well specified as in the example used here [2]. Figure 3. shows measured output impedances |S22| "return loss" (left axis) or VSWR (right axis) when the attenuator is well matched at the input. Also plotted are a "typical" signal generator match specification, and a precision fixed attenuator and precision coaxial cable that might be used at the interconnection points.

Despite the quality of the attenuator, in the "0 dB" case the DUT and any reflections from it would "see" the rather poor signal generator source match. In precision applications this range will often not be used or fixed attenuators added to "mask" the mismatch of the signal generator. A fixed attenuator value of 15 dB would be necessary in this case to improve signal generator match to the level of the attenuator. The signal loss might not be tolerable of course.

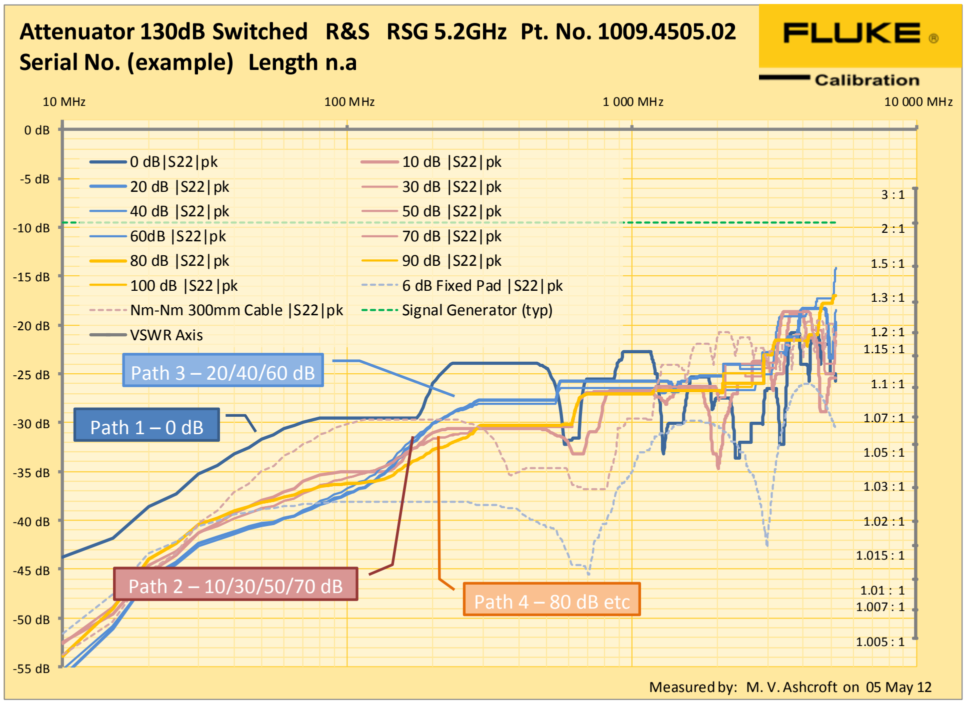

Figure 3: Measured |S22| return loss (or VSWR) for a bench precision switched attenuator and comparative values for a fixed attenuator, coaxial line and a signal generator (typical).

2. Levelling the Output of the Attenuator

To overcome the potential errors, a common approach is to determine the RF Power applied at the DUT using a precision Power Splitter, and a Power Sensor and readout. If signal power splits equally in the two paths, each (the Sensor and the DUT) will 'see' a signal that is 6 dB below the original. Thus we will have an 'accurate' indication of the RF Power at the DUT input, but at the expense of signal loss.

A realisation of this is shown in Figure 4.. In this example the attenuator is a component 27 GHz switched attenuator [3]. This could be fitted internally to the signal generator or sit externally.

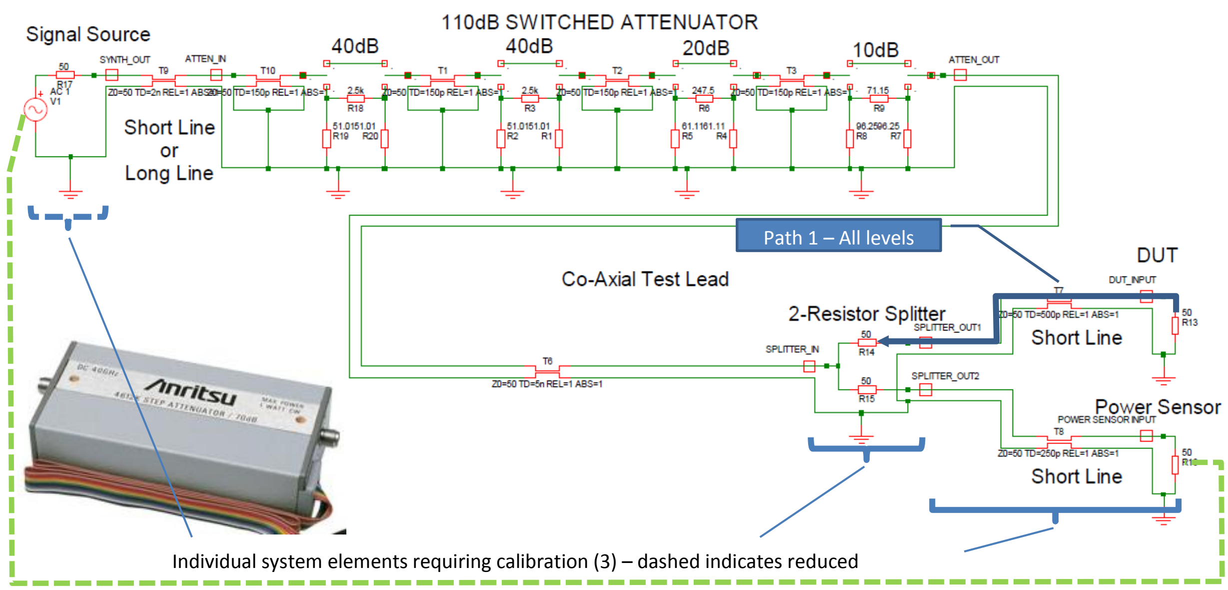

Figure 4: Single short source impedance path presented to the DUT by splitter / sensor feedback levelling.

Further, the use of the indicated power in a level control feedback loop (shown as dotted line in Figure 4.) [note 1]; one that adjusts the signal generator output to achieve a correct level at the Sensor, will realise a "stiffly" controlled level at the input to the splitter. This "stiff" RF Level will not vary if the DUT is removed, nor if we short circuit the input to the DUT [note2]. The Splitter input node will have very low RF impedance, and thus, if the Splitter is formed of two precision 50Ω resistors, the Splitter outputs will both have accurate 50Ω output impedance.

Note 1 – this can be an analogue control loop, a numerical control loop or even a mathematical post process
Note 2 – true only if the signal generator has sufficient headroom to drive the heavy mis-match presented to it.

The source match presented to the DUT is, in this configuration, a single short and well controlled path. The feedback loop will also remove flatness errors in the attenuator, cables and the signal source, leaving only residual errors associated with the splitter imbalance and the sensor.

Figure 5 plots the equivalent source impedance $|S_{22(Eq)}|$ and other parameters for the example two-resistor power splitter. The latter is derived from three separate two port S-parameter (vector) measurements of the Splitter, port pairs with an ideal match terminator on the third port in each case.

Equivalent source impedance $S_{22(Eq)} = S_{22} - S_{21} \,.\, S_{32} / S_{31}$

a vector calculation.

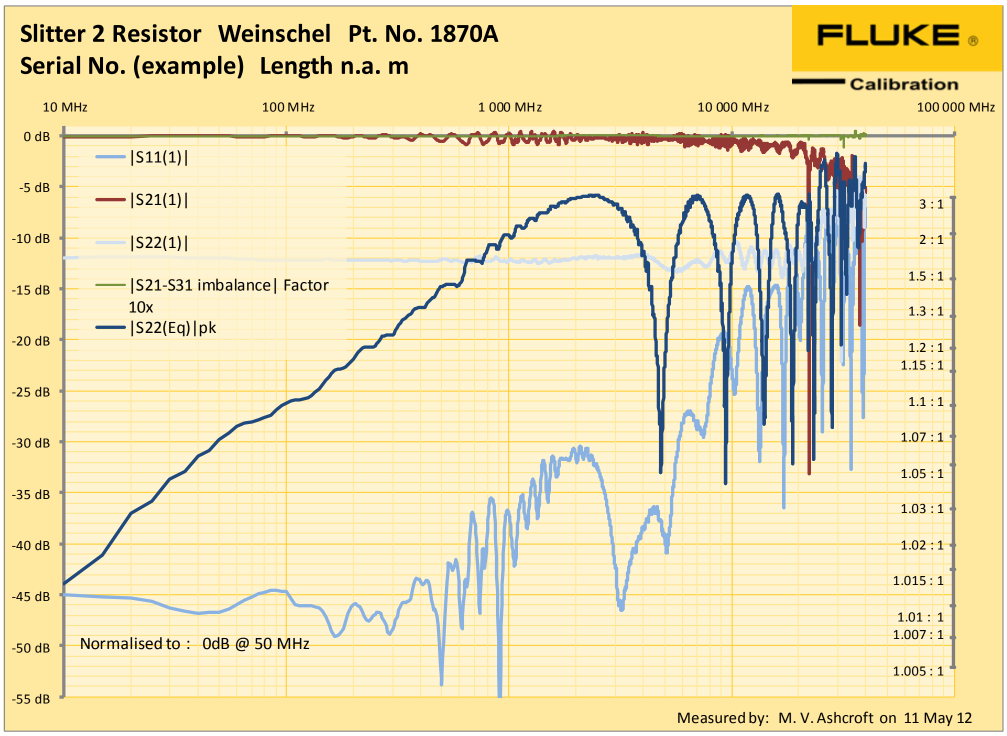

Figure 5: Splitter [4] "on carrier" Source Match and Port Imbalance

However, it is sensor linearity that now determines output level linearity. The switched attenuator is merely a way of reducing level applied to the DUT. Other than minimising overall signal loss there is no call upon its accuracy, match, stability etc.. All of these previous contributions are now inside the level control loop. Unfortunately, while match is now fixed and flatness much improved, linearity of a power sensor may not improve upon that achievable by an attenuator, and signal dynamic range (the lowest usable signal level) will be compromised, as might noise immunity. There is also a signal level loss of 6 dB or more in the splitter. Maximum attenuation reference level at 50MHz will typically be 9 dBm, given the available output power from a typical signal generator.

Before leaving this example, it is important to note that the two-resistor splitter presents good source match only in this control loop circumstance. If the feedback loop were not used, a three-resistor (star or delta) power divider must instead be used to optimise match, and not all of the above benefits would then be realised. Also note that the splitter presents correct impedance only at the signal frequency. Any other signal present at these output ports would not ‘see’ good match. This is referred to as “on-carrier” match. Off carrier return loss will be around -12 dB or a VSWR of 1.7 : 1.

It is also important to note that among many potential levelling signal pick-offs or ‘sniffers’, only the two resistor splitter achieves broadband accurate determination of source level and source impedance. Many signal generators for instance use signal pick-offs of lower loss (1 dB to 2 dB instead of 6 dB), but these do not result in ideal source match. This is why Signal generator match is rarely specified or certified beyond a typical and rather poor value. Referring back to the eight error sources listed above, potential error source No. 7 can be substantial if a two-resistor splitter is not used at the signal levelling point. The signal applied to the DUT will not accurately emulate that from a true 50Ω reference source.

3. Move the Splitter, to level the input of the Switched Attenuator.

In this next example the splitter controls the performance of the signal generator; the source absolute level, flatness and output match are all well defined by the levelling feedback. The configuration realises the stepped linearity accuracy of the attenuator, and the sensor/splitter level control loop can accurately discipline linearity between the attenuator steps.

The downsides are that the source impedance presented at the DUT is once again dependent upon four impedance defining paths, and still suffers 6 dB loss due to the Splitter. Maximum 50MHz reference level will again be 9 dBm, and -1 dBm if the first “masking” attenuator range is used.

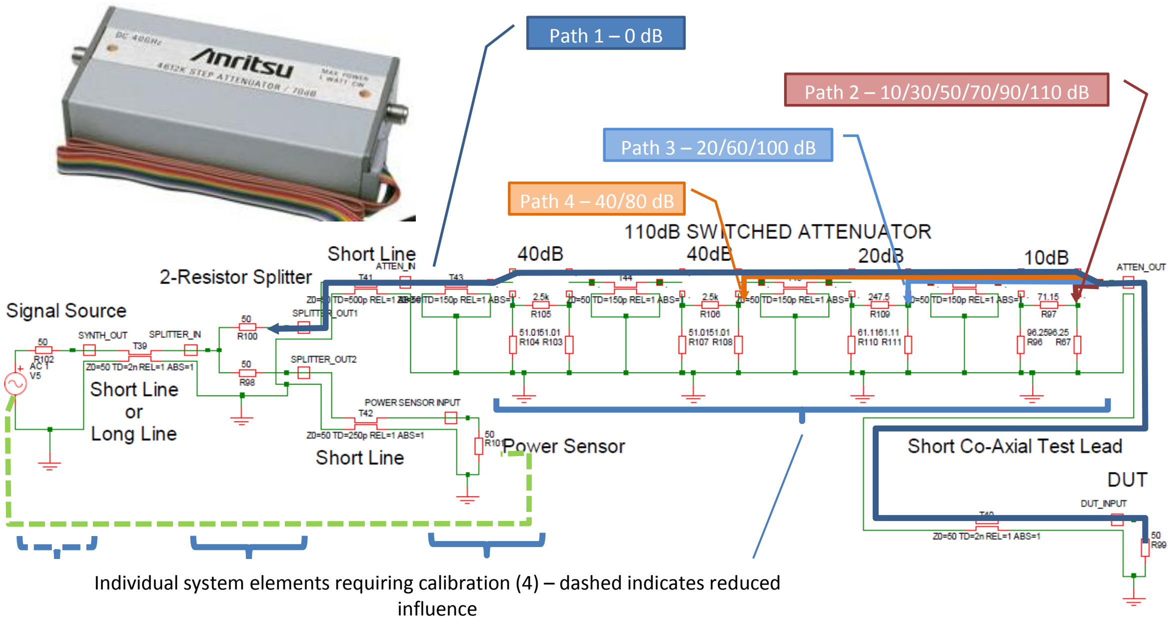

Figure 6: Signal generator within a levelling loop at the input to the component Switched Attenuator [4]. Individual elements requiring calibration also shown.

Figure 7 shows measured |S22| return loss (or VSWR) for the example 27 GHz component switched attenuator, for the above well matched input condition. Also plotted are a precision fixed attenuator and a precision coaxial cable that might be used at the interconnection points. It can be seen that the 6 dB fixed attenuator has similar output impedance to the switched device. Its use as a matching or masking pad at the output of the switched attenuator would not achieve a general improvement in match. However, if the extra loss can be tolerated, a masking pad would improve the change of match seen at lower frequencies (<500 MHz) and also the contribution of the coaxial line if placed right at the DUT input. The theoretical reduction of return loss is twice the attenuator value; but note that this is limited to its own match value. The maximum available benefit here is 10 dB, so there is no need to use a pad of greater than 5 dB in this case.

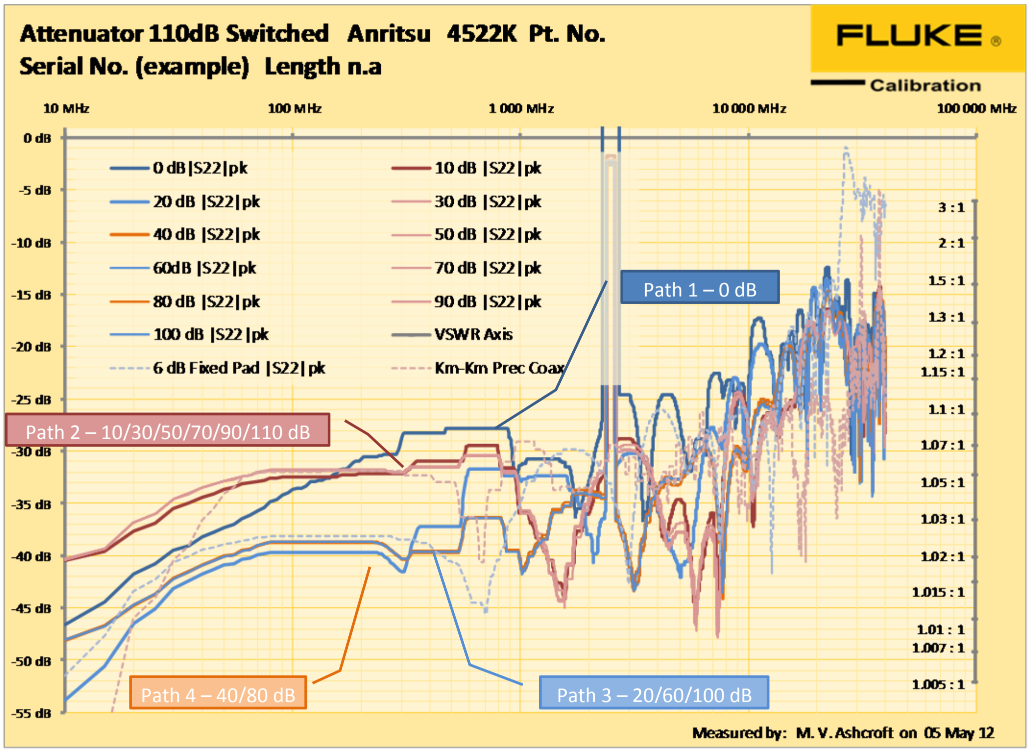

Figure 7: Measured |S22| return loss (or VSWR) for a precision component switched attenuator [4] and comparative values for a fixed attenuator and coaxial line.

4. The existing Fluke 9640A RF Reference Architecture

A novel architecture in its own right, the purpose-designed 9640A RF Reference partitions the switched Attenuator into two parts and moves half (70dB) closer to the DUT and half (60dB) into the signal source instrument. The levelling function also splits between two levelling points, both at the partitioned attenuator inputs – one in the reference Attenuator levelling head and the other in the main instrument.

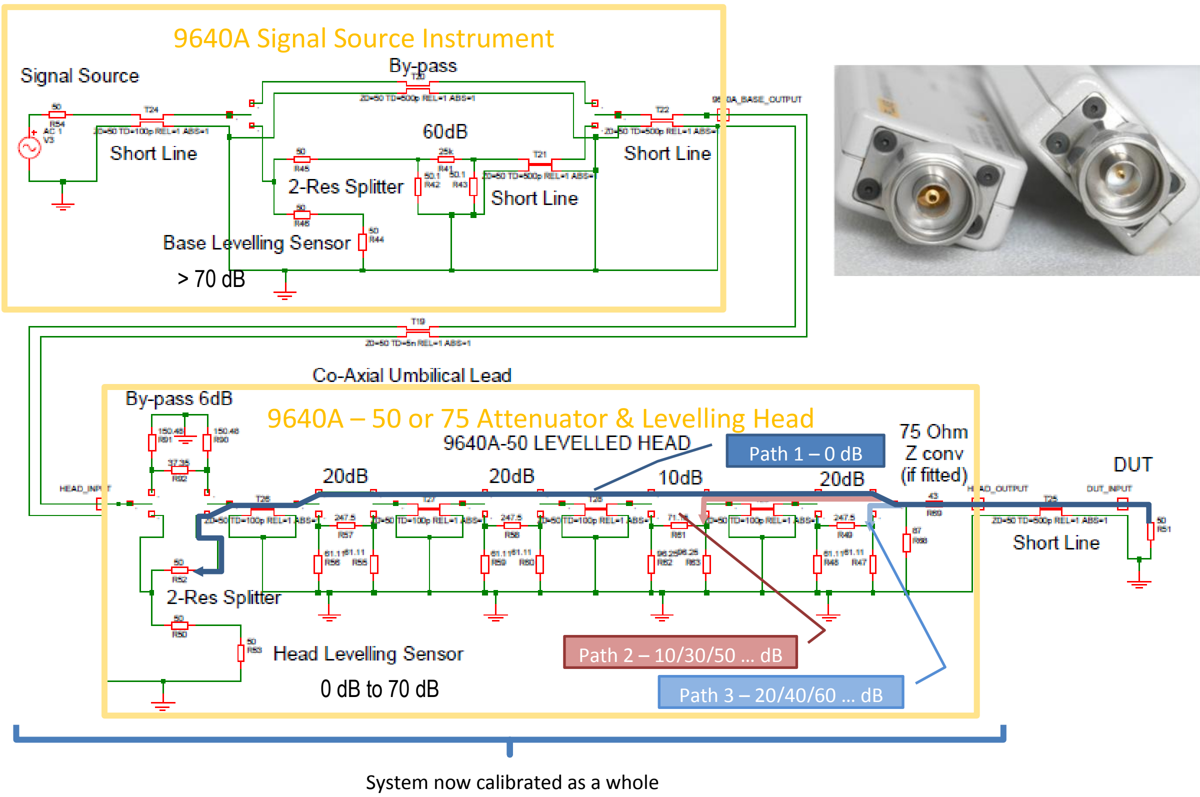

Figure 8: Existing 9640A architecture – Head / Base partitioned attenuation and levelling.

While this architecture still has three impedance defining paths, each is wholly contained within the attenuator and levelling head and are thus relatively short. The benefit here is that the impact of residual reflections is pushed up in frequency. The longer line, always necessary for practical interconnection of standard and a DUT, now sits with defined impedance at both ends, within a levelling control loop (for the higher level outputs – above -56 dBm) and always within the calibration of the host instrument. As of course are all the other signal delivery elements, right up to the DUT input.

In a further version of the attenuator and levelling head, a 75Ω impedance converting pad is included within the design and within the calibration.

A further benefit of the approach is that small RF signals are only present at the relatively well screened head / DUT interface. RFI from external sources and leakage around the attenuator are minimised by not routing small signals via coaxial cable and multiple interconnects.

Figure 9 shows that the four impedance defining paths have similar measured characteristics and that they compare well with high performance switched and fixed attenuators. This architecture supports a 50MHz reference level of up to 24 dBm, or a reference level of 10 dBm on its first attenuation range, for which much of the residual mismatch is masked by the 10 dB attenuator .

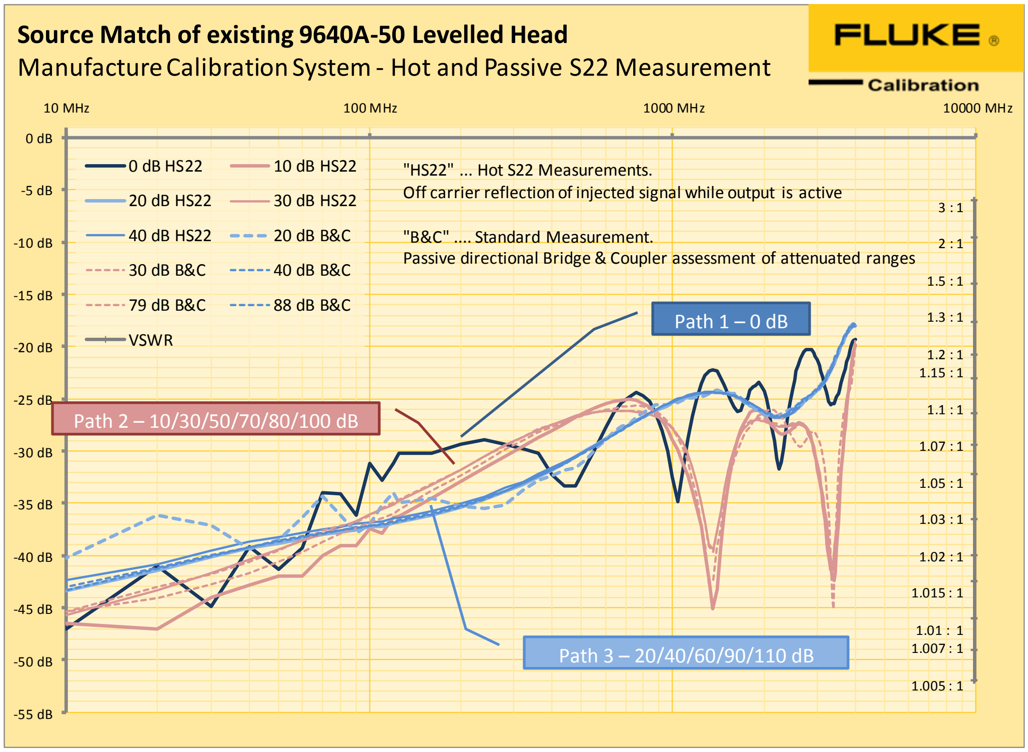

Figure 9: Measured |S22| return loss (VSWR) for existing 9640A architecture

This chart is the first example of a so-called “Hot S22” measurement, explained below.

A further reason for the lack of, or weak specification of Signal generator output match is that it is rather difficult to measure on a production line basis. The difficulty is that a Signal generator output impedance is typically not established until it is outputting signal. The match therefore has to be measured in the presence of the output signal (“Hot”). A further difficulty is that amplitude levelling mechanisms always present “on-carrier” match. In other words, the measurement is going to have to be made at (or very close to) the carrier frequency, and in the presence of the carrier. The method, developed at Fluke, is documented in references [6] and allows Fluke to certify the 9640A RF Reference output match at all output levels. At lower levels, those defined by the passive attenuators, a more conventional directional bridge and coupler measurement can be used. The above measurements are taken from a production calibration system using both methods with some overlap on suitable ranges.

5. A New Architecture for 9640A Attenuation and Levelling Heads

Having established the potential benefits of attenuator input levelling, output levelling, partitioning the attenuator and then attenuating very close to the DUT input; could all of these be combined in a single integrated design and calibration?

Taking the existing 9640A design as a starting point, conceptually a third splitter and levelling element could be added at the Head output. This would need to be done without further loss of signal, a physically larger Head or compromising noise or isolation at the output nodes.

The concept is shown in Figure 10.

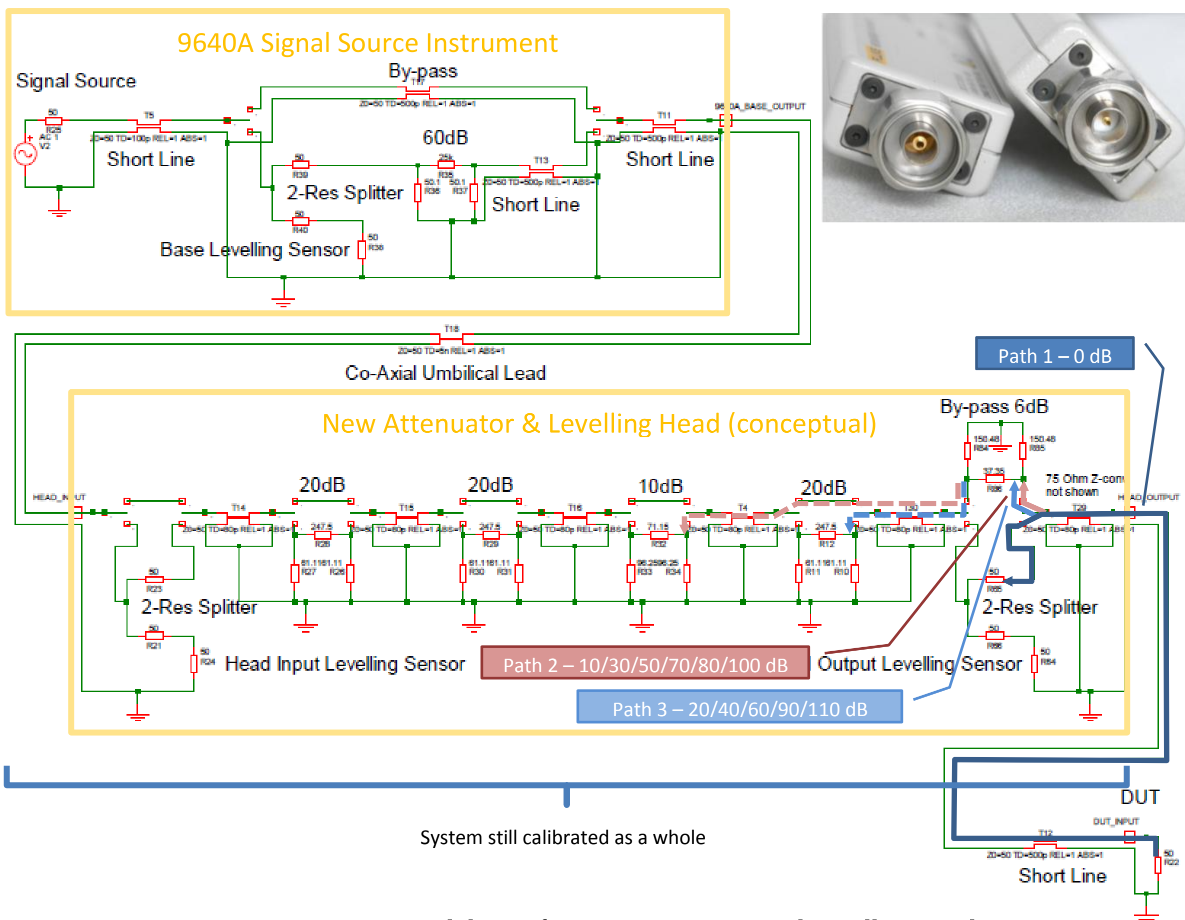

Figure 10: Conceptual design for a new Attenuator and Levelling Head.

In this design, high output levels (those routing via 0 dB attenuation) route via the Head output splitter. As attenuation deepens the level sensing moves to the input of the Head attenuator and the output is connected via an internal 6 dB masking pad. At >70dB the sense moves back into the base instrument, as it does in the existing 9640A design. The point at which sensing moves from output to input of the Head can be selected for optimum performance, but the data below assumes that the 10 dB attenuator is the first input-sensed range.

Two very short impedance defining paths are achieved, but in practice, with masking of only 6 dB in the output splitter by-pass path there is residual influence from the switched attenuators, shown dotted in Figure 10 above. This is an attractive electrical result, but at the expense of another electromagnetic relay in the signal delivery Head. To avoid making the Head longer and heavier, the implementation uses electronic switching and the switching is not as literal as shown in the diagram. Figure 11 below records initial results.

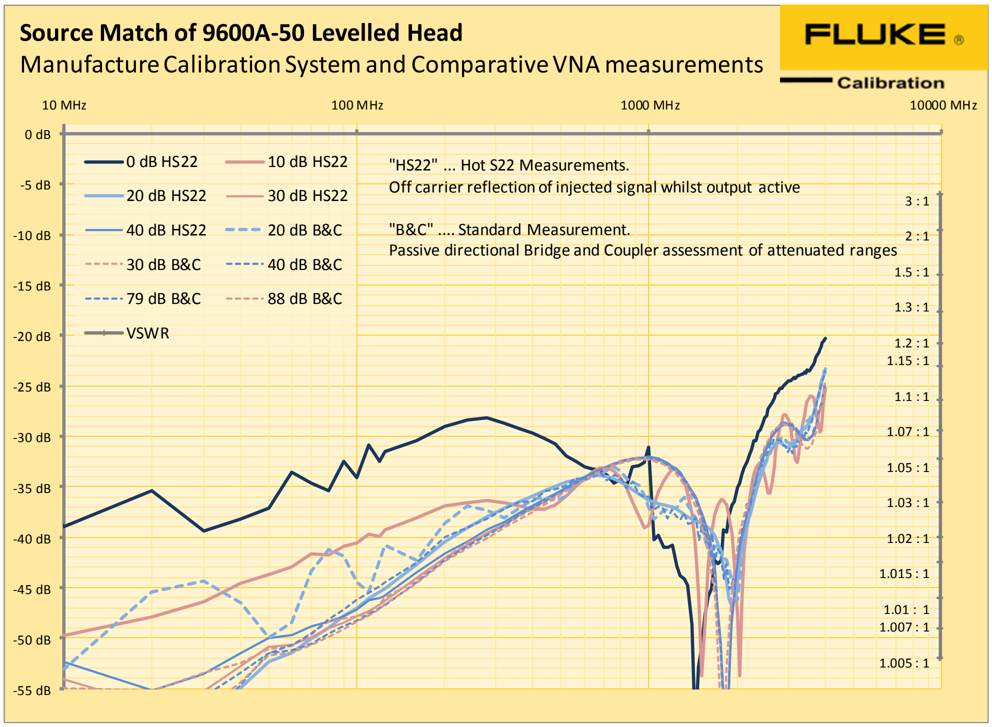

Figure 11: New Head measured |S22| return loss (and VSWR)
Using Hot S22 and Bridge / Coupler methods on manufacture calibration system.

These prototype results show an improvement in top range (0 dB) match and significant improvement in match and consistency of match at deeper attenuations. It is hoped that further work and measurement will achieve a match specification of less than -26 dB (<1.1 : 1) out to greater than 1GHz.

6. The impact of match and improved match on power uncertainty.

There are many basis that could be used to quantify and compare the effects of mismatch upon uncertainty; each would depend perhaps upon application, perhaps on preference. However Figure 12 shows the mismatch uncertainty (% power) that arises when uncorrected mismatch of a calibration standard interfaces with the mismatch of a DUT according to the formula:

Mismatch uncertainty $M = (1 + \rho_{Std} . \rho_{DUT}) - 1$

where ρ is the reflection coefficient and ρ = (VSWR-1)/(VSWR+1).

On the DUT (y-axis) two bands of mismatch represent workload such as power sensors (typically well matched) and spectrum analysers (typically less well matched). Along the Calibration Standards (x-axis) the mismatch of all the above discussed attenuator configurations and their respective paths is summarised.

The intersections of a Calibration Standard match value with a DUT match value indicate the resulting uncertainty due to the combination of mismatch. The table is colour contoured for uncertainty value.

Contour Coding								
0.001%	0.003%	0.005%	0.010%	0.030%	0.050%	0.100%	0.300%	
0.50%	1.00%	3.00%	5.00%					

1.00

Ref Coef	Return Loss	Refl Coef	0.000	0.001	0.001	0.002	0.003	0.005	0.010	0.015	0.020	0.024	0.029	0.034	0.038	0.043	0.048
		Return Loss		-60.01dB	-56.49dB	-52.06dB	-49.15dB	-46.06dB	-40.09dB	-36.61dB	-34.15dB	-32.26dB	-30.71dB	-29.42dB	-28.30dB	-27.32dB	-26.44dB
Coef	Loss	VSWR	1 : 1	1 : 1	1 : 1	1.01 : 1	1.01 : 1	1.01 : 1	1.02 : 1	1.03 : 1	1.04 : 1	1.05 : 1	1.06 : 1	1.07 : 1	1.08 : 1	1.09 : 1	1.1 : 1
0.000		1 : 1	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
0.001	-60.01dB	1 : 1	0.000%	0.000%	0.000%	0.000%	0.001%	0.001%	0.002%	0.003%	0.004%	0.005%	0.006%	0.007%	0.008%	0.009%	0.010%
0.001	-56.49dB	1 : 1	0.000%	0.000%	0.000%	0.001%	0.001%	0.001%	0.003%	0.004%	0.006%	0.007%	0.009%	0.010%	0.012%	0.013%	0.014%
0.002	-52.06dB	1.01 : 1	0.000%	0.000%	0.001%	0.001%	0.002%	0.002%	0.005%	0.007%	0.010%	0.012%	0.015%	0.017%	0.019%	0.021%	0.024%
0.003	-49.15dB	1.01 : 1	0.000%	0.001%	0.001%	0.002%	0.002%	0.003%	0.007%	0.010%	0.014%	0.017%	0.020%	0.024%	0.027%	0.030%	0.033%
0.005	-46.06dB	1.01 : 1	0.000%	0.001%	0.001%	0.002%	0.003%	0.005%	0.010%	0.015%	0.020%	0.024%	0.029%	0.034%	0.038%	0.043%	0.047%
0.010	-40.09dB	1.02 : 1	0.000%	0.002%	0.003%	0.005%	0.007%	0.010%	0.020%	0.029%	0.039%	0.048%	0.058%	0.067%	0.076%	0.085%	0.094%
0.015	-36.61dB	1.03 : 1	0.000%	0.003%	0.004%	0.007%	0.010%	0.015%	0.029%	0.044%	0.058%	0.072%	0.086%	0.100%	0.114%	0.127%	0.141%
0.020	-34.15dB	1.04 : 1	0.000%	0.004%	0.006%	0.010%	0.014%	0.020%	0.039%	0.058%	0.077%	0.096%	0.114%	0.133%	0.151%	0.169%	0.187%
0.024	-32.26dB	1.05 : 1	0.000%	0.005%	0.007%	0.012%	0.017%	0.024%	0.048%	0.072%	0.096%	0.119%	0.142%	0.165%	0.188%	0.210%	0.232%
0.029	-30.71dB	1.06 : 1	0.000%	0.006%	0.009%	0.015%	0.020%	0.029%	0.058%	0.086%	0.114%	0.142%	0.170%	0.197%	0.224%	0.251%	0.278%
0.034	-29.42dB	1.07 : 1	0.000%	0.007%	0.010%	0.017%	0.024%	0.034%	0.067%	0.100%	0.133%	0.165%	0.197%	0.229%	0.260%	0.291%	0.322%
0.038	-28.30dB	1.08 : 1	0.000%	0.008%	0.012%	0.019%	0.027%	0.038%	0.076%	0.114%	0.151%	0.188%	0.224%	0.260%	0.296%	0.332%	0.367%
0.043	-27.32dB	1.09 : 1	0.000%	0.009%	0.013%	0.021%	0.030%	0.043%	0.085%	0.127%	0.169%	0.210%	0.251%	0.291%	0.332%	0.371%	0.411%
0.048	-26.44dB	1.1 : 1	0.000%	0.010%	0.014%	0.024%	0.033%	0.047%	0.094%	0.141%	0.187%	0.232%	0.278%	0.322%	0.367%	0.411%	0.454%
0.070	-23.13dB	1.15 : 1	0.000%	0.014%	0.021%	0.035%	0.049%	0.069%	0.138%	0.206%	0.274%	0.341%	0.407%	0.472%	0.537%	0.602%	0.666%
0.091	-20.83dB	1.2 : 1	0.000%	0.018%	0.027%	0.045%	0.063%	0.090%	0.180%	0.269%	0.357%	0.444%	0.530%	0.616%	0.701%	0.784%	0.868%
0.111	-19.08dB	1.25 : 1	0.000%	0.022%	0.033%	0.055%	0.078%	[illegible]	0.220%	[illegible]	0.436%	0.543%	[illegible]	0.753%	0.857%	0.959%	1.061%
0.130	-17.69dB	1.3 : 1	0.000%	0.026%	0.039%	0.065%	0.091%	[illegible]	0.258%	[illegible]	0.512%	0.637%	[illegible]	0.884%	1.006%	1.127%	1.246%
0.149	-16.54dB	1.35 : 1	0.000%	0.030%	0.045%	0.074%	0.104%	[illegible]	0.295%	[illegible]	0.585%	0.728%	[illegible]	1.010%	1.149%	1.287%	1.423%
0.167	-15.56dB	1.4 : 1	0.000%	0.033%	0.050%	0.083%	0.116%	[illegible]	0.330%	[illegible]	0.655%	0.815%	[illegible]	1.130%	1.286%	1.441%	1.594%
0.184	-14.72dB	1.45 : 1	0.000%	0.037%	0.055%	0.092%	0.128%	[illegible]	0.364%	[illegible]	0.722%	0.898%	[illegible]	1.246%	1.418%	1.588%	1.757%
0.200	-13.98dB	1.5 : 1	0.000%	0.040%	0.060%	0.100%	0.140%	0.199%	0.396%	0.592%	0.786%	0.978%	1.168%	1.357%	1.544%	1.730%	1.914%
0.216	-13.32dB	1.55 : 1	0.000%	0.043%	0.065%	0.108%	0.151%	[illegible]	0.428%	[illegible]	0.848%	1.055%	[illegible]	1.464%	1.666%	1.866%	2.065%
0.231	-12.74dB	1.6 : 1	0.000%	0.046%	0.069%	0.115%	0.161%	[illegible]	0.457%	[illegible]	0.907%	1.129%	[illegible]	1.567%	1.783%	1.997%	2.210%

DUT Mismatch @ 50 MHz

Typ Spectrum Analyser and Power Sensor Mismatch

Calibration Standards Mismatch @ 50 MHz

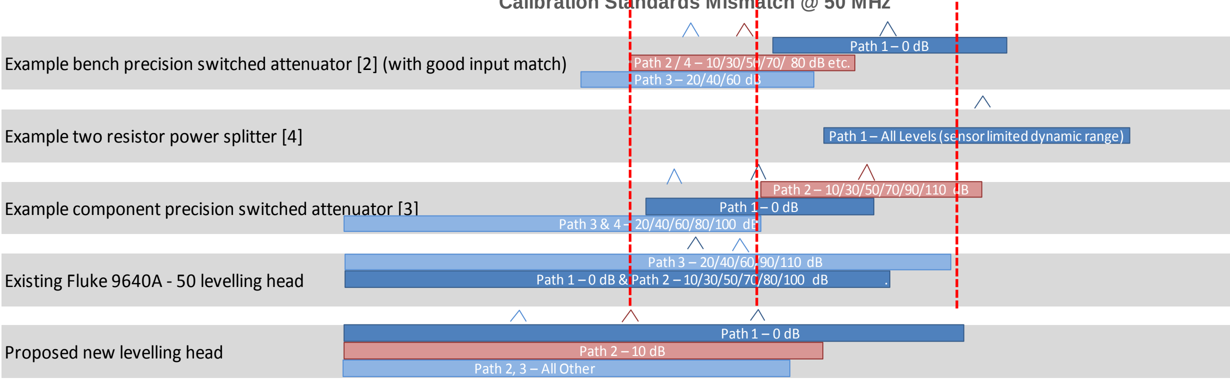

Figure12: Calibration Standard mismatch mapped through DUT mismatch to mismatch uncertainty contribution.

It is also necessary to account here the uncertainty in the measurement of mismatch (reflection coefficient) on both axes.

For each of the attenuator configurations discussed, each impedance defining path is given a coloured bar with nominal value above (see "^" symbols in Figure 12) and a typical uncertainty for that measured value (the span of each bar – typically not symmetrical). Assigned measurement uncertainties are Fluke values against the Fluke products, and for the non Fluke items the uncertainties are typical values accredited for a good RF laboratory using a VNA and match standards. The DUT (y-axis) would be treated similarly for a given DUT. It is seen that match measurement uncertainty will typically contribute heavily to the resulting mismatch uncertainty.

7. Conclusions

As indicated by the red dotted arrows in Figure 12, at nominal mismatch value the new head would support a mismatch uncertainty of 0.09% into a worst case power sensor and 0.2% into a worst case spectrum analyser, better than any of the alternative solutions on any available range. On the 0 dB range uncertainties rise to 0.27% (power sensor) and 0.59% (spectrum analyser), again the best of the worst case ranges among the alternatives considered. However, when, as it must, measurement uncertainty of the source mismatch is accounted the mismatch uncertainties rise to worst case of 0.53% and 1.17% respectively, comparable with the alternative solutions.

Nominal mismatch of the two Fluke attenuator and levelling Heads, existing and new, is lower than the predecessor or alternative solutions, particularly for an attenuation reference level of 10 dBm (or lower) for which the first attenuated range is used. However the somewhat higher measurement uncertainties, of a necessarily different mismatch measurement method, compromises the potential benefit to an overall comparable performance.

None-the-less, with leading edge mismatch and attenuation uncertainty, at least comparable with the very best of alternative solutions, the 9640 RF Reference is a powerful new tool in RF & microwave calibration. The product is supplied with a comprehensive certificate of calibration with uncertainties for all parameters at the point of delivery to the DUT.

The reader will not be surprised to discover that in order to realise the full potential benefit of the new head and its very low mismatch, Fluke Calibration is driving to reduce uncertainties in its traceability chain for mismatch and ultimately those for attenuation.

8. References

[1] Purpose designed integrated signal source, levelling and attenuator – The 9640A RF Reference from Fluke Calibration

Example comparative attenuators and splitters:

[2] Bench top precision switched attenuator – Rohde and Schwarz RSG 5.2GHz 139 dB attenuator.

[3] Component precision switched attenuator – Anritsu 4522K 27 GHz 110 dB attenuator

[4] Power Splitter – Weinschel 1870A N-type two resistor splitter

Materials referenced:

[5] A. Fantom. Radio frequency and microwave power measurement. IEE and Peter Peregrinus Ltd..

[6] P C A Roberts. Measuring output VSWR for an active levelled source. Measurement Science Conference 2008.