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1 Introduction

One of the factors one must take into account when performing a VNA measurement is the linearity of the mixers [1]. A correction is not normally made for linearity; instead, an estimate of the linearity is included in the uncertainty budget and is normally expressed with the unit dB/dB, i.e., the actual contribution is dependent on the measured reflection/transmission coefficient.

A technique for estimating the linearity in a VNA, outlined in [1], has been established for some years now. It is stated in [1] that the linearity should be assessed towards the lower end of the frequency range, where the attenuator has better repeatability, normally below 1000 MHz for a VNA of frequency range up to 18 GHz.

With the availability of broader bandwidth network analysers (e.g., up to 40, 50 or even 110 GHz), it may be questionable as to whether an assessment of linearity carried out at 50 MHz, for example, is valid at all frequencies over a broadband range.

It is also stated in [1] that measurements of attenuation greater than 50 dB should not be used to assess the linearity, owing to imperfect isolation contributions at these attenuation values. The 'typical' isolation given in [1] is 90 dB, a figure that would seem to be fairly low when compared to new network analysers such as the Agilent PNA or Rohde & Schwarz ZVB, which have typical dynamic ranges in the region of 120 dB [2] and 130 dB [3] respectively.

With greater dynamic ranges, it may be argued that attenuation measurements above 50 dB could be used in the assessment of linearity but where should the line be drawn?

This report aims to tackle the issues raised here and, where applicable, make recommendations for changes or additions to current methods used to assess linearity.

2 Assessing the linearity

The linearity of five different VNAs was assessed at a number of frequencies. The chosen VNAs were:

- HP8510C with 8515A 45 MHz – 26.5 GHz test set
- HP8510C with 8517B 45 MHz – 50 GHz test set
- Agilent E8364B PNA 10 MHz – 50 GHz
- Agilent 8753E 30 kHz – 6 GHz
- Anritsu 37397C 40 MHz – 65 GHz

and the linearity was assessed at the following frequencies where they were available on each of the above VNAs: 500 kHz, 1 MHz, 2 MHz, 5 MHz, 10 MHz, 20 MHz, 50 MHz, 100 MHz, 200 MHz, 500 MHz, 1 GHz, 2 GHz, 5 GHz, 18 GHz and 40 GHz.

At frequencies up to and including 2 GHz, an attenuator combination consisting of an HP 8494G 0 – 11 dB step attenuator and an HP 8496G 0 – 110 dB step attenuator was measured in 5 dB steps up to 75 dB (90 dB on the Agilent E8364B, owing to its greater dynamic range). This attenuator combination was calibrated by NPL's attenuation section up to 90 dB and is traceable to UK National Standards.

At frequencies above 2 GHz, an attenuator combination consisting of an Agilent 84904M 0 – 11 dB step attenuator and an Agilent 84908M 0 – 65 dB step attenuator was measured in 5 dB steps up to 75 dB. This attenuator combination was calibrated by NPL's attenuation section up to 75 dB and is traceable to UK National Standards.

For each VNA, the method described in [1] was used to evaluate the linearity at the different frequencies in both the forward and reverse transmission directions. For the E8364B, a second evaluation was carried out incorporating the attenuator measurements up to 70 dB.

3   Results and Discussion

Table 1 shows the linearity estimates obtained for the 50 GHz HP 8510C in this investigation. The linearity estimates for this and the other VNAs are summarised in Fig 1[1]. Figs 2a and 2b show plots of the difference between the attenuation measured on the HP 8510C with 8515A test set (45 MHz – 26.5 GHz) and the calibration values taken at 100 MHz and 18 GHz, respectively. Fig 3 is similar to Fig 2a and shows a plot for measurements up to 90 dB using the E8364B PNA[2].

3.1   Is linearity frequency dependent?

There does not appear to be any obvious frequency dependency on the value of linearity, although it does rise as the one approaches the band edges of the broadband VNAs.

When evaluating the uncertainty for reflection measurements, the observed changes in the linearity have no significant effect on the overall uncertainty and hence an estimate of linearity at a single frequency may be valid to cover the whole frequency band.

It is much harder to quantify the effect on transmission uncertainties, as many of the contributions are dependent on machine performance, such as the isolation, connector repeatability and the measurement of the transmission coefficient itself. Under some circumstances, the effect on the overall uncertainty is minimal; but under others, the effect is dominant.

As can be seen in Fig 1, the linearity across the frequencies can vary between instruments. When performing an initial evaluation of a VNA's linearity, it is suggested that it be done at a number of frequencies. Should this initial evaluation show that there is a significant variation across the frequency range, i.e., the final uncertainty is affected significantly by this variation, it is suggested that any further regular checks of linearity be made at all of these frequencies.

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[1] The forward and reverse linearity estimates were similar in size and hence the larger of the two has been chosen for display in Fig 1, with the exception of the 37397C, whose forward and reverse linearity estimates were significantly different in some cases so both are displayed in Fig 1.

[2] There is no equivalent 18 GHz plot, since the attenuator used at this frequency had a maximum attenuation of 75 dB.

Should this not be the case, it is recommended that evaluations be carried out regularly at one or two frequencies (e.g., one at the lower end of the operating range and one at the higher end).

It is recommended that VNAs be treated individually, as even those that are nominally identical may have subtle differences in performance.

Some examples of how the uncertainty is affected can be found in Appendix A.

3.2   Should linearity be expressed in dB/dB?

The graphs of the difference between the measured attenuator values and its calibrated values in Fig 2 do not show a systematic change, so the validity of expressing linearity as an attenuation dependent contribution may be questionable.

The attenuation dependent lines "S12 linearity" and "S21 linearity" in Fig 2a could easily be replaced by a flat line at a value of 0.011 dB to encapsulate all measurements below 50 dB.

A similar thing could be done with the graph in Fig 2b. The "S21 linearity" line could be replaced by a flat line at 0.007 dB up to 40 dB and another at 0.038 dB thereafter. Similarly, the "S12 linearity" line could be replaced by a flat line at 0.011 dB up to 45 dB and another at 0.04 dB thereafter.

A disadvantage to doing this is that the uncertainties in lower attenuation measurements (less than 10 or 20 dB, for example) may be larger.

On the other hand, it could be argued that the forward linearity plot in Fig 3 does have a systematic increase with attenuation so the method described in this section may not be suited to all linearity evaluations.

As this is likely to be a VNA-dependent effect, it is not possible to predict which method is the best to use for any particular VNA and it is suggested that users choose one of the methods outlined in this section as appropriate when performing a linearity evaluation.

3.3   Can attenuation values greater than 50 dB be used to assess linearity?

Of the VNAs described in this report, with the exception of the E8364B PNA, it is probably reasonable to say that measured attenuation values above 50 dB can be neglected, owing to effects of noise and/or isolation at these levels, which are evident in Fig 2 by the sudden increase in difference from the calibrated value.

In Fig 3, this change does not occur until after 70 dB and is typical of the measurements taken on the PNA.

Rather than give a value above which attenuator measurements should be discarded for use in linearity evaluations, it may be more appropriate to suggest that the user assess the point at which other effects manifest themselves and discard measurements above this value.

4   Conclusion

In order to tackle a number of issues raised regarding the assessment of linearity, estimates have been made at a number of different frequencies on a number of different network analysers based on the technique described in [1].

The technique has proven itself to be suitable under many circumstances, however there are some instances where other techniques may be appropriate and alternatives have been suggested, including an extension to the range of values used to estimate the linearity, a flat line, non-attenuation-dependent approach and the evaluation of linearity at a number of frequencies, particularly where changes in the linearity have an effect on the overall uncertainty.

It is left up to the user to assess which of these proposed methods is the more suitable for their own evaluations of linearity.

References

[1]   "EA Guidelines on the evaluation of Vector Network Analysers (VNA)", *European co-operation for Accreditation*, Publication Reference EA-10/12, May 2000.

[2]   "PNA Microwave Analyzers Data Sheet", *Agilent Technologies*
        (http://cp.literature.agilent.com/litweb/pdf/5988-7988EN.pdf)

[3]   "Vector Network Analyzer R&S ZVB Specifications Sheet", *Rohde & Schwarz*, Version 6.00, August 2006

Frequency (MHz)	Forward linearity (dB / dB)	Reverse linearity (dB / dB)
50	0.003 1	0.003 9
100	0.001 5	0.001 5
200	0.000 2	0.000 4
500	0.000 3	0.000 4
1000	0.000 3	0.000 8
2000	0.000 4	0.000 6
5000	0.000 7	0.000 5
18000	0.000 6	0.000 6
40000	0.011 0	0.026 0

Table 1 – Linearity estimate for the HP 8510C with 8517B test set (45 MHz – 50 GHz)
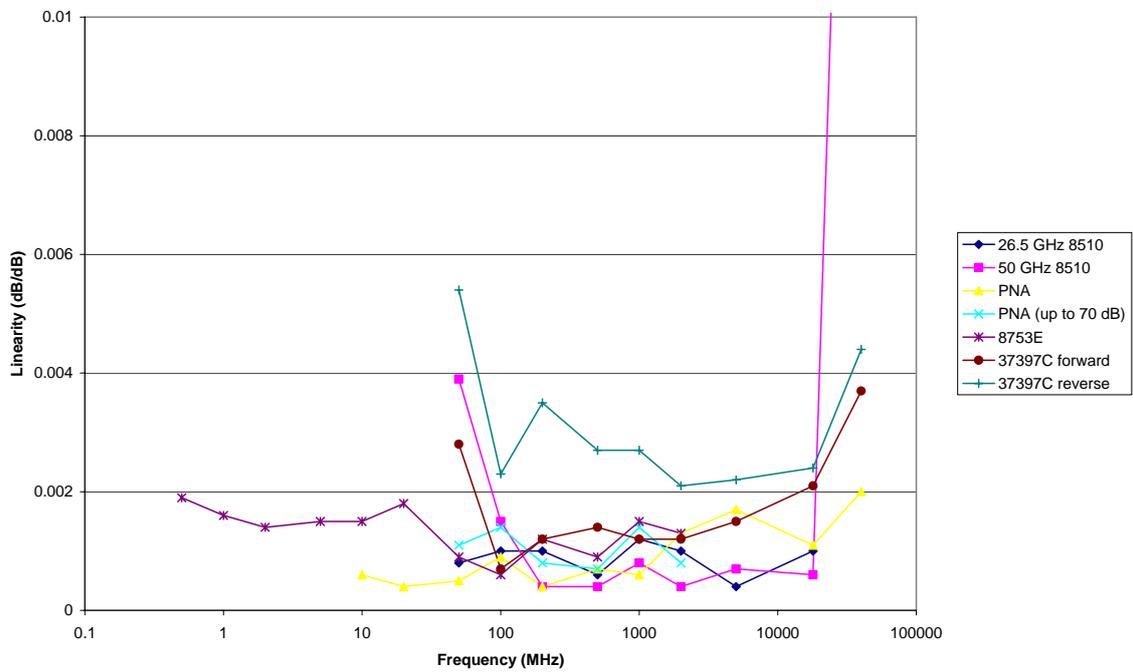

Fig 1 – Linearity estimates for all of the VNAs across the chosen range of frequencies
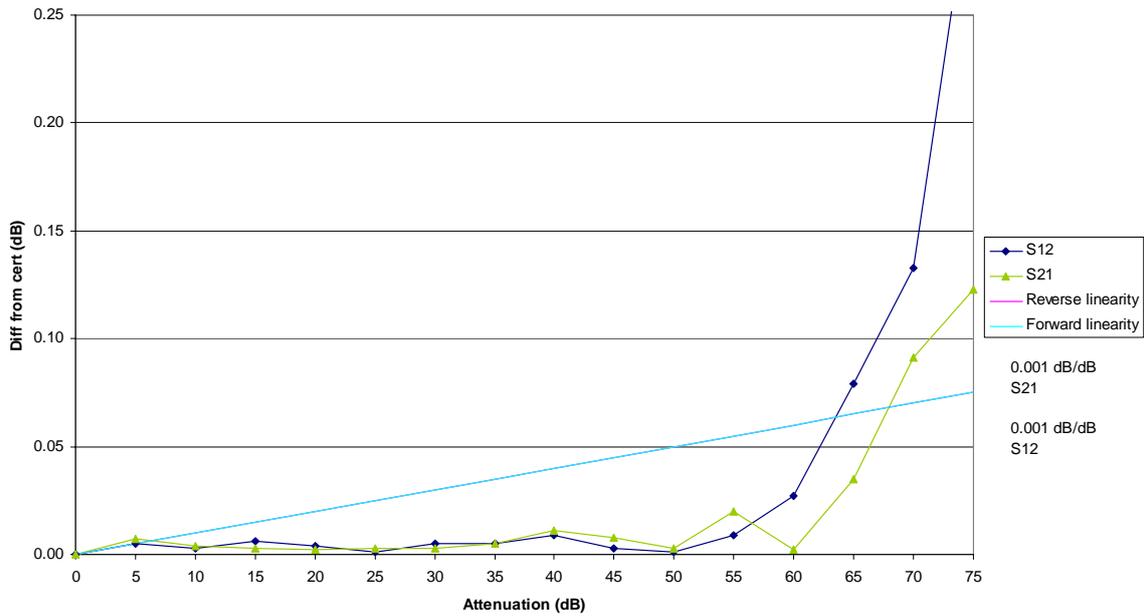
Fig 2a – Difference between the attenuation measured on the HP 8510C with 8515A test set and the calibration values at 100 MHz
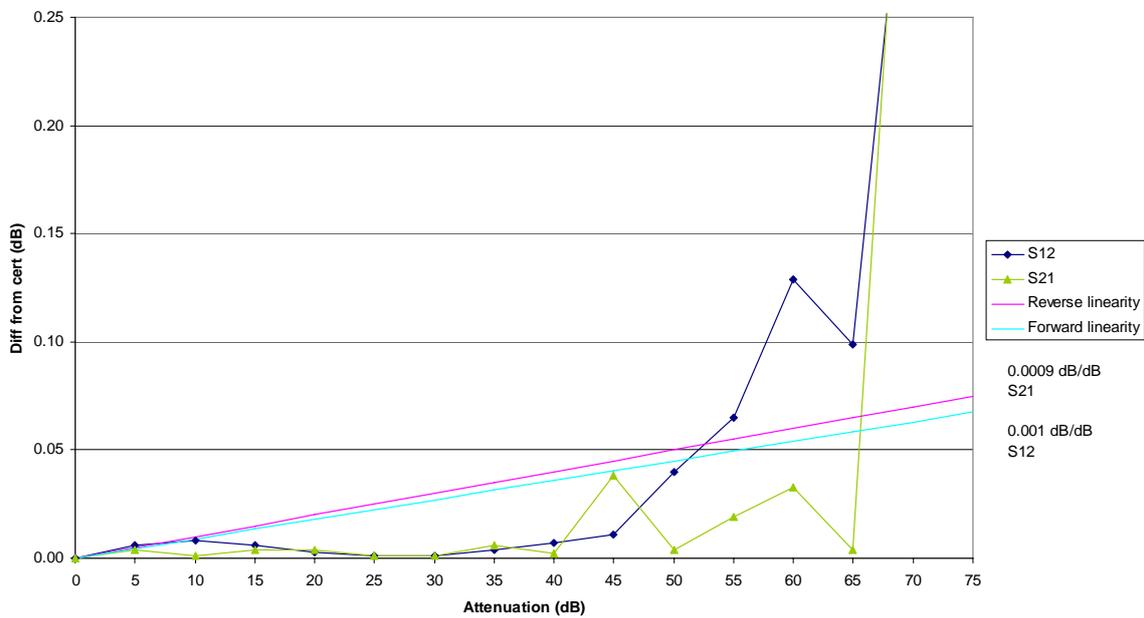

Fig 2b – Difference between the attenuation measured on the HP 8510C with 8515A test set and the calibration values at 18 GHz
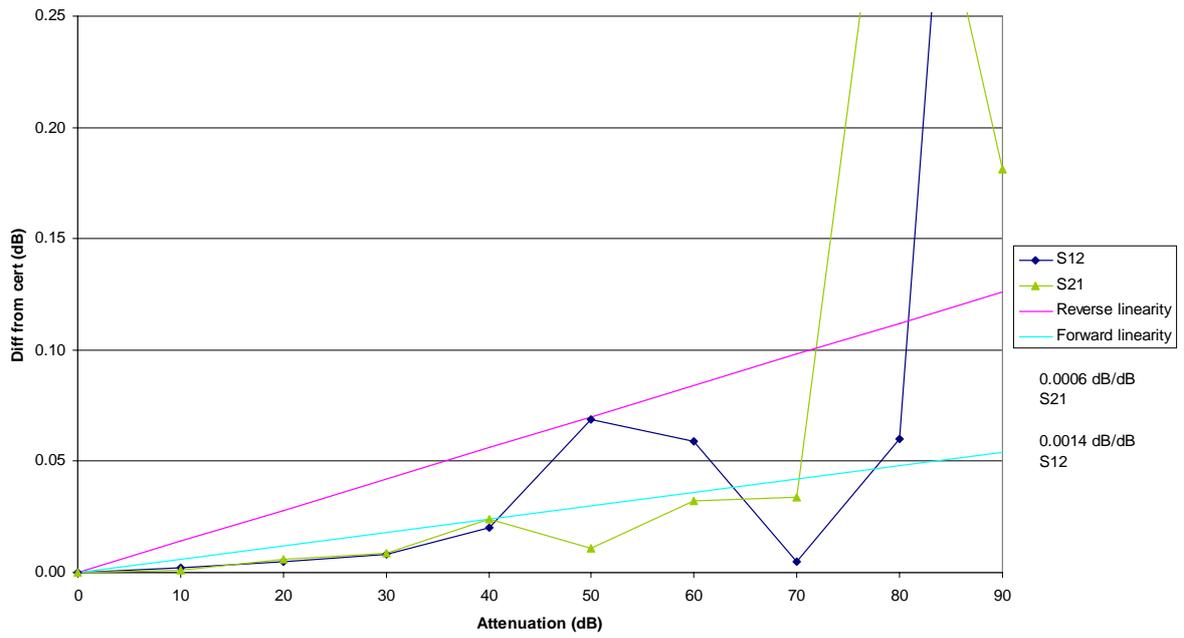
Fig 3 – Difference between the attenuation measured on the E8364B PNA and the calibration values at 100 MHz

Appendix A

A value for the linearity was evaluated for both forward and reverse transmission on an 8510C with 8515A 45 MHz – 26.5 GHz test set.

Frequency (GHz)	Forward linearity (dB / dB)	Reverse linearity (dB / dB)
0.05	0.000 8	0.000 6
0.1	0.001 0	0.001 0
0.2	0.001 0	0.000 8
0.5	0.000 6	0.000 4
1	0.001 2	0.001 0
2	0.001 0	0.001 0
5	0.000 4	0.000 3
18	0.000 9	0.001 0

Look now at how the uncertainty contribution due to linearity might vary with the different measured values.

Basing the calculations on the EA-10/12 guide, reflection coefficients and their uncertainties are reported in linear units and transmission coefficients and their uncertainties are reported in dB.

Linearity is evaluated in dB / dB, so this value must be converted to a linear one for use in a reflection coefficient uncertainty. The uncertainty contribution in the reflection, $u_{lin}(S_{xx})$, where x is the port number, due to linearity is calculated using

$$u_{lin}(S_{xx}) = S_{xx} \cdot \left(1 - 10^{L \cdot \log(S_{xx})}\right),$$

where L is the linearity in dB / dB [3].

The uncertainty contribution in the transmission, $u_{lin}(S_{xy})$, where x and y take the value 1 or 2 and $x \neq y$, due to linearity is calculated using

$$u_{lin}(S_{xy}) = L \cdot S_{xy}.$$

In order to see the effect linearity has on the overall VNA measurement uncertainty, consider the following examples based on measurements made:

1. One-port reflection measurement with VRC = 0.2 (Example 1 from EA-10/12 [1])
2. Two-port measurement of a 20 dB attenuator with VRC = 0.05 and isolation = 90 dB (Example 4 from EA-10/12 [1])
3. Two-port measurement of a 70 dB attenuator with VRC = 0.05 and isolation = 90 dB (Example 5 from EA-10/12 [1])
4. Two-port measurement of a 20 dB attenuator with VRC = 0.05 and isolation = 120 dB
5. Two-port measurement of a 70 dB attenuator with VRC = 0.05 and isolation = 120 dB

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[3] Although this equation is not stated explicitly, it is derived from the examples in the EA-10/12 document.

Example 1

In this example in [1], the contribution due to linearity in the reflection coefficient is 0.000 64 and the overall combined uncertainty ($k = 1$) is 0.009 0[4].

Replacing these values with the ones determined in this exercise, the uncertainty contributions and the overall uncertainties are given in the following table.

Frequency (GHz)	Forward reflection (S_{11})		Reverse reflection (S_{22})	
	Linearity contribution	*Combined uncertainty*	*Linearity contribution*	*Combined uncertainty*
0.05	0.000 26	0.009 1	0.000 19	0.009 1
0.1	0.000 32	0.009 1	0.000 32	0.009 1
0.2	0.000 32	0.009 1	0.000 26	0.009 1
0.5	0.000 19	0.009 1	0.000 13	0.009 1
1	0.000 39	0.009 1	0.000 32	0.009 1
2	0.000 32	0.009 1	0.000 32	0.009 1
5	0.000 13	0.009 1	0.000 10	0.009 1
18	0.000 29	0.009 1	0.000 32	0.009 1

It can be seen here that the contribution due to the linearity does not play a huge role in the final uncertainty budget.

It is worth noting that, in this example, the directivity is chosen as 0.010, which seems a little high. By choosing a more realistic value appropriate for an SOL calibration (e.g., 0.006), the combined uncertainty decreases (to 0.006 9) but the effect on the combined uncertainty due to a change in the linearity contribution remains small (assuming the linearity does not rise above 0.005 dB / dB).

Example 2

In this example in [1], the contribution due to linearity in the reflection coefficient is 0.040 dB and the overall combined uncertainty ($k = 1$) is 0.025 4 dB.

Replacing these values with the ones determined in this exercise, the uncertainty contributions and the overall uncertainties are given in the following table.

Frequency (GHz)	Forward transmission (S_{21})		Reverse transmission (S_{12})	
	Linearity contribution (dB)	*Combined uncertainty (dB)*	*Linearity contribution (dB)*	*Combined uncertainty (dB)*
0.05	0.016	0.017 5	0.012	0.016 7
0.1	0.020	0.018 5	0.020	0.018 5
0.2	0.020	0.018 5	0.016	0.017 5
0.5	0.012	0.016 7	0.008	0.016 1
1	0.024	0.019 7	0.020	0.018 5
2	0.020	0.018 5	0.020	0.018 5
5	0.008	0.016 1	0.006	0.015 9
18	0.018	0.018 0	0.020	0.018 5

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[4] It looks like there may be rounding errors and this figure is closer to 0.009 1.

It would seem here that the contribution due to the linearity has an effect on the final uncertainty budget, certainly when it is expressed in dB.

Converting the transmission coefficient and its uncertainty to linear values, the transmission coefficient is 0.1 (assuming it doesn't change with frequency) and its uncertainty ranges from 0.000 18 to 0.000 23, as the linearity contribution changes.

One might argue that this is an insignificant change in the uncertainty.

Example 3

In this example in [1], the contribution due to linearity in the reflection coefficient is 0.140 dB and the overall combined uncertainty ($k = 1$) is 0.507 0 dB [5].

Replacing these values with the ones determined in this exercise, the uncertainty contributions and the overall uncertainties are given in the following table.

Frequency (GHz)	Forward transmission (S_{21})		Reverse transmission (S_{12})	
	Linearity contribution (dB)	*Combined uncertainty (dB)*	*Linearity contribution (dB)*	*Combined uncertainty (dB)*
0.05	0.056	0.479 5	0.042	0.479 1
0.1	0.070	0.479 9	0.070	0.479 9
0.2	0.070	0.479 9	0.056	0.479 5
0.5	0.042	0.479 1	0.028	0.478 8
1	0.084	0.480 5	0.070	0.479 9
2	0.070	0.479 9	0.070	0.479 9
5	0.028	0.478 8	0.021	0.478 7
18	0.063	0.479 7	0.070	0.479 9

As with the previous example, it would seem here that the contribution due to the linearity has a very small effect on the overall uncertainty budget.

Again, this may be converted to linear units, with the transmission coefficient being 0.000 316 and the uncertainty ranging from 0.000 017 4 to 0.000 017 5.

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[5] This may be an error, as the crosstalk contribution does not appear to match that in the table in section 7.3.3.2 of the document.

Example 4

This is example 2 but replacing the isolation value with 120 dB.

Frequency (GHz)	Forward transmission (S_{21})		Reverse transmission (S_{12})	
	Linearity contribution (dB)	*Combined uncertainty (dB)*	*Linearity contribution (dB)*	*Combined uncertainty (dB)*
0.05	0.016	0.017 5	0.012	0.016 6
0.1	0.020	0.018 5	0.020	0.018 5
0.2	0.020	0.018 5	0.016	0.017 5
0.5	0.012	0.016 6	0.008	0.016 0
1	0.024	0.019 6	0.020	0.018 5
2	0.020	0.018 5	0.020	0.018 5
5	0.008	0.016 0	0.006	0.015 8
18	0.018	0.017 9	0.020	0.018 5

The values here are, for the most part, identical to those obtained in Example 2 and hence it could also be argued in this case that the change in linearity has little effect on the overall uncertainty.

Example 5

This is example 3 but replacing the isolation values with 120 dB.

Frequency (GHz)	Forward transmission (S_{21})		Reverse transmission (S_{12})	
	Linearity contribution (dB)	*Combined uncertainty (dB)*	*Linearity contribution (dB)*	*Combined uncertainty (dB)*
0.05	0.056	0.040 9	0.042	0.036 4
0.1	0.070	0.046 0	0.070	0.046 0
0.2	0.070	0.046 0	0.056	0.040 9
0.5	0.042	0.036 4	0.028	0.032 9
1	0.084	0.051 5	0.070	0.046 0
2	0.070	0.046 0	0.070	0.046 0
5	0.028	0.032 9	0.021	0.031 6
18	0.063	0.043 4	0.070	0.046 0

The change to the overall uncertainty here appears to be more significant than those observed in Example 3.

Converting the transmission coefficient and its uncertainty to linear values, the transmission coefficient is 0.000 316 and its uncertainty ranges from 0.000 001 15 to 0.000 001 87, as the linearity contribution changes.

Despite the greater range of uncertainty than that seen in Example 3, one could say that this is an insignificant change.