Evaluation of Uncertainty Measurement Calculation for Vector Network Analyzer From 300 kHz to 8.5 GHz

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A R T I C L E I N F O	A B S T R A C T
	Increasing the telecommunications products that allow Vector Network Analyzer is becoming more common tools to measure the S-Parameter. It will be an absolute number from the S-Parameter measurements produced in real and imaginary, other words it is also known as the product of the calculation. The calculation findings do not include the systematic and random errors. It's the reaction of the engineer to mitigate the likelihood of random and systemic errors. One of the common random error solutions is through the statistical analysis in the Vector Network Analyzer either repeated measurement or turn on high averaging measurement. The more data assessed, the greater the engineer's confidence in evaluating random errors did not contribute significant errors. Systemic Error is consistent and reproducible when the measurement is made. One way of harmonizing these errors is to evaluate uncertainty measurements in the calculation for Vector Network Analyzer to perform measurements of reflection and transmission. Transmission measurements produce the three systematic errors that were directivity, source match and frequency response reflection tracking. This paper will concentrate from 300 kHz to 8.5 GHz directivity experimental to determine the accuracy of the Vector Network Analyzer. The experimental results will check balance with the Vector Network Analyzer specification. It is a validation process to ensure the Vector Network Analyzer meets the specification in order to perform an accurate measurement. The estimation of measurement uncertainty also refers to the Metrology 100 series Joint Committee for Guide to the Expression of Uncertainty in Measurement. The uncertainty expended should apply to Student Table's confident level of 95%. It creates awareness to demonstrate the importance of measurement quality associated with the uncertainty, particularly for an ISO17025:2017 certified competence testing and calibration laboratory. Without the uncertainty associate to the measurement, it is not complying to the standard ISO17025:2017.

1. Introduction

The raise of the telecommunication products enabling Vector Network Analyzer (VNA) [1] is getting more popular instruments to making the S-Parameter measurements. The Vector Network Analyzer is measuring in Time Domain Reflection and Time Domain Transmission converting into time domain. The Vector Network Analyzer had been helped engineer to solve the Fourier Transformation calculation and giving the results in real and imaginary number. The real and imaginary would be an absolute number, other words it is also known as measurement result. The measurement results are not including the random and systematic errors yet.

In the Vector Network Analyzer random error is statistical deviations in any direction during calculation. This error's source is unknown. It is not a mistake that the technician made during the calibration of the Vector Network Analyzer. The same issue is also encountered even through a highest traceability chain in calibration performed by national measurement laboratory. It is not possible to eradicate random error from a calculation. It is the

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duty of the engineer to mitigate the probability of the random errors. One of the common random error solutions is through the statistical analysis in the Vector Network Analyzer either repeated measurement or turn on high averaging measurement. The more data taken into calculation, the greater the engineer's confidence in evaluating a random error did not contribute substantial errors to the calculation of the Device Under Test [2].

Systematic error in a Vector Network Analyzer is reproducible through the calibration experiment and unable to determine the systematic error by statistical analysis. This mistake demonstrates consistently the same direction in making measurements. Systematic error contributor may be calculated by instrument impact factors, environmental factors, incoming source frequency and others do not cause by statistical contribution.

Random and systemic errors and consequences can lead to measurement uncertainty reporting in a huge number. Calculation of measurement uncertainty often refers to the Metrology 100 series Joint Guide Committee which is the Guide to Expression of Uncertainty in Measurement. It is creating awareness to demonstrate the importance of measurement quality associate with the uncertainty.

Many aspects in our life, we are accustomed to the doubt to estimate length in Meter, weight in Kilogram, temperature in Kelvin, time in Second, electric current in Ampere, amount of substance in Mole and luminous intensity in Candela. These are the 7 units of measure defined by the International System of Units were defined with its traceability. Quantitative measurement is not complete without uncertainty being reported with the measurement. For example, estimate a weight of a kilo pack of sugar. The manufacturer always including a tolerance from the weight that they measured. The manufacturer also has a tolerance of the weight they were examining. This means the measurement is in question by the manufacturer. This is the key reason why calibration is necessary to retain its tractability to the International System of Units. Another example of new Fifth Generation of Mobile Technologies (5G) sub-6GHz low frequency spectrum antenna required calibration up to 7.125 GHz [3]. The antenna manufacturer required to purchase the Vector Network Analyzer to perform analysis of the antenna reflection and transmission. Vector Network Analyzer examinations will help determine whether the antenna produce is pass or fail. Vector Network Analyzer's accuracy is critical to ensure the antenna that is manufactured within the product's limits. In this paper the same approach definition applies in the two ports Vector Network Analyzer measurement for transmission and reflection. To calculate the measurement uncertainty, the associated contributor must be established which will affect the calibration. Such calibration would give the antenna manufacturer a source of uncertainty in the calibration report associated with an absolute measurement [4]. This uncertainty reported in the calibration reports consists of the Type A and Type B [5] uncertainty calculation from the calibration provider. Type A uncertainty consist of repeatability [6] and Type B uncertainty consists of product error such as reflection coefficient [7]. The calibration report will be used in a subsequent evaluation of uncertainty or other words names as "imported uncertainty".

This paper will implement a calibration of the 3 decibel (dB) fixed attenuator defined as a half power loss in the radio frequency transmission line [8]. The half power loss is the best case for simulating radio frequency components as measured in the Vector Network Analyzer in terms of transmission and reflection. It is a passive device and high stability in repeating measurement compare to other active device such as antenna, amplifier, mixer and filters in the production floor. These products manufactured in the production floor would own the wider specification, tolerance and low stability. It is not a good sample for Vector Network Analyzer to perform the calibration and measurement uncertainty analysis because wider specification and tolerance contribute inaccurate measurement. At the same time, it will cause the Vector Network Analyzer measured in low accuracy, low precision and high uncertainty in calibration. Evaluation of type A uncertainty required a high stability system upon repeated measurement. This is for achieving the optimal measurement of type A uncertainty. Meanwhile, uncertainty of type B would allow a well-known good Vector Network Analyzer to perform the calibration of the transmission and reflection. This paper will demonstrate through calibration process associated with expanded uncertainty to the 3 dB fixed attenuator measurement. The key advantage is the same technique often used for the process of calibration of power sensors, radio frequency cables and connectors. The evaluation of uncertainty measurement in calculation from 300 kHz to 8.5 GHz will be applied if the same PXIe-5632 Vector Network Analyzer remains.

This paper is an extension of the work originally presented in the 2016 7th International Conference on Mechanical, Industrial, and Manufacturing Technologies [9] and Journal of Engineering Science and Technology Vol. 14, [10]. The limitation of this paper is frequency bandwidth from 300 kHz until 8.5 GHz only and frequency response transmission tracking analysis did not perform.

At the end of this paper the effects of measuring uncertainty will be compared with the other well-known manufacturer of the Vector Network Analyzer. It is to compare the estimation of the expanded uncertainty in measurement with the specific frequency bandwidth range. Improvements for future research can be established from the comparison.

2. Evaluation of Uncertainty Measurement

2.1. Type A Evaluation of Uncertainty

Evaluation of measurement uncertainty classified into two categories Type A and Type B. Type A evaluation evaluates the uncertainty resulted from the statistical study. The statistical analysis may be an undergrowth series of repeated measurements of the same process. The series of repeated measurements will fill in a standard deviation of mean. Type B evaluates uncertainty other than statistical analysis. The uncertainty is based on the manufacturer published specification.

Estimation of Type A evaluation of uncertainty can be applied when a set of measurement was recorded under the same condition with minimum 2 repeated measurement. An example of a quantity Y input with N statistically independent (N > 1) observed as y_j (where j = 1, 2, 3, …, n). The estimation of quantity of Y is $\bar{y}$, arithmetic mean wrote as equation (1) or applying the function of Average in Excel shown by equation 1 [11].

$$\bar{y} = \frac{1}{N} \sum_{j-1}^{N} y_j \tag{1}$$

The arithmetic mean of $\bar{y}$ is evaluated in equation 2 or applying the function of VAR.S in Excel to estimate the variance of probability distribution define as $s^2(y)$ shown by equation 2 [11].

$$s^2(y) = \frac{1}{N-1} \sum_{j=1}^{N} (y_j - \bar{y})^2 \qquad (2)$$

After estimation of arithmetic mean and variance had been calculated, the experimental standard deviation for Type A uncertainty was calculated in equation 3 by applying the function of STDEV in Excel shown by equation 3 [12].

$$s^2(\bar{y}) = \frac{s^2(y)}{N} \qquad (3)$$

The Type A standard uncertainty $u(\bar{y})$ associated with the initial set of measurement repeated $\bar{y}$ is the experimental standard deviation formula in equation 3. The standard uncertainty calculation is applying the same formula in equation 3. In order to differentiate the standard uncertainty and standard deviation, shown by equation 4. Type A standard uncertainty share the same formula in equation 3.

$$u(\bar{y}) = s(\bar{y}) \qquad (4)$$

The main purpose of repeated measurement is to disperse the data into a statistical waveform. This study obtains 5 repeated measurements to fill in the Type A measurement uncertainty.

Table 1: PXIe-5632 Type B contributors

Frequency Range	300 kHz to <5 GHz	5 GHz to 8.5 GHz	Unit	
Directivity	0.0106	0.020	dB	
Source Match	0.0125	0.0195	dB	
Reflection Tracking	0.1	0.1	dB	
Transmission Tracking	0.12	0.12	dB	
Load Match	0.0048	0.0114	dB	
Power Step Resolution	0.01	0.01	dB	
Trace Noise	0.0060	0.0060	dB	

2.2. Type B Evaluation of Uncertainty for PXIe-5632

Type B contributor to the uncertainty was based on the product specification of the PXIe-5632 Vector Network Analyzer. It is necessary to list as many as which aspect of the system will lead to the error. Table 1 describing seven types of contributors.

Vector Network Analyzer directivity is the relation between the leakage signal and the reflected signal. The lower directional leakage signals the better measurement quality. Source match define as the internal reflection error between the Vector Network

Analyzer generator and device under test. Reflection tracking is the loss from the test port, cable and connection at port 1 and port 2 independently at the network analyzer. Transmission tracking is the loss from the test port, cable and connection from port 1 to port 2 at the network analyzer. Load match is the error occur from the device under test to the receiver of network analyzer. Power step resolution refer to the most sensitivity resolution setting in the Vector Network Analyzer. Trace noise is the stability of the power when making the measurement across the bandwidth [13] swept in the network analyzer.

In the practical to perform a complete test and calibration set up shown by Figure 1 is a full two port characteristic calibration. This set up consists of a NI PXIe-1071 chassis, NI PXIe-8135 Controller, NI PXIe-5632 Vector Network Analyzer, a pair of gore cable and NI Automatic VNA Calibration Module 70 kHz until 9 GHz.
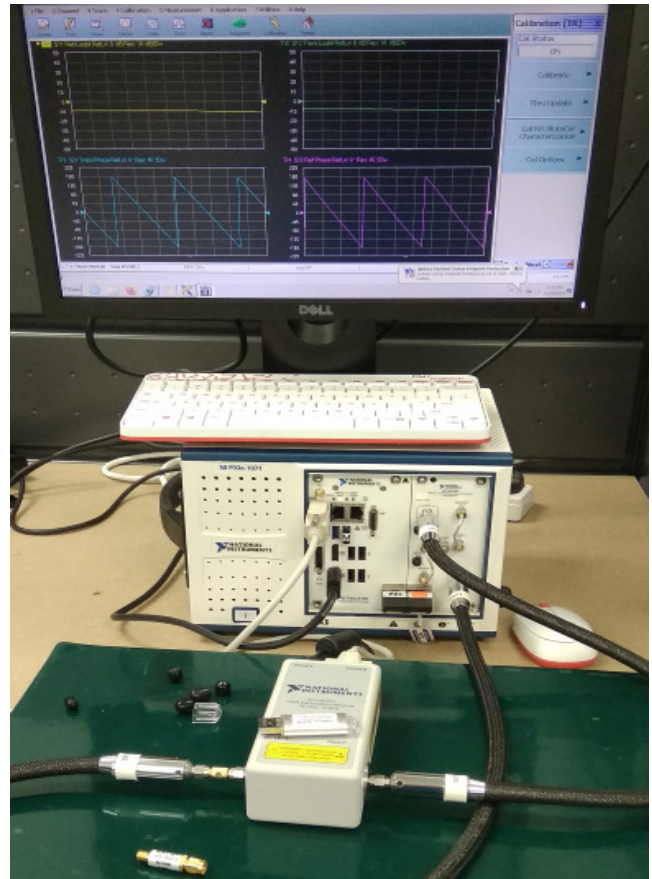

Figure 1 : A set up of PXIe-5632 Calibration

There are other variables that may contribute to the Type B uncertainty other than the 7 contributors mentioned in Table 1. The performance of the equipment would be degraded over time. In the product specification, some manufacturer may mention the aging or drift. It is up to engineers to either estimate the drift relative to the maximum or minimum specification limits or included as another Type B uncertainty component. One way of solving this problem is by calibrating the entire device shown in Figure 1. The manufacturer recommended one-year calibration interval for Vector Network Analyzer and Automatic Calibration Module. It is to ensure the absolute reading measured from this system is traceable to the International System of Units.

Once the calibration had been completed in Figure 1, this system is ready to measure a wide range of radio frequency devices such as antenna, amplifier, attenuator, splitter, filters and many more. In this paper, a 3 dB fixed attenuator manufacturer by Mini-Circuit with model VAT-3+ had been selected as shown by Figure 2.
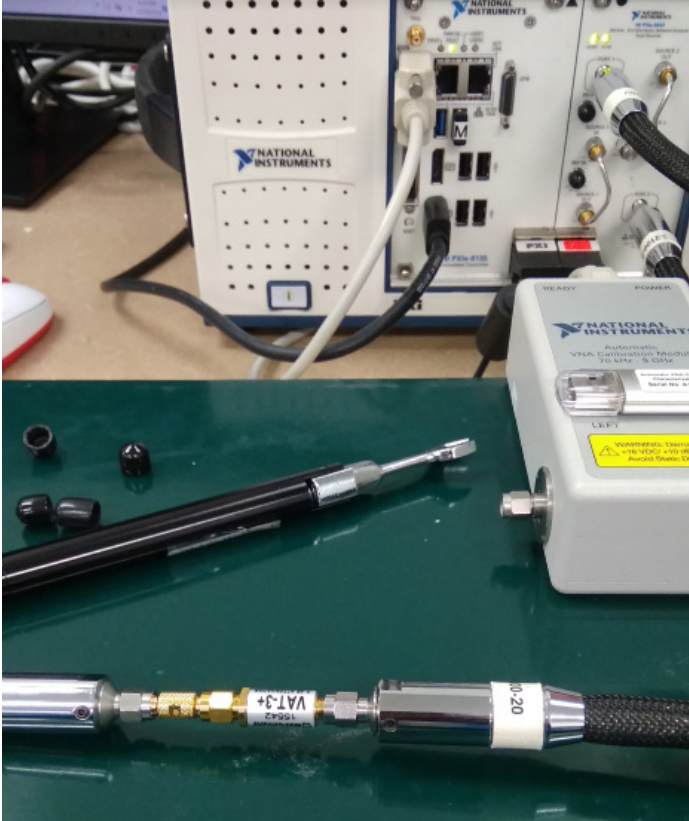

Figure 2: A 3 dB Fixed Attenuator under full two ports calibration

The 3 dB Attenuation L(X) to be calibrated was obtain shown by equation 5.

$$L(X) = \delta Lm + \delta Lk + \delta Lr \qquad (5)$$

Where:

δLm = Correction to mismatch loss

δLk = Correction for leakage for signal between input and output

δLr = Resolution of the network analyzer

The 3 dB Attenuation L(X) will be measured in the Vector Network Analyzer from 300 kHz until 8.5 GHz are known as absolute reading. These absolute reading will associate with estimated measurement uncertainty at the end of this paper. In order to measure the 3 dB Attenuation, there are 3 factors contribute to the measurement. It is identified as correction to mismatch loss, correction for leakage for signal between input and output and resolution of the network analyzer.

Correction to mismatch loss define as the calibration system consists of NI PXIe-5632 Vector Network Analyzer, a pair of gore cable and NI Automatic VNA Calibration Module 70 kHz until 9 GHz to perform the characteristics impedance calibration. Where

the characteristics impedance calibration accuracy traceable to the NI Automatic VNA Calibration Module.

Correction for leakage for signal between input and output is define as the power dissipate along the transmission line from the Vector Network Analyzer port 2 to port 1 (forwards transmission S21) and port 1 to port 2 (reverse transmission S12).

Resolution of the network analyzer refer to least significant digit measured from the Vector Network Analyzer. The least significant digit refers to the lowest digit from the display.

3. Uncertainty Analysis for PXIe-5632 Network Analyzer

Uncertainty analysis for PXIe-5632 Vector Network Analyzer required to combine Type A and Type B contributors. The Type A uncertainty had been completed in previous study. Refer to Table 2, there are 7 Type B contributors and 1 Type A contributor in the uncertainty analysis. Each of the Type A and B contributors required to identify the distribution type. Distribution type segregate by Normal Distribution, U-shape, Triangle or Rectangular.

Table 2: Uncertainty component's unit, evaluation and distribution type

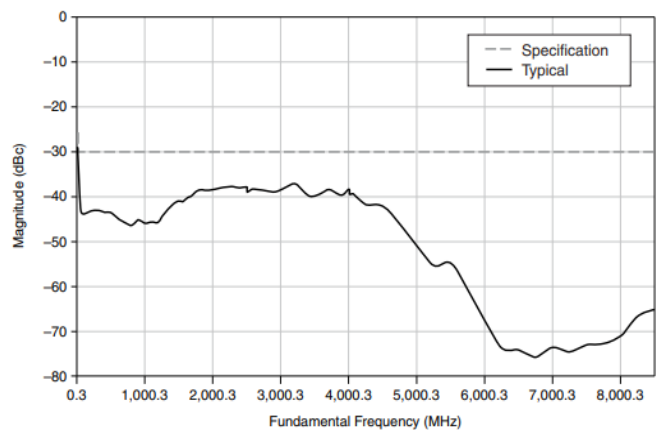| Uncertainty Component	Units	Evaluation Type	Distribution Type
Directivity	dB	B	U Shape
Source Match	dB	B	U Shape
Reflection Tracking	dB	B	Normal
Transmission Tracking	dB	B	Normal
Load Match	dB	B	U Shape
Power Step Resolution	dB	B	Rectangular
Trace Noise	dB	B	U Shape
Repeatability	dB	A	Normal

Figure 3 : PXIe-5632 Source Second Harmonics

Directivity, Source Match, Load Match and Trace Noise are identified as U-Shape distribution. The 4 contributors are mainly generated from the Vector Network Analyzer internal generators and receivers. It is systematic errors in the Vector Network Analyzer. An example PXIe-5632 generator second harmonic

recorded in the product specification [14] as shown by Figure 3. The trend of the source second harmonics does not populate in Normal Distribution, Rectangular or Triangle distribution. The source distribution type is populating close to U-Shape.

Reflection and Transmission Tracking were classified as normal distribution since uncertainty values recorded in dB were taken from the manufacturer specification. Element of repeatability uncertainty is normal distribution type. Table 3 will extend each of the uncertainty components calculation in divisor, standard uncertainty, degree of freedom and combine uncertainty.

Table 3: Uncertainty calculation from 300 kHz to <5 GHz

Uncertainty Component	Divisor	Standard Unc.	Degree of Freedom	Combine Unc.
Directivity	1.4142	0.0107	1000	0.0076
Source Match	1.4142	0.0195	1000	0.0138
Reflection Tracking	2	0.0200	1000	0.0100
Transmission Tracking	2	0.0700	1000	0.0350
Load Match	1.4142	0.0048	1000	0.0034
Power Step Resolution	3.4641	0.0100	1000	0.0029
Trace Noise	1.4142	0.0060	1000	0.0042
Repeatability	1	0.0176	4	0.0176
Combined Standard Uncertainty				0.0432
Effective Degree of Freedom				135.8664
Coverage Factor				1.96
Expanded Uncertainty				0.085
Unit				dB

For each variable, Table 3 calculates 4 contributors which were divisor, standard uncertainty, degree of freedom and combined uncertainty. Each part of the uncertainty was defined as the same element measured in dB. In this case, no conversion is necessary in order to convert to the same base unit. The sensitivity factor [15] for each contributor is equal to 1. U-Shape distribution divisor is 1.4142. The manufacturer reported standard uncertainty for reflection and transmission tracking are 0.02 dB and 0.07 dB respectively. Reflection and transmission tracking divisor are 2. Rectangular distribution divisor is 3.4641 [16].

The degree of freedom for the 7 Type B contributors are calculate as infinite. It is because the uncertainty contributors were based on the product specification. Which means the 7 Type B contributor are the worst-case [17] standard uncertainty. When a worst-case uncertainty contributor taken from the product specification, the values involved in the calculation was infinite.

Combined uncertainty [18] applied shown by equation 6.

$$U_L = \frac{\delta Us}{\delta Ud} \; x \; \delta Uf \tag{6}$$

Where:

δUs = Standard uncertainty contributor

δUd = Distribution type of divisor

δUf = Sensitivity Coefficient

Combined Standard Uncertainty U(s) [19] applied shown by equation 7.

$$U(s) = \sqrt{\sum_{L=1}^{N} (U_L)^2} \tag{7}$$

Where:

U_L = Uncertainty Components

Effective Degree of Freedom V(eff) [20] applied shown by equation 8.

$$V(eff) = \frac{U(s)^4}{\sum_{j-1}^{N} \frac{\delta Us^4 \delta Ud^4}{Vf}} \tag{8}$$

Where:

U(s) = Combined Standard Uncertainty

$\delta U(s)$ = Standard uncertainty contributor

δUd = Distribution type of divisor

Vf   = Degree of Freedom

Coverage factor refer to Effective Degree of Freedom in Table 3. It was calculated as 135.8664. Refer the value 135.8664 in Student T table. From Student T table, it was located between 100 and 1000 as shown by Figure 4. Choose the round up value at 95% confidence level as 1.962.

Figure 4 : Student T Table

Expanded Uncertainty E(u) [21] applied shown by equation 9.

$$E(u) = Us \; x \; Cf \tag{9}$$

Where:

U(s) = Combined Standard Uncertainty

Cf   = Coverage Factor

From Table 3, it was concluded that the Expanded Uncertainty from 300 kHz until 5 GHz reported at 0.085 dB. The same methodology applied from 5 GHz to 8.5 GHz frequency range as shown by Table 4.

Coverage factor refer to Effective Degree of Freedom in Table 4. It was calculated as 115.2108. Check the calculated reading 115.2108 from Student T table. From the Student T table, it was located between 100 and 1000 as shown by Figure 5. Choose the round up value at 95% confident level as 1.962.

Table 4: Uncertainty calculation from 5 GHz to 8.5 GHz

Uncertainty Component	Divisor	Std Unc.	Degree of Freedom	Combine Unc.
Directivity	1.4142	0.0200	1000	0.0141
Source Match	1.4142	0.0195	1000	0.0138
Reflection Tracking	2	0.0200	1000	0.0100
Transmission Tracking	2	0.0700	1000	0.0350
Load Match	1.4142	0.0227	1000	0.0161
Power Step Resolution	3.4641	0.0100	1000	0.0029
Trace Noise	1.4142	0.0060	1000	0.0042
Repeatability	1	0.0212	4	0.0212
Combined Standard Uncertainty				0.0495
Effective Degree of Freedom				115.2108
Coverage Factor				1.96
Expanded Uncertainty				0.097
Unit				dB

Figure 5 : Student T Table

From Table 4, it was concluded that the Expanded Uncertainty from 5 GHz until 8.5 GHz reported at 0.097 dB. The expanded uncertainty evaluation was reported respected to its frequency points as shown by Table 5. Forwards transmission (S21) and reverse transmission (S12) was the magnitude of absolute measurement associate with expanded uncertainty. The expended uncertainty should report in 2 decimal points.

Table 5: An Example of Calibration Report with Expanded Uncertainty

DUT Calibration Report				
Frequency (GHz)	S21	Uncertainty	S12	Uncertainty
0.0003	-2.939	0.084	-2.951	0.085
1	-3.092	0.084	-3.111	0.085
2	-3.154	0.084	-3.168	0.085
3	-3.189	0.084	-3.195	0.085
4	-3.29	0.084	-3.297	0.085
5	-3.239	0.084	-3.242	0.085
6	-3.379	0.093	-3.395	0.097
7	-3.408	0.093	-3.425	0.097
8	-3.497	0.093	-3.498	0.097
8.5	-3.553	0.093	-3.562	0.097

4. Discussion

In this paper the measurement uncertainty calculation was referred to the process flow of ISO / IEC Guide 98-1 to quantify the measurement uncertainty as Figure 6.
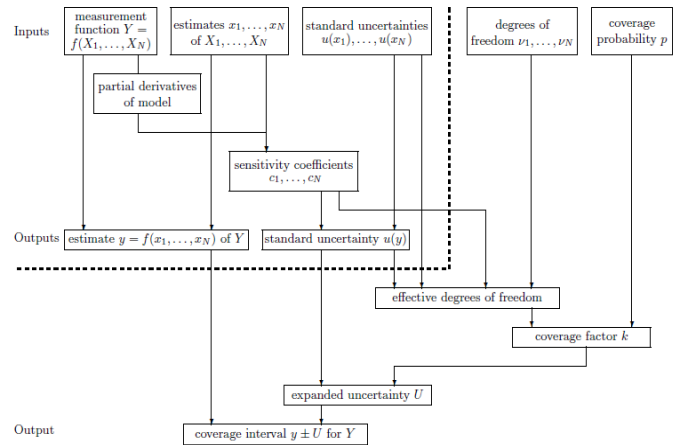

Figure 6 : ISO/IEC Guide 98-1 Uncertainty Calculation Process Flow

The flow diagram was divided into two major groups. It is input and output. In this paper, Tables 1 and 2 represent input. Whereas Tables 3, 4 and 5 reflect output. All tables describe the flows necessary to calculate the measurement uncertainty. There are total 6 systematic errors in reflection and transmission were found in the Vector Network Analyzer. It is identified as directivity, source match and frequency response reflection tracking for reflection. Transmission measurement generate another 3 systematic errors identified as isolation, load match and frequency response transmission tracking. The limitation from this paper to calculate the measurement uncertainty is without isolation taking into the consideration.

However, the vector Network Analyzer and Calibration Kits were used in the calculation of measurement uncertainty will undergo the process of validation to ensure whether the hardware meets the minimum specification as discuss in 4.1.

4.1. Vector Network Analyzer Directivity Validation by Using Anritsu Mechanical Verification Kits

The reading of Directivity and Source Match in Table 1 was released by the manufacturer as product specification. Validation is necessary to ensure the Vector Network Analyzer complies with the specification. To perform the validation, verification kits are expected using the airline, as shown in Table 6.

Table 6: Directivity and Source Match Experimental Test

Experimental	Directivity	Source Match
300 kHz to 5 GHz	Anritsu SC7953 Super Termination	Anritsu 23K50 Male Short
5 GHz to 8.5 GHz	Anritsu SC4808 20 dB Offset Termination and Anritsu SC7594 Airline	Anritsu 23KF50 Female Short and Anritsu SC7594 Airline

Directivity is load test and source match is short test. Both directivity and source match sharing the same Anritsu SC7594 airline in high frequency. Either the validation of the directivity or the source match is enough to justify the efficiency of the Vector Network Analyzer, and the calibration kits comply with the specification specified in Table 1. In this paper the validation of the directivity was chosen to compare against the product specification. This is because the vector network analyzer uses the directional couplers or bridges to make reflected measurements. When the Vector Network Analyzer calibrated with the calibration kits, a small amount of incident signal leakage through the directional couplers or bridges into the receiver. This incident happens on both ports 1 and 2 of the Vector Network Analyzer. The leakage signal will affect the accuracy and precision of the Vector Network Analyzer. The leakage signal in directivity validation could be validated using the SC7953 super termination and SC4808 20-dB offset termination attachment to Anritsu SC7594 airline as shown in Figure 7.

Figure 7 : Directivity Validation by Using Anritsu Verification Kit from 300 kHz to 5 GHz (left) and 5 GHz to 8.5 GHz (right)
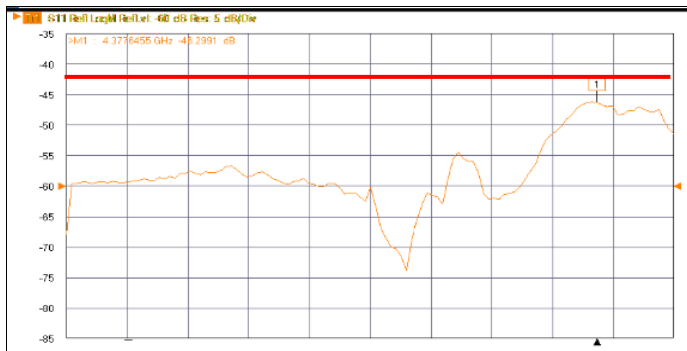

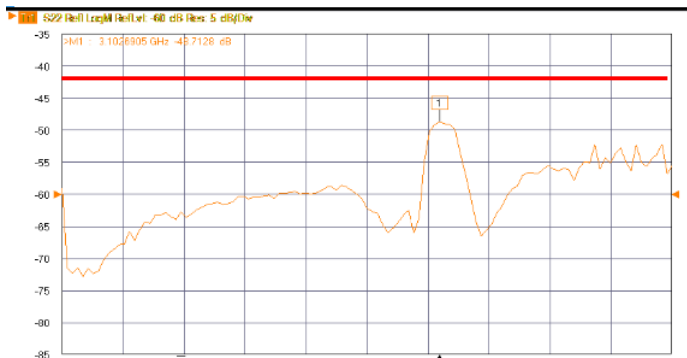Figure 8 : PXIe-5632 Port 1 Directivity Validation Results Measured from 300 kHz to 5 GHz

Figure 9 : PXIe-5632 Port 2 Directivity Validation Results Measured from 300 kHz to 5 GHz

Once the Anritsu SC7953 super termination attach to the ports 1 and 2 at the Vector Network Analyzer, the SC7953 super termination will absorb the power transmitted from the Vector Network Analyzer generator. The results of this test shown by Figure 8 for port 1 and Figure 9 for port 2 of the Vector Network Analyzer respectively measured at -46.29 dB and -48.21 dB.

The maximum product specification is -42 dB from 300 kHz until 5 GHz. This experiment shows that the Vector Network Analyzer performed better than the specification required.

Figures 10 and 11 demonstrate the ports 1 and 2 directivity test measured from 5 GHz until 8.5 GHz. The maximum accepted ripples are 3.1dB. The Vector Network Analyzer was found within the product specification.
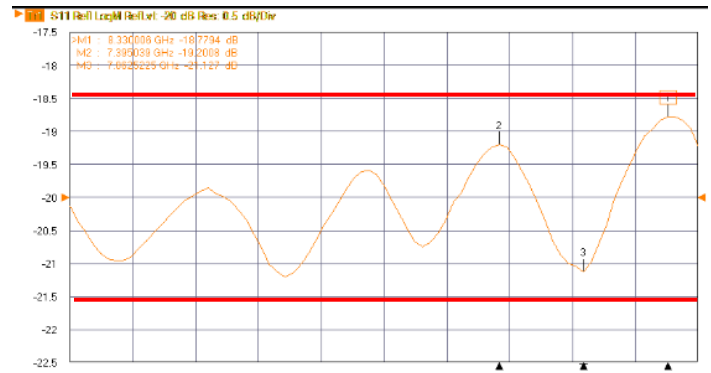

Figure 10 : PXIe-5632 Port 1 Directivity Validation Results Measured from 5 GHz to 8.5 GHz
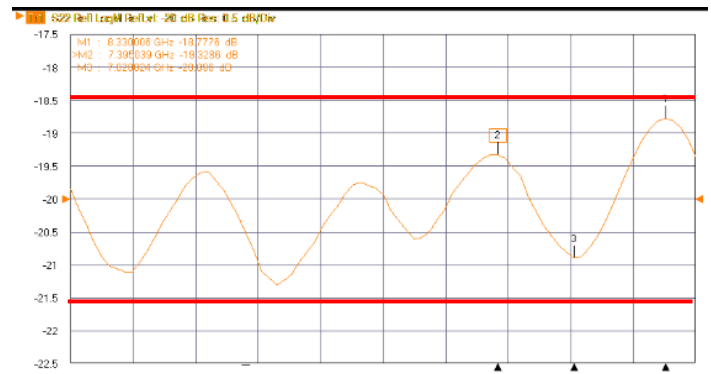

Figure 11 : PXIe-5632 Port 2 Directivity Validation Results Measured from 5 GHz to 8.5 GHz

In this validation experimental, the Vector Network Analyzer directivity measurement swept from 300 kHz to 8.5 GHz concludes the Vector Network Analyzer was performed better than the required specification. Since the directivity of the PXIe-5632 Vector Network Analyzer performed better than the warranted specification, directivity component listed in Table 1 is validated.

4.2. Vector Network Analyzer Mismatch Validation with 3 dB Fixed Attenuator Product Specification

The Anritsu Verification kit used to measure the Directivity and Source Match ripples. The ripples measured from the Vector Network Analyzer would be the Type B contributor respected to its frequency bandwidth. Meanwhile the Load Match from Table 1 was determined from below criteria as Table 7.

Table 7: Fixed Attenuator and VNA Mismatch Calculate in dB

Frequency	3 dB Attenuator	VNA	Mismatch (%)	dB
300 kHz to 5 GHz	1.15	1.016	0.1107	0.0048
5 GHz to 8.5 GHz	1.5	1.032	0.5256	0.0227

From Table 7, the voltage standing wave ratio for 3 dB attenuator measure at 1.15 and 1.5 were taken from the manufacturer specification. The voltage standing wave ratio for Vector Network Analyzer measured at 1.016 and 1.032 was conversion from the product specification Load Match 42 and 36 dB respectively. To calculate the Load Match from the Vector Network Analyzer together with the fixed attenuator VAT-3+ by applying the mismatch formula [22]. The calculated mismatch was in percentage. It is required to convert the mismatch in percentage to dB [23].

Table 2 used to determine the distribution type for each contributor. The main reason why reflection and transmission tracking did not category as U-Shape distribution type because from the product datasheet it was provided the info as uncertainty in typical. The uncertainty value reported in typical is identical to 2 sigma uncertainty. In order to calculate the Type B contributor for reflection and transmission tracking correctly, it is normal distribution type. If both reflection and transmission tracking identified as U-Shape distribution type, the expanded uncertainty will be increased as Tables 8 and 9. The uncertainty will be increased from 0.085 to 0.111 and 0.098 to 0.122. The expended uncertainty in Tables 8 and 9 could not classified incorrect expended uncertainty calculation because it is meet the ISO/IEC Guide 98-1 method. The only disadvantage for Tables 8 and 9 is the calculated expanded uncertainty approximately 30% increase from the initial calculation in Tables 3 and 4 respectively.

Table 8: Effect of Reflection and Transmission Distribution Type Changed from 300 kHz to 5 GHz

Uncertainty Component	Distribution Type	Divisor	Std Unc.	Combined
Directivity	U	1.4142	0.0107	0.0076
Source Match	U	1.4142	0.0195	0.0138
Reflection	U	1.4142	0.0200	0.0141
Transmission	U	1.4142	0.0700	0.0495
Load Match	U	1.4142	0.0048	0.0034
Power Step	Rectangular	3.4641	0.0100	0.0029
Trace Noise	U	1.4142	0.0060	0.0042
Repeatability	Normal	1	0.0176	0.0176
Combined Standard Uncertainty				0.0565
Effective Degree of Freedom				337.94
Coverage Factor				1.96
Expanded Uncertainty				0.111
Unit				dB

4.3. Vector Network Analyzer Reflection and Transmission Improvement

Distribution type identification for each contributor in table 2 is very important. We need to understand and identify the distribution type for each contributor correctly in order to compute the lowest expended uncertainty. The lower expended uncertainty calculated, the better system it is.

Table 9: Effect of Reflection and Transmission Distribution Type Changed from 5 GHz to 8.5 GHz

Uncertainty Component	Distribution Type	Divisor	Std Unc.	Combined
Directivity	U	1.4142	0.0200	0.0141
Source Match	U	1.4142	0.0195	0.0138
Reflection	U	1.4142	0.0200	0.0141
Transmission	U	1.4142	0.0700	0.0495
Load Match	U	1.4142	0.0227	0.0161
Power Step	Rectangular	3.4641	0.0100	0.0029
Trace Noise	U	1.4142	0.0060	0.0042
Repeatability	Normal	1	0.0212	0.0212
Combined Standard Uncertainty				0.0614
Effective Degree of Freedom				251.7565
Coverage Factor				1.98
Expanded Uncertainty				0.122
Unit				dB

4.4. PXIe-5632 Vector Network Analyzer Limitation and Improvement for Future Work

A comparison against the calibration and measurement capability for transmission S21 with other manufacturer had been completed in Table 10. The purpose of the comparison is to measure the gap analysis between other Vector Network Analyzer manufacturers and this study.

Table 10: Transmission S21 Comparison With other Manufacturer

Transmission S21	Study	OEM1	OEM2
Calibration and Measurement Capability in dB	0.086 to 0.094	0.057	0.029 to 0.056
VNA system in use	NI PXIe-5632	HP 8753ES	MS 462xx

The calibration and measurement capability for OEM1 and OEM2 were downloaded from Accredited body website. The manufacturer published the best capability in Transmission S21 measurement. The differences between this OEM1 and this study is approximate 33.7% better in measurement capability. Meanwhile the gap analysis between OEM2 and this study was approximate 66.2% better in measurement. Both OEM1 and OEM2 delivered the better number in expanded uncertainty calculation because both OEM1 and OEM2 select the higher accuracy of the Vector Network Analyzer. To improve this study, we need to focus at the main contributors is Tables 3 and 4 in order to enhance the system.

From Tables 3 and 4, it was found that Transmission Tracking and Repeatability contribute more than half of the expended uncertainty calculation. To improve the Transmission Tracking uncertainty contributor, we need a calibrated 3 dB attenuator from National Measurement Laboratory becomes a reference attenuator to calibrate the NI PXIe-5632 Vector Network Analyzer. A calibrated 3 dB attenuator from United Kingdom National

Measurement Institute, National Physical Laboratory (United Kingdom Accreditation Service number 0478) could carry the reflection and transmission uncertainty as low as 0.01 dB and 0.0012 dB respectively. The known attenuation value calibrated from National Physical Laboratory could overwrite the NI PXIe-5632 Vector Network Analyzer product specification in reflection and transmission Tracking accuracy by 2 time and 58 times improved respectively calculated in Tables 11 and 12.

Table 11: Reflection and Transmission Tracking Uncertainty With Reference Attenuator from 300 kHz to 5 GHz

Uncertainty Component	Standard Uncertainty	Combined
Directivity	0.0107	0.0076
Source Match	0.0195	0.0138
Reflection	0.0100	0.0071
Transmission	0.0012	0.0008
Load Match	0.0048	0.0034
Power Step	0.0100	0.0029
Trace Noise	0.0060	0.0042
Repeatability	0.0176	0.0176
Combined Standard Uncertainty		0.0243
Effective Degree of Freedom		14.4105
Coverage Factor		1.96
Expanded Uncertainty		0.048
Unit		dB

Table 12: Reflection and Transmission Tracking Uncertainty With Reference Attenuator from 5 GHz to 8.5 GHz

Uncertainty Component	Standard Uncertainty	Combined
Directivity	0.0200	0.0141
Source Match	0.0195	0.0138
Reflection	0.0100	0.0071
Transmission	0.0012	0.0008
Load Match	0.0227	0.0161
Power Step	0.0100	0.0029
Trace Noise	0.0060	0.0042
Repeatability	0.0212	0.0212
Combined Standard Uncertainty		0.0343
Effective Degree of Freedom		27.2742
Coverage Factor		1.98
Expanded Uncertainty		0.068
Unit		dB

Nevertheless, the significant improvement in reflection and transmission tracking accuracy also will help to recalculate the Type A repeated uncertainty contributor to a smaller number in uncertainty are based on theory and for future study.

4.5. Summary of Discussion

Table 13 is the summary of improvement calibration technique applied the 3 dB reference attenuator into the NI PXIe-5632 Vector Network Analyzer calibration system. When this technique applied in the NI PXIe-5632 calibration system, the calibration and measurement capability performance is like other manufacturer Vector Network Analyzer and the investment is the lowest among the others.

Table 13: Summary of Improvement Calibration Technique NI PXIe-5632 With Reference Attenuator

Transmission S21	Study	OEM1	OEM2
Calibration and Measurement Capability in dB	0.086 to 0.094	0.057	0.029 to 0.056
VNA system in use	NI PXIe-5632 With 3dB Reference Attenuator	Agilent 8753ES/ E5071C	Anritsu MS462x
Investment	Low - USD 20k	High - USD 50k	Medium- USD 35K

5. Conclusion

In this paper, an evaluation of measurement uncertainty for NI PXIe-5632 Vector Network Analyzer from 300 kHz to 8.5 GHz is calculated. This frequency bandwidth is widely used in telecommunications particularly in the calibration system for the 5 G sub-6GHz. This paper clarified the extended uncertainty measurement applied in the Vector Network Analyzer, valued to specific calibration techniques. A complete mathematical review shows the effects in each step involve changes to the contributor of uncertainty. This paper could help improve the scattering of parameters for commercial laboratories to extend the calibration potential in the new sector. The calibration technique of the 3 dB fixed attenuator also helps the commercial calibration laboratory explore existing measuring capacities and increase the degree of competence in the laboratory. In the discussion, it is explained different Vector Network Analyzer techniques applied in the NI PXIe-5632 could generate different expanded uncertainty in calculation. Based on the laboratory budget planning, the laboratory is free to choose which calibration technique would apply in the new scope. A part of the limitation of this paper is that isolation does not take into the estimation of measurement uncertainty calculation. It is because the manufacturer did not specify the specification for the isolation, but the systematic error of isolation could be established by validation or experimental. As future of this work, the first development is to increase the frequency from 8.5 GHz to 50 GHz. The second development is extending to Vector Network Analyzer Scattering Parameters port 1 (S11) and port 2 (S22). The calculation of the reflections S11 and S22 involved only port 1 or port 2. In addition, a measure of the test uncertainty ratio may also be added in future to satisfy the requirements of ANSI / NCSL Z540.

6. Acknowledgements

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