CHARACTERIZATION OF THE MEASUREMENT UNCERTAINTY FOR THE ELECTROMAGNETIC CONDUCTED AND RADIATED EMISSION TEST

MOHD ERDI BIN AYOB

A thesis submitted in fulfillment of the requirement for the award of the PERP Far 1 Degree of Master of Engineering Technology

APRIL 2017

For my beloved mother and father for their endless love, support and encouragement.

ACKNOWLEDGEMENT

First and foremost, I wish to express my ultimate gratitude to my parents for their love and support throughout my entire life in chasing my dreams. A special thanks to my lovely wife, daughters and sons for their patience and understanding having indirectly involved throughout the completion of my study.

My sincere appreciation to my supervisor, Prof. Madya Dr. Jumadi Bin Abdul Sukor for his guidance, support, word of wisdom, patience, encouragement and for his confidence in me for the entire duration of this research. He has been my inspirations to overcome great challenges and serve as a role model when I was serving the department right from day one in the FTK in 2012.

Also, I would like to extend my heartfelt appreciation to my co-supervisor Prof. Dr. Mohammad Zarar Bin Mohamed Jenu for giving me the opportunity to serve the EMCenter over the last 10 years and also for his outstanding ideas who sparked this EMC research in UTHM.

Last but not least, to my colleagues in UTHM and UTeM, I owe them a great deal of gratitude for helping me in multiple ways. Finally, this appreciation goes to the people who have involved directly and indirectly towards the completion of this thesis.



ABSTRACT

Electromagnetic Compatibility or EMC is the ability for the product or equipment under test (EUT) able to operate in its intended environment with causing undue interference or being unduly affected by it. The requirement for non-interference has been known for many years but it is only now with the introduction of legislation that we are seeing a major growth in demand for testing. The USA with its FCC regulations has for some time tried to control emissions from certain types of equipment. Japan has also had a voluntary code (VCCI) and Europe, after some delay, fully introduced mandatory regulations at the end of 1996.

The ultimate importance of an EMC testing is to ensure the EUT is not affected by the other operating EUT and vice versa. These conditions apply for both conducted (CE) and radiated emission (RE). Other areas are now introducing regulations and it seems likely that the system will spread to encompass the whole world in the future. Currently, measurement of an equipment under test (EUT) shall cast a doubt when the result is close to the specification limits. In the common practice, the MU is taken as an informational purpose only in the report and not for the EUT status. The implementation of the measurement uncertainty for the reporting is crucial since the EUT might fail the EMC test if the passing margin is below the International Special Committee on Radio Interference (CISPR) standards.

In acquiring the MU for the judgement criteria, comparison with the standards and inter-laboratory comparison shall take place. These include the standard classification for the EUT type, expanded uncertainty estimation to the CISPR standard (U_{CISPR}), EMC equipment factor estimation and proficiency test with the other accredited EMC laboratory using the Z-Score method. The inter-laboratory comparison used the same calibrated signal source which emits the stable broadband emission. Finally, the cumulative results are to be taken as a laboratory expanded



uncertainty U_{LAB} = 2u_c(y). The thesis focused the application of the expanded uncertainty deployment for the judgement criteria for the finalize EUT status.

The expanded uncertainty for both measurement CE and RE are 3.058 dB and 4.2 - 4.58 dB respectively which are well below the CISPR standard 3.6 - 5.2 dB. On the other hand, the inter-laboratory comparison between two EMC laboratories, EMcenter UTHM and EMC Singapore EPSON Ptd Ltd (SEP) have shown that about |1.41| for the Z-score analysis which met the CISPR requirement for the Z-score <|1.96|. Thus, both expanded uncertainty and Z-score results met the CISPR requirement which is required for the accreditation of an ISO 17025 (General requirements for the competence of testing and calibration laboratories).

Finally, the work further presented relating to the actual measurement of a sampled EUT of 45 units of CE and 44 units for RE. The measurement of the EUT comprises the QP margin to be compared with the CISPR limits and the U_{LAB} . For the EUT to be completely pass the EMC test, both condition CISPR limits and U_{LAB} must be met. A novel method has been implemented in the emission results to satisfy both conditions which later, to determine the EUT status and summarized in the final reporting. In CE measurement, about 26.67% of non-compliant EUT have a QP margin below than the $U_{LAB} = 3.058$ dB and 34.09 % of non-compliant EUT which have a margin below than the $U_{LAB} = 4.2 - 4.58$ dB for RE measurement. Prior to the new method, these EUT have passed the EMC test by taking only the QP emission compared to the CISPR limits. Again, by having the novel method, it is clearly verified the status of the EUT by taking the QP margin compared to the U_{LAB} as an additional verification to the EUT status.

Thus, a good verification prior and after the entire measurements which 21involved the: (1) comparison to the CISPR standard; (2) inter-laboratory comparison using the Z-score method, and; (3) actual measurement to the passed EUT. These results showed a good performance, usefulness and highlight the potential benefit of incorporating the measurement uncertainty for EUT judgement criteria.



CONTENTS

	TITL	-E	i	
	DEC	LARATION	ii	
	DED	ICATION	iii	
	ACK	NOWLEDGEMENT	iv	
	ABS	TRACT	v	
	CON	ITENTS	vii	
	LIST	OFTABLES	xii	
	LIST	OF FIGURES	xiv	
	LIST	OF SYMBOLS AND ABBREVIATIONS	xvii	
	LIST	OF APPENDICES	xix	
CHAPTER 1	INTE	RODUCTION	1	
	1.1	Introduction	1	
	1.2	Problem statement	5	
	1.3	Aim and objectives	6	
	1.4	Scope of work	6	
	1.5	Research contributions	7	
	1.6	Thesis organization	7	
CHAPTER 2	LITE	ERATURE REVIEW	9	
	2.1	Introduction to Measurement Uncertainty	9	
	2.2	Introduction to the EMC Testing	12	

2.2.1	Conducted Emission Test
2.2.2	Radiated Emission Test
2.2. 3	Inter-laboratory comparison using Z-
	score
Previo	us Works on Measurement Uncertainty
2 .3 .1	Median Value of a Measurement
	Uncertainty
2.3.2	Measuring Antenna for a Measurement

2.3.3 Reference Signal Source for a	
Measurement Uncertainty Evaluation	23
Quasi-Peak Levels at Close Limit Lines	
Chapter Summary/Research Gap	25
	28

2.4 Quasi-Peak Levels at Close Limit Lines 2.5 Chapter Summary/Research Gap

2.3

Uncertainty Evaluation

	2.5	Chapu	er Summary/Research Gap	20
				28
CHAPTER 3	METH	HODOI	LOGY	31
	3.1	Introd	uction	31
	3.2	Measu	rement Uncertainty for CE	35
		3.2.1	Appropriate standard classification	35
		3.2.2	Appropriate Input Quantities	35
			Classification for Expanded Uncertainty	
			Estimation and Comparison with	
			Standard	
		3.2.3	QP Level Estimation	37

- 3.2.3.1 Factor (dB) Estimation 37
 - 3.2.3.2 QP Reading 43

14

16

18

19

19

21

		3.2.4	Proficiency Test	44
	3.3	Measu	rement Uncertainty for RE	44
		3.3.1	Appropriate standards classification	44
		3.3.2	Appropriate Input Quantities	44
			Classification for Expanded Uncertainty	
			Estimation and Comparison with	
			Standard	
		3.3.3	QP Level Estimation	46
			3.3.3.1 Factor (dB) Estimation	46
			3.3.3.2 QP Reading	49
		3.3.4	Proficiency Test	52
	3.4	Expan	ded uncertainty deployment	53
	3.5	Chapte	er Summary	57
CHAPTER 4	RESU	LTSA	ND DISCUSSION	58
	4.1	Introdu	uction	58
	4.2	Comp	arison with standard for CE	58
		4.2.1	Results	58
		4.2.2	Discussions	60
	4.3	Inter-l	aboratory Comparison (ILC) for CE – Factor	60
		Estima	ation	
		4.3.1	Results	60
		4.3 .2	Discussions	62
	4.4	Inter-la	aboratory Comparison (ILC) for CE – QP	62
		Level	Estimation	

ix

		4.4.1	Results	62
		4.4.2	Discussions	68
	4.5	Comp	arison with standard for RE	69
		4.5.1	Results	69
		4.5.2	Discussions	72
	4.6	Inter-1	aboratory Comparison (ILC) for RE – Factor	72
		Estima	ation	
		4.6.1	Results	72
		4.6.2	Discussions	74
	4.7	Inter-1	aboratory Comparison (ILC) for RE – QP	75
		Level	Estimation	
		4.7.1	Results	75
		4.7.2	Discussions	80
	4.8	QP Le	vel Estimation of CE and RE for sampled	82
		EUT		
		4.8.1	Results	82
		4.8.2	Discussions	87
			4.8.2.1 Sample Results for QP Level	87
			Estimation of CE	
			4.8.2.2 Sample Results for QP Level	88
			Estimation of RE	
	4.9	Chapte	er Summary	88
CHAPTER 5	CONC	CLUSI	NC	90
	5.1	Conclu	usion	90

x

5.2	Research contribution	92
5.3	Recommendation for future work	92
REFERENCES		
APPE	NDICES	98
VITA		114

xi

LIST OF TABLES

1.1	Sample of measurement uncertainty budget [8]	5
2.1	Contribution factors [5]	11
2.2	Measurement Uncertainty [5]	12
2.3	Antennas for EMC testing [5]	17
2.4	Number of participated test site and the condition of	20
	radiated emission measurement [24-25]	
2.5	Expanded Uncertainties (U) from the ILC results [33]	25
2.6	QP level at a marginal level or close to the QP limit	27
	line [38]	
2.7	QP level at a marginal level or close to the QP limit	28
	line [39]	
2.8	Sample of EMC test report statements	29
3.1	The input quantities (xi) for CE (Conducted	36
	disturbance measurements from 9 kHz to 150 kHz and	
	150 kHz to 30 MHz). Table adopted from [5]	
3.2	LISN factor versus frequency (Toyo EP5CE software)	42
3.3	Uncertainty of Radiated Emission (Radiated	45
	disturbance measurements from 30 MHz to 200	
	MHz). Table adopted from [5]	
3.4	Uncertainty of Radiated Emission (Radiated	46
	disturbance measurements from 200 MHz to 1000	
	MHz). Table adopted from [5]	
3.5	Teseq CBL 6111D antenna factor (Toyo EP5CE	49
	software)	
3.6	Assessment of the z-score. Table adopted from [56]	53

3.7	Various types of EUT undergo EMC test for CE and	4
	RE measurements at EMCenter UTHM	
4.1	The expanded uncertainty (U_{LAB}) for CE measurement	59
	from 9 - 150 kHz	
4.2	The expanded uncertainty (U_{LAB}) for CE measurement	59
	from 0.15 -30 MHz	
4.3	CE measurement for EMCenter UTHM	63
4.4	CE measurement for SEP	65
4.5	Comparison of the QP levels	67
4.6	Z-score analysis for CE	68
4.7	Uncertainty of Radiated Emission (Radiated	70
	disturbance measurements from 30 MHz to 200 MHz)	
4.8	Uncertainty of Radiated Emission (Radiated	71
	disturbance measurements from 200 MHz to 1000	
	MHz)	
4.9	QP level from the reference signal source for	76
	laboratory EMCenter UTHM	
4.10	QP level from the reference signal source for SEP	77
4.11	Comparison of the QP levels	79
4.12	The Z-score analysis for RE	80
4.13	Summary of EUT status for CE	83
4.14	Summary of EUT status for RE	84
4.15	EUT final measurement for CE	85
4.16	Expanded Uncertainty for CE	85
4.17	Summary of a EUT status for the CE judgement	85
	criteria	
4.18	EUT final measurement for RE	86
4.19	Expanded Uncertainty for RE	86
4.20	Summary of a EUT status for the RE judgement	86
	criteria	
4.21	Summary of a the EUT sample results for CE	87
4.22	Summary of a the EUT sample results for RE	88

P

LIST OF FIGURES

1.1	Test Setup for the conducted emission (CE) [8]	2
1.2	Test Setup for the radiated emission (RE) [8]	3
1.3	Random errors [8]	4
1.4	Systematic errors [8]	4
2.1	Possibilities for reporting compliance [6]	9
2.2	Probability distributions [6]	10
2.3	The differences between conducted and radiated	13
	emission [8]	
2.4	Conducted Emission Test Setup [8]	15
2.5	Equivalent circuit for the LISN [11]	16
2.6	Radiated Emission Test Setup [8]	17
2.7	Bi-conical and double ridge horn antenna positioning	21
	[32]	
2.8	Measurement result with vertical polarization for	22
	double ridge horn antenna [32]	
2.9	Measurement result with vertical polarization for log	23
	periodic antenna [32]	
2.10	Output of a spectrum from the multi-tone generator for	24
	the ILC [33]	
2.11	Electric field strength at five frequencies for the ILC	24
	[33]	
2.12	Conducted Emission measurement data [38]	26
2.13	Conducted Emission measurement data (lower	26
	frequency span 1.00 – 5.00 MHz) [38]	
2.14	Radiated Emission measurement data [39]	27
3.1	3m Semi Anechoic Chamber (EMCenter UTHM)	32

3.2	10m Full Anechoic Chamber (Singapore EPSON Ptd	33
	Ltd)	
3.3	Measurement layout (RF antenna and turntable)	33
3.4	Characterization of an MU	34
3.5	Measurement for factor estimation	37
3.6	ETS-Lindgren 3810/2 10A single phase LISN (ETS-	38
	Lindgren)	
3.7	HP 11947A Transient Limiter (9 kHz – 200 MHz) for	38
	conducted emission (Hewlett-Packard Inc.)	
3.8	Connection for the Insertion / Path Loss estimation for	39
	CE measurement system	
3.9	Rohde & Schwarz SMB100A (9 kHz – 6 GHz) signal	40
	generator (Rohde & Schwarz GmbH & Co KG)	
3.10	Advantest R3131A (9 kHz – 3 GHz) spectrum	40
	analyzer (Advantest Corporation)	
3.11	Schaffner SCR 3102 EMI Receiver (9 kHz - 2.75	41
	GHz) for quasi-peak measurement (Schaffner	
	Holding)	
3.12	LISN factors in log scale versus frequency	42
3.13	Connection for the comb generator connected to the	43
	LISN [11]	
3.14	Com Power CGC 510 comb generator for conducted	43
	emission (Com-Power Corporation)	
3.15	Connection for the Insertion / Path Loss estimation for	47
	RE measurement system. Figure reproduced from [46]	
3.16	Teseq CBL 6111D antenna factor (Toyo EP5CE	48
	software)	
3.17	Com Power CGC 520 comb generator for radiated	50
	emission (Com-Power Corporation)	
3.18	Teseq CBL6111D Biconical Log Periodic Antenna	50
	(Bi-log) (Teseq AG)	
3.19	RE measurement setup with the comb generator using	51
	the bi-conical and log periodic antenna [27]	



3.20	Actual measurement setup for QP Reading	51
3.21	CE emission measurement setup for EUT	55
3.22	RE emission measurement setup for EUT	56
4.1	EMI receiver reading versus frequency	61
4.2	Factor versus frequency	61
4.3	CE measurement for EMCenter UTHM	62
4.4	CE measurement for SEP	64
4.5	Inter-laboratory comparison for CE at $0.15 - 30 \text{ MHz}$	66
	using the comb generator	
4.6	EMI receiver reading connected directly to the signal	73
	generator	
4.7	Insertion / path loss for RE	73
4.8	Comb generator radiated emission output for	75
	EMCenter UTHM	
4.9	Comb generator radiated emission output for SEP	77 A H
4.10	Inter-laboratory comparison for RE at 30 – 1000 MHz	78
	using the comb generator (CGO-520)	

xvi

LIST OF SYMBOLS AND ABBREVIATIONS

- AF Antenna Factor
- AMN -Artificial Mains Network
- CE **Conducted Emission**
- CE Conformité Européenne (European Conformity)
- CISPR -Comité International Spécial des Perturbations Radioélectriques JNKU TUN AMINA
- dB Decibel
- EMC -Electromagnetic Compatibility
- EMI **Electromagnetic Interference**
- EUT Equipment Under Test -
- FCC Federal Communication Commission -
- **GPIB** General Purpose Interface Board
- Ground Reference Plane GRP
- GTEM -Gigahertz Transverse Electromagnetic
- HPF High Pass Filter -
- ILC Inter-laboratory Comparison
- ISO International Standard Organization -
- LF Low Frequency
- LISN -Limited Impedance Stabilization Network
- MCMC-Malaysia Commission for Multimedia and Communication
- MU Measurement Uncertainty



- OATS Open Area Test Site
- PT Proficiency Testing
- QP Quasi Peak
- RE Radiated Emission
- RF Radio Frequency
- SAC Semi Anechoic Chamber
- VHF Very High Frequency

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
А	Calibration certificate – EMI measuring receiver SCR 310 2	99
В	Calibration certificate – LISN EMCO 3810/2	105
С	Calibration certificate – Bi-log antenna CBL 6111D	107
D	Calibration certificate – Comb generator CGO 520	113



xix

CHAPTER 1

INTRODUCTION

1.1. Introduction

The Electromagnetic Interference (EMI) in electrical and electronics within the stipulated radio spectrum often exists and not directly visible from the outside of the equipment. It deals with the generation, transmission and reception of the unintended radio signals. This interference phenomenon can be described in a coupling model which are the source, coupling path and victim. In order for the interference to take place from the source, the coupling path can be radiative or the radiated emission (RE), conductive, capacitive and inductive for conducted emission (CE) [1]. Since it occurs over a broad spectral range from very low frequencies up to millimeterwave range and above, the manufacturer is obliged to declare the conformity with the achieved goals of the required directive; a harmonized and compatible level regarding the emissions and immunity of the equipment [2]. The directive has been recognized in the US in 1979 by introducing the FCC article 15 subpart J on emission restrictions for computers [3]. The EMC standards clearly specify the limits and what is to be measured - the "measurand" and to define the method for measuring it. Nowadays, advancement in technology, consumer demand and enforcement requirements on an accredited lab test has resulted in acquiring ISO 17025 (General requirements for the competence of testing and calibration laboratories) certification [4].

All household products which are meant for the export market are required to pass the CE and RE tests. This is to ensure that such household product or the equipment under test (EUT) can satisfy the local regulatory requirement which is to be used in the designated country. The basic requirement of the test requires the voltage disturbance device and a proper impedance with noise isolation to the EUT as shown



in Figure 1.1. In this case, the measuring device is an Electromagnetic Interference (EMI) receiver which controlled via an EMC software through a general-purpose interface board (GPIB). On the other hand, the limited impedance stabilization network (LISN) provides the impedance matching and noise isolation from and to the EUT. The transient limiter degrade the voltage disturbance from the EUT at -10 dB to protect the EMI receiver [5]. On the other hand, the RE test is done at higher frequency range than the CE. The LISN is replaced by the measuring antenna as shown in Figure 1.2 [5]. While the voltage disturbance radiates from the EUT, the antenna captures this disturbance through its antenna elements.

The EMC measurements system deals with an advanced hardware with an abundance of technical parameters and multiple connectors which may lead to the measurement imperfection or errors if it is not addressed correctly. It is an unavoidable and most likely will jeopardize the final measurement result. Therefore, the result of the measurement only approximates to the true value of the measurand and is completely valid once it carries a statement of the uncertainty for that approximation.



Figure 1.1: Test Setup for the conducted emission (CE) [8].



Figure 1.2: Test Setup for the radiated emission (RE) [8].

In general, errors of measurement may have two components; (1), a random errors (Type A) and (2) systematic errors (Type B) [6]. The type A evaluation for the uncertainty is based on the statistical or calculation which is normally done under repetitive measurements. On the other hand, type B evaluations is based on scientific judgement using multiple information such as previous data, operator experience, manufacturer specifications, data from handbooks and calibration certificates [7]. The uncertainties exist from these two components [8]. Figure 1.3 shows the random errors value around the mean. Random errors arise from random variations.



A series of measurement which is taken under the same condition produces a scattered value around the mean. It cannot be eliminated but increasing the number of observation and deriving a mean value may reduce the uncertainty due to their effect. Then, in Figure 1.4, systematic errors arise from systematic effect at any given quantity, remains unchanged when a measurement is repeated under a constant condition such as the calibration error. It can be reduced by applying a correction factor to the data.



Figure 1.4: Systematic errors [8].

By establishing the measurement uncertainty (MU) budget such as in Table 1.1, all equipment, device, connectors and cables are classified as an input quantities xi and to be evaluated by a proper method according to the standards or procedure if available and each is expressed as a standard uncertainty, $U(x_i)$. The standard uncertainty components are combined to produce an overall value of uncertainty known as the combined standard uncertainty, $U_c(y)$ and the laboratory expanded

uncertainty U_{LAB} . The expanded uncertainty is required to meet the needs of international standards to provide a greater level of confidence by multiplying a coverage factor of k and shall be calculated as $U_{LAB} = k.u_c$ [9].

Input Quantities (xi)	Ux_i	Value	Probability	Divisor	ui(y)	ui(y) ²
		dB	Distribution			
Receiver reading	V_r	0.1	Normal	1	0.100	0.010
Attenuation: LISN-receiver	a_c	0.1	Normal	2	0.050	0.003
LISN voltage division factor	F_{AMN}	0.2	Normal	2	0.100	0.010
Combined standard	$U_{C}(\mathbf{y})$		Normal		0.25	0.0625
uncertainty						
Expanded uncertainty.	ULAB		k=2		-	0.125
Normal (k)						

Table 1.1: Sample of measurement uncertainty budget [8].

1.2. Problem statement



EMC testing is a series of various test which is inclusive the emission and immunity test as well as radiated and conducted for both. Those tests are needed to be fully complied and it is a mandatory requirement for most of the markets including the Australia, China, Europe, Japan, Korea, New Zealand and the U.S. With the vast and rapid growth in the electric and electronics, it has been known to be one of the main driven factor for the EMC testing laboratory to be accredited. Accreditation is a formal recognition for the EMC testing laboratory to be competent with the implementation of the quality system in accordance to the ISO/IEC 17025.

Based on ISO/IEC 17025: 2005, Clause 4.4.1 Note 2 stated that, upon accreditation, participation in the inter-laboratory comparison (ILC) for the proficiency testing (PT) is mandatory for CE and RE using samples or items of known value to determine the MU, limits of detection and confidence limits. It is crucial to characterize all known input quantities, (x_i) and laboratory's expanded uncertainties (U_{LAB}) prior to the PT exercise to takes place.

According to the numbers of actual EMC's sample reports from a several accredited test houses in Appendices E, F, G and H, it is clearly seen that the MU is

used as an informational purpose only which is inadequate to determine the status of the EUT which has the emission level $< U_{CISPR}$ or close to the emission limits. Therefore, in this context of research the MU is applied in the final measurement so that the EUT status could be correctly addressed whenever the EUT has exceeded the quasi peak (QP) with the MU limits.

1.3. Aims and objectives

This project aims to make the measurement uncertainty useable to the final measurement with the approach verified in the EMC Standards. By having a numerous manual and automated data collection, it will be carefully cross-checked for its integrity according to the standards. By introducing more analytical and various statistical methods for the data analysis, it will be able to minimizing the uncertainty AMINAK values. To achieve the aforementioned aim, the following objectives shall be implemented:

- i) To obtain the input quantity (x_i) voltage specifically for CE and RE.
- ii) To obtain the laboratory MU (U_{LAB}) within the CISPR standard ($U_{CISPR} = 3.6$ dB for CE and 5.2 dB for RE)
- iii) To perform a statistical comparison between two EMC test sites for the ILC to satisfy the Z-score requirement in accordance to the ISO/IEC 17025 standard.
- iv) To evaluate the MU value to the final QP measurement with the comparison to the QP limits.

1.4. Scope of work

The scopes of this research study are as follows:

- i) Characterization of the measurement uncertainty input quantities xi for CE and RE in household and information technology equipment for the EUT through standard measurement and calibration certificates.
- ii) Obtaining the measurement uncertainty (U_{LAB}) and to compare with the standards (U_{CISPR}) for Semi Anechoic Chamber based on the CISPR 16-4-2:

REFERENCES

- [1] P. Russer, "EMC measurements in the time-domain," 2011 XXXth URSI Gen. Assem. Sci. Symp., pp. 1–35, 2011.
- [2] D. Hansen, "20 Years of professional experience in international EMC-labs," 2002 3rd Int. Symp. Electromagn. Compat., 2002.
- [3] R. G. Bill Holz, "The Engineer's Guide To Global EMC Requirements : 2007 Edition," Intertek, 2007.
- [4] International Standard Organization, *General requirements for the competence of testing and calibration laboratories*, 2nd ed. Switzerland: ISO/IEC 17025, 2005.
- [5] B. S. Institution, Specification for radio disturbance and immunity measuring apparatus and methods Part 4-2: Uncertainties, statistics and limit modelling

 Measurement instrumentation uncertainty. United Kingdom: BS EN 55016-4-2, 2011.
- [6] U. K. A. Service, *The Expression of Uncertainty in EMC Testing*. Lab 34, 2002.
- [7] S. Bell, *A Beginner's Guide to Uncertainty of Measurement*, 2nd ed. National Physical Laboratory, 1999.
- [8] Schaffner, *EMC Measurment Uncertainty, a handy guide*. Schaffner EMC System Ltd, 2002.
- [9] E. Accreditation, *Evaluation of the Uncertainty of Measurement In Calibration*. France: EA-4 / 02 M, 2013.
- [10] J. Medler, "Uncertainty contribution of the EMI test receiver in RF disturbance measurements," 2010 Asia-Pacific Int. Symp. Electromagn. Compat., pp. 994– 997, 2010.
- [11] B. S. Institution, Specification for radio disturbance and immunity measuring apparatus and methods Part 2-1 : Methods of measurement of disturbances and immunity —. United Kingdom: BS EN 55016-2-1, 2013.
- [12] International Electrotechnical Commission, Specification for radio disturbance and immunity measuring apparatus and methods Part 2-3: Methods of measurement of disturbances and immunity – Radiated disturbance measurements. Switzerland: IEC CISPR 16-2-3, 2006.
- [13] Y. Akiyama, K. Kakuda, and T. Shimasaki, "Deviations of conducted disturbance voltages measured with AMN due to differences in height of the AMN and its grounding conditions," pp. 501–504, 2014.
- [14] P. Nicolae, S. M. Ieee, C. Stoica, M. S. Student, and G. Mihai, "Conducted

Emission Measurements for a Laptop," pp. 2–5, 2014.

- [15] A. Racasan, C. Munteanu, V. Topa, C. Pacurar, C. Hebedean, and C. Marcu, "Home appliances conducted electromagnetic emissions analysis and mitigation methods," 2015 9th Int. Symp. Adv. Top. Electr. Eng. ATEE 2015, pp. 356–361, 2015.
- [16] M. Alexander, M. Salter, and D. Cheadle, "Near-field validation of calculable dipole antennas in a fully anechoic room from 20 MHz to 1000 MHz (with applications to validation of EMC test sites and calibration of EMC antennas)," vol. 21, pp. 395–400, 2013.
- [17] C. R. Paul, Introduction to Electromagnetic Compatibility, 2nd ed. Wiley, 2006.
- [18] E. M. N. Mark I. Montrose, *Testing for EMC Compliance: Approaches and Techniques*. Wiley, 2004.
- [19] A. Technology and E. F. Sarajevo, "Proficiency testing and interlaboratory comparisons in laboratory for dimensional measurement," vol. 16, no. 1, pp. 115–118, 2012.
- [20] ANSI ASQ National Accreditation Board, *Guidance on Proficiency Testing / Inter-laboratory Comparisons*. USA, 2015.
- [21] M. Lin, "Evaluation for Test Competence," *Electromagn. Compat. 1998. 1998 IEEE Int. Symp.*, vol. 2, pp. 724–728, 1998.
- [22] L. E. Kolb, "Statistical Comparison," *Electromagn. Compat. 1996. Symp. Rec.*, pp. 241–244, 1996.
- [23] International Electrotechnical Commission, Information technology equipment - Radio disturbance characteristics – Limits and methods of measurement. Switzerland: CISPR 22, 2008.
- [24] K. Osabe and T. Kato, "Consideration of data evaluation criteria for radiated emission test in the PT program," *Int. Symp. Electromagn. Compat. EMC Eur.*, pp. 1–4, Sep. 2012.
- [25] K. Osabe and T. Kato, "Proposal for evaluation method of proficiency test results on EMI measurement," 2013 IEEE Int. Symp. Electromagn. Compat., pp. 138–143, Aug. 2013.
- [26] A. V. High, F. Line, and I. Stabilization, "Effectiveness Evaluation of Devices for AC Mains Cable Termination Control to Improve Reproducibility of Radiated Emission Measurement," pp. 818–823, 2014.
- [27] P. Mullner, W.; Austrian Res. Centers GmbH ARC, Austria; Kriz, A.; Preiner, "Comb generator measurement techniques," *Electromagn. Interf. Compat. 2008. INCEMIC 2008. 10th Int. Conf.*, pp. 291–295, 2008.
- [28] T. Toh, "Electromagnetic Interference Laboratory Correlation Study and Margin Determination," *IEEE Trans. Electromagn. Compat.*, vol. 51, no. 2, pp. 204–209, 2009.
- [29] W. Di Mullner, A. Di Kriz, H. Di Haider, and G. Kolb, "Conducted and Radiated Comb Generator Measurement Techniques," 2007 7th Int. Symp. Electromagn. Compat. Electromagn. Ecol., pp. 204–207, 2007.

- [30] K. Osabe, R. Watanabe, A. Maeda, and M. Yamaguchi, "Inter-laboratory Comparison Result as the Proficiency Testing Program of EMI Test Sites in Japan," 2007 IEEE Int. Symp. Electromagn. Compat., pp. 1–6, 2007.
- [31] A. Ales, F. T. Belkacem, and D. Moussaoui, "Laboratory line impedance stabilisation network: Experimental studies," 2011 10th Int. Conf. Environ. Electr. Eng. EEEIC.EU 2011 Conf. Proc., pp. 1–4, 2011.
- [32] Q. Cui and Y. Lu, "The influence of different measurement antennas on the radiated emission measurement," 2011 Int. Conf. Electron. Commun. Control. ICECC 2011 Proc., pp. 4010–4014, 2011.
- [33] J. V. Guimarães, M. H. C. Dias, and J. C. A. dos Santos, "Proficiency testing of electromagnetic compatibility (EMC) labs in Brazil by measurement comparisons," *Meas. Sci. Technol.*, vol. 20, no. 11, p. 115107, 2009.
- [34] P. Wilson, "On correlating TEM cell and OATS emission measurements," *IEEE Trans. Electromagn. Compat.*, vol. 37, no. 1, pp. 1–16, 1995.
- [35] International Electrotechnical Commission, *Testing and measurement techniques Emission and immunity testing in transverse electromagnetic (TEM) waveguides*, 2nd ed. Switzerland: IEC 61000-4-20, 2010.
- [36] I. of E. and E. Engineers, American National Standard for Methods of Measurement of Radio Noise Emissions from Low-Voltage Electrical and Electronic Equipment in the Range of 9 kHz to 40 GHz. USA: C63.4:, 2003.
- [37] K.-O. Muller, "Speeding up quasi peak weighting EMI tests," *IEEE 1991 Int. Symp. Electromagn. Compat.*, no. 1, pp. 169–172, 1991.
- [38] M. E. Ayob, "Conducted Emission KX-FT938," Parit Raja, 2011.
- [39] R. Anuar, "Radiated Emission AHM65PS12," Parit Raja, 2014.
- [40] P. Da Silva Hack and C. S. Ten Caten, "Measurement uncertainty: Literature review and research trends," *IEEE Transactions on Instrumentation and Measurement*, vol. 61, no. 8. pp. 2116–2124, 2012.
- [41] D. Heirman, "Uncertainty Considerations in Stating Pass / Fail CISPR Uncertainty Approach CISPR Approach to Uncertainty CISPR Values for Ucispr First Application of Ucispr First Application of Ucispr ISO / IEC 17025-," *Electromagn. Compat. 2008. EMC 2008. IEEE Int. Symp.*, pp. 1–4, 2008.
- [42] A. Marinescu, Y. E. Gulersoy, and G. Schmid, "An interlaboratory comparison for mobile phone SAR," *IEEE Int. Symp. Electromagn. Compat.*, pp. 1218– 1222, 2015.
- [43] M. Ishii, H. Yoshida, Y. Danjo, S. Kurokawa, and K. Fujii, "A study on the characteristics of semi-anechoic chambers below 30 MHz," *IEEE Int. Symp. Electromagn. Compat.*, vol. 1, pp. 934–939, 2014.
- [44] A. Degraeve, K. Armstrong, J. Peuteman, and D. Pissoort, "Development and construction of an EMC demonstration unit," pp. 422–427, 2013.
- [45] M. A. and J. Y. M. A. Rafiq, "Effect of Shielding g, Grounding, EMI Filt ters & Ferrite Beads on Rad diated & Conducted Em missions," *Recent Adv. Sp. Technol. (RAST), 2013 6th Int. Conf. on, Istanbul*, pp. 583–588, 2013.



[47] J. Tsai, L. Lin, Y. Tsai, and C. Chen, "Estimate the measurement uncertainty of broadband antenna (30MHz to 1GHz) calibration system," 2010 Asia-Pacific Int. Symp. Electromagn. Compat., pp. 945–948, 2010.

[46]

- [48] M. Samoto, N. Samoto, H. Shimanoe, I. Makino, and K. Shimada, "A Substitution Method for Antenna Calibration by the Use of Broadband Antenna (30 to 1000 MHz)," no. 1, pp. 691–696, 2014.
- [49] A. Technologies, Measurement Guide Agilent Technologies EMC Series Analyzers. USA, 2001.
- [50] D. Zhao, G. Teunisse, and F. Leferink, "Design and implementation of conducted emission reference source," 2014 IEEE Int. Symp. Electromagn. Compat., pp. 12–17, 2014.
- [51] J. Song, H. T. Hui, and Z. W. Sim, "Investigation of Measurement Uncertainties and Errors in a Radiated Emission Test System," *IEEE Trans. Electromagn. Compat.*, vol. 57, no. 2, pp. 158–163, Apr. 2015.
- [52] M. Zingarelli and R. Grego, "Improving EMC measurement uncertainty with digital EMI receivers & amp; optical fiber technology from 10 Hz up to 6 GHz," *10th Int. Symp. Electromagn. Compat.*, pp. 26–30, 2011.
- [53] I. Turer, M. Uysal, M. C. Akmehmet, and A. D. Bagdat, "Normalized site attenuation measurement of a semi-anechoic chamber in multiple test zones," *Int. Symp. Electromagn. Compat. EMC Eur.*, pp. 1–6, Sep. 2012.
- [54] H. M. Hironari Tanaka, Ikuo Makino, Hiroyuki Shimanoe, "An Evaluation of using Small Biconical Antennas in Normalized Site Attenuation," pp. 667–673, 2016.
- [55] J. Tsai, M. Donglin, Y. Tang, K. Huang, and L. Lin, "Improvement of the mutual coupling effect between Biconical antenna and antenna mast," no. 1, pp. 612–615, 2016.
- [56] D. B. Hibbert, "Interlaboratory Studies," *Encycl. Anal. Sci.*, vol. 7, pp. 449– 457, 2005.
- [57] I. N. A. Board, *Policy on Proficiency Testing*. Ireland: PS1, 2008.
- [58] International Standard Organization, *Statistical methods for use in proficiencytesting by interlaboratory comparisons*. Switzerland: ISO 13528, 2005.
- [59] E. P. Nicolopoulou, I. F. Gonos, I. a. Stathopulos, and E. Karabetsos, "Two interlaboratory comparison programs on EMF measurements performed in Greece," *IEEE Electromagn. Compat. Mag.*, vol. 1, no. 2, pp. 50–59, 2012.
- [60] R. Vogt-Ardatjew, U. Lundgren, S. F. Romero, and F. Leferink, "On-Site Radiated Emissions Measurements in Semireverberant Environments," *IEEE Trans. Electromagn. Compat.*, p. 10, 2016.
- [61] C. Carobbi, A. Bonci, M. Cati, C. Panconi, M. Borsero, and G. Vizio, "Experience on proficiency testing in Italy with emphasis on radiated emission measurements from 30 MHz to 1 GHz," *IEEE Int. Symp. Electromagn.*

Compat., vol. 2015-Septm, pp. 473-478, 2015.

- [62] B. Zhang, Z. Yuan, and J. He, "Comparison on the test results between reverberation chamber and anechoic chamber," 2012 Asia-Pacific Symp. *Electromagn. Compat.*, pp. 769–772, May 2012.
- [63] S. Chakrabarti, D. Dan, and G. Suresh, "Uncertainty analysis for conducted emission measurement," 2008 10th Int. Conf. Electromagn. Interf. Compat., 2008.

97