AN UNCERTAINTY MODEL OF A NON-IDEAL OPEN AREA TEST SITE FOR ELECTROMAGNETIC MEASUREMENT

IGNATIUS AGUNG WIBOWO

A thesis submitted in
fulfillment of the requirements for the award of the
Doctor of Philosophy of Electrical Engineering

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

Faculty of Electrical and Electronic Engineering
Universiti Tun Hussein Onn Malaysia

AUGUST 2018

to my beloved wife Ester, my son Marvel, and my daughter Ceara

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

ACKNOWLEDGEMENT

First and foremost, the author wants to thank God that gives the strength, confidence and patience so that the author can finish this thesis.

The author would like to express his sincere gratitude to his supervisor, Prof. Dr. Mohammad Zarar Bin Mohamed Jenu for the encouragement, guidance and ideas given throughout the entire process of completing this research.

Thanks are given to EMC Center UTHM, especially the technicians for their cooperation and assistance in the experimental works.

The author would also like to thank his family for their never ending support, encouragement, and endurance in the hard times during the completion of this thesis.

Last but not least, appreciation also goes to everyone who was involved directly or indirectly toward the accomplishment of this work.

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

ABSTRACT

An open area test site (OATS) is a standard facility to perform electromagnetic compatibility (EMC) compliance testing of electrical and electronic products. An ideal OATS is a flat area, free of any obstructions and external signals. Pre-compliance testing in a non-ideal OATS is an economical way to prepare a product for compliance testing. However, measurements in the non-ideal OATS have higher uncertainty. In addition, the existing model to analyse the measurement uncertainty is not adequate. Therefore, this research proposes an uncertainty model of a non-ideal OATS for electromagnetic measurement to analyse the measurement uncertainty components in the non-ideal OATS. In this research a normalized site attenuation (NSA) measurement uncertainty model was derived. A 3-m non-ideal OATS has been designed and built. The suitability of the location to build the OATS has been evaluated. To evaluate the measurement uncertainty in the site and the closeness of the site NSA to the ideal NSA, a series of NSA measurements in the non-ideal OATS were performed in the frequency range of 300 MHz to 1000 MHz. From the analysis, the expanded uncertainties of the OATS with a coverage factor of 2 were in the range of ±1.68 dB to ±1.98 dB. Besides, the OATS NSA values were inside ±4 dB margins as specified in CISPR 16-1-4:2010 standard. Therefore, the non-ideal OATS is eligible for pre-compliance testing. Based on many factors investigated in the sensitivity analysis, it was found that the dominant factor that contributed to the measurement uncertainty in the non-ideal OATS came from the antennas. In summary, this research mainly contributes to the development and evaluation of a low cost non-ideal OATS for pre-compliance testing.

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

ABSTRAK

Tapak uji kawasan terbuka (OATS) adalah kemudahan piawai untuk melaksanakan ujian kepatuhan keserasian elektromagnet (EMC) untuk produk elektrik dan elektronik. OATS yang unggul adalah kawasan yang rata, bebas daripada apa-apa halangan dan isyarat luar. Ujian pra-pematuhan dalam OATS tidak unggul semasa pembangunan produk adalah cara yang ekonomi untuk menyediakan produk untuk ujian kepatuhan. Walau bagaimanapun, pengukuran dalam OATS tidak unggul mempunyai ketidaktentuan lebih tinggi. Di samping itu, model yang ada untuk menganalisis ketidaktentuan pengukuran itu tidak mencukupi. Oleh itu, kajian ini mencadangkan model ketidaktentuan OATS tidak unggul untuk pengukuran elektromagnet digunakan untuk menganalisis komponen ketidaktentuan pengukuran dalam OATS tidak unggul. Dalam kajian ini, model ketidaktentuan pengukuran pelemahan tapak ternormal (NSA) diterbitkan. OATS tidak unggul 3-m telah direka dan dibina. Kesesuaian lokasi untuk membina OATS telah dinilai. Untuk menilai ketidakpastian pengukuran di tapak dan kedekatan NSA tapak kepada NSA unggul, satu siri pengukuran NSA dalam OATS tidak unggul telah dilakukan dalam julat frekuensi 300 MHz hingga 1000 MHz. Dari analisis, ketidakpastian OATS terkembang dengan faktor liputan 2 berada dalam julat ± 1.68 dB hingga ± 1.98 dB. Selain itu, nilai NSA OATS berada dalam jidar ± 4 dB seperti dinyatakan dalam piawaian CISPR 16-1-4:2010. Oleh itu, OATS tidak unggul layak untuk ujian pra-kepatuhan. Berdasarkan banyak faktor yang disiasat dalam analisis kepekaan, didapati bahawa faktor dominan yang menyumbang kepada ketidakpastian pengukuran dalam OATS tidak unggul datang dari antena. Ringkasnya, penyelidikan ini menyumbang kepada pembangunan dan penilaian OATS tidak unggul dengan kos rendah untuk ujian pra-kepatuhan.

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

CONTENTS

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

LIST OF TABLES

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

LIST OF FIGURES

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

LIST OF SYMBOLS AND ABBREVIATIONS

SYMBOLS

A - antenna aperture

A_N - normalized site attenuation

AF_r - receive antenna factor

AF_t - transmit antenna factor

b - surface height variation

c - velocity of light

c_i - sensitivity coefficients

d - deviation

d - distance

d_d - direct path from transmit to receive antenna

d_r - reflected path from transmit to receive antenna

E - electric field intensity

$\mathbf{E}$ - electric field intensity vector

$\mathbf{E}_{\boldsymbol{d}}$ - direct electric field intensity vector

$\hat{E}_h$ - normalized electric field intensity for horizontal polarization

$E_{\max}$ - maximum electric field in receive-antenna height-scanned between $h_{r\min}$ to $h_{r\max}$

$\mathbf{E}_{rn}$ - reflected electric field intensity vector

$\hat{E}_v$ - normalized electric field intensity for vertical polarization

f - function

f_M - frequency $=300/\lambda$ MHz

F_r - receive antenna directivity

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

F_t - transmit antenna directivity

$F_r(\theta)$ - normalized radiation pattern of receive antenna in vertical plane

$F_r(\varphi)$ - normalized radiation pattern of receive antenna in horizontal plane

$F_t(\theta)$ - normalized radiation pattern of transmit antenna in vertical plane

$F_t(\varphi)$ - normalized radiation pattern of transmit antenna in horizontal plane

g_r - receive antenna gain

g_t - transmit antenna gain

h_r - receive antenna height

h_t - transmit antenna height

H - magnetic field intensity

$\mathbf{H}$ - magnetic field intensity vector

I_0 - peak value of current of a dipole

I_t - transmit antenna current

k - coverage factor

k - number of different series of measurement

l - length

L - length of a dipole

n - number of observations

p - probability density

$\mathbf{P}$ - power density vector

P_d - power density

P_r - power delivered to load

P_t - power transmitted

$\overline{q}$ - arithmetic mean of observation

q_k - individual observations

r - horizontal distance between transmit and receive antenna

R_{dr} - detector resistance

R_{lr} - receive antenna loss resistance

R_{lt} - transmit antenna loss resistance

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

R_{rr} - receive antenna reradiating resistance

R_{rt} - transmit antenna radiation resistance

R_{sg} - signal generator resistance

s - standard deviation

s_p - pooled experimental standard deviation

u - uncertainty

u_c - standard uncertainty

U - expanded uncertainty

V_{dir} - direct voltage

V_{oc} - open circuit voltage induced by incident electrical field across receive antenna

V_{sg} - signal generator voltage

V_{site} - site voltage

V_r - load voltage

V_t - transmit antenna voltage

X_{dr} - detector reactanc**e**

X_r - receive antenna reactanc**e**

X_{sg} - signal generator reactance

X_t - transmit antenna reactanc**e**

Z_0 - impedance of space = $120\pi\ \Omega$

Z_{in} - input impedance

Z_{sg} - signal generator impedance

Z_t - transmit antenna impedance

Z_L - load impedance

Z_S - source impedance

β - free space wavenumber

δAF_r - correction for receive antenna factor

δAF_t - correction for transmit antenna factor

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

δb - correction for ground plane roughness
δf_M - correction for signal generator frequency
δp_c - correction for antenna phase centre location
δr - correction for antennas separation distance
δh_t - correction for imperfect transmit antenna height
δR_{dir} - correction for measurement repeatability of direct voltage
δR_{site} - correction for measurement repeatability of site voltage
δV_{sadir} - correction for spectrum analyser voltage reading when directly connected to signal generator
δV_{sgdir} - correction for signal generator voltage reading when directly connected to spectrum analyser
δV_{sasite} - correction for spectrum analyser voltage reading when performing site voltage measurement
δV_{sgsite} - correction for signal generator voltage reading when performing site voltage measurement
ε_0 - permittivity of vacuum = 8.85419×10^{-12} F/m
ε_{r2} - relative dielectric constant
Φ - phase shift due to the reflection
γ - grazing angle
Γ - ground plane reflection coefficient
Γ_h - horizontal reflection coefficient
Γ_v - vertical reflection coefficient
η_0 - intrinsic impedance of free-space
λ - wavelength
μ_0 - permeability of vacuum = $4\pi \times 10^{-7}$ H/m
θ_d - incident angle of direct path
θ_r - incident angle of reflected path
σ - variance
σ_2 - ground plane conductivity

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

ω - radian frequency

ABBREVIATIONS

AC - Alternating Current
AF - Antenna Factor
ANSI - American National Standard Institute
CALTS - Calibration Test Site
CDMA - Code Division Multiple Access
CENELEC - Comité Européen de Normalisation Electrotechnique
CISPR - Comité International Spécial des Pertubations Radioélectriques
COMTS - Compliant Test Site
EMC - Electromagnetic Compatibility
EMI - Electromagnetic Interference
ESDM - Experimental Standard Deviation of the Mean
EU - European Union
EUT - Equipment Under Test
FCC - Federal Communications Commission
FDTD - Finite Difference Time Domain
FM - Frequency Modulation
FSAF - Free Space Antenna Factor
GSM - Global System for Mobile Communications
GSAF - Geometry-Specific Antenna Factor
GUM - Guide to the Expression of Uncertainty in Measurement
ISO - International Standards Organization
IEC - International Electrotechnical Commission
JGCM - Joint Committee for Guides in Metrology
LPDA - Log Periodic Dipole Antenna
MS - Malaysian Standards
NSA - Normalized Site Attenuation
OATS - Open Area Test Site
PC - Phase Center
RF - Radio Frequency

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

SA	-	Site Attenuation
SAC	-	Semi Anechoic Chamber
SGP	-	Smith, German, & Pate
SSE	-	Sum of Squares due to Error
SSM	-	Standard Site Method
TAM	-	Three Antenna Method
TV	-	Television
TNSA	-	Theoretical Normalized Site Attenuation
UHF	-	Ultra High Frequency
US	-	United States
UTHM	-	Universiti Tun Hussein Onn Malaysia
VHF	-	Very High Frequency
VIM	-	International Vocabulary of Basic and General Terms in Metrology

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

LIST OF APPENDICES

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

CHAPTER 1

INTRODUCTION

1.1 Background

According to the International Electrotechnical Vocabulary by the International Electrotechnical Commission, electromagnetic compatibility (EMC) is defined as "the ability of an equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment" (International Electrotechnical Commission, 2017, para. 1). In order to function satisfactorily, the equipment or system has to also possess good immunity or susceptibility from electromagnetic interference (EMI). For example, it is necessary for a pacemaker not to produce any electromagnetic disturbance to the environment but more importantly, it has to be immune from self-interference as well as any outside EMI. In short, an electromagnetically compatible system does not interfere with the operations of other systems as well as its own operation and is immune from the emissions of other systems (Goedbloed, 1992). Hence, the field of EMC covers the electromagnetic emission issues which refer to the unwanted generation of electromagnetic energy by the equipment and the electromagnetic immunity or susceptibility issues which are related to the correct operation of the equipment in the presence of unwanted EMI.

Testing and evaluation for EMC involve the measurements of radiated emission, conducted emission, radiated susceptibility and conducted susceptibility (Montrose & Nakauchi, 2004). The radiated emission testing is done to measure EMI generated by equipment under test (EUT) which is radiated through the space (Agilent Technologies, 2010). The conducted emissions testing measures the unwanted signals that are on the AC power mains generated by EUT (Agilent

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

Technologies, 2010). The radiated susceptibility testing is conducted to determine the EUT's ability to operate in the presence of EMI propagated via space (Aero Nav Laboratories, 2014). The conducted susceptibility testing is performed to determine the EUT's ability to operate in the presence of EMI propagated via a conductor (Aero Nav Laboratories, 2014).

Among the above mentioned types of EMC testing, the radiated emission testing is mandated to be measured in an open area test site (OATS) as described in CISPR 11 (2010a), CISPR 22 (2008), CISPR 16-1-4 (2010b) and ANSI C63.7 (2015). The radiated emission testing measures the electromagnetic emissions emanating from EUT. The purpose of the testing is to verify the EUT’s ability to remain below specified electromagnetic emissions levels during its operation.

EMC testing is now a requirement of many global conformance and safety standards to many sectors including telecommunication, automotive, medical and consumer electronics. Many countries around the world have seen the importance of EMC. Therefore, EMC has become an important part of product design. In addition, compliance to EMC standards is required for importing electrical and electronic products into many countries world-wide (Armstrong & Williams, 2001). For instance, in Europe, the European Committee for Electrotechnical Standardization (CENELEC) on 1 January 1996 issued a mandatory directive regarding products to be marketed in the European Union (EU). This directive made it mandatory for electrical and electronic equipment which is to be sold in Europe meet certain requirements regarding electromagnetic emission and immunity (Singh & Garg, 1999).

EMC compliance testing is an activity to assess the compliance of a product to an EMC regulation or standard before the product may be exported. In order to get the certificate of compliance, the testing must be performed in a certified laboratory. The standard in the EMC compliance testing depends on which country the product will be sold. For example, information technology equipment to be sold in the US must be tested to comply FCC part 15 regulations, whereas if the product will be sold to Europe, it must be comply to EN55022 (CISPR 22) (Agilent Technologies, 2010).

Considering that the EMC compliance testing is relatively expensive and there is no guarantee that a product will pass the testing in one shot, it will be effective if preliminary testing which is usually called EMC pre-compliance testing

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

REFERENCES

Aero Nav Laboratories. (2014). *Electrical Testing*. Retrieved 16 July, 2015, from http://www.aeronavlabs.com/electromagnetic_interference_testing.htm

Agilent Technologies. (2010). *Making Conducted and Radiated Emissions Measurements*. Santa Clara, CA: Agilent Technologies.

American National Standards Institute (2004). *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*. New York, NY: ANSI C63.4-2003.

American National Standards Institute (2006). *American National Standard for Electromagnetic Compatibility - Radiated Emission Measurements in Electromagnetic Interference (EMI) Control - Calibration of Antennas (9 kHz to 40 GHz)*. New York, NY: ANSI C63.5-2006.

American National Standards Institute (2014). *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*. New York, NY: ANSI C63.4-2014.

American National Standards Institute (2015). *American National Standard Guide for Construction of Test Sites for Performing Radiated Emission Measurements*. New York, NY: ANSI C63.7-2015.

APREL Laboratories. (2004). Description and Characterisation of Open Area Test Site at APREL. Nepean, Canada: APREL Laboratories.

Archambeault, B. (1997). Pre-Construction Evaluation Modeling of Open Area Test Sites (OATS). *Proc. of 1997 IEEE International Symposium on Electromagnetic Compatibility*. Austin, TX: IEEE. pp. 462-467.

Archambeault, B. & Brench, C. E. (1999). Reducing Measurement Uncertainty in EMC Test Laboratories. *The Interference Technology Engineers Master*, pp. 172-185.

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

Armstrong, K. & Williams, T. (2001). EMC Testing, Part 1 - Radiated emissions.‘Do-It-Yourself’ Electromagnetic Compatibility (EMC) Testing Techniques. *EMC + Compliance Journal*, pp. 27-39.

Barbary, I., Fichte, L. O., Stiemer, M., Lange, S., Schaarschmidt, M., Pape, R., Kleine-Ostmann, T. & Schrader, T. (2015). On the Quality of a Real Open Area Test Site. *Proc. of 2015 IEEE International Symposium on Electromagnetic Compatibility (EMC)*. pp. 1201-1206.

Barès, C., Brousseau, C., Le Coq, L. & Bourdillon, A. (2003). Measurements and Simulations of Phase Center Displacement on Log-Periodic Antenna – Application to Radar System. *The IEE Electronics Letters, 39(11)*, pp. 867-868

Battermann, S. & Garbe, H. (2002). Effects of Realistic Groundplanes to NSA-Measurements of Open Area Test Sites (OATS). *Proc. of XXVIIth General Assembly of the International Union of Radio Science*. Maastricht, The Netherland.

Battermann, S. & Garbe, H. (2004). Influence of the Ground Plane Geometry on the Normalized Site Attenuation of an OATS. *Proc. of 2004 IEEE Antennas and Propagation Society International Symposium*. Monterey, CA: IEEE. pp. 503-506.

Bell, S. (1999). *A Beginner's Guide to Uncertainty of Measurement, Measurement Good Practice Guide*. Middlesex, UK: National Physical Laboratory.

Berry, J., Pate, B. & Knight, A. (1990). Variations in Mutual Coupling Correction Factors for Resonant Dipoles used in Site Attenuation Measurements. *Proc. of 1990 IEEE International Symposium on Electromagnetic Compatibility*. Washington, DC: IEEE. pp. 444-450.

Bittera, M., Hallon, J., Kováč, K. & Smieško, V. (2004). The Influence of the Antenna Cable to the Uncertainty of Radiated Emission Measurement. *Proc. of 14th International Czech-Slovak Scientific Conference "Radioelectronics 2004"*. Bratislava, Slovak Republic. pp. 237-240.

Bittera, M., Kováč, K., Smieško, V. & Hallon, J. (2008). Influence of Directivity Pattern of Bilog Antenna to Radiated EMI Measurement Uncertainty. *Proc. of 14th Conference on Microwave Techniques 2008*. Prague, Czech Republic: IEEE. pp. 1-4.

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

Bittera, M. & Smieško, V. (2010). Influence of Interface Cables Termination Impedance on Radiated Emission Measurement. *Measurement Science Review, 10(5)*, pp. 157-161.

Bittera, M., Smieško, V. & Kováč, K. (2007). Effect of Bundled Power Cable on Radiated Emission Measurement. *Measurement Science Review, 7(2)*, pp. 33-36.

Bittera, M., Smieško, V. & Kováč, K. (2011). Modified Uncertainty Estimation of Antenna Factor Measurement by Standard Site Method. *Measurement, 45(2012)*, pp. 190 - 198.

CENELEC (2005). *General Requirements for the Competence of Testing and Calibration Laboratories*. Brussels, Belgium: ISO/IEC 17025.

Chen, Z. (2015). An Improved Method for Simultaneous Calibrations of Gain, Phase Center and Near Boresight Patterns for Log-Periodic Dipole Arrays. *Proc. of 2015 9th European Conference on Antennas and Propagation (EuCAP)*. pp. 1-5.

Cui, Q. & Lu, Y. (2011). The Influence of Different Measurement Antennas on the Radiated Emission Measurement. *Proc. of International Conference on Electronics, Communications and Control 2011*. Ningbo, China: IEEE. pp. 4010-4014.

Dai, F., Su, D., Li, H., Zhou, F. & Jiao, S. (2006). A New Method to Calculate the Theoretical Value of the NSA. *Proc. of 7th International Symposium on Antennas, Propagation & EM Theory 2006*. Guilin, China: IEEE. pp. 1-3.

Deaver, D. (2000). An Application of the Guide to Measurement Uncertainty. *Proc. of Measurement Science Conference* Anaheim, CA: MSC. pp. 325-334.

Donglin, M., Xiao, L. & Dabo, L. (2015). Research on Unwanted Reflections in an OATS for Precise Omni Antenna Measurement. *Proc. of 2015 IEEE 6th International Symposium on Microwave, Antenna, Propagation, and EMC Technologies (MAPE)*. pp. 245-249.

Eadie, A. (2014). *The EMC Pre-Compliance Testing Guide*. Retrieved 25 July, 2015, from http://www.emcfastpass.com/main/pre-compliance-testing-guide/

EMC Bayswater. (2017). *3m or 10m Radiated Emissions Test Site*. Retrieved 22 June, 2018, from https://www.emcbayswater.com.au/blog/emc-testing/3m-10m-radiated-emissions-test-site/

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

EMC Fastpass. (2015). *The Beginner's Guide to EMC*. Retrieved 22 August, 2017, from http://www.emcfastpass.com/emc-testing-beginners-guide/emi-precompliance-testing/

Eriksson, O. (2007). *Sensitivity and Uncertainty Analysis Methods, with Applications to a Road Traffic Emission Model*. Department of Mathematics, Division of Statistics Linköpings Universitet: PhD.

Eser, S. & Sevgi, L. (2010). Open-Area Test Site (OATS) Calibration. *IEEE Antennas and Propagation Magazine, 52*.

Federal Communications Commission. (2009). *Title 47 of the Code of Federal Regulations (CFR), Part 15*. Washington, DC: Federal Communications Commission.

Frech, A. & Russer, P. (2012). Real-Time Ambient Noise Cancellation for EMI Measurements on Open Area Test Sites. *Proc. of 2012 Asia-Pacific Symposium on Electromagnetic Compatibility*. Singapore, Singapore: IEEE. pp. 213-216.

Frech, A., Zakaria, A., Braun, S. & Russer, P. (2008). Ambient Noise Cancellation with a Time-Domain EMI Measurement System using Adaptive Filtering. *Proc. of Asia-Pacific Symposium on Electromagnetic Compatibility 2008*. Singapore, Singapore: IEEE. pp. 534-537.

Friesen, D. R. & Flores, V. (1989). Effect of Flush Mounted Turntables on Site Attenuation. *Proc. of National Smposium on Electromagnetic Compatibility*. Denver, CO: IEEE. pp. 163-165.

Friis, H. T. (1946). A Note on a Simple Transmission Formula. *Proceedings of the IRE, 34(5)*, pp. 254-256.

Gavenda, J. D. (1994). Near-Field Corrections to Site Attenuation. *IEEE Transactions on Electromagnetic Compatibility, 36(3)*, pp. 213-220.

Goedbloed, J. J. (1992). *Electromagnetic Compatibility*. New York, NY: Prentice Hall.

Han-Chang, H., Ming-Iu, L. & Wang, K. (2004). Use of Wire-Grid Method to Evaluate the Effect of Finite Metallic Plane of OATS on NSA in LF (30-100 MHz) Region. *Proc. of International Symposium on Electromagnetic Compatibility 2004*. Silicon Valley, CA: IEEE. pp. 511-513.

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

Handlon, D. (2010). Radiated Emissions Measurements in an Open Area Test Site. *Proc. of Simposio de Metrologia 2010*. Santiago de Querétaro, Mexico: CENAM. pp. 1-6.

Hubbard, D. W. (2010). *How to Measure Anything, Second Edition*. Hoboken, NJ: John Wiley & Sons, Inc.

Hubing, T. H. (1989). The Effect of Cable Terminations on EMI Measurements. *Proc. of National Symposium on Electromagnetic Compatibility*. Denver, CO: IEEE. pp. 357-359.

Industry Canada. (1999). *Test Facilities and Test Methods for Radio Equipment*. Ottawa, Canada: Industry Canada.

International Atomic Energy Agency. (2008). Measurement Uncertainty, A Practical Guide for Secondary Standards Dosimetry Laboratories. Vienna, Austria: International Atomic Energy Agency.

International Electrotechnical Commission (2003). *Specification for Radio Disturbance and Immunity Measuring Apparatus and Methods - Part 4-2: Uncertainties, Statistics and Limit Modelling - Uncertainty in EMC Measurements*. Geneva, Switzerland: CISPR 16-4-2.

International Electrotechnical Commission (2008a). *Information Technology Equipment - Radio Disturbance Characteristics - Limits and Methods of Measurement (Second Revision)*. Geneva, Switzerland: CISPR 22.

International Electrotechnical Commission (2008b). *Specification for Radio Disturbance and Immunity Measuring Apparatus and Methods – Part 1-4: Radio Disturbance and Immunity Measuring Apparatus – Ancillary Equipment – Radiated Disturbances. Edition 2.1*. Geneva, Switzerland: CISPR 16-1-4.

International Electrotechnical Commission (2010a). *Industrial, Scientific and Medical Equipment - Radio-Frequency Disturbance Characteristics - Limits and Methods of Measurement*. Geneva, Switzerland: CISPR 11.

International Electrotechnical Commission (2010b). *Specification for Radio Disturbance and Immunity Measuring Apparatus and Methods - Part 1-4: Radio Disturbance and Immunity Measuring Apparatus - Antennas and Test Sites for Radiated Disturbance Measurements*. Geneva, Switzerland: CISPR 16-1-4.

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

International Electrotechnical Commission. (2017). *Electropedia: The World's Online Electrotechnical Vocabulary*. Retrieved 19 August, 2017, from http://www.electropedia.org/iev/iev.nsf/display?openform&ievref=161-01-07

International Organization for Standardization. (2006). *International Vocabulary of Basic and General Terms in Metrology (VIM)* (3 ed.). Geneva, Switzerland: International Organization for Standardization.

Intertek. (2010). Why 50% of Products Fail EMC Testing the First Time. Boxborough, MA: Intertek Testing Services NA, Inc.

Jian, S. & Hon Tat, H. (2013). Characterization of Uncertainties in RF Adapters for EMC Measurements. *Proc. of 2013 Asia-Pacific Symposium on Electromagnetic Compatibility*. Melbourne, Australia: IEEE. pp. 1-3.

Joint Committee for Guides in Metrology (2008). *Evaluation of Measurement Data - Guide to the Expression of Uncertainty in Measurement*. Sèvres, France: JCGM 100:2008.

Jung-Chun, T., Liang-Yang, L., Yung-Cheng, T. & Cheng-Chang, C. (2010). Estimate the Measurement Uncertainty of Broadband Antenna (30MHz to 1GHz) Calibration System. *Proc. of 2010 Asia-Pacific Symposium on Electromagnetic Compatibility*. Beijing, China: IEEE. pp. 945-948.

Kazemipour, A., Allal, D. & Begaud, X. (2005). Roughness of the Ground-Plane and Its Effect on The Antenna Calibration in an Open-Field Site. *Proc. of The XXVIIIth URSI General Assembly* New Delhi, India: URSI. pp. 1-4.

Kraft, C. (1992). The Effect of a Finite Conductivity Ground Plane on Open Area Site Attenuation. *Proc. of 1992 IEEE International Symposium on Electromagnetic Compatibility*. pp. 131-133.

Ku, H. H. (1988). *Statistical Concepts in Metrology - With a Postscript on Statistical Graphics*. Gaithersburg, MD: National Bureau of Standards.

Longfei, L., Huashen, W. & Donglin, M. (2013). The Measurement System of EMC Antenna Calibration Based on LabVIEW. *Proc. of 2013 IEEE 11th International Conference on Electronic Measurement & Instruments*. pp. 427-431.

Maas, J. S. & Hoolihan, D. D. (1989). The Effects of Ground Screen Termination on OATS Site Attenuation. *Proc. of 1989 IEEE National Symposium on Electromagnetic Compatibility*. Denver, CO: IEEE. pp. 166-170.

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

Maeda, A. (1990). Note on EMI Measurement at Open Field Test Site-Effect of EUT Shelter. *Proc. of 1990 IEEE International Symposium on Electromagnetic Compatibility*. Washington, DC: IEEE. pp. 241-246.

Martin, J. K., Pansing, S. & Bellamy, A. (2014). *Lessons Learned from the Design and Construction of an Open Area Test Site (OATS) and Sound Measurement Building*. *In Compliance*. Retrieved 22 June, 2018, from https://incompliancemag.com/article/lessons-learned-from-the-design-and-construction-of-an-open-area-test-site-oats-and-sound-measurement-building/

McConnell, R. A. (1992). A Derivation of the Normalized Site Attenuation Mutual Coupling Correction Factor and an Improved Method of Antenna Factor Determination. *Proc. of 1992 IEEE International Symposium on Electromagnetic Compatibility*. Anaheim, CA: IEEE. pp. 407-411.

Montrose, M. I. & Nakauchi, E. M. (2004). *Testing for EMC Compliance Approaches and Techniques*. Piscataway, NJ: John Wiley & Sons, Inc.

Morioka, T. & Komiyama, K. (2006). Uncertainty Analysis of Dipole Antenna Calibration Above a Ground Plane. *IEEE Transactions on Electromagnetic Compatibility, 48(4)*, pp. 781-791.

Müllner, W. & Buchmayr, M. (1999). Introducing Height Correction Factors for Accurate Measurements with Biconical Antennas above Groundplane. *Proc. of 13th International Zurich Symposium and Technical Exhibition on Electromagnetic Compatibility*. Zurich, Switzerland: Communication Technology Laboratory, Swiss Federal Institute of Technology Zurich. pp. 153-157.

Müllner, W. & Kriz, A. (2001). Site Attenuation of Limited-Size Ground Planes For Vertical Polarisation. *Proc. of 14th International Zurich Symposium and Technical Exhibition on Electromagnetic Compatibility*. Zurich, Switzerland: Communication Technology Laboratory, Swiss Federal Institute of Technology Zurich. pp. 341-346.

Myung, I. J. (2003). Tutorial on Maximum Likelihood Estimation. *Journal of Mathematical Psychology, 47*, pp. 90-100.

Osburn, J. D. M. (1996). EMC Antenna Parameters and Their Relationships. *ITEM 1996*.

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

Parhami, P., Marino, M., Watkins, S. & Nakauchi, E. (1999). Innovative Pre-Compliance Test Methodology Using Ambient Cancellation and Coherence Detection Techniques. *Proc. of 1999 IEEE International Symposium on Electromagnetic Compatibility*. Seattle, WA: IEEE. pp. 1022-1025.

Phillips, S. J. & Zombolas, C. (2004). Proliferation of RF Ambients Threaten the Validity of Open Area Test Site Measurements. *Proc. of 2004 IEEE International Symposium on Electromagnetic Compatibility*. Silicon Valley, CA: IEEE. pp. 902-907.

Qiao, D., Qi, Z., Mingliang, H. & Dong-an, S. (2014). Analysis of Scattering Property of Open-Area Test Site Ground Plane. *Proc. of 2014 XXXIth URSI General Assembly and Scientific Symposium*. Beijing, China: IEEE. pp. 1-4.

Rich, M. & Russell, I. (2000). *Building an Open Area Test Site (OATS) for Antenna Calibration*. Retrieved July 27, 2015, from http://www.compliance-club.com/archive/old_archive/020312.htm

Sakthivel, K. N., Das, S. K. & Kini, K. R. (2001). Uncertainty in Radio Frequency Emission Measurements due to the Effects of Electromagnetic Ambient. *Proc. of 2001 IEEE International Symposium on Electromagnetic Compatibility*. Montreal, Canada: IEEE. pp. 985-990.

Samoto, M., Samoto, N., Shimanoe, H., Makino, I. & Shimada, K. (2014). A Substitution Method for Antenna Calibration by the use of Broadband Antenna (30 to 1000 MHz). *Proc. of 2014 IEEE International Symposium on Electromagnetic Compatibility (EMC)*. pp. 691-696.

Santos, K. M. G., Perotoni, M. B., Novo, M. S., Osvaldo, J., Paulino, S., Faria, D. R. M., Andrade, C. L. & Alves, T. A. (2014). Study on Technical Feasibility of an Open Area Test Site in Brazil for the UHF Band (300 MHz to 1 GHz). *Proc. of The 23rd SAE BRASIL Congress*. São Paulo, Brasil: SAE International. pp. 1-9.

Schaffner. (2003). *EMC Measurement Uncertainty a Handy Guide*. Edison, NJ: Scaffner.

Singh, H. & Garg, R. (1999). EMC Standardization. *Proc. of the International Conference on Electromagnetic Interference and Compatibility '99*. pp. 296-299.

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

Smith, A. A., German, R. F. & Pate, J. B. (1982). Calculation of Site Attenuation from Antenna Factors. *IEEE Transactions on Electromagnetic Compatibility, EMC-24(3)*, pp. 301-316.

Song, J., Hui, H. T. & Sim, Z. W. (2015). Investigation of Measurement Uncertainties and Errors in a Radiated Emission Test System. *IEEE Transactions on Electromagnetic Compatibility, 57(2)*, pp. 158-163.

Song, Z., Xie, M., Wu, F., Gao, X. & Wang, W. (2013). A Phase-Matching Method for Antenna Phase Center Determination Basing upon Site Insertion Loss Measurement in OATS. *Proc. of 2013 International Symposium on Antennas and Propagation* Nanjing, China: IEEE. pp. 255-258.

Stecher, M. (2001). A Detailed Analysis of EMI Test Receiver Measurement Uncertainty. *Proc. of 2001 International Symposium on Electromagnetic Compatibility*. Montreal, Canada: IEEE. pp. 464-468.

Stellini, M. (2009). *Evaluation of Uncertainty and Repeatability in Measurement: Two Application Studies in Synchronization and EMC Testing.* University of Padova: Ph.D.

Sugiura, A. (1990). Formulation of Normalized Site Attenuation in Terms of Antenna Impedances. *IEEE Transactions on Electromagnetic Compatibility, 32(4)*, pp. 257-263.

Sugiura, A., Shinozuka, T. & Nishikata, A. (1992). Correction Factors for Normalized Site Attenuation. *IEEE Transactions on Electromagnetic Compatibility, 34(4)*, pp. 461-470.

Tae-Weon, K. & Hyo-Tae, K. (2001). Reproducibility and Uncertainty in Radiated Emission Measurements at Open Area Test Sites and in Semianechoic Chambers using a Spherical Dipole Radiator. *IEEE Transactions on Electromagnetic Compatibility, 43(4)*, pp. 677-685.

Tarico, F. (1989). Experiences in Building an Open Area Test Site. *Proc. of 1989 IEEE National Symposium on Electromagnetic Compatibility*. Denver, CO: IEEE. pp. 157-162.

Taylor, B. N. & Kuyatt, C. E. (1994). *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results*. Washington, DC: National Institute of Standards and Technology.

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

The European Parliament and the Council of the European Union. (2004). Directive 2004/108/EC of the European Parliament and of the Council of 15 December 2004 on the Approximation of the Laws of the Member States Relating to Electromagnetic Compatibility and Repealing Directive 89/336/EEC. *Official Journal of the European Union, OJ L 390*, pp. 24-37.

Trakadas, P. T. & Capsalis, C. N. (2001). A Mixed Model for the Determination of Normalized Site Attenuation in OATS. *IEEE Transactions on Electromagnetic Compatibility, 43(1)*, pp. 29-36.

Underwriter Laboratories. (2000). *Radiated Emission Measurements at Open Area Test Sites (OATS)*. Retrieved February 2, 2015, from www.nz.ul.com

United Kingdom Accreditation Service. (2002). *Lab 34: The Expression of Uncertainty in EMC Testing*. Middlesex, UK: UKAS Publisher.

van Dijk, N. (2005). Uncertainties in 3-m Radiated Emission Measurements Due to the Use of Different Types of Receive Antennas. *IEEE Transactions on Electromagnetic Compatibility, 47(1)*, pp. 77-85.

Wright, S. (2004). *Open Area Test Site (OATS) Development*. University of Southern Queensland: Bachelor's Thesis.

Wu, D. & Zhu, G. (2009). The Study on Geometry-Specific Antenna Factor. *Proc. of 2009 3rd IEEE International Symposium on Microwave, Antenna, Propagation and EMC Technologies for Wireless Communications*. Beijing, China: IEEE. pp. 195-198.

Yu, J. (2005). Uncertainty Model for the Dipole-Like Antenna Factor Measurements on an Open Area Test Site. *Proc. of 2005 Asia-Pacific Microwave Conference*. Suzhou, China: IEEE. pp. 1-4.

Zhong, C. (1999). Understanding the Measurement Uncertainties of the Bicon/Log Hybrid Antenna. *The Interference Technology Engineers Master*.

Zhong, C. (2004). EMC Antenna Fundamentals. *Conformity® 2004: The Annual Guide*.

Zhong, C., Foegelle, M. & Harrington, T. (1999). Analysis of Log Periodic Dipole Array Antennas for Site Validation and Radiated Emissions Testing. *Proc. of 1999 IEEE International Symposium on Electromagnetic Compatibility*. Seattle, WA: IEEE. pp. 618-623.

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

Zhong, C. & Foegelle, M. D. (1998). A Numerical Investigation of Ground Plane Effects on Biconical Antenna Factor. *Proc. of 1998 IEEE International Symposium on Electromagnetic Compatibility*. Denver, CO: IEEE. pp. 802-806.

Zombolas, C. (2015). *The Effects of Table Material on Radiated Field Strength Measurement Reproducibility at Open Area Test Sites*. *EMC Testing*. Retrieved 28 June, 2018, from https://www.emcbayswater.com.au/blog/emc-testing/the-effects-of-table-material-on-radiated-field-strength-measurement-reproducibility-at-open-area-test-sites/

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH