Declaration of Authorship

I confirm that the submitted work is my own work and that I have clearly identified and fully acknowledged all material that is entitled to be attributed to others (whether published or unpublished) using the referencing system set out in the programme handbook. I agree that the University may submit my work to means of checking this, such as the plagiarism detection service Turnitin UK. I confirm that I understand that assessed work that has been shown to have been plagiarised will be penalised.

The authors confirm that data underlying the findings are available without restriction. Details of the data and how to request access are available from the University of Surrey publications repository at http://epubs.surrey.ac.uk/blahTBD

Laurence Stant (Author)	Date

"What error drives our eyes and ears amiss? Until I know this sure uncertainty I'll entertain the offered fallacy."

William Shakespeare, The Comedy of Errors

"That's right!" shouted Vroomfondel, "we demand rigidly defined areas of doubt and uncertainty!"

Douglas Adams, The Hitchikers Guide to the Galaxy

Abstract

Abstract goes here

Research Outcomes

Publications

[1] H. Votsi, L. T. Stant, M. J. Salter, C. Li, N. M. Ridler, and P. H. Aaen, "An interferometric characterization technique for extreme impedance microwave devices," in *2020 94th ARFTG Microwave Measurement Conference (ARFTG)*, submitted.

[2] M. J. Salter, L. T. Stant, K. Buisman, and T. Nielsen, "An inter-laboratory comparison of NVNA measurements," in *2011 Workshop on Integrated Nonlinear Microwave and Millimetre-Wave Circuits*, Brive, Jul. 2018.

[3] L. T. Stant, M. J. Salter, N. M. Ridler, D. F. Williams, and P. H. Aaen, "Propagating measurement uncertainty to microwave amplifier nonlinear behavioural models," *IEEE Trans. Microw. Theory Techn.*, Nov. 2018.

[4] L. T. Stant, P. H. Aaen, and N. M. Ridler, "Evaluating residual errors in waveguide VNAs from microwave to submillimetre-wave frequencies," *IET Microw. Antennas Propag.*, vol. 11, no. 3, pp. 324–329, Feb. 2017.

[5] ——, "Comparing methods for evaluating measurement uncertainty given in the JCGM 'evaluation of measurement data' documents," *Measurement*, vol. 94, pp. 847–851, Dec. 2016.

[6] ——, "Evaluating residual errors in waveguide network analysers from microwave to submillimetre-wave frequencies," in *IET Colloquium on Millimetre-Wave and Terahertz Engineering & Technology 2016*, Institution of Engineering and Technology (IET), Mar. 2016.

Presentations

[1] L. T. Stant, "Comparing methods for evaluating measurement uncertainty given in the JCGM 'evaluation of measurement data' documents," 2nd NPL Postgraduate Institute Annual Conference, Teddington, UK, Oct. 2017.

[2] ——, "Comparing methods for evaluating measurement uncertainty given in the JCGM 'evaluation of measurement data' documents," Faculty of Engineering and Physical Sciences Annual Festival of Research, University of Surrey, Jun. 2017.

[3] ——, "Evaluating measurement uncertainty in microwave and terahertz frequency metrology," 6th Annual Postgraduate Research Conference, University of Surrey, Apr. 2016.

Acknowledgements

I would like to thank my supervisory team: Peter Aaen, Nick Ridler and Marian Florescu. Peter and Nick gave me many opportunities throughout the project and were especially helpful and encouraging when problems arose. Marian took over as my primary supervisor while writing this dissertation and offered great advice and support to help me complete my work.

Martin Salter at the National Physical Laboratory (NPL), Teddington, who learned about nonlinear behavioural models and their extraction alongside me, always provided fruitful discussions and these helped me a great deal in my understanding of the science and mathematics. Martin also assisted with or performed some of the measurements in our publications.

I would also like to thank Daniel Stokes and other scientists in the electromagnetic measurements labs at NPL, who provided training and access to use their equipment, including the National primary standards for impedance in a variety of coaxial and waveguide media. Their welcoming and friendly nature also made every trip to NPL interesting, even when the schedule consisted entirely of repeated measurements!

I must extend huge thanks to Dylan Williams and his group at the National Institute for Standards and Technology (NIST) in Boulder, CO, USA. When I made contact with Dylan in regards to extending his existing software uncertainty framework he was immediately helpful and encouraging. He extended his upcoming UK trip to European Microwave Week and stayed at the university for an additional week to work with me expanding his software. The following year he invited me to visit NIST for three weeks to spend more time integrating behavioural model extraction into his software, and to characterise phase references used in my experiments. Both Dylan and his colleagues were excellent hosts and it was really exciting to work in an office with so much knowledge and experience. Special thanks also to Gustavo Avolio who performed the characterisation of our phase references, and also reviewed my final publication.

Away from my desk, my mother has provided me with a lot of support during my studies and put up with my various complaints. She has never stopped believing that I could finish my project and must feel quite vindicated now!

I am enormously grateful to my colleague and friend throughout my entire university career, Sean Gillespie. Together we were Peter's first PhD students at the University of Surrey, and experienced all the ups and downs of starting a new lab. We saw the university change a lot over the previous nine years, and I'm sure we will both look back in future with very fond memories of it.

Finally, last but not least, I would like to thank my fellow students and staff at the Advanced Technology Institute at the University of Surrey: Haris, Gemma, Jonas, Morgan, Steve, Matei, Tony, John, Grace, Julian, Jose, Kostis, Scott, James, Bob - the list goes on. Together they made my time as a postgraduate thoroughly enjoyable and I will miss them all!

Contents

List of Figures

List of Tables

List of Abbreviations

AC Alternating Current

ACPR Adjacent Channel Power Ratio

ADS Advanced Design System

ANAMET Automatic Network Analyser Metrology

BER Bit Error Rate

BIPM International Bureau of Weights and Measures

DC Direct Current

DUT Device Under Test

EURAMET European Association of National Metrology Institutes

EVM Error Vector Magnitude

GUM Guide to the Expression of Uncertainty in Measurement

IEC International Electrotechnical Commission

IEEE Institute of Electrical and Electronics Engineers

IFBW Intermediate Frequency Bandwidth

IFCC International Federation of Clinical Chemistry and Laboratory Medicine

ILAC International Laboratory Accreditation Cooperation

ISO International Organisation for Standardisation

IUPAC International Union of Pure and Applied Chemistry

IUPAP International Union of Pure and Applied Physics

LPU Law of Propagation of Uncertainty

LSNA Large Signal Network Analyser

LSOP Large Signal Operating Point

METAS (Swiss) Federal Institute of Metrology

MUF Microwave Uncertainty Framework

NIST (US) National Institute of Standards and Technology

NMDG Network Measurement and Description Group

NMI National Metrology Institute

NPL (UK) National Physical Laboratory

NVNA Nonlinear Vector Network Analyser

OIML International Organisation of Legal Metrology

PAE Power-Added Efficiency

RF Radio Frequency

SI International System of Units

SOL Short-Open-Load

SOLR Short-Open-Load-Reflect

SOLT Short-Open-Load-Thru

SOSLT Short-Offset-Short-Load-Thru

TRL Thru-Reflect-Line

TPM Test Port Match

UKAS United Kingdom Accreditation Service

VIM International Vocabulary of Metrology

VIOMAP Volterra Input-Output Map

VNA Vector Network Analyser