MEASUREMENT UNCERTAINTY IN NON-LINEAR BEHAVIOURAL MODELS OF MICROWAVE AND MILLIMETRE-WAVE AMPLIFIERS

Laurence Stant

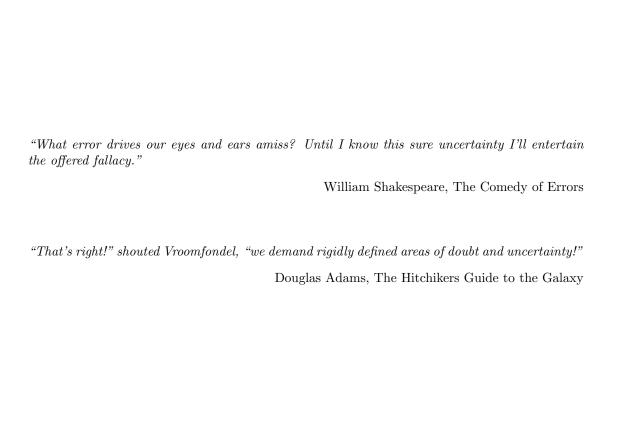A thesis submitted in partial fulfillment for the degree of Doctor of Philosophy

in the
Advanced Technology Institute and Department of Electronic Engineering
Faculty of Engineering and Physical Sciences
University of Surrey

September 2017

Declaration of Authorship

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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. Stant, N. Ridler, and P. Aaen, "Uncertainty evaluation of an active interferometric method for measuring extreme impedance on-wafer devices," *IEEE Transactions on Microwave Theory and Techniques*, 2018.

[2]   L. Stant, D. Root, N. Ridler, and P. Aaen, "Uncertainty evaluation of predicted optimum load match using x-parameters of microwave amplifiers," *IEEE Microwave and Wireless Components Letters*, 2018.

[3]   L. Stant, M. Salter, N. Ridler, D. Williams, and P. Aaen, "Propagating measurement uncertainty to microwave amplifier nonlinear behavioural models," *IEEE Transactions on Microwave Theory and Techniques*, 2018.

[4]   L. Stant, P. Aaen, and N. Ridler, "Evaluating residual errors in waveguide VNAs from microwave to submillimetre-wave frequencies," *IET Microwaves, Antennas & Propagation*, vol. 11, no. 3, pp. 324–329, Feb. 2017. DOI: `10.1049/iet-map.2016.0455`.

[5]   ——, "Comparing methods for evaluating measurement uncertainty given in the JCGM 'evaluation of measurement data' documents," *Measurement*, vol. 94, pp. 847–851, Dec. 2016. DOI: `10.1016/j.measurement.2016.08.015`.

[6]   ——, "Evaluating residual errors in waveguide network analysers from microwave to submillimetre-wave frequencies," in *IET Colloquium on Millimetre-Wave and Terahertz Engineering [amp] Technology 2016*, Institution of Engineering and Technology (IET), 2016. DOI: `10.1049/ic.2016.0016`.

Acknowledgements

I want to thank...

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Testing, testing[1], [2].

Bibliography

[1] L. Stant, P. Aaen, and N. Ridler, "Evaluating residual errors in waveguide network analysers from microwave to submillimetre-wave frequencies," in *IET Colloquium on Millimetre-Wave and Terahertz Engineering [amp] Technology 2016*, Institution of Engineering and Technology (IET), 2016. DOI: `10.1049/ic.2016.0016`.

[2] ——, "Comparing methods for evaluating measurement uncertainty given in the JCGM 'evaluation of measurement data' documents," *Measurement*, vol. 94, pp. 847–851, Dec. 2016. DOI: `10.1016/j.measurement.2016.08.015`.

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Bibliography

[1] L. Stant, P. Aaen, and N. Ridler, "Evaluating residual errors in waveguide network analysers from microwave to submillimetre-wave frequencies," in *IET Colloquium on Millimetre-Wave and Terahertz Engineering [amp] Technology 2016*, Institution of Engineering and Technology (IET), 2016. DOI: `10.1049/ic.2016.0016`.

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Bibliography

[1] L. Stant, P. Aaen, and N. Ridler, "Evaluating residual errors in waveguide VNAs from microwave to submillimetre-wave frequencies," *IET Microwaves, Antennas & Propagation*, vol. 11, no. 3, pp. 324–329, Feb. 2017. DOI: 10.1049/iet-map.2016.0455.

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Bibliography

[1] L. Stant, P. Aaen, and N. Ridler, "Evaluating residual errors in waveguide network analysers from microwave to submillimetre-wave frequencies," in *IET Colloquium on Millimetre-Wave and Terahertz Engineering [amp] Technology 2016*, Institution of Engineering and Technology (IET), 2016. DOI: `10.1049/ic.2016.0016`.

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Bibliography

[1] L. Stant, P. Aaen, and N. Ridler, "Evaluating residual errors in waveguide network analysers from microwave to submillimetre-wave frequencies," in *IET Colloquium on Millimetre-Wave and Terahertz Engineering [amp] Technology 2016*, Institution of Engineering and Technology (IET), 2016. DOI: `10.1049/ic.2016.0016`.

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6 Applications of Nonlinear Behavioural Models Incorporating Measurement Uncertainty

6.1 Introduction

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Bibliography

[1] L. Stant, P. Aaen, and N. Ridler, "Evaluating residual errors in waveguide network analysers from microwave to submillimetre-wave frequencies," in *IET Colloquium on Millimetre-Wave and Terahertz Engineering [amp] Technology 2016*, Institution of Engineering and Technology (IET), 2016. DOI: `10.1049/ic.2016.0016`.

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7 Conclusions

7.1 Further Work

Testing, testing[1], [2].

Bibliography

[1] L. Stant, P. Aaen, and N. Ridler, "Evaluating residual errors in waveguide network analysers from microwave to submillimetre-wave frequencies," in *IET Colloquium on Millimetre-Wave and Terahertz Engineering [amp] Technology 2016*, Institution of Engineering and Technology (IET), 2016. DOI: `10.1049/ic.2016.0016`.

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