RADO LAPUH

SAMPLING WITH 3458A

LEFT RIGHT D.O.O.

Sampling with 3458A, Understanding, Programming, Sampling and Signal Processing / Rado Lapuh

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Dedicated to my wife and our two sons who missed me during the thinking, exploring, measuring and writing of this book.

Contents

Foreword

Measurements with ever increasing accuracy and precision are the basis of science. They underpin the development of new and improved products and processes, global trade and the implementation of regulations. The International System of Units, the SI, ensures the worldwide comparability of measurement results and the National Metrology Institutes (NMI), working together under the roof of the Metre Convention, realise and disseminate the SI units with the accuracy required by science, economy and society. The concept of traceability to national standards and thus to the SI units guarantees that any end user can count on the reliability of measurement results if they are reported by a competent laboratory that is linked into the system.

One of the tasks of a NMI is to calibrate or to certify the measuring instruments that are available on the market. It is obvious that the tools and methods applied in this process cannot be the same as the ones that need to be tested. In addition to realising the appropriate SI units, metrologists need to develop scaling techniques and to take special care to characterise and validate all of the system components which may have an influence on the measurement result. Therefore, the accuracy level has to exceed that of the device under test.

In the field of electrical measurements, metrologists use quantum effects as reference standards. In this way, the unit of resistance, the ohm, and the unit of voltage, the volt, are linked to fundamental constants through the quantum Hall effect and the Josephson effect respectively. All of the other SI units that are needed in electrical measurements can be constructed from these two units using appropriate bridge techniques. The quantum standards are still difficult and costly to operate and maintain and are, thus, not accessible to most calibration laboratories. Good transfer instruments with good stability and linearity are needed for daily laboratory work. In the field of DC and low frequency electrical measurements, commercially available digital multimeters and calibrators are used for this purpose.

One of these high end multimeters, the 3458A, first introduced by Hewlett Packard in 1988, is the subject of this book. This instrument stands out from other multimeters due to its features, such as its self-calibration capability, the linearity of its ADC and its high speed sampling modes. Three decades after its introduction, the 3458A is still unrivalled in some of its characteristics.

In electrical measurements, sampling methods are superseding more and more of the traditional analogue bridge techniques. This book explains and describes the sampling capabilities of the 3458A multimeter and it gives many examples of its applications. The author, with his many years of experience in the field of electrical metrology, is very well qualified for this undertaking.

As someone who has used the 3458A multimeter for many years as a working tool, it gives me great pleasure to see it described in such detail in this book. I wish it a broad readership.

Beat Jeckelmann

Preface

In late 2010, the EURAMET (The European Association of National Metrology Institutes) Technical Subcommittee for Power and Energy discussed the use of an Agilent 3458A type digital multimeter in calibration laboratories across Europe. While a lot of research, publications and actual measurement set-ups have already been performed worldwide using 3458A sampling capability, including, but not limited to, highly accurate low frequency power measurement, this knowledge and experience was found to be rather segmented and not easily accessible to all calibration laboratories. A EURAMET project Nr. 1168 was initiated to collect all available information in a single and structured guide, which would provide calibration laboratories with all of the information necessary to set-up and use the sampling feature of the 3458A multimeter at its best. If necessary, further research would be conducted to complement available knowledge.

It just so happened that, at that time, the members of the Technical Subcommittee were not able to dedicate their resources to this project. Nevertheless, as the project's output was still of considerable interest, the project coordinator proposed to conduct the work as a personal project without fixed deadlines. That was accepted by the Technical Subcommittee and the author headed for a long trip on an unexpected journey.

After several years of collecting materials, studying 3458A capabilities, programming, measuring, analysing, writing and drawing, the initial goal is hopefully accomplished.

WITH GRATITUDE. All of this would not have been possible without the understanding and help of many colleagues, among whom I need to thank Matjaž Lindič[1] for allowing me to use the SIQ set of four 3458A multimeters when they were not in use and their licensed MATLAB numerical computing environment, Boštjan Voljč[1], Miha Kokalj[1], Marko Berginc[1], and Borut Pinter[1], for their tireless preparation of remote measurement setups, Gerd Vandersteen[2] for allowing me to publish their multi frequency sine fit MATLAB algorithm, Waldemar G. K. Ihlenfeld[3] for remarks on the intermediate book draft, Andreas Christensen[4] for

[1] Slovenski institut za kakovost in meroslovje (SIQ)

[2] Vrije Universiteit Brussel / ELEC

[3] Instituto Nacional de Metrologia, Qualidade e Tecnologia (Inmetro)

[4] Trescal

discussions on 3458A programming, Franz Josef Ahlers[5] for supporting and Jan Kučera[6] for providing information on the 3458A's internal timer sample clock time jumps, Oliver Kieler[5] and Ralf Behr[5] for providing their Josephson Arbitrary Waveform Synthesiser on which a comprehensive measurement campaign was performed, Richard L. Steiner[7] for sharing his experience on sampling timing related issues, Gert Rietveld[8] for providing insight into ratio measurement capabilities, Murray Early[9] for guarding and grounding discussions, among many other insider tips, Hüseyin Çaycı[10] for providing information on reading multiple instruments simultaneously by one computer, and Rok Lapuh[11] for solving polynomial expansion FIR filter equations and book design discussions.

A special thank you also goes to Helko van den Brom[8], Enriko Mohns[5] and Stefan Svensson[12] for providing all of the information on their measurement setup examples, utilising 3458A, and for their fruitful discussions covering various practical aspects of its use.

Huge input was provided during the technical proofreading by Martin Šíra[6], who found many errors and omissions, and made improvements to my draft. His humour made the otherwise painstaking correction process creative and fun. This book would not be the same without his valuable comments. I owe him a Maß of Pilsener.

Hard work was also done during the flawless proofreading performed by William Dawson[13], as my English did not make this a trivial task.

[5] Physikalisch-Technische Bundesanstalt (PTB)

[6] Český metrologický institut (ČMI)

[7] National Institute of Standards and Technology (NIST)

[8] Nederlands Metrologisch Instituut (VSL)

[9] Measurement Standards Laboratory of New Zealand (MSL)

[10] TÜBİTAK Ulusal Metroloji Enstitüsü (UME)

[11] Pipistrel Vertical Solutions d.o.o.

[12] Research Institutes of Sweden (RISE)

[13] National Physical Laboratory (NPL)

A NOTE ON THE TOOLS. The material was composed in LaTeX, using an Overleaf collaborative writing and publishing system[14]. A Tufte-Style book template was used for the design of the book. The text is set in Palatino and Helvetica typefaces. PGFPLOTS package, designed by Christian Feuersänger, was used to prepare all plots and TIKZ package, originally designed by Till Tantau, was used to prepare other drawings. GRAPHIC FOR MAC was used to create remaining vector GUIs and illustrations.

[14] `www.overleaf.com`

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Introduction

This book discusses the sampling capability[15] of an original 3458A type digital multimeter, which was developed by the Hewlett-Packard company and put on the market in 1988. The 3458A was so successful that it survived the production ownership of Hewlett-Packard, Agilent Technologies, since 1999, and Keysight, since 2014, with only minor changes, that were likely due to the lack of certain components that were originally used in the thirty year old design. Remarkably, the 3458A is still in production and there are no competing digital multimeters on the market, at least not in the precision low frequency sampling domain.

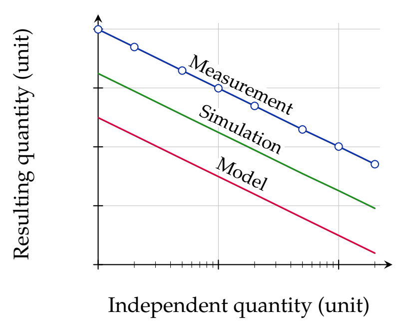
[15] Other instrument capabilities, while broad, interesting, and useful, are deliberately not covered in this book.

As the goal of this book is to cover the actual sampling capabilities of the 3458A that can be straightforwardly used in practical applications, the majority of the measurements presented were performed by the author during the preparation of the material[16]. Four instruments were used: two Hewlett-Packard 3458A, one Agilent Technologies 3458A, and one Keysight 3458A. All were used heavily for daily laboratory calibrations in SIQ but they were at the author's disposal during the rest of the day or during the weekends, often using TeamViewer remote access.

[16] The measurements obtained elsewhere are clearly marked with a credit to their authors.

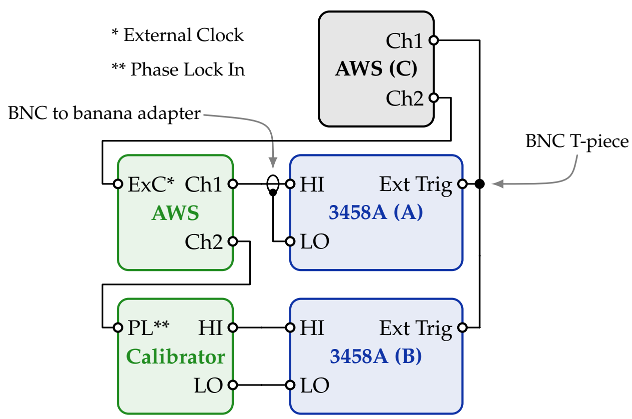
Specific conventions are used in the book to improve its readability:

- The GPIB commands used to program the 3458A are differentiated from other text, as they are surrounded by a rounded rectangle. For example, a 3458A GPIB command 'RESET' is written as `RESET`. The triggering hierarchy implemented in 3458A, with a variety of commands being involved, could be a challenge in the practical use of 3458A. This hierarchy and the correct event specification is crucial for successfully performing the correct sampling with 3458A and for that reason the commands defining trigger arming, trigger and sample related commands are additionally colour coded, like `TARM AUTO` being a trigger arm command, `TRIG AUTO` being a trigger command, and `NRDGS 10,TIMER` being a sample command. Specific GPIB bus commands, which are not 3458A commands, are given like `SPOLL`.



Colours are used to denote the model, simulation, or measurement result. For measurement results marked by circles, the lines between them are simply visual connections and do not represent the measurement result.

- Descriptions and associated graphs involve models, actual measurements and in a few places simulations. A model is defined as a dependency given by an equation or a manufacturer specification. A simulation is defined as a dependency obtained by numeric calculation or simulation where a model is not available. A measurement is defined as actual results that are either obtained directly by sampling, estimated or otherwise processed from the sampled data. As it is important to distinguish between them, they are colour coded in all plots. The model response is plotted in red, the simulation results are plotted in green, and the measured results are plotted in blue.
- Simplified schematic diagrams showing the measurement setups will be used throughout the book. The figure below provides an example in which only the instruments and signal wires used for the measurement are shown. No GPIB communication is shown although it is clear that these connections should be in place.



An example of a simplified schematic measurement setup. The 3458A is always shown in blue and the signal sources are always shown in green. Both the BNC coaxial cables and the banana plug voltage test leads are plotted in the same way but it should be clear from the instrument connectors which will be used. In this example, only the connections from the Calibrator to the 3458A (B) use test wires. All other connections use BNC (RG-58/U) cables.

- To make material easy to implement in an ongoing measurement, it is accompanied by the program listings, which were used to obtain the measurement results. These listings are conceptual and while similar to BASIC language, they cannot be directly run in any interpreter. However, they completely cover 3458A programming and it is up to a user to implement them in their own code.

This book has four main chapters and a set of appendices, which contain rather specific but valuable information. Chapter 1 covers the programming necessary to operate 3458A as a sampling device. Chapter 2 covers the instrument's measurement capabilities and how to make best use of them. Chapter 3 gives practical state-of-the-art examples as implemented in some National Metrology Institutes. Chapter 4 gives a rather simplified coverage of the theory and it is intentionally the last chapter as it contains reference material that is already familiar to many readers[17]. The material's technical content grows in that order too.

[17] The readers not very familiar with the sampling theory might want to familiarise with this Chapter first.