RF & Microwave

VNA Tools II: Metrology Software for the Vector Network Analyser

Multi-step measurement procedures and multidimensional measurement quantities are inherent challenges to measurements with the vector network analyser (VNA). A proper metrological treatment requires specialised software. The Radio-frequency and Microwave (RF & MW) Laboratory at METAS develops software to support VNA metrology since many years. Recently the activity has been intensified and an official software project under the name VNA Tools II (www.metas.ch/vnatools) has been started in collaboration with an industrial partner.

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A vector network analyser (VNA, see picture 1) is used to measure S-parameters (see previous article), which are together with RF power the fundamental quantities in RF & MW metrology. Metrology grade VNAs are precise but inaccurate instruments, i.e. measurements show a good repeatability but are affected by relatively large systematic errors, which are inherent to the measurement principle and thus unavoidable.

Known calibration standards need to be measured to determine the systematic errors before measurements of a device under test can be performed. The measurements are affected by device instabilities, environmental conditions, knowledge of the standards, connector and cable effects and so on. The uncertainty calculation for VNA measurements needs to take all this into account and is further complicated by the fact that the involved quantities are complex-valued.

Nowadays even at the level of National Metrology Institutes (NMI) the uncertainty evaluation of VNA measurements is generally unsatisfactory. This is largely due to the lack of appropriate software because the necessary calculations are too elaborate to be done by hand.

From VNA Tools to VNA Tools II

As the name *VNA Tools II* suggests, there is a predecessor software, *VNA Tools*, whose origin goes back to the year 1998. The specialists of METAS' RF & MW Lab developed this software using LabVIEW, with the primary purpose to perform all necessary calculations of the VNA measurement process externally and not to rely on the firmware of the VNA. The software supports a variety of calibration procedures, data visualisation, storage and export, device control and a reporting scheme. 23 licenses of this software are currently still in use in metrology labs around the world.

Around 2004, a first attempt to extend the application with proper measurement uncertainty evaluation [1] was started in collaboration with Blair Hall from IRL/MSL, the NMI of New Zealand. This work was slowed down by personal changes in METAS' RF & MW Lab and then revived in 2008 with the start of an official project under the name *VNA Tools II*.

This software project aims at a VNA metrology software with similar features as the original *VNA Tools* but with the additional possibility to evaluate measurement uncertainties in accordance with the guidelines of the ISO-GUM [2]. It also provides a framework to apply results of projects as *CoM070* and *CalCon* (see previous article) efficiently in the daily metrological work.

1 A vector network analyser is used to measure S-parameters, which are fundamental quantities in RF & MW metrology.

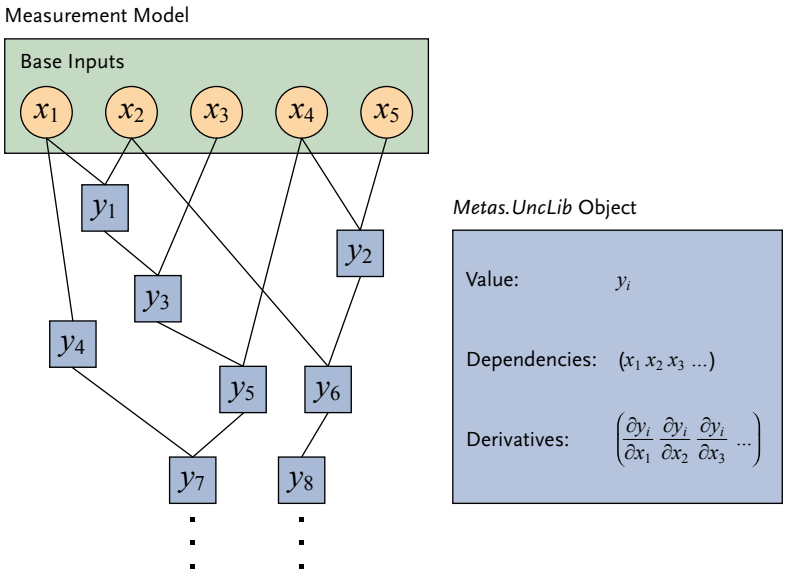
Metas.UncLib (www.metas.ch/UncLib) is an uncertainty calculator, which is generic, i.e. it can be used for any measurement problem that involves measurement uncertainty propagation. It is particularly well suited for more complicated problems which deal with complex-valued or multidimensional quantities and with advanced mathematics.

Metas.UncLib provides three different modes of uncertainty propagation, linear (*LinProp*), higher order (*DistProp*) and numerical (*MCProp*). *LinProp* propagates variances of probability density distributions through a linearised measurement model. It is the method of the ISO-GUM and should be considered as the preferred choice.

The implementation of *LinProp* is based on the GUM Tree [5] concept (mst.irl.cri.nz) of Blair Hall. An uncertain measurement quantity is stored in an abstract data type, which contains the value of the quantity and its dependencies with respect to basic input quantities as well as the derivatives with respect to these dependencies. Dependencies and derivatives are updated at each computational step (illustration 3) with the help of the chain rule. Its numerical implementation is known by the name «automatic differentiation».

This mechanism is particularly well suited for the implementation in a computer program, because a compiler supports it in a natural way by decomposing arbitrary complicated equations into elementary mathematical steps. It is important to understand that with this method only derivatives and dependencies are stored and not uncertainties. With the available information uncertainties and correlations can be calculated on demand for any intermediate or final result.

An object oriented design of the software is used to hide the complexity of the mechanism from the user and to perform the necessary calculations in the background. The *Metas.UncLib* implementation of GUM Tree is optimised for speed and low memory use and thus well suited for elaborate calculations with larger amounts of data.



3 Linear uncertainty propagation mechanism of *Metas.UncLib*. The measurement model is decomposed into steps (tree), each node representing an elementary mathematical operation. Uncertain quantities are represented by an abstract data type (*Metas.UncLib object*) with fields that are updated at each computational step.

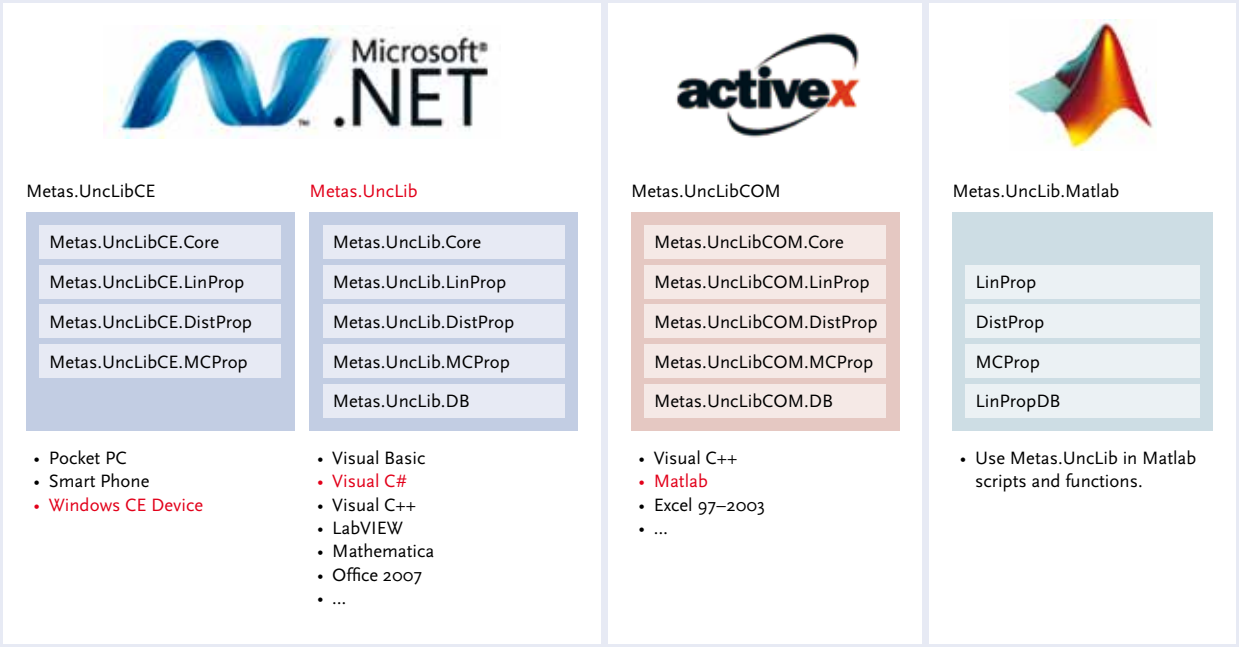
2 The generic uncertainty calculator *Metas.UncLib*.

Agilent Technologies, a company with a strong VNA metrology laboratory, is participating as a partner in this project. The primary objective of this collaboration is knowledge exchange in the fields of measurement uncertainty propagation, VNA characterisation and software development.

Multivariate Treatment of Measurement Uncertainties

S-parameters are multidimensional quantities and require a multivariate treatment [3] to determine the measurement uncertainty. A supplement to the ISO-GUM [4] about this topic is currently still in preparation. The multivariate treatment is already for simple problems rather tedious. It is based on matrix and vector formalism, which on the other hand conveniently lends itself to software implementation.

Uncertainty evaluation of VNA measurements has largely been done so far with a heuristic procedure, the so-called analysis of the residual errors. In this method, verification standards are measured with the VNA after calibration. Uncertainties are derived subsequently from these measure-



4 Interfacing options of *Metas.UncLib*.

The *DistProp* module is a generalisation of *LinProp* in the sense that higher order moments of distributions are propagated through a measurement model, which is approximated by higher order terms of its Taylor expansion. It is suited for cases where the linearised approach fails. The user can set arbitrarily high orders, but should be aware that the computational and memory burden drastically grows with increasing order.

As of the current version (1.1) of *Metas.UncLib* the implementation of *DistProp* is still experimental and additional work is needed to improve the performance and to make use of the information about higher order moments of the output distribution.

The *MCProp* module supports numerical propagation of distributions based on the so-called Monte Carlo method [3]. The implementation of this module as of the current version has only very limited features and is not recommended yet for serious use.

Metas.UncLib provides advanced storage possibilities for the *LinProp* module. It is possible to store uncertain objects in different formats (xml, binary) or even in a data base and at the same time conserving the full information about the stored objects.

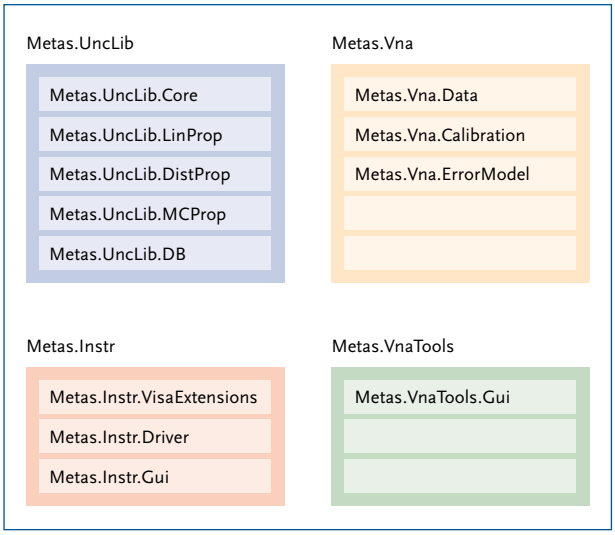
Metas.UncLib is a C# library which does not provide a graphical user interface. It has however interfacing capabilities through .NET and COM (illustration 4). METAS provides a wrapper library (*Metas.UncLib.Matlab*) which allows the use of *Metas.UncLib* from MATLAB (www.mathworks.com). It fully supports the convenient syntax for matrix and vector calculus of MATLAB.

Metas.UncLib and *Metas.UncLib.Matlab* are available from METAS for free and can be downloaded from www.metas.ch/UncLib.

ments under simplifying assumptions. Error terms are isolated from the measurement model and idealised properties are assigned to the verification standards. Apart from being conceptionally questionable as a method of uncertainty evaluation, the assumptions become increasingly incorrect with higher frequencies. The proper ISO-GUM approach requires that the values and uncertainties of basic input quantities are specified and subsequently propagated through the measurement equation.

A major contributor to the measurement uncertainty is the knowledge about the calibration standards. This requires in case of primary standards, as air lines or offset shorts, an exact characterisation by dimensional measurements or, in case of transfer standards, a characterisation with a VNA that has previously been calibrated by means of primary standards.

Other uncertainty contributions are related to VNA characteristics, as noise, drift and non-linearity. It is necessary to define



5 Software architecture of *VNA Tools II*.

test procedures to evaluate these effects and to specify measurement uncertainty contributions.

Finally, it is inevitable to quantify effects that are related to the measurement setup as environmental influences, connector repeatability and in particular cable movement. *VNA Tools II* provides a way to specify these uncertainty contributions and propagates them automatically through the measurement model to the final result.

Features of *VNA Tools II*

VNA Tools II is a complete rewrite of the software in the programming language C#. The reason to abandon LabVIEW in favor of C# is largely related to performance and syntax. A schematic overview of the software architecture is given by illustration 5. Core piece of the application is *Metas.UncLib* (see box 2), which is a generic library for measurement uncertainty calculation.

There are three other components which are specific to VNA measurements. *Metas.Vna* implements calibration and error correction algorithms and data handling. *Metas.Instr* enables the communication between the VNA and the controlling computer and *Metas.VnaTools* adds all the pieces together in a graphical user interface and provides a flexible way of using different measurements for different purposes.

VNA Tools II has an emphasis on modularity and flexibility and not so much on user friendliness. It should not be considered as a foolproof measurement application but rather as a metrology tool for the expert. It requires from the VNA user an in-depth understanding of what he is doing.

The framework for calibration and error correction has been set up in a very general way allowing for an arbitrary number of VNA ports, where each port may be defined for a different complex reference impedance. The error correction process supports over-determined calibrations in a flexible way. Different standards and different measurements can be combined to perform calibration and error correction. This powerful feature allows to test the consistency among different standards and to verify their characterisation.

The mechanism of *Metas.UncLib* keeps track of common influences and provides full control over correlations. The data storage concept preserves this information to the maximum extent possible.

Future Plans

The project is currently still ongoing. It is expected that by the beginning of 2011 a first internal version of *VNA Tools II* should become available, followed by a public release several months later. The burden of software development is currently on a single pair of shoulders and looking into the future it might be desirable to form a developer group at the level of national metrology institutes if enough interest can be generated. This could be a way to extend the application with new features and put it to use in other areas of VNA metrology, as wave guide or on-wafer measurements. In the more distant future it could even play a role in nonlinear VNA measurements.

References

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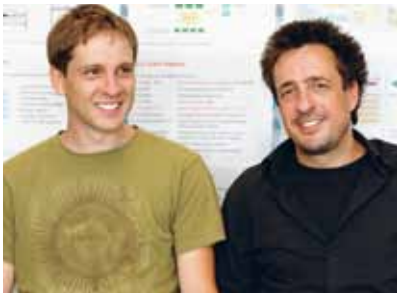
[5] B. D. Hall: An Extension of the GUM Tree method for complex numbers, Advanced Mathematical and Computational Techniques in Metrology VIII, World Scientific, Series on Advances in Mathematics for Applied Sciences, Vol. 78, pp 158–163, 2009.



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VNA Tools II: Metrologiesoftware für den Vektor-Netzwerkanalysator

Mehrstufige Messprozesse sowie mehrdimensionale Messgrössen sind eine Herausforderung bei Messungen mit Vektor-Netzwerkanalysatoren (VNA). Die Unsicherheitsberechnung für solche Messungen verlangt spezialisierte Software. Im Hochfrequenzlabor am METAS wird seit vielen Jahren Software für die VNA-Metrologie entwickelt. Vor kurzem wurden diese Anstrengungen intensiviert und das Softwareprojekt VNA Tools II in Zusammenarbeit mit einem Industriepartner gestartet.

VNA Tools II ist eine flexible Software für den Vektor-Netzwerkanalysator. Alle Berechnungen für die Kalibrierungen und die Fehlerkorrektur werden extern, und damit unabhängig von der VNA-Firmware, durchgeführt. Die Berechnung der Messunsicherheit geschieht nach international anerkannten Standards. Massgebliche Beiträge zur Messunsicherheit, die von der Kenntnis der Kalibrierstandards, der Geräteparameter und dem Messaufbau herrühren, lassen sich spezifizieren und können durch ein Messmodell zu den Messergebnissen hin fortgepflanzt werden.

VNA Tools II basiert auf dem generischen Unsicherheitsrechner Metas.Unc Lib (www. metas.ch/UncLib). Dabei handelt es sich um eine eigenständige Software-Bibliothek. Metas.UncLib erlaubt die automatische Fortpflanzung der Messunsicherheit unter vollständiger Berücksichtigung von Korrelationen. Ausserdem wird die Datenablage in verschiedenen Formaten und Schnittstellen zu anderen Anwendungen bereitgestellt.

Eine erste interne Version von VNA Tools II wird Anfang 2011 vorhanden sein; einige Monate später wird die Software veröffentlicht werden.

VNA Tools II: logiciel de métrologie pour l'analyseur de réseaux vectoriel

Des processus de mesure en plusieurs étapes et des mesurandes pluridimensionnels représentent un défi pour les mesures effectuées avec des analyseurs de réseaux vectoriels (VNA). Pour de telles mesures, le calcul de l'incertitude nécessite un logiciel spécialisé. Depuis de nombreuses années, le laboratoire Haute fréquences de METAS développe des logiciels adaptés à la métrologie VNA. Il vient d'intensifier ses travaux et a lancé le projet logiciel VNA Tools II en collaboration avec un partenaire industriel.

VNA Tools II est un logiciel souple d'emploi pour l'analyseur de réseaux vectoriels. Tous les calculs concernant les étalonnages et la correction des erreurs sont effectués à l'externe, indépendamment du micrologiciel VNA. Le calcul de l'incertitude de mesure est réalisé selon des normes reconnues au niveau international. Les contributions déterminantes à l'incertitude de mesure résultant de la connaissance des étalons, des paramètres des appareils et du montage de mesure peuvent être spécifiées et propagées aux résultats de mesure à l'aide d'un modèle de mesure.

VNA Tools II est fondé sur le module pour le calcul d'incertitude Metas.UncLib (www.metas.ch/UncLib). Il s'agit d'une bibliothèque logicielle autonome. Metas.UncLib permet la propagation automatique de l'incertitude de mesure en tenant entièrement compte des corrélations. En outre, le dépôt de données supporte divers formats et interfaces pour d'autres applications.

La mise à disposition d'une version interne de VNA Tools II est prévue pour le début de 2011, et la publication du logiciel suivra quelques mois plus tard.

VNA Tools II: applicazione di metrologia per l'analizzatore di reti vettoriale

I processi di misurazione a più stadi ed i misurandi multidimensionali rappresentano una sfida per le misure effettuate coll'analizzatore di reti vettoriale (VNA, Vector Network Analyzer). Per tali misure, il calcolo dell'incertezza di misura richiede un software specializzato. Da molti anni, il laboratorio Alta Frequenza del METAS sviluppa software specifici per la metrologia VNA. Recentemente, il laboratorio ha intensificato gli sforzi per iniziare il progetto software VNA Tools II, in collaborazione con un partner industriale.

VNA Tools II é un software flessibile per l'analizzatore di reti vettoriale. Tutti i calcoli concernenti le tarature e la correzione degli errori vengono effettuati all'esterno, indipendentemente dal programma interno allo strumento (firmware). Il calcolo dell'incertezza di misura è realizzato secondo norme riconosciute a livello internazionale. I contributi determinanti per l'incertezza di misura risultanti dalla conoscenza dei campioni, dei parametri degli apparecchi e della costruzione della misura, vengono specificati e possono essere propagati ai risultati di misura mediante un modello di misura.

VNA Tools II é basato su un calcolatore d'incertezza generico Metas.UncLib (www.metas.ch/UncLib). Si tratta di una Biblioteca software originale che consente la propagazione automatica dell'incertezza di misura tenendo conto delle correlazioni. Inoltre, il trasferimento dati supporta diversi formati e più interfacce per altre applicazioni.

Una versione interna di VNA Tools II sarà messa a disposizione all'inizio dell'anno 2011; l'applicazione verrà messa a disposizione del pubblico qualche mese più tardi.