Advanced Antenna Modelling Tool for Performance Verification and Diagnosis

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***Abstract*—A development project of a new software tool for uncertainty quantification (UQ) of an antenna's performance caused by the stochastic behaviour of design variables of the system has been performed within the ESA Contract No. AO/1-10116/19/NL/AS. The mathematical algorithms implemented in the tool allow for a very general formulation, where uncertainty can be added to both geometrical and electrical parameters of the system. An application case is given and the results are compared to reference solutions.**

***Index Terms*—Uncertainty quantification, antenna software**

I. Introduction

Designing antenna systems for modern telecommunication or Earth observation entails stringent performance requirements and error budgets. As the systems become increasingly complex and involve many subsystems, the need for accurate and reliable quantification of imperfections involved in the error budgets increase as well. In particular, advanced systems such as unfurlable reflectarrays or reflectors, where in-flight deployment is used, require detailed mechanical and thermal studies, all of which provide parameter ranges rather than specific parameter values. Further, for high-accuracy applications such as deep-space communication, even minor imperfections can have devastating consequences if not taken into account.

Modern computational electromagnetics software enables the RF engineer to simulate a large number of mechanical designs and in some cases automatically optimize performance. However, when quantifying the uncertainty in their design, e.g., the performance degradation introduced by mechanical imperfections, the engineers are currently on their own.

A common approach for obtaining some form of uncertainty quantification (UQ) typically involves running a very large number of simulations with random errors added to the system, followed by statistical examination of the acquired data – a so-called *Monte-Carlo* simulation. This approach require a very large number of simulations and the risk of user error is high. Further, the statistical accuracy is extremely poor, which could cause misleading conclusions about the final performance when the antenna is deployed. It is therefore clear, that more advanced approaches are needed.

The goal in this paper has been to develop a software tool enabling antenna designers to study the impact of uncertainties during the design phase. Accompanied by advanced UQ techniques, this will provide the designers with a tool to accurately identify uncertainties in their design. The software is closely coupled with TICRAs existing software tools, and is therefore applicable to antennas commonly used for satellite communication payloads or scientific instruments, including passive microwave components, feeds, reflectors, arrays, reflectarrays, etc. Further, it allows uncertainties to be associated with all geometrical and electrical input parameters and computes statistical output of all performance parameters of interest.

A single application case is included in this paper and discusses an UQ analysis of a reflectarray on a cubesat. At the conference, additional examples will be given.

II. Overview of Mathematical Techniques

From a mathematical standpoint, UQ involves the computation of the expected value, the variance and possibly confidence intervals of a function F that take as input uncorrelated stochastic variables $\bar{X}$. In the context of antenna analysis, F represents some key behaviour of an antenna system, often called an *output with uncertainties* (OwU), while $\bar{X}$ are the design variables expressed with uncertainties. With this, UQ represents the uncertainty in F caused by the uncertainty in $\bar{X}$. In principle, the uncertainty of the variables $\bar{X}$ can follow any distribution, but for now the developed software allows for uniform, beta, normal and truncated normal distributions.

Since the computationally most demanding part of evaluating OwU is the analysis of the antenna itself, an important ability of the software is the ability to analyse multiple antenna system outputs (OwUs) for each antenna analysis. In the case of multiple OwUs, each OwU is treated as an independent stochastic process. The OwU can represent any relevant output from the antenna system and therefore needs to be considered as a black-box system. This exclude intrusive UQ methods [1], suggesting the use of non-intrusive methods, since these require no modification or knowledge of the computation of F. This also means that any electromagnetic analysis algorithm can be used to analyse the system.

We distinguish between Monte-Carlo (MC) based techniques and Higher-Order methods. In particular, this software provides the classic MC sampling and a modified Quasi-MC (QMC) method [2]. Though the QMC modification alleviates some of the downsides to the classic MC approach, both MC and QMC often require a prohibitive number of function evaluations, and should be used mainly for validation or problems with an extreme number of variables.

Stochastic Collocation (SC) [3] and Polynomial Chaos Expansion (PCE) [4] are non-intrusive Higher-Order methods that are both available in the software. These methods are

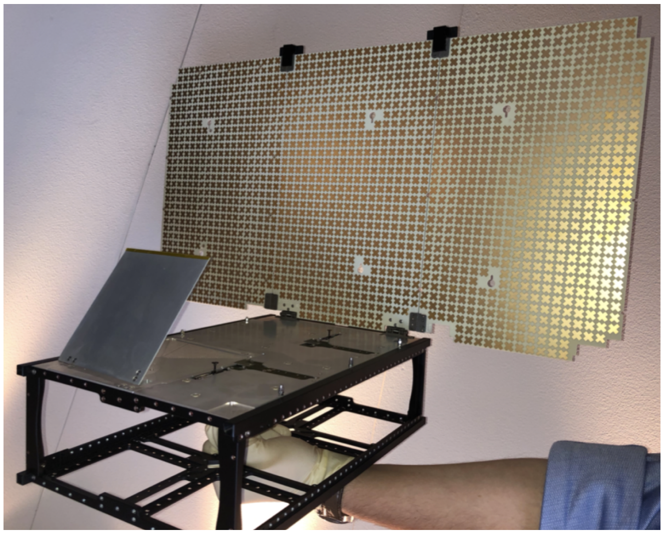

Fig. 1. Deployable reflectarray on a 6U cubesat.

complicated to implement, but reach better statistical accuracy in fewer system evaluations than the MC-based approaches. Their only drawback are the number of dimensions that can be considered. This is somewhat alleviated by the use of sparse grid constructions [5], but for some high-dimensional cases, the MC based approaches are the only option. A detailed treatment of these two methods cannot be presented here, but information may be found in the references.

III. Application Case: Reflectarray on Cubesat

In many practical cases, the influence of a nearby satellite body can affect antenna performance negatively. We therefore include an example where the platform has a very large impact on the antenna performance - the deployable reflectarray (RA) shown in Fig. 1. The flush-mounted all-metallic feed employs the entire top face as an inherent part of the feeding structure. The RA consists of three deployable panels with spring-loaded hinges with a total of 1703 cross-shaped reflectarray elements. The RA operates at X-band from 8.0 - 8.4 GHz.

This investigation relates to the hinge deployment angles of the reflectarray panels and the feed plate. Obviously an accurate deployment of the panels is a prerequisite for succesful communication with the satellite. Severe errors and possibly malfunction of the antenna may result if the hinges fails to open flawlessly. The deployment angles ψ_L, ψ_R, ψ_C, and ψ_F of the left, right, centre, and feed hinges, respectively, are therefore relevant quantities to investigate in an uncertainty quantification analysis. The angles' variations are assumed to follow uniform distributions within spans of $\pm 0.4°$, $\pm 0.2°$, and $\pm 0.5°$ for the lateral, central and feed hinges, respectively. The analysis is done using the SC method. A reference solution has been obtained using MC with 1000 samples (i.e., function evaluations), which in this case of 4 input variables is believed to be sufficiently accurate.

The result obtained by SC is compared with the MC reference in Fig. 2. The co-polar directivity of the reflectarray antenna is shown for $\phi = 90°$. The maximum deviation for the expected mean is less than 0.01 dBi around the main beam. Corresponding values for the confidence interval bounds are about 0.03 dBi around the main beam. It is noted that the results from the SC method were achieved using just 12 function evaluations and it is clear that it yields very accurate results with much fewer function evaluations than a corresponding MC analysis.

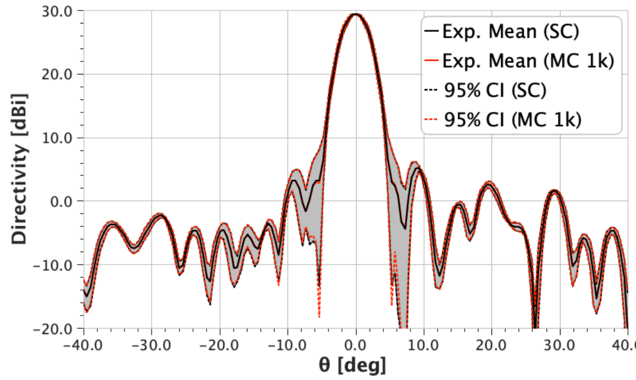

Fig. 2. Radiation pattern with confidence interval predicted by SC compared with MC using 1.000 samples. The Confidence interval is shown in grey.

IV. Conclusions and Perspectives

A software tool has been implemented enabling the user to easily, rapidly and reliably compute statistics such as confidence intervals for the effects of production uncertainties. Being a part of the TICRA Tools software framework, it enables uncertainty quantification analysis of any design that can be analysed using the TICRA Tools products.

With advanced UQ algorithms focused on minimizing the computational resources spent, several different designs can be analysed in fractions of the time needed for the industry-standard Monte-Carlo alternatives to the software. The UQ algorithms provide accurate and reliable statistical output, meaning that users can trust that the information such as confidence intervals are realistic.

An application example of a reflectarray mounted on a cubesat analysed with the Stochastic Collocation method served as a demonstration of the software's capabilities. Additional examples will be presented at the conference.

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