Determination of Manufacturing Tolerances using Uncertainty Quantification for the Realization of a Dual Circularly Polarized Elliptical Feed Horn

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***Abstract* — The manufacturing tolerances for the realization of a dual circularly polarized elliptical feed horn designed for a high-gain deployable K-Band reflectarray antenna-system are determined. The tolerances are found using higher-order uncertainty quantification. Measurement results are presented for comparison with the uncertainty quantification analysis.**

***Keywords*—Antennas, Antenna Feeds, Reflectarray Antennas, Antenna Tolerance Analysis, Uncertainty, Uncertainty Quantification.**

I. Introduction

Antennas used in modern communication systems, earth observations, and scientific research have strict performance requirements that are directly related to predicted error budgets. As the systems become increasingly complex and involve many subsystems, the need for accurate and reliable quantification of the imperfections involved in the prediction of error budgets becomes greater [1].

Poor understanding and quantification of the possible imperfections during the design process will lead to differences between the predicted and measured performance of the antenna system. Implementing uncertainty quantification (UQ) of performance requirements, based on predicted input error budgets (i.e., manufacturing tolerances) early in the design process can help engineers control some of their design variables to be less sensitive, and build much more reliable engineering models that will give better predictions of the performance of the manufactured antenna. This quantification also contains valuable information that might be necessary to know for the design of the subsystems that will rely on the antenna performance.

A simple sensitivity analysis, where the sensitivity to variations in the input variables is calculated, does not provide any information about the antenna performance when all variables are non-ideal at the same time. Also, the widely used brute-force Monte Carlo analysis converges slowly and is thus too time-consuming for performing the desired UQ analysis.

With the use of recently developed higher-order UQ methods, e.g., Stochastic Collocation or Polynomial Chaos Expansion – in combination with fast electromagnetic (EM) analysis methods – it is possible to do accurate UQ analysis even for electrically large antenna problems [2]. In this work such higher-order UQ methods are used to determine the manufacturing tolerances necessary to build a feed horn with minimal expected variation in antenna performance.

The paper is organized as follows. Section II describes the antenna system in general and Section III focuses on the mechanical model of the feed horn that is subject to the analysis to be conducted. Section IV describes the statistical model used to conduct sensitivity analysis and uncertainty quantification, which is followed by a sensitivity analysis of design variables that will demonstrate the impact of small variations on the output and provide an estimation of the mechanical tolerances necessary for compliant performance. Then a full uncertainty quantification of the output performances with respect to the estimated mechanical tolerances calculated. The final Section V compares S-parameter measurements of the feed horn with an expected performance estimated through UQ analysis.

II. Antenna System and Feed Horn

The requirements and design steps of the antenna system shown in Fig. 1 have been described in detail in [3]. The antenna is a K-Band reflectarray with 6810 rectangular patches, placed on an 8U CubeSat platform that is to be used in an in-orbit technology demonstration.

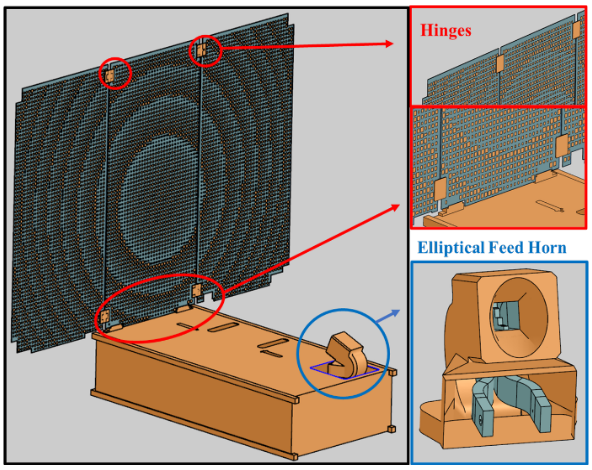

Fig. 1. Reflectarray antenna system placed on 8U CubeSat platform

The reflectarray is illuminated by a feed that consists of an elliptical aperture, a septum polarizer, and some radial bends to achieve a more compact structure that could fit in a single unit. The entire antenna system (feed, feed network, and reflectarray) has been optimised with goals associated with the reflectarray radiation pattern. The hinges and satellite body have also been included in the model. The analysis was performed with TICRA Tool, which offers fast and dedicated EM methods based on, e.g., higher-order Method of Moments [4].

III. Mechanical Model of the Elliptical Feed Horn

The first step in realizing the antenna system is to manufacture and measure the feed horn. This section and the rest of the paper will focus on the mechanical design of this feed horn. The detailed model of the feed horn is shown in Fig. 2.

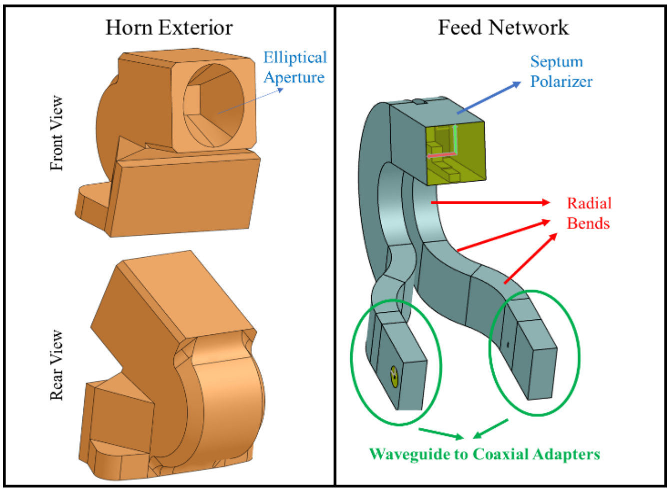

Fig. 2. Detailed model of the feed horn to be manufactured

An exploded view of the mechanical design is shown in Fig. 3. This view shows the final mechanical design. The output of the horn is connected to two low-noise amplifiers. During realization and measurements, these low noise amplifiers are replaced with coaxial to waveguide adapters. The feed horn is divided into 3 parts. The first part is the horn section, which will be machined as a single block. This block has two guiding pins for port alignments and four screws to attach to the feed network. The feed network is divided into two curved sections. The second part is the inner part which contains the waveguide network, and the third part is the outer part which is just a cover. The two parts are screwed together with 18 screws and assembled to the horn section. Finally, two coaxial to waveguide adapters are attached to the open ends of the waveguide network.

The critical parameters (with their variable names in parentheses) of the feed horn are the:

- square port side length of the septum polarizer (a_wg),
- height and length of the polarizer steps, (fn_d1, …, fn_d5, fn_h1, …, fn_h5),
- height of the rectangular waveguide section (b_wr42),
- waveguide bend radius (fn_bend_rad),
- horn aperture dimensions (major/minor axis lengths and horn length: a_ex, a_ey a_HL).

The parameters associated with the waveguide to coaxial adapters are not investigated since they are off-the-shelf components. However, the adapters have been modelled and included in calculations so that the EM model is an accurate model of the realized horn.

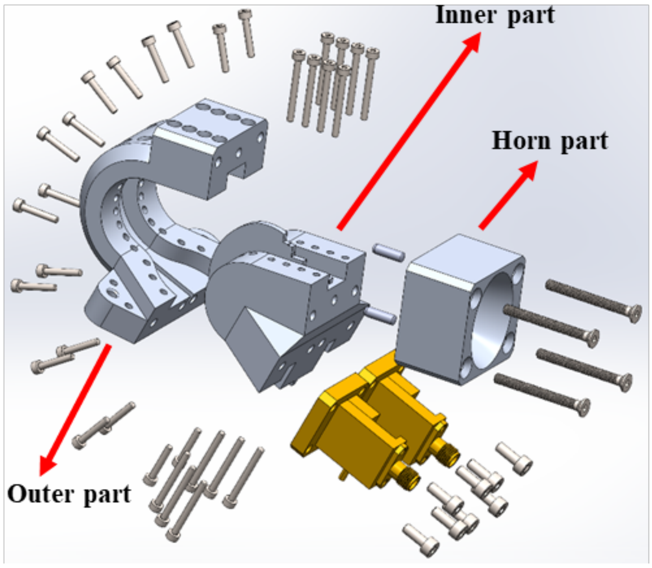

Fig. 3. Mechanical design of the feed horn (exploded view)

IV. Sensitivity Analysis and Uncertainty Quantification

No hardware device is exact; hence any automated machinery will cause some of the dimensions to deviate from their nominal values. Setting tolerances for critical dimensions will ensure that the manufactured parts will result in a compliant antenna. Determination of allowable tolerances through uncertainty quantification is a very reliable approach. However, with existing tools this may become a time-consuming task.

A common approach for obtaining some form of UQ involves running a very large number of simulations with random errors added to the system, followed by a statistical examination of the acquired data – a so-called Monte-Carlo simulation. This approach requires a very large number of simulations – which is time consuming to calculate - and the statistical accuracy is 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.

To improve the Monte-Carlo performance, methods based on higher-order approximations such as Stochastic Collocation (SC) or Polynomial Chaos Expansion (PCE) offer a far better convergence rate for a moderate number of parameters [2]. These higher-order UQ methods, also implemented in TICRA Tools [4], are used for statistical analysis of the feed horn in order to complete the mechanical design by determining the tolerances.

In this section, we will run a sensitivity as well as an UQ analysis to determine the maximum dimensional tolerance value to set on all dimensions that will lead to a maximum of ±1 dB variation in S-parameters (S11) of the feed horn.

A. Sensitivity Analysis

A simple sensitivity analysis adds small variations to the variables one-by-one and calculates the derivatives necessary to determine the sensitivity of the feed horn with respect to each parameter. The calculation is only done in the forward direction and multiple variations are not considered, meaning no correlation among these variables is taken into account. In Figs. 4 and 5 below, the sensitivity of S11 of the antenna is shown for each design variable. The variation in dimensions of the feed horn is 100 µm and 20 µm, respectively.

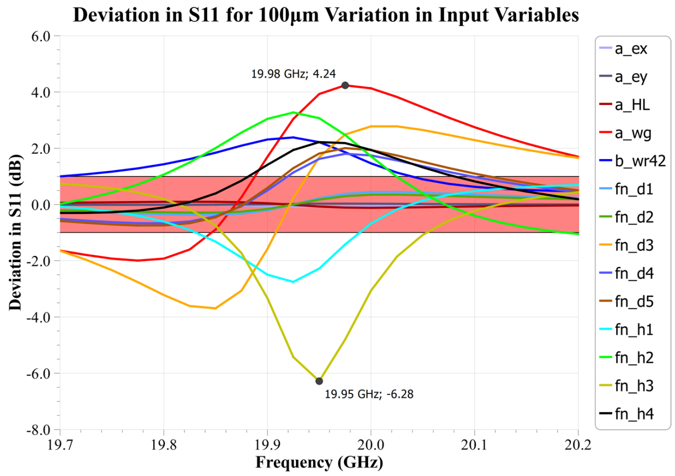

Fig. 4. Deviation in S11 for 100 µm variation in input variables

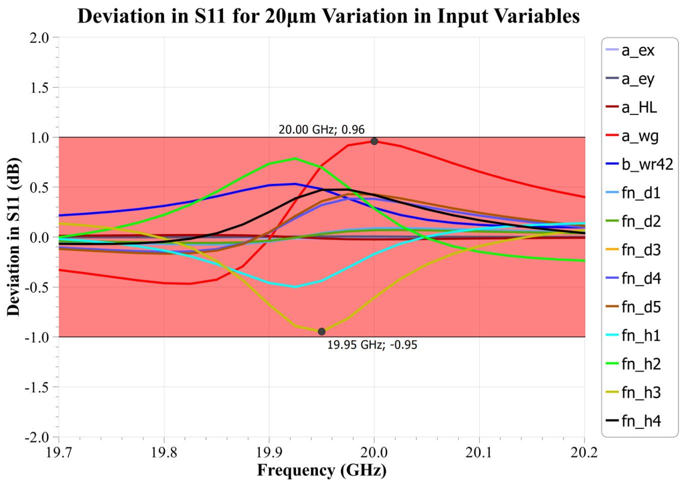

Fig. 5. Deviation in S11 for 20 µm variation in input variables

From these figures it can be seen that 100 µm tolerance will cause the antenna system to fail completely. However, for a variation of 20 µm the deviation of S11 from its expected value is less than ±1 dB. Setting the tolerance values of all dimensions to 20 µm may result in a reliable design. As mentioned earlier, the sensitivity analysis does not consider the correlation between variables, hence without a proper UQ analysis we cannot be certain.

B. Uncertainty Quantification

In the previous step we have achieved a good guess for the tolerance values to be used in manufacturing. In this subsection a UQ analysis using the Stochastic Collocation algorithm is performed. The same input variables as for the sensitivity analysis are used. The probability distribution related to the input variables is assumed to be uniform with ± 20 µm variations from nominal values. The outputs of interest from the analysis are the S-parameter S11 and far-field patterns ($\phi = 0°$, $\phi = 90°$). These parameters will be named Outputs with Uncertainty (OwU). The UQ analysis was able to reach convergence in 51 iterations at 21 frequencies. The confidence interval of the UQ analysis was set to 99%.

S-parameter OwU shows that the expected value of the S-parameters satisfies the requirements. The uncertainty around the expected values (lower and upper limits of the confidence interval) is around ±1 dB. These results are further discussed in Section V. The radiation pattern has not been measured yet and comparative results for far-field analysis and measurements can thus not be presented. However, the calculated far-field patterns for the feed horn with uncertainty are shown in Fig. 6.

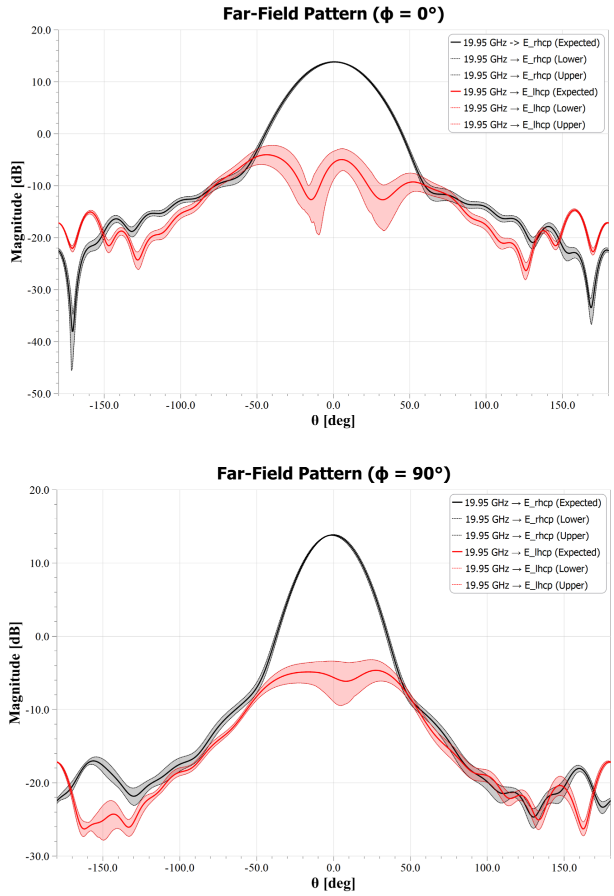

Fig. 6. Far-field outputs with uncertainty ($\phi = 0°$, $\phi = 90°$) for feed horn

V. MEASUREMENTS

The feed horn has been realized with the tolerance value determined in the previous section. The realized antenna is shown in Fig. 7. The S-parameters of the antenna have been measured with an Agilent Technologies E8361A Vector Network Analyzer. Results regarding the measured S-parameter values compared to calculated OwU for S11 are given in Fig. 8.

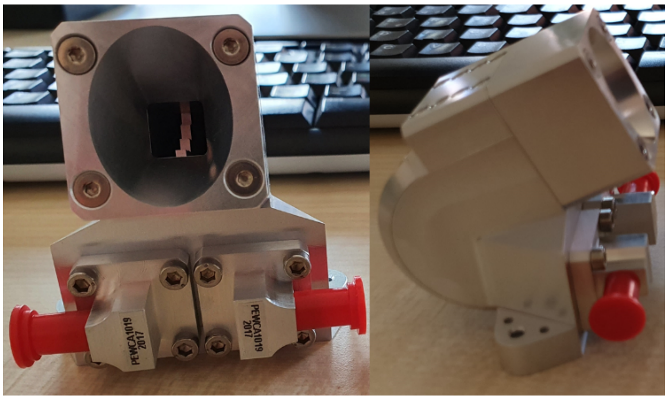

Fig. 7. Realized feed horn

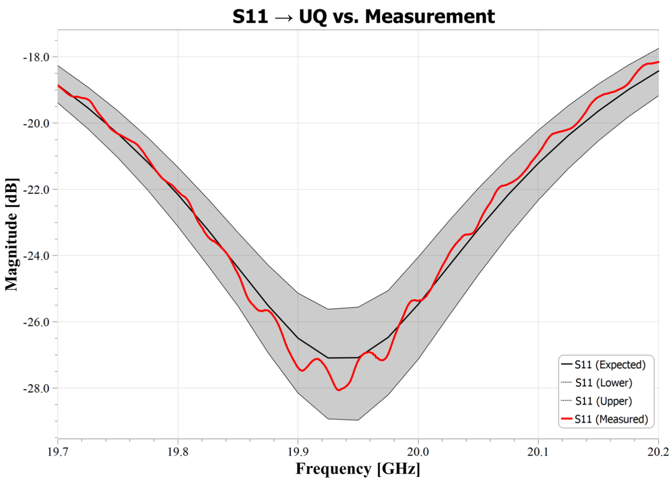

Fig. 8. UQ vs Measurement S11

The results shown in the figures above show that the UQ analysis is in very good agreement with the measured results.

VI. CONCLUSIONS

The mechanical design of a feed horn has been presented. Prior to manufacturing a sensitivity analysis and an uncertainty quantification analysis to determine the tolerances are demonstrated and outputs with uncertainty calculated are compared with the measured S-parameters.

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