Determination of Manufacturing Tolerances of a Feed Horn using Uncertainty Quantification

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***Abstract*— This work presents the realization of a feed horn designed for a high-gain deployable K-Band reflectarray antenna-system placed on an 8U CubeSat platform that is to be used in an in-orbit technology demonstration. The main focus of this work is to estimate the tolerances necessary for the mechanical design, such that antenna performance has minimal degradation. Tolerances will be determined based on sensitivity analysis and uncertainty quantification. Measurement results are presented for comparison with the uncertainty quantification analysis.**

I. Introduction

Antennas used in modern communication systems, Earth observations, and scientific research have strict performance requirements that are directly related to predicted error and uncertainty budgets. As systems become increasingly complex and involve many subsystems, the need for accurate and reliable uncertainty quantification analysis tools for predicting the error and uncertainty budgets become more important [1]. Implementing uncertainty quantification of performance requirements, based on predicted input error budgets, 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.

With the use of modern tools from the uncertainty quantification theory, in combination with state-of-the-art simulation software for antennas and antenna feed systems, it is possible to carry out accurate and efficient uncertainty quantification [2]. This work presents the use of such an uncertainty quantification (UQ) tool to determine the manufacturing tolerances necessary to build a feed horn with minimal expected variation in antenna performance.

II. Electromagnetic and Mechanical Model of the Feed Horn

The requirements and design steps of the antenna system and the feed horn shown in Fig. 1 have been described in [3]. When determining the tolerances for the feed, the impact of the mechanical tolerances on the complete system performance will be investigated through uncertainty quantification.

The reflectarray model was built in the TICRA Tools framework [4]. The reflectarray consists of 6810 rectangular patches and was modelled and analysed using QUPES, a dedicated software tool for design of quasi-periodic structures. The dual-polarized elliptical horn antenna and feed network have been modelled with CHAMP 3D. The feed 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 has been optimised using goals associated with the reflectarray radiation pattern. The hinges and satellite body have also been modelled such that their contributions are calculated and added to the reflectarray pattern using ESTEAM, which is a higher order Method of Moments (MoM) algorithm accelerated by the MLFMM solver, and it is well suited for the RF design of general antennas and is considered the industry standard for platform scattering.

The first step in realizing the antenna system is to manufacture and measure the feed horn. An exploded view of the mechanical design is shown in Fig. 1. The exploded view shows the final mechanical design. The output of the horn is connected to two low noise amplifiers (LNA). During realization and measurements, these low noise amplifiers are replaced with coaxial to waveguide adapters.

The following parameters (with their variable names in parentheses) of the feed horn are to be investigated:

- 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. These components have been modelled and included in calculations so that the EM model is an accurate model of the realized horn.

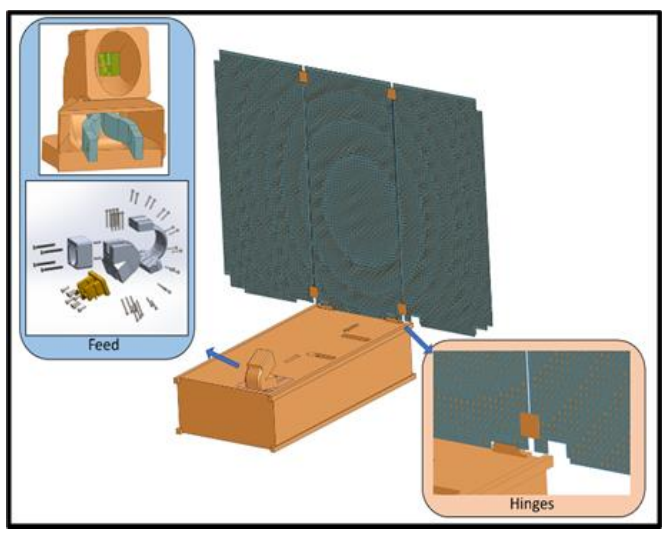

Figure 1. Reflectarray antenna system placed on 8U CubeSat Platform and mechanical design of the feed horn (Exploded View)

III. Sensitivity Analysis and Uncertainty Quantification

No measurement device is exact; hence any automated machinery dependent on measurement devices 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.

A common approach for obtaining these tolerances is to run some form of uncertainty quantification. However, general methods can be cumbersome to apply to complicated systems. In the TICRA Tools framework, an Uncertainty Quantification (UQ) product using methods based on higher-order approximations such as Stochastic Collocation (SC) or Polynomial Chaos Expansion (PCE) have been implemented. These methods offer a far better convergence rate for a moderate number of parameters [2].

In this section, we will run a sensitivity analysis and an uncertainty quantification analysis using the Uncertainty Quantification (UQ) product to determine the maximum dimensional tolerance value to set on all dimensions that will lead to a tolerable variation in S-parameters (S11) of the feed horn.

A. Sensitivity Analysis

The 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 [4]. This analysis will give us a good starting guess for the tolerance values to be used in UQ analysis. 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 in each analysis is 100 µm and 20 µm, respectively.

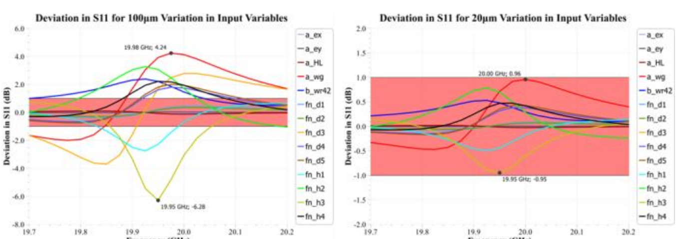

Figure 2. Deviation in S11 for100 µm and 20 µm variation in input variables.

From these figures it can easily 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 is less than ±1 dB, which is a tolerable deviation.

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 we will run a UQ analysis using the Stochastic Collocation algorithm. The probability distribution related to the input variables will be a uniform distribution with ± 20 µm variations from nominal values. The outputs from the analysis that are of interest will be the S-parameters and far-field patterns ($\phi = 0°$, $\phi = 90°$) of the complete antenna system. The UQ analysis was able to reach convergence in 51 iterations at 21 frequencies. The confidence interval of the UQ analysis was set to 95%. Calculated S-parameters and far-field pattern outputs with uncertainty in Fig. 3. show that the antenna system still satisfies the requirements with ± 20 µm variations in dimensions.

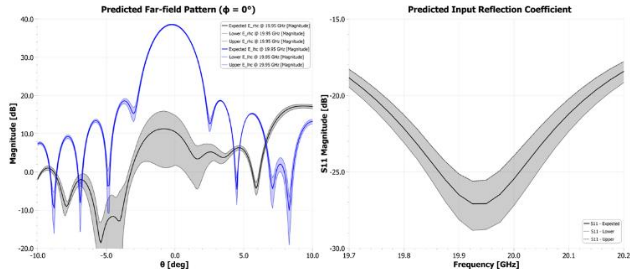

Figure 3. Calculated outputs with uncertainty.

IV. Measurements

The feed horn has been realized with the tolerance values determined in the previous section. 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 output with uncertainty for S11 are given in Fig. 4. Measured and estimated values are in good agreement.

V. Concusion

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. A good agreement between calculated outputs with uncertainty and measured S-parameters have been achieved.

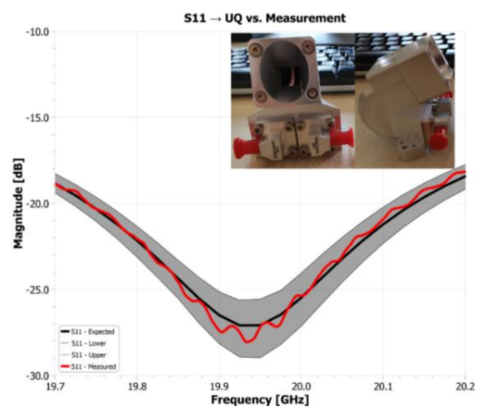

Figure 4. UQ vs Measurement S11(Realized horn shown in top corner)

References

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