Electromagnetic Assessment of Tolerances of the Square Kilometre Array Log Periodic Antenna Using Uncertainty Quantification

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***Abstract*—This work details the results of a so-called uncertainty quantification analysis conducted on the SKALA 4.2 log-periodic antenna, itself the intended production model of the antenna element for the SKA-Low Antenna Array. The antenna is modelled using the high-order Method of Moments software tool ESTEAM while the tolerance analysis is conducted using the Uncertainty Quantification software tool within TICRA Tools. The results of these analyses are presented, and conclusions drawn regarding the antenna model's electromagnetic robustness against geometrical deviations.**

***Index Terms*—antennas, computational electromagnetics, measurements, uncertainty analysis, log-periodic antenna, SKA, TICRA, ESTEAM, UQ**

I. Introduction

The most sensitive radio telescope ever conceived in the World, the Square Kilometer Array (SKA), will consist of two main observing facilities: SKA-Mid operating between 350 MHz and 15.3 GHz under installation in South Africa and SKA-Low covering the lower end of the frequency band (50 – 350 MHz) and located in Western Australia. The latter, which is the topic of this contribution, will implement a low-frequency aperture array technology consisting of 512 stations with digital beamforming capabilities. Each station will be populated by 256 dual-polarized log-periodic antennas closely packed in a circular area of 38 m diameter and laid over a metallic mesh [1]. SKA is now entered the construction phase, with several contracts signed between the SKA Organization and industries for the procurement of the hardware, software, and infrastructures vital for the two SKA radio telescopes.

The antenna selected for SKA-Low has been designed and validated through extensive numerical and experimental procedures. For instance, challenging electromagnetic simulations of the antenna have been performed including the mutual coupling with nearby antennas [2]. On the experimental side, several environmental, radio frequency, and astronomical tests have been conducted both in testing facilities using prototypes (for example, wind tunnel, vibrational plates, and anechoic chambers) as well as in the final operative site in Australia with a full station composed by 256 antennas supplied by Sirio Antenne, see Fig. 1 [3].

However, a thorough analysis that considers the tolerances throughout the antenna life-cycle (production, antenna assembly, in-situ installation, and operational) has never been conducted. For this reason, understanding how the combination of mechanical tolerances can affect performance would allow quantification of deviations between the "as-designed" and the "as-built" antenna, and to verify whether the latter meets the system requirements. This activity is also important to set the mechanical constraints in the antenna manufacturing and therefore keeping the production cost to a minimum.

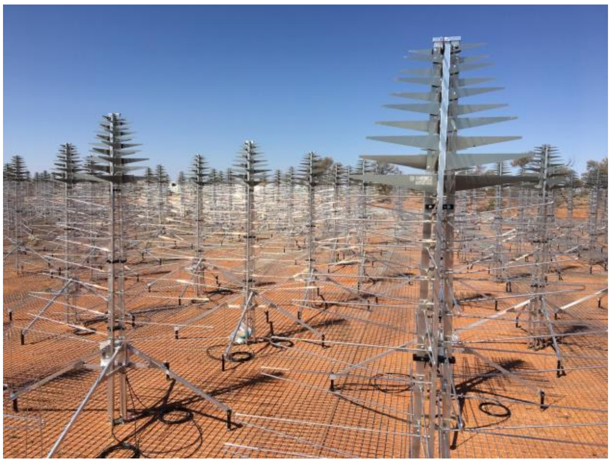


Fig. 1 Aperture Array Verification System 2 deployed in 2019 on the Murchison Radioastronomy Observatory in Western Australia to test a variety of aspects of the planned system. Credits: ICAR/INAF

For this purpose, the log-periodic antenna has been modelled using the software products ESTEAM and Uncertainty Quantification (UQ) within the TICRA Tools suite [4] to assess the dependence of the antenna geometrical parameters with respect to the electromagnetic key-parameters such as maximum directivity, cross-polarisation, and matching properties across the antenna frequency band. This paper focuses on the positioning tolerances of the antenna (tilt and vertical shift) with respect to the ground plane. Other tolerances in the antenna dimensions such as length, height, and the planarity of the dipoles will be analyzed at a later stage.

This paper is organized as follows: Section II and III describe the main characteristics of the log-periodic antenna and its modelling in the full-wave EM solver, respectively. Results from the UQ analysis are then presented and discussed in Section IV and finally conclusions are drawn in Section V.

II. The SKALA Antenna

The antenna reference design for the construction of SKA-Low is the version 4.1 [5] of the Square Kilometre Array Log-periodic Antenna (SKALA, [6]). This is an active dual-polarized antenna composed of two log-periodic dipole arrays orthogonally arranged so as to receive two linear polarizations. The dipole feeding lines of the antenna assembly consist of four central rectangular tubes called booms, slightly diverging towards the ground. The lowermost dipoles are based on a reinforced bow-tie shape to improve both the low frequency performance and the overall robustness, minimizing the lateral dimensions. The uppermost dipoles are implemented as a combination of wire triangular dipoles attached on the boom at low frequencies and solid triangles at high frequencies.

The antenna is terminated at the top of the booms through two orthogonal caps integrating a 50-ohm Low Noise Amplifier (LNA) board each. At the bottom, a common base plate connects the four booms providing a mechanical and electrical connection to the mesh grid, which acts as a ground plane, improving the RF performance at low frequencies and protection for conducted immunity purposes. The two coaxial cables are located inside the antenna tubes down to the antenna base where they exit the antenna to be connected to the sequential components of the receiving chain.

In 2021, Sirio Antenne manufactured and supplied 1300 SKALA 4.1 antennas for new verification systems and more recently (2022) it was awarded by the SKA Organization the contract to produce 78520 antennas with the full supply to be completed by the middle of 2026. Considering that each antenna consists of 4 arms, more than 600 arms per day need to be manufactured to meet the schedule. This required development of an industrialized design of the SKALA 4.1 antenna, called SKALA 4.2, allowing both achieving the target production rate and meeting the system requirements, thus assuring the same EM performance of the previous version.

The production of the SKALA 4.2 antennas involves significant manufacturing and assembly processes, from aluminium extrusion, to cutting, bending, machining, injection moulding, welding, torque tightening, and crimping. Each process introduces manufacturing tolerances, which inevitably affect the final assembly. Moreover, the ground on which the antenna is installed is not always completely flat, which adds to the production tolerances those of installation. Furthermore, the harsh environment of the Australian desert could also determine possible modification in the antenna properties over the 50-years life span of the project. Therefore, a quantitative analysis of the impact of misalignment and tolerances in the antenna geometry on the EM performance is extremely valuable.

III. RF Model of the SKALA Antenna

All analyses presented herein for the SKALA 4.2 antenna were performed using the higher-order MoM solver of the commercially available ESTEAM software product within the TICRA Tools suite [7]. The analyses conducted for this work include MoM-based simulations of both the nominal, undisturbed geometry of the antenna, as detailed in this section, and a tolerance study using the UQ product [8], also from the TICRA Tools suite.

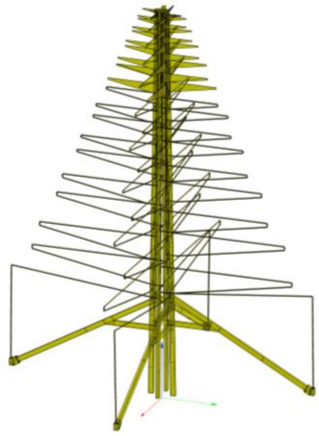


Fig. 2 The SKALA 4.2 log-periodic antenna as implemented in the ESTEAM environment. Note that the ground plane is not included in this figure for illustrative purposes but is included in all simulations presented herein

A Computer-Aided-Design (CAD) model of the SKALA 4.2 antenna structure was imported into the ESTEAM environment, which interprets the model in terms of higher-order curved quadrilateral patches which make up the so-called mesh, as illustrated in Fig. 2. The diversity of these generalised patches is such that a complex CAD model, such as that of the electrically small SKALA 4.2 antenna, composed of both curved wire and flat plate dipole structures, can be represented efficiently. The conductive ground plane was modelled as a 3m x 3m plate.

Electrical excitation of the antenna is achieved through model of the coaxial cable connecting the metal caps which house the LNAs atop the boom structures – see Fig. 3. The antenna structure is modelled as a Perfect Electrical Conductor (PEC), with the coaxial housing modelled as Teflon. This structure is then excited by means of a MoM excitation, being a TEM_{00} waveguide mode. This manner of excitation provides both the source field generation to excite the antenna structure and computation of the scattering parameters.

Simulations presented in this work were conducted at discrete frequency intervals from 110 MHz to 350 MHz. Surface current distributions resultant from these MoM simulations are illustrated in Fig. 4. Note the difference in current distributions between 110 MHz and 350 MHz in this figure, which highlight the different operational frequency regions of the SKALA antenna, namely the bottom wire dipoles resonate at the low frequencies and the upper solid triangles resonate at the high frequencies. Also note the influence of the ground plane structure, which is critical to resonance at the lowest frequencies.

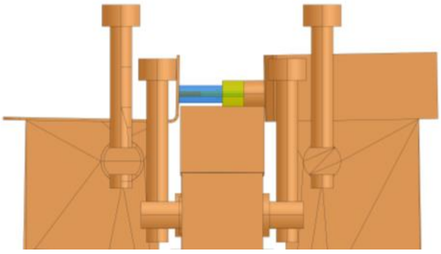
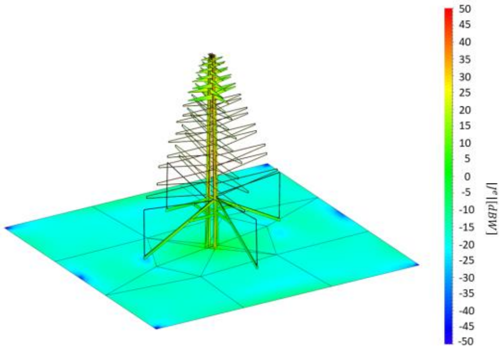
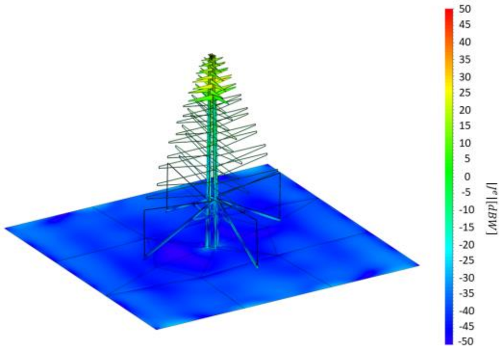


Fig. 3 A close-up view of the coaxial connection between the LNA housing structures atop the SKALA booms. Note the Teflon housing highlighted in blue.



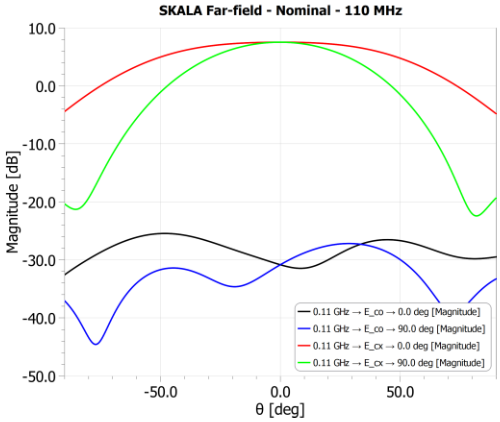
(a)



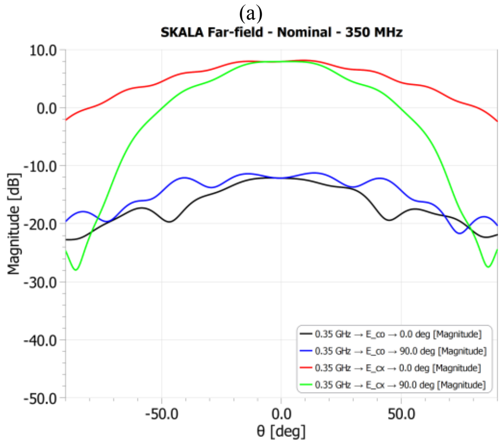
(b)

Fig. 4 Surface current distributions on the SKALA 4.2 log-periodic antenna as excited using the coaxial model at 110 MHz (a) and 350 MHz (b).

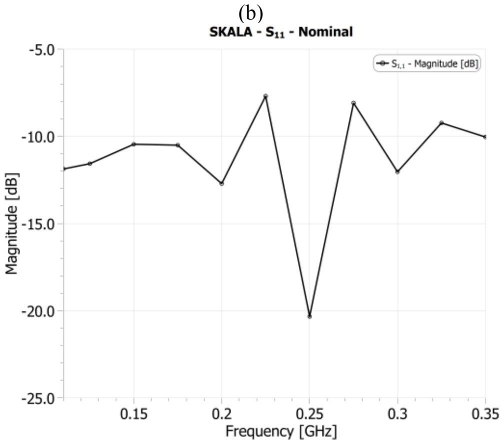
The results of these simulations, as illustrated in Fig. 5 demonstrate very close agreement to those measurement results presented in [5].



(a)



(b)



(c)

Fig. 5 Far-field pattern simulations at 110 MHz (a) and 350 MHz (b) for the SKALA 4.2 antenna with nominal geometry excited using the coaxial model. S_{11} parameters between 110 MHz to 350 MHz in (c).

IV. Uncertainty Quantification Analysis

As noted in Section II, the SKALA 4.2 antenna forms the basis embedded element in the final array that will ultimately comprise 131,072 such antennas [1], and thus represents a significant effort in terms of mass-scale manufacturing, assembly, and installation. All these aspects must combine with acceptable tolerances to ensure proper array performance.

Determination of tolerances through uncertainty quantification is a reliable approach to investigate the impact on the RF performances of manufacturing and installation errors. However, performing these tolerance analyses with the common existing tools may become a time-consuming task. In fact, a common approach for obtaining some form of uncertainty quantification is the classical Monte-Carlo analysis, which involves running a very large number of simulations with random errors added to the nominal model, followed by a statistical examination of the data. This approach is time consuming because requires a very large number of simulations and the statistical accuracy is poor, which could cause misleading conclusions.

In this paper, the effects of installation tolerances on the RF performance of individual SKALA antennas are analysed through a tolerance analysis using the aforementioned UQ software tool which is based on high-order methods and implemented in TICRA Tools. A similar approach is reported in [9]. This tool uses methods such as Stochastic Collocation (SC) or Polynomial Chaos Expansion (PCE), which offer a far better convergence rate for a moderate number of parameters with respect to classical Monte Carlo analysis. In the analyses reported in this paper the SC algorithm was used.

The first step of the UQ analysis is the identification of some installation problems which can occur during and after the deployment of the SKALA array. The following cases have been identified:

1. Ground plane vertical offset
2. Ground plane tilt
3. Antenna tilt with respect to the ground plane

These cases entail the definition of three variables and relative error distribution for the UQ analyses: vertical offset of the ground plane with uniform error distribution [0 mm, 50 mm], tilt of the ground plane with uniform error distribution [-2°,+2°], and tilt of the antenna with uniform error distribution in [-1°,+1°]. These parameters represent disturbances to nominal installation of the array elements arising from environmental effects, uneven ground, and even possible flooding, leading to the raising of the effective ground plane, where the water surface can form this new ground plane.

The outputs of interest for this analysis, known also as Outputs with Uncertainty (OwU), were the S_{11} parameters and far field patterns in the two principal planes ($\varphi = 0°$, $\varphi = 90°$). The UQ analysis was applied with a confidence interval of 95% and reached convergence after 5 iterations.

The results illustrated in Fig. 6 reveal relatively stable co-polarised beam patterns for all UQ tests, with higher sensitivity exhibited for the lowest frequency. Given that the antenna ground plane resonates most at the lower frequencies, this is expected. The worst-case uncertainty occurs for the ground offset case, as shown in Fig. 6 (a), of the order of approximately 4 dB at $\theta = 90°$ where the first null between main and side lobe appears. Given that this direction is well beyond the antenna field of view and the nominal directivity at this point is >25 dB below the peak this uncertainty is not considered cause for any concern.

The antenna pattern is more sensitive to the ground plane offset and antenna tilt cases, with the former being the most impactful, and the cross-polarised patterns have a higher uncertainty than the co-polarised. This is expected given the low levels of cross-polar (< 30 dB) and is similarly not considered cause for major concern. Conversely the antenna pattern is very robust when the ground tilt is considered, with maximum uncertainty of ~0.35 dB observed in the co-polarised patterns. Ground plane offset has the greater geometrical alteration compared to the two tilt cases between the antenna structure and the ground plane in the region closest to the antenna structure, thereby explaining the higher sensitivity for the ground plane case.

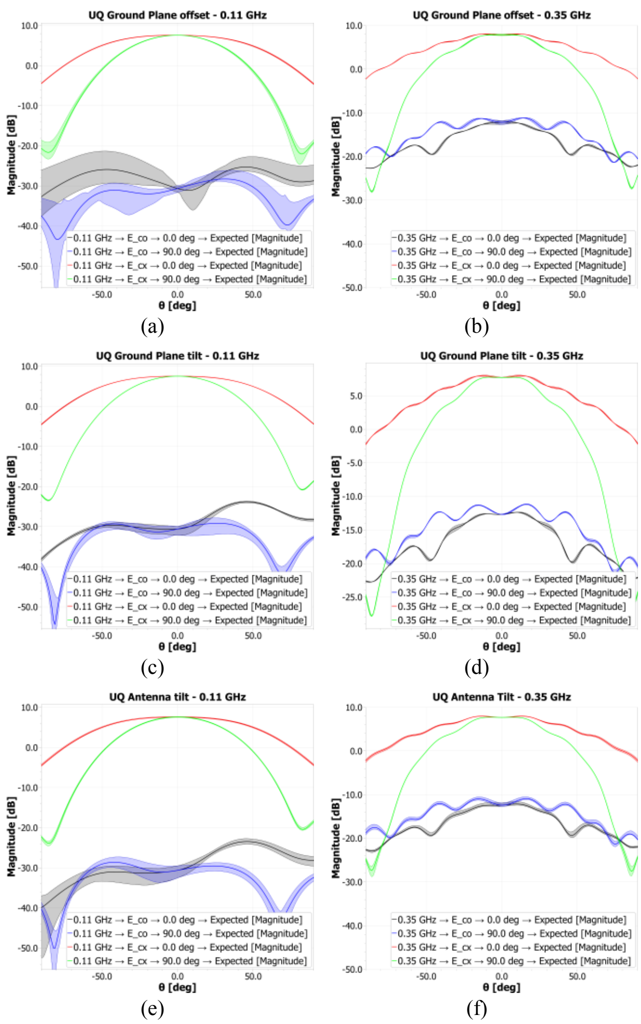


Fig. 6 Far-field beam pattern results from UQ analysis on the SKALA 4.2 antenna model. Ground plane offset results for 110 MHz (a) and 350 MHz (b), ground plane tilt results for 110 MHz (c) and 350 MHz (d), and antenna tilt results for 110 MHz (e) and 350 MHz (f)

In comparison to the beam pattern results, the S_{11} in Fig. 7 exhibit a greater robustness in all cases tested, with a maximum variation of 0.6 dB at the lowest frequency for the ground plane offset case.

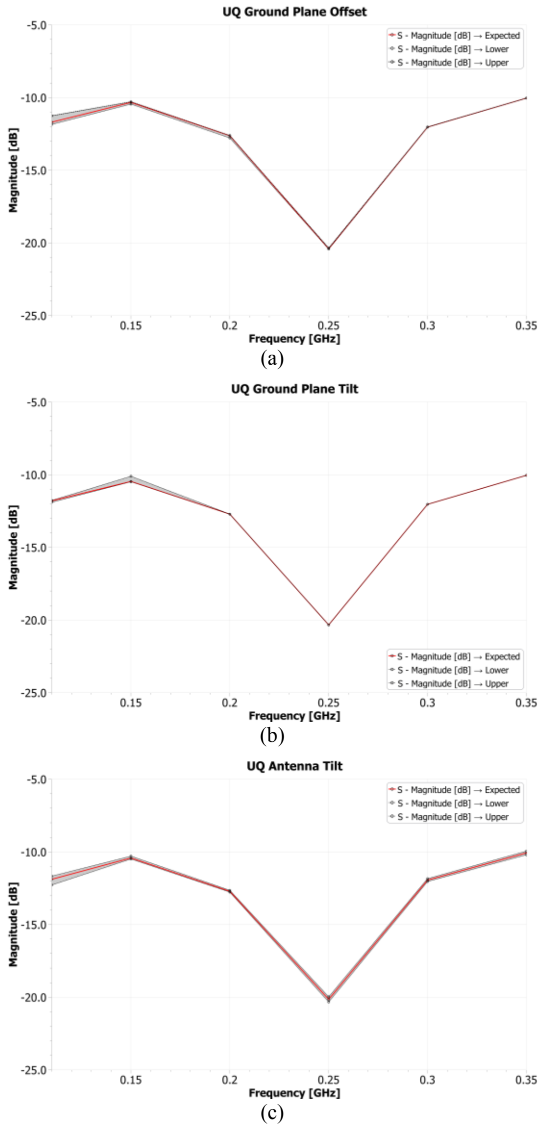


Fig. 7 S_{11} results from UQ analysis on the SKALA 4.2 antenna model for six frequencies between 110 MHz and 350 MHz. Ground offset (a), Ground tilt (b), and Antenna tilt (c)

V. Conclusions

The preliminary results of the UQ analysis presented herein have revealed a robust design for the SKALA 4.2 log-periodic antenna. It is noted here that this conclusion holds for the analyses thus far conducted, being for three independent geometry variations associated with typical antenna array installation. It is envisaged that the next stage of analysis will include additional uncertainty analyses that encompass the manufacturing and assembly tolerances with finder frequency resolutions. Furthermore, these analyses should be simultaneously combined to determine the worst-case aggregations of said tolerances and its eventual impact to the scientific SKA requirements. Finally, the eventual array performance should be investigated while incorporating these uncertainties.

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