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# LIST OF ABBREVIATIONS

| Abbreviation | Description |
|--------------|-------------|
| AADC         | Aperture Array Design and construction Consortium |
| AAVS         | Aperture Array Verification System |
| ASTRON       | Netherlands Institute for Radio Astronomy |
| AL           | Antenna and LNA |
| CCL          | Cambridge Consultants |
| CDR          | Critical Design Review |
| EM           | Electromagnetic |
| ICRAR        | International Centre for Radio Astronomy Research |
| IEIIT        | Institute of Electronics, Computer and Telecommunications Engineering |
| INAF         | Italian National Institute for Astrophysics |
| LFAA         | Low Frequency Aperture Array |
| LINFRA       | Local Infrastructure |
| LNA          | Low Noise Amplifier |
| RD-N         | nth document in the list of Reference Documents |
| RFoF         | Radio Frequency over Fibre |
| RX           | Receiver |
| SKA          | Square Kilometre Array |
| SKA-LOW      | SKA low frequency part of the full telescope |
| SKALAN       | nth version of the SKA Log-periodic Antenna |
| SKAO         | SKA Office |
| TBC          | To Be Confirmed |
| TBD          | To Be Determined |
| UCAM         | University of Cambridge |
| WP           | Work Package |
1 Introduction

1.1 Purpose of the document

This document describes the electromagnetic design process of the SKA1-LOW antenna.

1.2 Scope of the document

The SKA1-LOW antenna has been developed over the last decade. Since 2011 an antenna of the type Log-Periodic Antenna that is now in its 4th iteration, SKALA4 (SKA Log-periodic Antenna v4), has been developed and it is now the selected candidate for SKA1-LOW after the Cost Control project efforts of 2017. This document describes the electromagnetic design of the antenna. In the submission for the antenna selection process [RD6], a detailed description of the antenna performance can be found.

1.3 Authorship

1.4 Main authors

Eloy de Lera Acedo and Hardie Pienaar
2 References

2.1 Applicable documents

The following documents are applicable to the extent stated herein. In the event of conflict between the contents of the applicable documents and this document, the applicable documents shall take precedence.

| ID  | Title                                                      | Code                      | Issue |
|-----|------------------------------------------------------------|---------------------------|-------|
| [AD1]| SKA1 Level 0 Science Requirements                          | SKA-TEL-SKO-0000007       | 2     |
| [AD2]| SKA PHASE 1 SYSTEM REQUIREMENTS SPECIFICATION             | SKA-TEL-SKO-0000008       | 11    |
| [AD3]| SKA1-LOW CONFIGURATION COORDINATES – COMPLETE SET         | SKA-TEL-SKO-0000422       | 3     |
## 2.2 Reference documents

The following documents are referenced in this document. In the event of conflict between the contents of the referenced documents and this document, this document shall take precedence.

| ID   | Title                                                                 | Code               | Issue  |
|------|----------------------------------------------------------------------|--------------------|--------|
| [RD1] | SKA1-LOW Antenna Evaluation Criteria                              | SKA-TEL-SKO-0000800 | D      |
| [RD2] | LFAA Architectural Design and Analysis Report                      | SKA-TEL-LFAA-0200028 |        |
| [RD3] | Field Node Detailed Design Document                                 | SKA-TEL-LFAA-0200028 |        |
| [RD4] | SKA1-LOW antenna selection document                               |                    |        |
| [RD5] | SKA1-LOW antenna selection – panel report                         |                    |        |
| [RD6] | SKA1-LOW antenna candidates                                        |                    |        |
| [RD7] | N. Razavi et al., “Analysis of sky contributions to system temperature for low frequency SKA aperture array geometries”, Experimental Astronomy 2012. |                     |        |
| [RD8] | G. Mellema et al., “Reionization and the Cosmic Dawn with the Square Kilometre Array”, Experimental Astronomy 2013. |                     |        |
| [RD9] | E. de Lera Acedo et al., “Ultra-Wideband Aperture Array Element Design for Low Frequency Radio Astronomy”, IEEE TAP 2011. |                     |        |
| [RD10]| E. de Lera Acedo et al., “SKALA, a log-periodic array antenna for the SKA-low instrument: design, simulations, tests and system considerations”, Experimental Astronomy 2015. |                     |        |
| [RD11]| CST, [www.cst.com](http://www.cst.com)                              |                     |        |
| [RD12]| FEKO, [www.altair.com](http://www.altair.com)                       |                     |        |
| [RD13]| E. de Lera Acedo et al., “Spectral performance of SKA Log-periodic Antennas I: Mitigating spectral artefacts in SKA1-LOW 21-cm cosmology experiments”, MNRAS 2017. |                     |        |
| [RD14]| T. Carozzi and G. Woan, “A Fundamental Figure of Merit for Radio Polarimeters”, IEEE TAP 2011. |                     |        |
| [RD15]| Microwave Office, [https://www.awrcorp.com](https://www.awrcorp.com) |                     |        |
| [RD16]| Carrel R. “The design of log-periodic dipole antennas”, IRE International Convention Record.Vol 9.; 1961:61-75 |                     |        |
| [RD17]| E. de Lera Acedo, Station Design Report                            | SKA-TEL-LFAA-0300034 |        |
| [RD18]| E. de Lera Acedo et al., “Study and design of a differentially-fed tapered slot antenna array, IEEE TAP 2010. |                     |        |
3 SKALA4 electromagnetic design

3.1 Summary

This section describes the electromagnetic design of SKALA4. It focuses on the design process that led to SKALA4 and presents simulated results showing the expected performance of SKALA4 against the selection criteria defined in [RD1].

3.2 Simulation environment

Different simulation software packages have been used in the design of the antenna. These are:

- FEKO 8: For EM simulations of the single antenna using the MoM technique [RD12].
- CST 2016: For EM simulations of the single antenna using the FDTD technique [RD11].
- AWR13: For electronic simulations of the LNA [RD15].

3.3 Antenna and LNA design overview

3.4 SKALA base design

The original antenna and LNA design was based on meeting the flown-down requirements from the relevant SKA L1 requirements at the time of the design (2011-2012). The following paragraphs give a brief overview of the design constrains and design parameters that were used for the initial electromagnetic design.

The design of the antenna targeted the specifications required to deliver the electromagnetic performance required for the SKA1-LOW telescope [AD2]. At the time this included a frequency band from 70 to 450 MHz. One of the main figures of merit for a radio telescope is the Survey Speed. This is directly proportional to the Field of View (FoV), the channel bandwidth (dependent on the signal processing system) and the sensitivity squared. A brief description of the main design figures of merit that drove the initial design of the SKA1-LOW design antenna follows.

- **The sensitivity** in radio astronomy is proportional to the telescope’s effective aperture area over the system noise temperature (A/T) (see equation 1). Both of these terms are dependent on the antenna front end [RD9]. Therefore, the following parameters need to be optimized for a phased array antenna:
  - Radiation efficiency (η_rad). It does affect both the incoming desired wave, by weighting the Directivity (D_θ,Φ) transforming it into Gain (G_θ,Φ), and the system noise. The definition of Gain in here does not include the effect of impedance mismatch (IEEE definition). It affects the system noise in several ways: by directly weighting the undesired Sky noise temperature as well as representing the losses at the antenna terminals. These losses are due to the presence of non-perfect electric conductors in the antenna and the presence of ground soil, both at the physical temperature (T_0).
  - Antenna temperature, TA. The antenna temperature, which is a function of the array antenna gain, depends on several factors related to the sky noise temperature and it is a limiting factor only at the low end of the frequency band.
  - Receiver temperature (T_rec). This factor can dominate the system temperature and therefore the sensitivity at the high end of the band, where the sky noise is no longer
dominant [RD7] (see Figure 1). This is directly dependent on the matching between the antenna and the LNA.

![Figure 1: Approximated receiver temperature and sky noise temperature for SKALA1.](image)

- Antenna gain within the field of view. The antenna gain describes the spatial discrimination capabilities of the antenna, which has a direct impact on affective area and thus is one of the main factors in limiting the A/T of the system. As mentioned above, in this paper we follow the IEEE definition for the Gain (The ratio of the radiation intensity, in a given direction, to the radiation intensity that would be obtained if the power accepted by the antenna were radiated isotropically).

\[
\frac{A_{\text{eff}}}{T_{\text{sys}}} = \frac{\lambda^2}{4\pi} \cdot G_{\theta,\phi} \cdot \eta_{\text{rad}} \cdot T_A + (1 - \eta_{\text{rad}}) \cdot T_0 + T_{\text{rec}}
\]

- **Spectral and spatial smoothness.** Both of them are key for the calibration of the telescope. While the spatial smoothness is related to the beam of the antenna and heavily dominated by the effects of mutual coupling in the array environment (see [RD17] for more information), the spectral smoothness is mostly dominated by the matching between the antenna and LNA [RD13]. Thus, optimizing this spectral smoothness becomes a trade off with the reduction of receiver noise (matching for smoothness vs matching for low noise) as described in [RD3][RD6].

- **Low cross-polarization level** is required in order to be able to measure the foregrounds of the EoR [RD8]. Also, it is important for the telescope calibration. The required specification levels for the SKA-low science cases are currently under analysis. In the context of wide field radio astronomy, cross-polarization has been in the last few years assessed using the Intrinsic Cross Polarization ratio (IXR) [RD14] (see equation 3), which is a measure of the condition number of the Jones matrix (J) relating the projection of the field components in the sky (E) to the voltage signals at the output of the antenna terminals for both polarizations (V). It should be pointed out, however, that an IXR characterization requires far-field vector measurements. This of course imposes a limitation for low frequency arrays of the size of SKA stations as this can only be accurately done currently for single antennas or small arrays. This is good enough for the design process but imposes a limitation for large arrays where astronomical measurements will need to be further developed to provide the desired accuracy.
\[
\begin{pmatrix}
V_1 \\
V_2
\end{pmatrix} =
\begin{bmatrix}
I_{11} & I_{12} \\
I_{21} & I_{22}
\end{bmatrix}
\begin{pmatrix}
E_t \\
E_p
\end{pmatrix}
\]  \hspace{1cm}(2)

\[
IXR_j = \left( \frac{s(j)+1}{s(j)-1} \right)^2
\]  \hspace{1cm}(3)

- **The element’s footprint.** In order to deliver maximum brightness sensitivity; the filling factor of the SKA core must be as high as possible. In the core all the elements contribute to capture the relevant Fourier modes in a given angular scale. This can be pictured as all the antennas being cross-correlated to each other in an interferometry sense, so the distance between the antennas inside a station is as well a baseline contributing to the total sensitivity. Therefore a higher filling factor will maximize the information collected from the sky. Furthermore a smaller element’s footprint impacts positively the array maintenance. This means that the footprint needs to be kept to a minimum. Furthermore, the L1 requirements call for a station beam-width of 5 degrees at \(\sim110\) MHz (middle of the EoR frequency band) resulting in a given station diameter. The requirement is that each LFAA station will contain 256 elements. This results in the average area allocated per antenna is 4.43 m² in a 38m diameter station. This gives an approximate square footprint per element of 2.1x2.1 m, which consequently defines the transition between the dense and sparse regimes. Therefore, in order for the antenna elements to be positioned in such a random grid, the footprint of the antenna needs to be smaller than 2.1x2.1 m.

- **Antenna field of view.** The SKA calls to cover a region of the sky \(\pm 45^\circ\) from zenith [AD2]. The FoV of each element must therefore be \(\pm 45^\circ\) from zenith and will determine the maximum FoV of the instrument, since the elements will be electronically beam-formed/correlated. A very directive antenna will show great sensitivity at zenith but will underperform at large angles from zenith. Furthermore, a low directivity antenna will have similar values of A/T at all angles within the FoV but will struggle to deliver the required A/T at zenith. One of the key concepts behind the antenna system is the use of antennas that maximize sensitivity within the FoV. It is therefore worth noticing that it is not the half power beamwidth that matters here, but the A/T delivered at a given scan angle. Therefore, a slightly more directive element than one with a half-power beamwidth of 90° may, in turn, deliver a better overall sensitivity across most of the FoV at the expense of a small reduction near the edges of the FoV (see Figure 2). The SKALA element has been optimized to maximize this trade-off.
3.4.1 A Log-periodic Antenna for SKA

Several antenna types were explored as described in [RD2]. These include: conical log-spiral antennas, Vivaldi antennas and bow-tie antennas. It was finally concluded [RD5] that the best suited to meet the SKA requirements was a Log-Periodic Dipole Array (LPDA) [RD16]. LPDAs have been used for decades and they are well known wideband antennas with moderate to high directivity [RD16]. The main differences from an electromagnetic point of view between the typical standard LPDA and the antenna required for SKA1-LOW are:

- The antenna is part of an array environment in a wide frequency band operating both in the dense and sparse regimes.
- The antenna is pointing to the sky and has a metallic ground plane right underneath the bottom dipole that has a strong effect on the antenna performance, especially at the low end of the frequency band.

The basic design of SKALA is presented in [RD10]. It consisted on a 9 dipole LPDA designed to be fed by a differential LNA, for minimum noise in order to achieve maximum sensitivity in the desired FoV. The top dipoles of SKALA were not resonant in the original design band but they serve as dummy dipoles to preserve the ultra-wideband performance of the element. Furthermore, the bottom dipole was modified to improve the impedance matching to the LNA at low frequencies while reducing the footprint of the antenna. In order to maintain a similar environment for all the antennas in the SKA for calibratability reasons and in order to be more isolated from the soil conditions and achieve high polarization purity (see Figure 3), a metallic ground screen was used under the antenna elements.
Figure 3. IXR of SKALA at 50 MHz with a metallic ground mesh (top) and with a lossy ground with the Western Australian desert conditions (bottom).

3.4.2 Antenna feeding

The antenna feeding is differential (reference impedance = 100 Ω) to match a pseudo differential LNA (see Figure 4) seeking for minimum receiver noise and best power match between the array of dipoles and the transmission line seeking for best spectral smoothness.

Wide band antennas (including log periodic antennas) typically have input impedances of about 100-150 Ohm or even higher. Single ended LNAs have typical input impedance for power matching of 50 Ohms and noise input impedance of about 60-70 Ohms. An optimal design for SKA1-LOW needs to match the antenna impedance to the LNA achieving good compromise between noise and spectral smoothness in the gain [RD13]. Therefore achieving impedance matching over a large frequency band (typically larger than ~2-3:1) is hard using single ended LNAs and typically leads to designs more sensitive to tolerances. In fact, single ended variants have been explored in recent times but were discarded in March 2018 by LFAA. The SKALA4–AL prototype (single ended feeding) feasibility study implementation was discarded since it was not complaint with the LFAA architecture (coax output instead of RFoF), and showed worst performance (narrow band spikes/ripples across the band due to poor matching, potentially worse rejection of common modes and higher risk of damage due to lightning and lower sensitivity) without a cost benefit.

Furthermore, a differential LNA (seen from the antenna as 2 single ended transistor in series followed by a balun) shows typical impedances (both for noise and power matching) double compare to that of...
the single ended LNA, so ~100 Ohms for power matching and ~120-140 Ohms for optimum noise matching. Thus this is a better solution to ensure performance.

Testing differential LNAs is not difficult. Differential LNAs have 2 ports instead of 1 at the input (to match the differential antenna as described above) and a single ended output (so the rest of the RF chain is then single ended). Detailed performance characterization of a small number of units is typically done using multiport devices (e.g. 4-port VNAs) and/or balun transformers to feed the LNA. These are then de-embedded from the measurements using standard techniques. This is done in a large number of telescopes (MWA, LOFAR, LWA, etc.) and it is a well-understood process. Acceptance tests in large batches can easily be carried out using test jigs, as it was done for AAVS1 (~1.5 min/LNA).

Figure 4: LNA configuration.

3.5 Antenna design fundamentals

3.5.1 Description of the background design

The SKALA4 antenna (see Figure 5) has been designed to be part of a pseudo random array of 256 antenna elements (a SKA1-LOW station) as per [AD2]. The SKA1-LOW stations will be 38m in diameter (centre to centre) and circular in shape [AD3]. Furthermore, the array configuration will be pseudo-random. In [RD17] it is discussed why the antenna grid (station configuration) should not be regular due to detrimental mutual coupling effects as well as adverse effect of grating lobes in a 7:1 frequency band. In brief, a regular array, sampled at a given frequency (half wavelength separation between antennas) will only be free of grating lobes up to approximately twice that frequency. Translated to SKA1-LOW, this would mean an average separation of half a wavelength at approximately 175 MHz (85 cm). Consequently, the array would be dense at the low end of the band, with an effective area per element limited to 0.72 m$^2$, and therefore not meeting the L1 requirements for sensitivity. Then, if a sparse regular array is implemented, impedance anomalies across the frequency range as well as strong dips in the pattern of the embedded elements are to be expected [RD18][RD9]. These are typically referred to as “scan blindness” and are more easily observed the wider the frequency band and the wider the scan angle range. Consequently, the antenna for SKA1-LOW is part of a sparse irregular array (see [RD17] for more details).
3.5.2 Antenna dimensions

The following drawings show the main dimensions of the metal components of the SKALA4 antenna. SKALA4 has 16 dipoles per polarization (2 polarizations) and is placed on top of a metallic ground plane. The dipoles are triangular in shape and are connected to the central transmission line. This transmission line has an opening angle of 0 degrees (parallel transmission line). The feeding point is at the top of the antenna where the LNAs are located.
Figure 6: SKALA4 – Side (left) and top (right) views showing the dipoles from both polarizations (red and yellow, and blue and green). No plastic supports are shown, only metal parts.

Figure 7: SKALA4 – Side view showing the main dimensions.
**Figure 8:** SKALA4 – Top view near the feeding point.

**Figure 9:** SKALA4 – Side view near the top of the antenna (casework and plastic supports are not shown).
Figure 10: SKALA4 – Side view near the bottom of the antenna showing the bow-tie shape bottom dipole.

Table 1: Main SKALA4 dimensions

| Stage | L [m] | d [m] | h [m] |
|-------|-------|-------|-------|
| 1     | 0.800 | 0.210 | d_1   |
| 2     | 0.714 | 0.188 | d_2   |
| 3     | 0.637 | 0.167 | d_3   |
| 4     | 0.569 | 0.150 | d_4   |
| 5     | 0.508 | 0.133 | d_5   |
| 6     | 0.453 | 0.113 | d_6   |
| 7     | 0.405 | 0.106 | d_7   |
| 8     | 0.361 | 0.095 | d_8   |
| 9     | 0.322 | 0.085 | d_9   |
| 10    | 0.288 | 0.076 | d_{10} |
| 11    | 0.257 | 0.067 | d_{11} |
| 12    | 0.229 | 0.060 | d_{12} |
| 13    | 0.205 | 0.054 | d_{13} |
| 14    | 0.183 | 0.048 | d_{14} |
| 15    | 0.163 | 0.043 | d_{15} |
| 16    | 0.145 | 0.043 | \tau = \times d_{15} |

| d_{max} | 0.360 |
| e_{top}  | 0.176 |
| e_{bot}  | 0.370 |
| W        | 0.034 |
| G        | 0.0425 |
| I_{P}    | 0.0142 |
| \tau     | 0.8930 |
| \sigma   | 0.0657 |

3.5.3 Design goals/Selection criteria

The most relevant figures of merit for the design of SKALA4 are described in [RD1]. This document listed and described the selection criteria for the selection of the SKA1-LOW antenna. There is also a weighting scheme described in that document that gave higher weight to some figures of merit with respect to others. The goal of these criteria was to realize an antenna design that maximised science output for the lowest risk and cost. The criteria are summarized in Table 2. These criteria and their target values are derived from [AD1] (SKA LO Science Requirements). The full analysis and results for all the criteria is presented in [RD6].
| ID   | Criterion                                                                 |
|------|---------------------------------------------------------------------------|
| FC#1 | Average station sensitivity within 45° Zenith angle (for all azimuth angles) |
| FC#2 | Minimum station sensitivity within 45° Zenith angle (for all azimuth angles) |
| FC#3 | Average station sensitivity between 45° and 60° Zenith angle (for all azimuth angles) |
| FC#5 | Minimum station IXR within 45° zenith angle                                |
| FC#6 | Antenna footprint and station diameter                                     |
| FC#7 | Spectral smoothness I: cubic “not-a-knot-spline” fitting (large scale smoothness) |
| FC#8 | Spectral smoothness II: Trott & Wayth (fine scale smoothness)              |
| FC#9 | Spatial Smoothness                                                         |
| FC#10| Pattern Smoothness I: Deviation from idealised pattern                    |
| FC#11| Pattern Smoothness II: The first derivative                                |
| FC#12| Pattern Smoothness III: Number of coefficients                            |
| IC#1 | Impact on interfaces: Power Budget                                        |
| IC#2 | Impact on interfaces: Receiver                                             |
| IC#3 | Impact on interfaces: INFRA                                                |
| NFC#1| Robustness to environmental parameter                                     |
| NFC#2| Testability                                                                |
| NFC#3| Easiness to deploy                                                        |
| NFC#4| Maintainability                                                            |
| RC#1 | Schedule Risk                                                             |
| RC#2 | Technical Risk                                                            |
| CC#1 | Shipment Cost                                                             |
3.6 Parametric analysis leading to SKALA4

3.6.1 SKALA 4 design process

3.6.1.1 Initial Parameter Investigation

The initial efforts on SKALA4 were to optimise for flat directivity (and therefore sensitivity) over frequency. As a first step, the effect of different perturbations to the geometry was investigated using local parameter sweeps on SKALA3 [RD13]. The main parameters of an LPDA antenna are its growth ratio (tau), the spacing ratio (sigma) and opening angle (alpha). This initial investigation gave the following results.

| Design Variable | Spectral Smoothness | Overall Gain | Antenna Height | Matching to 100 ohms | IXR |
|------------------|---------------------|--------------|----------------|----------------------|-----|
| Increase Tau     | Better              | Increase     | Increase       | No Effect            | No Effect |
| Increase Sigma   | Better              | Increase     | Increase       | No Effect            | No Effect |
| Increase Alpha   | Worse               | Increase     | No Effect      | Increase             | Decrease |

Figure 11: SKALA4 – Simplified view with solid arms.

Table 3: Primary design variable effects on performances

Tau – factor determining the length decrease of the next element.
Sigma – factor that determines the distance decrease between the next set of elements
Alpha – opening angle between dipole arms
As a result, it was decided that the opening angle alpha should be made 0 to increase IXR and spectral smoothness. The lowering of gain also helped spread the field of view more evenly over the 60-degree cone.

During experimentation, it was found that tapering the elements into a triangular shape the spectral smoothness of the directivity (see Figure 12) was significantly improved at the cost of some low-frequency matching characteristics. Overall matching improves. However, the reduced surface area of the low-frequency dipoles increases their resonant frequencies. As a result, a scheme was introduced where the bottom dipoles would be for the most part square and gradually tapered into triangular elements as we approach the high-frequency elements at the top. This maintained the low-frequency response while benefitting from the spectral smoothness and matching advantages of the triangular elements. The parameter was called triangle_trim. Another mechanism that was experimented with to increase low-frequency matching is adding perpendicular flaps to the bottom elements. Unfortunately, these flaps are currently impractical for manufacturing and array maintenance.

![Figure 12: SKALA4 – Directivity comparison for different dipole shapes (elliptical, triangular and rectangular). Triangular dipoles deliver the flattest response over frequency.](image)

Another addition to the element shaping was to tilt the elements themselves. A slight upward tilt increases IXR sacrificing some spectral smoothness. Finally, the size of the boom has an impact on the matching, ripple and polarisation rotation. Reducing the size of the boom has an overall positive effect on the antenna performance.

A bow-tie geometry for the bottom dipole is used to increase the low-frequency matching. However, its geometry will be optimised to reduce its effect on the spectral smoothness. Introducing the bottom bowtie adds a significant transition at the low-frequency directivity over frequency performance.

**Table 4: Secondary design variable effects on performances**

| Document No.: | SKA-TEL-LFAA-0300031 | Authors: E. de Lera Acedo, Hardie Pienaar |
|---------------|----------------------|-------------------------------------------|
| Revision:     | 0.5                  |                                           |
| Date:         | 2018-10-30           |                                           |
It should be apparent that the optimisation problem is tightly coupled. The number of elements has not been investigated at this point. Parameterising the number of elements in our CEM software is not trivial and will be discussed in the next section. The next step in the process was to find the optimum antenna, given the specifications, using the new geometries that we have investigated here. It should be noted that the above behaviour of each design variable is dependent on all of the other variables. This will be seen later during the design process where two parameters are optimised at the same time.

3.6.1.2 Creating a fully parameterised script

To speed up the optimisation process of the antenna, the electromagnetic model was parameterised and fully scripted using a FEKO Lua script. The input parameters of the Lua script can be seen below. The values listed are for the SKALA 4 antenna.

| Design Variable | Spectral Smoothness | Overall Gain | Antenna Height | Matching to 100 ohms | IXR | Low Freq Matching |
|-----------------|---------------------|--------------|----------------|---------------------|-----|-------------------|
| Making Elements Triangular | Significantly Better | No Effect | No Effect | Increase | No Effect | Decrease |
| Triangle Trim | Worse | No Effect | No Effect | No Effect | No Effect | Increase |
| Upward Tilt | Worse | No Effect | No Effect | Worse | Increase | No Effect |
| Thinner Boom | Better | No Effect | No Effect | Increase | Increase | No Effect |
| Flaps | Worse | No Effect | No Effect | No Effect | No Effect | Increase |
| Bow-tie | Worse | No Effect | No Effect | No Effect | No Effect | Increase |

**Table 5: SKALA4 model parameters**

| Parameter       | Value | Description                                         |
|-----------------|-------|----------------------------------------------------|
| B_ratio         | 5.5   | Ratio between the bottom and top antenna lengths   |
| L_d1            | 0.8   | Half-length of the bottom element                  |
| N               | 16    | Number of elements                                 |
| Sigma           | 0.0657| Spacing ratio between elements                     |
| Bot_ext         | 0.37  | Length of the bottom dipole extension downward     |
| Top_ext         | 0.1757| Length of the bottom dipole extension upward       |
| Gnd_D           | 0.36  | Distance from the boom to ground                   |
| Triangle_trim   | 0.15  | Squaring factor of bottom elements                 |
| Alpha           | 0     | Opening angle of booms                             |
| Width Factor    | 1.5   | Element tapering angle factor                      |
| Tilt            | -0.1  | Tilt ratio of elements downwards                   |
| W               | 0.034 | Boom width                                          |
| G               | 0.042 | Feed-gap at top of antenna                         |
The script builds the antenna using the CADFEKO API. This proved to be a significant help in the optimisation process. With a parameterised antenna script it is possible to do parameter sweeps on \( N \) (number of elements) in the antenna. However, we still have the problem of how to choose the rest of the variables when doing the parameter sweep. Realistically, it is only possible to do parameter sweeps over two variables. The next step is to reduce our parameterised antenna into its two most important design variables.

### 3.6.1.3 Reducing Optimisation Variables

Most of the secondary design additions can be removed for this step. In this part of the process, we would like to optimise the fundamental variables of the antenna. The major design constraints are that the frequency range should be 50 MHz to 350 MHz while keeping the bottom element smaller than 1.6m across. Because we are not interested in receiving frequencies above 350 MHz, we can constrain the size of the top element. Also, the bottom element is electrically short at 50 MHz. So we choose the largest bottom dipole possible at 1.6 m. The ratio between the top and bottom element is called the bandwidth ratio (B\(_\text{ratio}\)). The half-wavelength at 350MHz is about 0.43. This leads to a bandwidth ratio of \( \frac{1.6}{0.43} = 3.73 \). However, to ensure that the top frequency element is part of the active region, the B\(_\text{ratio}\) is extended to 4. Through experimentation, it was later found that a bandwidth ratio of 5.2 is needed to ensure the antenna is still working well at 350 MHz.

### 3.6.1.4 Optimising Design Variables

#### 3.6.1.4.1 Primary

With the bandwidth ratio fixed and \( \tau \) a function of B\(_\text{ratio}\) and \( N \), \( \sigma \) and \( N \) can be optimised using a 2D parameter sweep. Triangle\(_\text{trim}\), tilt, ground plane and the bottom bow-tie are all removed for this step. The antenna that is being optimised can be seen below.
Using the parameterised antenna script the antenna could be simulated over a large range N and sigma values. In hindsight, a fixed antenna height would have constrained sigma for a given N. But at this point in the process there was not a hard limit on the height of the antenna.

At every point during the parameter sweep the following metrics were calculated:

- Maximum S11: Direct effect in the matching, spectral smoothness in fine channels, sensitivity
- Average S11: Direct effect in the matching, spectral smoothness in fine channels, sensitivity
- Average IXR: Measurement of the polarization performance
- Minimum IXR: Measurement of the polarization performance
- Height
- Standard deviation of the directivity at zenith: As a measurement of the spectral smoothness of the sensitivity
- Mean directivity at zenith: Measurement of the sensitivity in the +/- 45 degrees cone

The choice of these low level parameters is based on their direct impact on the final figures of merit (discussed later in the text). For example, the S11 has a direct and dominant impact on the matching to the LNA that in turns dominates the sensitivity at high frequencies and the spectral smoothness in narrow frequency channels. The directivity dominates the effective area and so the sensitivity as well as the field of view and the telescope’s spectral smoothness in wide frequency ranges. The IXR is directly the high level figure of merit used to assess polarization purity. The results for every metric is shown and discussed next.
Figure 15: SKALA4 – Maximum S11 vs Sigma and Num Elements.

Figure 16: SKALA4 – Average S11 vs Sigma and Num Elements.
Figure 17: SKALA4 – IXR at 45 degrees vs Sigma and Num Elements.

Figure 18: SKALA4 – Min IXR inside the +/-45 degrees cone vs Sigma and Num Elements.
Figure 19: SKALA4 – Standard deviation of the Directivity vs Sigma and Num Elements.

Figure 20: SKALA4 – Mean of directivity at zenith vs Sigma and Num Elements.
Before we investigate the rest of the metrics, it is a good idea to start with the height of the antenna given the N and sigma parameters. In the Maximum S11 metric plot it can be seen that lower element values with higher sigma values are best matched to the 100 ohm feed. However, there are some local regions in the higher element count configurations that could also be used. Not much is learned from the Average S11 metric. From the average IXR metric plot it seems that higher element count results in better overall polarisation performance. However, we are more interested in the minimum IXR metric.

The minimum IXR metric plot is much more dynamic. Nevertheless, there is a definite region where the minimum IXR is desirable between 14 and 18 elements.

The Directivity stddev at zenith is essentially an indication of the spectral smoothness at wide frequency scales. Here it is clear that higher element counts result in better spectral smoothness.

From all of these metric plots, it is apparent that there is a desirable region between 14-16 elements with a sigma value around 0.07. For a direct comparison, all of the metrics are plotted on top of each other. From this hand optimisation N and sigma could be chosen.

| N   | 16 |
|-----|----|
| sigma | 0.0657 |

With the primary variables chosen it was possible to move on to optimising the bottom dipole.

3.6.1.4.2 Secondary

The bottom dipole was optimised similarly as with the primary variables. The 2D parameter sweep this time was done over the antenna height above ground (gnd_D) and bottom dipole extension (ext). The same metrics were calculated as in the first instance. With the antenna already relatively large,
we are bounded to the lower gnd_D values in this optimisation. In the Maximum S11 metric plot desirable regions are split into bands. However, the maximum point only varies by about 1dB.

From the average S11 metric we confirm the notion that we would like to be as far as possible from the ground plane. However, we are constrained by the height of the antenna.

From both IXR metric plots we see a very low dependence on the gnd_D and ext variables. A very clear desirable region is seen in the (directivity stddev at zenith) metric. A height of about 0.3 with a 0.2 extension has the best spectral smoothness performance.

Finally, because the bottom dipole extension was created to decrease the lowest matched frequency, an extra metric was created. This metric calculates the first frequency point at which the matching is below -10dB. There are two clear optimum regions. However, to minimise the height, the second best region will most probably be chosen.

Just as before, all of the metrics are combined to choose the best values for the ground height and bottom dipole extension.

| Gnd_D  | 0.34 |
|--------|------|
| Ext (bot_ext) | 0.16 |

![Figure 22: SKALA4 – Height vs Height above ground and outer extension.](image)
Figure 23: SKALA4 – Maximum S11 vs Height above ground and outer extension.

Figure 24: SKALA4 – Average S11 vs Height above ground and outer extension.
**Figure 25:** SKALA4 – IXR at 45 degrees vs Height above ground and outer extension.

**Figure 26:** SKALA4 – Min IXR inside the +/-45 degrees cone vs Height above ground and outer extension.
Figure 27: SKALA4 – Standard deviation of the Directivity vs Height above ground and outer extension.

Figure 28: SKALA4 – Mean of the Directivity vs Height above ground and outer extension.
Figure 29: SKALA4 – Lowest frequency with S11 < -10 dB vs Height above ground and outer extension.

Figure 30: SKALA4 – Multidimensional plot vs Height above ground and outer extension.

The resulting antenna can be seen below followed by some data on its performance. Note that the bottom dipole at this point is a triangle with a bottom extension, this will later be expanded also to have a top extension forming the familiar bow-tie.
Figure 31: SKALA4 – Intermediate optimized model.
3.6.1.5 Adding the details

By adding some tilt to the antenna, the IXR requirement could be met. Also, by adding triangle_trim, increasing bot_ext and adding top_ext to the bottom dipole, it was possible to increase the matching in the 50 MHz regions. These additions did, however, reduce the spectral smoothness of the antenna. SKALA 4 can be seen below:
The boom transmission line is high (on the order of 300 ohms) compared to the elements and the system.

3.6.1.6 Final design to meet the high level FoMs

The final optimization of the design (see Figure 34) was based on tuning the different parameters by hand in order to optimize the aforementioned metrics. In this section we present the simulated performance of the final SKALA4 without mechanical details (also referred to as SKALA4_BT16 in the following graphs) against some of the main criteria described in [RD1] for that hand tuning. Further information can be found in [RD6]. For a full description of the antenna and electronics including the mechanics see [RD3].
3.6.1.6.1 FC1. Average station sensitivity within 45° Zenith angle (for all azimuth angles)

It is worth noting that the calculation of the reference values for sensitivity between 100 and 150 MHz have been calculated in RD1 assuming that the array is in the sparse regime, while in fact it will still be dense at those frequencies (which leads to lower sensitivity). In this calculation we have assumed that the sensitivity can never be bigger than that provided by the physical area of the station.
One of our main goals in the design of SKALA4 has been to improve the sensitivity and sensitivity smoothness across frequency, especially between 100 to 200 MHz where there was a valley for SKALA3. This was due to reduced directivity of the antenna at zenith but also across the whole +/- 45 degrees cone from zenith. SKALA4 has now improved this. Furthermore SKALA4 has up to 50% more sensitivity than the reference values at high frequencies and above ~20% improvement at lower frequencies.

Table 6: FC1 for SKALA4

| Freq. [MHz] | Value [m²/K] | Ref. value [m²/K] | % wrt. Ref. | % wrt. SKALA3 |
|------------|--------------|-------------------|-------------|---------------|
| 50-100     | 0.4273       | 0.3320            | +28.7       | +2.8          |
| 100-150    | 0.9373       | 0.8768            | +6.9        | +15.2         |
| 150-200    | 1.1667       | 0.9746            | +19.7       | +28.4         |
| 200-250    | 1.2361       | 0.9719            | +27.2       | +12.5         |
| 250-300    | 1.3007       | 0.9242            | +40.7       | +14.5         |
| 300-350    | 1.2800       | 0.8557            | +49.6       | +12.8         |

![Graph](a)
Figure 35: Average sensitivity for SKALA3 and SKALA4 across the frequency range (a) 50-100 MHz and (b) 100-350 MHz.

3.6.1.6.2 FC2. Minimum station sensitivity within 45° Zenith angle (for all azimuth angles)

Table 7: FC2 for SKALA4

| Freq. [MHz] | Value [m²/K] | Ref. Value [m²/K] | % wrt. Ref. | % wrt. SKALA3 |
|-------------|--------------|-------------------|-------------|--------------|
| 50-100      | 0.0805       | 0.0664            | +21.4       | -27.8        |
| 100-150     | 0.4786       | 0.4229            | +13.2       | -10.1        |
| 150-200     | 0.4823       | 0.5854            | -17.6       | -2.5         |
| 200-250     | 0.5777       | 0.5818            | -0.7        | -3.3         |
| 250-300     | 0.6622       | 0.5459            | +21.3       | +19.4        |
| 300-350     | 0.5833       | 0.5029            | +16         | +4.1         |

3.6.1.6.3 FC3. Average station sensitivity between 45° and 60° Zenith angle (for all azimuth angles)

Table 8: FC3 for SKALA4

| Freq. [MHz] | Value [m²/K] | Ref. Value [m²/K] | % wrt. Ref. | % wrt. SKALA3 |
|-------------|--------------|-------------------|-------------|--------------|
| 50-100      | 0.2067       | 0.1510            | +36.9       | +1.6         |
| 100-150     | 0.3936       | 0.3986            | -1.25       | -13.7        |
| 150-200     | 0.3439       | 0.4432            | -22.4       | -28.3        |
| 200-250     | 0.5119       | 0.4420            | +15.8       | +29.9        |
| 250-300     | 0.4535       | 0.4203            | +7.9        | -18.3        |
| 300-350     | 0.4803       | 0.3891            | +23.4       | +5.8         |

3.6.1.6.4 FC4. Average station IXR within 45° from Zenith (for all azimuth angles)

Table 9: FC4 for SKALA4

| Freq. [MHz] | Value [dB] | Ave. Value [dB] | Ref. Value [dB] | Ave. [dB] | dB wrt. Ref. | dB wrt. SKALA3 |
|-------------|------------|-----------------|-----------------|-----------|--------------|---------------|
| 50          | 29.323     | 27.8            | 15              | +12.8     | +0.9         |
| 70          | 31.468     | 31.44           | 15              | +12.8     | +0.9         |
| 100         | 26.923     | 26.914          | 15              | +12.8     | +0.9         |
| 110         | 27.030     | 27.030          | 15              | +12.8     | +0.9         |
| 200         | 25.297     | 25.297          | 15              | +12.8     | +0.9         |
| 250         | 25.648     | 25.648          | 15              | +12.8     | +0.9         |
| 350         | 23.234     | 23.234          | 15              | +12.8     | +0.9         |

3.6.1.6.5 FC5. Minimum station IXR within 45° Zenith angle (for all azimuth angles)

Table 10: FC5 for SKALA4

| Freq. [MHz] | Value [dB] | Min. Value [dB] | Ref. Value [dB] | dB wrt. Ref. | dB wrt. SKALA3 |
|-------------|------------|-----------------|-----------------|--------------|---------------|
| 50          | 16.915     | 12.42           | 15              | -2.58        | +1.7          |
| 70          | 15.929     | 12.42           | 15              | -2.58        | +1.7          |
| 100         | 12.769     | 12.42           | 15              | -2.58        | +1.7          |
| 110         | 12.323     | 12.42           | 15              | -2.58        | +1.7          |
3.6.1.6.6 FC7. Spectral smoothness I: cubic “not-a-knot-spline” fitting (large scale smoothness)

The sensitivity at zenith of a SKA1-LOW station (see Figure 36) is modelled with a not-a-knot-spline and the RMS error averaged across the entire frequency band is calculated. It is worth noting that the choice of the frequency points to fit the cubic spline is crucial in the result of this criterion. For example, if one choses points in the “pass-by-0”, the resulting RMS will always be lower as compared to choosing points at for example the minima or maxima of a function. The choice of frequency points in the selection criteria document (RD1), corresponding to the L1 requirements, are not evenly distributed and therefore have a strong effect on this result.

| Candidate   | RMS  | % wrt. SKALA3 |
|-------------|------|---------------|
| SKALA3      | 0.064| 0             |
| SKALA4_BT16 | 0.057| -11%          |

Table 11: FC7 for SKALA4
Figure 36: Zenith sensitivity for 1 station for SKALA3 and SKALA4 across the 2 main sub-bands (a) 50-100 MHz and (b) 100-350 MHz.

3.6.1.6.7 FC8. Spectral smoothness I (fine scale smoothness)
This criterion is heavily dependent on the matching between the antenna and the LNA and it is further described in [RD3][RD13].

Figure 37. Fine scale smoothness residuals for SKALA3 and SKALA4 after fitting a low order polynomial (order 3) locally (3 channels) as described in [1].

3.6.1.7 Loading of the transmission line and final dipole tuning

Loading the end of transmission line was explored as a way to optimize the performance of the antenna at low frequencies while keeping the footprint as small as possible. While this was a very
promising option, it was not possible to find a trade off between improved S11 and degraded radiation efficiency good enough without the use of a complicated filtering network.

It was also found that narrowband spikes could appear in the antenna response (see blue line in Figure 38) caused by secondary modes forming in the antenna outside of the main active region of the LPD antenna (see Figure 39). These can be fixed by tuning the dipole shape to avoid these modes forming. This is relatively easy for high impedance antennas (eg. differentially fed). Other solutions such as opening up the boom of the antenna could mitigate these spikes at the expense of a polarization rotation at the low end of the frequency band.

Figure 38. Narrow band spikes in the antenna directivity. Before dipole shape tuning (blue) and after (pink).
Figure 39. Secondary regions of the antenna supporting current modes causing narrow band spikes (yellow regions around the middle of the antenna). The active region is in red at this particular frequency.

4 History of the design and evolutions

The evolution of the SKALA design from SKALA0 until SKALA4 has been realized by a collaboration between the University of Cambridge (electromagnetic and overall design) and Cambridge Consultants Ltd (mechanical and LNA design). Below we can see photos of the different prototypes of SKALA before v4. They all have been tested at Lords Bridge, Cambridge UK and SKALA1, SKALA2 and SKALA4 have also been tested at the MRO, Western Australia. More information can be found in [RD17][RD3].
Figure 40: Early prototype of SKALA (SKALA0), 2011.

Figure 41: SKALA1 prototype, 2012.

Figure 42: SKALA2 prototype, 2015.

Figure 43: SKALA3 prototype, 2017.