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# SKA-Low Prototypes Deployed in Australia: Synoptic of the UAV-Based Experimental Results

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*Abstract* – As the Square Kilometre Array progresses toward the construction phase, the first prototypes of the low-frequency instrument were deployed in Australia. To support such a crucial phase, a measurement campaign took place in the Murchison Radio-astronomy Observatory area to validate the electromagnetic models of the arrays by characterizing the embedded element patterns and the array beams. This article shows the significant campaign results in a comprehensive and readable way. Such a synoptic visualization allows for a direct evaluation of the complete dataset.

## 1. Introduction

The future Square Kilometre Array (SKA) [1] radio telescope is approaching the final stage of its development. Within the bridging phase of the low-frequency instrument (SKA-low) [2], which will operate from 50 MHz to 350 MHz, two stations were built in the Murchison Radio-astronomy Observatory (MRO) area in Western Australia. Both the stations share an aperiodic (random) array layout of 256 dual-polarized antennas mounted on a ground plane with a diameter of about 40 m. The Aperture Array Verification System 2.0 (AAVS2.0) station is composed of log-periodic SKALA4.1-AL antennas [3], whereas the Engineering Development Array 2 (EDA2) [4] station is composed of bowtie antennas already used in the Murchison Widefield Array [5].

The accuracy of the electromagnetic models is a critical aspect for such advanced instruments. The embedded element patterns (EEPs) can present significant distortions with respect to the behavior of a stand-alone antenna [6]. In June 2019, a measurement campaign was carried out at MRO to validate the

electromagnetic models of both arrays through an experimental measurement of the EEPs and the digitally beamformed array patterns, exploiting the RF test source mounted on a small, unmanned aircraft. The measurements directly involved research institutions from Italy, Australia, and Malta. Before this campaign, the Italian team conducted several activities on low-frequency aperture arrays, including instrumental calibration [7–9] and near-field verification strategies [10, 11]. This article shows the relevant results of the MRO campaign, extending the contribution of the General Assembly and Scientific Symposium of the International Union of Radio Science 2020 [12]. In particular, a figure of merit for the agreement between simulated and measured pattern was adopted to obtain a direct synoptic visualization of the complete dataset. This data processing and organization is relevant for the future development of station verification strategies in the framework of SKA-low and other aperture arrays. Moreover, the EEPs already shown in [12] were updated after further data analysis that identified an issue in the time synchronization between the acquired data.

## 2. Experimental Setup

When the MRO campaign was carried out, only 48 antennas of 256 were deployed in three clusters of 16 elements for AAVS2.0; for this reason, its name was AAVS1.5 [13]. The EDA2 was fully deployed but only 48 antennas were connected to the receiver. The disconnected elements are included in the EDA2 model. The arrays shared nearly the same geometric layout. In particular, the layout of AAVS1.5 (illustration in Figure 1) is slightly enlarged, with respect to EDA2, to accommodate the larger footprint of the elements. The resulting station diameter is 40 m for AAVS1.5 and 35 m for EDA2.

Complex voltages were acquired for each element (both polarizations). The channel bandwidth of 0.78125 MHz was narrowed by a factor of 128 (digital filtering), with an oversampling factor of 32/27. This setting produces a data rate of about 27 Mbyte/min for each cluster of 16 antennas for both polarizations. The length of time series was about 3 min for each field cut. Although a relatively small subset of antennas was deployed when the campaign took place, more than 10 GB of data were collected in 2 days, corresponding to 14 flights.

The measurements at MRO were carried out by using the unmanned aerial vehicle (UAV) system already adopted in [14, 15]. A small multicopter

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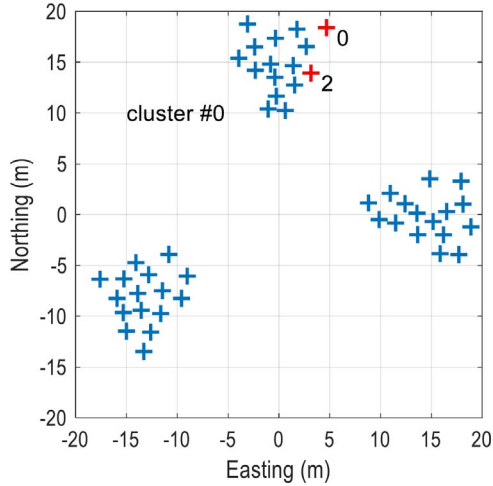


Figure 1. Layout of AAVS1.5. Antennas 0 and 2 of cluster 0 highlighted.

equipped with a tunable RF generator and a tunable dipole antenna operated as a flying test source, while a real-time kinematic differential GPS provided centimeter-level accurate position data. The displacement of a few centimeters between the phase centers of the GPS and test source antennas does not affect the amplitude measurements reported in this work.

The measurements were performed at frequencies of 50 MHz, 70 MHz, 110 MHz, 160 MHz, 230 MHz, and 320 MHz. They consisted in linear scans passing through the array center at constant height to characterize the radiation patterns with an angular coverage of  $\pm 45^\circ$  from zenith [16]. Such a flying height was originally programmed to 160 m for all measurements, but due to adverse wind conditions, some measurements were executed at 120 m. Note that the flight paths did not lie in the  $E$  and  $H$  planes of all the antennas; however, both measurements and simulations were computed on the measured path.

Rigorously speaking, the far-field condition is satisfied at the cluster level (see Figure 1) only up to

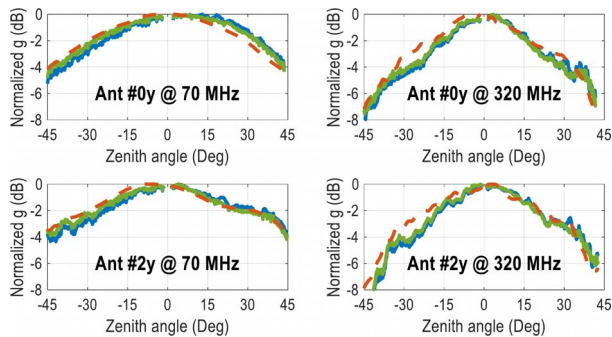


Figure 2. Normalized EEPs of antenna 0 (upper row) and 2 (lower row) of AAVS1.5 (north-south polarization, cluster 0) at 70 MHz (left column) and 320 MHz (right column). Blue: original measurements; green: measurements with time-shift correction applied; and red: simulations.

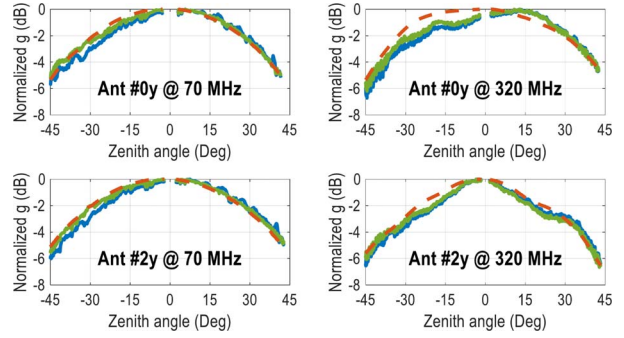


Figure 3. Normalized EEPs of antenna 0 (upper row) and 2 (lower row) of EDA2 (north-south polarization, cluster 0) at 70 MHz (left column) and 320 MHz (right column). Blue: original measurements; green: measurements with time-shift correction applied; and red: simulations.

120 MHz. Nevertheless, at higher frequency, the agreement between measurements and simulations (see Section 3) is still satisfactory. This is an indirect confirmation that the radius of influence is not very large and certainly below the subarray diameter. The procedure in [10] may be adopted to better quantify the near-field effects.

### 3. Results

Figure 2 shows the normalized EEPs of two antennas of AAVS1.5 (0 and 2 of cluster 0) at two different frequencies (70 MHz and 320 MHz). Element 0 is located at the edge of the cluster, whereas 2 is closer to other adjacent antennas. Figure 3 shows the results for the corresponding elements in the EDA2 station. As previously mentioned, both the arrays share the same layout. With respect to [12], further data analysis allowed us to identify an issue in the time stamp assignment. In particular, a time-shift of about 1 s was determined between the UAV data and the measured RF signal at the receiver level by aligning fast modulation features produced by wind gusts in small portions of the flight. The already good agreement between the original EEPs (blue curves) and the simulations (red curves) was further improved applying the time-shift correction to the measured signals. The re-elaborated EEPs (green curves) show both a better agreement and a smaller ripple. The logarithmic difference [see (6) of 17] was adopted as a figure of merit for the discrepancy between simulated and measured pattern. For the EEPs shown in Figures 2 and 3, the root mean square (RMS) value of the logarithmic difference (RMS discrepancy hereinafter; computed for each element across the zenith angle, about 400 samples) was reduced from an average value between the elements of 0.6 dB (original) to 0.4 dB (after the time-shift correction). The ripple reduction is associated to the improved effectiveness of the compensation for the UAV variable attitude during the flight [18].

Figures 4 and 5 show the synoptic visualization for AAVS1.5 and EDA2, respectively. It contains both

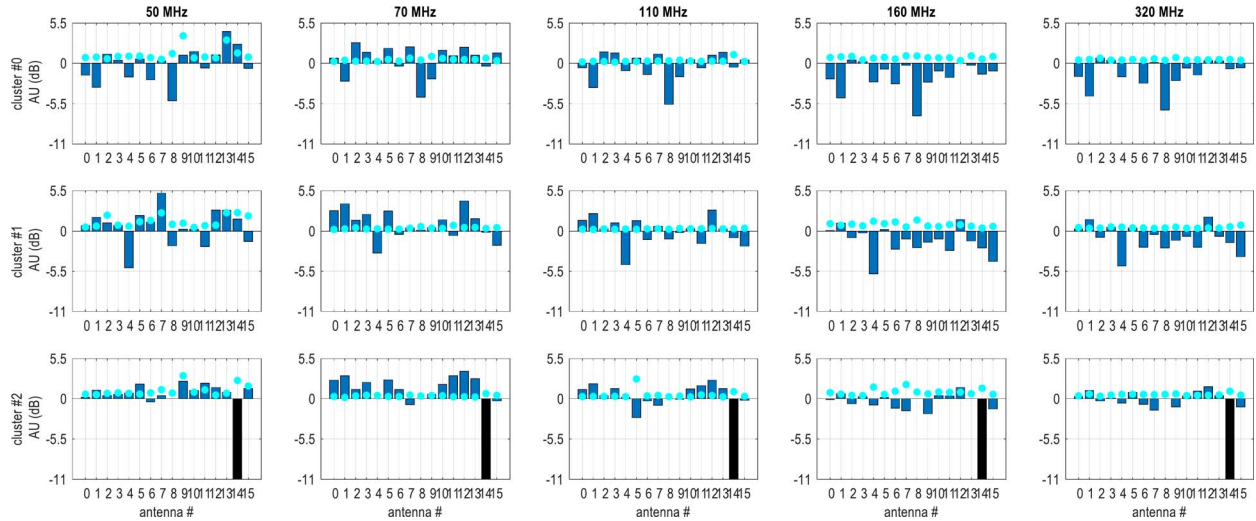


Figure 4. Synoptic visualization of the AAVS1.5 results. Clusters from 0 to 2 in each row. Frequencies from 50 MHz to 320 MHz in each column. Dots: RMS discrepancy between measured and simulated EEP. Bars: measured relative active element gain. The actual value of the black bar is out of range (damaged wired link).

the agreement between measured and simulated EEP and the active element gain for all the elements at all frequencies. Each cluster or frequency is arranged in a different row or column.

To allow for a direct comparison of the agreement between measurements and simulations regardless of the level (which depends on the receiver gain), each measured EEP was equalized to the corresponding simulated curve. In particular, a constant gain  $G_n$  is added to the measured EEPs to minimize the RMS discrepancy. The obtained RMS discrepancy of each element is shown with cyan or magenta dots. Larger values are concentrated at 50 MHz and 160 MHz for AAVS1.5 and at 320 MHz for EDA2. The magenta dots of some elements of EDA2 at 70 MHz indicate that the

low-noise amplifier (LNA) at the antenna level was close to the saturation point. The clipped signal caused a distortion in the measured pattern; however, the final RMS was still comparable to the other elements.

The bars report instead the measured relative active element gain distribution. Element 8 of cluster 2 and element 2 of cluster 2 were adopted as gain reference antennas for AAVS1.5 and EDA2, respectively, to focus the analysis on the relative differences between the array elements. Letting  $G_{ref}$  be the normalization constant of the reference element, the bars represent the quantity  $(G_{ref} - G_n)$ . The low gain level of element 14 of AAVS1.5 (black bar) highlights a damage in the optical link between the LNA and the receiver that caused a high signal loss. Other elements

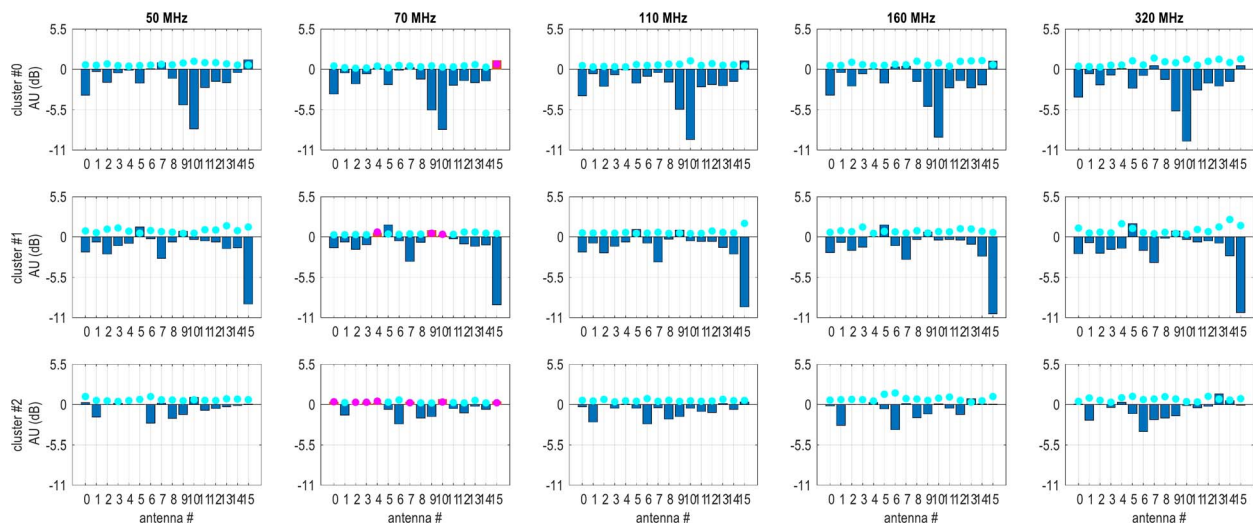


Figure 5. Synoptic visualization of the EDA2 results. Clusters from 0 to 2 in each row. Frequencies from 50 MHz to 320 MHz in each column. Dots: RMS discrepancy between measured and simulated EEP. Bars: measured relative active element gain.

Table 1. Measured and simulated active element gain at zenith for the chosen gain reference antenna of AAVS1.5

Frequency (MHz)	Measured gain (dBi)	Simulated gain (dBi)	Discrepancy (dB)
50	34.29	36.47	-2.18
70	46.69	48.80	-2.11
110	52.52	51.90	+0.62
160	51.58	52.24	-0.66
320	50.50	49.92	+0.58

show a considerably low gain (e.g., EDA2, 10 of cluster 0 and 15 of cluster 1), which reduces the signal-to-noise ratio, increasing the RMS discrepancy.

For the chosen reference antennas, the absolute gain level was measured according to the procedure described in [14] (i.e., a reference measurement of the UAV generator directly connected to the input of the receiver chain; input of the *smartbox*, where the element cables are collected) and was exploited to calibrate out several error contributions, such as transmitted power and receiver gain. Tables 1 and 2 report both the measured and simulated gain values at different frequencies (isolated antenna plus LNA). According to the error estimation of [19], the mismatched UAV dipole can explain discrepancies at 50 MHz. The error for the gain reference element of AAVS1.5 generally decreases at higher frequencies, whereas the EDA2 reference antenna shows a more variable discrepancy. The latter may be improved with a further refinement of the considered models, with particularly for the interaction between LNA and the antenna (transducer gain) in the embedded conditions.

Finally, Figures 6 and 7 show the normalized beamformed pattern of cluster 0 (16 antennas) of AAVS1.5 and EDA2, respectively. As expected, the results are rather similar to each other, even though some elements present different behavior. The measured array pattern (blue) was obtained by equalizing the complex EEPs at the zenith of the cluster. This corresponds to near-field focusing (i.e., a quadratic phasing of the array elements). The simulations (red) are, instead, performed in far field by using the method of moments of the Galileo EMT (ElectroMagnetic Toolkit). The good agreement confirms the accuracy of the array model, as well as the effectiveness of the near-field focusing concept for large array testing [20, 21].

Table 2. Measured and simulated active element gain at zenith for the chosen gain reference antenna of EDA2

Frequency (MHz)	Measured gain (dBi)	Simulated gain (dBi)	Discrepancy (dB)
50	-3.81	-1.99	-1.82
70	17.04	14.48	+2.57
110	19.94	18.88	+1.06
160	26.23	26.30	-0.07
320	20.44	24.06	+3.61

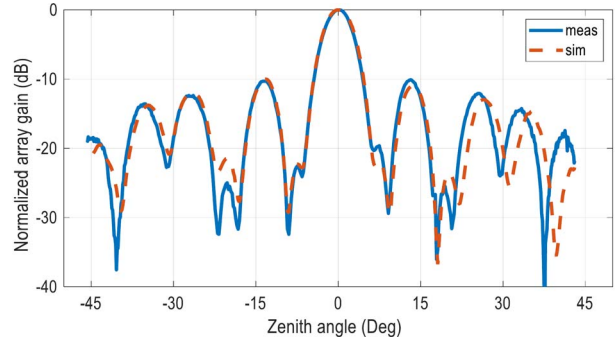


Figure 6. Normalized beamformed pattern of cluster 0 of AAVS1.5 at 320 MHz. Blue: measurements; and red: simulations.

## 4. Conclusion

This first measurement campaign in Western Australia by using a UAV-mounted test source was conceived to support the deployment the SKA-low prototypes and verify the array models. The presented synoptic visualization concentrates a large amount of data collected within a limited number of flights, highlighting the benefit of using a UAV-mounted test source for array characterization and operative verification. Further activities will concern the whole 256 element stations both in terms of the pattern characterization (also adopting near-field strategies) and the evaluation of the instrument performance (e.g., sensitivity).

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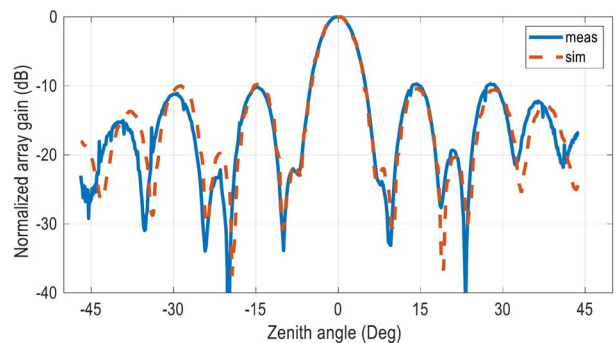


Figure 7. Normalized beamformed pattern of cluster 0 of EDA2 at 320 MHz. Blue: measurements; and red: simulations.

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