Calibration of aperture array receivers based on an unmanned aerial vehicle

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SKA-Low, the low frequency part of SKA, will be composed by aperture arrays formed by a large number of small antennas, that provides a large FoV and the capability to observe many parts of the sky at once.

- 250,000 dual polarized antenna elements organized in 911 stations of about 35 m diameter
- Frequency band: 50 - 350 MHz

The signals from all the elements of a station will be added together electronically to form a reception beam, therefore calibration of the SKA-Low stations will be fundamental.
For **narrowband signals** the synthetized beam is electronically “steered” within the FoV (single antenna pattern) by adjusting gain and phase for each antenna.

\[
y(k) = w^H v(k)
\]
For **wideband signals**, it is necessary to introduce delay blocks (FIFO) for coarse time compensation and also a gain and phase correction frequency by frequency (after a PFB).
MAD is a 3 x 3 regularly spaced antenna array, arranged in a rhomboidal configuration.
Vivaldi antenna (version 2)

MAD used as receiving element a prototype of Vivaldi antenna having the following features:

- Field of view of about 90 deg
- Unbalanced 50 Ohm excitation
- Low cross pol on the principal axes
- No ground plane required
- Small size
- Low cost
Medicina Array Demonstrator - Location
Medicina Array Demonstrator - Location

MAD

RFoF

Toward receiver room
MAD back-end

- Digital architecture implemented in a single ROACH Board
- FPGA: Xilinx Virtex-5 SX95T
- Correlator and Beamformer works in parallel
- Amplitude and Phase Coefficients are written in FPGA through software interface

<table>
<thead>
<tr>
<th>MAD Digital Back-end specifications</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>FPGA clock</td>
<td>160 MHz</td>
</tr>
<tr>
<td>ADC sampling clock</td>
<td>40 MSa/s</td>
</tr>
<tr>
<td>ADC sampling precision</td>
<td>12 bits</td>
</tr>
<tr>
<td>Frequency Resolution</td>
<td>19.5 kHz</td>
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<tr>
<td>Time resolution</td>
<td>51.2 μs</td>
</tr>
<tr>
<td>Auto Correlations</td>
<td>9</td>
</tr>
<tr>
<td>Cross Correlations</td>
<td>8</td>
</tr>
<tr>
<td>Correlator and Beamformer Output</td>
<td>10 Giga Bit Ethernet</td>
</tr>
</tbody>
</table>

Roach Board (https://casper.berkeley.edu/)
The UAV is equipped with a transmitter emitting a CW linear polarized signal with a power of about 3 mW, tunable in frequency from 35 MHz to 1.1 GHz.
The hexacopter was utilized in the MAD experiment for:

- Array topography
- Antenna embedded pattern measurements
- Analogue signal equalization
- Digital calibration in amplitude and phase of the receiving chains
- Beam shape measurements
An optical marker was installed at the top of each antenna in order to increase the position accuracy (sub-cm resolution)

The hexacopter was equipped with a high-resolution photo-camera
Trajectory requirements

- Operate in far field condition \( R \gg \frac{D^2}{\lambda} \)
- Minimize the fringe smearing
- Optimize the fringe patterns

**AAVS0 Far-field Measurements**

**Embedded Element Pattern measurement in the operative conditions**

**Trajectory requirements**

- Operate in far field condition \( R \gg \frac{D^2}{\lambda} \)
- Minimize the fringe smearing
- Optimize the fringe patterns
In order to define the absolute position of the UAV vs. time (i.e. the trajectory), a topographic tracking has been performed using a motorized total station (MTS). It was possible thanks to a dedicated reflector installed on the bottom part of the UAV.

Performances of the MTS within 1 km of operative distance:

- Angular resolution: 1 arcsec
- Range accuracy: 3 mm
Different flight trajectories were adopted depending on the aim of the measurement, as instance:

- Stationary (analogue equalization and digital amplitude calibration)
- Linear trajectories (phase calibration)
- «L» shaped trajectories (ADC dynamic range check in both pol)
- «X» shaped trajectories (beam shape)

Normalized Total Station Data

Height = 60 m
Speed = 1 m/s
Before the calibration, an analogue amplitude equalization is necessary to ensure that the signal lies within the backend dynamic range (from about \(-30 \text{ dBm}\) to \(+10 \text{ dBm}\)).

It was performed by means of a spectrum analyzer and a dedicated digital board controlling the attenuators of each IF channel.

All the signals were equalized at \(+0 \text{ dBm}\) with the UAV in stationary flight above the zenith of the array center.

The minimum step in the gain control of the analogue chains is 0.5 dB.
The amplitude of each complex coefficient was calculated by an algorithm based on the matching between the signal power ratios observed and simulated.

This amplitude calibration procedure takes into account:

- antenna pattern for each array element obtained by e.m. simulations
- UAV trajectory
- Transmitting antenna pattern (well known from e.m. simulations and measurements in anechoic chamber)

The last two information are necessary to calculate the path losses and the gain of the transmitter in the direction of the receiving antenna.

The EM simulations of the antenna patterns were performed by CST (Computer Simulation Technology), including the soil effect and the mutual coupling effects between the antennas in the array.
Results of the amplitude coefficient calibration

Before amplitude calibration

After amplitude calibration
Phase coefficient calibration

The phase coefficients were determined by means of a multiparametric fitting between simulated and observed fringe patterns.

For each polarization, fringes were obtained cross correlating the signals from an appropriate subset of (N-1) baselines, among a total number of baselines of \( \frac{N(N-1)}{2} \), where N is the number of the array elements.
Cross correlations before the phase calibration

<table>
<thead>
<tr>
<th>Antenna ID</th>
<th>Phase correction [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>V001</td>
<td>109.26</td>
</tr>
<tr>
<td>V002</td>
<td>148.68</td>
</tr>
<tr>
<td>V003</td>
<td>140.98</td>
</tr>
<tr>
<td>V004</td>
<td>270.49</td>
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<td>V005</td>
<td>8.11</td>
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<tr>
<td>V006</td>
<td>215.07</td>
</tr>
<tr>
<td>V007</td>
<td>0.00</td>
</tr>
<tr>
<td>V008</td>
<td>353.91</td>
</tr>
<tr>
<td>V009</td>
<td>332.95</td>
</tr>
</tbody>
</table>

Phase reference antenna
Cross correlations after the phase calibration

<table>
<thead>
<tr>
<th>Antenna ID</th>
<th>Residual phase error [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>V001</td>
<td>1.85</td>
</tr>
<tr>
<td>V002</td>
<td>0.90</td>
</tr>
<tr>
<td>V003</td>
<td>0.60</td>
</tr>
<tr>
<td>V004</td>
<td>1.12</td>
</tr>
<tr>
<td>V005</td>
<td>-0.19</td>
</tr>
<tr>
<td>V006</td>
<td>-0.04</td>
</tr>
<tr>
<td>V007</td>
<td>0.00</td>
</tr>
<tr>
<td>V008</td>
<td>-0.69</td>
</tr>
<tr>
<td>V009</td>
<td>0.04</td>
</tr>
</tbody>
</table>

*Phase reference antenna*
Beam shape before and after calibration

- The beamformer was set to point the beam at zenith
- The measured pattern shows that, after the calibration, the beam array was correctly oriented
Future works

• Use a differential GPS installed onboard the UAV in order to avoid the Total Station and to improve the time synchronization in the UAV positioning

• Automate the analogue equalization of the signals

• Develop a pipeline for the calibration software

• Improve the UAV autopilot for automatic take-off and landing

• Test the applicability of the UAV calibration technique to larger arrays, for instance the Sardinia Array Demonstrator (SAD) and the Aperture Array Verification System 1 (AAVS1)
Sardinia Array Demonstrator (SAD)

SAD will be composed by 128 elements arranged in a central core and in a number of smaller stations. The array will be installed in the Sardinia Radio Telescope (SRT) area and it will operate in the band 200 - 450 MHz.

SAD will be an extremely useful test bed to extend and refine the calibration techniques based on UAV that were successfully tested in the MAD experiments.