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In-Situ Characterization of International Low-Frequency Aperture Arrays by Means of an UAV-based System

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Abstract

Low Frequency Aperture Array (LFAA) systems are opening up new frontiers for ground-based radio astronomical instruments. These instruments require advanced measurement procedures and systems for characterization and calibration of their front-end. For this purpose, a test source mounted on an Unmanned Aerial Vehicle (UAV) has been developed in Italy. This system has proven to be a reliable, accurate, portable and effective tool to characterize LFAA systems as demonstrated during measurement campaigns on two Aperture Array Verification Systems for the LFAA of the SKA in the UK and on a LOFAR station in The Netherlands. This contribution gives an overview of these campaigns, the continuous development of the UAV-based measurement system and the envisaged future improvements.

1. Introduction

Low Frequency Aperture Array (LFAA) technology is successfully used in several new radio astronomical facilities like the Low Frequency Array (LOFAR) [1] in Europe and the Murchison Widefield Array (MWA) [2] in Australia. Both systems are considered technological pathfinders for the LFAA system of the future Square Kilometre Array (SKA) [3], which is envisaged to be installed in Australia. These instruments require advanced measurement procedures and systems to characterize and calibrate their front-ends. For this purpose, a test source mounted on an Unmanned Aerial Vehicle (UAV) has been developed in Italy. This UAV-based system has been initially tested on the Medicina Array Demonstrator (MAD), which is a 3×3 regularly spaced array of Vivaldi antennas installed on the premises of the Medicina radio astronomical station (Italy). The MAD campaign allowed us to successfully measure the far-field embedded element patterns, to equalize the gain amplitude and phase of each receiving chain (calibration) and finally to measure the array pattern and the fringes of each baseline at the operating frequency of 408 MHz [4].

In the period 2014-2016, the system has been transported to and set up in the UK and The Netherlands for characterizing the Aperture Array Verification System (AAVS) for the SKA and LOFAR respectively. As preparatory work for these international campaigns, the performance of the antennas of AAVS and LOFAR have been first measured in Italy with the UAV system [5,6].

In this paper, we present an overview of these past international campaigns, summarizing the goals and achievements of each campaign. The experience gained during these campaigns has helped us to improve the measurement system and the measurement procedures. This is a process that will continue towards the SKA, so we conclude our paper by providing a summary of improvements that we expect in the near future.

Figure 1. The hexacopter carrying the RF transmitter (white box) and the dipole.

2. Measurement System

The UAV-based antenna measurement system was conceived during the Aperture Array Verification Program [7] to verify the antenna candidates designed for the LFAA of SKA. As reported in [8], the original system consisted of a micro-UAV (a hexacopter with an overall size of 72 cm) equipped with a continuous-wave single-frequency RF generator and a telescopic dipole. The dipole length was tuned according to the operating frequency. More recent versions of the system (see Fig. 1) use a discrete set of fixed-length dipoles instead to improve the measurement repeatability.

In [8], the UAV position was tracked using on-ground laser-based topographic instruments called motorized total stations with an accuracy better than 1 cm. Very good measurement performance has been obtained with this configuration. However, the tracking with total stations, which required expert operators, was not easy to achieve in intense daylight conditions. For these reasons, a tracking strategy based on Post-Processing Kinematic Differential Global Navigation Satellite System (PPK-DGNSS) has been subsequently adopted. It requires a dual-frequency GNSS receiver on board of the UAV and an additional one (master station) on the ground. The DGNSS solution is obtained by using the open-source software RTKLIB with an accuracy of about 2 cm in the horizontal plane and 7 cm in height. Such an accuracy level is definitely acceptable in the present application context. Moreover, the DGNSS position data is intrinsically referenced to the GNSS time, which is a crucial aspect as far as correlation with the RF data is concerned. The latter are in fact acquired using either a GPS-triggered spectrum analyzer [8] in span zero mode or the array digital back-end, which should put a GNSS time stamp on the acquired data [4].

The telemetry link of the UAV, which is required both to load the flight plan before takeoff and to monitor the system status during the flight, has been recently moved from 433 MHz to 2.4 GHz (same frequency as the radio-control) in order to be as far as possible from the maximum operating frequency of the LFAA of SKA (350 MHz). This solution also avoids the generation of intermodulation products between the RF transmitter and the telemetry transmitter that can enter the onboard GNSS receiver bandwidth, dramatically reducing the available Signal-to-Noise Ratio.

Finally, a multi-frequency solution has been adopted to speed-up the LOFAR campaign. In order to transmit a small set of uniformly-spaced continuous-wave signals within the observing band of the Low Band Antenna (LBA) of LOFAR (10 – 90 MHz), the RF generator output has been set to about 6 MHz by means of a frequency divider. The divider output is square-wave like providing high level of odd higher order harmonics (see Fig. 2). At every flight, the 5, 7, 9 and 11-th harmonics have been simultaneously acquired by the LOFAR back-end demonstrating a very high measurement efficiency of the overall system.

3. Measurement Campaigns

This section summarizes some of the main results obtained in the UAV-based measurement campaigns carried out on international LFAAs during the last years.

3.1 AAVS 0

The Aperture Array Verification System 0 (AAVS0) was an ultra-wideband 16-element sparse random array (Fig. 3) installed at the Mullard Radio Astronomy Observatory (MRAO) at Lord's Bridge, Cambridge (UK). The main purpose of AAVS0 was to test the technologies developed for the SKA1-low front-end, in particular the antenna element and the differential Low Noise Amplifier (LNA).

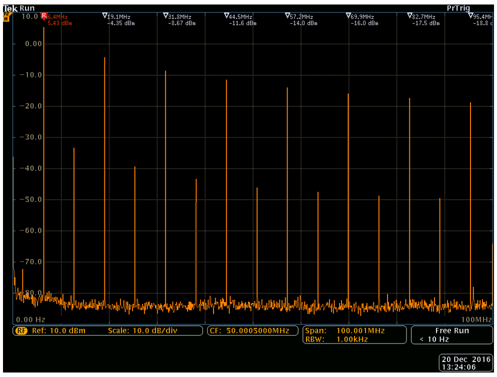

Figure 2. Transmitted spectrum from the UAV in the multi-frequency solution.

Figure 3. Picture of the AAVS0 array. The array was installed over a platform covered with a metallic mesh.

The antenna element was the SKALA-1, a 9-element dual polarized log-periodic antenna, specifically designed for SKA1-low [9]. The UAV measurement campaign on AAVS0 was performed on September 9 – 12, 2014. A spectrum analyzer acquired the RF signals from a selected antenna measuring its embedded element-pattern along the cut of the hexacopter trajectory. Subsequently, all the individual antenna/LNA signals were summed together by an analogue power combiner to produce the array beam. The embedded and the array radiation patterns were measured at 50, 150, 250 and 350 MHz along the E-plane and the H-plane. They have been compared with electromagnetic simulations in order to validate the antenna design. A raster scan on a small planar area over the array, obtained through multiple UAV flights, allowed us to map the array main beam and its first sidelobes with high accuracy. Figure 4 shows the measured AAVS0 array beam at 350 MHz. The agreement with electromagnetic simulations (not shown) is good for the main beam and consistent for the sidelobes.

3.2 LOFAR

LOFAR is a radio interferometer consisting of two different antenna types: the LBA, operating in the frequency range 10 – 90 MHz, and the High Band Antenna (HBA) working between 120 and 240 MHz. These antennas are organized in 50 aperture array stations distributed over The Netherlands, Germany, Sweden, the

UK, France and Poland. The UAV-based campaign was carried out on the LOFAR station CS302, located near Exloo (NL), from April 18 to 21, 2016. This station consists of 96 dual-polarized LBAs and 48 HBA tiles divided in two sub-arrays. The layout of the CS302 station is displayed in Fig. 5.

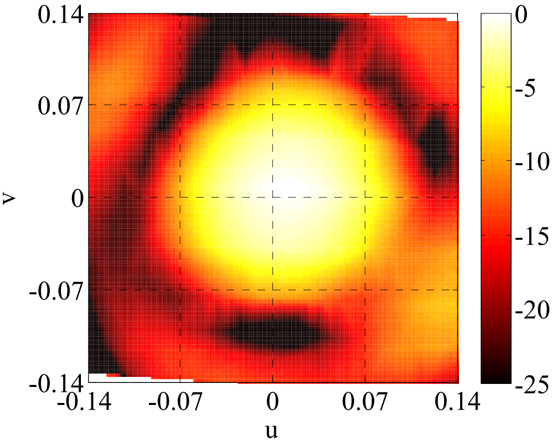

Figure 4. The AAVS0 array beam measured at 350 MHz by a hexacopter raster scan over the array.

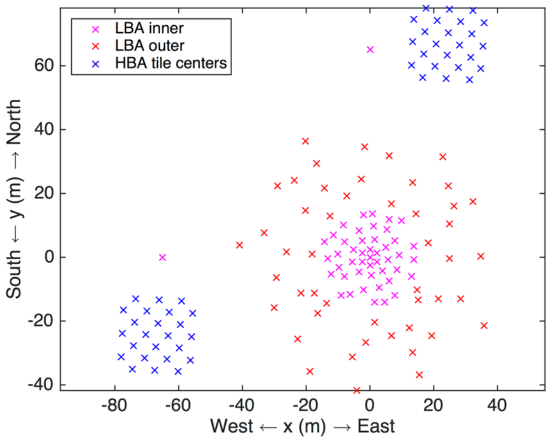

Figure 5. Layout of the LOFAR station CS302.

The principal aims of the campaign were to validate the beam models for the LOFAR stations including the mutual coupling and to test the calibration of the LBA station in its operative environment. Another goal of the campaign was to demonstrate that the UAV is able to measure individual elements and tiles in a station, for which the far-field condition is satisfied, although the full station was in near-field. Actually the embedded-element patterns of the LBAs were obtained from different UAV flights demonstrating the reliability and the repeatability of the measurement. Spin flights, in which the UAV is kept in a stationary position while spinning around its own axis, have been performed as well on the LOFAR station. The spin flights have permitted us to measure the polarization performance and to verify that the orthogonality between the two dipoles of central element was very good toward zenith (Fig. 6). As far as the LBA embedded-element patterns are concerned, Fig. 7 shows the response at 57 MHz for 4 elements of the array (each of them with a different color) for different flights. The agreement between different flights is remarkable and proves the repeatability of the measurement system (consistently with error budget analysis reported in [6]). The embedded element pattern are more distorted for the elements that are closer to the array center (blue and green curves), where a closer spacing is implemented.

Finally, a novel UAV-aided position calibration method was also successfully tested in this campaign [10].

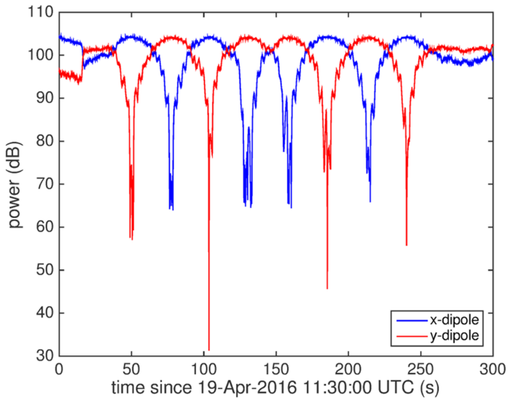

Figure 6. Output power of the x- and y-dipoles of the central LBA element measured during the spin flight.

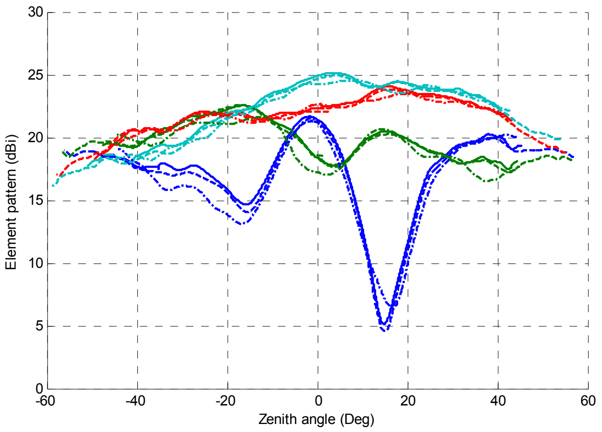

Figure 7. Measured LBA embedded patterns at 57 MHz: Central Element (blue), Element #2 (green), Element #26 (red), Element #42 (cyan). Elements with higher label number are further from the center.

3.3 Pre-AAVS 1

The latest UAV campaign was performed on the pre-AAVS1 array during September 5 – 8, 2016. The differences of this array with respect to AAVS0 were: the use of an improved version of the array element (SKALA-2 [11]) and the digital back-end for the signal acquisition. The main goals of this campaign were to validate the electromagnetic model of the SKALA-2 in the relevant array configuration and to evaluate the performance of the new front-end.

Besides the standard UAV linear flights, aimed to measure the embedded element radiation patterns at 50, 175 and 350 MHz, several innovative UAV-based measurement techniques were implemented. In particular, the hexacopter performed different types of beam scans (radial, azimuthal and 2D dense raster) in order to improve the measurement accuracy and to evaluate the polarization performance in terms of Intrinsic Cross-Polarization Ratio (IXR). Moreover, some vertical flights were accomplished to estimate the system sensitivity. Finally, an antenna placed away from the array was adopted as reference in the phase pattern measurements. The data collected in the pre-AAVS1 campaign are currently being analyzed. A preview of the array beam at 175 MHz is illustrated in Fig. 8.

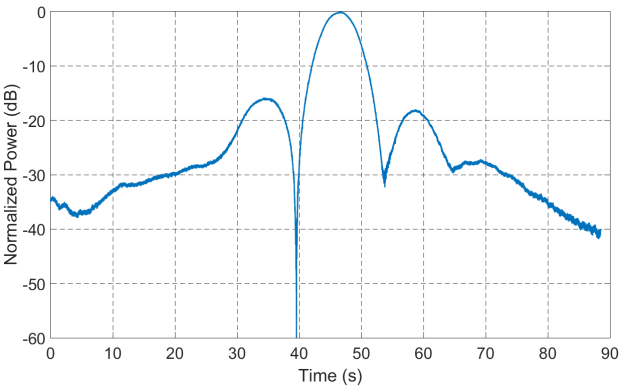

Figure 8. Pre-AAVS1 array beam at 175 MHz.

4. Improvements to the measurement system and future campaigns

Future versions of the measurement system will take advantage of the modern low-cost Real Time Kinematics (RTK) DGNSS hardware. This solution will simplify both the data acquisition and processing procedure. Moreover, the RTK system will be used as primary position sensor of the UAV, providing smaller discrepancies between the real trajectory and the programmed flight plan.

The usage of both a comb generator and a more broadband antenna will be investigated in order to achieve more flexibility in terms of the frequency selection with respect to the divider-based multi-frequency option described in Section 2.

Additionally, a significant amount of effort will be devoted to improve the error budget summarized in [6] in terms of both verification and reduction of the estimated error quantities. This task will be carried out both using third-party calibrated reference antennas (which are now available on the market) and investigating a self-calibrating strategy for the UAV-based test source.

Finally, the UAV system will be improved in the operation management, like for example standardizing and automating the measurement procedures and reducing the number of people involved on the field. This improvement is relevant in view of a possible UAV campaign in Australia on one of the pathfinders of the SKA and even more if this system will be adopted by the SKA for routinely characterizing and instrumentally calibrating the LFAA of SKA1-low during normal operations.

5. Acknowledgements

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