Low Frequency Array Verification with Unmanned Aerial Vehicles

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Outline

• UAV low frequency array verification: why and how

• Some results on international campaigns
  • Low Frequency Array (LOFAR) - CS302 station, Exloo (NL), April 2016
  • Pre-Aperture Array Verification System 1 (pre-AAVS1), Cambridge (UK), Sept. 2016
    • Embedded element patterns, near filed data, array beams

• On-going and future activities
UAV Low Frequency Array Verification

• Why UAV?
  Challenges: Mutual coupling between antennas, effects from surrounding environment (soil, cables), anechoic chamber tests infeasible

• UAV equipped with a continuous-wave RF transmitter and a dipole antenna acting as a far-field test source

• Antenna Under Test (AUT) on the ground
  • The received power is measured during the flight

• Predefined trajectory and autonomous GPS-based navigation (e.g. E-/H-plane cuts)
  • DGNSS for accurate position

• User-defined horizontal orientation (heading angle) to perform co-/cross-polar measurements

- transportability
- no runways are required
- vertical and standing flight are allowed
- time of flight (5-15 mins)
UAV-based Measurements

- **AUT pattern** along the flight trajectory is computed from received power by removing the other contributions (Friis eq.)
  - *Path loss* & *test source pattern* must be computed and kept into account

- For quasi-rectilinear paths:
  - Source *distance* & *orientation* are not constant

- Additional data needed:
  - **UAV position data**: *differential GNSS (DGNSS)* provides centimeter-level accuracy
  - **UAV orientation data**: *Inertial Measurement Unit (IMU)* is exploited to avoid pattern distortion
  - **Data synchronization** is important (position, orientation and RF)
Scan Strategies

Cross-Scan

2D Cartesian Raster

2D Radial Raster

3D Azimuthal Raster
Scan Strategies

- Enable fast recovery of AUT pattern over E-plane and H-plane for linearly-polarized antennas
Scan Strategies

- More complex strategy enabling derivation of 2D pattern maps
- E.g. along $x$ or $y$
- Allows for fine details over a small area (OK for mapping main beam + some side lobes)
Scan Strategies

- More complex strategy enabling derivation of 2D pattern maps
- «Generalization» of a cross scan
- Cover a large area BUT the sampling density is not uniform
Scan Strategies

- More complex strategy enabling derivation of 2D pattern maps
- Angular sampling is uniform
- Cover a large area (each circle – made with fixed distance from AUT – is made at a different heights: there is no need to fly too far)
Scan Strategies

Regardless of the strategy, polarization can be either $x$ and $y$ or $\vartheta$ and $\varphi$

- Drone heading can be set independently and does not need to be aligned with the trajectory
  - The user can choose which polarization will be measured
LOw Frequency ARray (LOFAR)

Three Arrays in Three Days with multi-frequency TX
(32 MHz, 44 MHz, 57 MHz, 70 MHz, 125 MHz, 152 MHz, 180 MHz)

LBA inner & outer: 48+48 dual-pol elements 10–80 MHz

HBA: 48 tiles with 16 dual-pol bow-ties 120–240 MHz

Exloo, NL
Turin

LBA
HBA
HBA subarray
LBA inner
LBA outer

LOFAR CS302 station
LOFAR Embedded-Element Patterns @57 MHz (close to dipole resonance)

100 m height, 3 flights

Good agreement among 3 different flights

Cut NW, Yaw NE, NE pol., f = 57.2265 MHz

Resonance freq. is the freq. at which maximum telescope sensitivity is expected

EEPs of central elements are very different from those of more isolated dipoles (problem for telescope performance and/or its calibration/characterization)←both mutual coupling effects and high mismatch at the LNA input → better understanding and array modeling
Example of LOFAR Near-Field data

Near field model by Pietro Bolli@INAF

Array Beam
- LBA inner array
- 70 MHz, 100 m height (>400 m FF condition → NF!)
- Array preliminary verification in NF*:
  - Same model used to simulate FF pattern was here provided to a commercial solver to compute a generic NF response (the real UAV position and orientation during flight have been included in the model)
  - Residual discrepancy of 0.5 dB

SKA Aperture Array Verification System (AAVS)

- 16 SKALA antennas: 9-element dual-polarized log-periodic
- Single-/embedded-element patterns & Array patterns
- 50–650 MHz

Lord’s Bridge - Cambridge, UK

Turin
RFI at Lord’s Bridge

- DAB signal: Minima every 100 ms
- Much lower energy entering the LNA (sat region) $\rightarrow$ much higher gain $\rightarrow$ peaks every 100 ms in the received signal
- Need to filter the received signal

**Received Signal**

Freq = 175.0 MHz, Span = 0.0 kHz, ResBW= 10.000 kHz
SweepTime= 500.0 msec, Npoints= 401

- DAB signal recorded by Spectrum analyzer (RFI)

- TX signal is ON
- TX signal is off
- 100 ms

**RF Meas dB**

- Ant 002 (pol Y)
- LP version

- Freq = 226.0 MHz, Span = 0.0 kHz, ResBW= 10.000 kHz
- SweepTime= 500.0 msec, Npoints= 401

Low Frequency Array Verification with Unmanned Aerial Vehicles
II National Workshop of SKA Science and Technology, Bologna, Dec. 2018
Array Pattern

- Measurement
- FW Simulation
- Array Factor

50 MHz H-plane
Array Pattern

- Measurement
- FW Simulation
- Array Factor

Array Pattern from Normalized Elements (dB)

350 MHz H-plane

Zenith Angle (Deg)
On-going activities

• Data processing for LOFAR HBA
• Phase reconstruction with reference antenna outside the array. This can be used to perform near-field to far-field transformations
• Improve orientation accuracy (with additional RTK-aided IMU hardware) for cross-polarization and IXR measurements
• Improve overall system functionality for future SKA commissioning → campaign planned in 2019 in Australia for the validation of the SKA1-LOW demonstrators
Thanks for your attention!

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Low Frequency Array Verification with Unmanned Aerial Vehicles
Backup Slides
**Received Power Pattern**

\[
P_R(\hat{r}) = P_S \frac{G_S(\hat{r}, \alpha, \beta, \gamma) G_{AUT}(\hat{r})}{\left(\frac{4\pi R}{\lambda}\right)^2} \left| \hat{p}_S(\hat{r}, \alpha, \beta, \gamma) \cdot \hat{p}_{AUT}(\hat{r}) \right|^2 G_R
\]

- **Source transmitted power**
- **Gain pattern of the test source**
- **AUT gain pattern**
- **Polarization vectors**
- **Path Loss**
- **Polarization mismatch between the source and the AUT**
- **LNA gain and cable losses**

\[r = R\hat{r}\] is the distance vector between the UAV and the AUT (from Total Station)

\[\alpha, \beta, \gamma\] Orientation (Euler) angles of the UAV (from on-board IMU)

**The receiving system is also synchronized with GPS**
Biconical Antenna at 150 MHz

Cross polar levels ≈-25 dB

Extraction of the AUT pattern

- Test source has a two-fold symmetry i.e. cross polarization is very low on the principal planes.
  
  **Co-polar orientation** \( p_s^x \approx 0 \) and \( p_s^{co} \approx 1 \)

\[
M = |p_s^{co}p_{AUT}^{co} + p_s^x p_{AUT}^x|^2 \approx |p_{AUT}^{co}|^2
\]

- The **AUT measurement pattern** can be extracted from the **Received Power Pattern**, removing the **Simulated Test Source Pattern** and **Path loss**.

\[
G_{AUT}^{co}(\hat{r}) = \frac{P_R(r)}{P_S \cdot G_S(\hat{r},\alpha,\beta,\gamma) \cdot G_R} \left(\frac{4\pi R}{\lambda}\right)^2
\]
UAV measurement scheme (in-flight)

(1) \[ P_{\text{al}} = P_{\text{TX}} - A_{\text{TX}} - A_{\text{Balun}} - A_{\text{Mis}} + G_{\text{LNA}} - A_{\text{Cable}} + G_{\text{RX}} \]

(2) \[ g_{\text{AUT}} = \text{RFMeas} - P_{\text{al}} - g_{s} + \text{PL} \]

Known a priori or experimentally determined with reference measurements.
Reference measurement scheme in order to evaluate the receiver gain $G_{RX}$

$$G_{RX} = P_{ref} - P_{TX} + A_{TXRef}$$

Power read at the receiver (dBm o ADC units)
NOTE IMPORTANTI

• P_TX compare in (1) e (3) con segno opposto, semplificandosi. La misura di reference rende superfluo conoscere P_TX (ciò migliora l’accuratezza di misura)
• Conoscere P_TX diventa necessario se si inserisce un valore di G_RX noto a priori o determinato sperimentalmente in altro modo

• Se viene usato lo stesso attenuatore sia in volo che per la misura di reference, allora A_TX_Ref = A_TX e si semplificano in (1). E’ superfluo caratterizzare l’attenuatore in laboratorio.
• Se vengono usati due attenuatori diversi (vedi Cambridge 2016), bisognerebbe caratterizzare gli attenuatori in laboratorio
Error Budget @350 MHz

<table>
<thead>
<tr>
<th>Value</th>
<th>Error (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A  Rec. Power</td>
<td>-33.88 dBm</td>
</tr>
<tr>
<td>B  Transm. Power</td>
<td>-0.35 dBm</td>
</tr>
<tr>
<td>C  Ins. Loss (balun)</td>
<td>0.80 dB</td>
</tr>
<tr>
<td>D  Mismatch Loss (UAV dipole)</td>
<td>0.28 dB</td>
</tr>
<tr>
<td>E  Source Gain</td>
<td>5.68 dBi</td>
</tr>
<tr>
<td>F  Path Loss</td>
<td>59.46 dB</td>
</tr>
<tr>
<td>G  Cable Loss</td>
<td>9.06 dB</td>
</tr>
<tr>
<td>H  AUT Gain</td>
<td>30.38 dBi</td>
</tr>
</tbody>
</table>

\[ H = A - B + C + D - E + F + G \]

Friis

- Characterization in laboratory (RF generator, source antenna, cables)
- Other simulated and measured quantities (g, P_{rec})
- Resulting uncertainty with RMS criterion

\[ H = \pm 0.14 \text{ dB} \]
Medicina Array Demonstrator (MAD)
Calibration of a Small Array and Beam-Forming @408 MHz

Fiber optics link & digital beamforming
Medicina Array Demonstrator Calibration and Array Patterns @408 MHz

- Amplitude & phase equalization during a stationary flight at zenith (100 m height)
- Digital beamforming & beam measurement with a second flight
Reactive Loading Inside the Array

LOFAR LBA central-element @57 MHz

- Mismatched amplifiers can produce distortion in the Embedded-Element-Patterns
- Significant change in LOFAR EM Model

G. Virone, et al. “Strong Mutual Coupling Effects on LOFAR: Modeling and In-Situ Validation”, IEEE TAP, Year: 2018,
LP Filtering – an example over Ant002
Array Pattern

175 MHz Azimuthal Raster - Theta

Array pattern from normalized elements [dB]

POL Y (A channel, NS dipoles)

MEASUREMENT

ARRAY FACTOR

SIMULATION

Equalization at theta~0, phi~30
Array Pattern

175 MHz Azimuthal Raster – Theta and Phi

POL Y (A channel, NS dipoles)

Equalization at theta~0, phi~30
Pre-AAVS0 2D pattern map

2D array beam pattern at 350 MHz produced by an analogue power combiner and flying the UAV on a Cartesian raster scan.
Beamforming

\[ Y = R(\theta, \phi) \sum_{i=1}^{N} w_i e^{-jkr_i} \]

\[ = R(\theta, \phi) AF \]

\[ AF = \sum_{i=1}^{N} w_i e^{-jkr_i} \]

\[ AF = w^T v(k) \]

**Radiation pattern of the single array element**

**ARRAY FACTOR:** is a function of the positions of the antennas in the array and the weights used. By tailoring these parameters the antenna array’s performance may be optimized to achieve desirable properties. For instance, the antenna array can be steered (change the direction of maximum radiation or reception) by changing the weights.

**Steering vector:** the set of phase delays

**Phased array weighting:**

\[ w_n = e^{jn\pi \cos \theta_d} \]

\[ AF = w^T v(k) = \sum_{n=0}^{N-1} e^{jn\pi (\cos \theta_d - \cos \theta)} \]

in order to steer towards \( \theta_d \)