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Measurement of the LOFAR-HBA beam patterns using an 1 **Unmanned Aerial Vehicle in the near-field** 2

3

G. Virone,^{a,*} F. Paonessa,^a L. Ciorba,^a S. Matteoli,^a P. Bolli,^b S. J. Wijnholds,^c G. Addamo^a

4 ^a Consiglio Nazionale delle Ricerche (CNR), Istituto di Elettronica ed Ingegneria dell'Informazione e delle

5 6 7 Telecomunicazioni (IEIIT), Corso Duca degli Abruzzi 24, Turin, Italy, 10129.

^b Istituto Nazionale di Astrofisica (INAF), Osservatorio Astronomico di Arcetri, Largo Enrico Fermi 5, Florence, 8 9 Italy, 50125.

[°] Netherlands Institute for Radio Astronomy (ASTRON), Oude Hoogeveensedijk 4, Dwingeloo, Netherlands, 7991.

10 11

12 Abstract. An Unmanned Aerial Vehicle (UAV) is exploited to characterize in-situ the High Band Antennas (HBAs) 13 of the LOw Frequency ARray (LOFAR) CS302 station located in Exloo, The Netherlands. The size of an HBA array 14 is about 30 m. The Fraunhofer distance (a few kms) is not reachable in the frequency band (120 - 240 MHz) within 15 the flight regulation limits. Therefore, far-field patterns cannot be directly measured. The UAV, equipped with an RF 16 synthesizer and a dipole antenna, flies in the near-field region of the considered array. Measurement of three different 17 frequencies (124, 150, 180 MHz) is efficiently made during the same UAV flight. The near-field focusing method is 18 exploited to validate the far-field pattern of the array under test within an angular range around the beam axis. Such a 19 technique avoids both the time consuming $\lambda/2$ sampling of the aperture field and the further application of 20 computationally heavy near-field to far-field transformations. The array beam is well reconstructed in the main lobe 21 and first sidelobes within a 2D scan plane sampled with a radial raster. A further post-processing technique is proposed 22 and validated on a subarray of HBAs. It suggests efficient ways for the future characterization of regular aperture 23 arrays for SKA-Mid Phase 2.

24

25 Keywords: antenna measurements, unmanned aerial vehicle, near-field focusing, VHF band, large arrays, hybrid 26 beamforming. 27

- 28 *Giuseppe Virone, E-mail: giuseppe.virone@ieiit.cnr.it
- 29

30 Introduction 1

31 The LOw Frequency ARray (LOFAR) [1] is a radio telescope composed of 52 stations located in

- 32 Europe. Each station is composed of two subarrays, one with Low-Band Antennas (LBAs) and
- 33 one with High-Band Antennas (HBAs). Their operating frequency range is 10 - 90 MHz and 120
- 34 - 240 MHz, respectively. LBAs are arranged in a random configuration whereas HBAs are placed
- 35 in a regular lattice.
- 36 LOFAR is a pathfinder for the international Square Kilometre Array (SKA). The SKA will become
- 37 the biggest and most sensitive radio telescope in the world. Aperture arrays are envisioned for both

38 SKA1-Low (50 - 350MHz, random configuration) [2], [3] and possibly SKA1-Mid Phase 2 (400
39 MHz – 1.45 GHz, regular configuration) [4], [5], [6]. Dishes will be adopted for higher frequencies
40 up to 14 GHz.

All these powerful radio telescopes need to be validated and accurately calibrated. Of course, testing these large arrays is not an easy task due to their large size and the low operating frequencies. A few approaches have been proposed exploiting measured data in far or quasi-far field condition. For example, a holographic technique has been applied to the Engineering Development Array 2 of SKA1-LOW [7] and LOFAR [8] to retrieve aperture fields. Other tests on LOFAR have been performed using astronomical calibration sources [9] and RF sources mounted on cranes [10].

48 More recently, thanks to the technological development of Unmanned Aerial Vehicles (UAVs), 49 flying test sources have been developed to test aperture arrays even at element level [11] - [16] 50 with a high signal-to-noise ratio and a huge scan flexibility. Due to the large electrical size of the 51 aperture arrays, the Fraunhofer distance cannot always be reached. Therefore, validation of 52 LOFAR LBA array has been performed comparing measurement and simulation in the near field 53 [17], [18]. All previous papers featured sparse arrays with particular emphasis on the random 54 configuration [19]. In this work, the UAV-based measurement strategy is extended to the LOFAR 55 HBA (Fig. 1) which is a large regular array. Near field focusing [20], [21] is adopted and its 56 validity is assessed by comparison to the far-field simulated data (Section 2). This procedure has 57 been applied on a two-dimensional scan path to provide a more complete characterization (Section 58 3). A first attempt to develop a far-field reconstruction strategy (to overcome the artifacts of the near-field focusing) and the corresponding definition of efficient near-field scan strategies for 59 60 regular arrays such as the aperture arrays for SKA-Mid Phase 2 is presented in Section 4.

- 61 To summarize, the novelty aspects of this paper are:
- 62 1) The verification of all tiles within a single flight over a LOFAR-HBA substation;
- 63 2) The application of near-field focusing to an array of tiles pointed in the same far-field direction
- 64 to provide an end-to-end verification of the system from the antennas to the digitized data;
- 65 3) The usage of radial raster scans to represent the beam pattern in the u-v plane with a limited set
- of linear scans, which is an efficient choice in view of the limited UAV flight duration compared
- 67 to cartesian rasters [11];
- 68 4) The definition of a far-field reconstruction strategy to partially overcome the artifacts of the
- 69 near-field focusing and its validation on a subarray of the HBA substation.





72 array of the CS302 station. The array size is about 30 m.

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74 1.1 UAV-mounted test source and the HBA

The UAV is visible in Fig. 1. It is equipped with a differential Global Navigation Satellite System
(GNSS) receiver for accurate positioning within a few centimeters, a dipole antenna and a RF

synthesizer [13]. Three higher-order harmonics of the RF synthesizer (i.e., it was operating as a comb generator) have been used during the same flight. In this way, three different frequencies (i.e., 124, 150 and 180 MHz) have been measured simultaneously. This procedure is applicable when the receiver acquisition system can simultaneously record many frequency channels to drastically reduce the flight time of the UAV.

82 Fig.1 also shows the Eastern HBA array of the CS302 LOFAR station located in Exloo. The 83 detailed geometry of this LOFAR HBA subarray is shown in Fig. 2. It is composed of 24 square 84 tiles (red numbers from 0 to 23) with a size of about 5 by 5 m². Each tile is composed of a regular 85 distribution of 4 by 4 dual-polarized elements i.e. thin crossed-bowtie dipoles suspended over a 86 ground plane by means of a polystyrene support structure. The dipole length is about 0.7 m. Within 87 each tile, the element spacing is 1.25 m [1]. The distance between tile centers is 5.15 m, therefore, 88 the spacing between elements of adjacent tiles is slightly larger (1.4 m) than within the tile. 89 Nevertheless, the overall distribution can be considered as very close to a uniform regular array. 90 Through the analog beam forming, each tile can be pointed within a field of view of 60 degrees 91 around zenith. Furthermore, signals from all tiles can be summed together by digital beam forming.



Fig. 2 Element positions in the LOFAR HBA subarray. Red and black numbers refer to tile number (0-23) and
element number (0-15) inside the single tile, respectively. The black dashed curve shows an example of a UAV path
(its projection to the ground) oriented along the North-West direction.

The two element polarizations are oriented along the North-West and North-East directions. For the considered CS302 station, the orientation of the regular array distribution is 48° from North (see Fig. 2). Hence, there is a 3° rotation between element polarization directions and array lattice principal directions. Nevertheless, the labels "North-West" and "North-East" will be still adopted in this paper for both polarization and array principal (periodicity) directions for the sake of simplicity.

105 **2** Beam patterns using near-field focusing

106 Several flights with linear trajectories and constant height have been performed. A sketch of a 107 UAV path projected to the ground and oriented North-West is shown in Fig. 2 with the black-108 dashed line. This section presents the results obtained for a flight where both the UAV speed vector 109 and the onboard dipole are oriented North-West. This corresponds to an E-plane scan of the array 110 elements oriented North-West. The UAV flight duration to perform this single linear path was 111 approximately 1 minute (flight speed was about 3 m/s) whereas 2-3 minutes are necessary for take-112 off and landing. The flight height has been maintained at 140 m due to regulation limitations. This 113 already satisfies the far-field condition for each tile (Fraunhofer distance is 60 m at 180 MHz) but 114 is not enough for the full array (about 1.1 km at 180 MHz). This fact is confirmed in Fig. 3, where 115 the measured tile beams (E-plane, 124 MHz) are shown for the tiles closest to the projection of the 116 UAV path (dashed black line in Fig. 2), i.e., tiles 6-11 and 12-17. The effect of UAV pattern and 117 path loss has been removed as in [22]. All beams are reported with respect to the curvilinear 118 abscissa on the UAV path. The origin of the curvilinear abscissa is set where the UAV path 119 projection is closest to the center of the HBA array. The analog beam formers were programmed 120 to point the tile beams at zenith. However, because of the low altitude of the UAV, the maxima of 121 the tile beams occur at different values of the curvilinear abscissa. In particular, the maxima of 122 tiles 11 and 17 occur at about -13 m, whereas the maxima of tiles 6 and 12 occur at +13m. This is 123 consistent with the distance between tile centers of about 26 m. The successful comparison with 124 simulations at tile level was already reported in [23]. In this work, the tile beams are instead used 125 to estimate the full array pattern by means of a near-field focusing method [20]. However, it 126 should be mentioned that, differently from [17], the presence of analog beam-formers at tile level 127 prevents the application of the required parabolic phase shifts across the array aperture i.e., to each

128 array element. Such near-field focusing can only be applied on the tile signals. In other words, the 129 tile beams are pointed to zenith (far-field) whereas the array of tiles will be focused in near-field. 130 All the tile beams in Fig. 3 are normalized in magnitude and phase at the origin of the curvilinear 131 abscissa to produce the near-field focusing for the array of tiles. The parabolic phase shifts for the 132 various tiles are automatically produced by the different electrical distances with respect to the 133 UAV-mounted source placed in the near-field.

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Fig. 3 Normalized E-plane radiation pattern for tiles 6-11 (left) and 12-17 (right) at 124 MHz.

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Fig. 4 Normalization constants (dB) for tiles 6-17 at 124 MHz.

Normalization constants in magnitude are shown in Fig. 4. It is apparent that tile number 10 requires a larger normalization constant with respect to the other tiles to achieve proper equalization. From Fig. 3, it can be also noted that its signal is noisier and the sidelobes are higher with respect to all the other tiles. This can be explained with a fault in the analog beam former of tile 10.



Fig. 5 Far field pattern (black line) and focused near field (blue line) of tiles 6-11 (left panel) and 12-17 (right panel)
at 124 MHz.

150 The equalized (magnitude and phase) signals from the two tile rows 6-11 and 12-17 have been 151 summed together to obtain the radiation patterns at 124 MHz that are shown in Fig. 5 (blue line) 152 as a function of the zenith angle. The zenith angle has been computed using the curvilinear abscissa 153 and the UAV height. A far-field simulation obtained using a combination of WIPL-D and array 154 factor is also shown in Fig. 5 (black solid line with circular markers). WIPL-D has been used on a 155 subarray of 3 by 3 tiles, i.e., 12 by 12 dipoles. This configuration requires neither significant 156 computational effort nor specific acceleration methods. However, it allows to estimate the effect 157 of mutual coupling on the tile beam. Differences between the nine simulated tile beams in the 3 by 158 3 tile array have been found to be negligible with respect to the measured discrepancies [23]. For 159 this reason, an array factor approach has been adopted using the simulated tile beam (central tile 160 within the 3 by 3 array) as element pattern. The agreement is satisfactory within $\pm 15^{\circ}$ from zenith. 161 This is consistent with the near-field focusing method, which guarantees a good agreement 162 between far-field and near-field focused beams only in the proximity of the beam axis [20]. The 163 level of first sidelobes (-13 dB) is consistent with the uniform amplitude excitation. The pattern of 164 the array of tiles 6-11 shows larger discrepancies with respect to simulation because of the faulty 165 tile 10. Almost the same level of agreement has been obtained at 150 and 180 MHz (see Fig. 6, 166 only the array of tiles 12-17 has been reported for brevity). As expected, the angular region with good agreement becomes narrower at higher frequencies ($\pm 10^{\circ}$ from zenith) because the 167 168 Fraunhofer condition increases with frequency and all frequencies were measured during the same 169 flight and, hence, at the same height.



171 Fig. 6 Far field pattern (black line) and focused near field (blue line) of tiles 12-17 at 150 MHz (left) and 180 MHz
172 (right).

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174

175 The same near-field focusing procedure has been applied to the full HBA array in Fig. 2. No further 176 faulty tile has been found besides number 10 (it should be noted that all the tiles in Fig. 2 have 177 been verified in such a single flight). Figs. 7, 8 and 9 show the measured (near-field focused) and 178 the simulated (far-field) radiation patterns at 124, 150 and 180 MHz. The angular region showing 179 good agreement is again ranging from $\pm 15^{\circ}$ to $\pm 10^{\circ}$ at lower and higher frequencies, respectively. 180 The Full Half Power Beamwidths are 5.2°, 3.9° and 3.4° at 124, 150 and 180 MHz, respectively. 181 The low level of the first sidelobes is due to the array geometry. It should be noted that all the tiles 182 in Fig. 2 contribute to the array pattern. The number of tiles along the direction that is orthogonal 183 to the UAV scan i.e. the number of tiles along North-East direction is six in the array center and 184 two at its edges. As far as the North-West cut reported in Figs. 7, 8 and 9 is concerned, this is 185 equivalent (in the far-field) to a linear array with edge tapering, which in turn explains the low 186 sidelobes. This fact can be easily demonstrated by computing the array factor along the North-187 West cut.



189 Fig. 7 Far field pattern (black line) and focused near field (blue line) of tiles 1-24 (full HBA subarray) at 124 MHz.



191 Fig. 8 Far field pattern (black line) and focused near field (blue line) of tiles 1-24 (full HBA subarray) at 150 MHz.



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Fig. 9 Far field pattern (black line) and focused near field (blue line) of tiles 1-24 (full HBA subarray) at 180 MHz.

196 **3** Radial Rasters as an efficient scan strategy

197 The results in section 2 concern a single linear scan performed along the North-West direction. 198 Additional linear scans were performed with an angular offset of 22.5° to achieve a more complete 199 coverage of the u-v plane (directional cosines). All angular steps were performed with two 200 orientations of the UAV-mounted dipole i.e., parallel and orthogonal to the speed vector to sample 201 both the θ - and φ -components of the radiation patterns. Each raster has been split as two flights for 202 each field component i.e. a total of four flights. The duration of each flight has been approximately 203 10 minutes. The full flight duration capability of the UAV has not been exploited due to the severe 204 wind condition observed during the campaign. A larger margin on the battery charge has been

maintained for safety reasons. Longer flight durations up to 40 minutes are now available with
modern UAVs operating in calm wind condition. The measured results for the North-West
polarized elements of tile number 9 (see Fig. 2) are shown in Fig. 10.

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Fig. 10 Measured θ - (left) and φ - (right) components of the radiated pattern in dB of tile 9 at 180 MHz (Elements polarized along North-West, i.e. +135° from u axis).

214 The North-West radiation pattern cut (+135° from u axis) for the (radial) θ - component (on the left 215 panel of Fig. 10) corresponds to the E-plane co-polar pattern for the tile elements polarized along 216 the North-West direction (same cut that is discussed in both section 2 and [23]), where both main 217 lobe and sidelobes are visible. The cut oriented North-East (θ - component, left side of Fig. 10) 218 instead represents a cross-polar H-plane pattern, which is quite low in magnitude as expected. The 219 H-plane co-polar pattern in visible in the right panel of Fig. 10 where the (azimuthal) φ -component 220 is shown. The North-East cut shows again both main lobe and first sidelobes. This is consistent 221 with the square geometry of the tiles.



Fig. 11 Measured (left) an simulated (right) beam patterns in dB for tile 9 at 180 MHz (NorthWest polarized elements).

The power pattern, i.e., the combination of the two orthogonal pattern components in Fig. 10, is shown in Fig. 11 (left). Both E-plane and H-plane are now visible on the same plot as North-West and North-East paths, respectively. The symmetry of the beam, which is due to the square geometry of the tiles is clearly visible. The overall pattern is very consistent to the simulated data on the right of Fig. 11. The main difference is the depth of the nulls, which is mainly related to source orientation errors, modeling errors and of course manufacturing and position uncertainties of the real tile. Manufacturing tolerances are neither calibrated nor corrected for in the analog beamformer.



240 241

Fig. 12 Measured (left) and simulated (right) beam patterns in dB of the HBA array in Fig. 2 at
180 MHz (North-West polarized elements).

The near-field focusing method described in section 2 has been applied to the full HBA shown in Fig. 2. The result is shown in Fig. 12 (left side) and is in good agreement with the simulation (right side). The beam symmetry and width are consistent. Artifacts are still visible in both the North-West and North-East paths. Nevertheless, these results provide a good in-situ validation of the HBA substation.

250 For brevity, we have only presented results for the HBA elements polarized along the North-West

direction. However, similar results have been achieved for the North-East ones.

252 4 Far-field reconstruction

This section presents an alternative strategy to partially overcome the artifacts due to near-field focusing method already discussed in section 2. It is based on the consideration that the performed UAV flights satisfy the far-field condition for the tiles but not for the array of tiles. For the tiles, both amplitude and phase of the acquired signals are available (complex voltages). The amplitude patterns can be easily obtained by geometrical considerations i.e. the amplitude data for each tile (after removal of UAV pattern and path loss, see for example Fig. 3) are expressed as a function of a local reference system centered on the tile itself, instead of the center of the full array. The resulting patterns for tiles 12-17 are shown in Fig. 13. The frequency of 180 MHz has been selected for this example because it represents a worst case for the near-field focusing artifacts.



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Fig. 13 Reconstructed far-field E-plane radiation patterns for tiles 12-17 at 180 MHz:
 magnitude (left) and phase (right). Near field plots are instead shown in Fig. 3.

As far as far-field phase patterns are concerned, their determination is less straightforward because the UAV-mounted RF source is not phase-locked to the on-ground acquisition system of the telescope. In other words, the relative phase between transmitter and receivers is drifting during the flight in an uncontrolled way. For this reason, only differential phase data can be used [24]. In [25], a reference antenna with known phase pattern was placed in the proximity of the SKA-LOW array prototype to reconstruct a near-field phase pattern. In this campaign, no reference antenna was available. Therefore, one of the central tiles (i.e., tile number 15) is used as reference. This, of course, relies on the knowledge of its phase pattern by simulations (see Fig. 13, right side, violet curve). Under this hypothesis, the phase patterns of all other tiles ϕ_i can be computed as

275

$$\phi_i = \phi_i + \varphi_j - \varphi_i + k(r_j - r_i) \tag{1}$$

276 where the time/position dependence of all the terms has been understood, ϕ_i is the phase pattern 277 of the reference tile (*i* =15 in our case), φ_i and φ_i are the phase of the acquired complex voltages, 278 k is the wave number and r_i , r_i are the distances between the UAV-mounted source and the centers 279 of tiles j and i, respectively. It should be mentioned that in (1), the direction dependence of the 280 source pattern has been neglected (it is in the order of a few degrees). Moreover, only the co-polar 281 component is considered (transmitter and receiver are matched in polarization). The relative 282 distances r_i and r_i are computed exploiting the UAV position data measured by GNSS and the 283 knowledge of the tile center positions (nominal data have been used, however, an accurate 284 measurement with ground-based instruments such as total station or GNSS is viable). The resulting 285 reconstructed far-field phase patterns for tiles 12-14 and 16-17 are shown on the right side of 286 Fig. 13. They are quite similar to each other because local reference systems (centered on each 287 tile) have been adopted. Each of them shows narrow anomalies where the phase rotates of 360° 288 around the zenith angle $\pm 20^{\circ}$. These anomalies are due to the two nulls on the pattern of the 289 reference tile. At the nulls, the phase exhibits abrupt variations of 180°. In these regions, the 290 accuracy of the models is generally lower and therefore, a perfect cancellation between the terms 291 ϕ_i and ϕ_i does not occur in (1). A reference antenna with a smoother behaviour would be desirable 292 to avoid such anomalies (this can be implemented by either activating only one dipole within a tile 293 that will be hence used as reference only or exploiting an additional external reference antenna in 294 the proximity of the HBA). Nevertheless, after summation of the tile patterns in Fig. 13, the 295 resulting beam in Fig. 14 (red curve) is more consistent to the far-field simulation (black curve)

296 than the previous near-field focusing data (blue curve). It should be mentioned that, before 297 summation, the tile phase patterns in Fig. 13 have been both converted to the same reference 298 system by exploiting again the knowledge of the tile center positions and equalized at zenith (array 299 calibration). The angular regions where the discrepancies occur are consistent with the position of 300 the reconstructed far-field phase pattern anomalies in Fig. 13. A better agreement has been also 301 achieved at 124 MHz (see Fig. 15) using the same reconstruction method. The overall 302 improvement has been quantified computing the average (along zenith angle) of the weighted logarithmic difference $\Delta_{w,log}$ in [26] with β =0.5 between measurements and simulation. For the 303 304 near-field focusing (blue curve), the quantity $\Delta_{w,log}$ is 0.89 dB and 1.15 dB at 124 and 180 MHz, 305 respectively. A smaller $\Delta_{w,log}$ of 0.68 dB has been achieved for the reconstructed far-field case 306 (red curve) at both frequencies.



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310

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Fig. 15. E-plane radiation pattern for the subarray of tiles 12-17 at 124 MHz.

313 The method presented in this section has only been applied to the linear array of tiles 12-17 which 314 is close to the North-West scan path performed by the UAV (see Fig. 2). The array of tiles 6-11 315 has not been considered because of the faulty tile. The best condition for the presented far-field 316 reconstruction is a scan path that intersects the maxima of the tile beams, whose pointing is set 317 before the flight. Otherwise, the information of the principal cut of the tile radiation pattern is not 318 available. A linear flight parallel to the array lattice direction (almost North-West in this case) will 319 intersect the maximum number of tile beam maxima. According to these considerations, a cartesian

320 raster with 6 x 6 orthogonal linear scans and a spacing of 5.15 m (distance between tile centers) 321 would have allowed the measurements of all the tile patterns in their principal planes and the 322 subsequent reconstruction of the full array far-field pattern along the North-West and North-East 323 planes by using the method presented in this section. It should be noted that a raster that is suitable 324 for a near-field to far-field transformation would have required a spacing of less than $\lambda/2$ i.e., 0.8 m 325 at 180 MHz, with a strong impact on the UAV flight time requirement. Moreover, a 326 computationally heavy inversion algorithm must be applied [27] to transform the scan paths 327 performed by UAV in the near-field. The presented solution, together with the exploitation of a 328 smoother and well-known reference antenna could be considered for the characterization of the 329 regular arrays of SKA-mid.

330

331 5 Conclusion and future developments

The application of near-field focusing to an array of LOFAR-HBA tiles pointed in the same farfield direction demonstrated that a useful end-to-end system validation can be performed even considering only a limited angular range around the beam axis. Simulated and measured results are in good agreement as far as beamwidth and first sidelobes are concerned. The method also pointed out the presence of a faulty tile in the Eastern HBA subarray of the CS302 station.

The combination of a few linear scans with different orientations has been performed to achieve a radial raster. This procedure confirmed the agreement between measurements and simulations on the full u-v plane, although with limited coverage. The angular step of 22.5° could be reduced at the expense of a longer flight/scan duration.

A far-field reconstruction method has been proposed and validated on a linear subarray of the HBA
 substation. It allows to partially overcome the artifacts of the near-field focusing strategy

exploiting the usage of a known reference antenna and the knowledge of the tile positions. This suggests a validation procedure for regular aperture arrays such as SKA-mid that is based on a cartesian raster in the near-field with a spacing that is equal to the tile spacing, which is several times larger than $\lambda/2$. This efficient scan strategy will provide far-field pattern information on the principal planes only, which could already be satisfactory as far as validating stations in-situ is concerned.

349

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433 Giuseppe Virone was born in Turin, Italy, in 1977. He received the degree in electronic 434 engineering (summa cum laude) and the Ph.D. degree in electronics and communication 435 Engineering from the Politecnico di Torino, Italy, in November 2001 and 2006, respectively. He 436 is currently a Senior Researcher at the Istituto di Elettronica e di Ingegneria Informatica e delle 437 Telecomunicazioni (IEIIT), Italian National Research Council (CNR). He joined IEIIT as a 438 Research Assistant in 2002. He coordinated more than 15 scientific projects funded by both the 439 industry and other scientific research organizations and joined more than 30 research projects as a 440 collaborator. He authored 43 journal papers, 134 conference papers, and 3 European patents. His

441 activities concern the design, numerical analysis, and characterization of microwave and
442 millimeter waveguide passive components for feed systems, antenna arrays, frequency selective
443 surfaces, compensated dielectric radomes, and industrial sensing applications.

444 Fabio Paonessa was born in Turin, Italy, in 1985. He received the BS and the MS degrees in 445 biomedical engineering and the PhD degree in electronics engineering from the Polytechnic of 446 Turin, in 2008, 2010, and 2017, respectively. From 2011 to 2012, he was a Research Assistant 447 with the Department of Electronics, Polytechnic of Turin. In 2013, he joined the Applied 448 Electromagnetics Group of the Institute of Electronics, Computer and Telecommunication 449 Engineering (IEIIT), Italian National Research Council (CNR). He became Researcher in 2018. 450 His activities include the scientific applications of the unmanned aerial vehicles for the 451 characterization of antenna arrays and radar systems and wireless sensor networks related 452 applications.

Lorenzo Ciorba was born in Avezzano, Italy, in 1993. He received the master's degree (110/110) 453 454 in mathematical engineering from Politecnico di Torino, Italy, in March 2018, with the thesis 455 "Hybrid Antenna Measurement and Simulations" with Prof. G. Vecchi as a supervisor. In June 456 2018, he joined the Applied Electromagnetics and Electronic Devices Group of the Institute of 457 Electronics, Computer and Telecommunication Engineering (IEIIT), Italian National Research 458 Council (CNR), as a Research Fellow. From November 2018, he has been a Ph.D. student in 459 electrical, electronics and Communications Engineering at Politecnico di Torino. His scientific 460 interests regard computational electromagnetics and characterization of antennas, in particular 461 UAV-based near field antenna measurements.

462 Stefania Matteoli received her B.S. and M.S. (cum laude) degrees in Telecommunications
463 Engineering and the Ph.D. in "Remote Sensing" from University of Pisa, Italy, in 2003, 2006, and

464 2010 respectively. She is currently a permanent researcher at the National Research Council of 465 Italy within the Institute of Electronics, Computers and Telecommunication Engineering. From 466 January 2010 to December 2016 she was first a post-doctoral fellow and then a temporary 467 researcher with the Department of Information Engineering, University of Pisa, Italy. From May 468 2008 to October 2008, she was a visiting student at the Chester F. Carlson Center for Imaging 469 Science, Rochester Institute of Technology, Rochester, New York. She is Associate Editor of the 470 IEEE GEOSCIENCE AND REMOTE SENSING LETTERS and of the SPIE Journal of Applied 471 Remote Sensing. Her main research interests include signal and image processing applied to 472 various remote sensing applications and to antenna array data processing.

473 Pietro Bolli received the Laurea degree in electronic engineering and the Ph.D. degree in computer 474 science and telecommunications engineering from the University of Florence, Italy, in 1999 and 475 2003, respectively. In 2002, he started his professional career as a Microwave Engineer at the 476 Italian National Institute for Astrophysics (INAF) conducting research in the field of technology 477 applied to radio astronomy. He is currently Senior Technologist at the INAF Arcetri Astrophysical 478 Observatory, where he is involved in the design, characterization, and calibration of the low 479 frequency instrument of the Square Kilometer Array. P. Bolli is the Italian responsible for the 480 protection of the frequency bands used by radio astronomers and represents INAF in the 481 Committee on Radio Astronomy Frequencies (CRAF). He is also Officer of the Commission J 482 (Radio Astronomy) of the Italian Committee of the Union Radio Scientifique Internationale 483 (URSI). He is co-author of about 140 scientific publications, which have appeared in international 484 referred journals and conferences. 485 Stefan J. Wijnholds received the M.Sc. degree in astronomy and the M.Eng. degree in applied 486 physics (both cum laude) from the University of Groningen, The Netherlands, in 2003, and the

487	Ph.D. degree (cum laude) from Delft University of Technology, Delft, The Netherlands, in 2010.
488	After his graduation in 2003, he joined the R&D Department of ASTRON, the Netherlands
489	Institute for Radio Astronomy, Dwingeloo, The Netherlands, where he works on the development
490	of the next generation of radio telescopes based on phased array technology. From 2006 to 2010,
491	he was also affiliated with the Delft University of Technology, Delft, The Netherlands. Since 2016,
492	he is affiliated with the Electrical and Electronic Engineering Department of the University of
493	Stellenbosch, South Africa, as Extraordinary (Associate) Professor. In 2018, he became a Senior
494	Researcher at ASTRON overseeing work on the institutional technology development roadmap to
495	address the Big Data challenges posed by large phased array systems. His research interests lie in
496	the area of array signal processing, specifically calibration and imaging, and system design of the
497	next generation of radio telescopes.
498	
499	Biographies and photographs for the other authors are not available.
500 501 502 503	
504 505	Caption List
506	Fig. 1 The UAV after take-off is reaching the first waypoint to perform the required scan path over
507	the LOFAR Eastern HBA array of the CS302 station. The array dimension is about 30 m.
508	Fig. 2 Element positions in LOFAR HBA subarray. Red and black numbers refer to tile number
509	(0-23) and element number (0-15) inside the single tile, respectively. The black dashed curve
510	shows an example of a UAV path (its projection to the ground) oriented along the North-West
511	direction.
512	Fig. 3 Normalized E-plane radiation pattern for tiles 6-11 (left) and 12-17 (right) at 124 MHz.

- 513 **Fig. 4** Normalization constants (dB) for tiles 6-17 at 124 MHz.
- 514 Fig. 5 Far field pattern (black line) and focused near field (blue line) of tiles 6-11 (left figure) and
- 515 12-17 (right figure) at 124 MHz.
- 516 Fig. 6 Far field pattern (black line) and focused near field (blue line) of tiles 12-17 at 150 MHz
- 517 (left) and 180 MHz (right).
- 518 Fig. 7 Far field pattern (black line) and focused near field (blue line) of tiles 1-24 (full HBA
 519 subarray) at 124 MHz.
- Fig. 8 Far field pattern (black line) and focused near field (blue line) of tiles 1-24 (full HBA
 subarray) at 150 MHz.
- Fig. 9 Far field pattern (black line) and focused near field (blue line) of tiles 1-24 (full HBA
 subarray) at 180 MHz.
- 524 Fig. 10 Measured θ (left) and φ (right) components of the radiated pattern of tile 9 at 180 MHz

525 (North-West polarized elements).

- Fig. 11 Measured (left) an simulated (right) beam patterns for tile 9 at 180 MHz (North-West
 polarized elements).
- 528 Fig. 12 Measured (left) an simulated (right) beam patterns of the HBA array in Fig. 2 at 180 MHz
- 529 (North-West polarized elements).
- Fig. 13 E-plane radiation patterns for tiles 12-17 at 180 MHz: magnitude (left) and phase (right).
- 532 **Fig. 14.** E-plane radiation pattern for tiles 12-17 at 180 MHz.
- 533 Fig. 15. E-plane radiation pattern for tiles 12-17 at 124 MHz.