

UAV-Enabled Outdoor OTA Validation Platform for 28 GHz Phased-Array Beamforming Antennas

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Abstract—This paper presents a UAV-enabled outdoor over-the-air antenna pattern measurement system operating at 28 GHz. A directional horn antenna mounted on an unmanned aerial vehicle acts as the transmitter, while a ground-based phased-array receiver performs electronic beam scanning. The proposed approach reduces dependence on large anechoic chambers and mechanical positioning systems, enabling practical millimeter-wave antenna characterization in realistic outdoor environments. Although UAV-assisted antenna measurements have been previously investigated, their application to electronically steerable 28 GHz phased-array beam characterization remains largely unexplored. A fully automated measurement platform is developed using MATLAB-based control software for synchronized beam steering, data acquisition, and data processing. Experimental measurements are conducted under real flight conditions, including UAV motion and wind-induced disturbances, and are validated against laboratory reference measurements. The results show good agreement between the UAV-based and reference antenna patterns, demonstrating the feasibility of reliable outdoor phased-array characterization. The proposed system provides a low-cost, portable, and scalable alternative to conventional antenna measurement facilities and offers a practical framework for future beamforming evaluation and sixth-generation aerial communication testing.

Index Terms—mmWave, UAV, phased array, beamforming, antenna measurement, 28 GHz, OTA measurement, TMYTEK, drone-assisted characterization

I. INTRODUCTION

Millimeter-wave (mmWave) communication systems operating at 28 GHz are among the key enabling technologies for beyond-5G and future 6G wireless networks because of their capability to support high data rates and highly directional beamforming [1], [2], [3], [4]. The large available bandwidth at mmWave frequencies enables multi-gigabit wireless links, while phased-array beamforming compensates for severe propagation losses through directional transmission and reception. UAV-based antenna measurement techniques have also emerged as a promising approach for flexible and cost-effective antenna characterization, particularly for far-

field pattern measurements under realistic operating conditions [5]. Recent advances in massive MIMO architectures, phased-array antenna modules, and over-the-air (OTA) beamforming systems have further accelerated the deployment of practical mmWave communication platforms for 5G and emerging 6G applications [6]–[10].

Antenna characterization at mmWave frequencies is challenging due to large free-space propagation losses, strict alignment requirements, and far-field measurement constraints. Traditional antenna measurements are commonly performed inside anechoic chambers using mechanical positioners and rotating platforms. Although accurate, these systems are expensive, time-consuming, and difficult to scale for large phased arrays and realistic deployment scenarios [4]. Furthermore, conventional chamber-based measurements may not accurately capture real outdoor propagation conditions and beam dynamics encountered in practical wireless deployments [11], [12].

Recently, UAV-assisted antenna measurements have emerged as a promising approach for flexible and cost-effective antenna characterization. Existing studies have demonstrated UAV-based beam-pattern measurements, air-to-ground channel sounding, and phased-array validation at mmWave frequencies [1], [2], [5], [13], [14]. However, most reported works exhibit several limitations. Some primarily focus on propagation channel characterization rather than direct phased-array antenna pattern measurements [2], [3], while others rely on controlled measurement environments, mechanical scanning mechanisms, or simplified validation scenarios that do not fully represent realistic outdoor operating conditions [1], [5]. Furthermore, the integration of commercial electronically steerable phased-array systems within fully automated UAV-assisted over-the-air (OTA) measurement platforms remains relatively unexplored.

In parallel, several studies have investigated 28 GHz phased-array antennas and beamforming systems for 5G applications [7], [8], [15]. Although these works demonstrate advanced

beam-steering capabilities and antenna architectures, their experimental validation is generally conducted in laboratory environments, compact antenna test ranges, or conventional chamber-based setups, which require significant infrastructure and may not accurately capture practical outdoor deployment conditions.

Early work by Virone et al. [16] demonstrated the feasibility of UAV-assisted antenna pattern verification using a micro unmanned aerial vehicle (UAV) carrying a measurement probe. Their system enabled outdoor radiation pattern measurements of conventional antennas and established the viability of replacing fixed measurement towers with mobile aerial platforms. However, the study primarily focused on low-frequency antenna characterization based on mechanical spatial sampling and did not address millimeter-wave (mmWave) frequencies, phased-array beamforming systems, or electronically steerable antennas.

Subsequent research has further investigated the capabilities and limitations of drone-based antenna measurements. In particular, Culotta-López et al. [17] analyzed the principal uncertainty sources affecting UAV-assisted outdoor far-field antenna measurements, including positioning errors, platform attitude variations, and mechanical instabilities. Their work highlighted the practical challenges associated with achieving high measurement accuracy in realistic flight environments and emphasized the importance of uncertainty assessment in drone-based antenna testing.

In parallel, the commercial company QuadSAT has demonstrated drone-based antenna testing services for large satellite communication ground stations, including measurement campaigns on ESA's Estrack antennas in Kiruna, Sweden. These demonstrations validated the feasibility of UAV-assisted characterization of large reflector antennas and tracking systems, highlighting the growing industrial adoption of drone-based antenna measurement technologies [18]. However, these efforts primarily focus on large satellite reflector antennas, whereas UAV-based characterization of electronically steerable mmWave phased-array systems remains significantly less explored.

As mmWave phased-array systems continue to evolve for beyond-5G and 6G applications, there is a growing need for compact and cost-effective antenna measurement solutions. This proposed work extends the state of the art by combining UAV-assisted measurements with a commercial 28 GHz electronically steerable phased-array beamformer capable of fully electronic beam scanning. Unlike previous studies focusing on conventional antennas or measurement uncertainty analysis, the proposed platform enables practical over-the-air (OTA) characterization of mmWave phased-array beamforming systems under realistic outdoor flight conditions. Furthermore, the measured antenna patterns are quantitatively validated against laboratory reference measurements using RMSE, maximum absolute error, correlation coefficient, and beamwidth error metrics. This approach mostly rules out the need for large anechoic chambers and mechanical scanning infrastructure while providing a scalable framework for 5G and future 6G

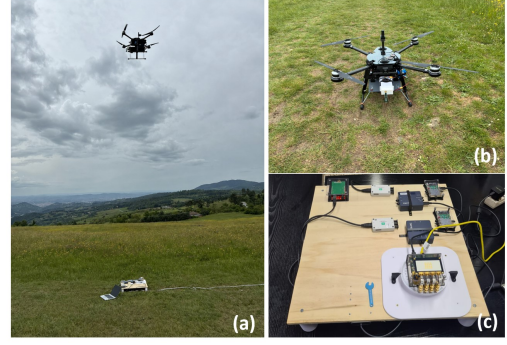


Fig. 1. (a) Snapshot of the Airolit UAV in flying mode carrying the 28 GHz horn antenna transmitter during real-time outdoor OTA measurements; (b) The Tx system mounted on the drone; (c) The snapshot of Rx system.

beamforming antenna characterization.

II. MEASUREMENT SYSTEM AND EXPERIMENTAL SETUP

A. UAV Platform

The experimental setup employs an Airolit Explorian XLT multirotor UAV which is specially developed to handle heavy payloads and powerful sensors, carried the 28GHz transmitter system.

The UAV-mounted transmitter consists of:

- 28 GHz Horn antenna with Gain: 16 dBi & Beamwidth: 26.9°
- RF transmitter front-end including signal source TMYTEK PLO 28 GHz (Model: MF50-TV02-C) and RF Amplifier with 17 dB gain (Model: AMP-WA-2040-BEK28, Amplifier draws 12 V from onboard battery of the UAV)
- Lightweight onboard power supply
- Mounting encasing manufactured in the laboratory using 3D printer

Fig. 1(b) shows the experimental UAV platform used during the outdoor measurements.

B. Receiver System

The receiver consists of TMYTEK equipment, viz. BBoard 5G Lite phased-array beamformer (Model: BB-BOARD-BPB0B-28) operating at 28 GHz along with a 4 x 4 element Phased Array Antenna & Power Detector (Model: COMP-PD-0040-BEK28) controlled by MATLAB programming. Fig. 1(c) shows the receiver setup.

The phased-array receiver characteristics are the following:

- Receiver gain: 15 dBi
- Beamwidth: 30°
- Electronic beam steering capability
- Multi-channel phase control

Beam steering is achieved through phase progression across the array elements according to:

$$\Delta\phi = \frac{360^\circ d \sin(\theta_s)}{\lambda} \quad (1)$$

where:

- $\Delta\phi$ is the inter-element phase increment (degrees)
- d is the spacing between adjacent antenna elements
- λ is the wavelength
- θ_s is the beam steering angle

The TMYTEK BBoard phase shifter provides a phase resolution of 5.625° . This corresponds to a minimum beam steering increment of approximately 2° near broadside. The TMYTEK beamformer has an angular scanning capability of -45° to $+45^\circ$. Accordingly, the measurements were limited to a steering range of -30° to $+30^\circ$ with 2° resolution, balancing angular coverage with measurement duration to mitigate the effects of UAV motion and hovering instability.

III. MEASUREMENT METHODOLOGY

The UAV continuously transmits a 28 GHz signal while a ground-based phased-array receiver electronically scans different beam directions and records the received power. MATLAB-based software, interfaced with the TMYTEK control platform through Python scripts, enables automated beam steering, data acquisition, and processing. Unlike conventional chamber-based measurements that rely on mechanical rotation, the proposed system performs outdoor over-the-air (OTA) measurements using fully electronic beam scanning. A transmitter–receiver separation of 5 m is used, which satisfies the far-field requirements of the considered 28 GHz system.

The measurement system consists of a 16 dBi horn antenna mounted on an Airolit UAV as the transmitter and a TMYTEK BBoard 5G Lite phased-array receiver operating at 28 GHz (See Fig. 1(a)). The receiver provides approximately 15 dBi gain and a beamwidth of about 30° , enabling fully electronic beam scanning. The relatively broad beam response improves robustness against UAV motion and environmental disturbances, allowing reliable pattern measurements under practical operating conditions.

During the experiments, the UAV hovered approximately 5 m above ground in the presence of wind and air turbulence, resulting in platform motion and orientation variations. Despite these disturbances, stable antenna radiation pattern measurements were successfully obtained, demonstrating the robustness and practicality of the proposed UAV-based measurement approach.

IV. EXPERIMENTAL RESULTS

A. Measured Radiation Patterns

Fig. 2 compares the laboratory reference antenna pattern with the raw and 5-point smoothed UAV-based outdoor over-the-air (OTA) measurement results at 28 GHz. Both the laboratory reference measurements and the UAV-based outdoor measurements were conducted with an approximate transmitter-to-receiver separation distance of 5 m. Two datasets were acquired during the flight campaign to evaluate the phased-array beam-steering performance under different angular coverage conditions. Dataset 1 covers a steering range of -20° to $+20^\circ$, providing improved measurement stability around boresight, whereas Dataset 2 extends the steering range to

-30° to $+30^\circ$ to characterize the antenna response over a wider angular range.

The measured E-plane co-polarized radiation patterns exhibit good agreement with the laboratory reference, particularly within the main-lobe region. A slight displacement of the peak received power from the nominal boresight direction (0°) is observed in both datasets, which is attributed to antenna alignment tolerances, UAV positional drift, orientation errors, and residual phase and amplitude mismatches in the phased-array beamformer. Application of a 5-point smoothing filter effectively suppresses short-term measurement fluctuations while preserving the overall radiation pattern, resulting in closer agreement with the laboratory reference.

Compared with Dataset 1, Dataset 2 exhibits larger deviations at wider steering angles, particularly beyond approximately $+10^\circ$. These discrepancies are mainly caused by reduced array gain, lower received signal levels, increased sensitivity to alignment errors, and beam distortion associated with large scan angles. Furthermore, wind-induced UAV motion introduced roll, pitch, and yaw variations during hovering, resulting in short-term fluctuations in the measured received power and occasional antenna misalignment.

Moreover, portions of the UAV body and supporting structure intermittently entered the receiver antenna scanning region, particularly at positive steering angles. This introduced additional attenuation and localized distortion in the measured radiation patterns, leading to observable degradation in both the raw and smoothed outdoor measurement results. These effects highlight the practical challenges associated with real-flight mmWave OTA antenna characterization under realistic outdoor operating conditions.

TABLE I
QUANTITATIVE COMPARISON BETWEEN UAV MEASUREMENTS AND
LABORATORY REFERENCE

Metric	Dataset 1	Dataset 2
RMSE (dB)	5.32	4.74
MaxAE (dB)	7.59	10.88
Correlation Coefficient (R)	0.91	0.87
Peak Error (dB)	5.84	6.19
Peak Offset ($^\circ$)	-2	2
3-dB Beamwidth Error ($^\circ$)	2.1	3.5

Table I summarizes the quantitative agreement between the UAV-based OTA measurements and the laboratory reference pattern. Dataset 1, measured over the reduced steering range of -20° to $+20^\circ$, achieves an RMSE of 5.32 dB and a correlation coefficient of 0.91, indicating strong agreement with the laboratory reference despite measurement uncertainties arising from UAV motion and antenna alignment. Dataset 2 extends the steering range to -30° to $+30^\circ$ and achieves an RMSE of 4.74 dB with a correlation coefficient of 0.87. Although Dataset 2 covers a wider angular region, its lower correlation coefficient reflects increased pattern distortion at larger steering angles, where reduced received signal levels and increased sensitivity to alignment errors become more

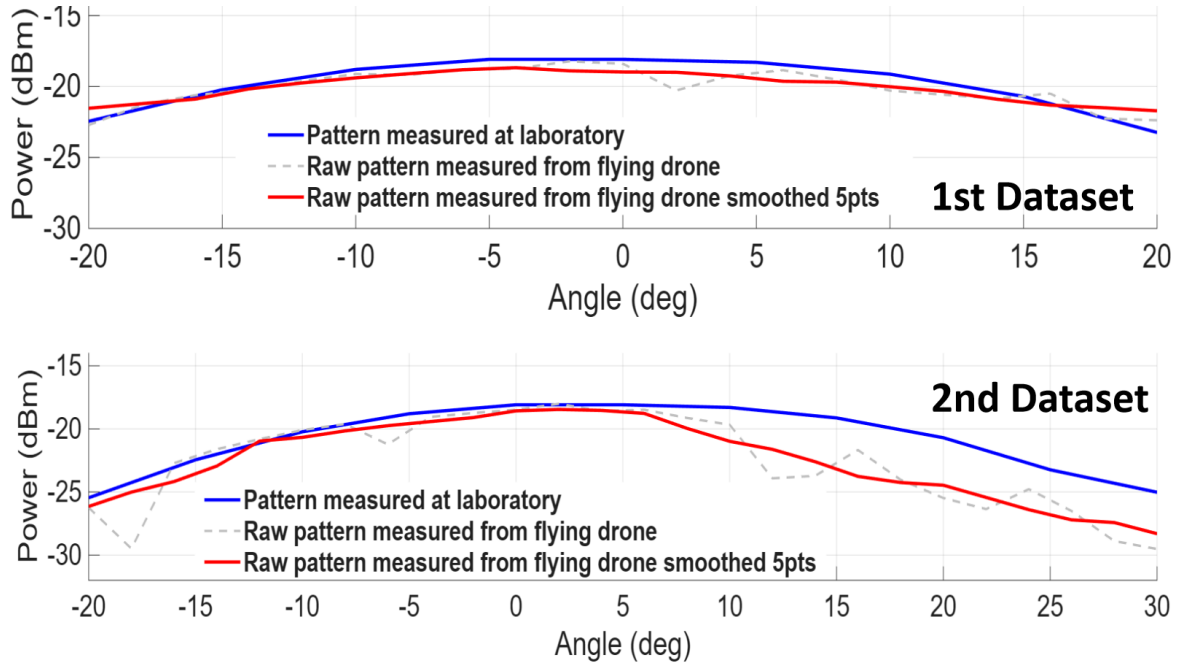


Fig. 2. Comparison between laboratory reference antenna patterns and UAV-based outdoor OTA measurements at 28 GHz.

significant.

The maximum absolute error (MaxAE) represents localized worst-case deviations between the measured and reference patterns and is primarily associated with transient UAV attitude variations, wind-induced motion, and occasional antenna misalignment during hovering. The measured 3-dB beamwidth errors remain relatively small for both datasets, confirming that the proposed measurement system accurately preserves the main-lobe characteristics of the phased-array antenna despite the challenging outdoor environment. The 3-dB beamwidths of the measured patterns were evaluated with respect to the corresponding laboratory reference, and the resulting beamwidth errors are reported in Table I. Overall, the quantitative metrics demonstrate that the proposed UAV-assisted OTA measurement platform can reliably characterize 28 GHz phased-array radiation patterns under realistic outdoor flight conditions.

It should also be noted that the measurements were conducted under outdoor conditions with wind speeds reaching approximately 20 mph, introducing substantial UAV motion and orientation fluctuations throughout the measurement campaign. Nevertheless, the relatively broad beamwidth of the phased-array receiver reduces sensitivity to short-term UAV motion, enabling reliable radiation pattern measurements without requiring complex mechanical stabilization systems.

B. Drone Flight Trajectory

The UAV flight trajectory recorded during the measurements is shown in Fig. 3.

The trajectory plot illustrates the actual UAV motion during the outdoor measurement campaign under realistic flight conditions. The dense concentration of latitude and longitude

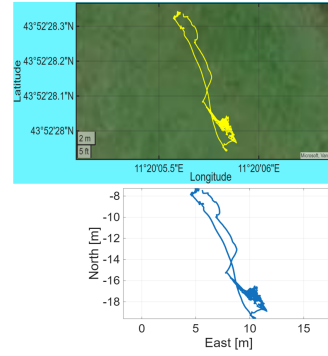


Fig. 3. Recorded UAV flight trajectory during the outdoor measurement campaign.

points visible in the central region of Fig. 3 corresponds to the hovering region where the UAV remained approximately stationary during antenna pattern measurements. This dense cluster indicates the measurement location where beam scanning and received power acquisition were continuously performed.

The elongated trajectory paths extending toward and away from the dense hovering region represent the UAV travel path during takeoff, approach, and return flight between the receiver setup location and the designated hovering measurement position.

V. DISCUSSION

Compared with existing UAV-assisted mmWave antenna measurement approaches summarized in Table II, the proposed system offers a practical framework for phased-array OTA

TABLE II
COMPARISON WITH EXISTING UAV-BASED MMWAVE MEASUREMENT WORKS

Feature	Traditional Chamber	Existing UAV Works	Proposed Work
Measurement Environment	Indoor laboratory/chamber measurements [11], [14], [15]	Outdoor UAV-based antenna measurements [1], [16]–[18]	Real outdoor OTA measurements under flight conditions
Scanning Method	Mechanical positioners and turntables [11]	Mechanical UAV trajectory scanning [16], [17]	Fully electronic beam steering with phased-array receiver
Frequency Range	Sub-6 GHz and mmWave [11], [15]	Primarily sub-6 GHz to mmWave [1], [2], [16]	28 GHz mmWave
Transmitter Platform	Static antenna setup	UAV-mounted antenna systems [1], [2], [16], [18]	Airolit UAV-mounted horn antenna
Receiver Architecture	Horn antennas and chamber receivers [4], [11]	Conventional antenna receivers [16], [17]	TMYTEK phased-array receiver
Commercial Phased Array Usage	Limited [3], [6]	Rarely reported [1]	TMYTEK BBoard 5G Lite phased-array platform
Beam Steering Technique	Mechanical steering	Mechanical or trajectory-based scanning [16], [17]	Real-time electronic beam steering
28 GHz Phased-Array Measurements	Laboratory-based measurements [4], [11]–[14]	Not demonstrated	Fully demonstrated outdoors
Real Flight Validation	Not applicable	Yes [17], [18]	Yes, including wind-induced disturbances
Outdoor Beamforming Characterization	Rare	Limited [1], [17], [18]	Fully demonstrated for phased-array beams
Automated Measurement Control	Laboratory automation [11], [12]	Partially automated [17]	Fully automated MATLAB-based control and data acquisition
Measurement Cost	High	Medium	Low-cost deployment
Anechoic Chamber Requirement	Required	Partially required or used for validation [16], [17]	Not required
Main Contribution	High-accuracy laboratory antenna testing	UAV-based antenna verification and propagation studies [1], [16]–[18]	Practical outdoor OTA characterization of a commercial 28 GHz phased-array antenna using UAV-assisted measurements

characterization under realistic flight conditions. Unlike conventional anechoic chamber measurements that require controlled environments and mechanical positioning systems, the proposed approach utilizes a commercial TMYTEK phased-array antenna and beamformer with fully electronic beam steering capability mounted on a UAV platform, enabling low-cost and flexible outdoor measurements.

The main novelties of the proposed system are summarized as follows:

- UAV-assisted OTA characterization of a 28-GHz phased-array antenna under real-flight conditions.
- Fully electronic beam scanning without mechanical antenna rotation.
- Integration of a commercial TMYTEK beamformer for practical phased-array evaluation.
- Low-cost and compact measurement framework suitable for outdoor deployment.
- Experimental validation at a 5 m measurement distance under wind-induced UAV motion and alignment disturbances.

VI. CONCLUSION

Compared with conventional chamber-based characterization, the proposed UAV-assisted platform provides a portable and low-cost approach for outdoor OTA evaluation while maintaining good agreement with laboratory reference patterns. The proposed methodology can be extended to advanced applications, including 3D radiation pattern mapping, massive MIMO antenna characterization, dynamic beam-tracking evaluation, and AI-assisted beam optimization. These capabilities

make the framework a promising platform for future beyond-5G and 6G aerial communication systems requiring efficient OTA characterization of highly directional beamforming antennas.

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