

Numerical Assessment of Quiet-Zone Formation in a Phantom-Free BAN-OTA Fading Emulator Using Vivaldi Scatterer Antennas

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Abstract—Body-area-network (BAN) radio links degrade through several mechanisms that ordinary free-space antenna measurement does not capture, including body shadowing, Rayleigh fading, antenna–body coupling, and polarization mismatch, which act simultaneously. The conventional over-the-air (OTA) approach places a large saline-filled phantom inside a fading emulator. The phantom, however, occupies much of the test region, pushes the device under test (DUT) away from the uniform-field zone, and makes large or multiple antennas difficult to evaluate fairly. This paper numerically assesses whether a phantom-free BAN-OTA emulator can still form a reliable quiet zone, with human-body shadowing to be emulated subsequently by per-scatterer power control using variable attenuators. The field of each surrounding scatterer is reconstructed from its complex far-field directivity, and the contributions are coherently superposed under controlled excitation phases to synthesize the fading field in the emulator. A quiet zone is defined as the region where the envelope follows the Rayleigh distribution and the average received power stays within 1 dB of the center value. Using this criterion, conventional half-wavelength dipole scatterers are compared with wideband Vivaldi scatterers, and the effect of the cross-polarization power ratio (XPR) on the quiet zone is examined. The results provide a design basis for a Vivaldi-based BAN-OTA emulator that requires no large phantom inside the quiet zone.

Index Terms—Body area network, over-the-air testing, fading emulator, quiet zone, Vivaldi antenna, Rayleigh fading, XPR, electric-field reconstruction.

I. INTRODUCTION

BAN systems assume wireless links between devices close to the human body, and thus their link quality is not set by free-space antenna properties alone. In a mobile setting, a body-worn terminal faces several impairments at once: shadowing by the body, Rayleigh fading from multipath, antenna–body coupling, and polarization mismatch as the body moves and the antenna rotates. Because these act together, a BAN antenna is harder to evaluate than it is in a conventional free-space radiation-pattern measurement carried out in a traditional anechoic chamber.

To test BAN antennas under more practical use scenarios, fading emulators with saline-filled dynamic phantoms have been studied, in which surrounding scatterer antennas create a multipath field while a saline-filled dynamic phantom reproduces the dynamic shadowing and electromagnetic interaction of the human body. Building on a spatial fading emulator based

on Clarke’s model [1] and an arm-swinging dynamic phantom [2], later work combined the two for BAN-OTA testing [3] and used attenuators to set the direct-to-scattered ratio for a target Rice channel [4], while BER and MIMO-OTA assessment confirmed the large joint effect of shadowing, polarization mismatch, and fading on BAN link quality [5], [6].

The same spatial-fading idea underlies the multi-probe anechoic chamber (MPAC) method standardized for MIMO OTA conformance testing, where a ring of probe antennas driven by a fading emulator reproduces a target channel around the DUT [7], [8]. A central question there is the quiet zone, the region near the emulator center over which the synthesized field stays close to the target. Its size is set mainly by the number of probes and the field-synthesis method, as quantified for spatial correlation and probe count [9], [10] and for a reduced chamber radius [11]. The present study applies the same quiet-zone reasoning to a phantom-free BAN emulator, in which the surrounding elements act as scatterers rather than plane-wave probes.

A conventional phantom-based OTA configuration, however, has practical limits as a general platform. A large saline-filled phantom occupies much of the emulator and, unless small relative to the OTA radius, pushes the DUT off the central quiet zone. Therefore, a measured difference between antennas can reflect the spatial nonuniformity of the emulator rather than the antennas. This worsens for MIMO or physically large antenna arrays used in human vicinity, whose aperture then falls partly outside the uniform-field region [12]. Filling and moving a saline-filled phantom near OTA instruments is also cumbersome, and the positioning and assembly involved can introduce unexpected measurement errors.

The present work is motivated by such a phantom-free emulator, in which the body shadowing is carried by the scattered waves themselves through per-scatterer variable attenuators. This keeps shadowing and polarization mismatch separate: the shadowing is treated as time-varying scatterer power, while the polarization mismatch is left to the orientation and polarization response of the DUT. Thus, the body shadowing tolerance of an antenna and its polarization robustness are not conflated into a single attenuation. As a preliminary study, this paper addresses a requirement for such an emulator: whether the scatterer antennas can, on their own, form a reliable quiet zone.

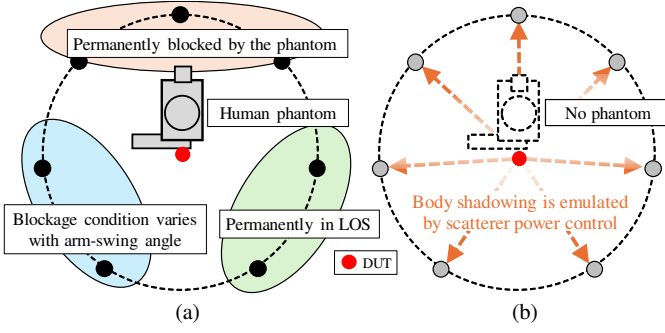


Fig. 1. Comparison of BAN-OTA emulator setups. (a) Conventional configuration, in which a large saline-filled phantom is placed inside the fading emulator and displaces the DUT from the central quiet zone. (b) Proposed phantom-free configuration under development, in which human-body shadowing is emulated by scatterer power control using variable attenuators, allowing the DUT to remain at the center of the quiet zone.

Prior to building the full OTA system, the dependence of the quiet-zone size on the scatterer directivity, frequency, XPR, and excitation phases is examined.

II. PROPOSED PHANTOM-FREE BAN-OTA CONCEPT

A. Limitations of Phantom-Included Evaluation

Figure 1 contrasts the two concepts. In the conventional measurement of Fig. 1(a), a saline-filled phantom inside the emulator reproduces the physical shadowing of the human body, but when it is large relative to the OTA radius, it displaces the DUT from the central quiet zone, where the average power and phase are nonuniform. Therefore, a measured difference between antennas then includes the spatial nonuniformity of the emulator.

In the proposed layout of Fig. 1(b), the phantom leaves the quiet zone and the time-varying shadowing loss is moved into the scatterer paths through variable attenuators, making measurements more repeatable and freeing the center for a DUT such as a MIMO or physically large antenna.

B. Role of Vivaldi Scatterer Antennas

The scatterer antenna determines the usable bandwidth of the emulator. BAN terminals span several bands from a few hundred megahertz to the microwave range, and a wideband scatterer is therefore desirable. A resonant half-wavelength dipole radiates efficiently only near its design frequency and would have to be rebuilt for each band. In this study, a Vivaldi antenna was used as the scatterer antenna. It is a planar tapered-slot element whose slot widens along an exponential profile, narrow at the feed and opening toward the aperture, and therefore has no single resonant length. The wave radiates progressively as the local slot width approaches half a wavelength, giving an end-fire beam over a wide band [13], [14], as shown in Fig. 2. Two such elements placed orthogonally provide the dual-polarization control needed to set the XPR, and the lower single-element gain is equalized by the variable attenuators.

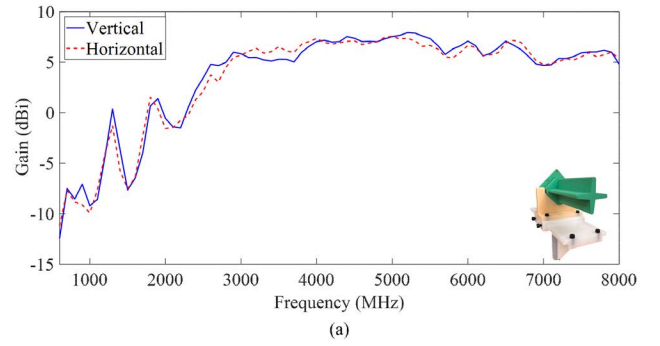


Fig. 2. Gain of the Vivaldi scatterer antenna in the vertical and horizontal polarizations as a function of frequency. The element maintains a usable gain over a wide frequency range from several hundred megahertz to several gigahertz. The single-element gain itself is not critical here, because the per-scatterer power is equalized by the variable attenuators.

The directivity of the Vivaldi element must also be considered: unlike the omnidirectional dipole, it concentrates power toward boresight and its polarization response varies with angle, and thus the field uniformity and the balance between the vertical and horizontal polarizations at the center are more sensitive to the element orientation and the chosen XPR. Section V evaluates whether a usable quiet zone is still formed under these conditions.

III. ELECTRIC-FIELD RECONSTRUCTION AND FIELD SYNTHESIS

A. Geometry and Single-Scatterer Model

The emulator places $N = 7$ scatterer antennas on a circle of radius $R = 1.2$ m around the OTA center. The n -th scatterer is located at the angular position $\alpha_n = 2\pi(n-1)/N$, that is, at $(R \cos \alpha_n, R \sin \alpha_n)$, and is oriented so that its main beam points toward the center. Its boresight direction is therefore $\beta_n = \alpha_n + \pi$. The evaluation region is divided into 2-cm square cells, and the center of the i -th cell is denoted $\mathbf{r}_i = (x_i, y_i)$.

We do not approximate the scatterers as isotropic point sources. Each element instead keeps its complex far-field directivity in the horizontal plane ($\theta = 90^\circ$), measured as a function of azimuth ϕ for polarization $p \in \{V, H\}$ and written $F_n^p(\phi)$. We denote by $H_{i,n}^p$ the field that the n -th scatterer alone produces at cell i . The observation angle is the direction of the cell as seen from the scatterer, referenced to its boresight,

$$\phi_{i,n} = \angle(\mathbf{r}_i - \mathbf{r}_n) - \beta_n, \quad (1)$$

where $\phi_{i,n} = 0$ is the toward-center direction, and $R_{i,n} = |\mathbf{r}_i - \mathbf{r}_n|$ is the scatterer-to-cell distance with $k = 2\pi/\lambda$.

The field at each cell is reconstructed by applying the Huygens-Fresnel principle: the radiated field is propagated to the observation point through the free-space scalar Green's function $G(R) = e^{-jkR}/(4\pi R)$, an outgoing spherical wave with $1/R$ decay and e^{-jkR} phase. Evaluating the complex directivity in the cell direction and propagating it gives

$$H_{i,n}^p = F_n^p(\phi_{i,n}) \frac{\exp(-jkR_{i,n})}{R_{i,n}}. \quad (2)$$

Equation (2) differs from an isotropic point source in that $F_n^p(\phi_{i,n})$ retains the angular amplitude taper and phase progression of the actual element. Therefore, a directional Vivaldi and a near-omnidirectional dipole produce different fields at the same cell. Since the cells span a region comparable to a wavelength, this per-path phase determines whether the seven contributions add coherently into a uniform zone. Only the radiated far-field directivity is used, appropriate for a relative assessment of field uniformity. The distance $R_{i,n}$ is floored at a small fraction of λ to avoid divergence, and $F_n^p(\phi)$ is interpolated periodically in ϕ .

B. Transfer Matrix and Coherent Superposition

Evaluating (2) for all M cells and all N scatterers defines, for each polarization, an $M \times N$ transfer matrix

$$[\mathbf{G}^p]_{i,n} = H_{i,n}^p, \quad (3)$$

whose n -th column is the field that the n -th scatterer alone produces over the whole grid. The emulator field follows by exciting the scatterers with complex weights and summing. Let the excitation vector for phase set s be $\mathbf{w}_s = [e^{j\psi_{1,s}}, \dots, e^{j\psi_{N,s}}]^T$, where $\psi_{n,s}$ is the phase of the n -th element, and let a_V and a_H be the polarization weights. The composite field over all cells is then the single matrix–vector product

$$\mathbf{E}(s; \text{XPR}) = (a_V \mathbf{G}^V + a_H \mathbf{G}^H) \mathbf{w}_s. \quad (4)$$

In (4), the spatial structure is fixed by $\mathbf{G}^V$ and $\mathbf{G}^H$ (geometry and element directivity), while $\mathbf{w}_s$ sets the instantaneous multipath realization. Element by element this reads

$$E_i(s; \text{XPR}) = \sum_{n=1}^N (a_V H_{i,n}^V + a_H H_{i,n}^H) \exp(j\psi_{n,s}). \quad (5)$$

The polarization weights follow the target XPR through $\rho = 10^{\text{XPR}/10}$ as

$$a_V = \sqrt{\frac{\rho}{1+\rho}}, \quad (6)$$

$$a_H = \sqrt{\frac{1}{1+\rho}}, \quad (7)$$

and thus, $\text{XPR} = 0$ dB gives equal average power to the two polarizations.

C. Synthesis of the Spatial Fading Distribution

A single weight vector $\mathbf{w}_s$ fixes one interference pattern over the cells. To synthesize a fading environment, we follow the Clarke-type spatial-fading-emulator principle [1]: the per-scatterer phases $\psi_{n,s}$ are drawn independently and uniformly on $[0, 2\pi)$, and $S = 2000$ such phase sets yield an ensemble $\{E_i(s)\}_{s=1}^S$ at each cell. When the seven contributions arrive with comparable amplitude and uncorrelated phase, the in-phase and quadrature parts of E_i become independent zero-mean Gaussians, and the envelope $|E_i|$ approaches the intended Rayleigh distribution. Near the OTA edge, or when one or two paths dominate, the envelope deviates from Rayleigh. The same ensemble supports the quiet-zone evaluation of Section IV, where the Rayleigh-fading behavior and the power

uniformity are assessed at each cell and the quiet zone is taken as the region where both hold.

IV. QUIET-ZONE EVALUATION METHOD

In this study, we use the quiet-zone concept of standardized MIMO OTA conformance testing [8], defining the quiet zone as the region around the OTA center where the emulator both reproduces Rayleigh fading and keeps the average received power uniform. Each cell is classified as valid or invalid from the phase ensemble $\{E_i(s)\}_{s=1}^S$, and the quiet-zone radius is obtained from the spatial distribution of valid cells. The classification combines a statistical criterion and a power-uniformity criterion, both of which a cell must satisfy.

A. Rayleigh-Fading Criterion

The first criterion tests whether the envelope at a cell follows the intended Rayleigh statistics. For cell i , the envelope samples $|E_i(s)|$ are compared with a Rayleigh distribution whose parameter is estimated from the samples, and the agreement is measured by the Kolmogorov–Smirnov (KS) distance D_i , the largest absolute difference between the empirical and theoretical cumulative distribution functions [15]. A companion similarity index $\eta_i = 100(1 - D_i)$ expressed in percent is used for readability. Because a Rayleigh envelope arises from a circularly symmetric zero-mean field, we also require the coherent part of the field to be small relative to its RMS value, which is quantified by the ratio $\mu_i = |\langle E_i \rangle| / \sqrt{\langle |E_i|^2 \rangle}$, where $\langle \cdot \rangle$ denotes the average over the phase ensemble. A cell passes the Rayleigh criterion when $D_i \leq 0.07$, $\eta_i \geq 90\%$, and $\mu_i \leq 0.10$.

B. Power-Uniformity Criterion

The second criterion tests whether the average power at a cell matches that at the OTA center. With $\bar{P}_i = \langle |E_i|^2 \rangle$ the mean power at cell i and $\bar{P}_0$ the mean power at the center cell, the power deviation is

$$\Delta P_i = 10 \log_{10} \frac{\bar{P}_i}{\bar{P}_0}, \quad (8)$$

and the cell passes the power-uniformity criterion when

$$|\Delta P_i| \leq 1 \text{ dB}. \quad (9)$$

A cell is counted as valid only if it satisfies both the Rayleigh criterion above and the power-uniformity criterion (9).

C. Quiet-Zone Radius

The quiet-zone radius follows from how the valid cells fill the region around the center. For each candidate radius r , we compute the fraction of valid cells within the disk of radius r , and the quiet-zone radius r_{QZ} is the largest r for which this fraction stays at or above 90%. The evaluation is carried out on a grid of 2-cm cells extending to a radius of 1.2 m, with the per-cell statistics taken over $S = 2000$ random phase sets.

TABLE I
NUMERICAL EVALUATION CONDITIONS

Parameter	Value or condition
Number of scatterers	7
Scatterer radius	1.2 m
Evaluation grid	2-cm cells, up to 1.2-m radius
Scatterer types	Vivaldi and half-wavelength dipole
Vivaldi pattern frequency	1000 MHz
Dipole pattern frequency	1000 MHz
Vivaldi condition	port 1 and port 2 simultaneous excitation
Dipole condition	vertical and horizontal dipoles
Phase condition	random phases and measured OTA phase file
Number of random phase sets	2000
XPR range	-35 to +35 dB
Rayleigh criterion	KS distance ≤ 0.07 , similarity $\geq 90\%$, coherent ratio ≤ 0.10
Power-uniformity criterion	$ \Delta P \leq 1$ dB relative to center
Quiet-zone threshold	valid-cell fraction $\geq 90\%$

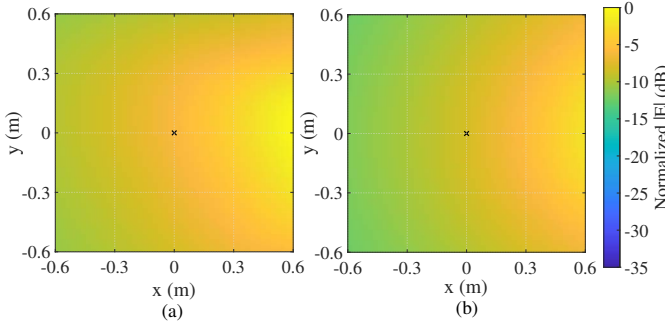


Fig. 3. Comparison of reconstructed single-antenna field distributions in the same evaluation region. (a) Vivaldi scatterer with simultaneous excitation of port 1 and port 2. (b) Half-wavelength dipole scatterer with simultaneous excitation of the vertical and horizontal dipoles.

V. NUMERICAL CONDITIONS

Table I lists the numerical conditions. The Vivaldi case combines the port-1 and port-2 fields for dual-polarized excitation, while the half-wavelength dipole case, with vertical and horizontal dipoles combined, serves as the reference for the previous Toyama configuration. The Vivaldi and dipole patterns are both characterized at 1000 MHz.

Several factors set the reliable measurement range: the phase setting, scatterer power control, scatterer directivity, frequency, and XPR. This paper focuses on the antenna-type comparison and the XPR dependence; the frequency dependence and the power-control-based shadowing emulation belong to the planned framework and will follow once the measurement system and attenuator control are in place.

VI. RESULTS AND DISCUSSION

A. Validation of the Field Reconstruction

Before applying the reconstruction to the quiet-zone analysis, we checked it against a CST full-wave simulation of the same scatterer over a centered region of about 0.6 m, with both maps normalized to their peak. The two differ

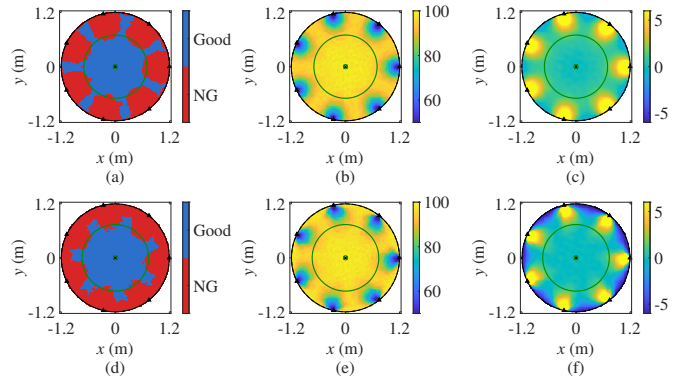


Fig. 4. Quiet-zone evaluation for the half-wavelength dipole (top row) and Vivaldi (bottom row) scatterer configurations at XPR = 0 dB. (a),(d) Valid-cell maps indicating the cells that satisfy both the Rayleigh-fading and the power-uniformity criteria. (b),(e) Rayleigh-similarity maps showing the agreement of the empirical envelope distribution with the theoretical Rayleigh distribution. (c),(f) Mean received power relative to the center cell. The dipole and Vivaldi configurations form comparable valid regions around the center.

by a root-mean-square error of 0.68 dB and have a two-dimensional correlation coefficient of 0.993. As a result, the level difference stays below 1 dB and the spatial shapes are nearly identical. The close agreement confirms that the directivity-based reconstruction reproduces the full-wave field accurately enough for the quiet-zone evaluation, and that retaining the element directivity rather than assuming an ideal point source is essential to this accuracy.

B. Single-Antenna Field Distribution

We first compare the field produced by each scatterer individually, as shown in Fig. 3. The Vivaldi result in (a) combines port 1 and port 2, and the dipole result in (b) combines the vertical and horizontal dipoles. The two differ by about 2 dB in level, but their spatial distributions are close under the same normalization. This offset reflects the lower single-element gain of the Vivaldi and does not affect the emulator, where the per-scatterer power is set by the attenuators.

C. Quiet-Zone Formation for Vivaldi and Dipole Scatterers

Next, the seven-scatterer field is evaluated over 2000 random phase sets, with the per-scatterer phases drawn independently and the fields combined coherently. At XPR = 0 dB, the vertical and horizontal components carry equal average power. Figure 4 presents the dipole (top row) and Vivaldi (bottom row) results. The valid-cell maps in Fig. 4(a) and (d) mark the cells satisfying both criteria of Section IV. The two configurations form comparable valid regions around the center. Therefore, replacing the dipoles with Vivaldi scatterers is feasible once the excitation and polarization balance are calibrated.

The Rayleigh-similarity maps, Fig. 4(b) and (e), and the mean-power maps, Fig. 4(c) and (f), show high similarity and small power deviation over the central region for both scatterer types, degrading toward the edge where one or two peripheral

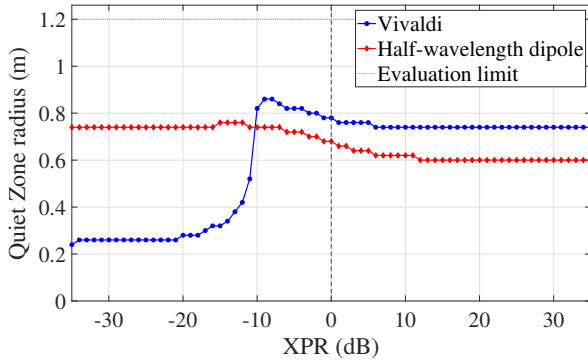


Fig. 5. Quiet-zone radius as a function of XPR at 1000 MHz for the Vivaldi and half-wavelength dipole scatterers. The radius is the largest centered radius within which at least 90% of the cells satisfy the Rayleigh-fading and power-uniformity criteria.

paths dominate. A centered DUT thus receives almost the reference power with the intended Rayleigh statistics.

D. Effect of XPR

Figure 5 shows the quiet-zone radius as a function of XPR, swept from -35 to $+35$ dB. The Vivaldi radius depends strongly on XPR: about 0.26 m for the strongly horizontal fields at negative XPR, rising sharply near -10 dB, and reaching about 0.74 m once the field becomes vertically dominant at $XPR \geq 0$ dB. The dipole radius, in contrast, stays near 0.74 m at negative XPR and falls to about 0.6 m beyond 0 dB. The Vivaldi thus forms its largest and most stable quiet zone for a vertically dominant field, consistent with its directional, dual-polarized radiation.

These results indicate that XPR is itself a calibration parameter of the emulator: if left uncontrolled, an apparent gain or loss of the DUT may originate from the emulator field rather than from the antenna. This is particularly relevant for BAN, where polarization mismatch from arm motion and antenna orientation is a dominant impairment.

E. Implication for Variable-Attenuator Human-Shadowing Emulation

The final goal is to reproduce human-body effects without a large phantom in the quiet zone: the shadowing and polarization loss, from simulation or measurement, is assigned to the scatterer paths as time-varying power weights through the variable attenuators, while polarization mismatch is left to the orientation and polarization response of the DUT rather than folded into the same attenuation.

This shadowing emulation requires that the scatterer array first form a sound quiet zone, which the present analysis confirms, and that the directivity, XPR, frequency, and phase-control sequence each be calibrated, since each shifts the reliable region.

VII. CONCLUSION

This paper numerically assessed the quiet-zone formation of a phantom-free BAN-OTA fading emulator built from seven

scatterer antennas, aiming to keep body-worn, MIMO, or physically large antenna arrays at the center without a human body or large saline-filled phantom inside the quiet zone. The emulator field was reconstructed from the complex far-field directivity of each scatterer, synthesized by coherent superposition, and the quiet zone defined through the Rayleigh-fading and power-uniformity criteria.

Under the conditions examined, the Vivaldi and half-wavelength dipole configurations form comparable quiet zones, and the XPR sweep shows that the quiet-zone radius depends strongly on the polarization balance, particularly for the Vivaldi. Vivaldi antennas are thus promising scatterers for a wideband BAN-OTA emulator once their directivity and polarization are calibrated. Future work covers building the emulator with variable attenuators for time-varying shadowing and comparing measurements with the method proposed in this study.

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