Fast and Accurate Group Delay Antenna Measurements based on Spherical Near Field Multi-Probe Systems

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***Abstract*— Group Delay (GD) is an important parameter in advanced antenna systems, especially for applications demanding high timing precision and signal fidelity, such as GNSS, satellite communications, and modern 5G networks. This work presents, for the first time, the validation of absolute GD measurements using spherical near-field Multi-Probe Array (MPA) systems, which enable rapid and accurate 3D antenna characterization. To achieve reliable absolute GD measurements, a GD substitution method is employed to correct for the GD introduced by the measurement system itself. This is accomplished by measuring a reference antenna with known GD under the same test conditions of the test antenna. The use of multi-purpose reference antennas is proposed to perform both gain and GD calibration simultaneously, simplifying the overall calibration workflow.**

Experimental validation is carried out in the 5–6 GHz band using a variety of antenna types, including horn, dipole, and bicone antennas, demonstrating excellent agreement between measured and simulated GD values across both frequency and spatial domains. The results confirm the robustness and accuracy of the proposed methodology. Importantly, this study reinforces the capability of MPA systems not only for conventional amplitude-related metrics such as gain, radiation pattern and efficiency, but also for accurate characterization of phase-related quantities like the GD. This confirms MPA systems as versatile and powerful tools for comprehensive antenna performance evaluation.

***Index Terms*—antennas, group delay, calibration, substitution method, phase measurement, near field, multi probe.**

I. INTRODUCTION

Group Delay (GD) is a critical antenna parameter in a wide range of applications where timing precision and signal integrity are essential. In systems such as Global Navigation Satellite Systems (GNSS) [1], satellite communications [2], and radar platforms, GD directly influences signal synchronization, positioning accuracy, and overall system performance. For GNSS in particular, even small variations in antenna GD can lead to significant errors in location estimation, making its precise characterization indispensable.

GD measurement is also increasingly relevant in 5G and advanced wireless communication systems, especially in the 5–6 GHz frequency range, which is used by technologies such as Wi-Fi 6E, Wi-Fi 7, and 5G NR [3]. In these systems, GD affects modulation fidelity, latency, and beamforming accuracy, making it a key parameter for optimizing performance in high-speed, multi-antenna environments.

Traditionally, GD characterization has relied on far-field measurement techniques, including the two-antenna method, where one antenna with known GD is used as reference [4]-[5], and three-antenna method, which allows calibration of all antennas involved [6]-[7]. These methods, while accurate, are often limited to single-direction or single-cut measurements and require time-consuming setups, especially when full angular coverage is needed.

Multi-Probe Array (MPA) systems are widely used for fast and accurate near-field antenna measurements [8]-[10]. In particular, in a Spherical Near-Field (SNF) configuration, MPA systems electronically scan elevation angles using probe arrays while the Device Under Test (DUT) is rotated in azimuth. This enables rapid full-sphere acquisition without the need for mechanical probe movement. Once the complex field data are collected, a Near-Field to Far-Field (NF/FF) transformation is applied to compute far-field metrics with arbitrary angular resolution [11], [12]. Examples of SNF MPA systems are shown in Fig. 1. Depending on the size of the DUT, these systems can be highly compact, offering a reduced footprint leading to cost-effective measurement environments.

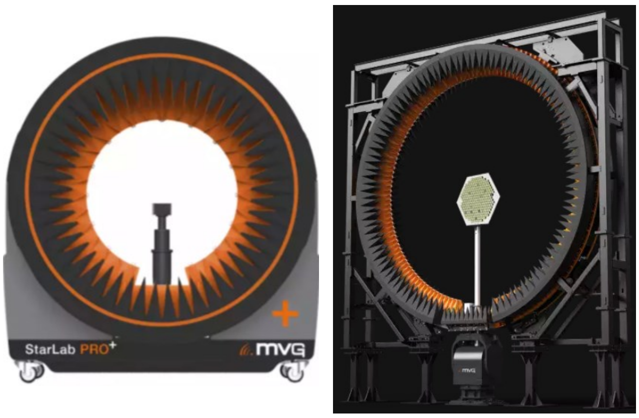

Fig. 1. Examples of spherical MPA systems: Starlab Pro (left), SG-EVO (right) [10].

Besides conventional amplitude and power-related metrics, MPA systems also support the characterization of phase-related quantities, enabling efficient GD mapping across the entire 3D angular space, which is particularly advantageous for complex or omnidirectional antennas. This capability was recently demonstrated in [13], where it has been shown that MPA systems outperformed Compact Antenna Test Range (CATR) setups in measuring relative GD for electrically small GNSS antennas.

Building on this capability, the present study investigates the measurement of absolute GD using MPA systems. Achieving this requires an additional calibration step to compensate for the GD introduced by the measurement system itself. Inspired by the far-field two-antenna GD calibration method [4], a GD substitution technique is implemented and validated. Similar to the conventional gain/efficiency calibration method [14], this method involves measuring a reference antenna with a known GD under identical conditions as the DUT.

In this approach, multi-purpose reference calibration antennas (i.e. SH wideband horns by MVG, [15]) are utilized simultaneously as gain, efficiency and GD standard. The proposed approach is validated in the 5-6 GHz [3] band through full-wave simulations and experimental measurements, demonstrating excellent agreement and low uncertainty. The methodology establishes practical calibration strategies and implementation guidelines for efficient and reliable absolute GD characterization across a broad range of antenna types and applications.

II. Group Delay Definition

Group delay quantifies the time it takes for the envelope of a signal to propagate through a device, such as a filter, amplifier, antenna, or an entire system. As expressed in equation (1), GD is mathematically defined as the negative derivative of the phase Φ with respect to frequency f.

$$GD(\theta,\varphi,f) = -\frac{1}{2\pi}\frac{d\Phi(\theta,\varphi,f)}{df} \quad (1)$$

In practical measurements, relatively small frequency steps are typically used to approximate the derivative of the phase with respect to frequency by computing finite differences between successive samples.

The concept of spatial group delay refers to the GD evaluated in any arbitrary direction (θ,φ) around the DUT, enabling a comprehensive angular characterization.

It is important to distinguish between relative and absolute group delay. Relative GD can be derived directly from the raw phase data without dedicated calibration and is generally sufficient when analyzing GD variations across spatial directions [13]. On the other hand, determining the absolute GD requires a calibration step to compensate for the GD introduced by the measurement system itself. In this study, this is achieved through the GD substitution method, which involves measuring a reference antenna with known GD under identical conditions.

III. Group Delay Measurements in Multi Probe Array Systems

MPA systems enable fast and accurate characterization of the key radiating properties of a DUT, including radiation pattern, directivity, gain, efficiency, and polarization. In SNF MPA configurations, such as those illustrated in Fig. 1, the elevation scanning is performed electronically via an array of probes. This approach significantly reduces measurement time compared to conventional single-probe systems, which rely on mechanical probe movement. Most MPA systems feature a rotatable probe array, allowing flexible elevation sampling steps. Azimuthal scanning is achieved by rotating the DUT around the vertical axis, thereby completing the SNF acquisition. The use of dual-polarized, wideband probes further accelerates the measurement process by enabling simultaneous acquisition of two orthogonal field components and facilitating broadband measurements when required.

An essential step in ensuring measurement accuracy is the orthomodal calibration [12], which equalizes the on-axis amplitude and phase response of each probe and compensates for non-ideal cross-polarization effects.

As in conventional single-probe systems, passive antenna measurements are conducted using a Vector Network Analyzer (VNA) capable of recording complex signals. The far-field radiation pattern is then computed using the standard NF/FF transformation [11]. Realized gain is typically determined via the substitution method, using a standard gain or efficiency antenna as a reference [14].

While amplitude-related metrics are routinely measured and well-documented in MPA systems, phase-related parameters such as GD have received comparatively less attention. However, the availability of phase information enables effective derivation of GD across the full 3D space surrounding the antenna [13]. To derive the absolute GD, an additional calibration is required to compensate for the intrinsic GD introduced by the MPA system. Analogous to gain/efficiency calibration [14], measuring a reference antenna with known/calibrated GD allows for accurate GD calibration of the MPA system. This approach, referred to as the GD substitution method, will be described in detail in the following section.

Since MPA systems exhibit relatively high group delay (or electrical length), several frequency samples are required to adequately characterize the rapid phase variations and prevent aliasing. To address this, a dedicated electrical length calibration is periodically performed using a calibration antenna positioned at the center of the MPA. This calibration is conducted at a single spatial point but with a dense frequency sweep. Analogous to the thru calibration in a VNA, the electrical length calibration is used to flatten the phase response of the MPA system, compensating for the high slope of the phase response. Although the electrical length calibration is not sufficient for a full GD calibration, it enables an efficient implementation of the GD substitution method, reducing frequency points and simplifying the measurements without sacrificing the accuracy.

IV. Group Delay Substitution Method

Once the electrical length calibration is completed, the MPA system is effectively calibrated for GD using the substitution method. Like the well-established gain substitution technique [14], the GD substitution involves measuring a reference antenna with a known GD under the same test conditions as the DUT. The equation used for GD calibration is provided in (2).

$$GD_{DUT}(\theta,\varphi,f) = GD_{DUT,raw}(\theta,\varphi,f) + GD_{REF}(\theta_0,\varphi_0,f) - GD_{REF,raw}(\theta_0,\varphi_0,f) \quad (2)$$

where:

- $GD_{DUT}(\theta,\varphi,f)$ is the GD of the DUT to be determined in any (θ,φ) direction and at each frequency f
- $GD_{DUT,raw}(\theta,\varphi,f)$ is the GD of the DUT in any direction before the calibration
- $GD_{REF}(\theta_0,\varphi_0,f)$ is the reference GD of the reference antenna in the (θ_0,φ_0) direction (e.g. boresight or peak of the radiation pattern)
- $GD_{REF,raw}(\theta_0,\varphi_0,f)$ is the measured raw GD of the reference antenna in the same (θ_0,φ_0) direction

It is important to note that both the raw GD of the DUT ($GD_{DUT,raw}$) and that of the reference antenna ($GD_{REF,raw}$), are derived from the NF/FF transformed complex radiation patterns of the respective antennas. The difference between the known GD of the reference antenna GD_{REF}, and its raw measurement represents the calibration term. This term captures the GD contribution of the measurement system and is used to correct the DUT's GD measurement.

As clear from (2), the uncertainty in the DUT's GD measurement is directly influenced by the uncertainty in the reference antenna's GD. In this study, the MVG SH2000 dual-ridge horn antenna is employed as the GD reference. This wideband antenna is commonly used, alongside others in the same family [15], as a gain standard. The approach here is to leverage its double role, using the same antenna for both gain and GD calibration of the MPA system.

The reference GD of the SH2000 has been determined through high-fidelity full-wave simulations [16]. The non-negligible contribution from the antenna connector has been accounted for a posteriori, including its equivalent electrical length obtained from dedicated measurements. To validate these simulated values, three SH2000 antennas were measured using a quasi-far-field three-antenna setup [6], illustrated in Fig. 2. The GD values at boresight obtained from these measurements were compared with the simulated GD of the SH2000 in the same direction, as shown in Fig. 3.

The excellent agreement between measured and simulated GD values confirms the low uncertainty contribution of the SH2000, estimated to be less than 0.02 ns. This result also demonstrates the repeatability of this antenna (including the mating of the connector), making it a reliable choice for GD calibration, even in the absence of dedicated GD characterization data (i.e., typical GD values).

As shown in [5], the same GD calibration approach using the same reference antenna has also been used in another measurement scenario, achieving excellent results.

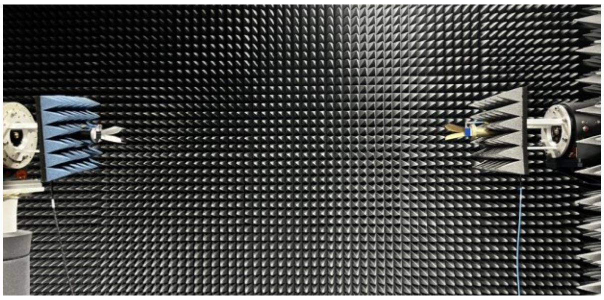

Fig. 2. SH2000 antennas measured a the quasi-FF three antenna measurement setup.

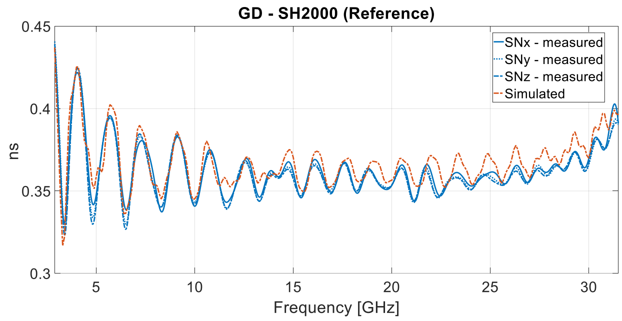

Fig. 3. GD of the SH2000 used as reference calibration antenna. Measurement of three serial numbers (SN) against simulation data.

V. Validation

GD validation measurements were performed using the StarLab 18 GHz MPA system, as illustrated in Fig. 4. This SNF system has a 90 cm diameter and is equipped with two probe arrays covering the 0.65–6 GHz and 6–18 GHz frequency bands. For this analysis, the focus was placed on the 5–6 GHz range [3].

In addition to the SH2000 horn antenna used as the GD reference (Fig. 4, top-left), three different antennas were selected as DUTs for the validation:

- SGH395 (Fig. 4, top-right): A standard gain horn (WR187) with approximately 18 dBi gain at the boresight ($\theta_0 = 0°$)
- SD5960A (Fig. 4, bottom-left): A sleeve dipole with a nominal operating band of 5.4–5.9 GHz and approximately 1.8 dBi peak gain on the horizon cut ($\theta_0 = 90°$)
- WD3000 (Fig. 4, bottom-right): A bicone antenna with a nominal band of 3–6 GHz and approximately 1 dBi average gain on the horizon cut ($\theta_0 = 90°$)

All measurements were conducted using the minimum spatial sampling defined by each DUTs minimum sphere [11], and a frequency step of 10 MHz within the 5–6 GHz band.

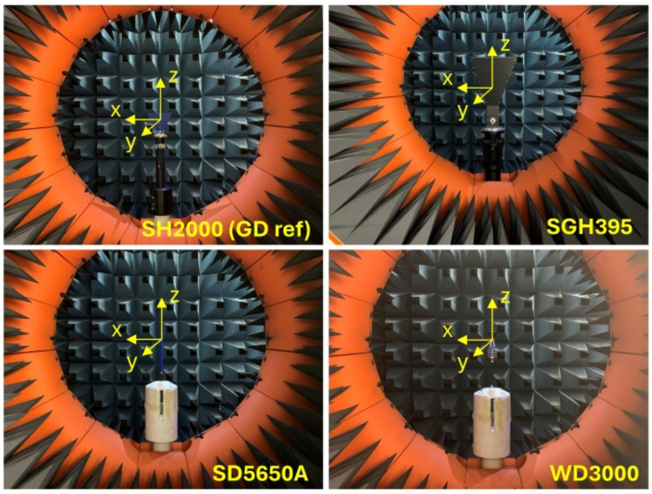

Fig. 4. GD reference antenna and AUTs in the StarLab 18GHz.

The determined absolute GD at the expected peak of the radiation pattern (e.g. $(\theta_0, \varphi_0) = (0, °0°)$ for the horn and $(\theta_0, \varphi_0) = (90, °0°)$ for the dipole and the bicone antenna) are shown in Fig. 5. Solid traces are the measured GD, while dashed ones are the GD obtained from high fidelity simulations of the same antenna [16], in the same coordinate system. A 10-point (100 MHz) moving average has been applied to the measured data to mitigate measurement errors (such as residual mismatches within the system) and the effect of numerical derivate approximation [5].

The excellent agreement between measured and simulated GD values validates this GD measurement methodology. In particular, the SGH395 horn (blue traces) exhibits a higher GD due to its greater electrical length, which is accurately captured. Additionally, the slow oscillation of approximately 0.1 ns across frequency is well resolved, with a maximum deviation from simulation of about 0.05 ns.

The expected GD difference of approximately 0.30–0.35 ns between the SD5960A dipole (red traces) and the WD3000 biconical antenna (green traces) is also clearly observed. The superimposed ripple of ±0.07 ns is likely attributable to the omni-directional nature of these DUTs, which increases the residual equivalent reflectivity of the measurement environment. The close resemblance of the two ripples is a direct consequence of the similarity in the radiation patterns of the two antennas.

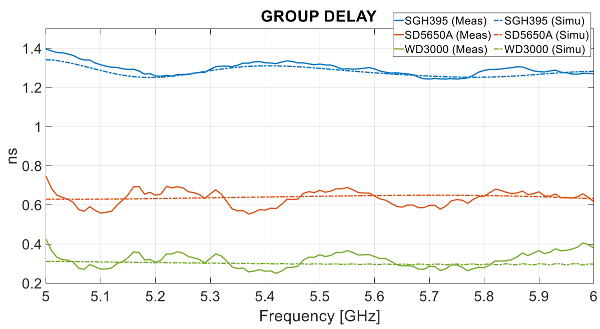

Fig. 5. Comparison between measured and simulated GD of the considered DUTs.

In MPA systems, the complex radiation pattern of the DUT is effectively measured across any (θ, φ) directions enabling equally effective spatial characterization of the GD.

As an example, the spatial GD of the SGH395 horn antenna, obtained using the same measurement procedure described earlier, is presented for its E-plane. Fig. 6 shows 2D-maps of the measured and simulated normalized radiation pattern cuts in the forward hemisphere across the frequency range. This amplitude comparison is here reported to visualize the pattern distribution, including nulls and low field regions, where phase measurements tend to be less reliable.

The corresponding spatial GD results, both measured and simulated, are shown in Fig. 7. An excellent agreement is observed across all directions and frequencies. Notably, the GD behavior near pattern nulls is accurately captured, with values approaching 0 ns as predicted. This further confirms the robustness and precision of the GD measurement approach.

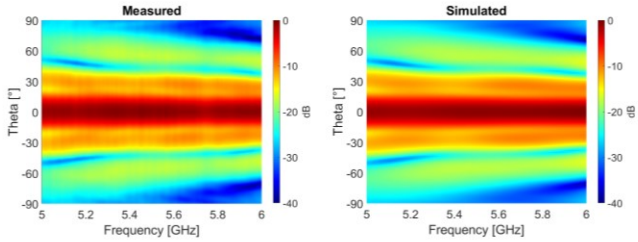

Fig. 6. Comparison between measured and simulated normalized radiation pattern of the SGH395. θ-frequency 2D colormap at φ=90° (E-Plane).

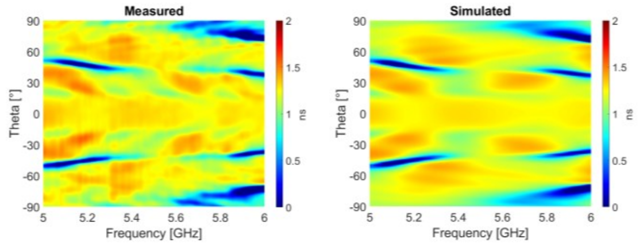

Fig. 7. Comparison between measured and simulated GD of the SGH395. θ-frequency 2D colormap at φ=90° (E-Plane).

VI. Conclusions

This work presents, for the first time, the validation of absolute GD measurements performed using spherical near field MPA systems. The proposed methodology leverages the inherent speed and spatial coverage of MPA systems to enable efficient GD characterization across the full angular domain.

To compensate for the GD introduced by the measurement system, a GD substitution method is implemented, analogous to conventional gain calibration techniques.

Multi-purpose reference antennas, such as the SH2000 wideband horn, are proposed to enable simultaneous gain and GD calibration within a single measurement, streamlines the overall calibration process. The repeatability of the SH2000 and low uncertainty have been validated through comparison of high-fidelity simulations and quasi-far-field measurements, confirming its reliability as a GD calibration standard.

Validation of the proposed GD measurement technique was carried out in the 5–6 GHz band using various antenna types, including horn, dipole, and biconical antennas, showing excellent agreement between measured and simulated GD values, both across frequency and spatial directions.

The results confirm the robustness, accuracy, and practicality of the proposed GD measurement technique, establishing MPA systems as a powerful tool for fast and reliable absolute GD characterization in modern antenna testing environments.

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