Gain and Efficiency Calibration Antennas for Low Frequency Automotive Measurement Systems

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***Abstract*— This paper presents the development of a set of calibration monocone antennas, each mounted on a small ground plane, designed for automotive range calibration. These antennas cover a frequency range from 70 MHz to 6 GHz using only four antennas, with the flexibility to extend to an even broader frequency spectrum. The wideband monocone antennas offer significant advantages for automotive facility calibration, as they closely resemble the wide-coverage antennas commonly used in vehicle communication systems, enabling full range calibration with a minimal number of antennas. To accurately derive performance data for the low-frequency monocone antennas, scaled models were employed. These scaled models are highly precise replicas of their higher-frequency counterparts, enabling measurements that maintain critical parameters such as gain, directivity, and efficiency. The data obtained from scaled measurements can be effectively extrapolated to full-scale performance. The paper also discusses key design considerations and provides details on the scaled modeling approach, as well as the validation experiments conducted in a full-scale automotive measurement facility.**

***Index Terms*—antennas, antenna measurements, automotive, calibration, measurements.**

I. INTRODUCTION

Measurement of scaled antennas is a valuable technique when direct measurement or calibration of full-scale antennas is not feasible [1][2]. By proportionally reducing the size of the antenna and increasing the measurement frequency, the electromagnetic behavior of the original antenna can be replicated, preserving key properties such as gain, directivity, efficiency, and input impedance. In this paper we report on the use of this technique to generate a set of calibration monocone antenna on a small ground-plane to cover the frequency range from 70 MHz to 6 GHz with only a few antennas each designed such that they are a very accurate scaled replica of the higher frequency version of the same antenna. In this way, the performance data needed in the calibration of general automotive antenna measurement system can be derived from measurements on the scaled models at more convenient frequencies [3].

II. CALIBRATION ANTENNA CONSIDERATIONS

It is generally good practice to calibrate the system using a reference antenna with radiation pattern characteristics similar to those of the unknown device under test (DUT) or antenna. However, this can be difficult when the properties of the DUT are truly unknown.

In the case of automotive antennas, which are typically designed to provide full or partial coverage in the upper hemisphere and exhibit rotational symmetry to ensure complete angular coverage from the vehicle, the reference antenna should share similar characteristics. Additionally, a wideband reference antenna is preferred, as it reduces the number of antennas needed for calibration across a broad frequency range. Accurate reference data is crucial, as the uncertainty associated with the reference antenna plays a significant role in the overall measurement uncertainty budget for a given test range [1], [2].

Feed cable interactions can perturb radiation pattern measurements, so it is advantageous to select a reference antenna that is less affected by such issues.

Monocone antennas on a limited ground plane (GP) are often considered ideal calibration standards. They are valued for their broad bandwidth, omnidirectional radiation pattern, simplicity, high efficiency, and stable impedance characteristics. These features make monocone antennas particularly well-suited for applications requiring wide frequency coverage and reliable performance, such as communication, testing, and spectrum monitoring.

Additionally, monocone antennas are highly scalable, making it easy to adjust their dimensions while maintaining good radiation characteristics. Minimal dielectric material is required in the feed section, while the rest can be constructed from low-loss materials like aluminum. An example of such a scalable monocone antenna is shown in Fig. 1.

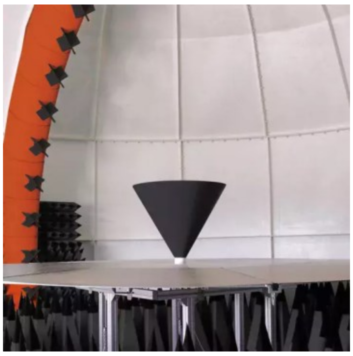

Fig. 1. Example of a wide band monocone antenna as reference antenna for gain and effeciency in automotive applications.

III. DETERMINATION OF ANTENNA PERFORMANCE THROUG SCALED MODEL MEASUREMENT

Scale modeling, which involves reducing the size of the antenna and structure while proportionally increasing the measurement frequency, is a valuable technique when actual measurements or antenna calibration are impractical. While radiation pattern is typically the primary concern in model measurements, gain and efficiency are also crucial when generating calibration devices for a measurement range. Fortunately, these properties can be reliably approximated through measurements of a scaled model.

If the scaling process is precisely followed, the electromagnetic fields are reproduced in the same shape, preserving characteristics such as gain, directivity, radiation efficiency, input impedance, mutual impedance, boresight error, and other properties that depend on field ratios. However, certain characteristics, like power levels for high-voltage breakdown and noise temperature, cannot be scaled because of their frequency-dependent nature.

Scale modeling is based on Maxwell's equations, which states that electromagnetic performance depends on dimensions relative to the wavelength. The scaling factor, N, is arbitrary and typically greater than one. By dividing the dimensions of the antenna by N and multiplying the frequency by the same factor, the antenna's electromagnetic behavior remains consistent [4].

To ensure an accurate simulation, the following requirements must be met:

1. The linear dimensions of the model should be 1/N times those of the full-scale antenna.
2. The operating frequency and material conductivity should be N times those of the full-scale antenna.
3. The permittivity and permeability must remain the same at the scaled frequency. Conductivity is adjusted by including the imaginary components of permittivity and permeability.

The electromagnetic parameters and their mapping between the real and the scaled model are summarized in TABLE I. , where N, usually greater than one, is the scaling factor.

TABLE I. REAL AND SCALED MODEL, RELATIONS BETWEEN GEOMETRICAL AND ELECTROMAGNETIC PARAMETERS.

Parameter	Real model	Scaled model
Length (linear)	L	L / N
Frequency	f	f * N
Permittivity	ε	E
Permeability	μ	μ
Conductivity	σ	σ * N
Input impedance	Z	Z
Antenna Gain	G	G

In some cases, more general scaling forms are desired. For the most accurate results, the antenna's electrical parameters should remain unchanged without altering permittivity or permeability. Conductivity, which must be multiplied by N, is often the most challenging parameter to match. While it is sometimes possible to find materials that fit this scaling requirement, the model should ideally use metals with the highest possible conductivity. Generally, for non-resonant antennas, errors due to scaling are minimal when using good conductors like Copper or Aluminum.

Additionally, antenna losses tend to be smaller at lower frequencies, meaning that the upper bound on losses can be assessed at higher frequencies during scaled testing. Following the correct scaling procedure and ensuring that the antenna design avoids extreme current or charge concentrations, the scaled radiation patterns should match the full-scale patterns. While efficiency and gain may not be reproduced exactly, measurements taken at higher frequencies on the scaled model will provide an upper bound on losses and, thus, a reasonable estimate of the error in efficiency and gain if low-loss materials are used [5].

IV. MONOCONE DESIGN CONSIDERATIONS

As previously mentioned, monocone antennas are ideal candidates for calibrating low frequency automotive systems. These radiators provide a wideband upper hemisphere rotationally symmetric pattern, naturally matched to 50 Ohms without any significant resonant behavior. Their mechanical construction is sufficiently simple, mostly metallic and suitable for scaling. Fig. 2 show a set of these antennas covering 70 MHz to 6 GHz in four antennas, properly paired with geometrically scaled ground planes.

Fig. 2. Set of monocone antennas covering 70MHz to 6GHz, paired with geometrically scaled conductive ground planes.

The design driver relies on the feature that the antenna section above the ground plane up to the end of the conical conductor is the part that mainly determines the radiative properties. Therefore, the geometrical dimensions of these parts must be accurately scaled and raw materials maintained. On the other hand, the section from the ground plane down to the input connector only impacts the input impedance, thus its RF transparency is the main performance to achieve. A coaxial design based on a conical taper allows to interface the monocone feeding gap to the RF input connector in a simple and flexible way. A detailed sketch of the feeding gap of the 70 MHz monocone antenna showing these characteristics is represented in Fig. 3.

The selection of appropriate raw materials is a key factor for the design. The use of low loss conducting materials, such as Aluminum or Copper alloys, and high-performance dielectrics allows to minimize the ohmic losses, that are known to be difficult to correlate between real and scaled model. The same consideration applies to the selection of the input RF connector, driven by loss considerations and mating repeatability.

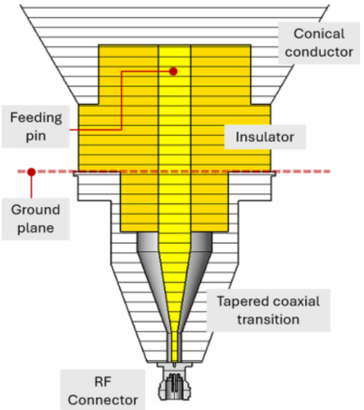

Fig. 3. Detailed view of the feeding section of the 70MHz monocone antenna.

Another relevant factor is the electrical continuity between the monocone antenna and the ground plane. Any asymmetry in this contact may affect the rotationally symmetric characteristic of the radiation pattern and modify the input impedance. Therefore, each antenna is equipped with a precision interface to guarantee accurate centering and uniform contact. This is ensured by a recessed ring in the ground plane that accepts the interface of the monocone antenna and pulling the monocone from below with enough tightening screws.

V. Validation measurements in automotive range.

The use of scaled antenna models for low frequency range calibration is validated in this section by comparing the measured results in two sub-bands. The low frequency 70 MHz monocone antenna over a 4m ground plane is measured in a truncated automotive range and compared to scaled model, 10 times higher in frequency, characterized in a full arch multiprobe system. The antenna models under test are depicted in Fig. 4, top left for the 70 MHz monocone antenna (SMC70+GP400) and bottom left for the 700 MHz monocone antenna (SMC700+GP40).

The low frequency monocone is measured in a 12-meter diameter multi-probe system able to measure down to 17.5° below the horizon. The system is installed in a 17 x 15 x 11m anechoic chamber with 48-inch absorbers on the floor.

It is well-known that antenna measurements at such low frequencies are very challenging because of the equivalent electrical sizes of the anechoic chamber and the limited reflectivity provided by the absorbers.

Such devices are normally used as gain / efficiency / calibration standard in automotive systems [6]. However, in such cases, the so-called upper hemisphere efficiency (UHE) should be used instead of the full 3D efficiency to achieve a more accurate calibration of the system [6]. The UHE can be obtained truncating the integration domain to the horizon.

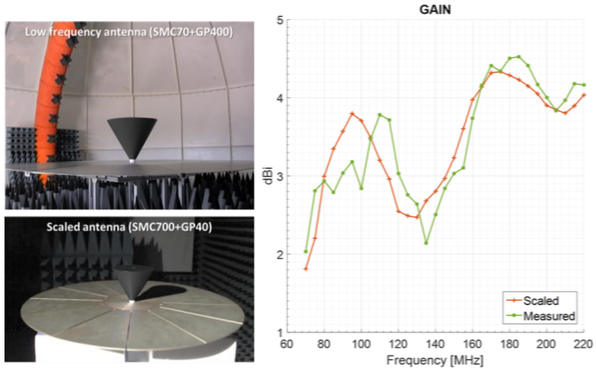

Fig. 4. Measurement of a low frequency monocone antenna with 4m-ground plane (SMC70+GP400) and comparison with a 10-time scaled version of the antenna (SMC700+GP40).

Standard data processing based on the Spherical Wave Expansion (SWE) based NF/FF transformation is applied to the measurement. The measured peak gain is shown on the right side of Fig. 4 (green trace). Since the SMC70+GP400 is a reference calibration antenna, the gain in this case is obtained by enforcing the known UHE of the antenna (substitution method). This assumption has been demonstrated to be accurate within 0.1 dB at these frequencies. Taking advantage of high-fidelity modeling including material characteristics over frequency, the radiation efficiency of the real and scaled model is compared, confirming this worst case figure.

The trace shown on the right side of Fig. 4 (red trace), is the gain of the 10-time scaled version of the antenna (SMC700-GP400) measured in a smaller multiprobe system able to perform a full spherical acquisition. As described in Chapter 2, scaled antennas like this one are commonly used to characterize the full scaled reference devices. Since the two measurements have been normalized to the same UHE, as previously explained, the difference between the two gain curves is thus only due to the differences in the measured pattern. Such a difference is approximately +/-1dB at maximum and is usually considered good for such low frequencies.

To further investigate the difference among these measurements, the radiation patterns at 70, 100, 150 and 200 MHz are compared in Fig. 5. The patterns of the full-size antenna measured in the multiprobe automotive system (green traces) show some ripples which are due to the residual reflections and truncation errors. Nevertheless, the agreement with the pattern measurement of the scaled antenna can be considered very good in the upper hemisphere. The full wave simulated model of the

SMC70+GP400 is also included in comparison (blue traces), and it also agrees well with the two measurements.

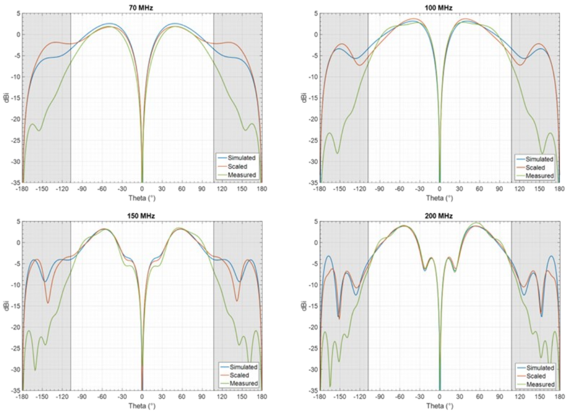

Fig. 5. Measured gain radiation patterns of a low frequency (70-220MHz) monocone antenna (SMC70) on a 4m meter ground plane (GP400) compared with the full wave simulation and measurement of a 10 time scaled model of the antenna.

VI. CONCLUSION.

The paper describes how the concept of scaled antenna models is used to design, develop and validate automotive range calibration. Focus is on monocone antennas that are often considered ideal calibration standards. They are valued for their broad bandwidth, omnidirectional radiation pattern, simplicity, high efficiency, and stable impedance characteristics. The presented antenna models cover the frequency range from 70 MHz to 6 GHz in four monocone radiators. These models have been designed as precise replicas considering the proper relations between geometrical and electromagnetic parameters. This allowed reproduce the electromagnetic field in the same shape, preserving characteristics such as gain, directivity, radiation efficiency. The validation is carried out by comparing the performance measured on real (70 MHz) and scaled model (700 MHz) in the two corresponding sub-bands and in two different measurement systems (truncated vs full arch). The measured data in real band shows a very good agreement with full-wave simulated model and with measurement of the scaled antenna, confirming the effectiveness of the proposed approach.

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