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Novel Method to Measure the Gain of UHF Directional Antennas Using Distance Scan

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***Abstract*—A novel antenna gain measurement method is described which uses power transfer values that are measured while varying the distance between two antennas (Distance Scan). It can be executed with simple means and is cost-effective. The Distance Scan method yields derived free space antenna gain values if a calibrated reference antenna is used and can be combined with the Three Antenna Method to obtain absolute antenna gain values. The method is demonstrated with the antenna gain measurement of three 12 element Yagi-Uda antennas and two 15 element Log-Periodic Dipole Antennas (LPDA's) on 8 frequencies. The measurement results of the LPDA's are compared with values obtained by external calibration, confirming the validity of this method.**

***Index Terms*—antenna gain, measurement, distance scan, directional antenna, UHF.**

I. INTRODUCTION

A free space antenna gain measurement method that can be performed with simple means and a minimum of preparation time is highly desirable when external calibration is not feasible due to time limitations or financial constraints. This document will introduce such a method, producing good results, even with Commercial-Off-The-Shelve (COTS) equipment. The measurement method was devised for the measurement of Ultra High Frequency (UHF: 300-3000 MHz) directional antennas, employed in a trans-horizon propagation measurement campaign [1]. Time limitations inhibited calibration prior to the start of the measurement campaign, and the calibration had to be postponed to the end of it. And although antenna gain figures were supplied by the manufacturer, a verification of these figures prior to the measurements was considered necessary. The method described can be used for antennas with linear polarization and approximately 6-16 dBi antenna gain.

Several publications on antenna gain measurements are available, such as [2-4] and [5, pp.805-844], containing a large number of measurement methods for a variety of antenna types and applications. Measurements in anechoic chambers [3, pp.17-19 are excellent for measuring free space antenna gain, but these chambers need to be sufficiently large for the Antenna Under Test (AUT) and for the wavelength involved. The frequency range for which wall and floor echo absorbers are designed should be respected, and their performance verified before the measurement [3, p.40]. Due to their high realization cost, they are not a common commodity. When sufficient property is available, outdoor slanted ranges and reflection ranges [2, pp.13-16] will yield excellent results if well-designed. Ground reflections could also be reduced by installing 'diffraction fences' [3, pp.97-99] on the ground in between the AUT and the reference antenna to attenuate the unwanted wave, or a 'chicken run' structure to deflect it sideward [4]. The contribution of the ground reflection on outdoor ranges can be made measureable if both the AUT and the reference antenna are synchronously rotated around their longitudinal axis using stepper motors and rotating coaxial joints. The design, construction and operation of such sites require considerable experience and effort. Measurements over a well-defined standard-size reflective area using a height scan to find the height at which constructive interference from the reflected wave occurs can be used for comparative emission measurements. The CISPR16 [6] EMC (Electro-Magnetic Compatibility) standard describes a height scan measurement for that purpose. Antenna gain or antenna factor calibration values for EMC antennas should not be confused with free space antenna gain: these values include the ground gain on the standard site, generally defined at 3 or 10 meters distance [7]. These figures deviate substantially from the free space antenna gain values.

While a height scan could be used to reconstruct the direct wave out of the values measured with destructive and with constructive interference, this will be difficult with highly directive antennas, where the vertical beam is narrow. Both the AUT and the reference antenna would have to move vertically in a synchronized fashion to avoid this influence. The Distance Scan method provides a solution that is easy to implement. Ideas were borrowed from our helicopter measurement system for VHF broadcast antenna diagrams [8]. In these helicopter measurements we compensated for the varying distance to obtain the free space EIRP value and performed a horizontal flight towards the antenna at constant height to search for a measurement distance with the lowest influence of the ground reflection. We applied this same principle to a set-up where antennas were mounted on two masts of identical height (10 meters) of which the distance was varied (from 2 to 20 meters). The antennas remained pointed to each other, avoiding the influence of the vertical radiation diagram of the main beam. The limited vertical beam width helps to reduce the influence of the ground reflection.

This document describes the Distance Scan method and demonstrates its application by the determination of the free space antenna gain of three Yagi-Uda antennas and two Log-Periodic Dipole Antennas (LPDA's) on several UHF frequencies. Absolute antenna gain values are calculated using the Three Antenna Method. The LPDA's were externally calibrated after the measurements were completed. Even though an improvised antenna range was used, the values obtained using Distance Scan correlated very well with these values, confirming the validity of the method.

The structure of this article is as follows. The AUT's are described in Section II. The distance scan method is described in Section III and extended with the Three Antenna Method in Section IV. The Distance Scan method is demonstrated in Section V. Finally, the so obtained values are compared with the external free space calibration performed by the National Physical Laboratory (NPL) in Section VI, followed by Conclusions.

II. ANTENNAS UNDER TEST

For the propagation measurements, three ruggedized 12 elements Yagi-Uda antennas [5, pp.481-483] were purchased. The radiator of these antennas is encapsulated in a fiberglass radome to endure salt build-up. This was no luxury, as the antennas were installed on top of the highest dune in the area, exposed to high winds and salty moisture. Fig. 1 shows a picture of the 12 elements Yagi antenna. The antenna has one radiator, 7 parasitic director and 4 parasitic reflector elements. The manufacturer claimed an antenna gain of 14 dBi, an E-plane half-power beam width of 35° and an H-plane beam width of 50°. The antenna boom length was 1 to 1.2 meters, depending on the design frequency.

Fig. 1. The 12 elements UHF Yagi-Uda antenna.

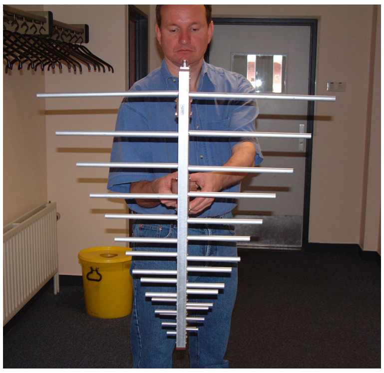

Fig. 2. The 200 MHz to 1 GHz Log-Periodic Dipole Antenna.

The two LPDA's [9, pp.703-708] were originally purchased for EMC measurements, but were later set apart to be used as reference antennas. Their mechanical structure - large diameter dual boom and large diameter tubular elements - gave them better mechanical stability than the newer versions with thinner, massive elements. A picture of the antenna is shown in Fig. 2. Their operation frequency range is from 200 MHz to 1 GHz, with a free space antenna gain of 6.5 dBi. The boom length is 75 centimeters.

III. DISTANCE SCAN METHOD

The measurement set-up for the Distance Scan method is depicted in Fig. 3. Two antennas are mounted on masts of equal height (approximately 10 meters), facing each other. A signal generator feeds RF power into the first antenna. The second antenna is connected to a calibrated receiver that measures the received power. The distance between the antennas can be increased gradually by moving the mast on which the second antenna is mounted along a straight line. The antennas keep facing each other and the antenna height remains the same. While increasing the distance from 2 to 20 meters, both the distance and the received power are measured and recorded. From the recorded power and distance measurements we then calculate the product of the antenna gains by applying Friis' Theorem [9]. In free space, under far field conditions, the power transferred from antenna 1 to antenna 2 can be expressed as:

$$\frac{P_{RX}}{P_{TX}} = \frac{A_{e_{RX}} A_{e_{TX}}}{R^2 \lambda^2}, \qquad (1)$$

Where P_{TX} is the power fed to the first antenna, P_{RX} the power output from the second antenna, Ae_{Tx} and Ae_{Rx} the effective aperture of both antennas, R the distance between both antennas and λ is the wavelength of the transmission. According to [10, p.727], the effective aperture of the antenna can be expressed as:

$$A_e = \frac{\lambda^2 G}{4\pi}, \qquad (2)$$

Where G is the antenna gain, expressed as a linear value, and Ae the effective aperture in square meters.

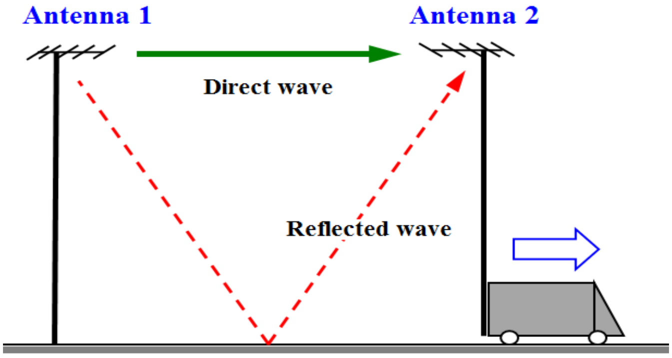

Fig. 3. The Distance Scan antenna gain measurement method. Antenna height is 10 meters, distance between antennas 2-20 meters.

Combining (1) and (2) gives:

$$G_{RX}G_{TX} = \frac{P_{RX}}{P_{TX}}\frac{R^2 16\pi^2}{\lambda^2} \qquad (3)$$

Therefore, from the measured power ratio P_{TX}/P_{RX} and distance, we can calculate the product of their antenna gains. If this product is plot against distance a horizontal straight line will show. However, when ground reflections are present, an interference pattern will show as oscillations around that straight line. This interference pattern continues up to a distance of approximately 550 meters (for an antenna height of 10 meters), after which P_{RX} decreases more rapidly than (1) predicts [11]. The linear average of the maxima and minima of these oscillations will be equal to the value obtained in the free space situation.

The ratio of the direct and the reflected wave determines the amplitude of these oscillations. The attenuation of the ground reflection depends on wave polarization, soil type and on the angle of incidence [10, pp.609-617]. The Distance Scan method is very well suited for the measurement of directional antennas with an antenna gain between 6 and 16 dBi. The vertical diagram of the antennas reduces the power transmit towards the ground reflection point and the vertical diagram of the receive antenna provides further discrimination between the direct wave and the reflection. When a is the largest dimension of the antenna, the far field criterion [12] is met when:

$$R \geq 2\frac{a^2}{\lambda} \qquad (4)$$

For antennas smaller than 1.2 meters and a frequency below 663 MHz, R is 6.4 meters (worst case). For an antenna height of 10 meters, the optimum measurement distance is between 4 and 24 meters. The measurement site has to be sufficiently open, so that reflections off buildings and trees are 6-10 dB weaker than the ground reflection. Meeting this criterion is not difficult due to the use of directive antennas and due to the short measurement distances.

To further study the Distance Scan method, we simulated a horizontally polarized 12 elements Yagi-Uda antenna for 435 MHz at 10 meters above clay ground (σ=30mS/m, ε_r=20) with NEC-4.2 [13] Method-of-Moments antenna simulation software [14]. The electrical field strength, resulting from the direct wave and the reflections, is simulated at the same height and increasing distance from the antenna. These values are used as input to the calculations used in the Distance Scan method and the calculated antenna gain is plot against distance in Fig. 4. To avoid a 3 dB error, it should be noted that NEC uses field strength amplitudes rather than RMS-values [15, p.111]. The receive antenna is not modeled but replaced by an aperture corresponding with a 0 dBi receive antenna. This means that mutual coupling between the antennas when in close proximity is not shown here. The red curve in Fig. 4 measures the distance from the dipole radiator in the Yagi-Uda antenna. In the blue curve this distance is corrected for the active center of the antenna, in this case an offset of 67 centimeters. As we see, the simulated Distance scan yields values that oscillate around the free space value.

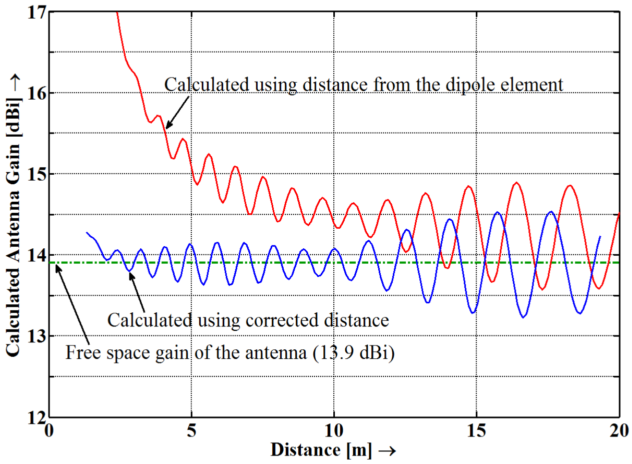

Fig. 4. Simulation using NEC-4.2 [13] of the Distant Scan measurement of a 13.9 dBi Yagi-Uda antenna 10 meters above ground. The red line shows the raw measurement, the blue line includes distance offset correction (see text). The green dashed line shows the free space gain of the antenna.

IV. EXTENSION OF THE DISTANCE SCAN METHOD WITH THE THREE ANTENNA METHOD

If one of the antennas is a reference antenna with known antenna gain, the Distance Scan will yield the antenna gain of the AUT. If both antenna gains are unknown, the result of the measurement is the product of the gain of the antenna pair. When the antenna gain products G_AG_B, G_AG_C and G_BG_C of three antenna pairs are measured, their individual antenna gains G_A, G_B and G_C can be calculated using the Three Antenna Method [3, p.95]. The logarithmic representation of the antenna gains and antenna gain products is used:

$$A=10\log^{10}(G_A),\ B=10\log^{10}(G_B),\ C=10\log^{10}(G_C) \qquad (5)$$

$$\begin{aligned} X &= 10\log^{10}(G_AG_B)\\ Y &= 10\log^{10}(G_AG_C)\\ Z &= 10\log^{10}(G_BG_C) \end{aligned} \qquad (6)$$

$$\begin{aligned} A &= (\ X+Y-Z)\ /2\\ B &= (\ X-Y+Z)\ /2\\ C &= (-X+Y+Z)\ /2 \end{aligned} \qquad (7)$$

With this extension, the Distance Scan method can be used to produce absolute free space antenna gain values.

V. DEMONSTRATION OF THE DISTANCE SCAN METHOD

Our improvised antenna range consisted of a small straight asphalt road on a dike in a flat grassland area. For the moveable antenna mast we used a van equipped with an extendable 10 meter long mast. To measure the distance, the positions of the fixed mast and the moveable antenna where both measured with the same Differential Global Positioning System (DGPS) receiver with sub-meter accuracy. Generator power and received antenna power where measured via the same set of cables using a measurement receiver.

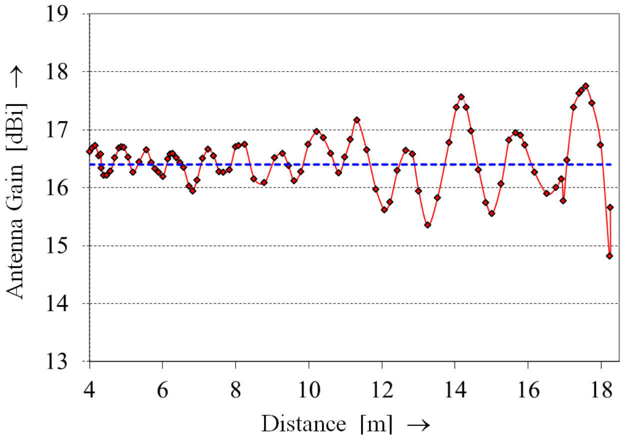

Fig. 5. One of the Distance Scan measurements: combined antenna gain of a Yagi-Uda antenna and a LPDA antenna versus the distance between the antennas, measured at 519 MHz at 9.45 meters above ground.

One of the measurements is given in Fig. 5 as an example. The red line connects subsequent measurement points and shows the additive and destructive interference caused by the ground reflection. The mean of the linear values is shown as a dashed blue line. The antenna height of both antennas was 9.45 meters, the distance was varied from 2 to 20 meters. Horizontal polarization was used. Vertical polarization is more favorable with regard to the magnitude of the ground reflections, but the antenna-to-mast mounting of the Yagi-Uda antennas prevented mounting them vertically.

Distance Scan measurements were performed for pairs of the three Yagi-Uda antennas and the two LPDA's on each of the frequencies used in the propagation measurement campaign. The other measurements produced curves very similar curves to Fig. 5. The irregularities in the 'oscillations' are very likely the result of antenna pointing errors, reflections against the vehicles and drift in the distance measurements in this rather improvised set-up. Some of the measurements were done twice to examine measurement repeatability. Those measurements produced the same values and nearly identical graphs, with only some phase differences.

In the propagation measurement campaign one of the Yagi-Uda was used on two frequencies, the other two were each used on three frequencies, covering a total of 8 frequencies. Three antenna pairs were measured on each operating frequency: the AUT combined with the first LPDA, the AUT combined with the second LPDA and both LPDA's together. The measurement antenna gain products of these pairs are presented in Tables I to III.

TABLE I. MEASURED GAIN PRODUCTS OF YAGI-UDA ANTENNA '1'

	Antenna pairs:		
Yagi-Uda '1'	x	x	
LPDA 'A'	x		x
LPDA 'B'		x	x
Frequency	Combined antenna gain [dBi]		
535 MHz	17.7	16.8	14.0
559 MHz	18.3	17.0	13.3
583 MHz	18.3	17.3	13.0

TABLE II. MEASURED GAIN PRODUCTS OF YAGI-UDA ANTENNA '2'

	Antenna pairs:		
Yagi-Uda '2'	x	x	
LPDA 'A'	x		x
LPDA 'B'		x	x
Frequency	Combined antenna gain [dBi]		
519 MHz	16.4	15.2	12.3
543 MHz	17.5	16.9	13.0

TABLE III. MEASURED GAIN PRODUCTS OF YAGI-UDA ANTENNA '3'

	Antenna pairs:		
Yagi-Uda '3'	x	x	
LPDA 'A'	x		x
LPDA 'B'		x	x
Frequency	Combined antenna gain [dBi]		
615 MHz	18.3	17.2	12.7
663 MHz	17.9	17.1	11.7
639 MHz	18.0	17.4	13.0

TABLE IV. CALCULATED GAINS OF INDIVIDUAL ANTENNAS

	519	535	543	559	583	615	639	663	MHz
Yagi-Uda '1'		10.3		11.0	11.3				
Yagi-Uda '2'	9.7		10.7						
Yagi-Uda '3'						11.4	11.7	11.2	dBi
LPDA 'A'	6.8	7.5	6.8	7.3	7.0	6.9	6.3	6.8	
LPDA 'B'	5.6	6.6	6.2	6.0	6.0	5.8	5.5	6.2	

Using the Three Antenna Method the individual antenna gains are calculated from the measured gain products of the antenna pairs. The results are given in Table IV. The results are also shown graphically in Fig. 6. Note that the three Yagi-Uda antennas are optimized for the channels they operate on, this is not one antenna operating from 500-700 MHz. The results follow the patterns that are expected from Yagi-Uda with a fixed boom length and LPDA antennas.

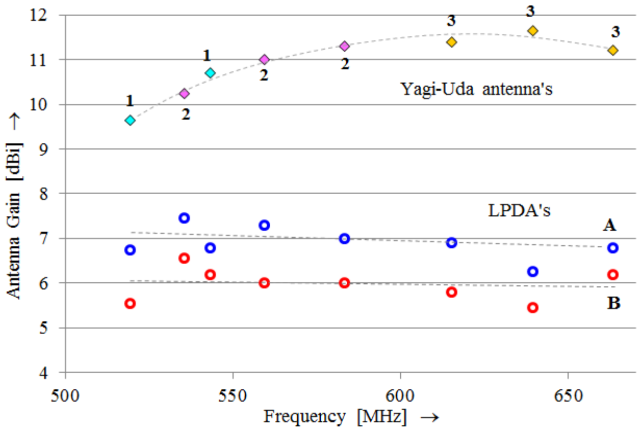

Fig. 6. Absolute antenna gain values measured with Distance Scan and calculated using the Three Antenna Method. Values can also be found in Table IV.

VI. VALIDATION BY EXTERNAL CALIBRATION

After these Distance Scan measurements and once the propagation measurement campaign had started, the two LPDA antennas were sent to the National Physical Laboratory (NPL) in England for calibration. Free space antenna gain values were obtained every 25 MHz, with an expanded measurement uncertainty of 0.5 dB (2σ). According to these NPL measurements, the antenna gain of both LPDA's was very similar, with less than 0.1 dB difference on most frequencies.

Fig. 7 compares the NPL values with the values obtained with Distance Scan and the Three Antenna Method. The mean error for LPDA 'A' is -0.16 dB with a standard deviation of 0.4 dB. The mean error for LPDA 'B' is -1.13 dB with a standard deviation of 0.4 dB. LPDA 'A' shows excellent conformance with the NPL calibration. The values of LPDA 'B' seem to have a systematic error, but are still well within expectations, considering the unprepared antenna site and the improvised distance measurement. Therefore, the results are considered very encouraging and are seen as a confirmation that the Distance Scan method is valid approach.

The combined measurement uncertainty of the Distance Scan measurements shown in Table V can be derived from (3) by analyzing the contribution of each of the uncertainty sources and is approximately 42% or 1.5 dB (2σ) for our equipment. The accuracy can be further improved by using a laser distance meter instead of the DGPS and a slightly higher number of measurement points per meter distance.

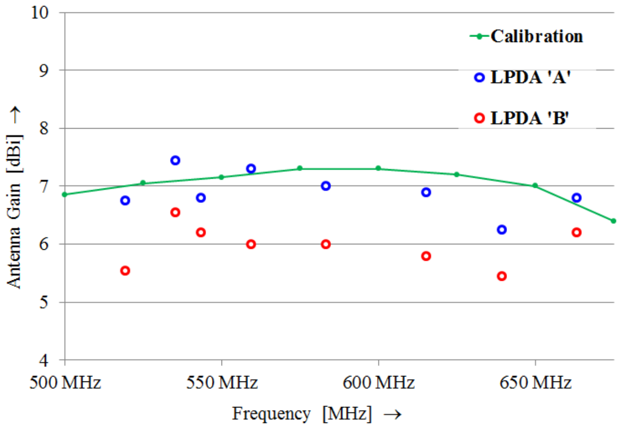

Fig. 7. Comparison of external calibration values of the LPDA's with the antenna gain obtained with Distance Scan.

TABLE V. COMBINED MEASUREMENT UNCERTAINTY CALCULATION

Symbol	Source of the uncertainty	Uncertainty		Probability distribution	Divisor	Sensitivity coefficient	Standard uncertainty
f	Signal generator frequency (1 ppm)		0%	normal	2	2	0%
R	Distance measurement		13%	normal	2	2	13%
P_{RX} / P_{TX}	Meas.receiver, incl. cables	0.7 dB	17%	normal	2	1	9%
Avert	Vertical alignment error	0.8 dB	20%	uniform	1.732	1	12%
Ahor	Horizontal alignment error	0.5 dB	12%	uniform	1.732	1	7%
Agnd	Influence of ground irregularity	0.2 dB	5%	normal	2.000	1	2%
Aref	Influence of reflections other than gnd	0.3 dB	7%	normal	2.000	1	4%
$U(G_{RX}G_{TX})$	Combined standard uncertainty			normal			21%
U	Expanded standard uncertainty (95% conf.)			normal (k=2)			42%

If a test range can be prepared for this measurement, a simple lorry could support the moveable mast and some guiding mechanism for the lorry could improve antenna bore sight throughout the displacement. Vertical polarization would further reduce the ground reflections and therefore enhance accuracy. Simultaneous measurement on multiple frequencies could be realized by using the IQ modulator of the reference transmitter to generate multiple carriers at selected frequencies. The measurement receiver and measurement software is already capable of recording multiple frequencies. This would speed up the measurements considerably.

VII. CONCLUSIONS

A simple antenna gain measurement method for directional UHF antennas using Distance Scan is described and demonstrated. Three UHF Yagi-Uda antennas and two LPDA's are measured on 8 frequencies. The Three Antenna Method was used to calculate the antenna gain of the individual antennas. External calibration of the two LPDA's confirms the validity of this measurement method. This method provides a cost-effective alternative when external antenna calibrations are not feasible due to time limitations of financial constraints.

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