論 文

30～1000 MHz 주파수 범위에서의 전자기장의 세기 표준

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Field Strength Standards in 30～1000 MHz Frequency Range

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Abstract

This paper presents the field strength standard established using a standard antenna method in the frequency range of 30～1000MHz at KRISS(Korea Research Institute of Standards and Science).

Designs on antenna elements and a balun, and the characteristics of an antenna voltmeter are described. The uncertainties in generating the standard fields are analzed and estimated to be 5～14%.

요 약

본 논문에서는 30～1000 MHz 주파수 범위에서 표준 안테나 방법을 사용한 전자기장의 세기 표중에 대하여 기술하고 있다. 관련된 안테나 소자와 밸런을 제작하였으며 또한 안테나 볼트미터의 특성에 대하여도 살펴보았다. 본 방법을 이용한 전자기장 세기의 불확도는 5～15 %로 분석되었다.

Ⅰ. Introduction

Generation of the standard fields is needed to calibrate antennas, probes, and field strength meters to be used for field strength measurements in various areas, including EMI/EMC measurements. The needs for accurate measurements of the field strength are increassing rapidly as, for example, many coutries legislate EMC regulations and make them more stringent, and electromagnetic waves have ever-increasing applications in modern life and people are concerned about the biological effects on human beings.

Usually two methods, the standard antenna and standard field methods, are used to generate the known fields[1]. In the standard field method, the field strength is determined from the geometry of a transmitting antenna and the amplitude of the signal applied to it. This method is used in the frequency range above 1 GHz with

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horn/OEG antennas. From the geometry of a receiving antenna and the measured quantities on the receiving part such a RF open circuit voltages, the field strength is determined in the standard antenna method which is used in the frequency range below 1 GHz with dipole antenns. The antenna characterisitics should be calculated theoretically or emprically from the geometry of the transmitting or receiving antenna.

The standard antenna method is adopted at KRISS to establish the field strength standards in 30~1000MHz range, where the demands for the calibration of EMC antennas are growing up.

In this paper the construction of standard receiving antennas-antenna elements, a balun, and an antenna voltmeter-is described and the uncertainties in generating the standard fields are analyzed in dtail.

Ⅱ. Standard Receiving Antennas

1. Antenna Elements

Fig. 1 shows the field site instrumentation for the generation of the standard fields using the standard antenna method. A half wavelength resonant dipole is used a a standard receiving antenna with its imput impedance and effective length determined from the current distribution when used for transmitting.

The fundamental parameter of a standard antenna is the length of the antenna element at the operating frequency. In order to determine the length of the antenna element for a half wavelength resonat dipole an integral equation on current distribution on a transmitting dipole in free space is solved using the method of moments[2]. Assuming a dipole antenna of length 2l and radius a driven with delta-gap voltage source V at its center, an integral equation on current distribution J is given by

$$\frac{1}{j\omega\varepsilon_0} \int \overline{\overline{Ke}}(r, r') \cdot J(r')dr' = -V\delta(z)z_0 \qquad (1)$$

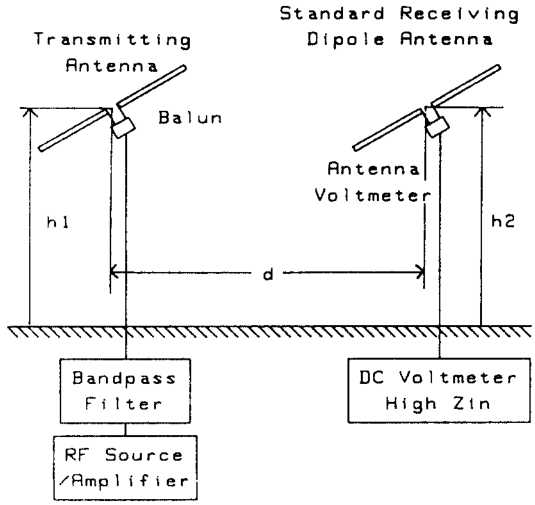


Fig. 1. Field site instrumentation for generating the standard fields.

where z_0 is the unit vector in z direction, ω is angular frequency, and ε_0 is the permittivity in vacuum. And $\delta(z)$ is the Dirac delta function, r' is the vector on the antenna surface, and time dependence $\exp(j\omega t)$ is suppressed.

$$\overline{\overline{Ke}}(r, r') = (\overline{\overline{I}}\ k_0 + \nabla\nabla) \cdot \overline{\overline{G}}(r, r') \qquad (2)$$

where I is the unit dyadic, $k_0 = \omega\sqrt{\mu_0\varepsilon_0}$, μ_0 is the permeability in vacuum, and r and r' are the position vectors of the observation and source respectively. And G is the free space electric dyadic Green's function given by

$$G(r, r') = I\,\frac{e^{-jk_0R}}{4\pi R} \qquad (3)$$

$$R = \sqrt{(x-x')^2 + (y-y')^2) + (z-z')^2}. \qquad (4)$$

In above equations it is assumed that the radius is much smaller than the wavelength and the current flows only along the center axis of the antenna element. The current distribution J can be approximated by the series expansion

$$\underline{J}(r)=\frac{I(z)}{2\pi a}=\sum_{m=1}^{M} a_m F_m(z) \quad (5)$$

where $F_m(z)$ is a piecewise sinusoidal mode. Substituting Eq. (5) into Eq. (1) and applying Galerkin's method, a set of linear equations on $\{a_m\}$ is constructed and the unknown coefficients can be obtained.

From the current distribution the input impedance and the effective length of the dipole antenna can be determined.

$$Z_{in}=R_{in}+jX_{in}=\frac{V}{2\pi a J(O)} \quad (6)$$

$$h_{eff}=\frac{1}{I(o)}\int_{-l_o}^{l_o} I(z')dz' \quad (7)$$

In Eq. (7) $2l_o$ is the length of a half wavelength resonant dipole and is determined so that the imaginary part of the input impedance goes to zero. The input impedance is about 72 Ω at the resonant length. The dimensions and the effective length are given in Table 1 at several frequencies.

Table 1. Dimensions of antenna elements

Frequency (MHz)	Diameter (mm)	Lenght (mm)	Effective Length(mm)
30	6.350	4,805	3,154
100	6.350	1,426	947
300	6.350	482.3	315
400	1.588	356.5	237
1000	1.588	140.9	97

2. Balun

As shown in Fig. 1, à balun is used to drive the transmitting dipole. In designing a Roberts balun [3] used and shown in Fig. 2(a), the characteristic impedance and propagation constant should be known for a parallel transmission line consisting of outer surfaces of two coaxial cables. And these parameters can be determined from the inductance and capacitance per unit length of the transmission line.

The cross section of a parallel line is shown in Fig. 2(b) and the inductance and capacitance of it are given by[4]

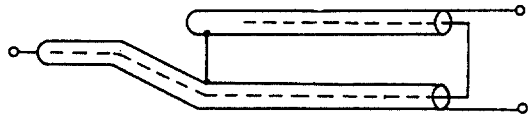


Fig. 2. (a) The structure of the balun

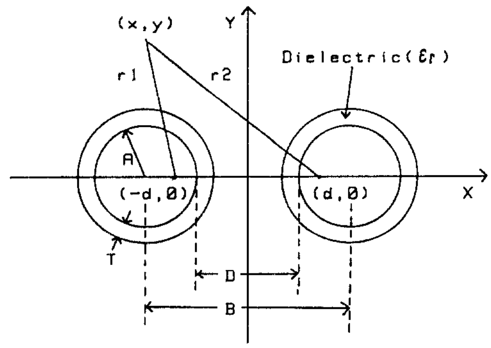


Fig. 2. (b) The cross section of parallel transmission line.

$$L=\frac{\mu_0}{\mu_0}\ln\left(\frac{B}{2A}+\sqrt{\frac{B^2}{4A^2}-1}\right) \quad (8)$$

$$C=\frac{\pi\varepsilon_0\varepsilon_{reff}}{\ln\left(\frac{B}{2A}+\sqrt{\frac{B^2}{4A^2}-1}\right)} \quad (9)$$

where ε_{reff} is the factor representing the effect of the dielectric coating on the outer surfaces. The factor equals to unity with no dielectric coating, but with dielectric coating, as is the usual case, ε_{reff} is the function of the geometry and the relative dielectric constant ε_r. In order to determine the capacitance numerically Finite Element Method (FEM) is applied in the transformed coordinates(ξ, η) shown in Fig. 3, and the transformation given by Eq. (10) satisfies the Cauchy-Riemann condition [4].

$$\eta=\frac{1}{2}\left[\ln\{(x-d)^2+y^2\}-\ln\{(x+d)^2+y^2\}\right]$$

$$\xi=\sin^{-1}\left[\frac{y}{\sqrt{(x-d)^2+y^2}}\right]-\sin^{-1}\left[\frac{y}{\sqrt{(x+d)^2+y^2}}\right] \quad (10)$$

In Eq. (10) d is determined from the geometry as

$$d^2=\frac{B^2}{4}-A^2 \quad (11)$$

In applying FEM to the geometry in Fig. 3, triangualr meshes with first order basis functions are used to get the solution of the Laplace equation on the portential between two plates. Using the geometrical symmetry the solution was obtained in one quarter plane and the boundary conditions are as follows:

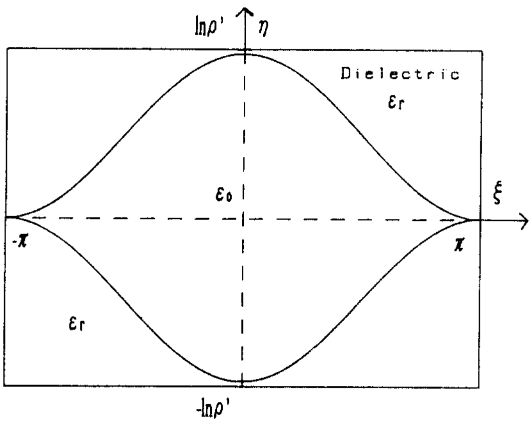


Fig. 3. Geometry of a parallel transmissionline in transformed space.

$$\begin{cases} V=V_1 \ \text{at}\ \eta=\ln\rho',\ \ \xi=0\sim\pi \\ V=0_1 \ \text{at}\ \eta=0,\ \ \xi=0\sim\pi \\ \frac{\ }{\xi}=0 \ \text{at}\ \eta=0\sim\ln\rho',\ \ \xi=0 \\ \qquad \eta=0\sim\ln\rho',\ \ \xi=\pi \end{cases} \quad (12)$$

with

$$\rho'=\frac{B}{2A}+\sqrt{\frac{B^2}{4A^2}-1} \quad (13)$$

Capacitance can be determined from the normal derivatives of the potential on the plates. Fig. 4 shows the capacitance per unit length as the ratio of distance to radius varies when the relative dielectric constant ε_r=2.3. And in Fig. 5 the capacitance variation with respect to the relative dielectric constant is shown. From Fig. 4 the effect of the dielectric coating is small when the distance to radius ratio is large, but becomes large when two outer conductors get closer.

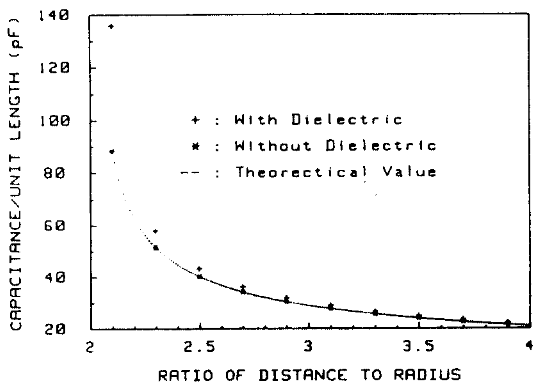


Fig. 4. Capacitance per unit length of a parallel transmission line with respect to the distance /radius ration.

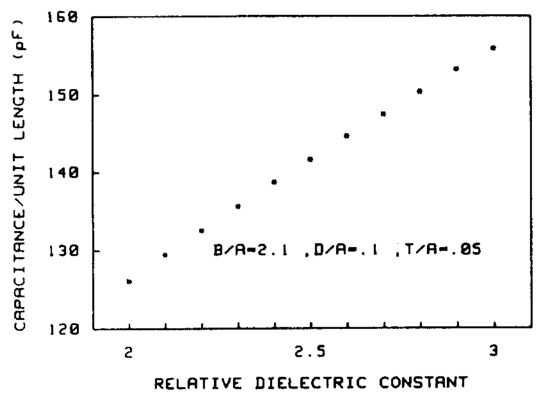


Fig. 5. Capacitance per unit length of a parallel transmission line with respect to the relative dielectric ocnstant.

3. Antenna Voltmenter

An antenna voltmeter is used to measure the open circuit voltage at the terminal of a receiving antenna and thus obtain the field strength using

$$|V_{oc}| = |h_{eff}| \cdot |E|. \tag{14}$$

A diode, an RC low pass filter and a parallel resistive transmission line are used to convert RF voltage into DC voltage. A high impedance Schottky barrier diode is used to reduce the loading effect on the receiving antenna, and the resistive lines to attenuate RF signal and not to disturb the field. The resistance value of the resistive lines is R=60~90 kΩ/m and the attenuation constant α is given by

$$\alpha \approx \sqrt{\frac{\omega RC}{2}} \tag{15}$$

where the capacitance per unit length can be calculated using the same method as that mentioned in Ⅱ-B. The schematic diagram of the antenna voltmeter is shown in Fig. 6.

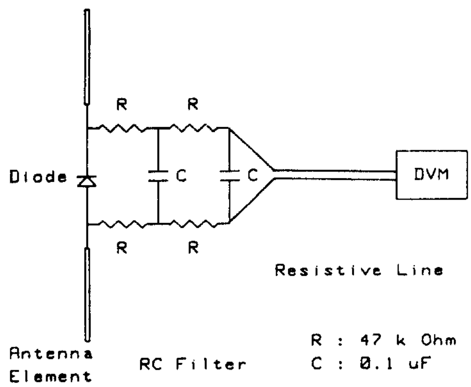


Fig. 6. Schematic diagram of the antenna voltmeter.

Ⅲ. Uncertainty Analysis

1. Equivalent Circuit of the Antenna Voltmeter

Fig. 7 shows the equivalent circuit of the antenna voltmeter. The equivalent circuit of the diode consists of a parallel combination of nonlinear resistance Rd and a linear capacitance Cd. Here, the nonlinear resistance Rd is characterized by its v-i characteristic, i.e.,

$$i(t) = Is \cdot [\exp\{av(t)\} - 1] \tag{16}$$

where $i(t)$ is the current through Rd, $v(t)$ is the voltage across it, I_s is the saturation current of the diode which is assumed to be 300 nA, and $a = q/knT \simeq 38V^{-1}$. And the capacitance value is taken to be 1 pF.

In Fig. 7 Rl takes two values. For RF component of the voltage across the diode it is the resistance of two resistors in RF filter connected in series and for DC component the series resistance of four resistors in RC filter, ressssistive lines, and input impedance of DVM. Ra is the input impedance of the dipole and Ca is connected in series with Ra considering the physical situation of the antenna and its value is given by $\omega C_a = 1000$ S.

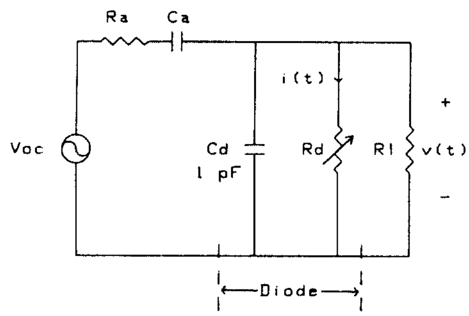


Fig. 7. Equivalent circuit of the antenna voltmeter.

2. Frequency Characteristics

The output DC voltages vs. RF input voltages to the antenna voltmeter are calculated numerically by solving nonlinear differential equations obtained from the equivalent circuit using Newton-Raphson iteration method and Convolution-Based Sample Balance (CBSB) technique [5][6]. As shown in Fig. 8, the antenna voltmeter has square-law characteristics in the region of small RF input voltage and linear characteristics when large RF voltage is applied.

The frequency characteristics of the antenna voltmeter when constant RF voltage applied is calculated using the same method.

The results are shown in Table 2 and $V_{DC,30}$ and $V_{DC,1000}$ are the DC output voltage at 30 MHz and 10000 MHz respectively. When the applied voltage is large, the frequency characteristics is flat.

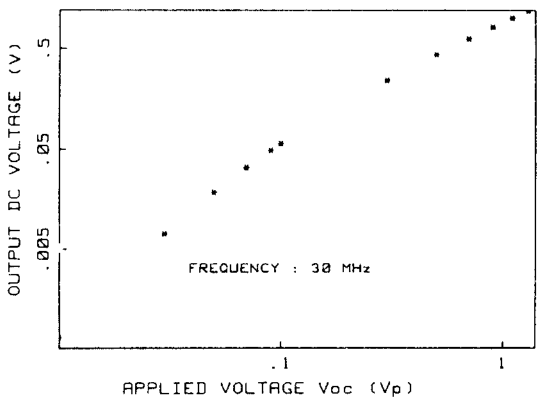


Fig. 8. Antenna voltmeter characteristics, V_{DC} vs. V_{oc}.

Table 2. Frequency characterisitics of the antenna voltmeter

V_{oc} (V_p)	$\frac{V_{DC,30} - V_{DC,1000}}{V_{DC,30}}$ (%)
0.5	9.6
1.0	9.2
1.5	9.0

3. Ground Effect

Usually the antenna calibration below 1 GHz is done at an Open Area Test Site (OATS), so it is necessary to analyze the ground effect on the standard receiving antenna. The impedance and its effective length of a half-wavelength resonant dipole above the perfect ground plane are calculated using the method of moments. With the impedance and effective length varying as the height from the round plane, DC output voltage of the antenna voltmeter is calculated at 30 MHz and 1000 MHz when the electric field strength E=0.3 V/m and E=6 V/m, respectively. Also Newton-Raphson iteration method and CBSB technique are used to solve nonlinear differential equatins. As can be seen from the results shown in Fig. 9, the output DC voltage varies within 0.5 % when the receiveing antenna is positioned at 3~6 m from the ground plane.

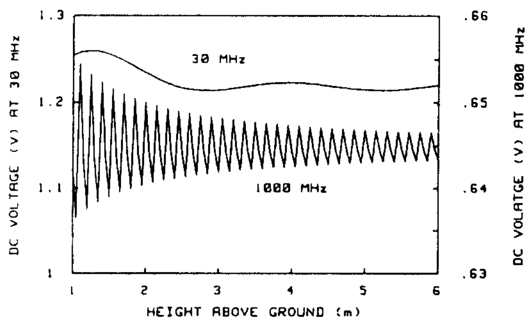
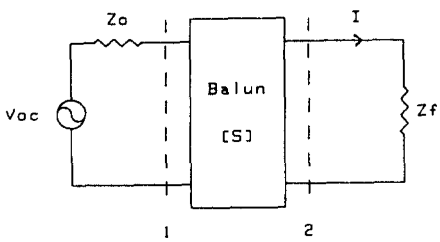


Fig. 9. The variations of DC output voltaga with respect to the height above the ground plane.

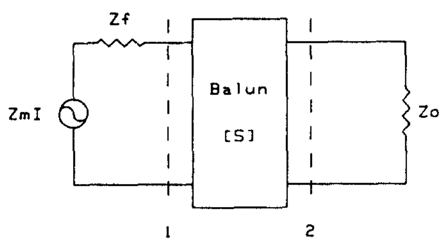
4. Distance Between Antennas

The electric field should be uniform along the antenna axis at the receiving antenna position and this far field condition can be satisfied when the distance between transmitting and receiving antennas is very large. But because of the limitations in size of the site and the transmitting power, calibration should be done at relatively close distance.

In order to estimate the effect of the distance on the effective length, near field gain of a half wavelength resonant dipole is calculated using EMF method and a gain extrapolation technique [7][8]. When a dipole antenna is located above the perfect ground plane, the impedance is changed by the mutual impedance from its image. So the dipole can be seperated into two modes, transmitting mode and receiving mode. The equivalent circuit in transmitting mode and in receiving mode are receiving mode. The equivalent circuit in transmitting mode and in receiving mode are shown in Fig. 10. The distance between two mode antennas is twice the height of the dipole. From Fig. 10, an insertion loss between the transmitting mode and receiving mode antennas can be calculted at terminal plane 1 or 2, and it is equated to the Friss transmission equatin between two identical antennas.



(a) In transmitting mode.



(b) In receiving mode.

Fig. 10. Equivalent circuit of the dipole.

The free space impedance Zf and mutual impedance Zm are calculated using EMF method as the heigh varies up to 6 m. Applying a gain extrapolation technique to the insertion loss vs. the distance data, the far field and near field gain of a dipole can be obtained. The results are shown in TAbe 3 with the theoretical value. From the results the error in effective length can be estimated to be less than 2.4 % or 0.05 dB when the distance between the antennas is more than twice the wavelength

5. Antenna Voltmeter Calibration

The relation of DC ouput voltage vs. RF input

Table 3. Near field gain of a dipole

Frequency (MHz)	Theoretical gain(dB)	Gain at infinity(dB)	Gain at 2λ(dB)
30	2.086	2.071	2.019
100	2.122	2.127	2.071
300	2.238	2.238	2.191
400	2.137	2.137	2.087
1000	2.211	2.211	2.164

voltage of the antenna voltmenter should be known to calculate the electric field strength from the DC output voltage measured when it is connected to a receiving dipole antenna. In Fig. 11 the equivalent circuit of the calibration set-up for the antenna voltmeter is shown. R_Y is the impedance of a receiver, a spectrum analyzer or a Thermal Voltage Converter calibrated with RF voltage standards. Rg is the impedance of the signal source and C_b is the blocking capacitor to prevent the DC component from flowing into the receiver and signal source.

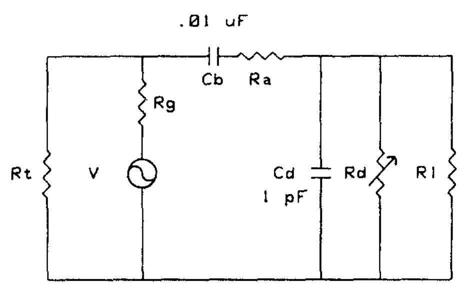


Fig. 11. Equivalent circuit of the calibration set-up for the antenna voltmeter.

DC output voltages with respect to the RF voltages measured at the receiver are calculated numerically when $R_a=0\,\Omega$ and $R_a=72\,\Omega$. And DC output voltages with respect to the open circuit voltages are calculated when the antenna voltmeter is connected to a receiving antenna-the measurement set-up. The results are shown in Table 4. In Table 4 the applied voltage is the RF voltage measured at the receiver and the open circuit voltage in the calibration and measurement set-ups respectively. As can be seen from the results the difference between the calibration set-up and the measurement set-up is very small. So the uncertainty due to the calibration can be estimated to be within 2 % including the uncertainty of RF voltage standards.

Table 5. Comparison of the measurement and calibration set-ups

Applied Voltage (V_p)	V_{DC}(V) (cal. set-up)		V_{DC} (V)
	Ra = 72 Ω	Ra = 0 Ω	(meas. set up)
0.1	0.05609	0.05621	0.05614
0.3	0.23451	0.23487	0.23467
0.5	0.42131	0.42188	0.42156
1	0.89523	0.89731	0.89672
1.3	1.18325	1.18463	1.18388
1.5	1.37502	1.37660	1.37564

Ⅵ. Conclusions

In this paper the designs on standard receiving antennas are described, and the uncertainties in generating the standard fields using the standard antenna method are analyzed. The standard receiving antenna consists of a half-wavelength resonant dipole and an antenna voltmeter, and a balun is used for the trasmitting dipole.

When the distance between the transmitting and receiving antennas is more than two wavelengths, the error from the proximity effect is about 2.4 %. The error from the ground plane effect is less than 0.5 % when the receiving antenna is posiitioned at 3~6 m above the ground. If the calibration data at one frequecy is used for all frequencies, the error due to frequency characteristics of the antenna voltmeter is about 9 %. This error could be eliminated by calibrating it at all frequencies. The error from the calibration uncertainty including the RF voltage standards is estimated to be less than 2 %. The error from the dimensional accuracy of the antenna elements is negligible.

So antennas and probes can be calibrated in the standard fields generated using the standard receiving antenna with the total uncertainty of 5~14 % in the frequency range of 30~1000 MHz.

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