PROPOSAL OF ACCURATE SAR-PROBE CALIBRATION USING REFERENCE ANTENNAS IN THE LIQUID AT HIGHER FREQUENCY

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INTRODUCTION

It is imperative that the procedure of the SAR probe calibration above 3 GHz should be established, because of a scope for the use of the mobile communication device in the corresponding frequency range. In 300 MHz to 3 GHz, the sensitivity factor of the SAR probe can be determined by two-step procedure, or the absolute sensitivity to tissue equivalent liquid is calibrated by multiplying the absolute sensitivity in free space by the ratio of probe response in free space to that in the liquid. The probe calibration in the liquid is generally implemented in comparing rectified DC output voltage of the probe with the corresponding electric field intensity given explicitly at the point of measurement in the liquid. For example, a calibration system used in 800 MHz to 3 GHz consists of a rectangular waveguide, a matching dielectric slab as a spacer and so on [1]. Above 3 GHz, however, we cannot help but worry about deterioration in the accuracy of the calibration by use of the waveguide system, from the point of view that the field disturbance due to the probe insertion can not be negligible as the diameter of the probe is comparable to the cross section of the waveguide.

On the contrary, the sensitivity of the probe can be also determined in one-step procedure, or the absolute sensibility is directly calibrated in the liquid as follows: [1]

1. Two identical reference antennas are inserted in the tank filled with the liquid, and absolute gain of each antenna is determined by two-antenna method. Then, the power intensity radiated by the reference antenna can be perfectly estimated everywhere in the liquid, if the gain is measured in the far-field region.
2. The reference antenna and a SAR probe under test are inserted in the liquid, and the relation between the output voltage of the probe and the electric field intensity is recorded as a function of the distance between the antenna and the probe. Then, the absolute sensitivity can be estimated.

In the one-step procedure, we note that the electric field intensity is a function of the distance from the reference antenna, *R*. The electric field is attenuated by an exponential damping factor of $e^{-\alpha R}$ due to the dielectric loss in the liquid as well as by a spatial loss factor of $1/R$ due to the spherical spreading of the energy by the antenna. The material attenuation is denoted by an attenuation constant α. In general, the dielectric loss in the liquid is much larger than the spatial loss so that the error in measuring the distance should be reduced to maintain the precision of the calibration. Moreover, the field is required to be measured in the far-field region of the reference antenna, because this calibration is based on the Friis transmission formula in the dispersive medium. However, the level of the electric field intensity in the far-field region is small enough to equal the level of the noise floor in the measurement system because of the dielectric loss in the liquid [2]. This is a source of error in the calibration, for the field can not be ideally measured in the far-field region. Thus, in the one-step procedure, the range of the distance is restricted instead of no limitation on the size of waveguide aperture.

In this paper, we propose a modified one-step procedure as a candidate of SAR probe calibration above 3 GHz without using the waveguide system. To be concrete, the measurand S_{21} between the ports of two antennas can be related to the distance *R* by use of the regression analysis. Hence the absolute gain of the antenna in the liquid can be precisely calibrated in the proposed procedure. To verify the principle of the new one-step procedure, in particular, the calibration of the gain of the reference antenna, which are assumed to be a half-wavelength dipole in the liquid, we numerically examine the ratio of the magnitude of the far electric field to that of the near electric field and the gain obtained by application of the proposed procedure as a function of the distance *R*. In the numerical analysis, we use a Richmond's code of the methods of moment for the wire antenna in the homogeneous and lossy medium.

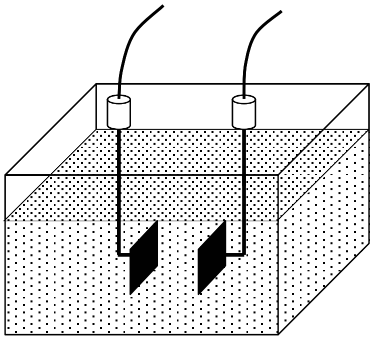

Fig. 1. Measurement System for the Calibration of the Reference Antenna

PRINCIPLE OF CALIBRATION

In measuring the absolute gain of the reference antenna by use of the two-antenna method, the transmitting and receiving antennas are aligned or polarization matched with each other, then *S* parameters for the two-port network which represents two antennas and propagating medium, are measured by the vector network analyzer. The two antennas are assumed to be identical and it follows that their gains are equal. Substituting measured *S* parameters into the following equation can determine the absolute gain of the reference antenna *G* [1].

$$G = \frac{|S_{21}| e^{\alpha R} \cdot (2\beta R)}{\sqrt{(1-|S_{11}|^2)(1-|S_{22}|^2)}} \tag{1}$$

where *R* is the distance between two antennas, and α and β are the attenuation and phase constants in the liquid, respectively. When the reference antenna is assumed to be an ideal point source which produces an isotropic field, the magnitude of the electric field $|\mathbf{E}|^2$ at the distance *R* from the point source can be determined as follows [1]:

$$|\mathbf{E}|^2 = \frac{P_{in}(1-|\Gamma|^2)Ge^{-2\alpha R}}{4\pi R^2} \frac{120\pi}{\mathrm{Re}(\sqrt{\dot{\varepsilon}_r})} \tag{2}$$

where P_{in} is the input power of the reference antenna, Γ is the reflection coefficient at the port of the reference antenna, and $\dot{\varepsilon}_r$ is the complex dielectric constant of the liquid. The total field is related to the output voltage of the SAR probe as follows [1]:

$$|\mathbf{E}|^2 = \sum_{i=1}^{3} |\mathbf{E}_i|^2 = \sum_{i=1}^{3} \frac{V_i}{K_i}, \tag{3}$$

where the subscription *i* belongs to the dipole sensor *i* of the SAR probe. In each sensor, the rectified DC voltage V_i is produced by the detector at the probe tip. The factor K_i denotes the absolute sensitivity of the *i* th sensor. The absolute gain is obtained by substituting the attenuation constant α, which can be determined by measured *S* parameters and given $\dot{\varepsilon}_r$, into (1) [1]. In this paper, however, it can be also determined by measuring the *S* parameters as a function of the distance R [2] to improve the accuracy of the distance. The Friis transmission formula including the dumping factor in the liquid can be written in dB form as

$$|S_{21}|_{\mathrm{dB}} = A - 20\log_{10} R - 8.686\alpha R\,. \tag{4}$$

The constant *A* is independent of the distance *R*, which is used in the following expression of the absolute gain

$$G_{\mathrm{dB}} = 0.5\left[A + 20\log_{10}(2\beta) - (M_1)_{\mathrm{dB}} - (M_2)_{\mathrm{dB}}\right] \tag{5}$$

where $(M_i)_{\mathrm{dB}} = 10\log_{10}(1-|\Gamma_i|^2)$ is a mismatch or reflection efficiency in dB form and Γ_i is a reflection coefficient of the reference antenna. On the other hand, the change of the phase in the liquid is a linear function of the distance *R* as follows:

Table I. Minimum Distance for the Far-Field Region of the Half-Wavelength Dipole Antenna.

Frequency [MHz]	$\mathrm{Re}(\dot{\varepsilon}_r)$	σ [S/m]	$R_{\min}$ [mm]
900	41.5	0.87	25.2
1450	40.5	1.20	16.0
1950	40.0	1.40	12.0
2450	39.2	1.80	9.6
5200	35.8	4.90	4.7

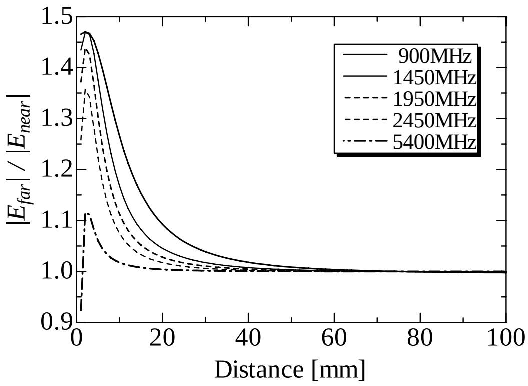

Fig. 2. The Ratio of the Magnitude of the Far-Field to that of the Rigorous Field Radiated by the Half-Wavelength Dipole Antenna. .

$$\angle S_{21} = B - \beta R \tag{6}$$

where the constant *B* is independent of the distance *R*. Because $|S_{21}|_{\mathrm{dB}}$ and $\angle S_{21}$ are functions of the distance *R*, the constants α, β, *A* and *B* can be determined by the regression analysis which best fits the magnitude and phase of measured S_{21} to the equations (4) and (6), respectively. Then, we can obtain the absolute gain *G* of the reference antenna by use of (5).

NUMERICAL RESULTS

To examine the problems on the far-field criteria in the calibration, the behavior of the electric field radiated by an uninsulated half-wavelength dipole antenna in the liquid can be numerically examined by use of the code of the method of moments for the thin-wire structure in a homogeneous conducting medium developed by Richmond [3]. The dipole antenna is used as a reference antenna in the simulation and it has a radius of 1 mm and the conductivity of 5.8×10^7 S/m, which means that the antenna is assumed to be made of the pure copper. The computer code can bring out the values of the far- and near- electric fields.

First, the minimum distance for the far-field region of the half-wavelength dipole in the liquid can be given as

$$R_{\min} = \frac{2D^2}{\lambda_e} = \frac{2(\lambda_e/2)^2}{\lambda_e} = \frac{\lambda_e}{2} \tag{7}$$

where *D* is the maximum dimension of the reference antenna. When the half-wavelength dipole is used as the reference antenna, the length of the dipole is equal to the minimum distance of the far-field region. In Table I, some numerical values of the minimum distance are listed with the values of the electric property of the liquid.

The ratio of the intensity of the far-field to that of the near-field is calculated as a function of the distance from the center of the half-wavelength dipole. Fig.2 shows examples of resulting ratio for the half-wavelength dipole antenna for 900, 1450, 1950, 2450, and 5200 MHz. As seen from this figure, the ratio is not equal to unity extremely near the antenna, but it is nearly equal to unity if the distance is more than 60 mm for 900MHz, 40 mm for 1450-2450 MHz, and 20 mm for 5200MHz. The above discussion is only based on the ratio of the far-field to the near-field so that it should not be used to determine whether the field is satisfied with the far-field criteria. Only as a guide, however, we can observe the far-field, a distance apart three times as long as the length of the dipole antenna, or about one and a half wavelength in the liquid.

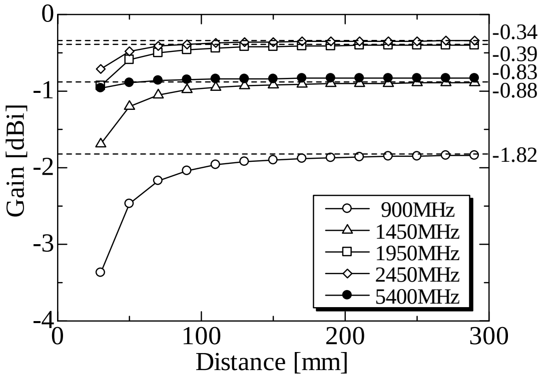

Fig. 3. The Centered Distance versus the Simulated Gain of the Half-Wavelength Dipole Antenna.

To clarify the problem on the selection of the fitting range, we also simulate the relationship between the fitting range and the corresponding gain of the reference antenna, as shown in Fig.3. In this figure, the horizontal axis denotes the centered distance between the antennas in the regression analysis R, where the curve fitting is performed from $R-10$ mm to $R+10$ mm. The dashed lines in Fig.3 denote the values of the gain of the reference antenna calculated by Richmond's code at some frequencies. If the curve fitting is successful, calibrated gain must have a good agreement with calculated one. As seen from the figure, the calibrated gain is closer to the calculated one as the distance between antennas is larger. At lower frequencies, we can find that the difference between the calibrated and calculated gains is larger as the distance is smaller. Conversely, at higher frequencies, we can say that the calibrated gain approaches to the calculated one, even if the distance is not always larger.

CONCLUSION

As an alternative to the SAR probe calibration with the waveguide system, the modified one-step calibration procedure based on the propagating property of the far field in the liquid is adopted by calibrating the gain of the reference antenna by use of the regression analysis. The procedure is numerically performed to examine the problems involved. It is based on the assumption that the antenna could be regarded as a point source. However, practical reference antennas have finite dimensions and the coupling between the antennas is not negligible so that the validity of the Friis transmission formula should be checked especially when the distance between the antennas is extremely smaller. The proposed procedure is simulated by Richmond's code for the method of moments, which can estimate the mutual coupling between the antennas in the liquid, if the half-wavelength dipole antenna is used as the reference antenna. As a result, the proposed procedure can correctly estimate the absolute gain of the reference antenna if the distance is more than three times as long as a half of the wavelength in the liquid. The distance dependence of the calibrated gain is caused by the fact that the measurement is not always performed in the far-field region. However, if the intensity of the electric field radiated by the reference antenna might be estimated by the other ways, the correction of the gain is not always needed to calibrate the SAR probe.

In future, we will construct the measurement system for the proposed procedure and validate it. Also, we will evaluate the uncertainties of the gain of the reference antenna and electric field intensity at the probe position. And, we are going to formulize the one-step procedure of the SAR probe without using the gain calibration when the measurement is not performed in the far-field region.

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