Chapter 5

Robust Setup for Precise Calibration of E-Field Probes in Tissue Simulating Liquids at Mobile Communications Frequencies

Abstract **In this paper a new calibration setup for accurate calibration of E-field probes within tissue simulating liquids at mobile communications frequencies is presented. The developed setup is based on a standing open waveguide which is partly filled with tissue simulating liquid. A dielectric slab separates and matches the impedances of the air and the liquid filled parts. The symmetry of the construction and the high losses in the liquid ensure that the field distribution inside the tissue simulation liquid follows the TE_{01} pattern. The medium depth (>3 skin depths) was chosen so that the reflections at the upper surface of the liquid are negligible. Volume SAR can be determined from the decay inside the lossy liquid and from power measurements which can be traced to a standard calibration procedure. The technique provides excellent accuracy, with a standard uncertainty of only ±2.8-3.6% depending on the frequency and media. It is also robust and easy-to-use. Since the wireless bands between 800 MHz and 2.5 GHz can be covered by only three setups, this technique offers straightforward implementation as**

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a standard calibration procedure for closing an important gap in the process of defining standardized dosimetric certification procedures for mobile phones.

5.1 Introduction

Since the beginning of 1997, dosimetric evaluations of mobile communication devices have been routinely required by the US Federal Communication Commission (FCC) prior to equipment authorization [1]. Early on it became evident that some cellular phones have only small margins with respect to the safety limits [2], which places strong requirements on the absolute accuracy of the evaluation procedure.

The accuracy of classical calibration procedures for E-field probes in tissue simulating liquids is not better than ±30% [3]. Although this was sufficient for earlier applications, the dosimetric evaluation of handheld transmitters requires significantly enhanced accuracy.

The broad-band calibration procedure based on a transfer calibration with temperature probes [4] enables calibration of the dosimetric probes with an enhanced precision of better than ±10%. The same paper discussed the possibility of calibrating the E-field probe using the FDTD numerical technique. Although this approach is applicable for any medium and frequency, the achievable precision was not better than ±10-20% (standard uncertainty) and therefore not suitable for this application. Simultaneous with the reduction of the calibration error, the uncertainties of other components have also been considerably improved, such that the calibration uncertainties have become the dominant error source in experimental dosimetric assessments [5]. Improvements are also be desirable with respect to the ease of application. Furthermore, a calibration procedure traceable to national or international standards has become a basic requirement. In view of this, possibilities for a precise, robust and standard calibration procedure have been evaluated in the following sections.

5.2 General Considerations

For calibration purposes the probe performance must be measured in an absolutely known field. The calibration gained hereby is only accurate for the specific setup used in the calibration. To extrapolate the probe performance to typical measurement situations, it is necessary to know all the relative errors in the probe, such as isotropy error, linearity error, etc. It is also

important to know the range of possible measurement situations for which the calibration can be applied.

For calibration in air, homogeneous or partly homogeneous fields are preferred. In lossy liquids, such fields are difficult to produce and also unlikely to be encountered in typical measurement situations. Gradient fields are easier to produce and even preferable when the direction and slope of the gradient are similar to the measurement situations for which the probe is destined. However, to assess the possible error of the probe several points must be carefully considered:

- The E-field sensors of the probe measure the local E-field inside the probe. This internal field depends not only on the outside field, but also on the probe construction and the dielectric properties of the surrounding media. The probe must be calibrated in the media for which it is destined, and the sensitivity of the calibration on the media parameters should be investigated. The same applies indirectly for the frequency, since the dielectric parameters of lossy media are frequency dependent.

- The relative properties of the probe materials and surrounding media strongly influence the directivity of the probe, especially in the planes through the probe axis, because the relation between the internal probe field and external field is certainly different for field components normal to the probe axis compared to components along the probe axis. The isotropy error must be assessed in the corresponding media, and any restrictions in the validity range of the calibration must be indicated (e.g., whether the probe is limited to measurements in fields normal to the probe axis). For more details see [6].

- In lossy media with high field gradients the position of the calibration center in the probe must be indicated. Precise probe positioning is necessary. Any uncertainty of the probe position will increase the calibration uncertainty.

- In probes with several sensors, the sensors are usually displaced with respect to the calibration center. This will produce an additional isotropy error depending on the direction and decay of the field gradient. The maximum error can be estimated from the sensor displacement and the field gradient.

- The probe might behave differently in the immediate vicinity of the media boundaries than when it is completely surrounded by the media. These effects must be considered during measurements near the boundaries.

If the probe is destined for a specific measurement task (e.g., SAR measurements in liquid filled shell phantoms), the above mentioned relative errors of the calibration can be significantly reduced when the calibration setup is similar to the typical measurement situation.

In lossy liquids the unit of interest is often not the field strength but the specific absorption rate (SAR) which can be derived from the E-field measurement (5.1). Since the SAR is proportional to liquid conductivity, a direct calibration in terms of SAR would be valid only for liquids with exactly the same conductivity. The E-field sensitivity depends more on the complex dielectric constant of the liquid and is less sensitive to the conductivity alone. The E-field calibration therefore has a broader range of validity and is preferred for routinely performed tests such as the certification of mobile phones, for which the dielectric parameters of tissue simulating liquid may slightly vary over time.

5.3 Calibration Procedures

For the calibration of E-field probes in lossy liquids, an electric field with an accurately known field strength must be produced within the measured liquid. For standardization purposes it would be desirable if all measurements which are necessary to assess the correct field strength would be traceable to standardized measurement procedures. In the following two different calibration techniques are summarized:

5.3.1 Transfer Calibration with Temperature Probes

In lossy liquids the specific absorption rate (SAR) is related both to the electric field (E) and the temperature gradient (dT/dt) in the liquid.

$$SAR = \frac{\sigma}{\rho}|E|^2 = c\frac{dT}{dt} \tag{5.1}$$

whereby σ is the conductivity, ρ the density and c the heat capacity of the liquid.

Hence, the electric field in lossy liquid can be measured indirectly by measuring the temperature gradient in the liquid. Non-disturbing temperature probes (optical probes or thermistor probes with resistive lines) with high spatial resolution (<1-2 mm) and fast reaction time (<1 s) are available and can be easily calibrated with high precision [2]. The setup and the exciting source have no influence on the calibration; only the relative positioning uncertainties of the standard temperature probe and the E-field probe to be calibrated must be considered. However, several problems limit the available accuracy of probe calibrations with temperature probes:

- The temperature gradient is not directly measurable but must be evaluated from temperature measurements at different time steps. Special precaution is necessary to avoid measurement errors caused by temperature gradients due to energy equalizing effects or convection currents in the liquid. Such effects cannot be completely avoided, as the measured field itself destroys the thermal equilibrium in the liquid. With a careful setup these errors can be kept small.

- The measured volume around the temperature probe is not well defined. It is difficult to calculate the energy transfer from a surrounding gradient temperature field into the probe. These effects must be considered, since temperature probes are calibrated in liquid with homogeneous temperatures. There is no traceable standard for temperature rise measurements.

- The calibration depends on the assessment of the specific density, the heat capacity and the conductivity of the medium. While the specific density and heat capacity can be measured accurately with standardized procedures ($\sim 2\%$ for c; much better for ρ) , there is no standard for the measurement of the conductivity. Depending on the method and liquid, the error can well exceed $\pm 5\%$.

- Temperature rise measurements are not very sensitive and therefore are often performed at a higher power level than the E-field measurements. The nonlinearities in the system (e.g., power measurements, different components, etc.) must be considered.

Considering these problems, the possible accuracy of the calibration of E-field probes with temperature gradient measurements in a carefully designed setup is about $\pm 10\%$ (RSS) [4]. Recently, a setup which is a combination of the waveguide techniques and the thermal measurements was presented in

[7]. The estimated uncertainty of the setup is ±5% (RSS) when the same liquid is used for the calibration and for actual measurements and ±7-9% (RSS) when not, which is in good agreement with the estimates given in [4].

5.3.2 Calibration with Analytical Fields

In this method a technical setup is used in which the field can be calculated analytically from measurements of other physical magnitudes (e.g., input power). This corresponds to the standard field method for probe calibration in air; however, there is no standard defined for fields in lossy liquids.

When using calculated fields in lossy liquids for probe calibration, several points must be considered in the assessment of the uncertainty:

- The setup must enable accurate determination of the incident power.
- The accuracy of the calculated field strength will depend on the assessment of the dielectric parameters of the liquid.
- Due to the small wavelength in liquids with high permittivity, even small setups might be above the resonant cutoff frequencies. The field distribution in the setup must be carefully checked for conformity with the theoretical field distribution.

In the following section a setup which allows the analytical calculation of the SAR will be introduced.

5.4 New Waveguide Setup for Probe Calibration

Rectangular waveguides are self-contained systems. In the frequency band in which only the dominant TE_{01} mode exists, highly accurate fields can be generated for calibration purposes if reflections can be minimized or compensated for. Considerable standing waves unavoidably occur if a lossy liquid is inserted in the waveguide. However, the cross sectional field distribution which is defined only by the geometry is not modified by these standing waves, a fact which can be utilized for generating well defined fields inside lossy liquid.

Three different standard waveguides (R9, R14 and R22) with overlapping frequency ranges were realized covering the frequency range of interest, i.e., from 800 up to 2500 MHz. In each waveguide, a planar, dielectric slab (ϵ_r = 3.3) was introduced to minimize reflections (return loss < -10 dB). The lossy tissue simulating liquid in which the probe had to be calibrated was

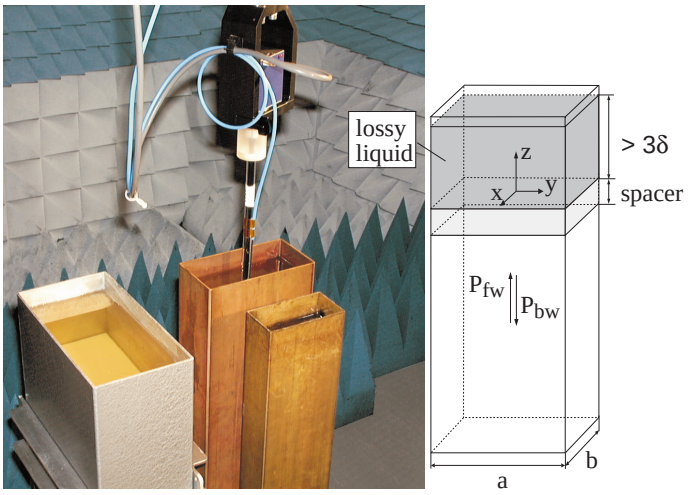

Figure 5.1: Experimental setup for assessment of the conversion factor when using a vertically rectangular waveguide.

filled into the vertically standing waveguide. The medium depth had to be chosen such that the standing waves within the liquid were negligible, i.e., larger than three times the skin depth (< -50 dB at the interface liquid-slab). The attenuation of the waveguide adapters was determined to be 0.05 dB by the transmission method using two identical adapters. Table 5.1 gives an overview of some of the construction details.

	R9	R14	R22
WG cross section*	248 x 124	165 x 82.5	109 x 54.7
Spacer height*	50	30	25
Liquid height*	150	130	80

* all dimensions in mm

Table 5.1: Description of the waveguide systems.

With these setups, the total power absorbed by the lossy liquid can be accurately determined by measurement of the forward and reflected powers. Since all power entering the lossy liquid is absorbed by the liquid, the volume SAR can be determined as:

$$SAR^V = \frac{4\,(P_{fw} - P_{bw})}{ab\delta}\, cos^2(\pi\frac{y}{a})\, e^{(-2z/\delta)} \tag{5.2}$$

where ab is the cross sectional area of the waveguide, P_{fw} and P_{bw} the forward and backward powers inside the waveguide and δ the skin depth inside the lossy liquid.

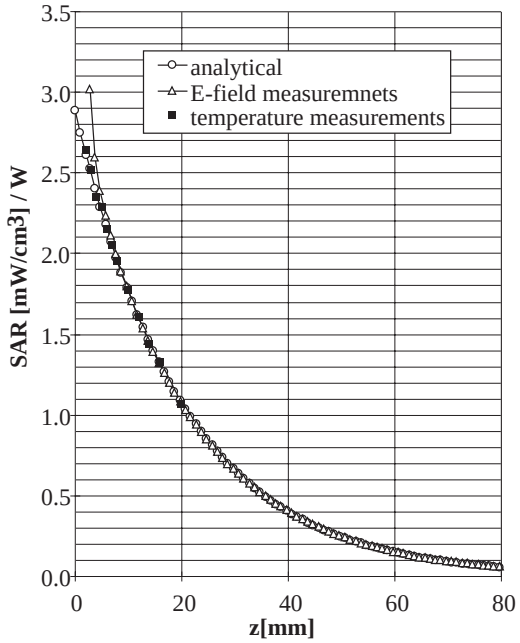

Figure 5.2: Comparison of SAR assessed by an analytical approach and by E-field or temperature measurements at 900 MHz (R9 setup). The enhanced reading in the close vicinity of the spacer caused by boundary effects is not evaluated for the calibration.

The volume SAR^V in $[mW/cm^3]$ can be determined from power measurements regardless of the dielectric parameters of the lossy liquid. The skin depth used in equation (5.2) can be assessed by measuring along the z-axis and applying an exponential curve fitting. Nevertheless, for the desired calibration in terms of the external E-field, the conductivity of the liquid must be known.

$$E_x = \sqrt{\frac{SAR^V}{\sigma}} \tag{5.3}$$

The conductivity can be derived from the permittivity and the attenuation constant (α=$1/2\delta$) in the lossy liquid:

$$\sigma = \frac{\alpha}{\pi f}\sqrt{\frac{\alpha^2}{\mu_0^2} + \frac{\omega^2 \varepsilon_0 \varepsilon_r}{\mu_0}} \tag{5.4}$$

This equation provides higher accuracy in assessing the conductivity of the lossy liquid because: (i) the measurement error for permittivity is smaller than for conductivity and (ii) the derived conductivity error is only half of the assessed permittivity error. However, the attenuation constant must be assessed with high accuracy.

The distribution of (5.2) is only valid provided higher modes are not generated in the liquid. This has been verified by taking scan measurements at different heights from the dielectric spacer. The measurements were performed using the rectangular E-field probe ER3DV5, which has three dipole sensors aligned to the probe coordinate system and thus provides the possibility to assess the dominant field component. The measurements showed that the E_y and E_z components were zero and the E_x component of the filed followed the sinusoidal distribution of the incident TE_{01} mode (see Fig.5.3). The relative theoretical distribution was within $\pm$1.5% for the entire volume. In addition, the SAR values assessed by temperature measurements along the z-axis were compared with (5.2), the agreement of which is much better than the expected worst-case uncertainty of the temperature rise assessment (see Fig. 5.2).

In Fig. 5.2 the position of the calibration center in the probe is at a height of z=2.7 mm, which is the distance from the probe tip to the center of sensor elements. The higher sensitivity of the E-field probe for the first few measured points, as seen in Fig. 5.2, is due to the boundary effects caused by the immediate vicinity of the dielectric spacer (at z=0 mm probe is in direct contact with the spacer). These points are therefore not included in the evaluation procedure. Furthermore, in addition to the assessment of the enhancement factors for each probe sensor, the setup also allows additional factors to be specified for compensation of the boundary effect whenever the probe is oriented normal to the measured surface [8].

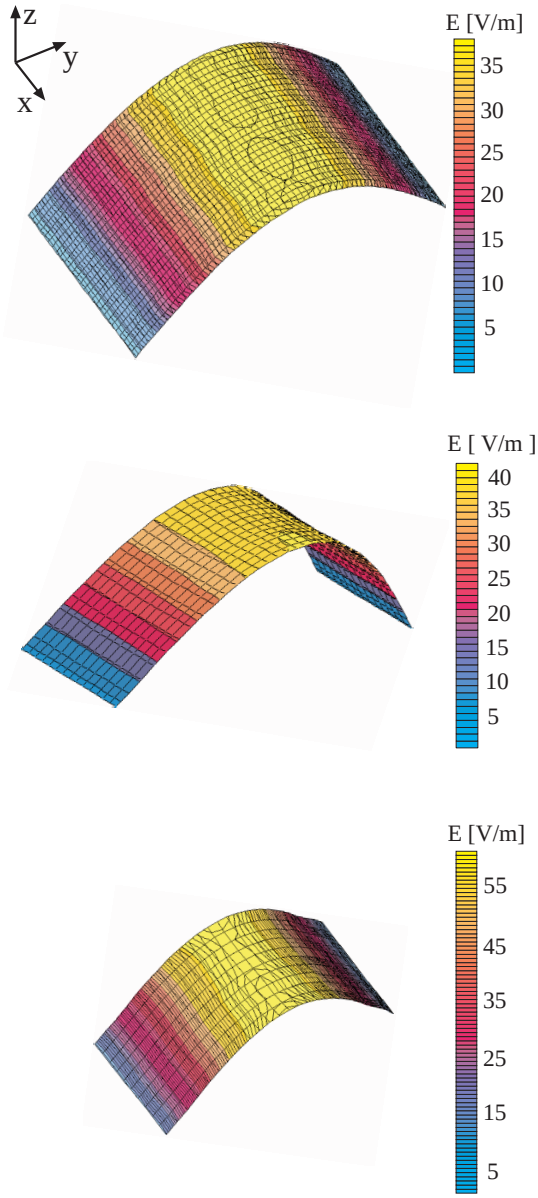

Figure 5.3: Verification of the analytical field distribution in the liquid by scanning the entire volume of R9, R14 and R22 waveguide with ER3DV5 probe. Presented plane is at a height of 5 mm from the dielectric spacer.

5.5 Uncertainty Analysis

The uncertainty budget has been evaluated for the presented calibration procedure according to the NIS81 [9] and NIST1297 [10] documents. The results for the three middle frequencies of each setup/band are given in Table 5.2.

	Probability Distribution	Standard Uncertainty 900 MHz	1500 MHz	1800 MHz
Incident power	rectangular	±1.2%	±1.2%	±1.2%
Mismatch uncertainty	rectangular	±0.6%	±0.6%	±0.6%
Exp. fitting error (95% confidence)	normal	±0.4%	±0.2%	±0.2%
Liquid permittivity	rectangular	±2.3%	±2.8%	±2.9%
Probe positioning	normal	±0.5%	±0.8%	±1.0%
Field homogeneity	rectangular	±0.6%	±1.2%	±1.4%
Combined Standard Uncertainty:		±2.8%	±3.4%	±3.6%

Table 5.2: Uncertainty Budget.

The values reveal the effect on SAR uncertainty for each error component.

- The power reading error is derived from comparison between several calibrated power meters (from different manufacturers) and calibrated power sources. Although the manufacturers guarantee a traceable accuracy to the NIST standard of ±5%, the above comparison gave the measurement uncertainty of only ±2%.

- The reflections in the waveguide were determined with a HP8753A network analyzer and four point calibration in the waveguide. The S-parameters of the coax-to-waveguide adapters, directional couplers and attenuators were determined with NWA.

- The accuracy of the attenuation constant was derived from a statistical analysis on the probe data at distances from 5 up to 40 mm from the liquid boundary in 1 mm steps. The probe was rotated around it's axis and the average reading was used to cancel probe isotropy error. Using these data, the 95% confidence range on the attenuation constant was determined.

- The liquid permittivity was measured with the open coaxial dielectric probe kit HP85070A. The uncertainty was determined according to the HP probe kit manual. The conductivity of the liquid was measured as well, but was not used in the evaluation. It should be mentioned here that although using the HP probe does not constitute the most accurate method, it is easy to use and quite commonly employed.
- The probe positioning error is calculated from the accuracy of the mechanical surface detection accuracy of ± 0.1 mm and analytical SAR gradient of 5-10% per mm depending on the frequency band.
- Field homogeneity was evaluated for the entire measured volume inside the waveguides.
- Error sources with negligible impact are not mentioned in the table (e.g., assessment of waveguide dimensions, etc.).

5.6 Conclusions

The here presented waveguide system is a robust and easy-to-use setup enabling calibration of dosimetric E-field probes with high precision. Even more important is that the calibration of the setup can be reduced to power measurements which can be traced to a standard calibration procedure. The practical limitation given by the waveguide size to the frequency band between 800 and 2500 MHz is not severe in the context of compliance testing, since the most important operational frequencies of mobile communications systems are covered. The presented waveguide system is therefore well suited for implementation as a standard calibration technique for dosimetric probes in this frequency range. For frequencies below 800 MHz, transfer calibration with temperature probes remains the most practical way to achieve calibration with decent precision.

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