Robust phase-retrieval for quick whole-body SAR assessment using dual plane amplitude-only data

J. Fridén, H. Isaksson, B. Hansson and B. Thors

A robust phase-retrieval method with stable convergence and back-propagation properties for quick experimental whole body specific absorption rate (SAR) assessments is presented. A combination of a fast and coarse method and a more accurate gradient-based method is used to optimise the overall performance. To prevent the solution being trapped in a local minimum, several initial phase distributions are used. An accurate measurement procedure has been developed which reduces measurement time by roughly a factor of 2.5–4 at common mobile communication frequencies compared with a volume scan based procedure.

Introduction: Human exposure to radio frequency (RF) electromagnetic fields is usually quantified in terms of the specific absorption rate (SAR), which is the rate of dissipated energy per unit mass within the exposed body. In the frequency range 100 kHz to 10 GHz, basic restrictions on SAR are provided to prevent established adverse health effects related to whole-body heat stress and excessive localised tissue heating [1]. For measurement based SAR assessments, the radiating device is placed under a phantom filled with tissue-equivalent liquid. The SAR is traditionally obtained using a volume scan of the magnitude of the electric field components. These measurements can be time-consuming, especially for whole-body SAR assessments, and with an increasing number of frequency bands and antennas on each device under test (DUT) it is desirable to speed up the procedure.

Previous attempts to decrease the time required for experimental SAR assessments are either biased to the field shapes of existing DUTs [2, 3] or assume that the measurement system provides both amplitude and phase of the field components [4]. Here, a method suited to commercially state-of-the-art SAR measurement systems is proposed which is not biased to any specific design of the DUT.

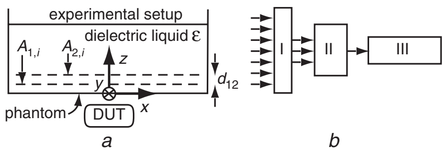

Fig. 1 *Experimental setup and phase-retrieval algorithm*

a Experimental setup
b Phase-retrieval algorithm

Method: The approach, illustrated in Fig. 1, is based on a dual-plane amplitude-only scan [5, 6] of the electric field components generating amplitude distributions $A_{1,i}$ and $A_{2,i}$. Here, i denotes either of the Cartesian components *x, y*, or *z*. A phase-retrieval algorithm is applied to recover the full complex field on the lower measurement plane. This field is then propagated into a volume and the whole-body SAR is calculated according to

$$\mathrm{SAR_{wb}} = \frac{1}{m}\int \sigma |E_{\mathrm{RMS}}|^2 \, \mathrm{d}V \qquad (1)$$

where σ, E_{RMS}, and m denote the conductivity, the root mean square (RMS) electric field, and an appropriate mass, respectively. Similar to [4], a prerequisite for good accuracy is that the fields have decayed sufficiently at the edges of the measurement planes. To improve convergence and avoid local minima [6, 7], several phase distributions are used and finally a gradient search is applied. A more detailed description of the algorithm is given below.

Fundamentals: A complex electric field component $E_{1,i}$ at one plane is propagated to a parallel plane by [5, 6]

$$E_{2,i} = \mathcal{T}E_{1,i} = \mathcal{F}^{-1}\exp(-jk_z d)\mathcal{F}E_{1,i} \qquad (2)$$

where $\mathcal{F}$ is a two-dimensional spatial Fourier transform, k_z is the z-component of the wave number vector, and d is the distance between the planes. Note that $|E_{j,i}| = A_{j,i}$. In the algorithm described below, the following error measures are used for forward propagation (F), back propagation (B) and dual plane (D) errors

$$\Delta_{\mathrm{F}}(E_{1,i}) = \left(\sum_{xy} A_{2,i}^4\right)^{-1} \sum_{xy}\left(|\mathcal{T}E_{1,i}|^2 - A_{2,i}^2\right)^2 \qquad (3)$$

$$\Delta_{\mathrm{B}}(E_{2,i}) = \left(\sum_{xy} A_{1,i}^4\right)^{-1} \sum_{xy}\left(|\mathcal{T}^{-1}E_{2,i}|^2 - A_{1,i}^2\right)^2 \qquad (4)$$

$$\Delta_{\mathrm{D}}(E_{1,i}) = \sum_{xy}\left(\left[|E_{1,i}|^2 - A_{1,i}^2\right]^2 + \left[|\mathcal{T}E_{1,i}|^2 - A_{2,i}^2\right]^2\right) \qquad (5)$$

Note that the dimension of the error measures is power squared (W^2) which is used to obtain differentiable error measures, and that the summation is carried out over all points in each plane.

Algorithm: The input data is the measured amplitude distributions $A_{1,i}$ and $A_{2,i}$ on two parallel planes where plane 1 is closest to the radiating device (see Fig. 1).

Step I: Forward propagation: A number of phase distributions $\phi_{1,i}^n, n = 1, \ldots, N_{\mathrm{I}}$ are pre-calculated. Each phase distribution is that of either a dipole antenna, random plane-wave bundle, or constant. The plane-wave bundles consist of sets of randomly chosen plane waves with radial wave numbers $k_\rho \leq k_0/|\sqrt{\varepsilon_r}|$ used to reflect the near normal wave propagation in the tissue simulating liquid ($\varepsilon_r \simeq 40$). For each phase distribution, the complex field $E_{1,i}^n = A_{1,i}\exp(j\phi_{1,i}^n)$ is formed and the forward propagation error Δ_{F} is calculated. The $N_{\mathrm{II}} < N_{\mathrm{I}}$ best results are kept for further use in step II.

Step II: Amplitude-conserving iteration: The N_{II} complex fields are propagated back and forth between the planes, using $\mathcal{T}$ and $\mathcal{T}^{-1}$. At each step the calculated phase is saved for further use while the amplitude distribution is reset to the measured values [5–7]. After a given number of iterations Δ_{F} is calculated and the best result is kept for step III.

Step III: Gradient search: A quasi-Newton gradient search method is applied to the best result after step II, where the norm Δ_{D} is used. Thereafter, repeated use of (2) is used to retrieve the electric field in a volume and calculate the SAR.

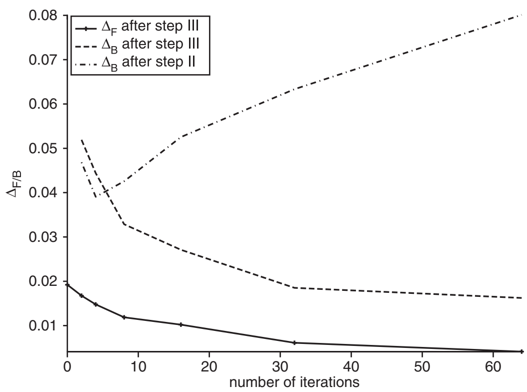

Fig. 2 *Forward and backward propagation errors $\Delta_{F,B}$ using data from Sony-Ericsson P990 mobile phone*

Table 1: Relative error in whole-body SAR plus measurement time required

DUTs	f (MHz)	$\Delta\mathrm{SAR_{wb}}$ (%)	Measured time (min) Volume/dual plane	Time gain factor
Racal 167–100	900	−4.9	37.5/15	2.5
Kathrein 738 573	900	−1.9	20/8	2.5
	1800	−0.9	32/8	4
Sony-Ericsson G900	900	2.5	15/6	2.5
	1800	3.9	60/15	4
	2000	3.7	60/15	4
Kathrein 80010248	900	−0.8	22.5/9	2.5
	1800	1.3	52/13	4
	2000	−2.9	68/17	4

Results and conclusions: Back propagation towards the phantom bottom is stable if step III is applied (see Fig. 2). Accurate results were obtained by sampling the electric field over an area including RF energy within 25 dB from the maximum, using a stepsize between consecutive samples of half a medium wavelength. In Table 1 results are given for one mobile phone and three small base station antennas. Using the proposed phase retrieval method, measurement time could be reduced with a factor of 2.5–4 compared with the volume scan based procedure. The obtained whole-body SAR results were within 5% of the volume scan data.

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