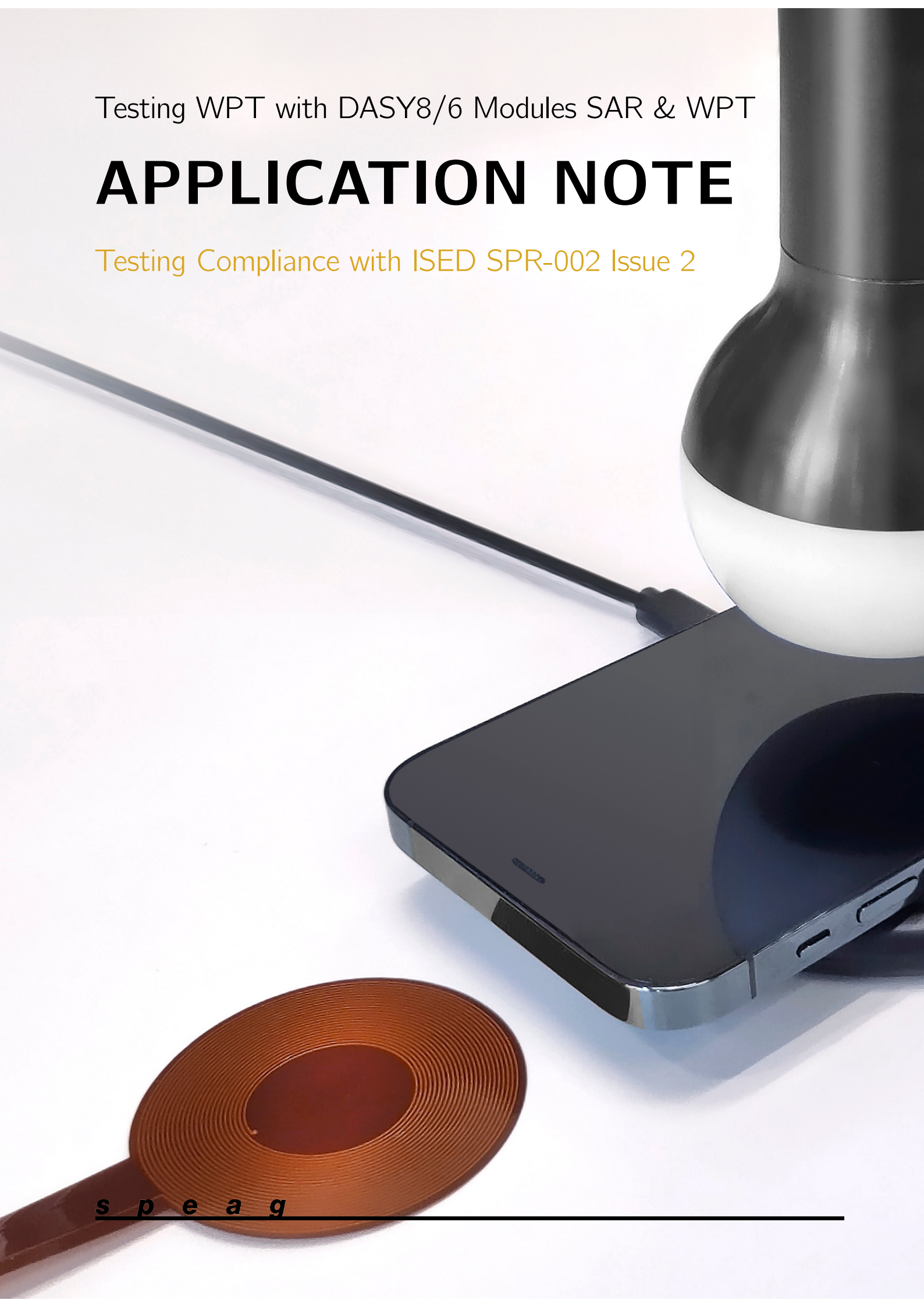


Testing WPT with DASY8/6 Modules SAR & WPT

APPLICATION NOTE

Testing Compliance with ISED SPR-002 Issue 2



Testing Compliance of WPT Devices with DASY8/6 Modules SAR & WPT According to ISED SPR-002 Issue 2 (Revision 2)

1 Scope of this Document

This application note provides guidance on how to demonstrate compliance with the basic restrictions of the local induced electric (E-) field and specific absorption rate (SAR) in accordance with Issue 2 of ISED SPR-002 [1]:

- ≥ 4 MHz: DASY8/6 Module SAR V16.2+ measures the induced SAR and E-fields inside the standard phantom directly and fully complies with RSS-102 [3] and ISED SPR-002 Issue 2 [1];
- < 4 MHz: DASY8/6 Module WPT V2.4+ (i) measures the incident fields, including phase, in a volume equivalent to the entire half-space at high resolutions, (ii) reconstructs the Maxwell field in this volume generated by the complete WPT system that may include the transmitter and receiver, e.g., the wireless charger with the phone on top, and (iii) computes the induced SAR and E-fields inside the standard phantom by means of simulations applying the fully validated Sim4Life solver (P-EM-QS). The method formally also fully complies with Section 8 of [1] (Computational Assessment) but is much more accurate and reliable as it only uses measured data as input for the simulations.

Hence, the methods described here provide the most accurate assessments of the actual maximum exposure currently available.

Note: Even though the methods are fully compatible with Sections 6 and 8 of ISED SPR-002 Issue 2 [1], submission of a statement to declare that *"The evaluation is performed according to the attached Application Note "Testing Compliance of WPT Devices with DASY8/6 Modules SAR & WPT According to ISED SPR-002 Issue 2 (Revision 2)" issued by SPEAG."* is recommended.

2 Summary of ISED SPR-002 Issue 2

2.1 Scope and Method

The scope of ISED SPR-002 Issue 2 [1] encompasses:

- assessments against the radiofrequency (RF) exposure limits to prevent both nerve stimulation (NS) and thermal effects
- assessments against both the reference levels (RL) and basic restrictions (BR)
- measurement-based and computational assessments

The method to assess the BR by measurements is at the top of the assessment method hierarchy (see Figure 1.1) and is, therefore, the first choice.

Note: Computational assessments based on modeling of the device-under-test (DUT) have large uncertainties, as the exposure is determined by the incident field strengths at the surface of the DUT. It is a fundamental law that the validation of the incident fields at the surface governs the uncertainty assessment of computational methods.

Note: Determination of the coverage factor usually requires hundreds of simulations with anatomical models to generate sufficient statistical power [2].

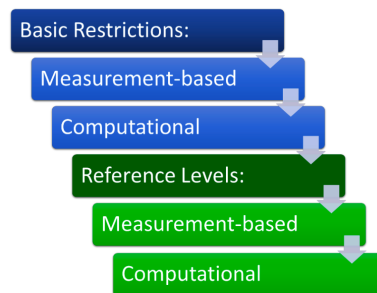


Figure 1.1: Assessment method hierarchy specified in [1]

2.2 Instrumentation Requirements

Section 5 of ISED SPR-002 Issue 2 [1] sets out the general requirements for compliance testing of wireless power transfer (WPT) devices. In particular, assessments are required to be performed at zero distance (i.e., at the touch position, especially for NS-based assessments). ISED SPR-002 Issue 2 refers to RSS-102 [3] regarding the requirements for measurement-based assessments against the BR for the SAR, whereas the requirements for measurement-based assessments against the BR for the induced E-field will be defined in a future issue.

Section 7 of ISED SPR-002 Issue 2 provides the requirements for measurement-based assessments against the RL. In particular, the detailed requirements of the probe and the sensor inside the probe are specified (Sections 7.1.6 and 7.1.7, respectively). A comparison of the specifications of the MAGPy probe Version 2 with these requirements is provided in Table 1.1. Section 8 of ISED SPR-002 Issue 2 provides the requirements for simulation-based assessments and suggests the use of the same material properties for the tissue-simulating liquid as in Section 8.3.4 of IEC/IEEE 63184 [4].

	Sensitivity [A/m or V/m]	Ampl. flatness [dB]	Linear range [A/m or V/m]	Linearity error [dB]	Sensor size ^a [mm]	Isotropy [dB]
SPR-002 Issue 2	H: ≤ 1 A/m E: ≤ 1 V/m	≤ 1	defined as a function of RL	≤ 0.5	$\leq d_{meas}/1.7$	≤ 1
MAGPy probe V2	H: 0.1 A/m E: 0.08 V/m	<0.2 (typ.)	H: 0.1–3200 A/m E: 0.1–2000 V/m	H: <0.2 (typ.) E: <0.5 (typ.)	H: 10 mm E: 50 mm	<0.5 (typ.)

^a Sensor size requirement in ISED SPR-002 Issue 2 was defined as a function of the distance relative to the center of the probe antenna, i.e., d_{meas} , in order to limit the errors in high gradient fields, i.e., integration of the sensor size

Table 1.1: Comparison of the specifications of MAGPy probe Version 2 with the probe and sensor requirements outlined in ISED SPR-002 Issue 2 [1]. **The distance requirement is not relevant for assessment with DASY8/6 Module WPT V2.4+, as the system determines the induced fields via simulations (see the note below).**

Note: The minimal distance requirements are not applied for the probe system used in DASY8/6 Module WPT V2.4+, as the system does not rely on single measurements but utilizes field reconstruction to assess the actual exposure. As the measured incident fields are the input for the simulations, validation of the DUT model is not required.

3 SPEAG's Measurement Solutions

3.1 DASY8/6 Module SAR V16.2+

DASY8/6 Module SAR V16.2+ meets all performance requirements of IEC/IEEE 62209-1528:2020 [5] and RSS-102 [3] for frequencies between 4 MHz and 10 GHz. This Application Note provides guidance on how the maximum instant *in vivo* E-field is determined from the SAR scan.

3.2 DASY8/6 Module WPT V2.4+

DASY8/6 Module WPT V2.4+ meets all performance requirements of IEC/IEEE 63814 [4]. It is composed of the isotropic probe MAGPy-8H3D+E3D Version 2, the reference probe (MAGPy-RA ϕ V2), and the data acquisition system (MAGPy-DAS) mounted to the DASY8/6 robot via the emergency stop (MAGPy-ES). At each probe location, 8 isotropic magnetic (H-) field values plus the phase are acquired, as well as the isotropic E-field measurement.

The field is measured on a high density grid (7.33 mm resolution) such that the incident quasi-static H-field (amplitude and phase) of the entire measured volume can be reconstructed by our advanced and validated vector potential reconstruction (see Appendix A for more information). The incident E-field distribution is measured in the same volume, enabling the accurate determination of the field impedance at $d = 30$ mm. Due to the geometric

design of the E_z -field sensor, the measured information is sufficient for a reliable estimation of the E-fields at the surface of the DUT, i.e., $d = 0$, and its potential coupling to the tissue simulating media, even for very localized E-field sources. The energy absorbed in the phantom, compared to the energy stored in the H-field, is very small for frequencies < 4 MHz (see Section 8.9 of the DASY8/6 Module WPT Manual [6]), i.e., < -20 dB ($< 1\%$). Therefore, the incident field is not affected by the presence of the phantom for inductive sources.

The local E-field and SAR induced by the incident H-field are assessed without approximation and with known uncertainty by Sim4Life's Quasi-Static EM Solver (P-EM-QS) (ZMT Zurich MedTech AG) based on the measured and reconstructed fields. The local E-field and SAR induced by the incident E-field¹ are determined by a conservative approximation that is valid for local E-field sources [7]. The validity of the local E-field condition is automatically assessed by the system, including checking whether the field impedance is less than 10% of the plane wave impedance of 377Ω .

The total field evaluation (see Appendix B for its validation) provides the assessed total peak local induced E-field and total peak spatial-average SAR (psSAR1g/10g), which are compared to the BR.

The dedicated graphical user interface (GUI) fully automates the testing workflow. More details about DASY8/6 Module WPT V2.4+ are provided below and in the DASY8/6 Module WPT V2.4+ Manual [6].

Note: The method implemented in DASY8/6 Module WPT V2.4+ is equivalent to the use of the validated P-EM-QS solver of Sim4Life (see Appendix C) to determine the induced E-field and SAR by simulations but without modeling the DUT and without the validation uncertainties. Thus, the method is much more accurate than compliance testing by simulations, since the only remaining uncertainty is the reconstruction and measurement uncertainty, which is typically less than 1.3 dB. For typical and realistic simulation modeling uncertainty, see [8].

4 Test System and Procedures for Frequencies ≥ 4 MHz

4.1 System Requirements

DASY8/6 Module SAR V16.2+ meets all performance requirements of IEC/IEEE 62209-1528:2020 [5] and RSS-102 [3] for frequencies between 4 MHz and 10 GHz (see DASY8/6 Module SAR Manual [9]). To determine the induced instant peak E-field ($pE_{ind,inst}$) and the peak spatial-average SAR values (psSAR1g/10g) as required by ISED SPR-002 Issue 2 [1], the following system configuration is recommended:

- DASY8/6 Module SAR software
- ELI phantom
- HBBL4-250Vx head simulating liquid
- EX3DVx probe with conversion factor assessment at 6 MHz (covers 4–9 MHz) and 13 MHz (covers 9–19 MHz)
- confined loop antennas CLA-6 and CLA-13 for system check and validation purposes

4.2 Measurement Procedure

The workflow to demonstrate compliance with the BR, illustrated in Figure 1.2, is equivalent to standard psSAR evaluations with an additional step – Determination of $pE_{ind,tissue,inst}$ – described below.

¹The highest E-field generated by WPT systems is often traceable to local charge accumulations (e.g., across the discrete capacitor to achieve resonance, at the end of conductors), which decay rapidly (proportional to $1/d^4$) but which can potentially induce strong fields in the body [7]. These charge accumulations are difficult to predict and to simulate accurately. However, this issue is overcome with DASY8/6 Module WPT V2.4+ as it uses measurements to determine the actual field characteristics and to conservatively determine the field contribution.

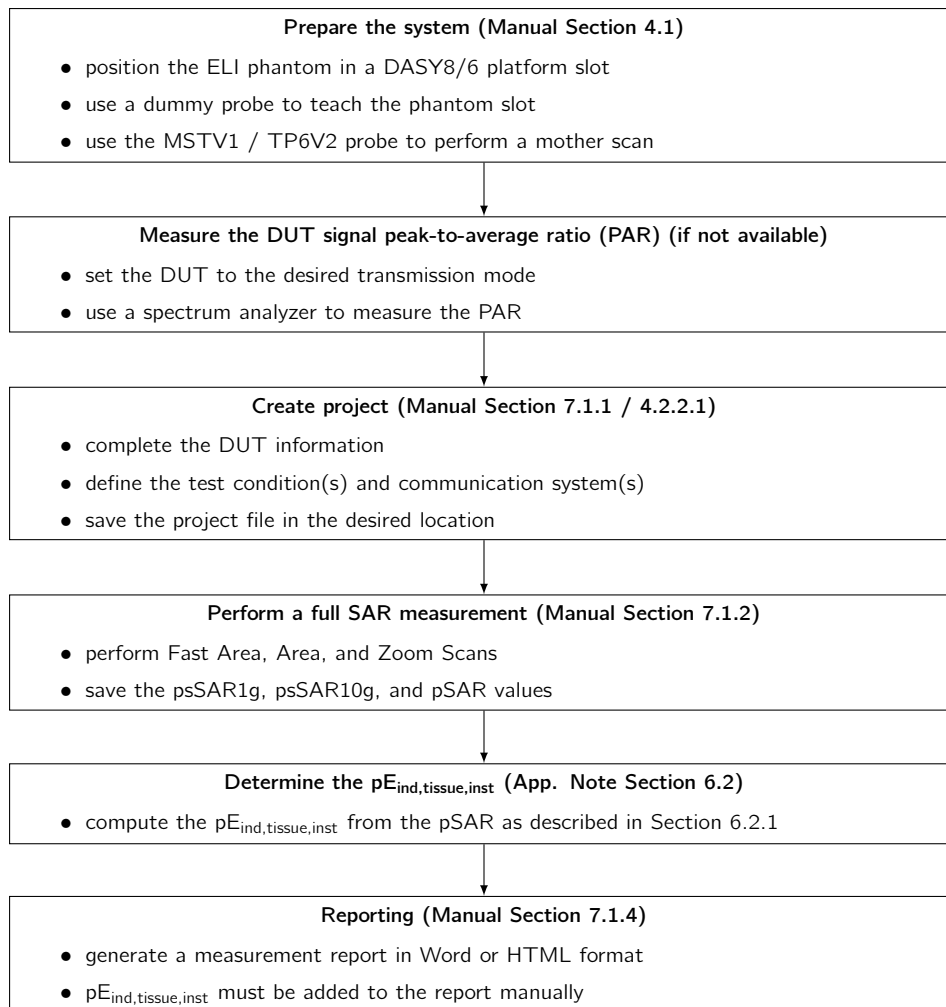


Figure 1.2: DASYS8/6 Module SAR step-by-step measurement procedure

4.2.1 Determining $pE_{ind,tissue,inst}$

The $psSAR_{1g/10g}$ is determined from a regular Zoom Scan (see Figure 1.3). In addition, DASY8/6 Module SAR reports the $pSAR$ (maximum SAR at the inner phantom surface), which is used to calculate the $pE_{ind,tissue,inst}$.



SAR Results	
Measured psSAR	
psSAR1g [W/kg]	0.395
psSAR8g [W/kg]	0.114
psSAR10g [W/kg]	0.097
pSAR [W/kg]	1.81

Figure 1.3: $psSAR_{1g/10g}$ and $pSAR$ results derived from a Zoom Scan measured with DASY8/6 Module SAR

The pE_{ind} (maximum E-field value at the phantom surface) can be calculated with:

$$pE_{ind} = \sqrt{psSAR \cdot \frac{\rho}{\sigma}} \quad (1.1)$$

where pE_{ind} = maximum E-field value at the phantom surface in V/m
 $psSAR$ = local specific absorption rate in W/kg
 σ = conductivity in S/m
 ρ = equivalent tissue density, set to 1000 kg/m^3 to account for the actual density of brain or body tissue

The $pE_{ind,inst}$ (maximum instantaneous E-field value at the phantom surface) is then given by:

$$pE_{ind,inst} = pE_{ind} \cdot \sqrt{PAR} \quad (1.2)$$

where $pE_{ind,inst}$ = maximum instantaneous E-field value at the phantom surface in V/m
 pE_{ind} = maximum E-field value at the phantom surface in V/m
 PAR = signal peak power to average ratio (linear)

$$pE_{ind,tissue,inst} = pE_{ind,inst} \cdot CF \quad (1.3)$$

where $pE_{ind,inst}$ = maximum instantaneous E-field value at the phantom surface in V/m
 CF = coverage factor, which translates the induced fields in the standardized homogeneous tissue to those in non-homogeneous tissues, after taking field enhancements at dielectric boundaries into account, as generally determined in [2]
 $pE_{ind,tissue,inst}$ = maximum instantaneous E-field values in non-homogeneous tissues

Note: The Peak-to-Average Ratio (PAR), which is often reported in dB, should be converted to linear to calculate the $pE_{ind,inst}$.

Note: The $pE_{ind,inst}$ as well as the 5 mm-line and $2 \times 2 \times 2 \text{ mm}^3$ -cube averaged induced E-field will be directly provided in DASY8/6 Module SAR V17.0.

4.3 Uncertainty

The uncertainty for evaluation of any WPT source for $psSAR_{1g/10g}$ is determined according to IEC/IEEE 62209-1528:2020 [5]. Typically, the uncertainties ($k = 2$) are $<22.8\%$ for $psSAR_{1g/10g}$ (see Table 1.2) and $<12.5\%$ for $pE_{ind,inst}$, based on the assumption of a maximum extrapolation uncertainty of less than 5%.

DASY8/6 Uncertainty Budget According to IEC/IEEE 62209-1528 (Frequency band: 4 MHz–300 MHz range)								
Symbol	Error Description	Unc. Value	Prob. Dist.	Div.	(c_1) (1 g)	(c_1) (10 g)	Std. Unc. (1 g)	Std. Unc. (10 g)
Measurement System Errors								
CF	Probe Calibration	$\pm 13.3\%$	N	2	1	1	$\pm 6.65\%$	$\pm 6.65\%$
CF _{drift}	Probe Calibration Drift	$\pm 1.7\%$	R	$\sqrt{3}$	1	1	$\pm 1.0\%$	$\pm 1.0\%$
LIN	Probe Linearity	$\pm 4.7\%$	R	$\sqrt{3}$	1	1	$\pm 2.7\%$	$\pm 2.7\%$
BBS	Broadband Signal	$\pm 0.6\%$	R	$\sqrt{3}$	1	1	$\pm 0.3\%$	$\pm 0.3\%$
ISO	Probe Isotropy	$\pm 7.6\%$	R	$\sqrt{3}$	1	1	$\pm 4.4\%$	$\pm 4.4\%$
DAE	Other Probe+Electronic	$\pm 0.8\%$	N	1	1	1	$\pm 0.8\%$	$\pm 0.8\%$
AMB	RF Ambient	$\pm 1.8\%$	N	1	1	1	$\pm 1.8\%$	$\pm 1.8\%$
Δ_{sys}	Probe Positioning	± 0.006 mm	N	1	0.04	0.04	$\pm 0.10\%$	$\pm 0.10\%$
DAT	Data Processing	$\pm 1.2\%$	N	1	1	1	$\pm 1.2\%$	$\pm 1.2\%$
Phantom and Device Errors								
LIQ(σ)	Conductivity (meas.)	$\pm 2.5\%$	N	1	0.78	0.71	$\pm 2.0\%$	$\pm 1.8\%$
LIQ(T_σ)	Conductivity (temp.)	$\pm 5.4\%$	R	$\sqrt{3}$	0.78	0.71	$\pm 2.4\%$	$\pm 2.2\%$
EPS	Phantom Permittivity	$\pm 14.0\%$	R	$\sqrt{3}$	0	0	$\pm 0\%$	$\pm 0\%$
DIS	Distance DUT – TSL	$\pm 2.0\%$	N	1	2	2	$\pm 4.0\%$	$\pm 4.0\%$
D _{xyz}	Device Positioning	$\pm 1.0\%$	N	1	1	1	$\pm 1.0\%$	$\pm 1.0\%$
H	Device Holder	$\pm 3.6\%$	N	1	1	1	$\pm 3.6\%$	$\pm 3.6\%$
MOD	DUT Modulation	$\pm 2.4\%$	R	$\sqrt{3}$	1	1	$\pm 1.4\%$	$\pm 1.4\%$
TAS	Time-average SAR	$\pm 1.7\%$	R	$\sqrt{3}$	1	1	$\pm 1.0\%$	$\pm 1.0\%$
RF _{drift}	DUT drift	$\pm 2.5\%$	N	1	1	1	$\pm 2.5\%$	$\pm 2.5\%$
VAL	Val Antenna Unc.	$\pm 0.0\%$	N	1	1	1	$\pm 0\%$	$\pm 0\%$
RF _{in}	Unc. Input Power	$\pm 0.0\%$	N	1	1	1	$\pm 0\%$	$\pm 0\%$
Correction to the SAR results								
C(ϵ, σ)	Deviation to Target	$\pm 1.9\%$	N	1	1	0.84	$\pm 1.9\%$	$\pm 1.6\%$
C(R)	SAR scaling	$\pm 0.0\%$	R	$\sqrt{3}$	1	1	$\pm 0.0\%$	$\pm 0.0\%$
u(Δ SAR)	Combined Uncertainty						$\pm 11.4\%$	$\pm 11.3\%$
U	Expanded Uncertainty						$\pm 22.8\%$	$\pm 22.5\%$

Table 1.2: Uncertainty budget for peak 1 gram and 10 gram mass-average SAR measured with DASY8/6 Module SAR, assessed according to IEC/IEEE 62209-1528.

5 Procedures for Frequencies <4 MHz

5.1 System Requirements

To determine the induced E-field and SAR in the frequency range between 3 kHz and 4 MHz, the following equipment is required:

- DASY8/6 Module WPT V2.4+ including:
 - MAGPy-8H3D+E3D Version 2 probe (with the integrated data acquisition system MAGPy-DAS)
 - MAGy-RA ϕ V2 reference probe (as a phase reference)
 - MAGPy-ES emergency stop system
- WPT sources (incl. V-Coil500/3, V-Coil350/85, and V-Coil50/400) for system check and validation purposes

5.2 Measurement Procedure

The workflow to demonstrate compliance with the BR is illustrated in Figure 1.4. Detailed descriptions of each step can be found in Section 7 of the DASY8/6 Module WPT Manual [6].

5.3 Uncertainty

Guidance about the uncertainty evaluations for DASY8/6 Module WPT is provided in the Manual [6]. Typical uncertainties ($k = 2$) are <34% for psSAR1g/10g (see Tables 1.3 and 1.4) and <18% for pE_{ind} (see Table 1.5).

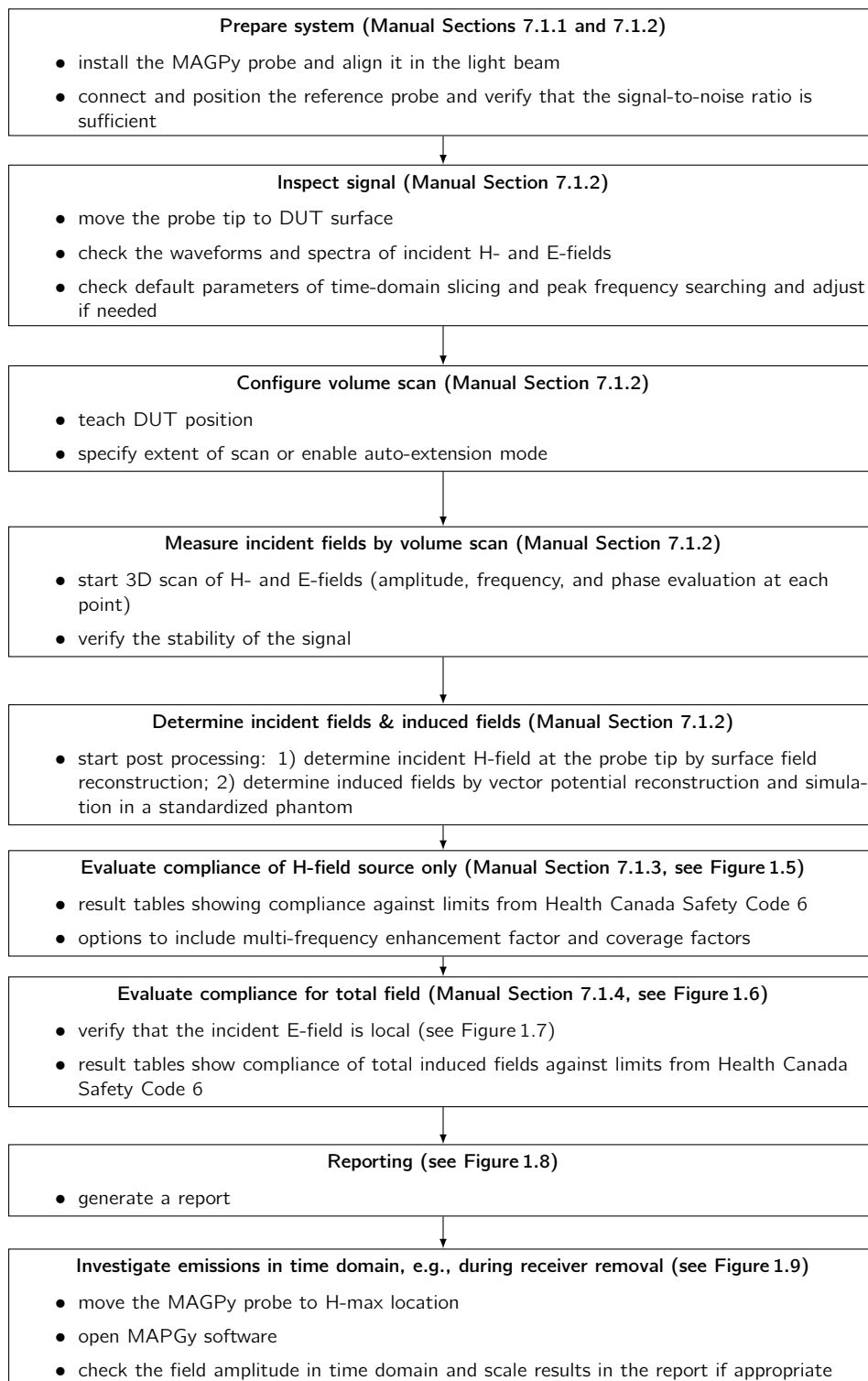


Figure 1.4: DASY8/6 Module WPT step-by-step measurement procedure

Distance [mm]	ICNIRP 2010/2020 [dB]				ICNIRP 1998 [dB]				IEEE 2019 [dB]				FCC [dB]				HC Code 6 [dB]			
	RL		BR		RL		BR		RL		BR		RL		BR		RL		BR	
	Peak H _{inc}	Peak E _{inc}	Peak E _{ind}	psSAR	Peak H _{inc}	Peak E _{inc}	Peak J _{ind}	psSAR	Peak H _{inc}	Peak E _{inc}	Peak E _{ind}	psSAR	Peak H _{inc}	Peak E _{inc}	Peak E _{ind}	psSAR	Peak H _{inc}	Peak E _{inc}	Peak E _{ind}	psSAR
2.0	26.1	33.5	-21.9	-27.4	42.6	33.0	10.6	-27.4	8.6	15.4	-25.5	-27.4	43.6	26.2	-21.9	-23.4	42.6	33.5	-21.6	-23.4

Figure 1.5: Table in the DASy8/6 Module WPT GUI showing the compliance evaluation results for the induced fields exclusively due to the incident H-field. Note that the "Total field evaluation" option (highlighted by the orange box) is un-checked in this case.

Distance [mm]	ICNIRP 2010/2020 [dB]				ICNIRP 1998 [dB]				IEEE 2019 [dB]				FCC [dB]				HC Code 6 [dB]			
	RL		BR		RL		BR		RL		BR		RL		BR		RL		BR	
	Peak H _{inc}	Peak E _{inc}	Peak E _{ind}	psSAR	Peak H _{inc}	Peak E _{inc}	Peak J _{ind}	psSAR	Peak H _{inc}	Peak E _{inc}	Peak E _{ind}	psSAR	Peak H _{inc}	Peak E _{inc}	Peak E _{ind}	psSAR	Peak H _{inc}	Peak E _{inc}	Peak E _{ind}	psSAR
2.0	26.1	33.5	-21.1	-27.4	42.6	33.0	11.6	-27.4	8.6	15.4	-24.7	-27.4	43.6	26.2	-21.1	-23.4	42.6	33.5	-20.8	-23.4

Figure 1.6: Table in the DASy8/6 Module WPT GUI showing the compliance evaluation results for the total induced fields (i.e., the exposures from both the incident H-field and E-field are assessed). Note that the "Total field evaluation" option (highlighted by the orange box) is checked in this case.

Scan info	Scan statistics	DUT info	Tool info	Tool options
Maximum H-field [RMS]	x: 42.67 A/m, y: 22.61 A/m, z: 191.09 A/m			
Maximum H-field location	x: 3.67 mm, y: 3.67 mm, z: 8.00 mm relative to DUT			
Maximum E-field [RMS]	x: 36.07 V/m, y: 17.06 V/m, z: 91.61 V/m			
Maximum E-field location	x: 7.33 mm, y: -29.33 mm, z: 500.00 μm relative to DUT			
Local E-field check	Successful (max. E/H ratio 1.43 ohm)			
H-field decay check	Successful			
Multi-freq. enhancement factor variation	H_FIELD: 0.0 dB			
Peak frequency	MIN: 399.93 kHz, MAX: 400.12 kHz, MEDIAN: 400.00 kHz, MEAN: 400.00 kHz, STD. DEV.: 11.23 Hz			

Figure 1.7: The part of the DASy8/6 Module WPT GUI for displaying the statistic information of the volume scan, e.g., the result of the local E-field check (highlighted by the orange box, where the maximum E/H ratio is also reported).

Simulation	Results	Compliance	Compliance (w/ coverage)	Frequency-domain	Time-domain
Available simulations		New simulation			
Simulation from 2023/10/27 17:11:30, 1 distances from 2.0 to 2.0 mm		Distances [mm] 2.0, 5.0			
		Distance limits MIN: 0.0 mm, MAX: 22.7 mm			
		Distances relative to DUT 2.0 mm, 5.0 mm			
		Tissue conductivity [S/m] 0.75			
		Tissue density [kg/m³] 1000			
		Simulation resolution [mm] 1			
Generate report		Show results		Simulate	

Figure 1.8: The part of the DASy8/6 Module WPT GUI for setting up the simulation and generating the report in DASy8/6 Module WPT. After finishing the simulation, a report can be generated by clicking the "Generate report" button (highlighted by the orange box).

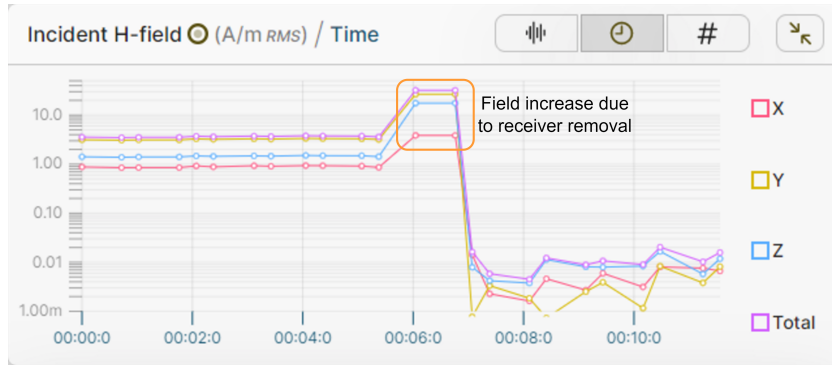


Figure 1.9: The time-domain plot of the incident H-field in the MAGPy GUI. The data were recorded from a commercial wireless charger while removing the smartphone placed on the charger. The same procedure can also be used to monitor the stability of the source.

DASY8/6 Uncertainty Budget for psSAR1g according to IEC/IEEE 63184						
Item	Error Description	Unc. Value (±dB)	Probab. Distr.	Div.	(c_i)	Std. Unc. (±dB)
Measurement system						
1	Amplitude calibration uncertainty	0.35	N	1	1	0.35
2	Probe anisotropy	0.60	R	$\sqrt{3}$	1	0.35
3	Probe dynamic linearity	0.20	R	$\sqrt{3}$	1	0.12
4	Probe frequency domain response	0.30	R	$\sqrt{3}$	1	0.17
5	Probe frequency linear interp. fit	0.15	R	$\sqrt{3}$	1	0.09
6	Spatial averaging	0.10	R	$\sqrt{3}$	1	0.06
7	Parasitic E-field sensitivity	0.10	R	$\sqrt{3}$	1	0.06
8	Detection limit	0.15	R	$\sqrt{3}$	1	0.09
9	Readout electronics	0	N	1	1	0
10	Probe positioning	0.19	N	1	1	0.19
11	Repeatability	0.10	N	1	1	0.10
12	Surface field reconstruction	0.20	N	1	1	0.20
Numerical simulations						
13	Grid resolution	0.02	R	$\sqrt{3}$	1	0.01
14	Tissue parameters	0	R	$\sqrt{3}$	1	0
15	Exposure position	0	R	$\sqrt{3}$	1	0
16	Source representation	0.09	N	1	1	0.09
17	Convergence and power budget	0	R	$\sqrt{3}$	1	0
18	Boundary conditions	0.10	R	$\sqrt{3}$	1	0.06
19	Phantom loading/backscattering	0.10	R	$\sqrt{3}$	1	0.06
Combined uncertainty ($k = 1$)						0.63
Expanded uncertainty ($k = 2$)						1.27 (33.9%)

Table 1.3: Uncertainty budget for peak 1 gram mass-average SAR measured with DASY8/6 Module WPT, assessed according to IEC/IEEE 63184.

DASY8/6 Uncertainty Budget for psSAR10g according to IEC/IEEE 63184						
Item	Error Description	Unc. Value (±dB)	Probab. Distr.	Div.	(c_i)	Std. Unc. (±dB)
Measurement system						
1	Amplitude calibration uncertainty	0.35	N	1	1	0.35
2	Probe anisotropy	0.60	R	$\sqrt{3}$	1	0.35
3	Probe dynamic linearity	0.20	R	$\sqrt{3}$	1	0.12
4	Probe frequency domain response	0.30	R	$\sqrt{3}$	1	0.17
5	Probe frequency linear interp. fit	0.15	R	$\sqrt{3}$	1	0.09
6	Spatial averaging	0.10	R	$\sqrt{3}$	1	0.06
7	Parasitic E-field sensitivity	0.10	R	$\sqrt{3}$	1	0.06
8	Detection limit	0.15	R	$\sqrt{3}$	1	0.09
9	Readout electronics	0	N	1	1	0
10	Probe positioning	0.19	N	1	1	0.19
11	Repeatability	0.10	N	1	1	0.10
12	Surface field reconstruction	0.20	N	1	1	0.20
Numerical simulations						
13	Grid resolution	0	R	$\sqrt{3}$	1	0
14	Tissue parameters	0	R	$\sqrt{3}$	1	0
15	Exposure position	0	R	$\sqrt{3}$	1	0
16	Source representation	0.04	N	1	1	0.04
17	Convergence and power budget	0	R	$\sqrt{3}$	1	0
18	Boundary conditions	0.10	R	$\sqrt{3}$	1	0.06
19	Phantom loading/backscattering	0.10	R	$\sqrt{3}$	1	0.06
Combined uncertainty ($k = 1$)						0.63
Expanded uncertainty ($k = 2$)						1.25 (33.4%)

Table 1.4: Uncertainty budget for peak 10 gram mass-average SAR measured with DASY8/6 Module WPT, assessed according to IEC/IEEE 63184.

DASY8/6 Uncertainty Budget for Peak Local E_{ind} according to IEC/IEEE 63184						
Item	Error Description	Unc. Value (\pm dB)	Probab. Distr.	Div.	(c_i)	Std. Unc. (\pm dB)
Measurement system						
1	Amplitude calibration uncertainty	0.35	N	1	1	0.35
2	Probe anisotropy	0.60	R	$\sqrt{3}$	1	0.35
3	Probe dynamic linearity	0.20	R	$\sqrt{3}$	1	0.12
4	Probe frequency domain response	0.30	R	$\sqrt{3}$	1	0.17
5	Probe frequency linear interp. fit	0.15	R	$\sqrt{3}$	1	0.09
6	Spatial averaging	0.10	R	$\sqrt{3}$	1	0.06
7	Parasitic E-field sensitivity	0.10	R	$\sqrt{3}$	1	0.06
8	Detection limit	0.15	R	$\sqrt{3}$	1	0.09
9	Readout electronics	0	N	1	1	0
10	Probe positioning	0.19	N	1	1	0.19
11	Repeatability	0.10	N	1	1	0.10
12	Surface field reconstruction	0.30	N	1	1	0.30
Numerical simulations						
13	Grid resolution	0.09	R	$\sqrt{3}$	1	0.05
14	Tissue parameters	0	R	$\sqrt{3}$	1	0
15	Exposure position	0	R	$\sqrt{3}$	1	0
16	Source representation	0.27	N	1	1	0.27
17	Convergence and power budget	0	R	$\sqrt{3}$	1	0
18	Boundary conditions	0.10	R	$\sqrt{3}$	1	0.06
19	Phantom loading/backscattering	0.10	R	$\sqrt{3}$	1	0.06
Combined uncertainty ($k = 1$)						0.73
Expanded uncertainty ($k = 2$)						1.45 (18.2%)

Table 1.5: Uncertainty budget for peak local (i.e., not spatial averaged) induced E-field measured with DASY8/6 Module WPT, assessed according to IEC/IEEE 63184.

6 Conclusions

This application note provides guidance on how to use DASY8/6 Module SAR V16.2+ for measurement-based assessments and DASY8/6 Module WPT V2.4+ for combined measurement and simulation assessments against the BR for the pE_{ind} and $psSAR_{1g/10g}$ in accordance with ISED SPR-002 Issue 2 for inductive WPT devices.

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A Reconstruct a Vector Potential \vec{A} From a Magnetic Field

The induced current simulation requires a vector potential instead of the H-field as input. The vector potential \vec{A} has the property of $\text{curl}(\vec{A}) = \vec{B}$, and in free space $\vec{B} = \mu_0 \vec{H}$.

This equation is non-trivial, as any additional gradient field still fulfills $\text{curl}(\vec{A} + \text{grad}(\phi)) = \vec{B}$. Luckily, an explicit formula, which requires $\text{div}(\vec{B}) \equiv 0$ on a rectilinear grid, can be derived [10]. For the x-component, the formula reads (others are cyclic permutations)

$$A_x = - \int_0^y \left[\frac{1}{3} B_z(x, v, z) + \frac{1}{6} B_z(x, v, 0) \right] dv + \int_0^z \left[\frac{1}{3} B_y(x, y, w) + \frac{1}{6} B_y(x, 0, w) \right] dw \quad (4)$$

where the subscripts x, y, z denote the components along their corresponding axes, and v and w denote the integration variables. The axis origin, i.e., the point at which the path integrals begin to integrate, can be arbitrarily chosen. Currently, the most dominant location of the \vec{B} field is chosen as the origin to minimize numerical integration artifacts. Details are provided in [10].

B Validation of the DASY8/6 Module WPT Evaluation of the Total Field

B.1 Evaluation of the Induced Fields by the Validation Source V-Coil50/6780 V2

B.1.1 Instrumentation and V&V Sources

The configuration of the DASY6 Module WPT system used in the validation measurements is listed in Table 6.

System	Type: Software Version: Manufacturer:	DASY6 Module WPT V2.4 Schmid & Partner Engineering AG, Switzerland
Positioner	Robot: Serial No: Controller: Serial No: Manufacturer:	TX90 XL F/18/0004593/A/001 CS8C F/18/0004593/C/001 Stäubli, France
Probe	Type: Serial Number: Calibrated On: Next Calibration: Frequency Range: H-Field Dynamic Range: E-Field Dynamic Range: H-Field Sensor Area: E-Field Sensor Length: Probe Length: Probe Tip Diameter: Manufacturer:	MAGPy-8H3D+E3D V2 3065 Apr. 6, 2023 Apr., 2024 3 kHz–10 MHz 0.1–3200 A/m 0.1–2000 V/m 1 cm ² 5 cm 335 mm 60 mm (flat tip) Schmid & Partner Engineering AG, Switzerland
6.78 MHz Verification Source	Source Model: Source Serial No.: Source Dimensions: Source Output Freq.: Source Current: Source Evaluated On: Source Manufacturer:	V-Coil50/6780 V2 1014 250 mm×125 mm×35 mm 6.78 MHz 0.394 A Jan. 29, 2024 Schmid & Partner Engineering AG, Switzerland

Table 6: DASY6 Module WPT system and Validation Source

B.1.2 Method

The 6.78 MHz validation source was simulated with the fullwave finite-difference time-domain solver and the magneto quasi-static (MQS) solver in Sim4Life V7.2, and also measured with DASY6 Module WPT V2.4. The total field approximation was also applied, with the incident E-field obtained from simulation/measurement as the input. This approaches a worst-case evaluation, as the contributions of the incident E-field to the induced E-field is further reduced at lower frequencies.

B.1.3 Results

The results are summarized in Table 7.

Simulation vs. Measurement	Method	pE_{ind} [V/m]	$psSAR_{1g}$ [W/kg]	$psSAR_{10g}$ [W/kg]
Simulation	Fullwave	109	4.05	1.97
	MQS	107	4.06	1.95
	Total field approximation	107	4.06	1.95
Measurement	MQS	104	3.97	1.97
	Total field approximation	104	3.97	1.97

Table 7: Results of the induced E-field evaluations performed with Sim4Life V7.2 and DASY6 Module WPT V2.4.

B.2 Conclusions

The MQS assessment implemented provides accurate results for the E-field and SAR induced by the H-field only. The total field approximation implemented in DASY8/6 Module WPT V2.4+ provides a reliable assessment of the maximum induced fields, e.g., $psSAR_{1g/10g}$ and pE_{ind} .

C Verification Report of the Low Frequency Magneto Quasi-Static Solver



Verification Report MQS001AA201507

Sim4Life and SEMCAD X Low Frequency Magneto Quasi–Static Solver

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Executive Summary

The THESS S.A. was mandated by ZMT Zurich MedTech AG (Offer No. 1420) to independently verify the Sim4Life and SEMCAD X platforms. The here documented MQS001AA201507 verification benchmark for the EM LF Magneto Quasi-static Solver was developed and tested for the Sim4Life Version v2.0 and SEMCAD X v14.8, and documented such that ZMT can automatically run the test for any new software version.

The MQS001AA201504 benchmark verifies the EM LF Magneto Quasi-static Solver against the analytically calculated value of the magnetic field generated by a circular thin-wire coil inside an adjacent conducting sphere. This benchmark tests the following solver features:

- that the EM LF Magneto Quasi-static Solver converges to the right solution
- that material interfaces are properly handled
- that the Biot-Savart sources are correctly implemented
- that post-processing correctly calculates derived quantities such as current density.

The agreement of the theoretically calculated magnetic field with the values derived from the Sim4Life and SEMCAD X platform is very good: The current density values at different positions inside the sphere match for the two methods with a deviation smaller than 0.5% for the finer discretization of the computational domain. With increasing grid resolution, the simulation results converge to the analytical solution.

In conclusion, the numerical MQS solver of Sim4Life and SEMCAD X therefore meets the requirements for modeling the magneto-quasistatic equation.

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1 Objectives

The objective of this verification report MQS001AA201507 is to document the verification of the Sim4Life v2.0 and SEMCAD X v14.8 Low Frequency Magneto Quasi-static Solver by comparing numerical to analytical solutions of a specific problem.

The MQS solver first calculates a magneto-static vector potential (A_0) using the Biot-Savart law and subsequently determines the induced E-fields and currents using potential continuity while considering the inhomogeneous dielectric property distributions in the human anatomy [2]. The equation $\nabla \cdot \sigma \nabla \phi = -j\omega \nabla \cdot (\sigma A_0)$ is solved (σ : conductivity, ω : angular frequency, ϕ : electric scalar potential) which is valid at frequencies where ohmic currents dominate over displacement currents.

The following features of the EM LF Magneto Quasi-static solver have been identified as fundamental and requiring verification:

- that the EM LF Magneto Quasi-static Solver converges to the right solution
- that material interfaces are properly handled
- that the Biot-Savart sources are correctly implemented
- that post-processing correctly calculates derived quantities such as current density

For that purpose an analytically solvable benchmark case has been chosen such that it makes use and covers all of these critical features. The benchmark is a homogeneous sphere exposed to current carrying ring wire.

2 Methodology

2.1 Introduction

The field of Magnetostatics was widely studied during the 19th century. The work of J.B. Biot and F. Savart made possible the calculation of the magnetic field originating from an electric current. They provide an approximation of the Maxwell equations valid for low frequency, provided a quasi-static behavior that can be assumed in the case of slow time variations (low frequency) and sufficiently small dimensions. The approximation condition is $(\frac{d}{\lambda})^2 \ll 1$, where d is the diameter of the computational domain and λ the wavelength. The law of Biot-Savart can be used in order to easily calculate the value of the magnetic field inside a head-sized sphere, with the dielectric properties of the human brain, created by an adjacent circular loop coil.

The numerically derived results of the EM LF Magneto Quasi-static Solver of the Sim4Life and SEMCAD X platform are compared with the theoretically calculated results in order to evaluate the reliability and accuracy of the former and this deviation is examined with respect to

- the relative solver tolerance used to terminate the numerical process,
- the grid step of the computational domain,
- the implementation of the material interfaces

2.2 Analytical solution

A surface coil (loop of uniform current) adjacent to a homogeneous conducting sphere can be used in order to predict the performance of MRI surface coils close to the human head. By solving the inhomogeneous boundary value problem of the system, the electromagnetic field inside the sphere can be calculated. The sphere's parameters, i.e. the relative dielectric constant ϵ_r and the conductivity σ , are chosen so as to model the human brain.

The magnetic field produced by the surface coil adjacent to the homogeneous sphere has been calculated by solving the inhomogeneous boundary value problem of a ring of radius R carrying uniform current I adjacent to a conducting dielectric sphere of radius α centered at the origin of a spherical coordinate system (Fig. 1).

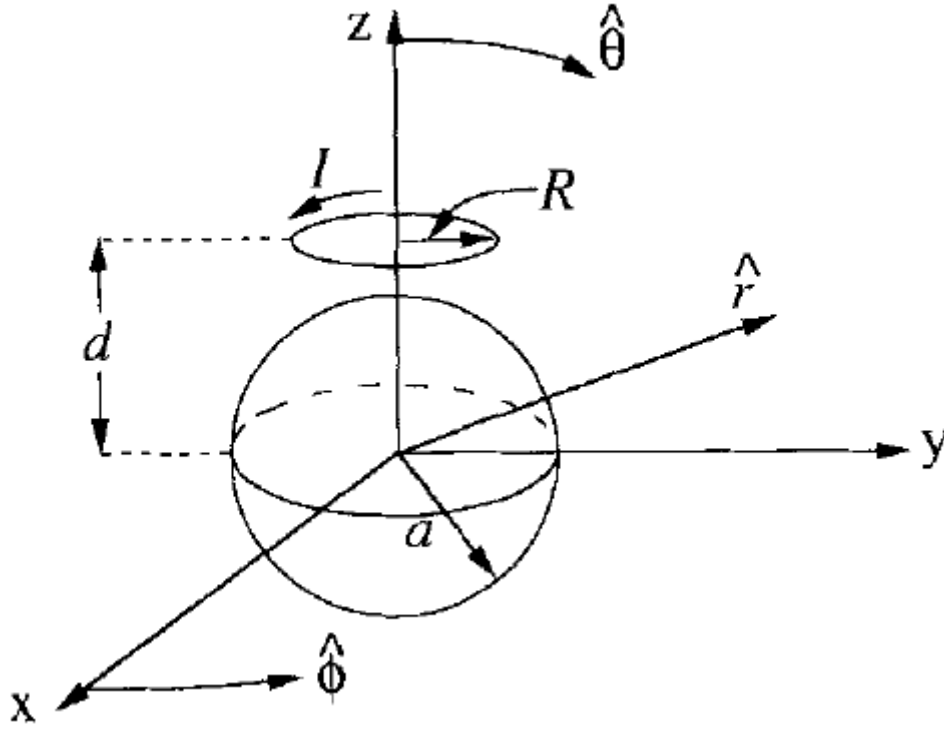


Figure 1: Schematic arrangement of a homogeneous conductive sphere near a circular current loop. The sphere is centered at the origin of the spherical coordinate system

The magnetic field inside the sphere is given by [1]

$$B_r(r, \theta, \phi) = \sum_{i=1}^{\infty} b_{i0} \sqrt{\frac{l(l+1)(2l+1)}{4\pi}} P_l(\cos\theta) \frac{j_l(k^{in}r)}{k^{in}r} \quad (1)$$

$$B_\theta(r, \theta, \phi) = - \sum_{i=1}^{\infty} b_{i0} \sqrt{\frac{(2l+1)}{l(l+1)4\pi}} \sin\theta \frac{dP_l(\cos\theta)}{d\cos\theta} \frac{1}{k^{in}r} \frac{\vartheta(j_l(k^{in}r))}{\vartheta r} \quad (2)$$

$$B_\phi(r, \theta, \phi) = 0 \quad (3)$$

where $j_l(kr)$ denotes the spherical Bessel functions of the first kind and $P_l(\cos\theta)$ are Legendre polynomials.

The wavenumber inside the sphere k^{in} is obtained from Maxwell's equation ,

$$\nabla \times \vec{B} = \mu_0 \vec{J} + \mu_0 \epsilon \frac{\partial \vec{E}}{\partial t}. \quad (4)$$

where μ_0 is the permeability of free space. Substituting $\vec{J} = \sigma \vec{E}$ and defining the relative dielectric constant as $\epsilon_r = \frac{\epsilon}{\epsilon_0}$ equation (4) is transformed to

$$i\omega \nabla \times \vec{B} = (i\omega \mu_0 \sigma + \epsilon_r \frac{\omega^2}{c^2}) \vec{E} \quad (5)$$

where ω is angular frequency, σ is electrical conductivity and c is the speed of light. The wave number inside the sphere k^{in} is the square root of the coefficient of

$$(k^{in})^2 = i\omega \mu_0 \sigma + \epsilon_r \frac{\omega^2}{c^2} \quad (6)$$

Solving equation (5) for the electric field, one is allowed to express the current density \vec{J} as

$$J_\phi(r, \theta, \phi) = \frac{i\omega\sigma}{k^{in}} \sum_{i=1}^{\infty} b_{l0} \sqrt{\frac{(2l+1)}{l(l+1)4\pi}} j_i(k^{in}r) \sin\theta \frac{dP_l(\cos\theta)}{d\cos\theta} \quad (7)$$

The b_{l0} are found by satisfying the boundary conditions of the magnetic field at the surface of a homogeneous conducting, dielectric sphere given an incident magnetic field produced by an adjacent ring of uniform current

$$b_{l0} = \mu_0 I 2\pi \sqrt{\frac{(2l+1)}{l(l+1)4\pi}} \frac{(k^{out})^2 R^2 h_i^{(1)}(k^{out}\sqrt{d^2+R^2})}{\sqrt{d^2+b^2}} \frac{dP_l(\xi)}{d\xi} \quad (8)$$

$$\frac{k^{in}(j_i(k^{out}\alpha)y_{i+1}(k^{out}\alpha) - y_i(k^{out}\alpha)j_{i+1}(k^{out}\alpha))}{k^{in}h_i^{(1)}(k^{out}\alpha)j_{i+1}(k^{in}\alpha) - k^{out}j_i(k^{in}\alpha)h_{i+1}^{(1)}(k^{out}\alpha)}$$

where k^{out} is the wave number in free space, y_i and $h_i^{(1)}$ are spherical Bessel functions of the second and third kinds, respectively, and ξ is the cosine of the angle subtended by the loop $\xi = \frac{d}{\sqrt{d^2+R^2}}$

2.3 Numerical Modeling

This verification study intends to compare the current density J calculated by the analytical solution, with the numerical results obtained by Sim4Life and SEMCAD X for the same problem. A sphere of 60mm radius and a surface coil of 20mm radius were placed at a distance of 50mm between the coil center and the nearest point of the sphere. For mathematical convenience the z axis of the coordinate system was chosen to be parallel to the axis of the coil. The sphere's relative dielectric permittivity ϵ_r and electrical conductivity σ are that of a human brain (white matter: $\sigma = 0.0626 S/m$, $\epsilon_r = 69800$).

3 Results

3.1 Criterion of convergence

No difference in the numerical results was observed when changing the value of relative tolerance (which is the criterion of convergence for the computational process) from 10^{-6} to 10^{-12} . In particular the maximum difference between the values of the electric field induced inside the sphere, as extracted at the center, is 0.000172%.

3.2 Grid step

Simulations with uniform grids and varying grid step were performed (0.3, 0.5, 1, 2, 3, 4 and 5 mm) and they gave similar results (Fig. 2). For comparison the magnetic field along two axes (Fig. 3) was extracted and is presented with the theoretical, as is calculated by the Law of Biot-Savart (Fig. 4) and (Fig. 5).

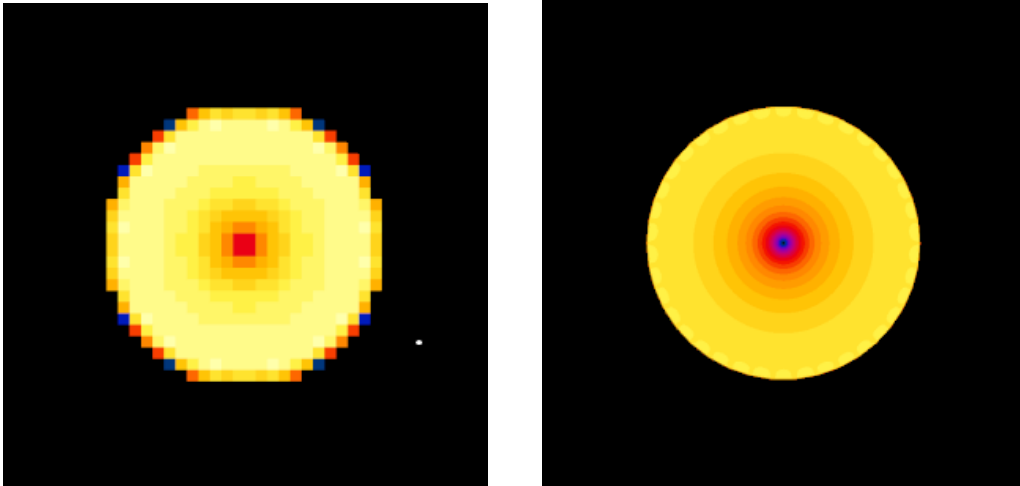


Figure 2: Slice views of the electric field inside the sphere for coarse (Grid Step: 5mm) and fine grid (Grid Step: 0.3mm).

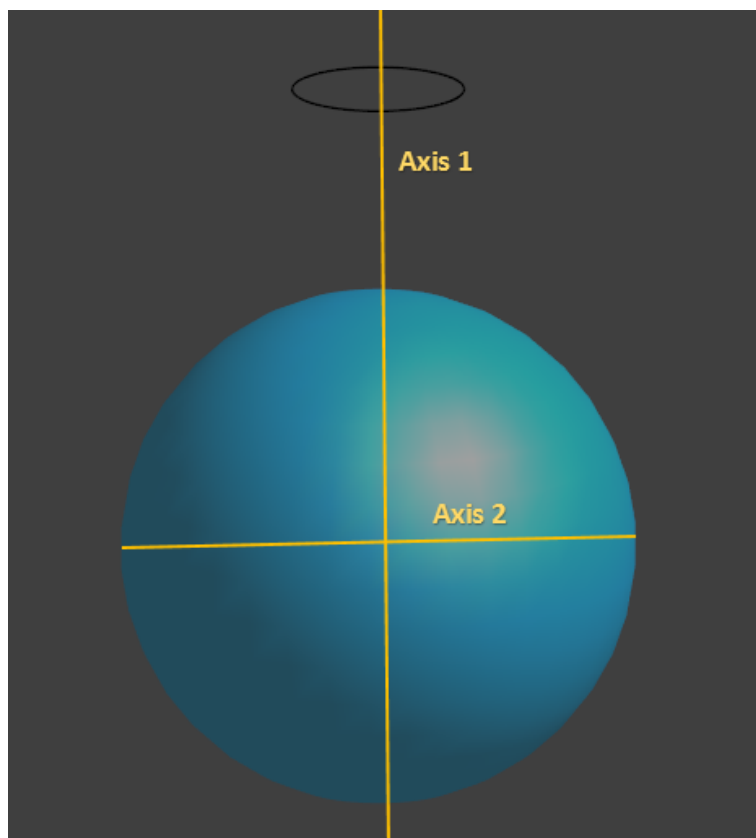


Figure 3: The two axes of extraction.

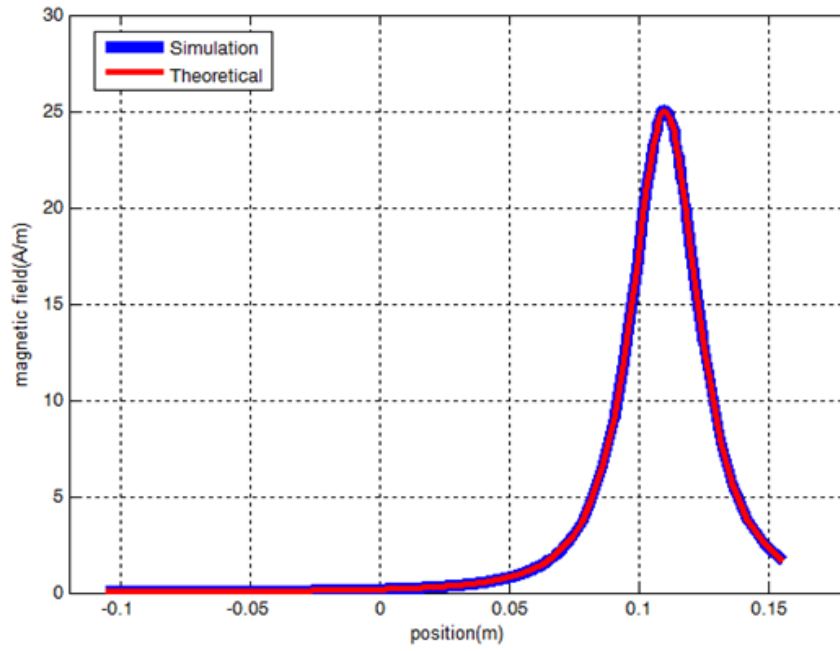


Figure 4: The extracted and the theoretical magnetic field along Axis 1 (Grid step: 0.3mm)

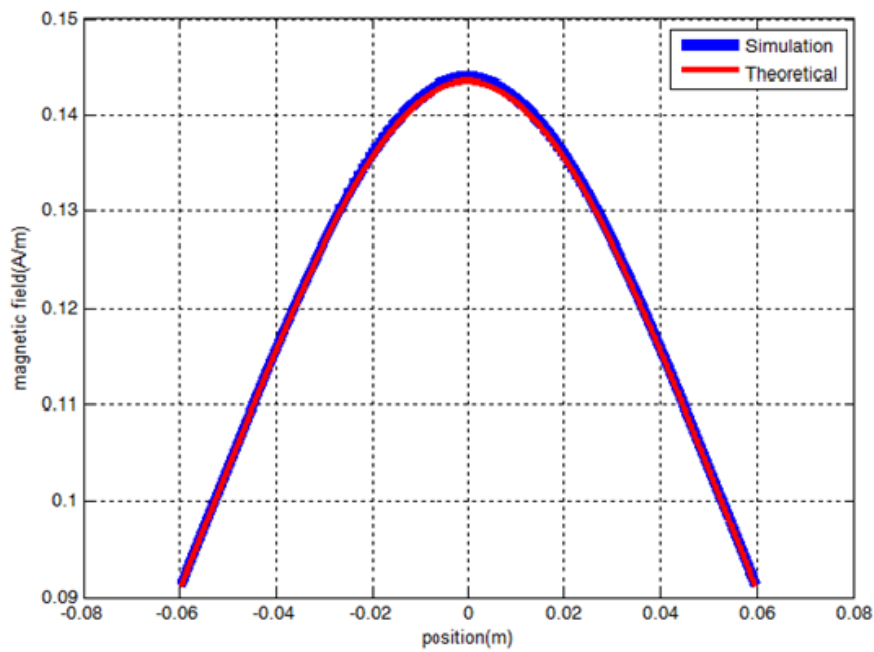


Figure 5: The extracted and the theoretical magnetic field along Axis 2 (Grid step: 0.3mm)

For the comparison between the theoretical and the simulated current distribution at the sphere, the deviation of the numerical solution from the analytical solution was evaluated at circles of distances 5, 10, 30 and 50mm from the center of the sphere (Fig. 6).

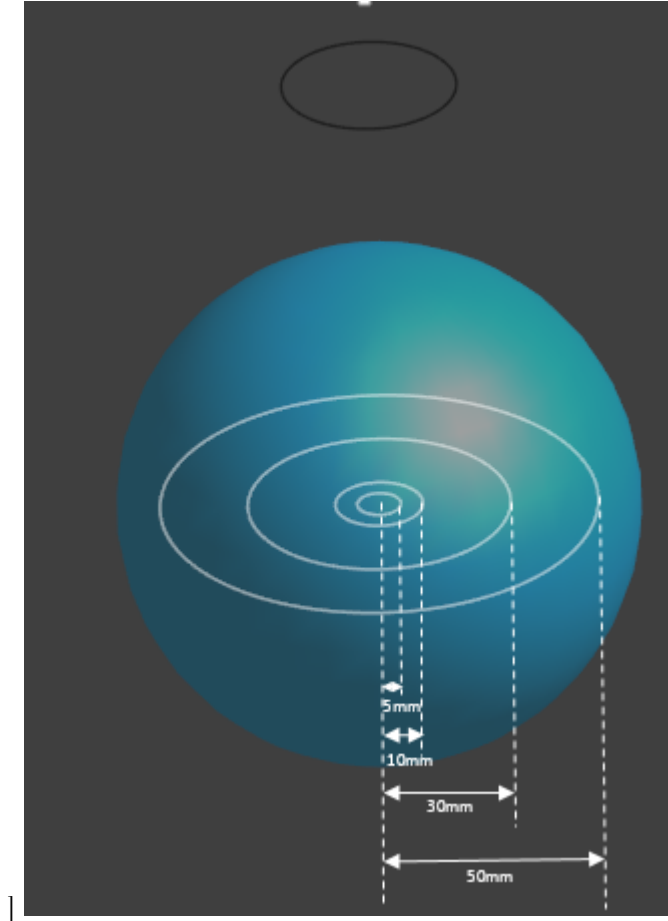


Figure 6: The two axes of extraction.

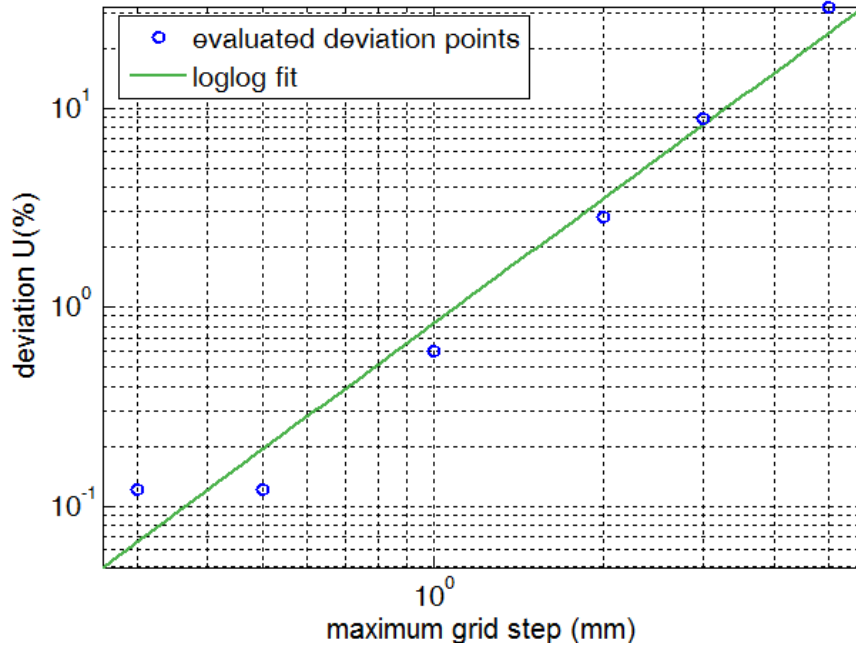
The computational space was discretized with a uniform grid of variable maximum step and the deviation between the numerical (N) and the analytical (T) solution for the current density was evaluated at the points of the numerical solution:

$$\text{deviation } U = \left| \frac{N - T}{T} \right| 100\% \quad (9)$$

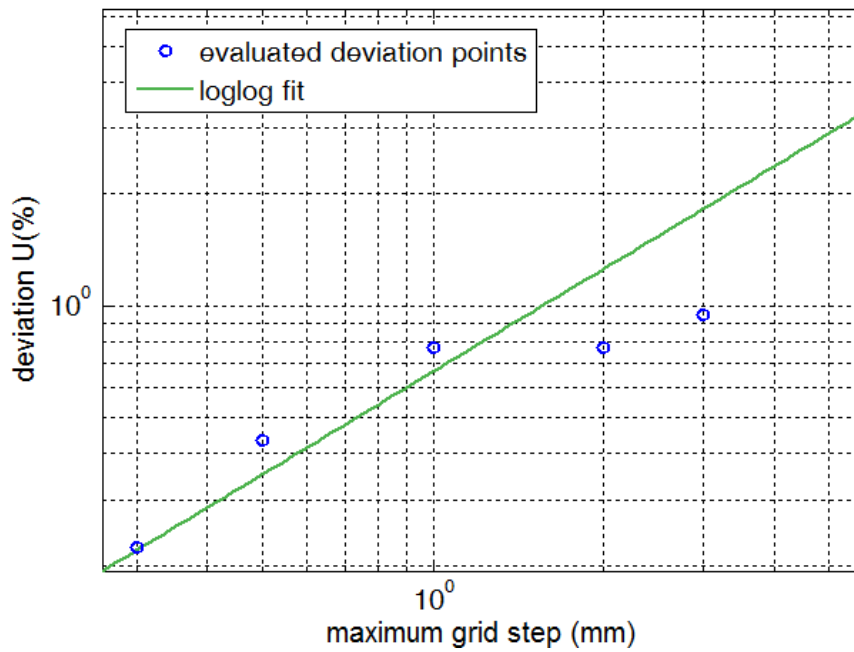
The maximum deviation on the above circles are shown in (Fig. 7). It is clear that, in every case, for a finer discretization of the grid (smaller grid step) the deviation continuously decreases and the numerical solution converges to the analytical solution.

3.3 Material interfaces

For the model with uniform grid step of 0.1mm, the radial component of the magnetic field was extracted on either side of the surface of the sphere, along a circle. At material interfaces, i.e., at the interface of air with the sphere, the radial component of the magnetic field should be identical when approaching the interface from both sides. The absolute value of the relative difference between the two values is shown in (Fig. 8). The deviation never exceeds 0.14% indicating that material interfaces are correctly handled by the solver.



(a)



(b)

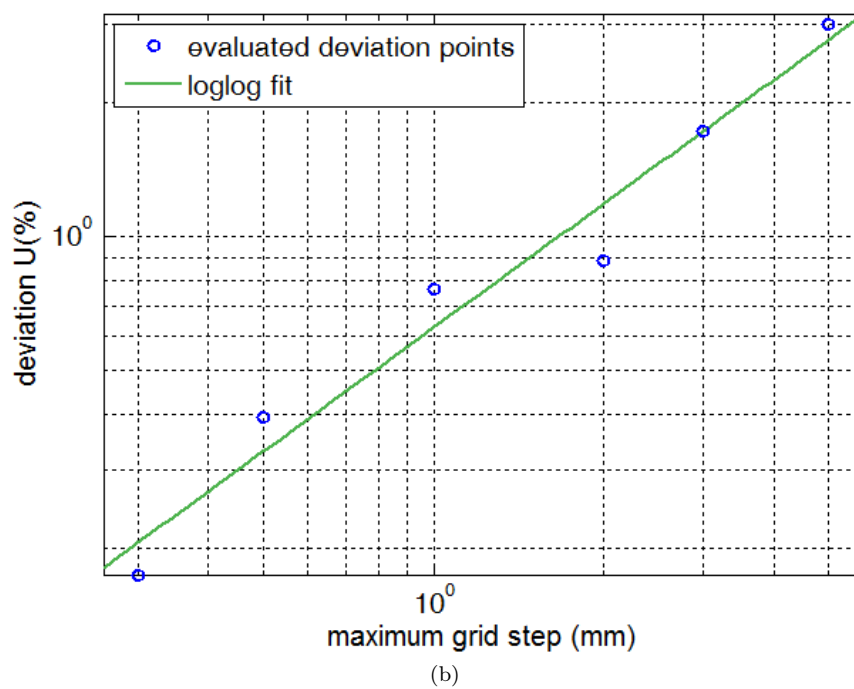
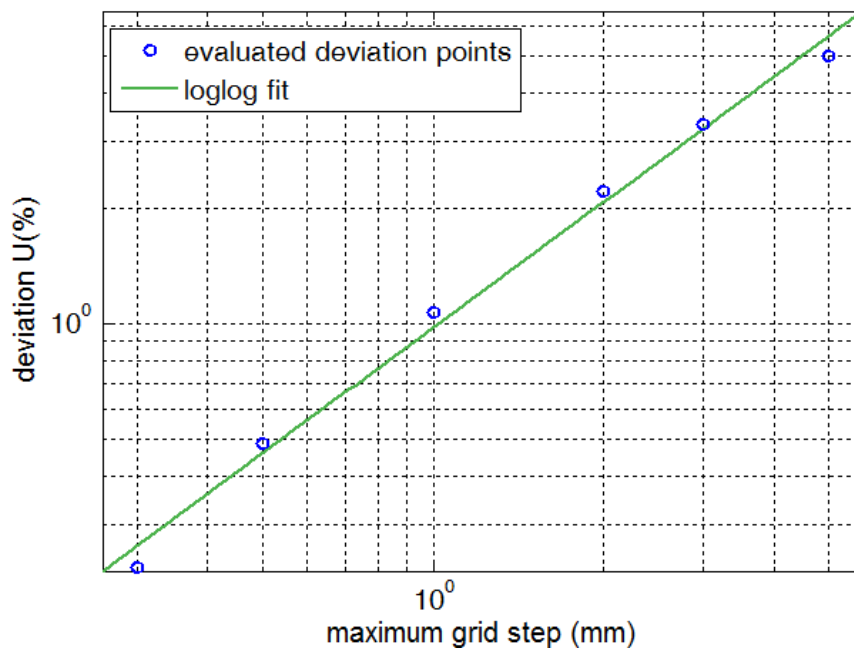


Figure 7: Maximum deviation (see equation (9)) of the numerical from the analytical solution along a circle at distance of 5mm (a), 10mm (b) 30mm (c) and 50mm (d) from the center of the sphere as a function of the maximum grid step.

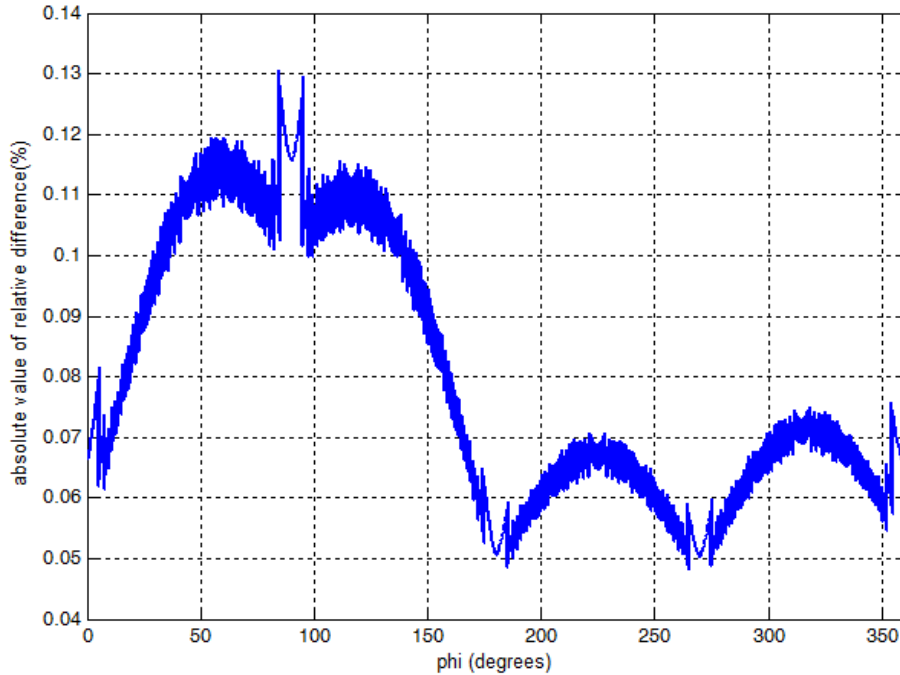


Figure 8: Relative difference (absolute value) between the perpendicular magnetic field components on either side of the sphere's surface. (Grid step: 0.1mm).

4 Conclusion

The purpose of this verification study was to examine the agreement between the numerical results obtained by the Sim4Life and SEMCAD X LF MagnetoQuasi-static solver and the analytically obtained results. It was shown that grid resolution has an important impact on accuracy. It is possible to keep the deviation between numerical and analytical solutions lower than 0.5%, by choosing the appropriate discretization (grid step). With increasing resolution, the simulation results converge to the analytical solution. Proper numerical convergence has been ascertained by varying the convergence criterium. The benchmark case tests the following fundamental solver features:

- that the EM LF Magneto Quasi-static Solver converges to the right solution
- that material interfaces are properly handled
- that the Biot-Savart sources are correctly implemented
- that post-processing correctly calculates derived quantities such as current density

The current density values at different positions inside the sphere match for the two methods with a deviation smaller than 0.5% for the finer discretization of the computational domain. With increasing resolution, the simulation results converge to the analytical solution.

Neither the spatial discretization nor the solution algorithm employed by Sim4Life and SEMCAD X use any assumptions based on the shape of the computational domain. This renders the approach suitable for any complex structures which might occur in biomedical applications. Because of this generalized verification approach it is valid to expect similarly accurate performance of the solver in simple geometries like the presented benchmarks and in more complex geometrical models.

In conclusion, the numerical MQS solver of Sim4Life and SEMCAD X therefore meets the requirements for modeling the magneto-quasistatic equation.

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