Fast SAR - Concept, Implementation, Results of Validation and Verification

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MIC MRA International Workshop 2016

ETH
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Swiss Federal Institute of Technology Zurich

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Motivation & Challenges

- wireless became pervasive
  - ~0.7 billion devices 2000 (voice)
  - ~5 billion devices today (data, voice)
  - ~80 billion devices by 2020 (lifestyle, biomedical/healthcare, data, voice)
- challenges
  - antennas integrated into smaller and smaller devices occupying minimal volume
  - minimal power consumption
  - directly connected to world and to other body-mounted and implanted devices
  - integrated wireless power transfer
  - integrated intelligent sensors (some of them EM based)
- technical contraints
  - SAR regulations
  - Over-the-Air (OTA) and Inside-the-Body (ITB) performance
  - EMC/EMI hostile environment

Content

- Challenges
- Concept and Basis of SAR Standards
- Implementation, Uncertainty, and Validation of Gold Standard SAR Systems
- Implementation, Uncertainty, and Validation of Vector Array Systems
- Future of SAR Evaluations
- Conclusions

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Declaration of Financial Interests or Relationships

- founder and shareholder of NFT
- founder & president of the board of ZMT
- founder & president of the board of SPEAG
- IT'IS performed research for various wireless, medical device companies,
- collaborations with regulators, e.g., FCC, FDA, NIST, NICT, NIM, TMC, RRA, etc.
- member of TC106/62209, IEC TC106/62253, ICES TC43/SC2, ICES TC28/SC1, SC2, SC3, SC4, CTIA ERP, ANSI 63.19, ITU SG1, WP-1B, IEC/62/MT40, ISO TS10974 JWG AMID, V&V40 (ASME), MDIC

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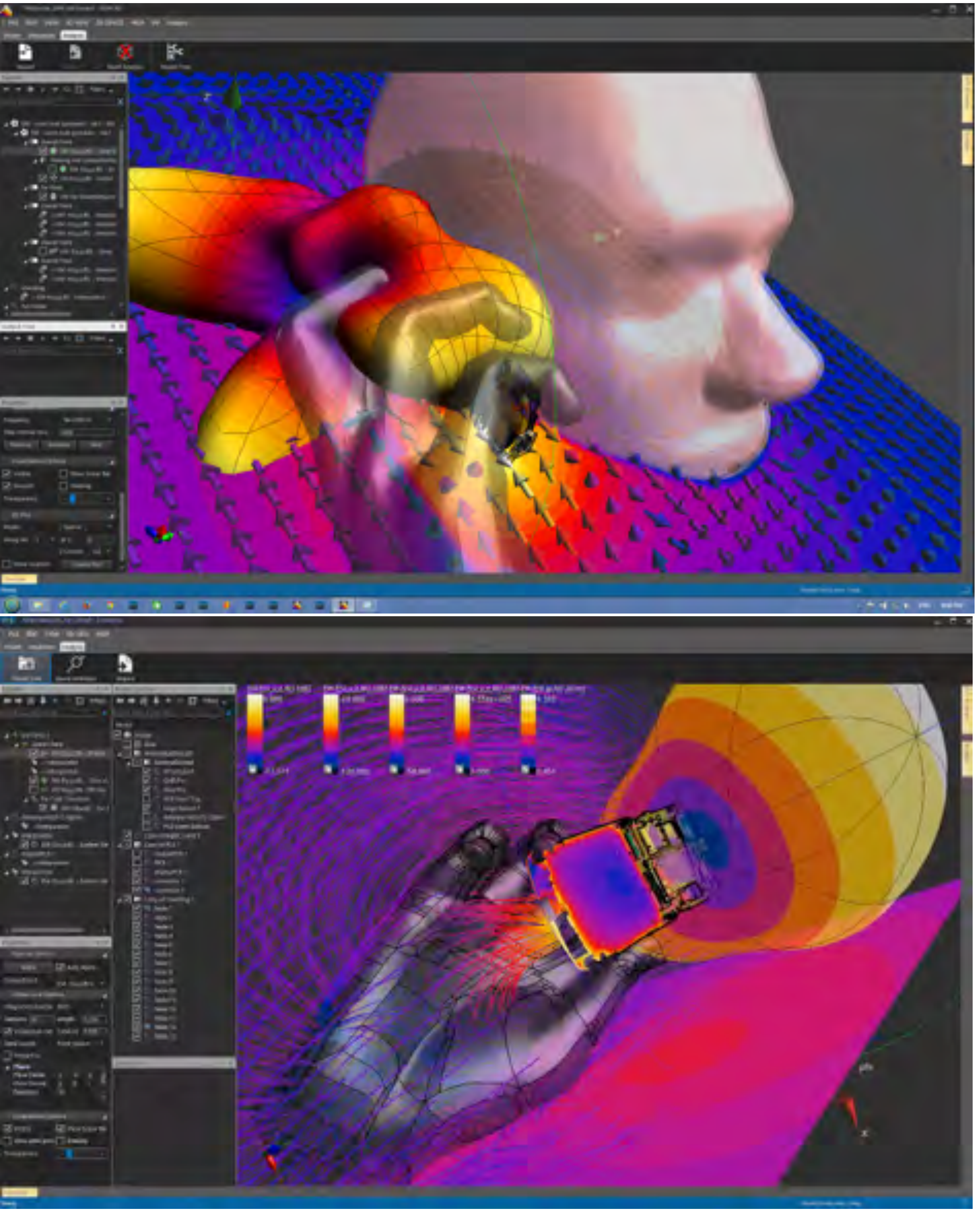
Challenges

Challenges: Hand-Held Devices



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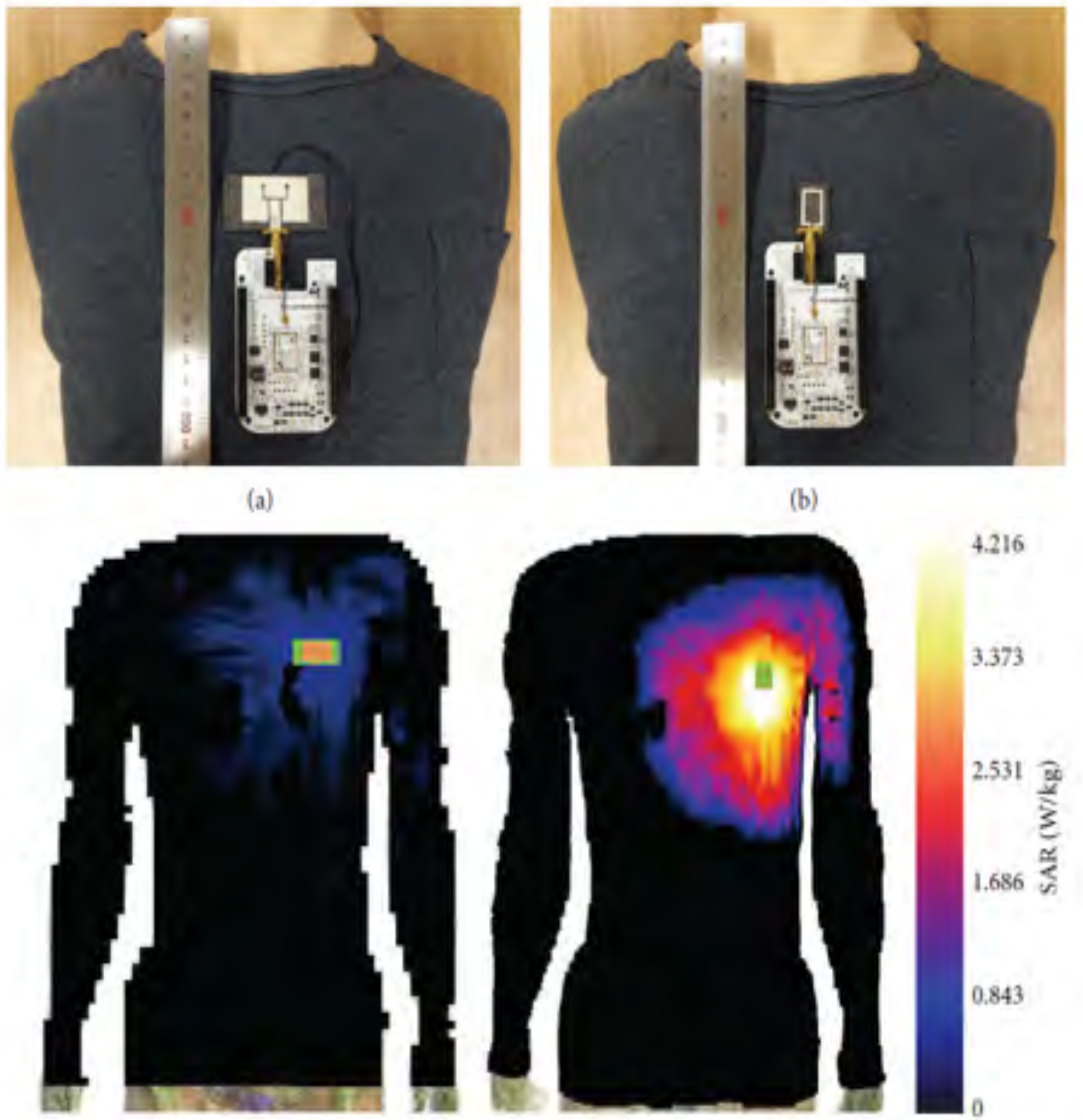
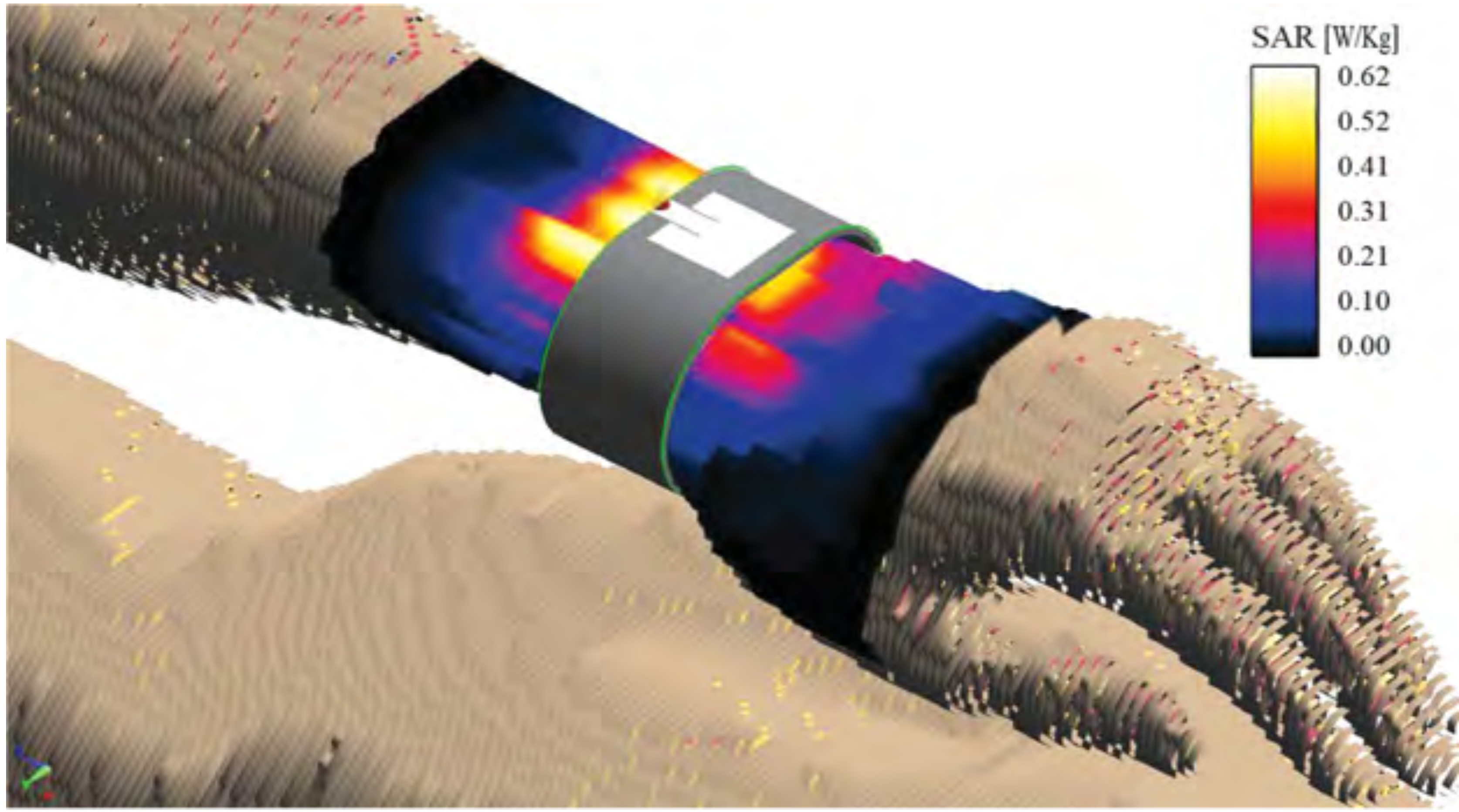
Challenges: Body-Mounted Antennas



RE 13: Simulated SAR values of two antennas on the body at 5.8 GHz: (a) reconfigurable beam-steering antenna, (b) loop antenna.



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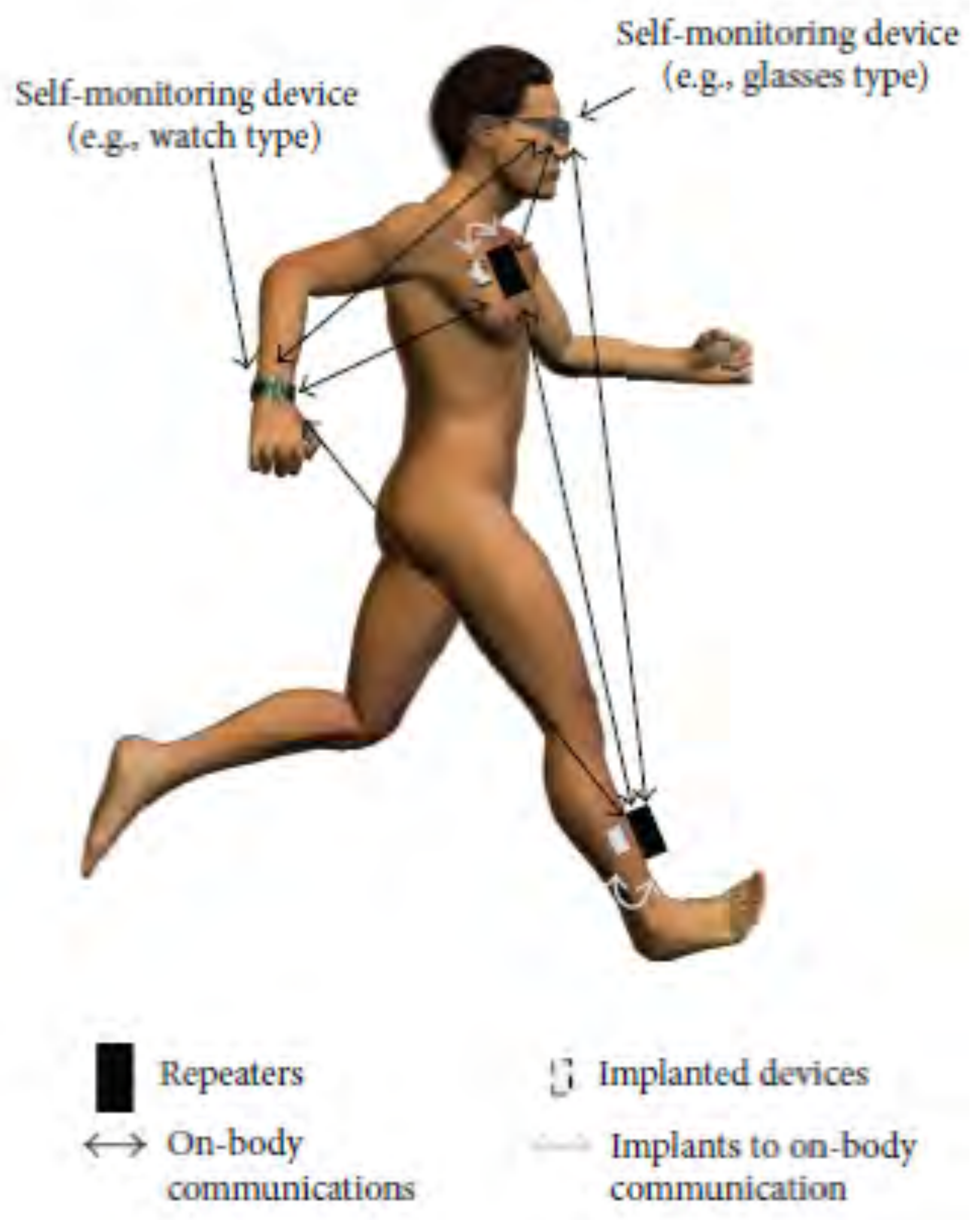
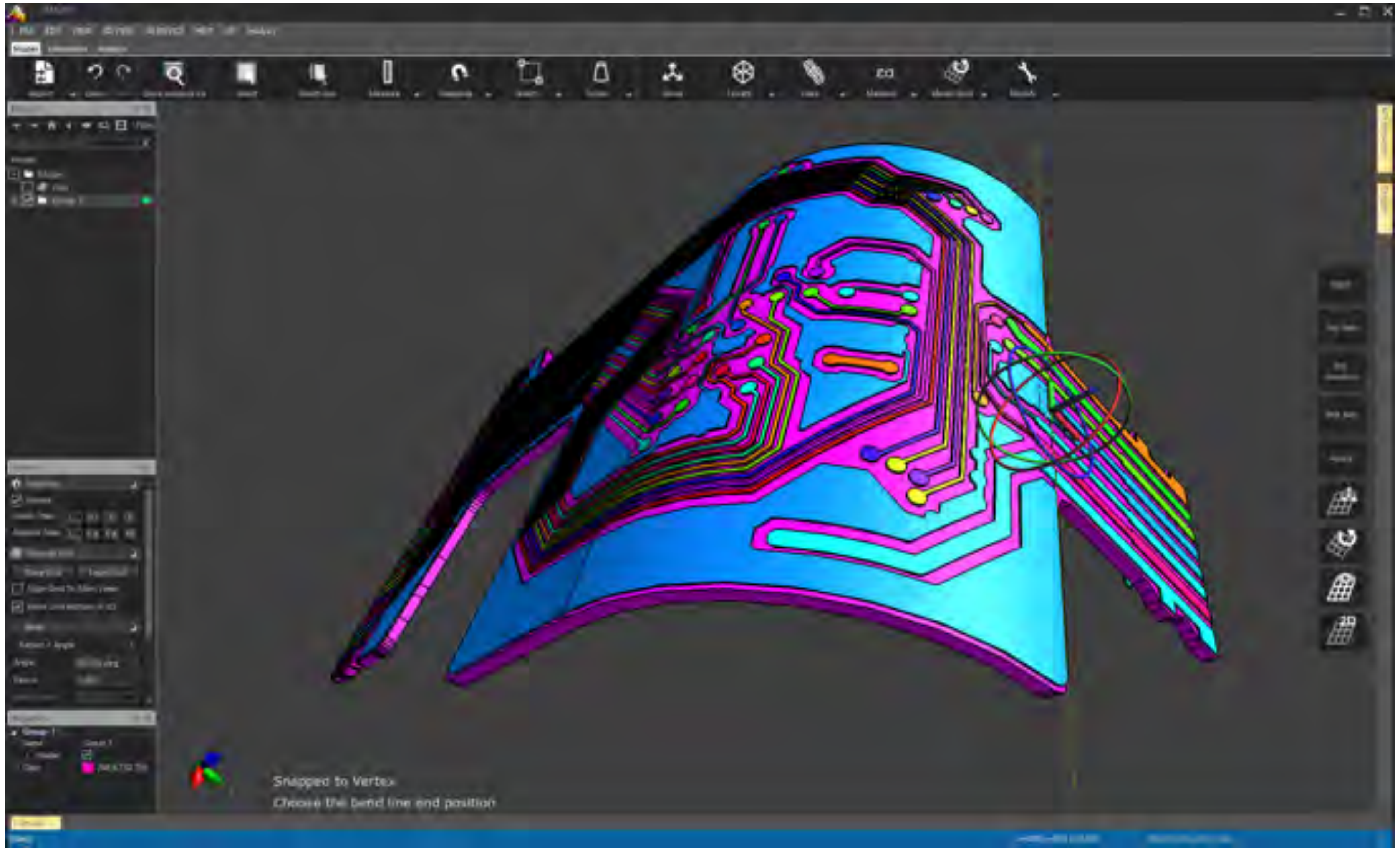
Challenges: Rapidly Changing Link Environment





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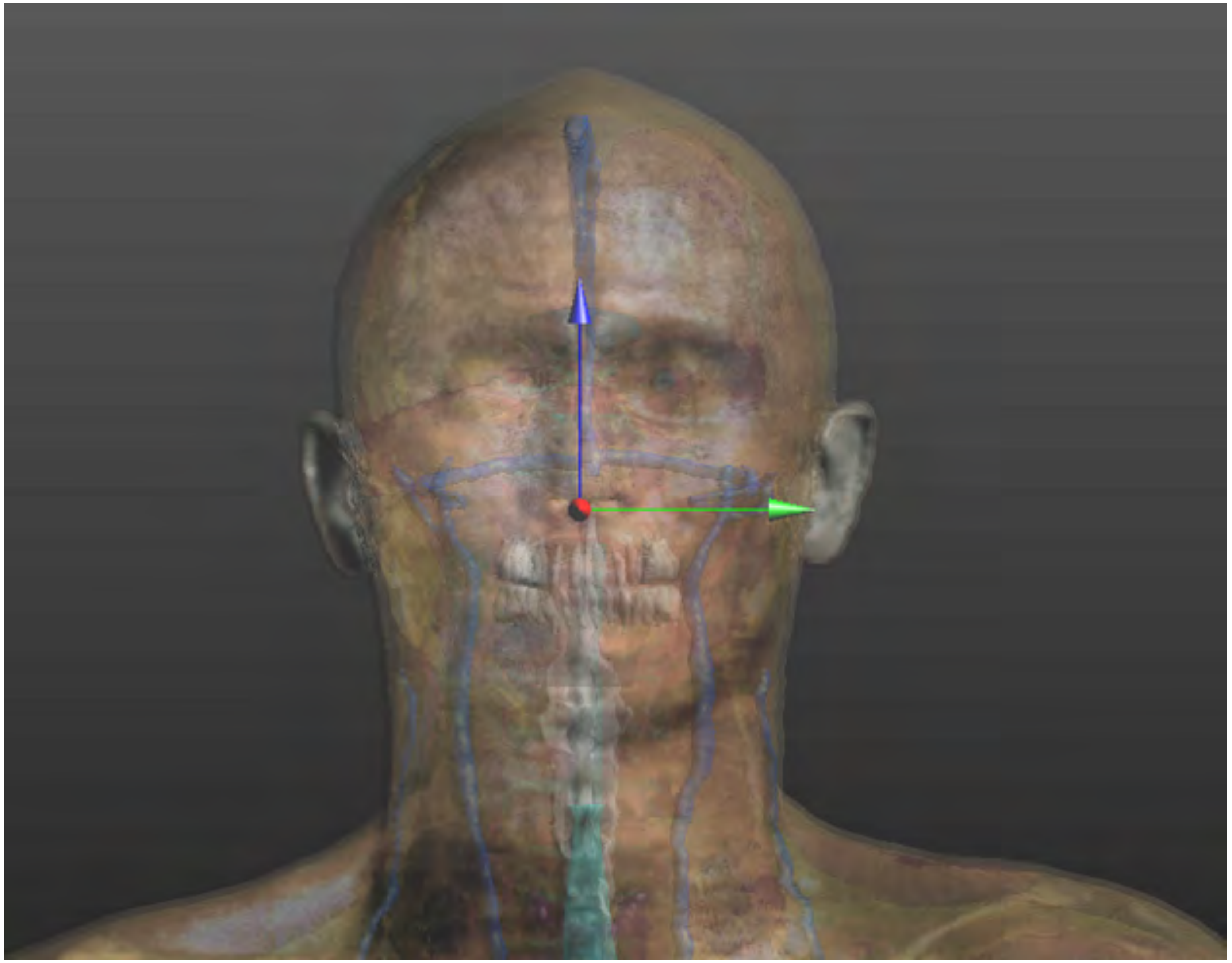
Challenges: Tissue-Embedded Antennas (all side exposures)



- electrically small antennas
- symmetrical design desirable
- close proximity to the head and pinna
- head/pinna very variable between people
- tolerant to environment

Challenges: Implanted Antennas (Wireless Endoscopy)

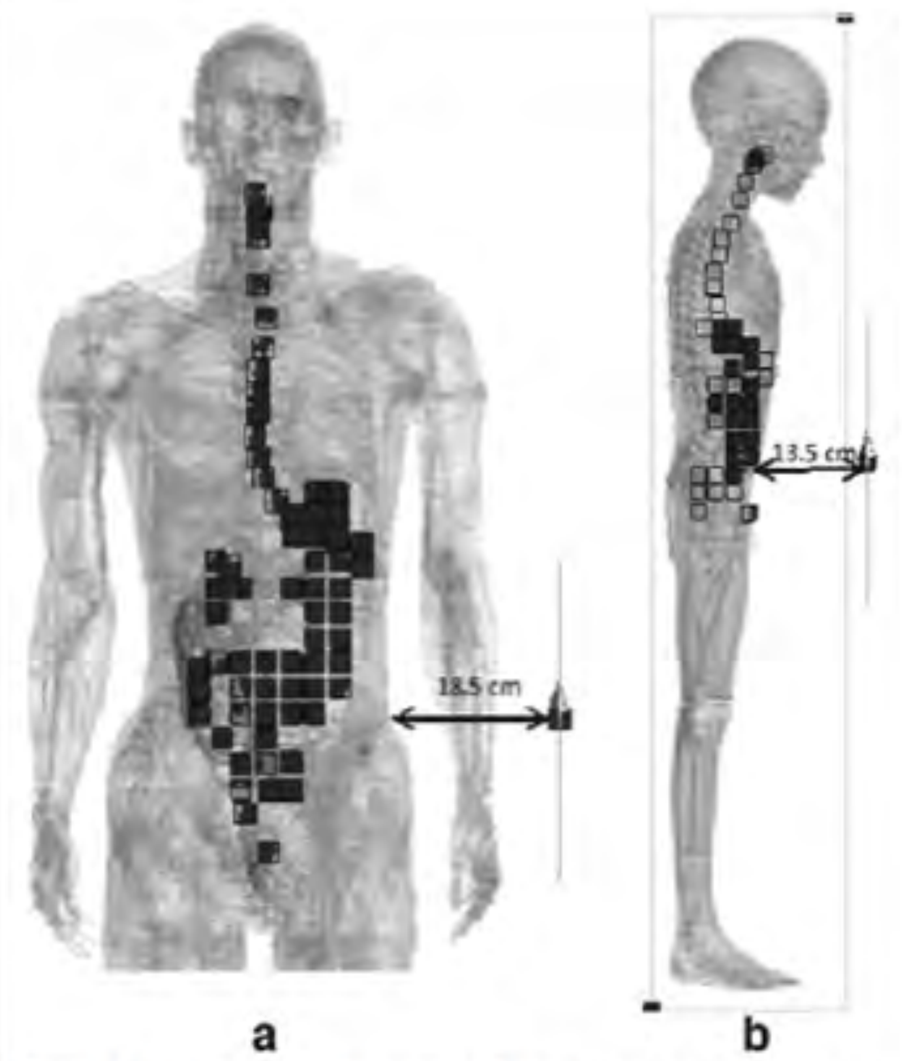
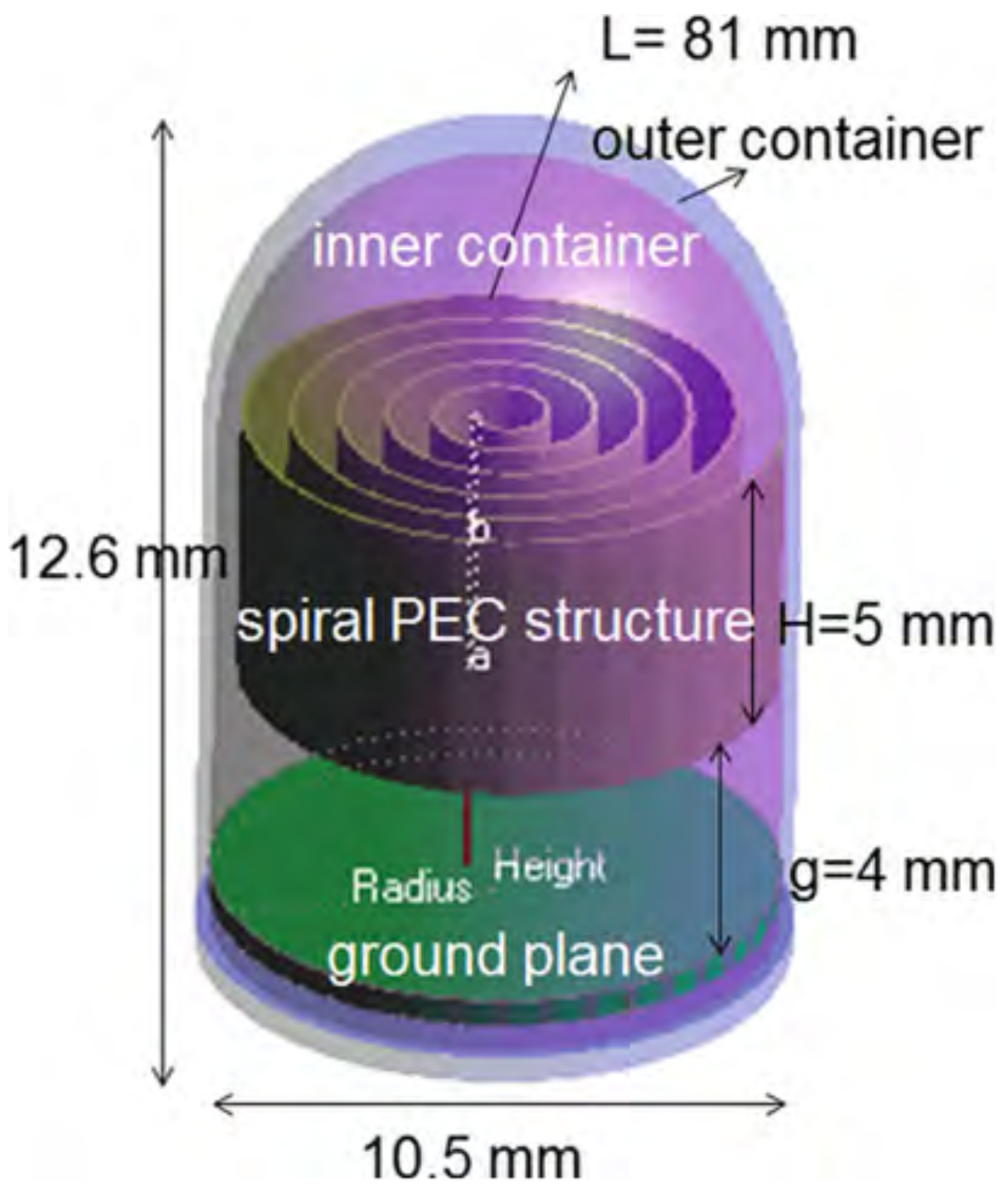
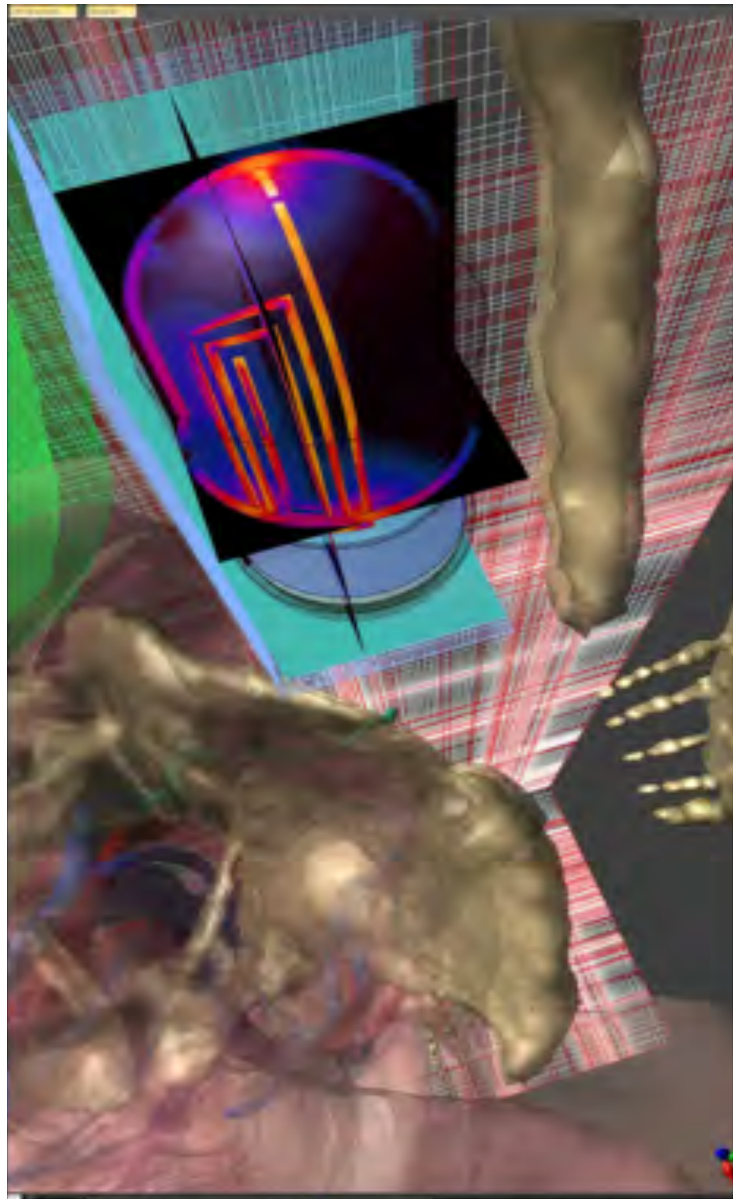
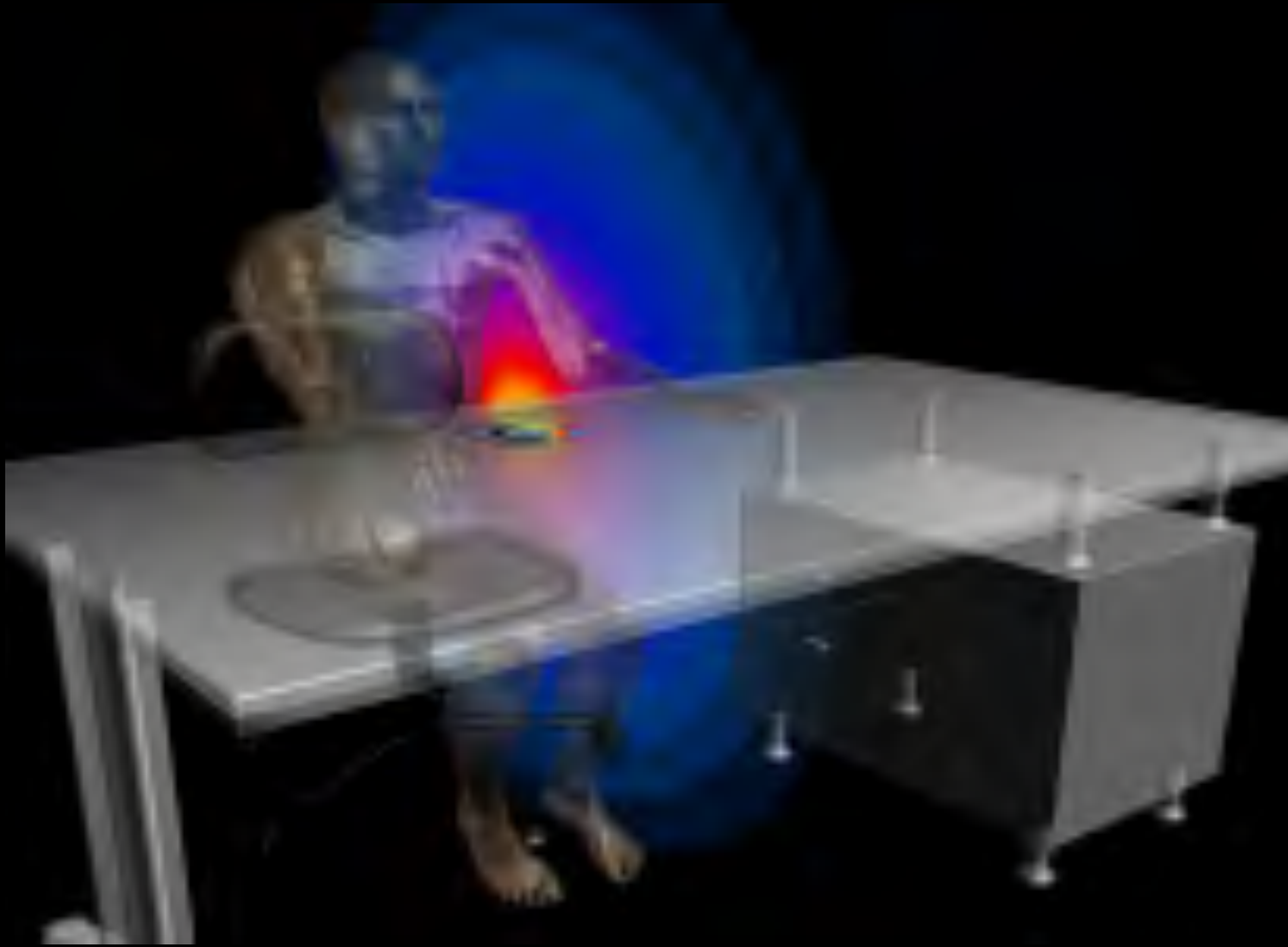


Figure 2 Configuration: locations of endoscopy capsule along digestive tract in realistic human body models. (a) Adult man Duke. **(b)** 6-Year-old boy Thelonius. Squares indicate investigated positions of the capsule.





Challenges: Wireless Power Transfer (strong gradient, interference w/ implants)



Concept and Basis of SAR Standards

- concept behind SAR standards
- basis of SAR standards
- the gold standard

Basis of SAR Standard: Absorption Mechanism

- Kuster and Balzano, Trans. IEEE on VT, 1992
- Kuster, BEMS, 2015

Concept Behind the SAR Standards

- issue
  - hand-held and body-worn devices expose locally
  - safety limits expressed in SAR averaged over any 1g or 10g of tissue (shape cube)
  - exposure is close to these limits
- objectives
  - scientifically sound, reliable, and reproducible compliance evaluation with minimal uncertainty
  - minimal overestimation
  - objective (devices that cause low exposures result in low exposures in the test and vice versa)
  - minimal test effort
- implementation
  - phantom shape and tissue simulation liquid to warranty conservative assessment (95th percentile)
  - well-defined device positions and operational conditions
  - minimally disturbing measurement instrumentation calibrated to ISO17025
  - smallest possible uncertainty, rigorous uncertainty assessment
  - thorough and comprehensive validation

Basis of SAR Standard: Absorption Mechanism (*d* < 200 mm)

- SAR = ***RF**$_{losses}$* ~ *j^2/d^2* or *~q^2* (only very close to the surface)
- ***exposure is not directly related to the radiated power!***
- ***strongly design dependent***

$$\text{SAR} = \frac{\sigma}{\rho} \frac{\mu\omega}{\rho\sqrt{\sigma^2 + \varepsilon^2\omega^2}} (1 + c_{\text{corr}}\gamma_{\text{pw}})^2 H_{t_{\text{inc}}}^2 \qquad (1)$$

in which γ_{pw} is the plane-wave reflection coefficient for the H_t field

$$\gamma_{\text{pw}} = \frac{2\left|\sqrt{\varepsilon'}\right|}{\left|\sqrt{\varepsilon'} + \sqrt{\varepsilon_0}\right|} - 1 \qquad (2)$$

$$H^2 \sim j^2/d^2$$

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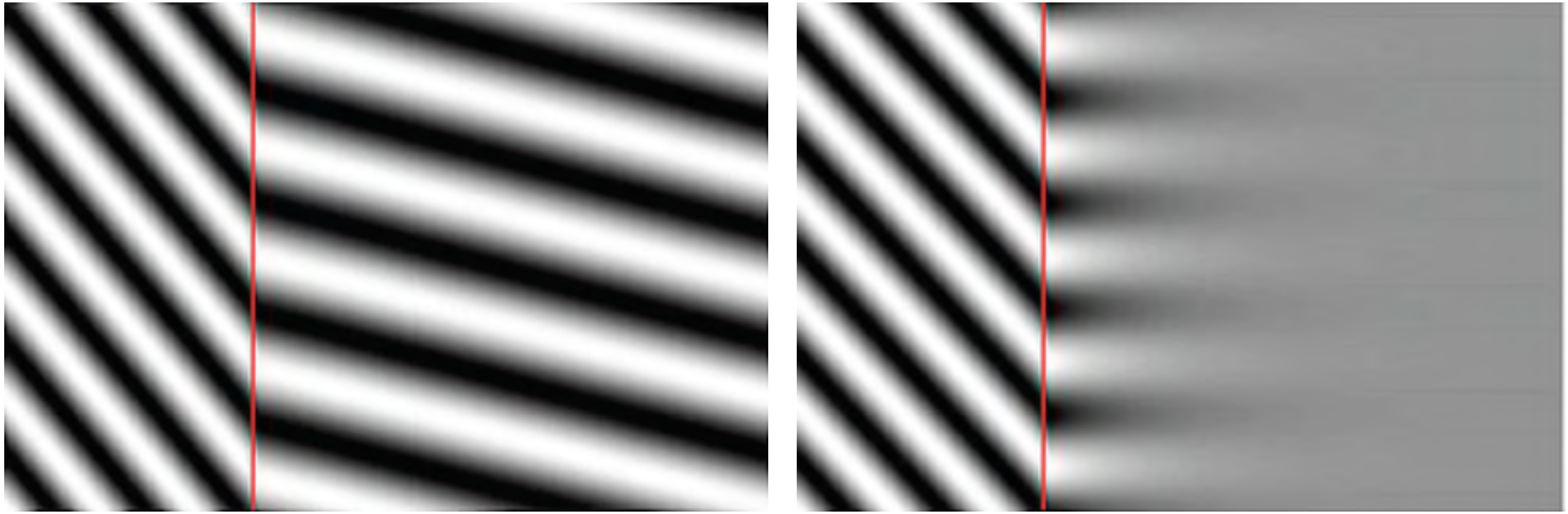
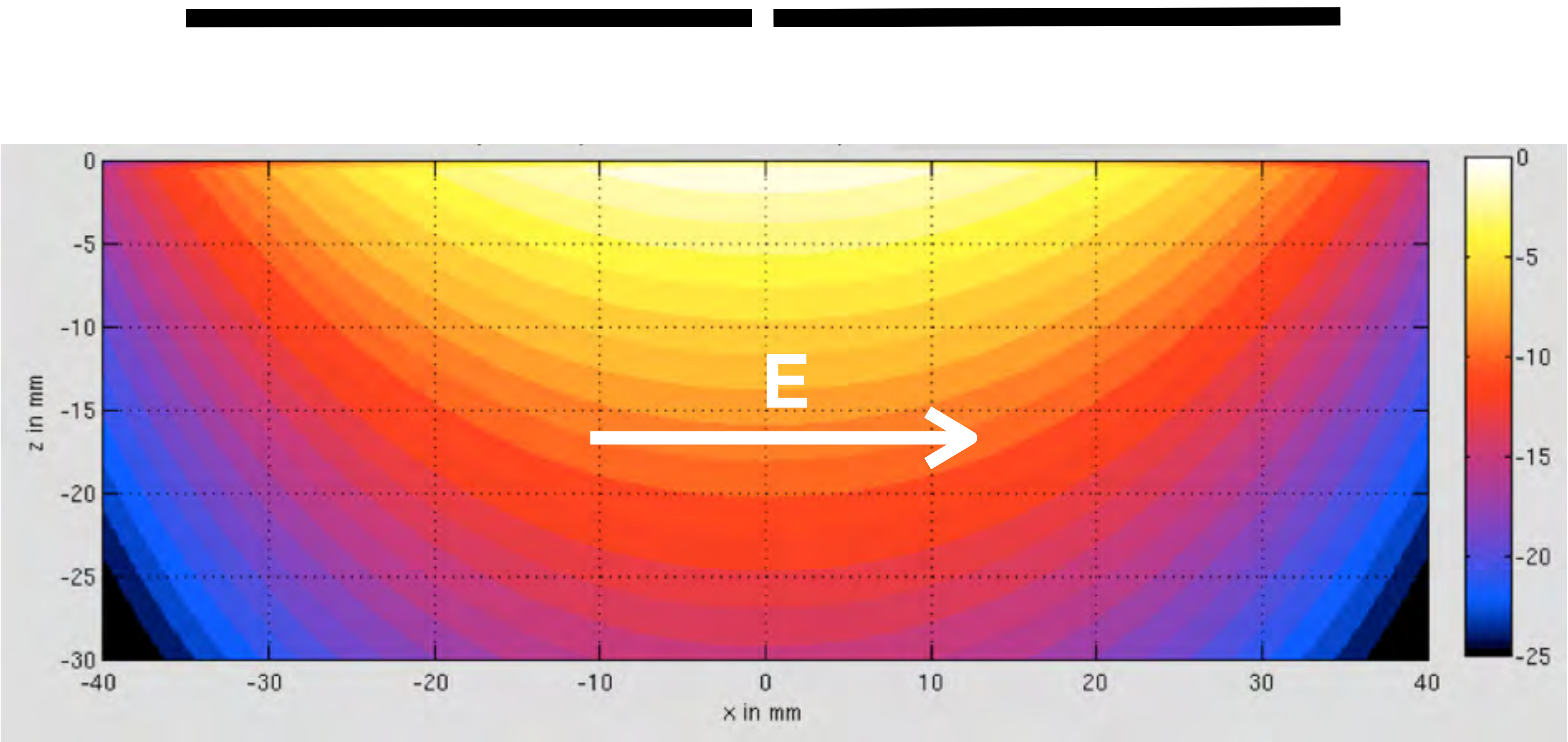
Inductive vs. Capacitive Coupling

- inductive coupling: propagating
- capacitive coupling: significant content of evanescent waves
- evanescent waves decay highly over-exponentially



SAR (dB) of Dipole: 1800 MHz @ *d* = 10 mm



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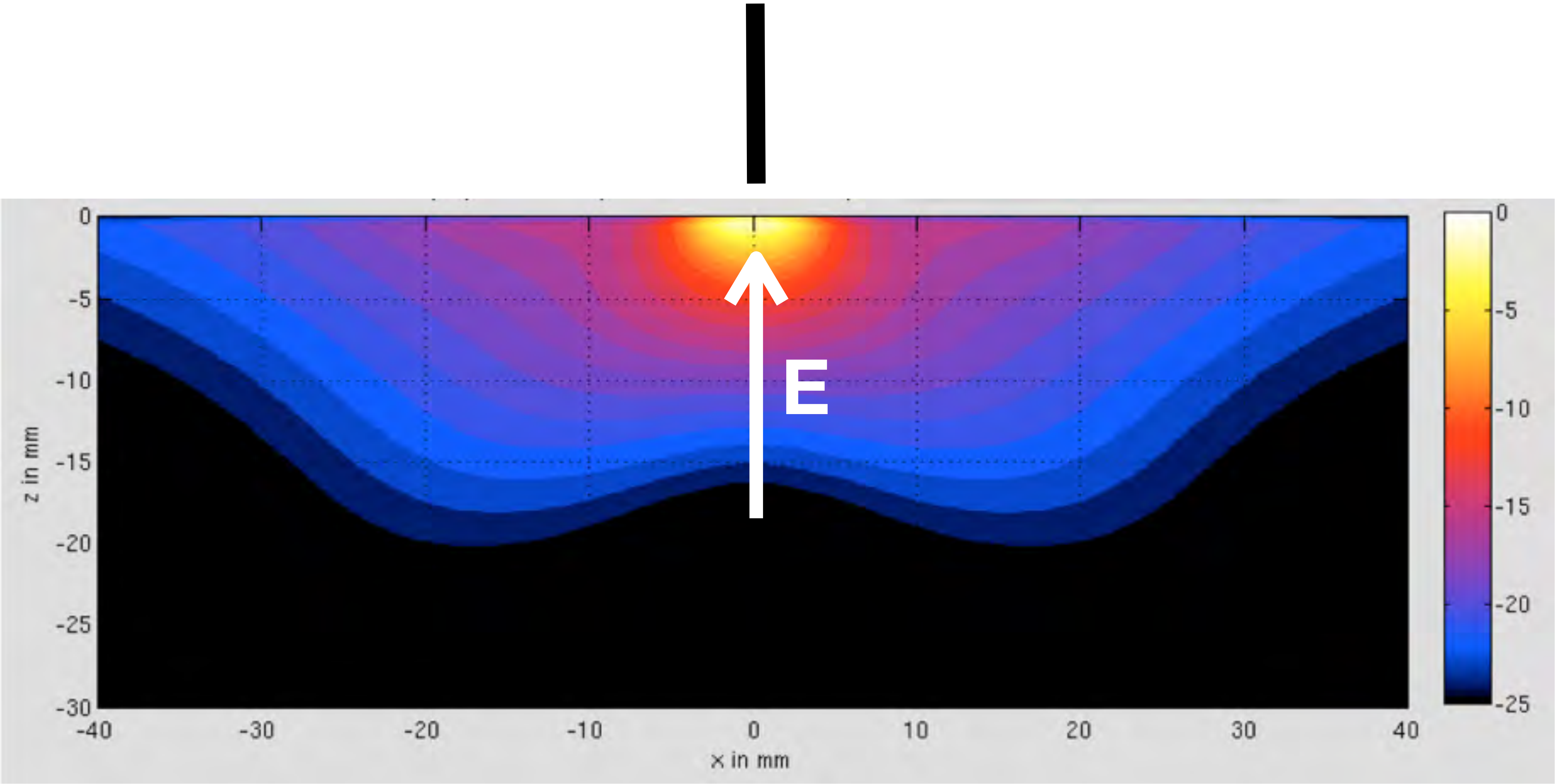
SAR (dB) of Dipole: 1800 MHz @ *d* = 2 mm



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Basis of SAR Standards: Instrumentation Requirements

- **probe technology** (Bassen et al., 79, Schmid 94, Pokovic 99)
- **calibration technology** (Pokovic 99, Kühn 09, Kühn 11)
- **phantoms** - shape, tissue simulating media
  - dependence on **inner anatomy** (Hombach 96, Meier 96, Drossos 01, Christ 08)
  - dependence on **outer anatomy** (Meier 96, Schoenborn 98, Christ 05, Kuehn 09)
  - dependence on **age** (Gandhi 93, Schoenborn 98, Christ 05, Kuehn 09)
  - dependence of **ear modeling** on the psSAR (Burkhardt 00, Christ 09)
  - enhancements due to **metallic implants** (Meier 96, Kyriakou 11)
  - dependence of the **hand on head exposure** (Meier 95, Li, 11, Li 12)
  - procedure for **body-worn** devices (Christ et al. 06, Kühn et al. 09)
- **assessment procedures**
  - IEEE1528, IEC62209-1, IEC 62209-2
  - FCC KDB865664

Basis of SAR Standards: Uncertainty and Validation

- **uncertainty** assessment procedures and budget (Pokovic, 99)
- **verification** (IEEE1528, IEC62209, FCC KDB865664)
- **validation** of procedures
  - validation of SAM head - *in silico* (Beard 05, Christ 06)
  - validation of instrumentation - *in silico* compared to experimental (Meier 94, Burkhardt 98, Chavannes 98, 06, Gosselin 12, etc.)
  - inter-lab comparison of calibration with NIST (USA), NPL (UK), NICT (Japan), STUK (Finland), NIM (China), TMC/CTTL (China)
- **inter-lab repeatability**
  - inter-lab comparison with test labs: > 50 labs

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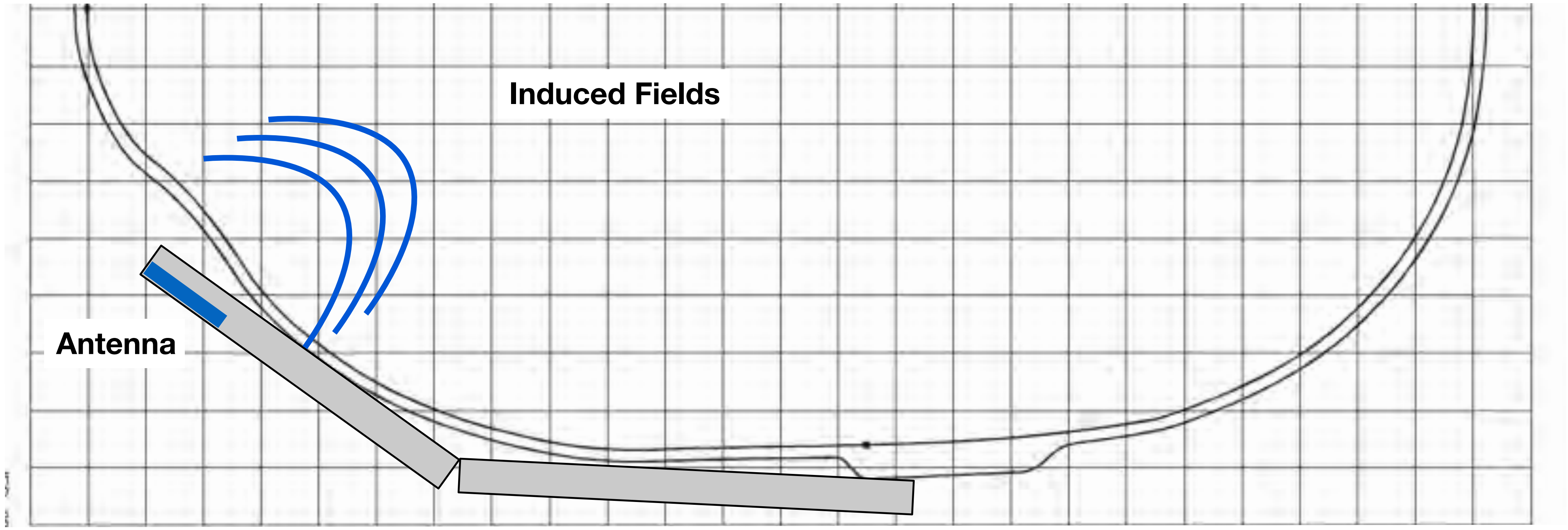
Basis of SAR Standards: Non-Disturbed Phantom System

- replacement of the 7 billion human anatomies and various handheld positions with
  - one homogeneous phantom (conservative shape and media)
  - two device positions (cheek and 15° tilt)
- standard objective
  - assessment of the non-disturbed psSAR 1g and 10g



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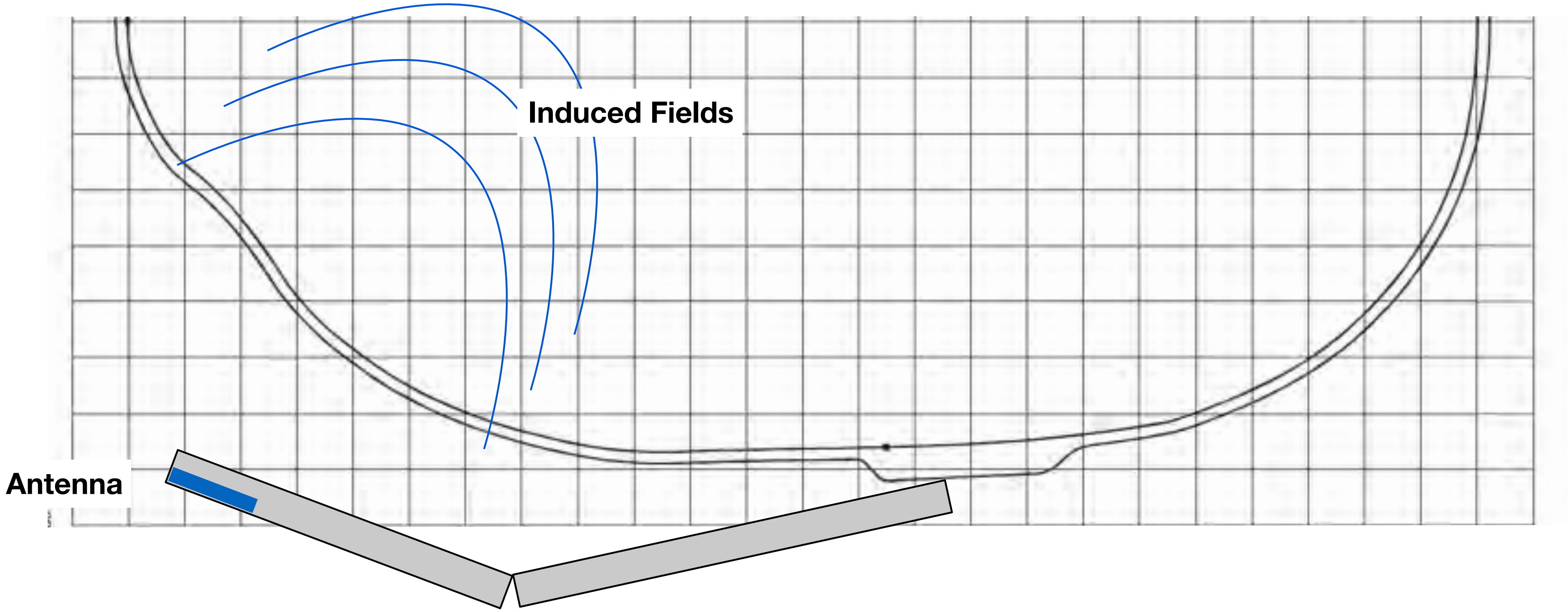
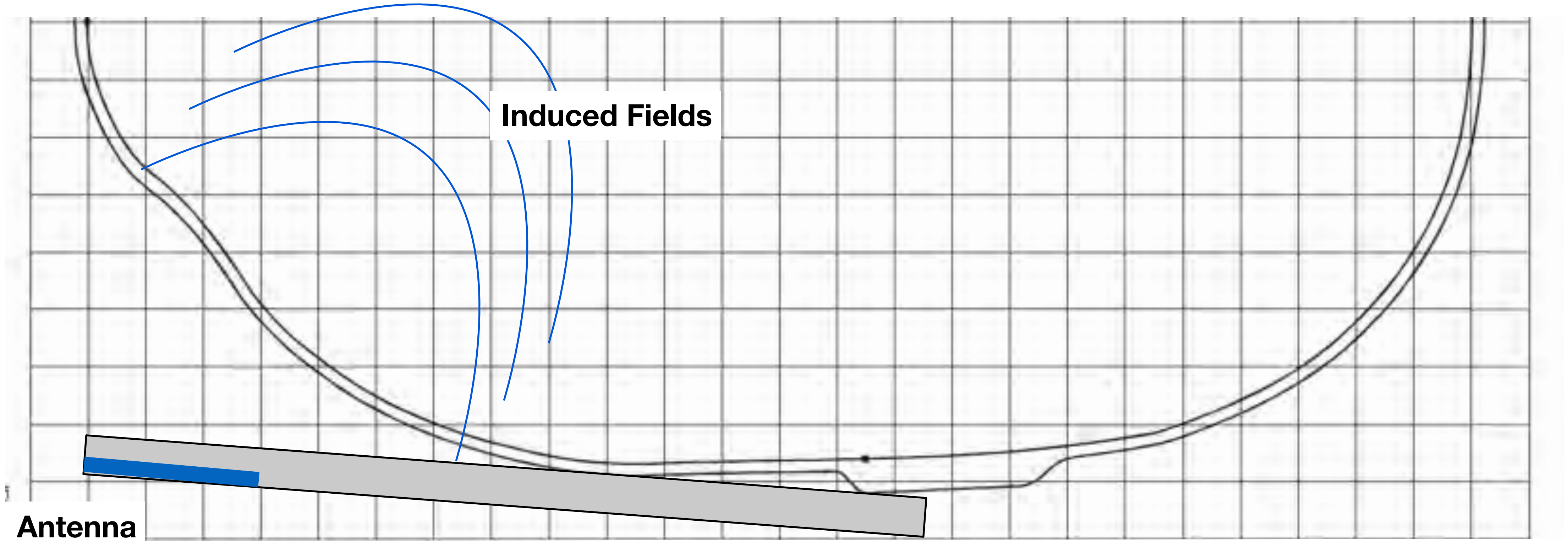


Basis of SAR Standards: Latest Issue

- Lee at al. in TEMC, pp 1281-84, Vol. 57 2015 points to an underestimation of SAR for bottom mounted antenna in bar-type phone model
  - this is obvious and a function of the head shape
  - often devices are optimized to meet the standard
  - realistic test conditions are important



SAR Comparison of SAM Phantom and Anatomical Head Models for a Typical Bar-Type Phone Model

Ae-Kyoung Lee, *Member, IEEE*, Seon-Eui Hong, Jong-Hwa Kwon, and Hyung-Do Choi

Abstract—The current IEEE 1528 and IEC 62209-1 standards specify a simplified physical model of the human head to provide conservative measurement procedures of the peak spatial-average specific absorption rate (SAR) of a mobile phone. This means that the evaluated SAR in a specific anthropomorphic mannequin (SAM) head model should be higher than in the heads of a significant majority of users under normal operational conditions. In this paper, the conservativeness of the SAM is investigated by numerically comparing the SAR in the SAM with those in four anatomical head models at different ages for exposure from a typical bar-type mobile phone. A numerical bar-type phone model with an internal antenna at the bottom of the phone body was implemented at 835 and 1850 MHz. This model provides an SAR pattern and levels similar with the commercial bar phones released in Korea. For two standard test positions, spatial peak 1- and 10-g SARs were calculated for both the SAM phantom and anatomical head models. The SARs were also calculated when the antenna is located on top of the phone. The results show that the SAM phantom provides a conservative evaluation for a phone model with the antenna on the top. However, when the antenna is located at the bottom, the hotspot in the SAM occurred farther from the antenna feed point,

Thus, whether the SAM phantom is sufficiently conservative has been a controversial issue [5]–[8]. In this paper, spatial peak 1- and 10-g SAR values of a SAM phantom are compared with those of four anatomical head models, exposed to electromagnetic field radiation from a bar-type mobile phone with an antenna located at the bottom of the phone body. Most bar-type mobile phones with an internal antenna that have been released in Korea have the antenna at the bottom of the phone. To understand the effects of the antenna location inside a phone, the SAR results were also compared when the phone was turned upside down.

II. Models and Method

A. Mobile Phone Models

Studies testing the conservativeness of the SAM phantom have been carried out for various types of mobile phone models.

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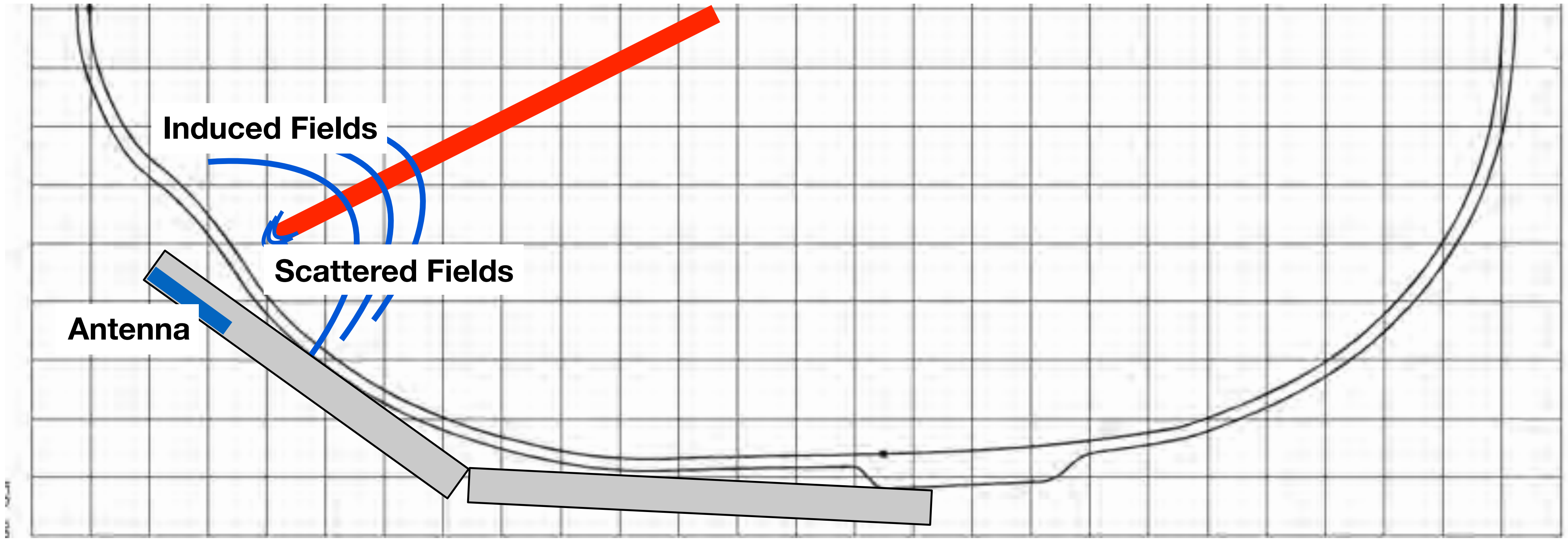
Implementation of Single Probe Systems

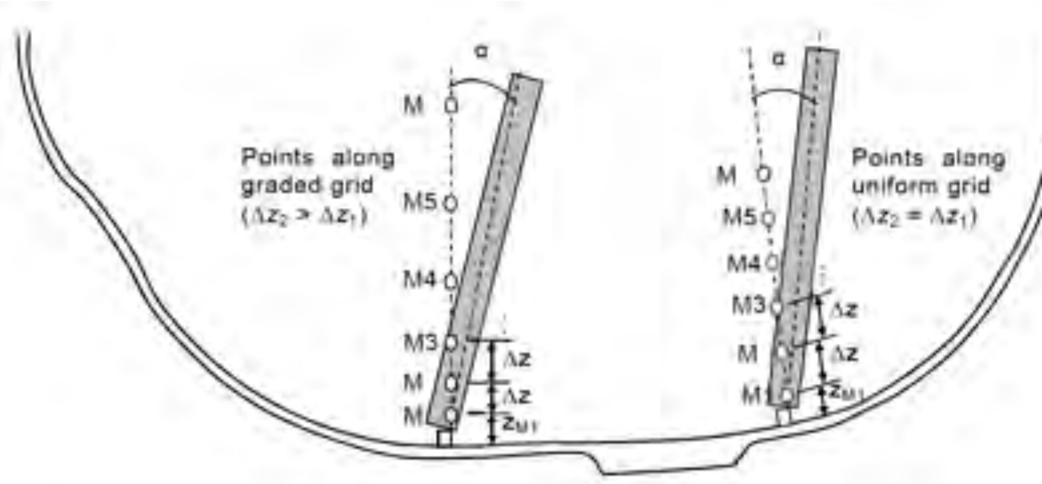
Requirements of IEEE 1528, IEC 62209-1/2

- detailed description of phantom (shell &and media)
- minimal requirements of probe (size, sensitivity, isotropy)
- detailed definition of scanning requirements
- well-defined description of uncertainty assessment
- well-defined description of system check or verification
- well-defined validation procedure

Basis of SAR Standards: Distortion by Single Probe Systems

- distortion: minimized by the standard requirement (one probe, small tip, and normal to surface)
- psSAR: measured at sufficient points
- uncertainty: independent of location and DUT





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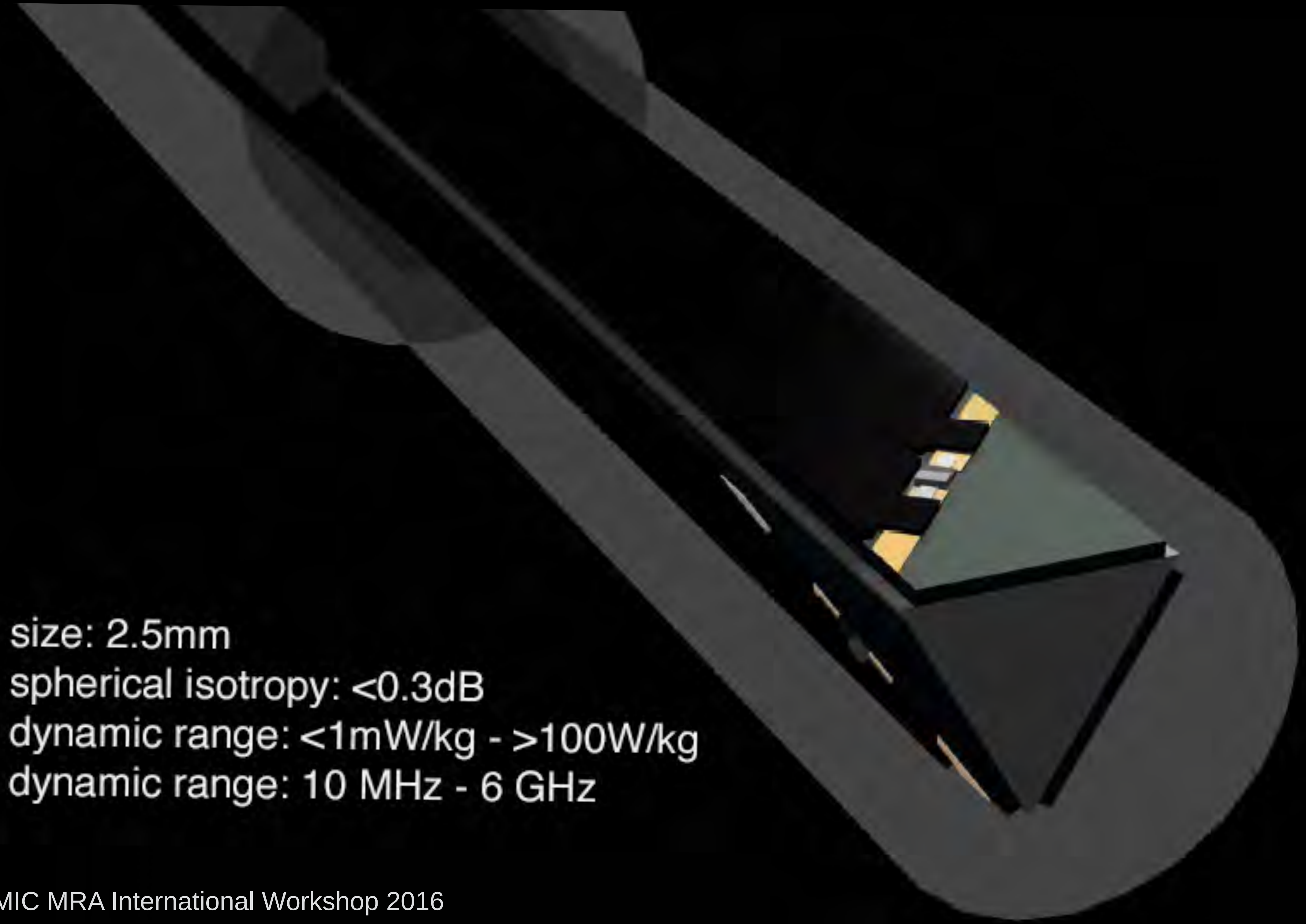
Dosimetric Probes



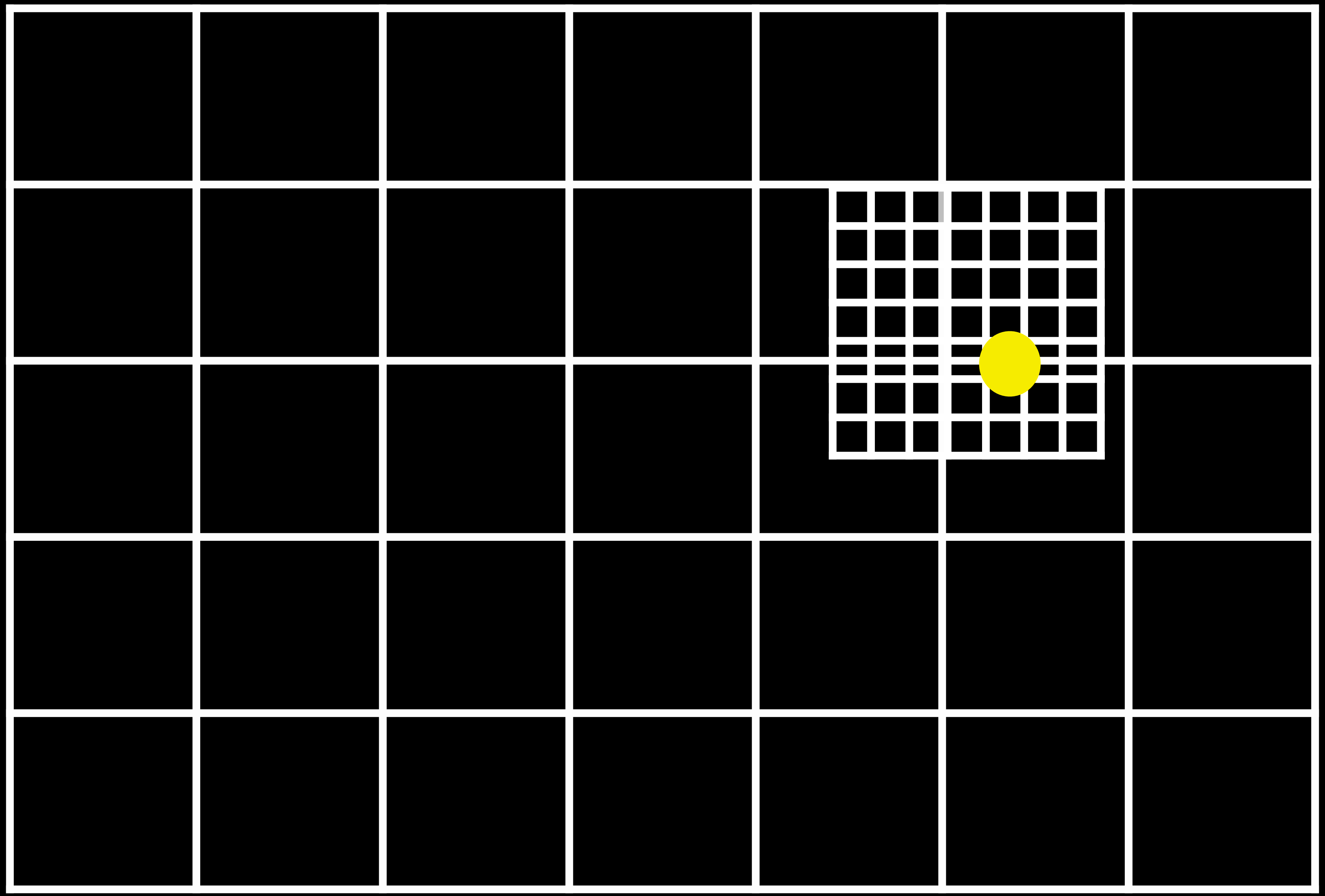
best amplitude accuracy

optimized isotropy

minimized cross-section

primary calibration (ISO17025)

Exposure Adaptive Grids



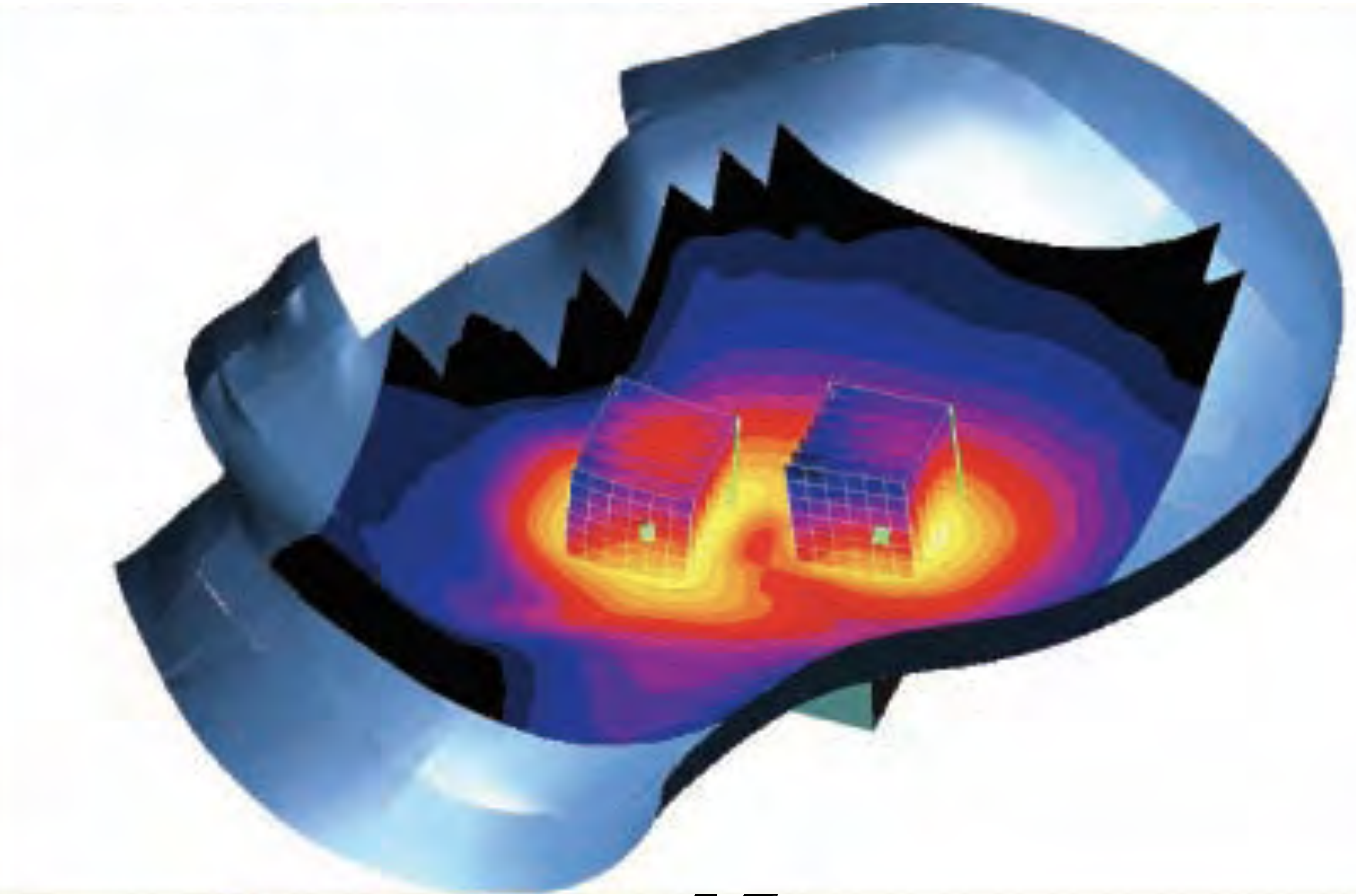
area scan

determine maximums (within x dB)

measurement of psSAR1g and 10g in volume scans and with sufficient points

Concept of Scanning and Post Processing

- area scan to find maxima
- volume scans to assess the 1g and 10g
- only measured SAR values are used



- exception
  - fast SAR for decision making only

Concept of Uncertainty Assessment

62209-1Ed.2/CDV © IEC: 2011 – 69 –

Table 7 – Example of measurement repeatability evaluation template for system check (applicable for one system)

A	b	c	d	e = f(d,k)	f	g	h = c x f / e	i = c x g / e	k
Source of uncertainty	Description	Tolerance/ uncertainty ± %	Probability distribution	Div.	c_i (1 g)	c_i (10 g)	Standard uncertainty ± %, (1 g)	Standard uncertainty ± %, (10 g)	v_i or v_{eff}
Measurement system									
Probe calibration drift		2.0	N	1	1	1	2.0	2.0	∞
Isotropy (Axial and Hemispherical)	7.2.1.1	4.7	R	√3	0	0	0	0	∞
Boundary effect	7.2.1.4	0.0	R	√3	0	0	0	0	∞
Linearity	7.2.1.2	8.3	R	√3	0	0	0	0	∞
Detection limits	7.2.1.2	4.7	R	√3	0	0	0	0	∞
Modulation response	7.2.1.3	1.0	R	√3	0	0	0	0	∞
Readout electronics	7.2.1.5	4.0	R	√3	0	0	0	0	∞
Response time	7.2.1.6	1.0	N	1	0	0	0	0	∞
Integration time	7.2.1.7	0.0	R	√3	0	0	0	0	∞
RF ambient conditions – noise	7.2.3.7	0.0	R	√3	0	0	0	0	∞
RF ambient conditions – reflections	7.2.3.7	3.0	R	√3	0	0	0	0	∞
Probe positioner mech. restrictions	7.2.2.1	3.0	R	√3	0	0	0	0	∞
Probe positioning with respect to phantom shell	7.2.2.3	0.4	R	√3	1	1	0.2	0.2	∞
Post-processing	7.2.4	2.9	R	√3	1	1	1.7	1.7	∞
System check source									
Deviation between experimental dipols		2.0	N	1	1	1	2.0	2.0	∞
Input power and SAR drift measurement	7.2.3.6	4.7	R	√3	1	1	2.7	2.7	∞
Other source contributions		1.0	R	√3	1	1	0.6	0.6	∞
Phantom and set-up									
Phantom uncertainty (shape and thickness tolerances)	7.2.2.2		R	√3	1	1			∞
Uncertainty in SAR correction for deviations in permittivity and conductivity	7.2.6	1.9	N	1	1	0.84	1.9	1.6	∞
Liquid conductivity (temperature uncertainty)	7.2.3.5		R	√3	0,64	0,43			∞
Liquid conductivity (meas.)	7.2.3.3		N	1	0,64	0,43			M
Liquid relative permittivity (temperature uncertainty)	7.2.3.5		R	√3	0,6	0,49			∞
Liquid relative permittivity (meas.)	7.2.3.4		N	1	0,6	0,49			M
Combined standard uncertainty			RSS						
Expanded uncertainty (95 % confidence interval)			k=2						

- based on GUM
- divided into uncorrelated components
- all components accessible by anybody
- uncertainty evaluation described in detail
- volume scan to assess the 1g and 10g
- only measured SAR values are used

- exception
  - fast SAR for decision making only

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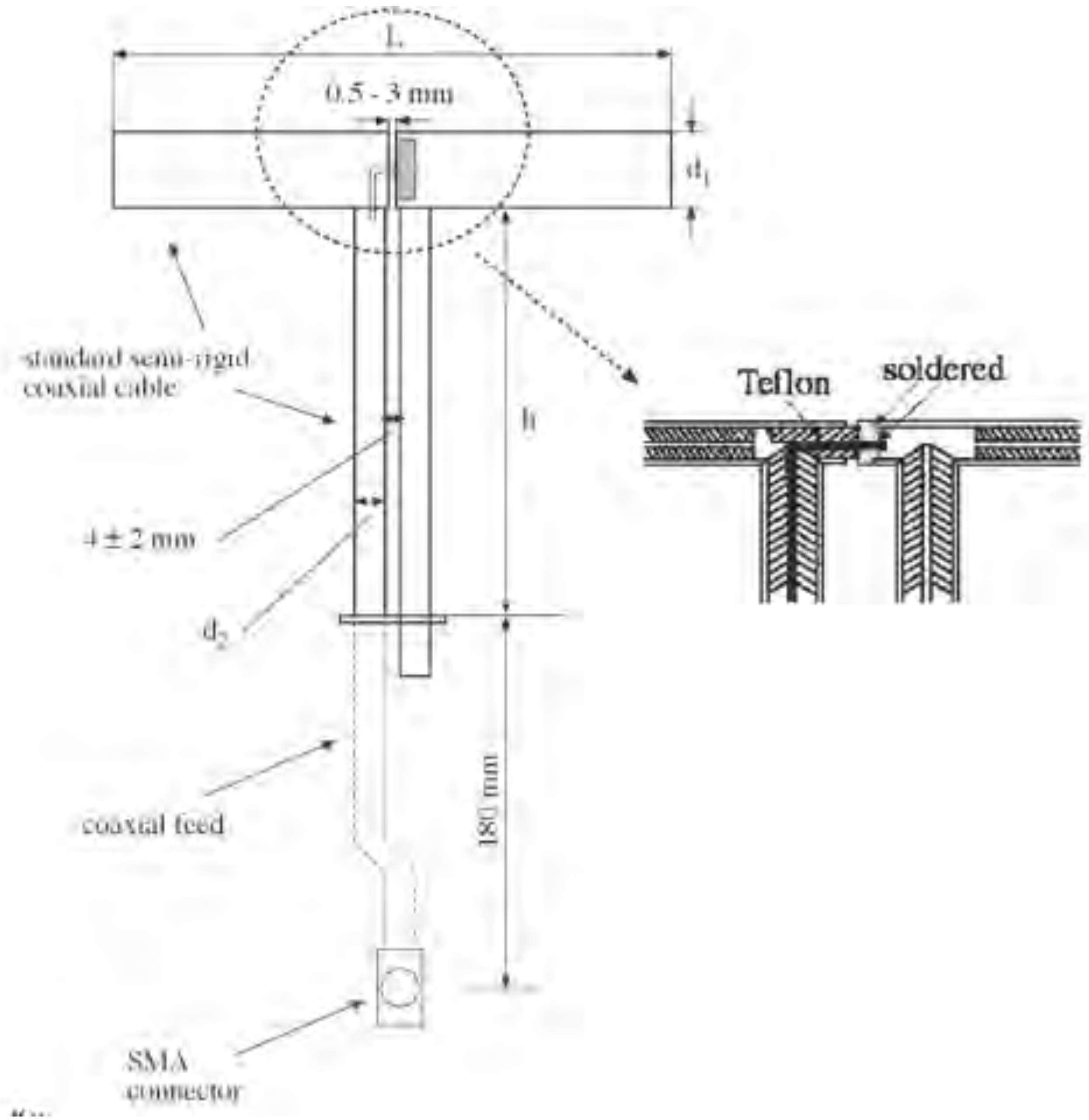
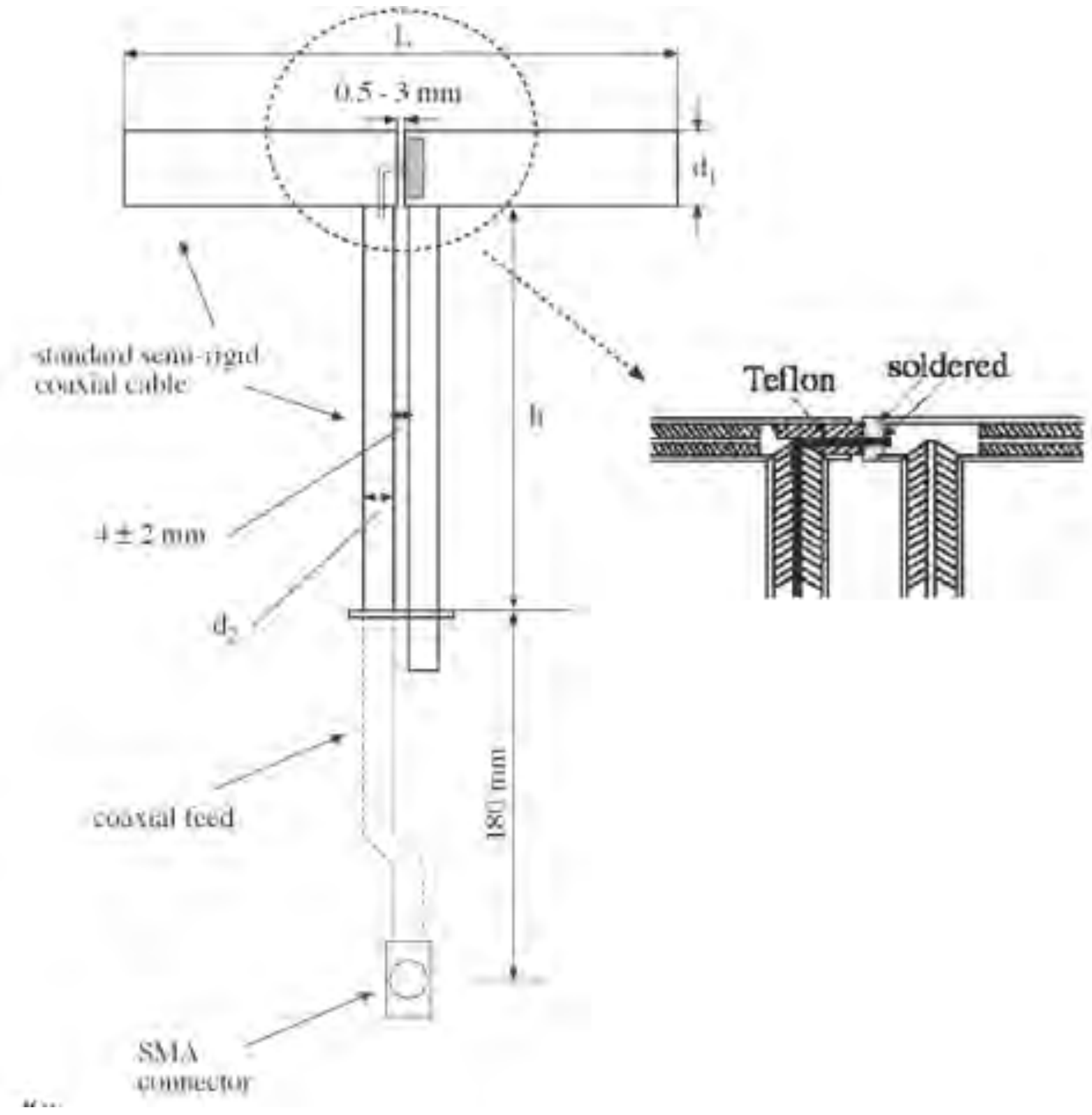
Single Probe System Verification



- dipole sources (CLA for *f* < 300 MHz)
- system check/verification
  - correct probe
  - correct liquid
  - correct software settings
- at flat section only
  - procedure defined in detail and optimized
  - scanning everywhere the same
  - field distortion/interference everywhere the same

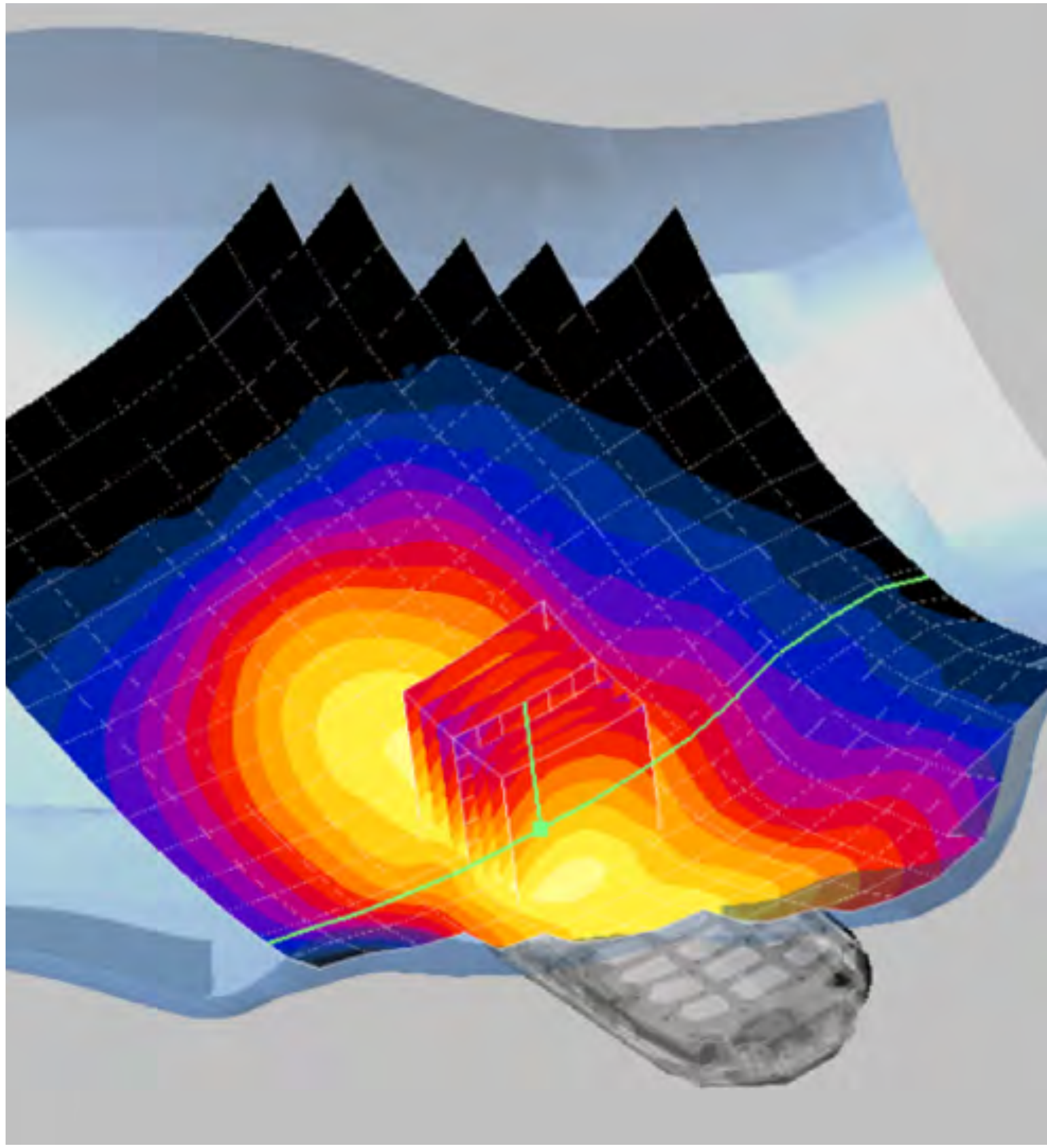
Single Probe Validation



- dipole sources
- system validation
  - dynamic range
  - isotropy
  - modulation
  - spatial resolution
- at flat phantom only
  - procedure defined in detail and optimized
  - scanning everywhere the same
  - field distortion/interference everywhere the same

Standards (SAR, etc.)

- IEC 62209
- FCC KDB 865664 …
- IEEE 1528
- ANSI-C63.19
- IEC 62232
- EN 50385
- EN 50383:2010
- EU Directive RED 2014/53/EU
- AS/NZS 2772-2:2011
- ARIB STD T-56 3.1
- IS16133
- DT-IFT-007-2015
- etc.



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Single Probe Systems ARE The Gold Standard

- primary calibration ISO17025 calibration of probe
- probe does not distort the field to be measured
- same accuracy everywhere (≧ 1 mm from surface)
- scanning adaptive (corresponds to more than 300’000 probe location)
- measures the 1g and 10g psSAR w/o approximation
- uncertainty budget and procedure defined in detail
- can be independently validated (all components accessible by the user)
  - probe
  - data acquisition
  - phantom shell
  - tissue simulating liquid
- most accurate system possible

Other Advantages of Single Probe System

- < 4 MHz to > 6 GHz
- adaptive to any phantom
- compliant with all standards (e.g., FCC KDB865664, IEEE 1528, IEC 62209, ANSI-C63.19, IEC62232, EN50385, EN50383:2010, EU Directive RED 2014/53/EU, AS/NZS 2772-2:2011, ARIB STD T-56 3.1, IS16133, DT-IFT-007-2015)
- disadvantage until now: measurement time 10 – 20 minutes per scan

Latest Developments in Single Probe Systems

faster, automated, easier-to-use

TCB Council Workshop, October 28, 2015

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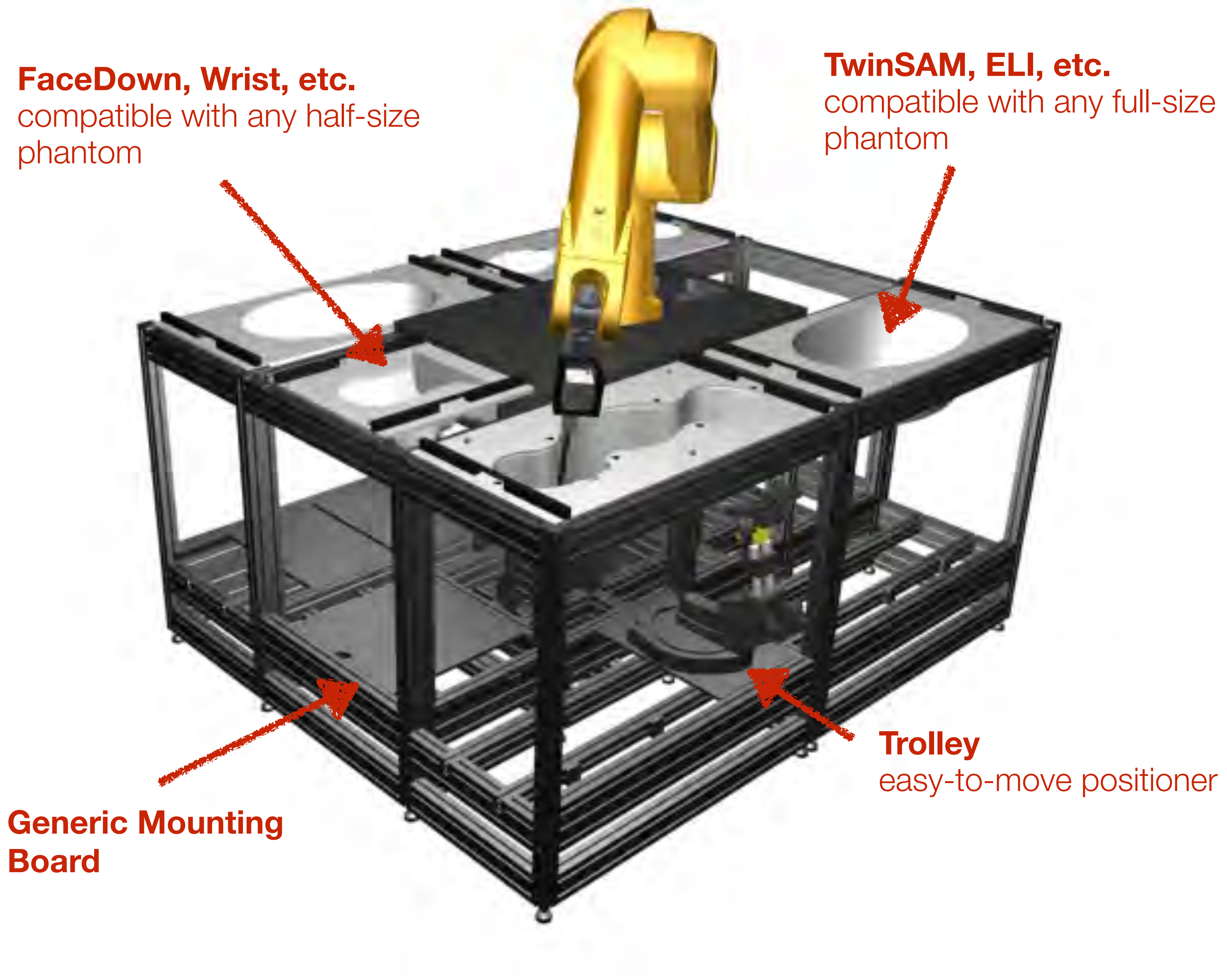
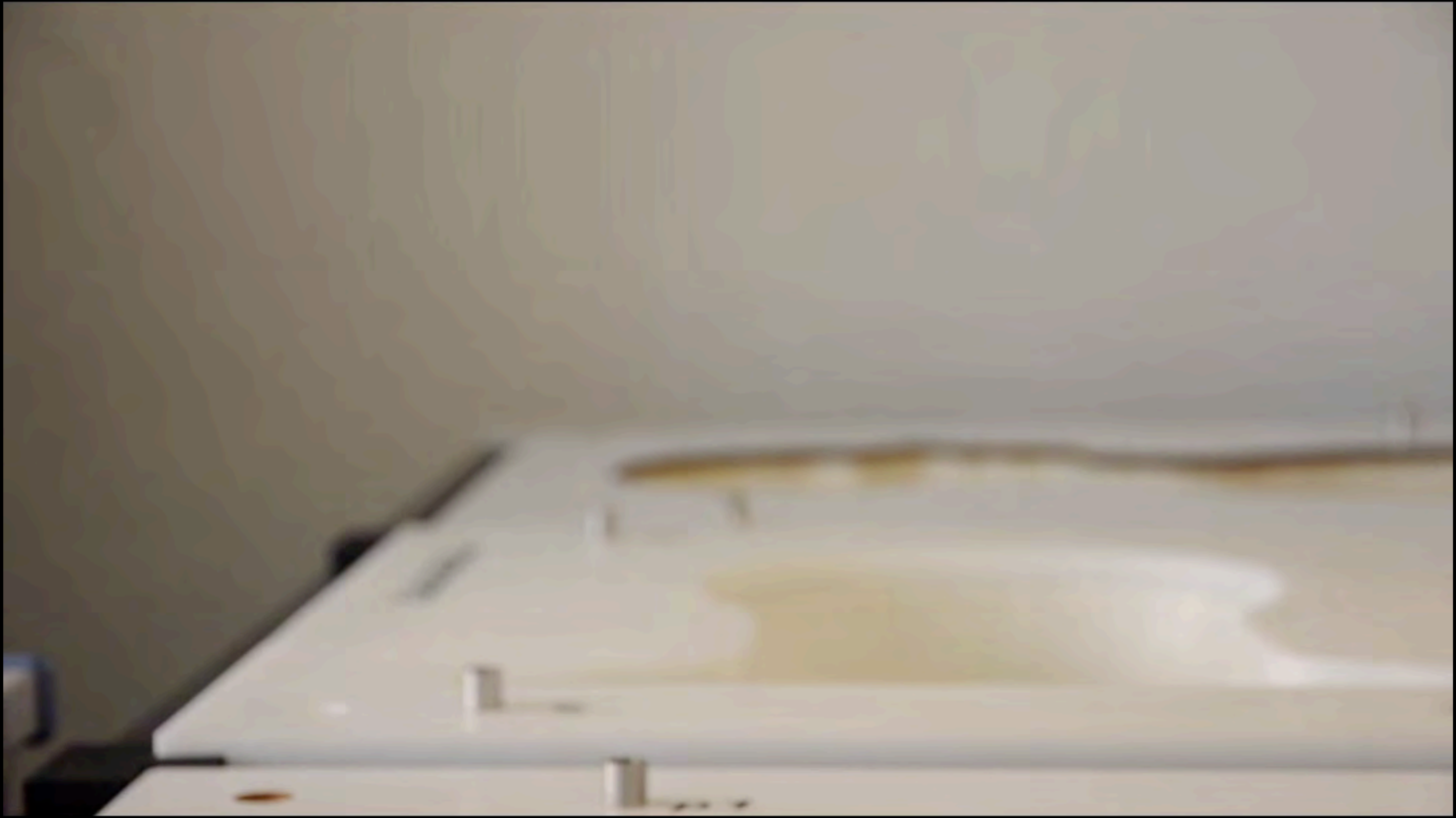
Concept DASY6: Same Hardware -> Compatible w/ All Standard



Concept DASY6: Optimized & Accelerated Movements

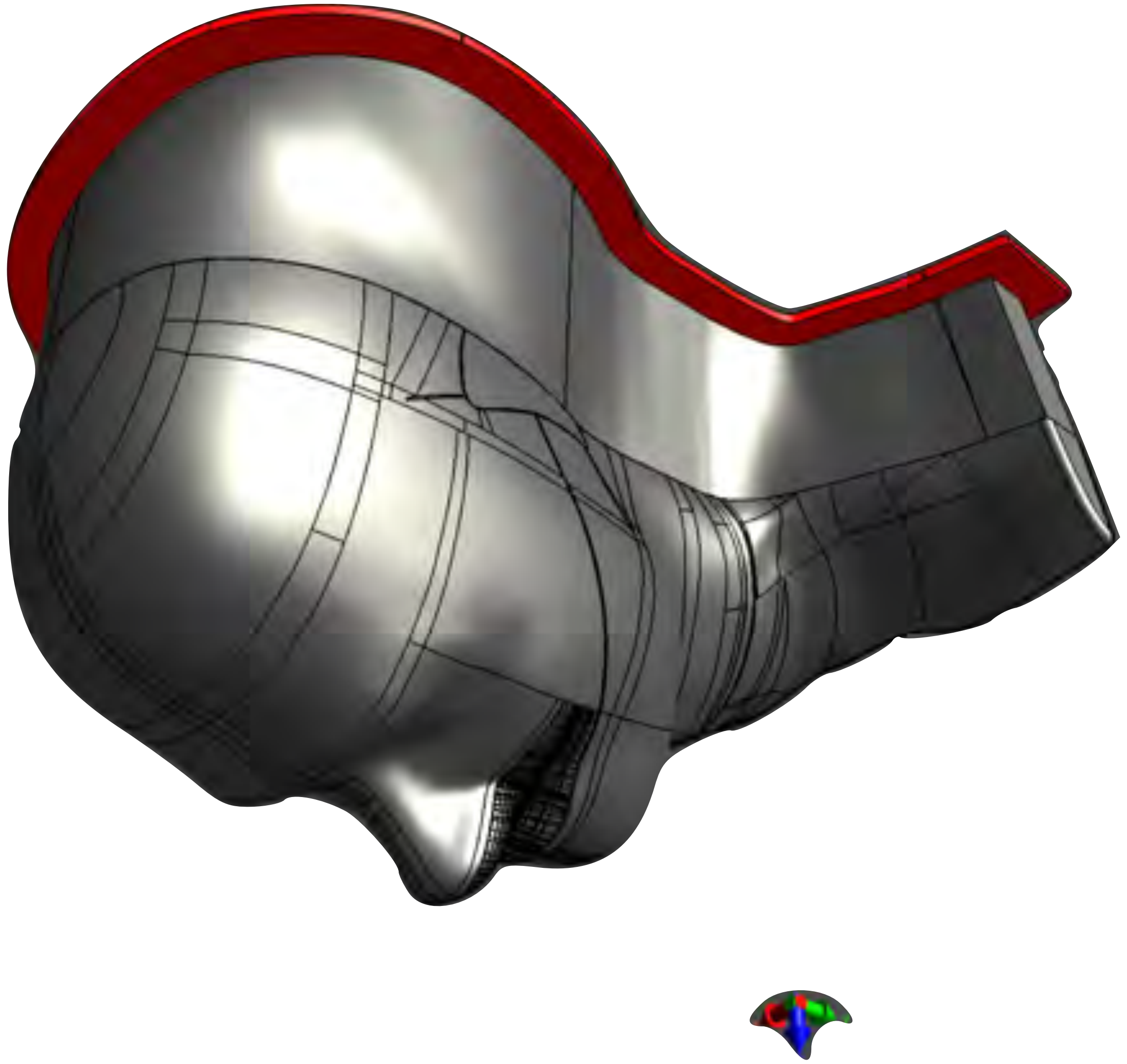
- mother scan (every few weeks or when phantom is exchanged)
- ultra-fast scan
  - time: ~10s
  - output: 1g, 10g of volume scan equivalent (when the scan confirms that same pattern has been measured before; applies only when antenna and band are the same)
- area scan
  - time: 3× faster than traditional system with surface detection
  - output: max location, 1g, 10g (fast SAR algorithm; MOTOROLA to be replaced with next release)
- volume scan (verified)
  - time: 30% faster than DASY52
  - output: 1g, 10g, decay etc.

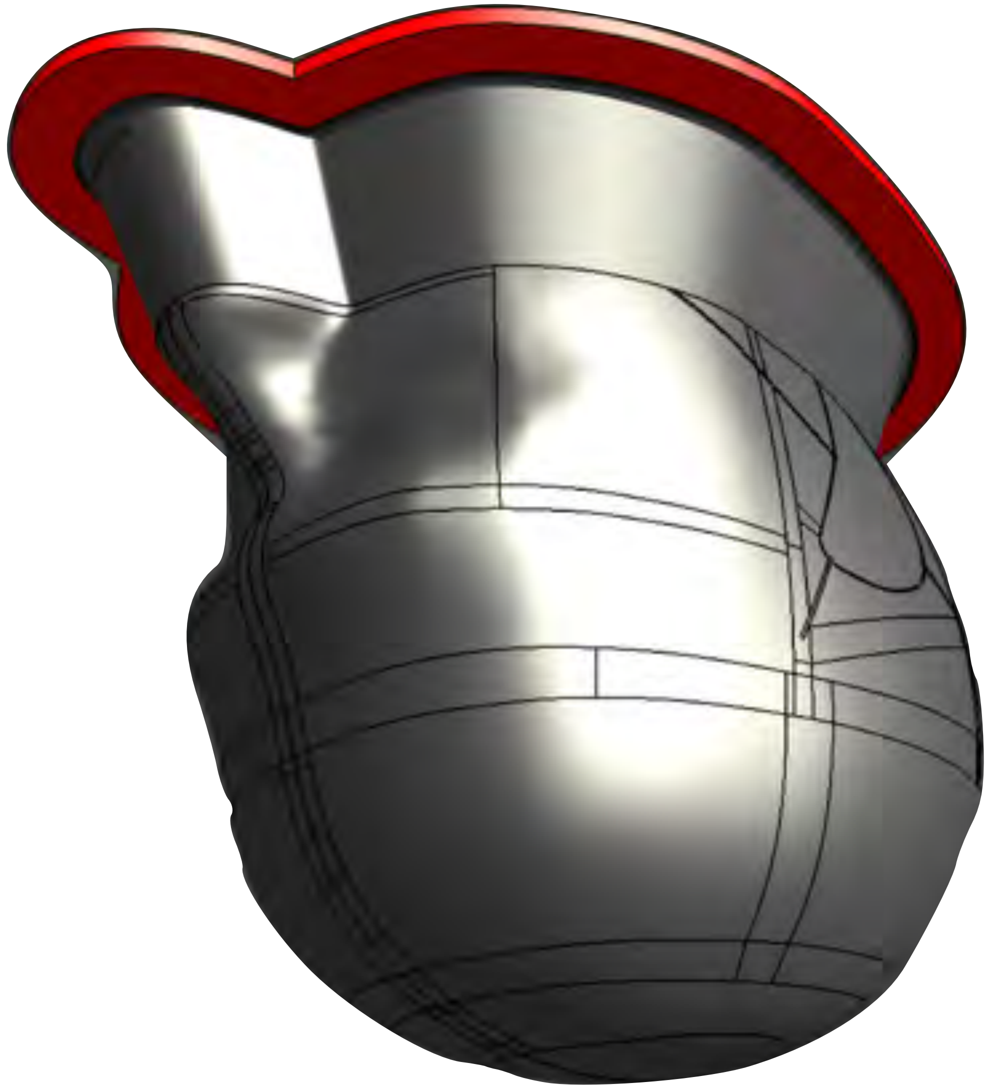


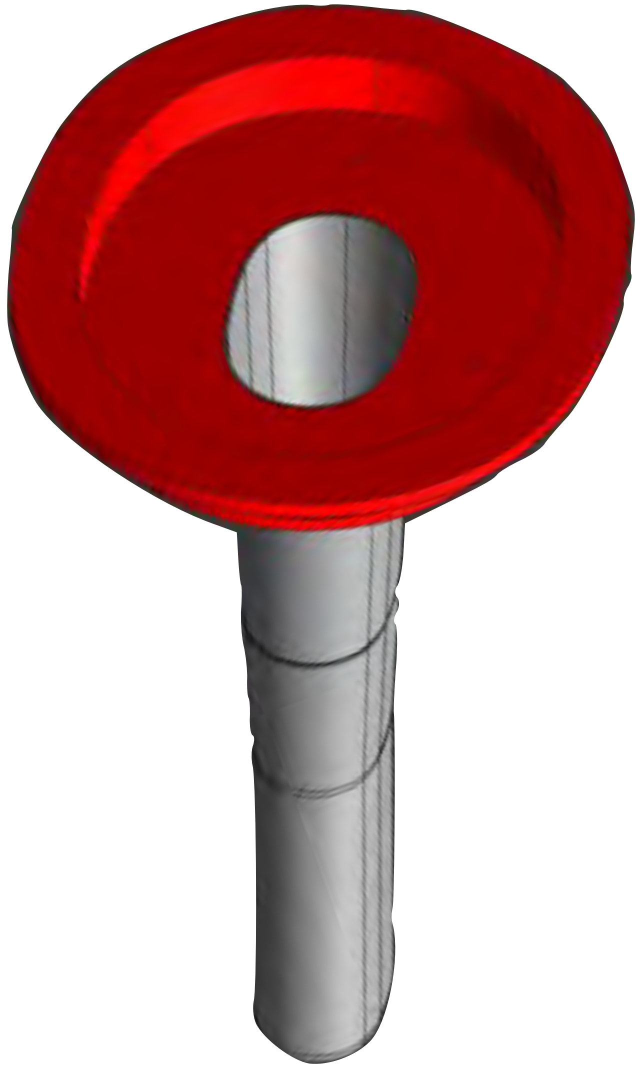
Concept DASY6: Integration of Base-Station Emulators

- Rohde & Schwarz CMW500
- Rohde & Schwarz CMU200
- Anritsu MT8820C
- Keysight (Agilent) E5515C/E 8960 (V6.2))
- Python interface enables the user to program and control base-station emulators and other hardware

Compatible to any New Phantom: FaceDown, Head-Stand, Wrist, etc.







Concept DASY6: Intelligent Software

- optimized workflow
- minimal user interaction
- accelerated movements (full compliance 3 - 10 times faster)
- reconstruction based on vector array system (more reliable than MOTOROLA algorithm)
- expert systems for any standard always updated to the latest requirements for base-station integration (automated switching of channels and linearization verification, etc.)
- full access via Python
- advanced auto-reporting

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Concept of Vector Array Systems

- large number of sensors that acquire in parallel or sequentially
- array is 2D or 3D (planar or conformal to the surface)
- field is reconstructed in 3D by Maxwell-equation-based expansion functions (PWE)

First Generation of Array Systems for QA

- iSAR Flat, Unified Head, Quad by SPEAG (Switzerland)
- SARLITE by SATIMO (France)
- QuickSAR by EM-Safety (South Korea)
- SARA C by IndexSAR (United Kingdom)
- target QA, not compliance testing

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What Changed in the Last Years

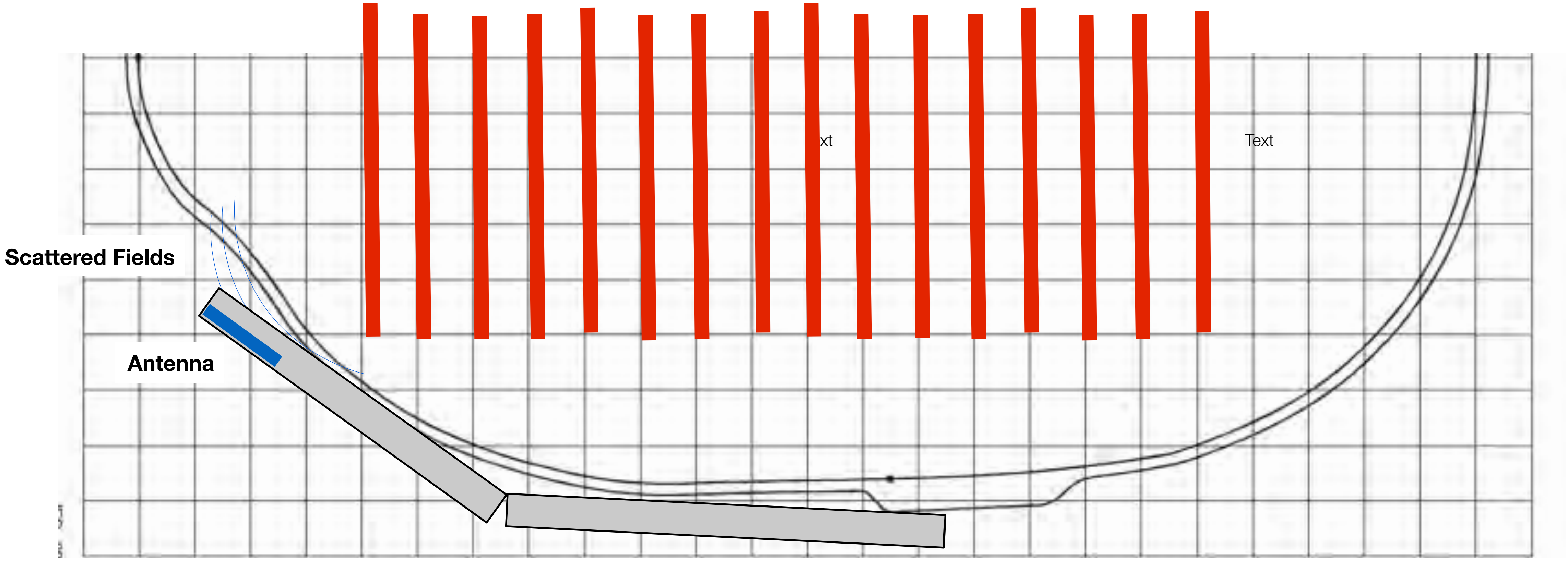
- more communication systems: GSM, UMTS, LTE, WLAN
- multiple bands
- more antenna, dynamic antenna tuning, MIMO
- user conditions: proximity sensors, wrist phantoms
- 10× to 100× more test conditions
- need for much faster systems in compliance testing

2nd Generation of Array Systems for Compliance Testing

- cSAR3D by SPEAG
- ART-MAN by ART-FI
- other system in developments
  - SATIMO
  - THESS
  - IndexSAR

Concept of Array Systems

- large number of sensors that acquire in parallel or sequentially (metal or dielectric)
- array is 2D or 3D (planar or conformal to the surface)
- field is reconstructed in 3D by Maxwell-Eq-based basis functions (PWE)



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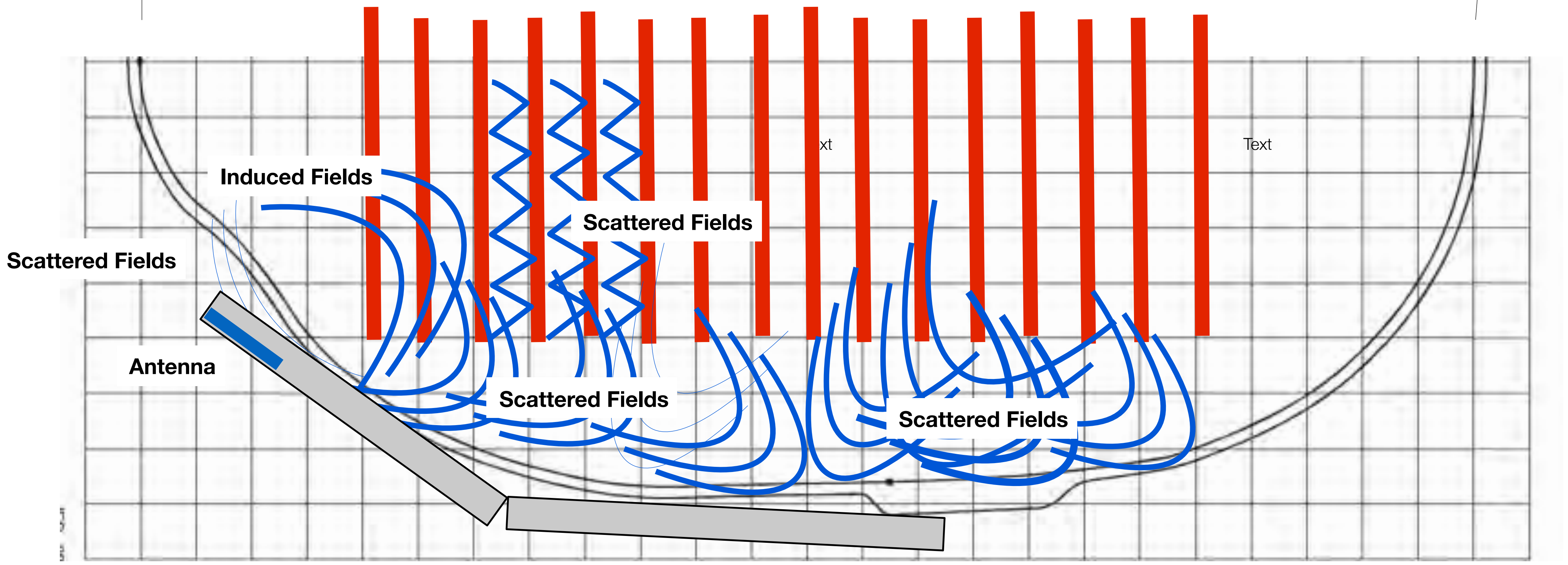
Distortion by Array Systems

- distortion: significant but compensated as much as possible
- psSAR: estimated due to advanced field reconstruction
- validity: uncertainty/scattering/reconstruction is source dependent, difficult to assess



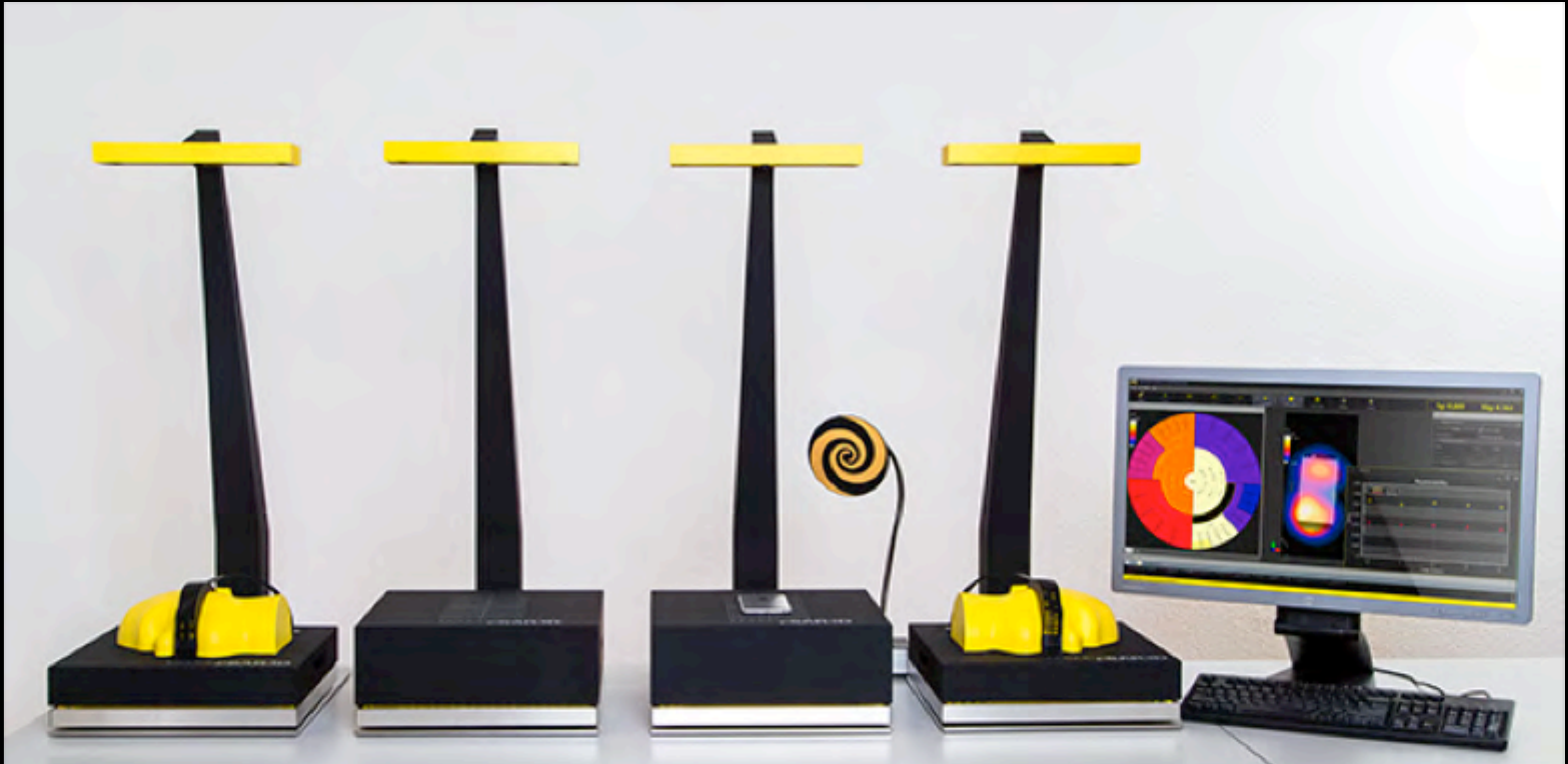
Issues: Vector Array Systems

- large number of fixed probes (> 1000 sensors)
  - calibration of > 1000 sensors
- but still very sparse probe density
  - tricks to overcome under-sampling problems
- more or less distorts the field to be measured
  - compensation required
- estimation of field distribution anywhere in the head to assess peak spatial SAR
  - standard PWE equivalent expansion techniques
  - advanced maxwell-eq-based basis functions
- most uncertainty sources are correlated and source dependent
  - source dependent uncertainty
  - uncertainties cannot be independently verified as in Part 1/2

- **vector array systems are black box systems**

Example: ART-MAN (http://www.art-fi.eu/technology)

Example: cSAR3D (www.speag.com)



Example: cSAR3D (www.speag.com)

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Solution to Overcome the Inherent Issues (IEC 62209-3)

- system performance requirements
- technology based uncertainty assessment
- validation of performance independent of technology
- validation of uncertainty independent of technology
- performance is the only criteria for acceptance or rejection of systems

All About Performance (IEC 62209-3)

- psSAR1g and 10g up to 10 W/kg for head and body exposures
- dynamic range for CW: 0.01 – >100 W/kg
- frequency: 30 – 6000 MHz
- any modulation
- any DUT
- with an uncertainty of <±30% (state of the art: <21/24%) with respect to the non-disturbed phantom
- otherwise special considerations are required

Concept of Uncertainty, Verification & Validation

- uncertainty
  - list of uncertainty sources to be considered
  - the significance and the best method to assess the uncertainty depend on the technology
  - global methods to assess and combine these uncertainties are specified
  - method technology dependent but must be rigorously documented; the uncertainty components can be assessed based on theoretical considerations or numerically
- verification
  - quick and easy test to make sure that all component are working
  - gives correct results
  - technology dependent but guidance provided
- validation
  - independent of input from the manufacturer/vendors
  - must be comprehensive, i.e., include the characteristics of all current and future devices
  - experimental validation must include the minimum set of sources sufficient to detect any underestimated uncertainties
- confirmation by round-robin testing

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Uncertainty Sources I

- calibration uncertainty
- post-processing
- backscattering from the sensor array
- scattering within the array
- mutual coupling between the sensors
- coupling with the device under test
- signal pickup of the transmission lines

- geometrical deviations from the nominal location of the sensor
- sensor locations with respect to each other
- amplitude uncertainty as a function of amplitude and modulation
- phase uncertainty as a function of amplitude and modulation
- amplitude drifts
- phase drifts

- amplitude noise
- phase noise
- under-sampling
- array boundaries
- amplitude and phase of the basis functions
- reconstruction algorithm for any potential induced field distribution

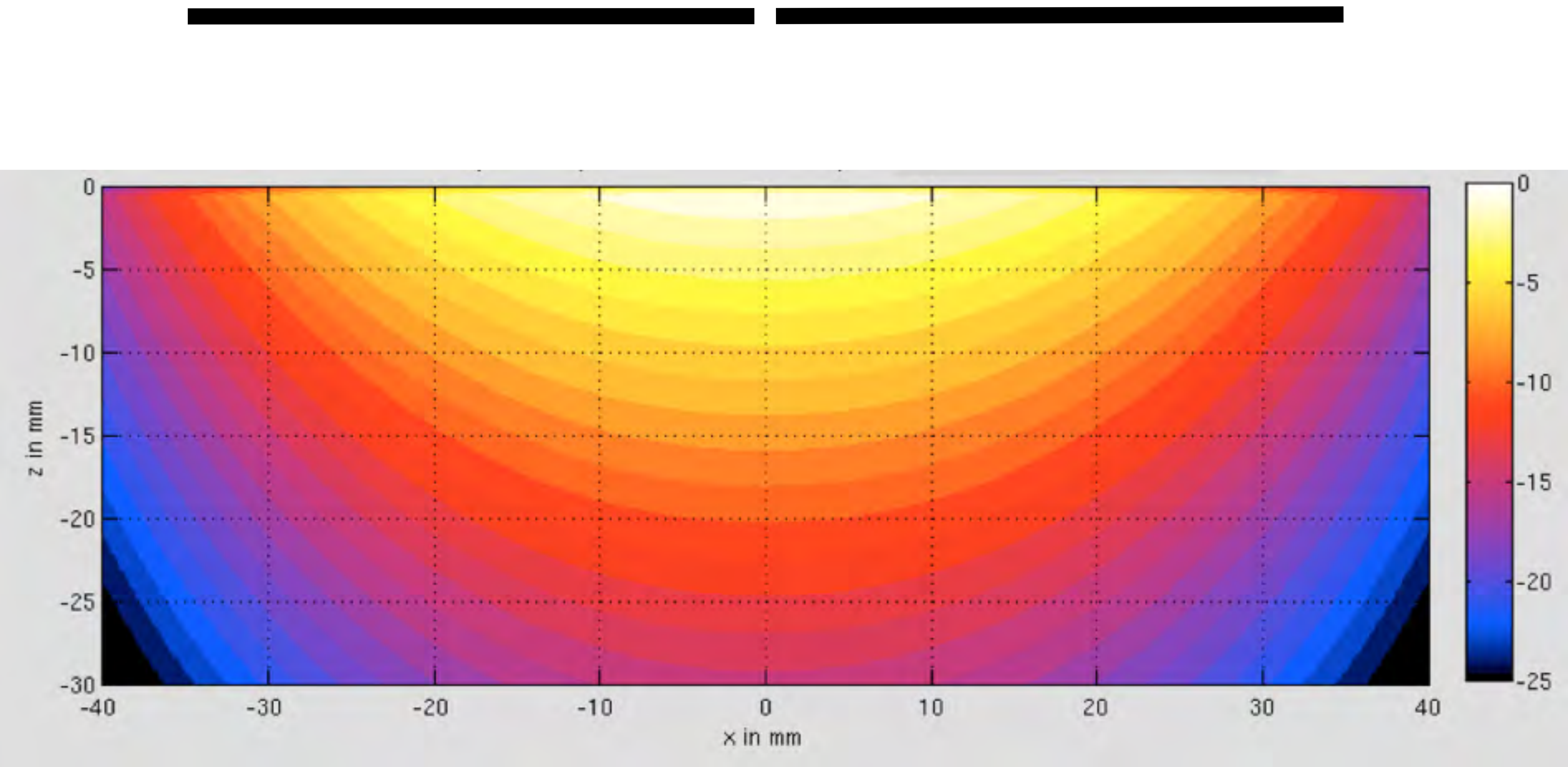
Uncertainty Sources II

- integration uncertainty
- phantom shell uncertainty
- test sample positioning
- device holder
- output power drift
- linearity
- detection limits
- modulation response
- readout electronics
- response time
- integration time
- RF ambient – noise
- RF ambient – reflections

Concept of Validation Section

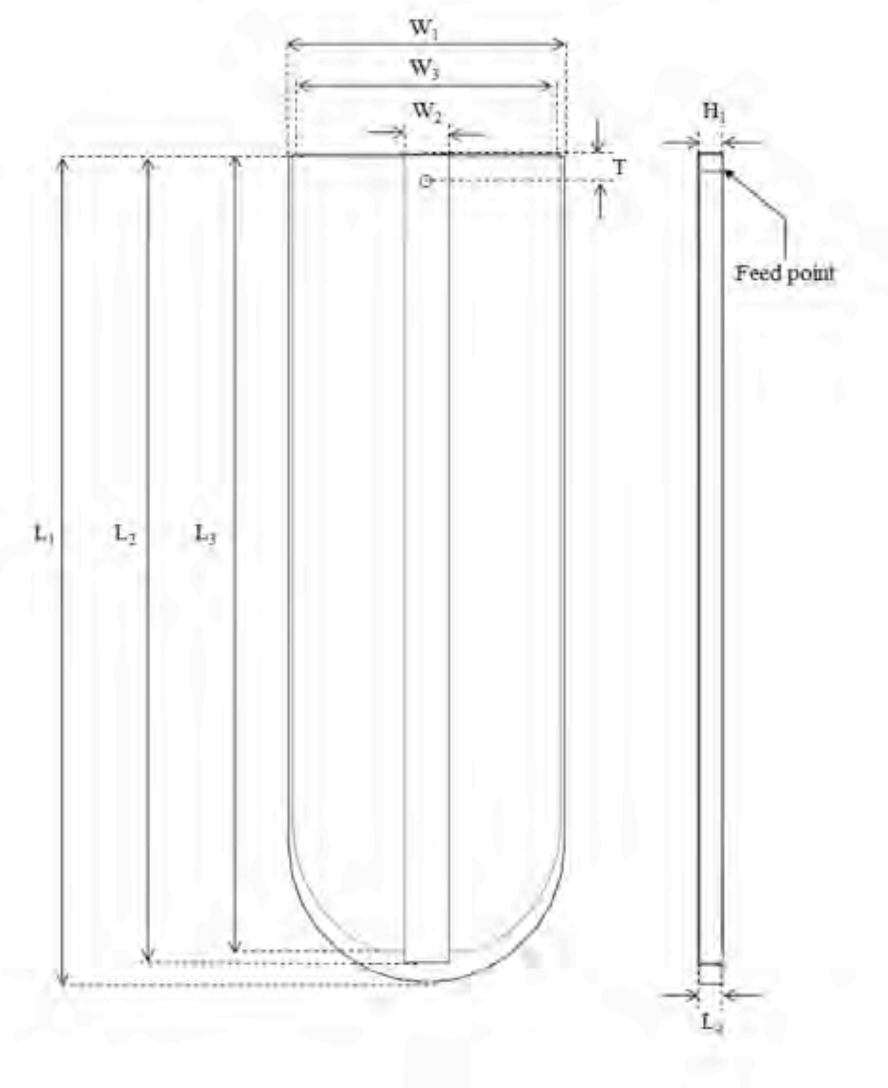
- independent of technology and design
- well-defined sources to test full range of SAR distributions
  - operational frequencies (700 – 6000 MHz)
  - modulations (CW, GSM, WCDMA, LTE, etc.)
  - polarizations (normal and parallel to phantom surface)
  - phantom coupling (capacitive and inductive coupling)
  - power levels (SAR1g from 0.1 to 10 W/kg)
  - distribution (3 dB radius from 5 to 50 mm)
  - single and multiple peaks
  - phantom locations
- calibration of sources
  - ISO/IEC 17025
  - uncertainty < 20% (k = 2)
  - both numerical and experimental target values

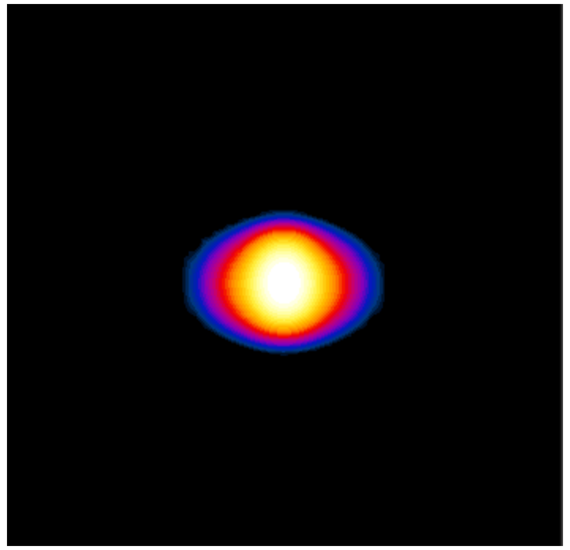
Inductive Coupling Sources: Dipoles

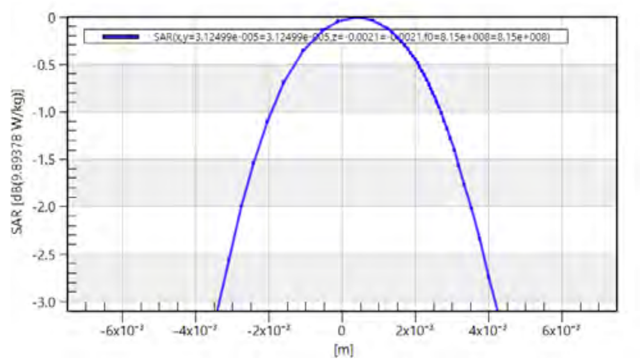


Capacitive Coupling Sources: Vertical PIFA (VPIFA)

VPIFA-750, VPIFA-835, VPIFA-1950, and VPIFA-3700







+/-3.85mm

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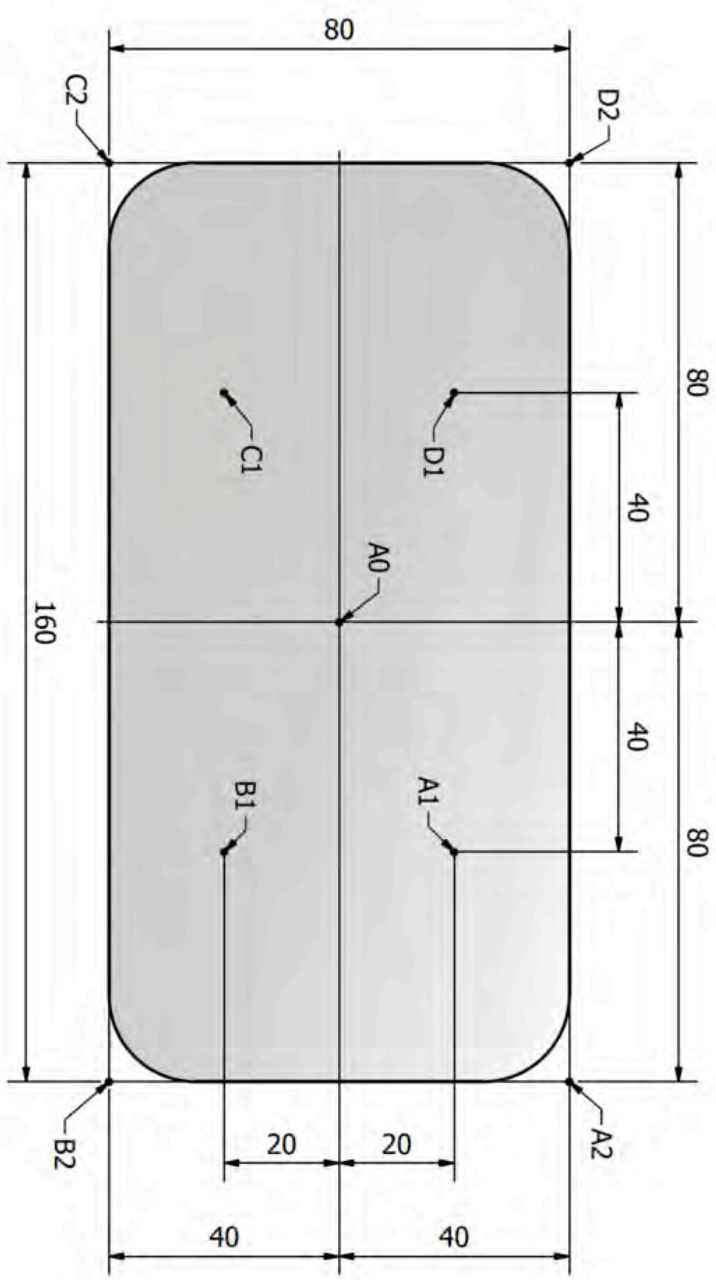
Sources

- dipole antennas, as defined in IEC 62209-1, Annex G
- PIFAC-900, PIFAC-1950, PIFAC-2450, PIFAC-3700
- PIFAE-835, PIFAE-1950, PIFAE-2450, PIFA-3700, PIFAE-5200
- VPIFA-750, VPIFA-835, VPIFA-1950, VPIFA 3700
- multi-peak generic phone sources
- source sensitive to backscattering from sensor array
- numerical and experimental target values wherever possible

Minimal Set of Modulations

Tech.	Description	UID
CW	CW	10000
GSM	EDGE-FDD (TDMA, 8PSK, TN 0)	10025
Bluetooth	IEEE 802.15.1 Bluetooth (GFSK, DH1)	10030
WLAN	IEEE 802.11a/h WiFi 5 GHz (OFDM, 6 Mbps)	10062
WLAN	IEEE 802.11a/h WiFi 5 GHz (OFDM, 54 Mbps)	10069
WLAN	IEEE 802.11g WiFi 2.4 GHz (DSSS/OFDM, 54 Mbps)	10077
LTE-FDD	LTE-FDD (SC-FDMA, 100% RB, 20 MHz, QPSK)	10100
LTE-TDD	LTE-TDD (SC-FDMA, 100% RB, 20 MHz, QPSK)	10103
LTE-FDD	LTE-FDD (SC-FDMA, 1 RB, 20 MHz, QPSK)	10169
LTE-TDD	LTE-TDD (SC-FDMA, 1 RB, 20 MHz, QPSK)	10172

Validation Points Flat



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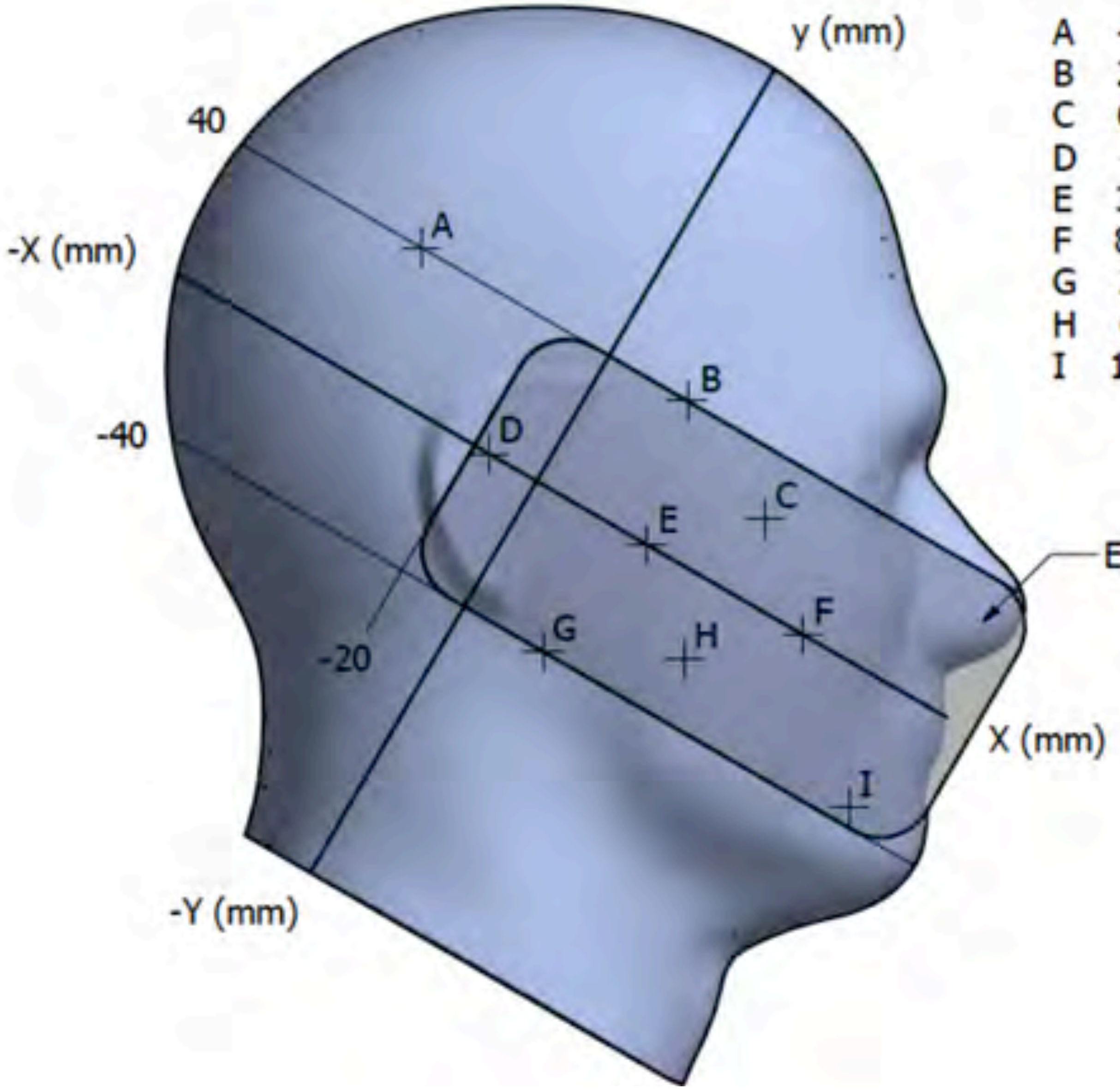
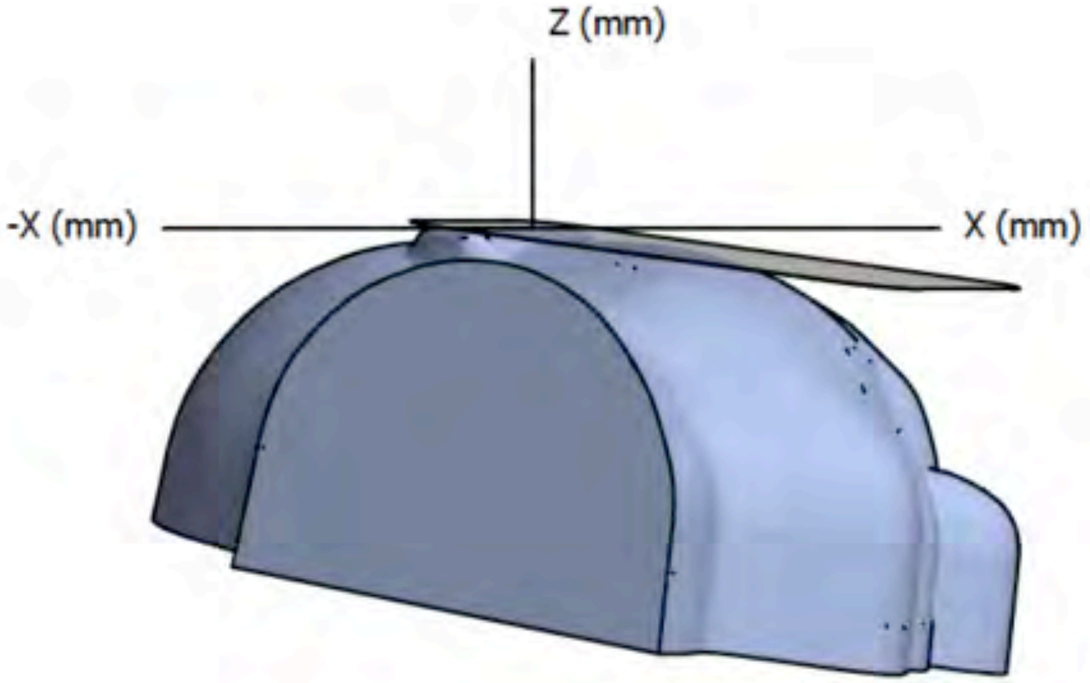
Validation Points Head



A	-60 / 40 / -7.08
B	25 / 40 / -12.06
C	60 / 22.5 / -11.38
D	-15 / 0 / 0
E	35 / 0 / -4.77
F	85 / 0 / -19.11
G	25 / -40 / -12.54
H	60 / -22.5 / -8.14
I	120 / -35 / -43.82



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Test Conditions with Target Values

No	Source Annex G	f_1 [MHz]	P_{in} [dBm]	f_2 [MHz]	P_{in} dBm	Mod UID	Loc Pos Deg	d [mm]	psSAR 1g	psSAR 10g	Unc (k=2)
1	D750	750	30			10000	A0,1,2, B1,2 C1,2, D1,2 0, 45, 90	15	8.2	5.36	0.5 dB
2	D750	750	20			10000 10169 10172	A0,1,2, 0, 67, 90	15	0.82	0.536	0.5 dB
3	D750	750	30			10000	B1,2 0,45,90	5	7.96	3.81	0.5 dB
4	D750	750	30			10000	C1,2 22.5	25	4.84	3.42	0.5 dB
5	D1950	1950	20			10000 10100 10103	A0,1,2, B1,2 C1,2, D1,2 0,67,90	10	4.05	2.10	0.5 dB
6	D1950	1950	24			10103	A0, 1,2 0, 45, 90	10	10.2	5.27	0.5 dB
	D1950	1950	30			10000, 10100	A0, A1, A2 0, 45, 90	10	40.5	21.0	0.5 dB
7	D1950	1950	30			10000	A0, D1,2 0,45,90	5	60.2	28.0	0.5 dB
8	D1950	1950	30			10000	A0,1,2, 22.5	25	6.6	4.0	0.5 dB
9	D2450	2450	10			10000 10030 10077	A0,1,2, B1,2 C1,2, D1,2 0,45,90	10	0.532	0.249	0.5 dB
10	D2450	2450	24			10030 10077	D1,2 0, 45, 90	10	13.4	6.25	0.5 dB
11	D2450	2450	30			10000	D1,2 0,45,90	10	53.2	24.9	0.5 dB
11	D2450	2450	26			10000	A0, B1,2 0,45,90	5	38.2	16.2	0.5 dB
12	D2450	2450	20			10000	A0 22.5	25	2.54	1.39	0.5 dB
13	D5800	5800	10			10000	A0,1,2, B1,2 C1,2, D1,2 0,67,90	10	0.780	0.223	0.8 dB
14	D5800	5800	30			10000 10062 10069	A0,1,2 0,67,90	10	78.0	21.9	0.8 dB
15	D5800	5800	20			10000	A0, D1,2	5	27.28	5.69	0.8 dB

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Example Vector Array Evaluation: Flat Phantom

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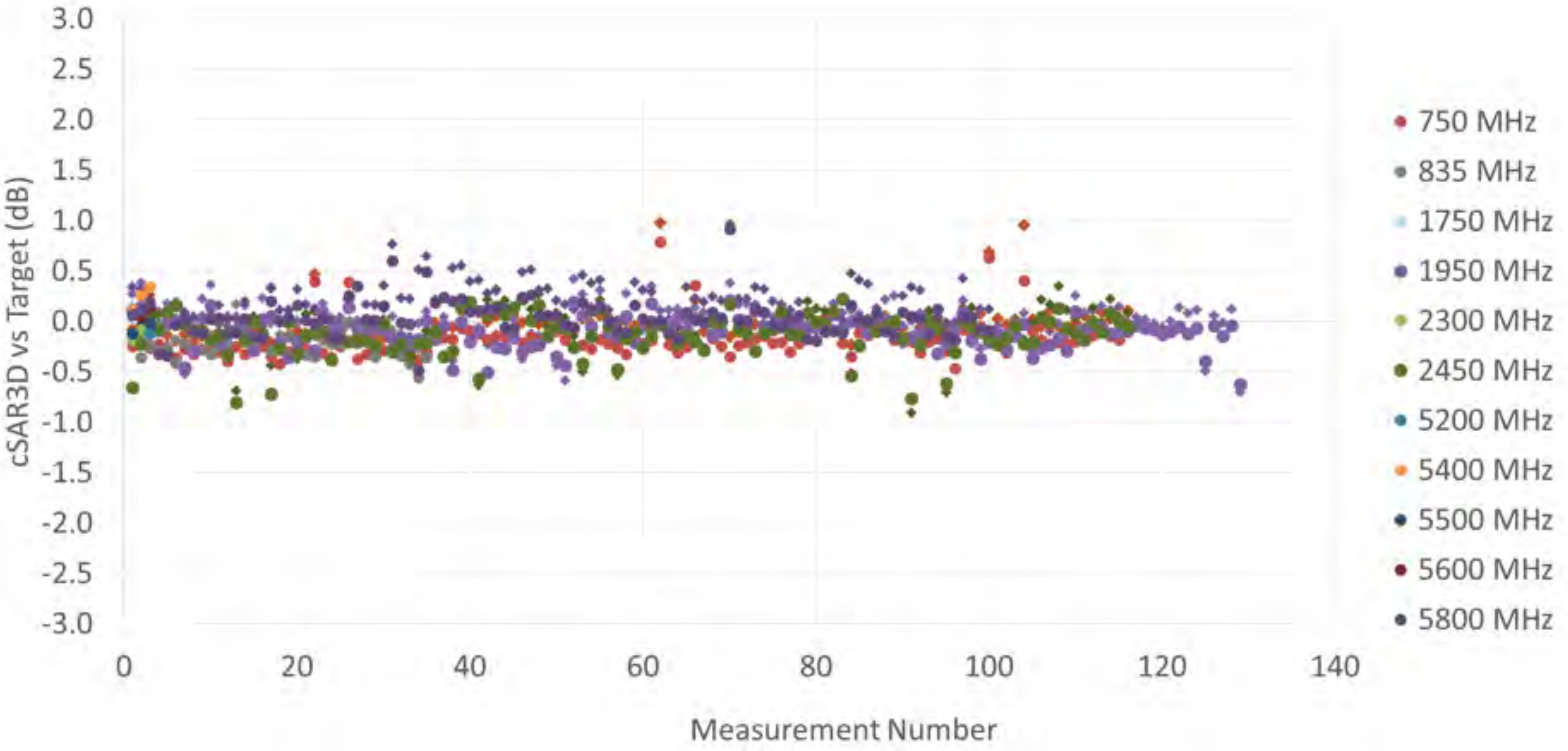
cSAR3D Flat 1g(o)/10g(◊): All Dipoles/All Frequencies (N = 515, σ = 5%)



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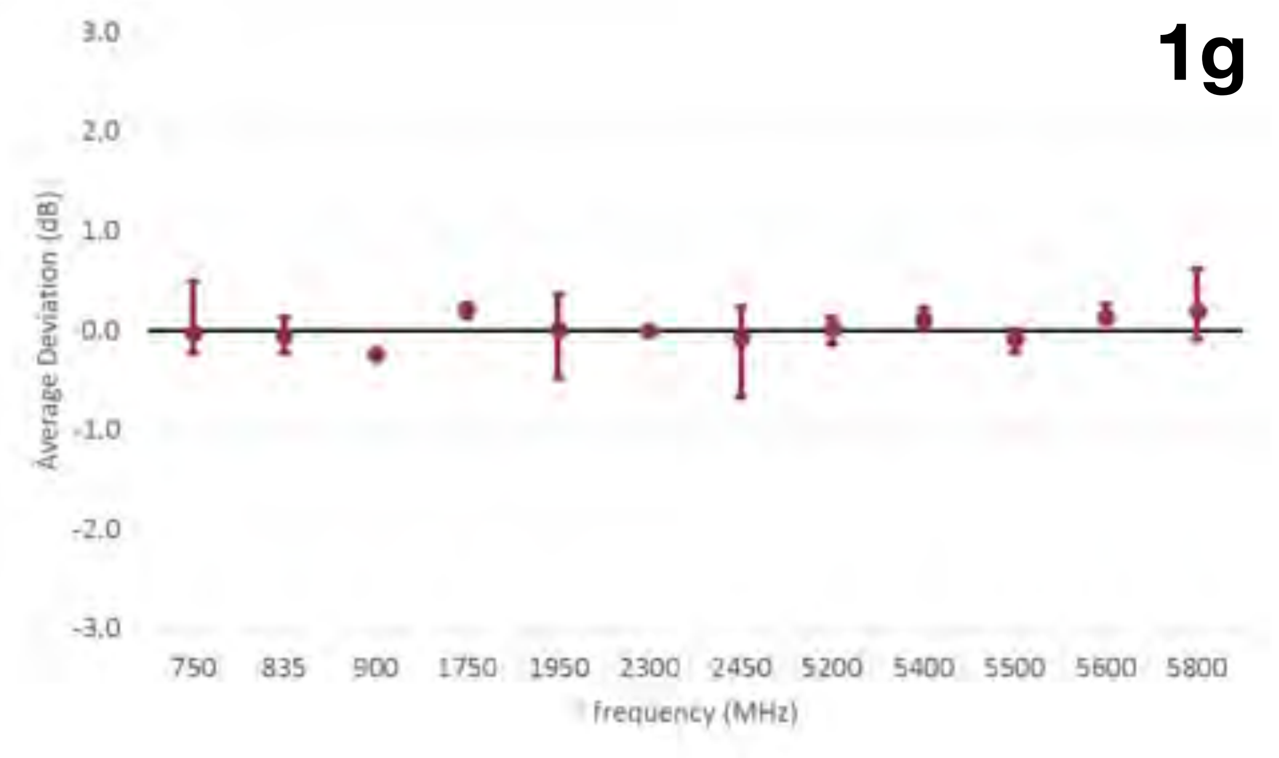
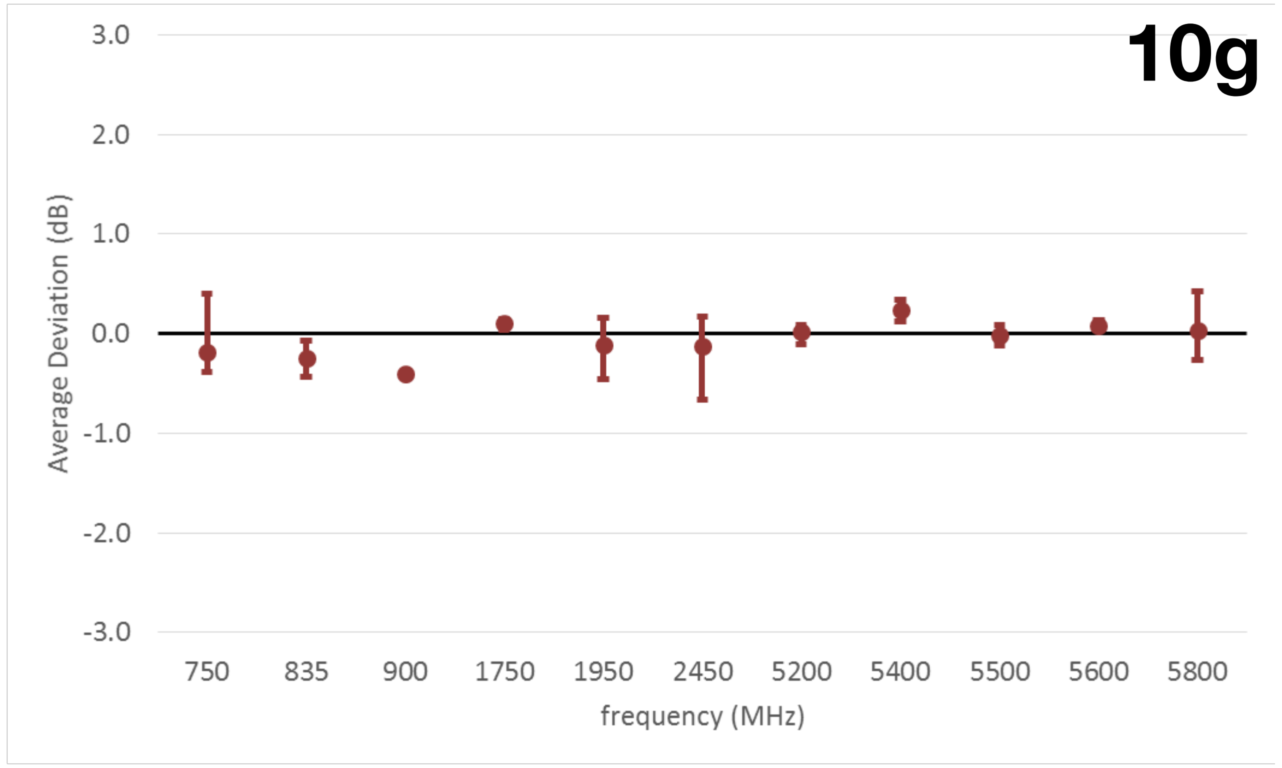
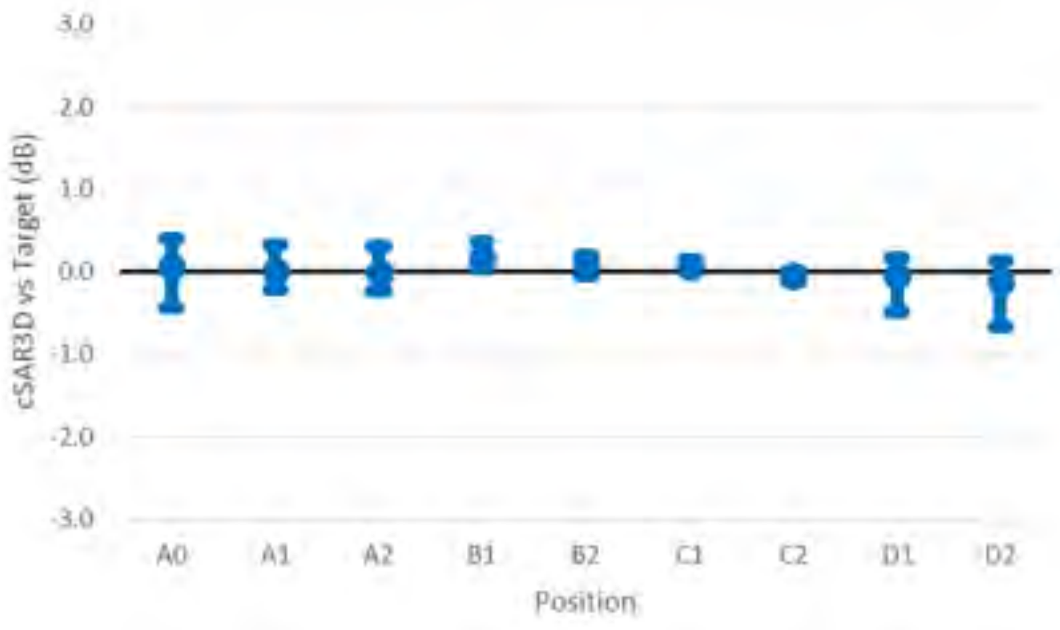
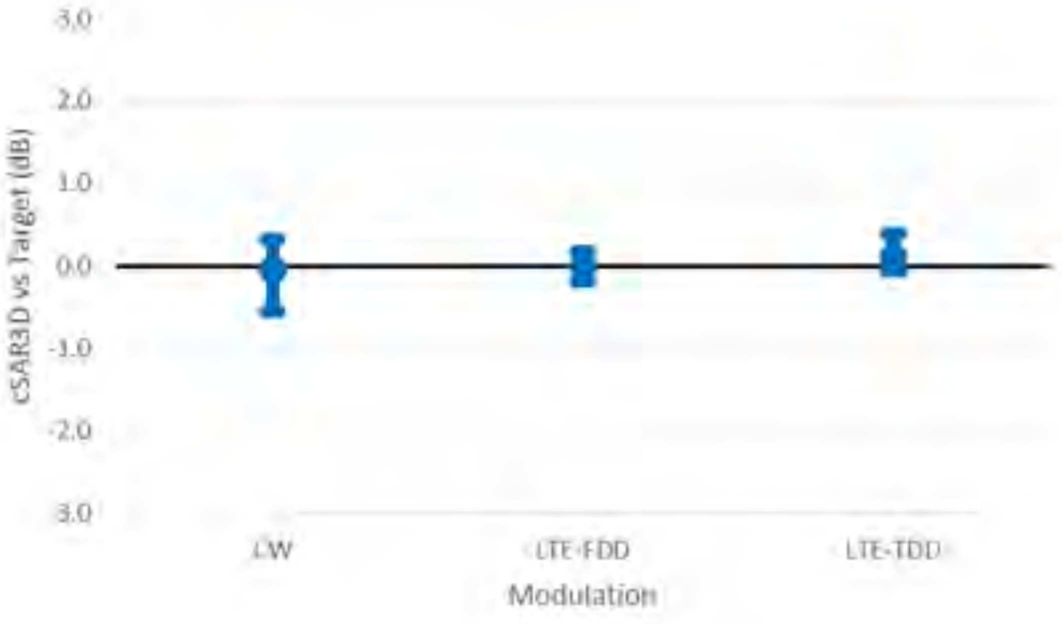
cSAR3D Flat (95% range): All Dipoles/All Frequencies (N = 515, σ = 5%)

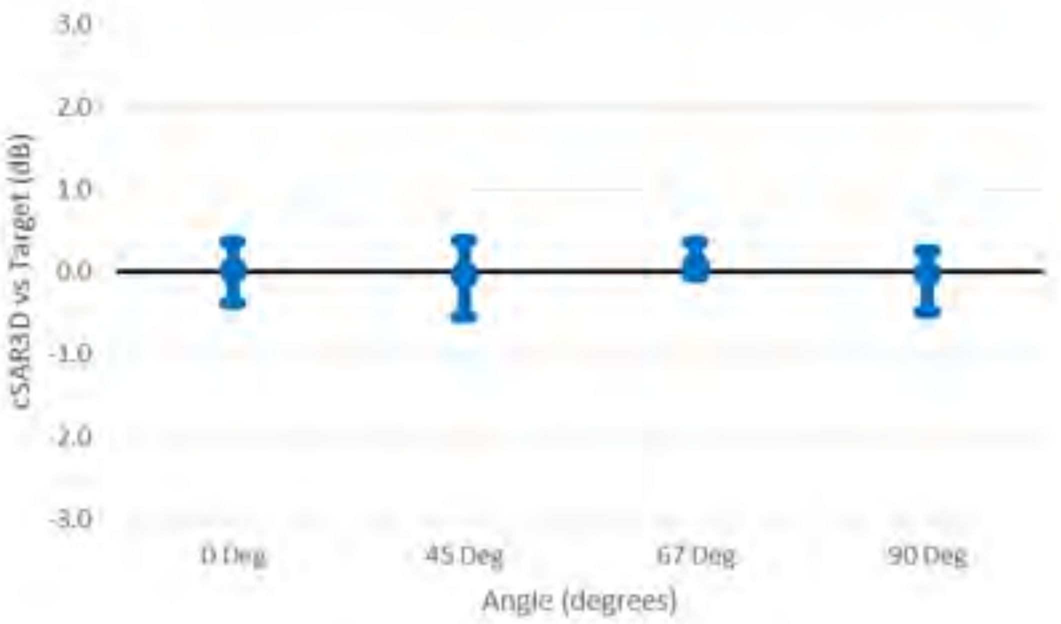


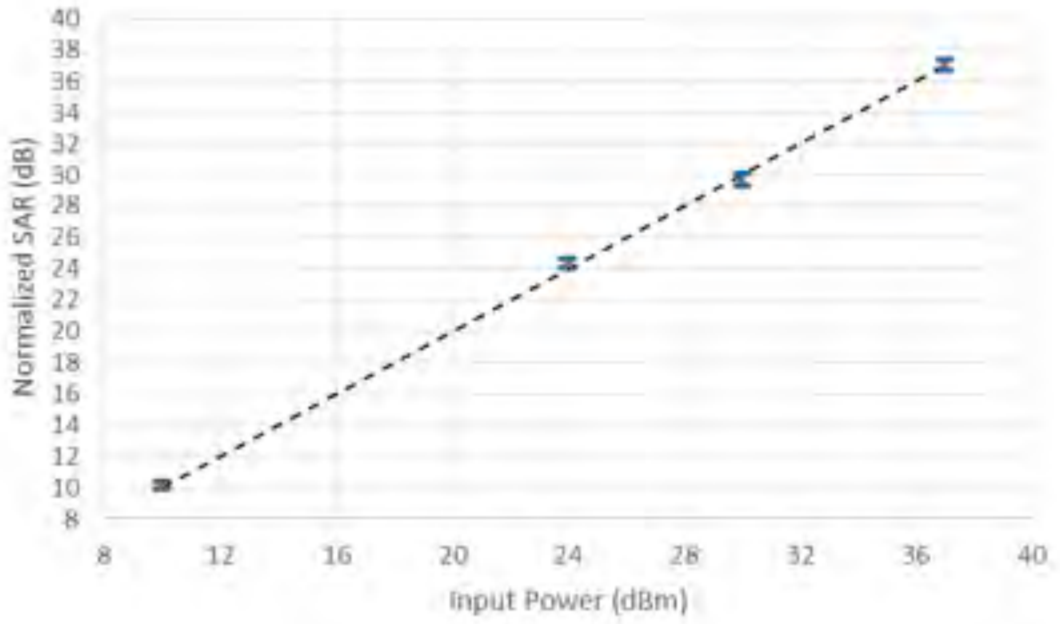


cSAR3D Flat (1950 MHz) for psSAR1g: 95% range









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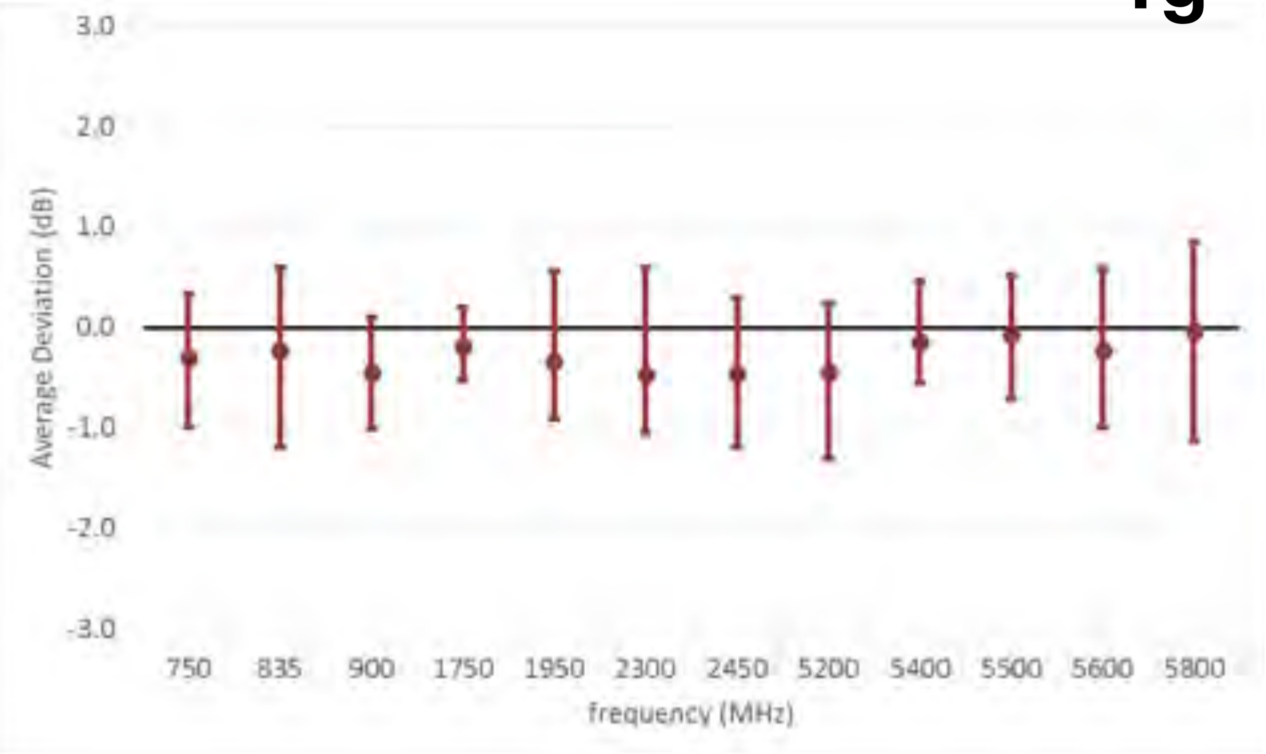
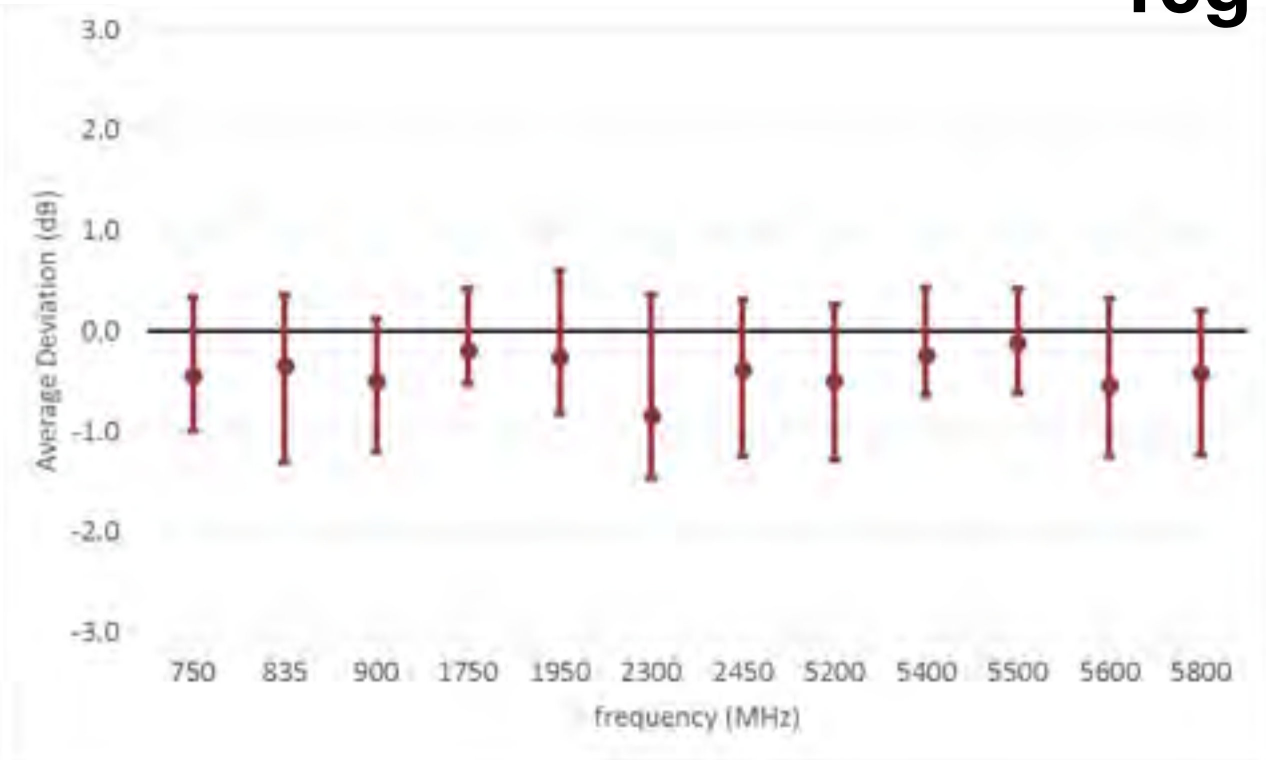
Example Vector Array Evaluation: Head Right Phantom

cSAR3D Right Head (95% range): All Dipoles/All Frequencies ($N = 748$, $\sigma = 10\%$)

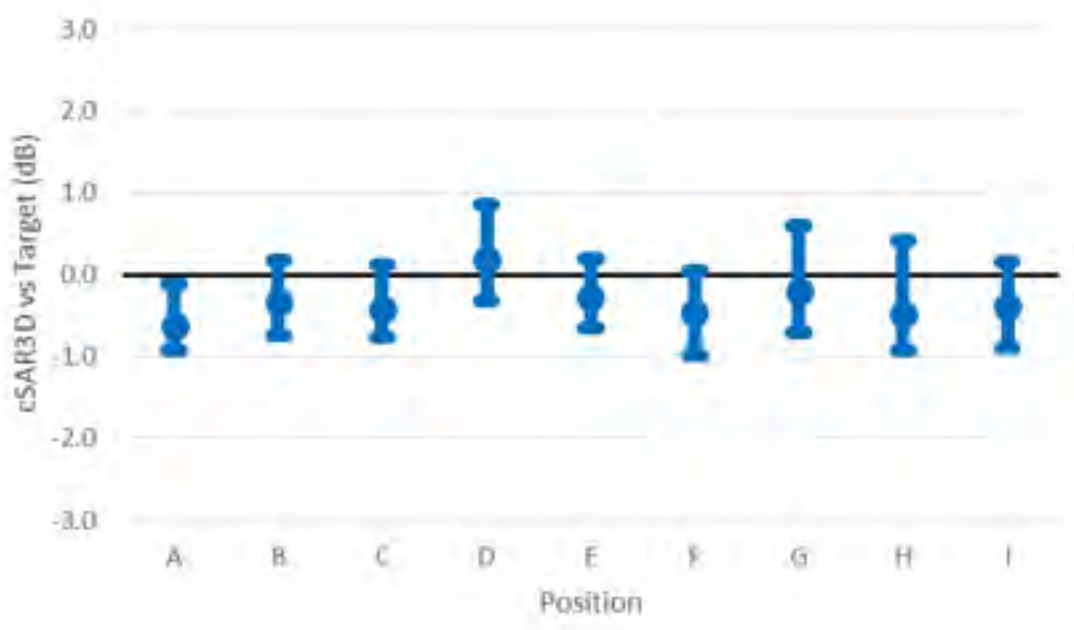
1g

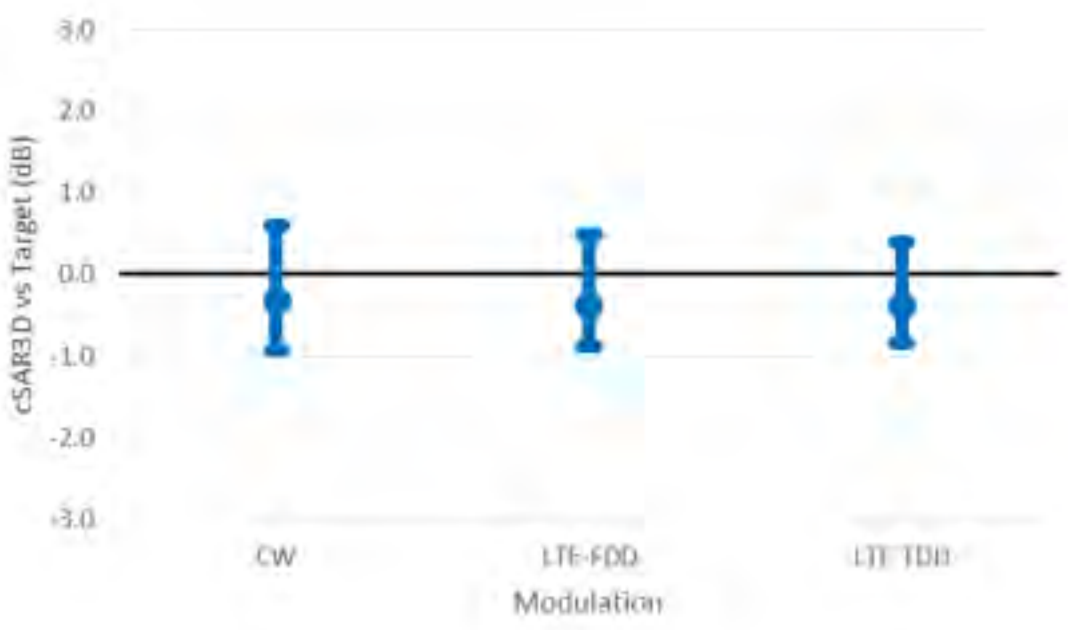


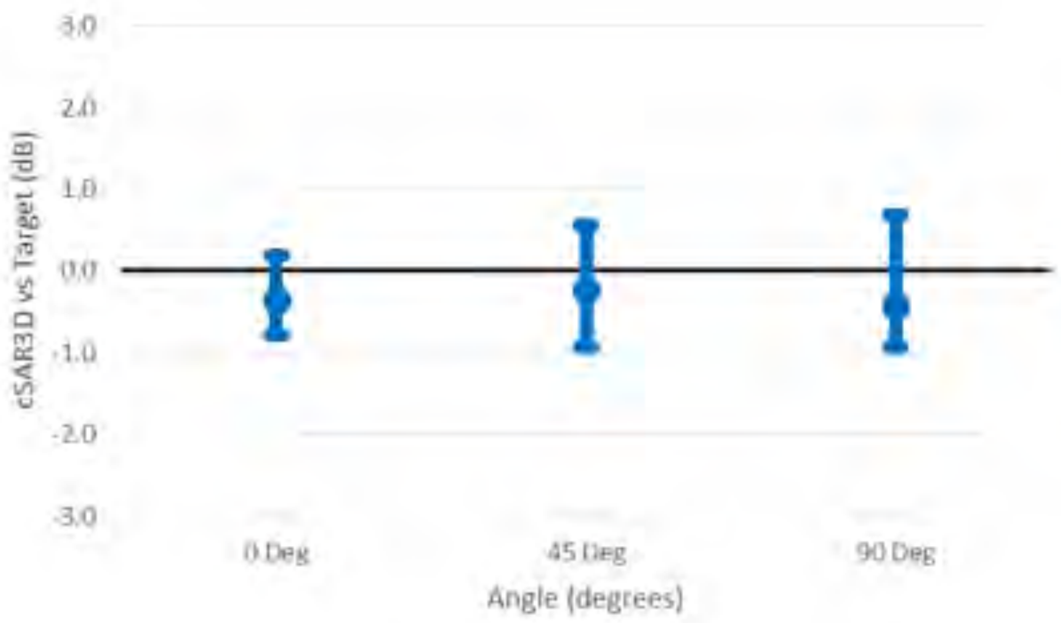
10g

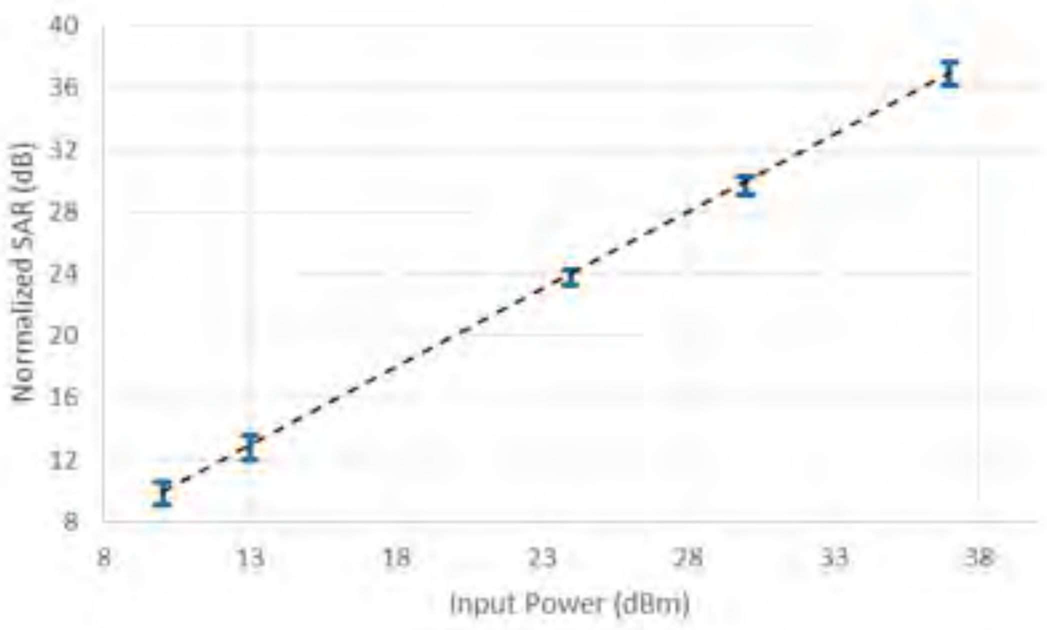


cSAR3D Right Head (1950 MHz): 95% range



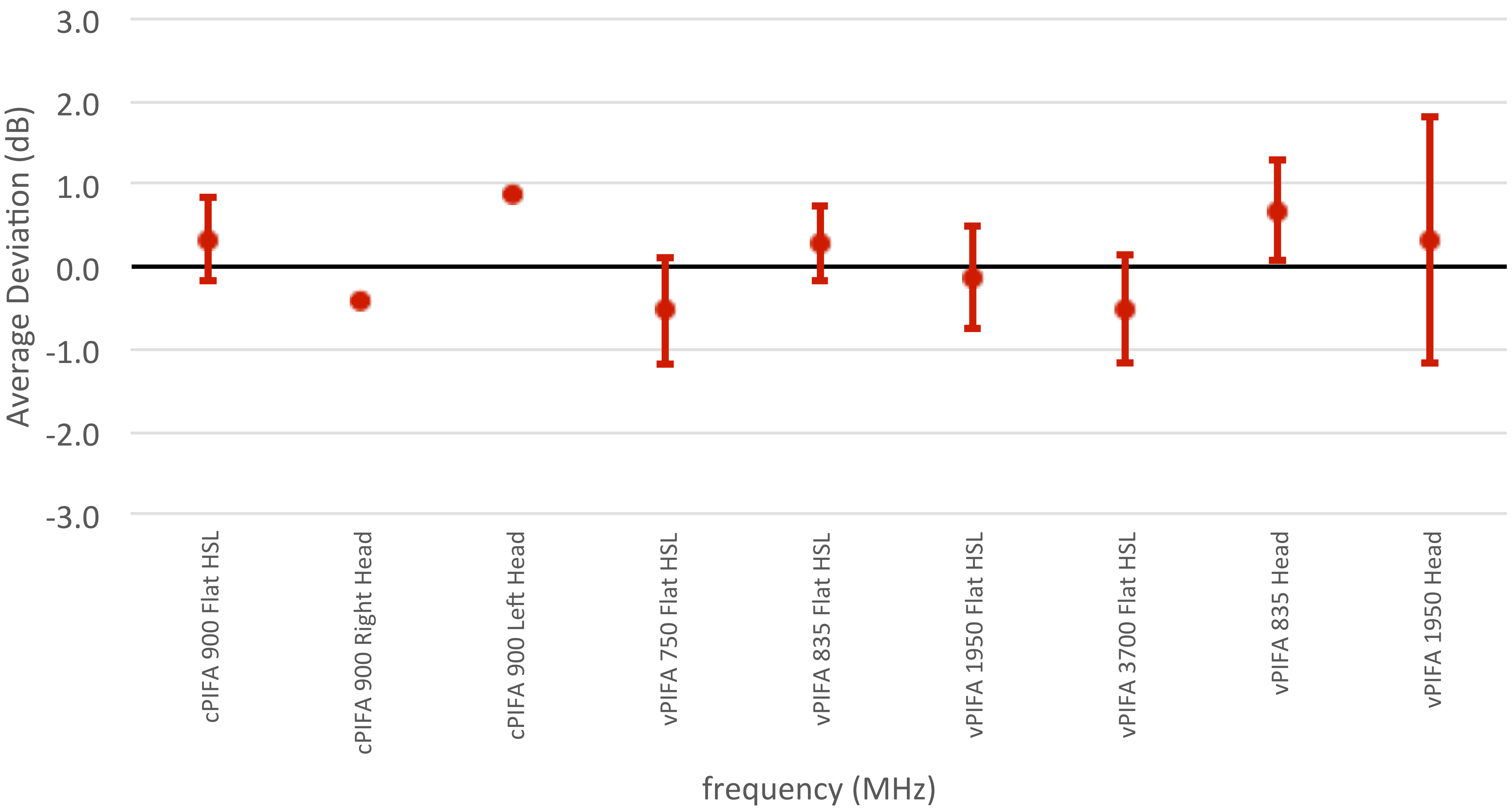






Performance for Capacitively Induced Fields (Vertical PIFA)

cSAR3D 10g (2* STDEV): PIFA



Conclusions

Summary: Single Probe vs. Vector Array Systems

	Single Probe Systems	Vector Array Systems
Standard Compatibility	all standards	IEC 62209-3 only
Government	all	???
Comparability	excellent (all components well-defined)	moderate to good (manufacturer defined)
Test Time	minutes	seconds
Uncertainty	~20% (well defined)	~>30% (manufacturer)
Repeatability	~10%	<10%
Verification	standard	manufacturer defined
Validation	standard	**comprehensive source set needed (standard)**
maintenance	complex / wet	simple / dry

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