Personal Dosimetry for RF Exposures – The Metrology Challenges

Fondation Santé et Radiofréquences
Second Scientific Meeting

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Measurement Objectives

Why make a measurement?

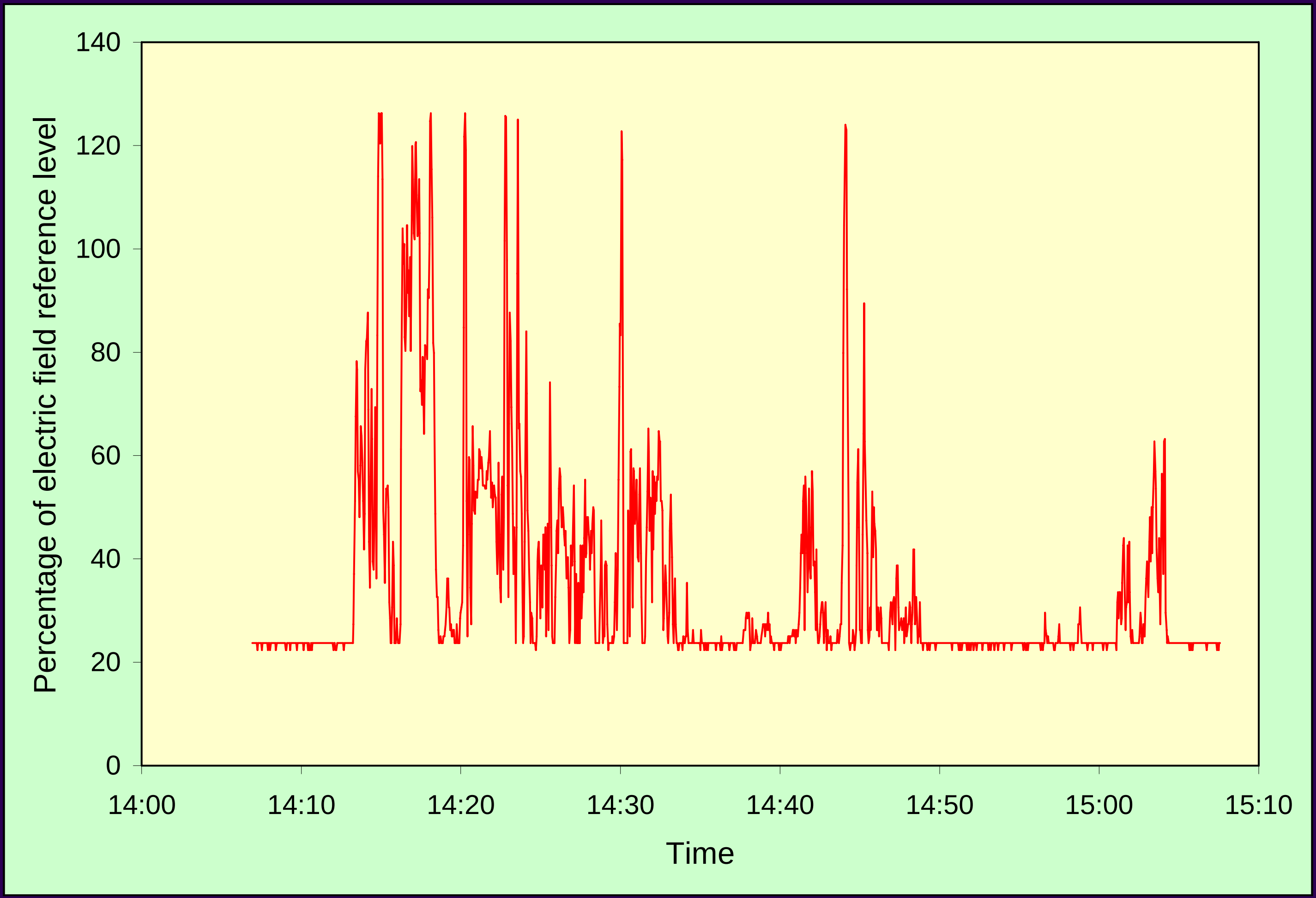
- Compliance with safety standards
- Gain information about exposure
- Health-related research

Types of measurement

- Spot measurement
- Maximum exposure
- Average exposure
- Personal exposure

Aspects of time and space

Personal Exposure Record from HF Broadcast Site



Outline

- PEM performance requirements
- Quality assurance aspects
- Dosimetric interactions
  - Low frequencies
  - High frequencies
- Sources close to the body
- Exposure metrics
- Shadowing effect of the body
- Future work

General Measurement Performance Requirements

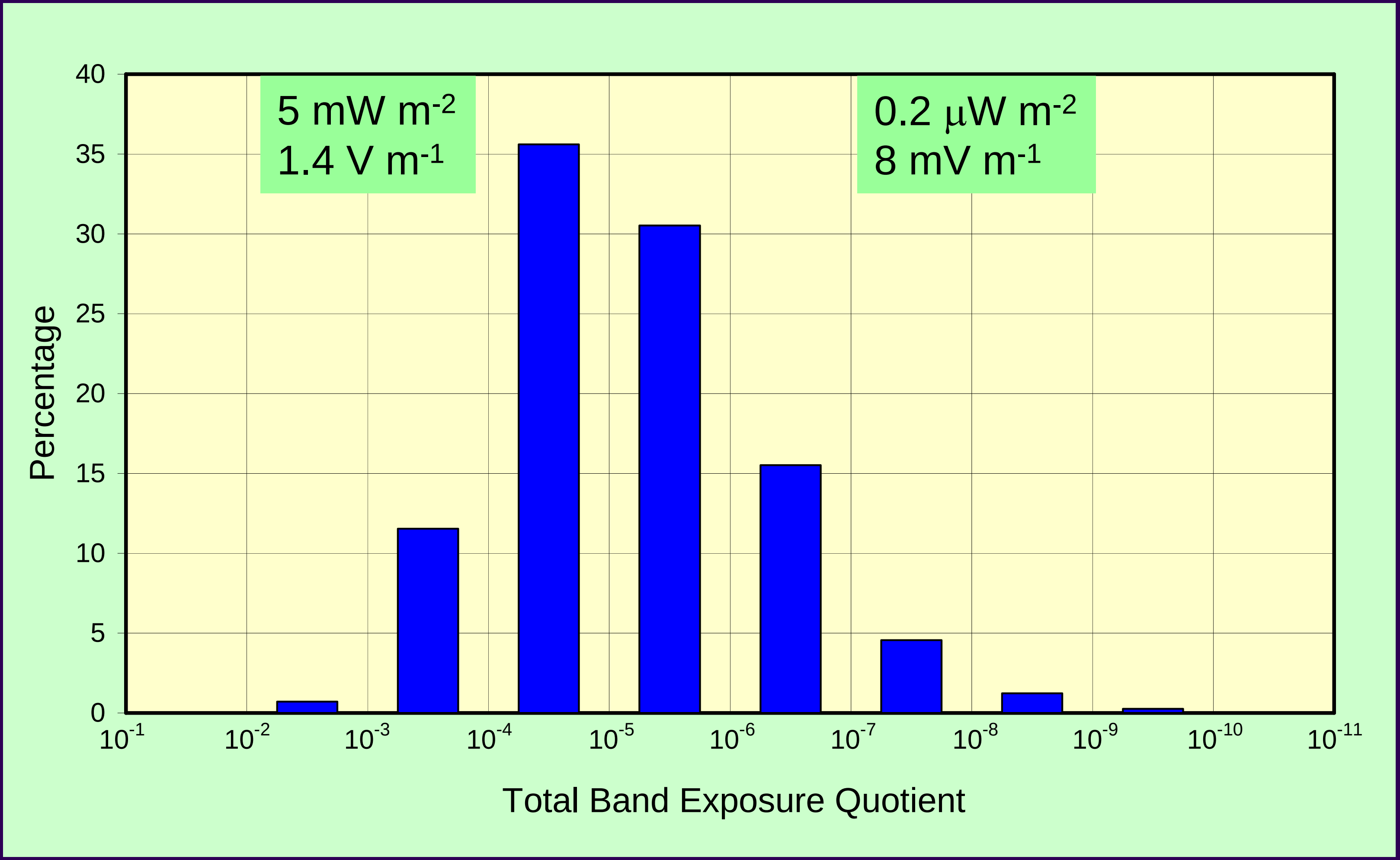
- Appropriate frequency range
  - Immunity to signals outside this range
- Adequate dynamic range
  - Sensitive enough
  - Doesn’t overload
- Calibration with defined uncertainty
  - Frequency response
  - Directional characteristics
  - Response to modulated/pulsed signals
  - Linearity / summation of multiple signals

Additional (Practical) Requirements for a PEM

- Small
- Lightweight
- Long battery life
- Tamper-proof
- Robust (impact, vibration, water, temperature)
- Discreet
- Easily worn/carried

  - Practical requirements impose compromises in the measurement performance of the PEM

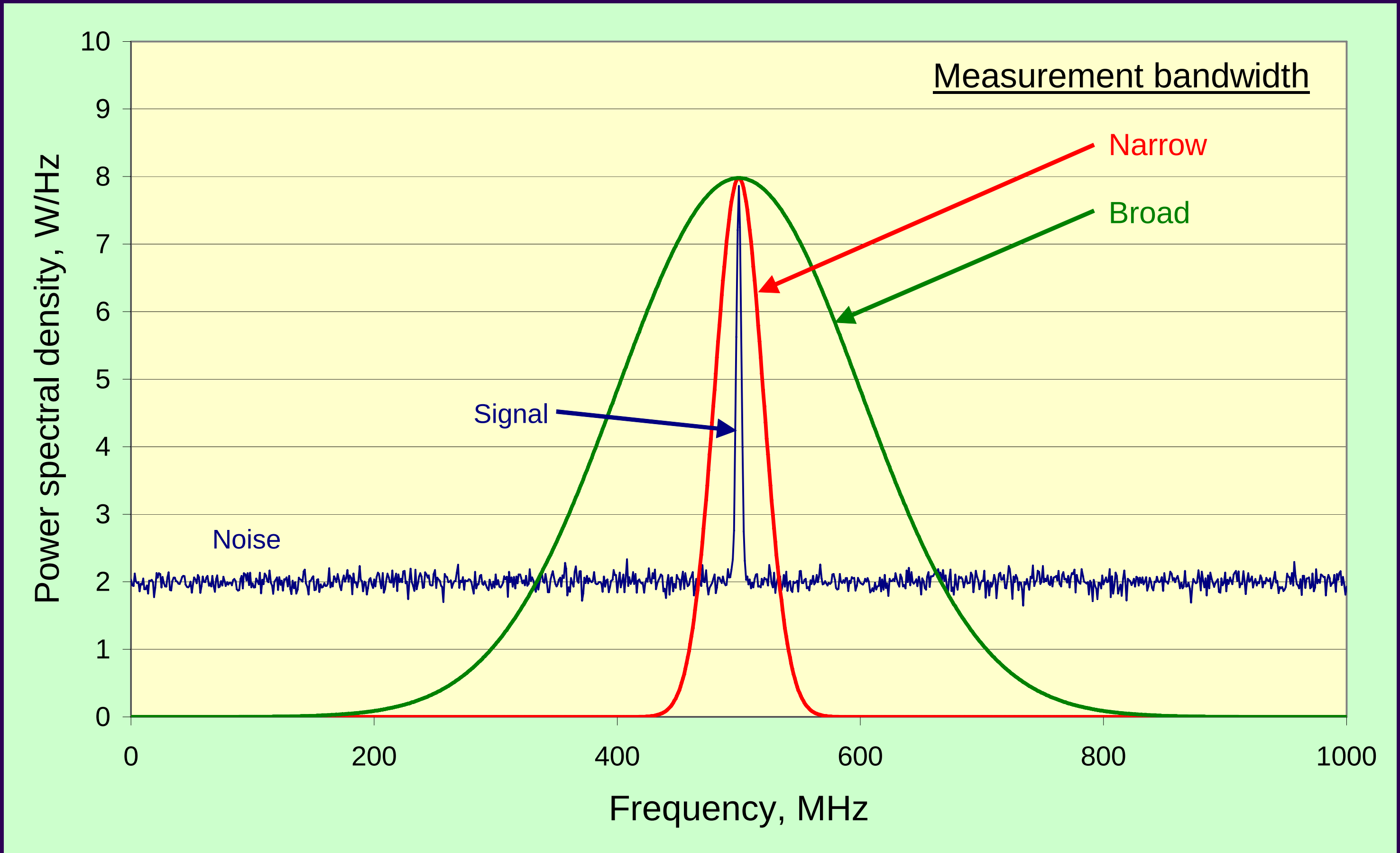
Spot Measurements near Base Stations



Radiofrequency Exposure Characteristics

Span the frequency range:	**80 MHz – 2.5 GHz**
VHF broadcast (radio)	88 - 108 MHz
TETRA base stations	390 - 395 MHz
UHF broadcast (TV)	470 - 854 MHz
GSM900 phones	880 - 915 MHz
GSM900 base stations	925 - 960 MHz
GSM1800 phones	1710 - 1785 MHz
GSM1800 base stations	1805 - 1880 MHz
DECT cordless phones	1880 - 1900 MHz
3G phones	1920 - 1980 MHz
3G base stations	2110 - 2170 MHz
Wireless LANs (802.11g)	2400 - 2500 MHz
Wireless LANs (802.11a)	5150 - 5725 GHz
Typical field strengths:	$1\ mV\ m^{-1} – 1\ V\ m^{-1}$
Typical power densities:	$100\ nW\ m^{-2} – 10\ mW\ m^{-2}$

Sensitivity and Measurement Bandwidth



PEM measures electric field strength samples in multiple frequency bands

Sensitivity

- Requirements of an RF PEM are demanding
- Data acquired so far have a large number of non-detects
  - Around 90% overall
  - Being handled with ROS algorithm (statistical extrapolation method)
- Need to evaluate consequences of non-detects
  - Uncertainty in calculated field values
  - Limits to performance of ROS algorithm
- Will greater sensitivity improve the situation?

Quality Assurance Aspects

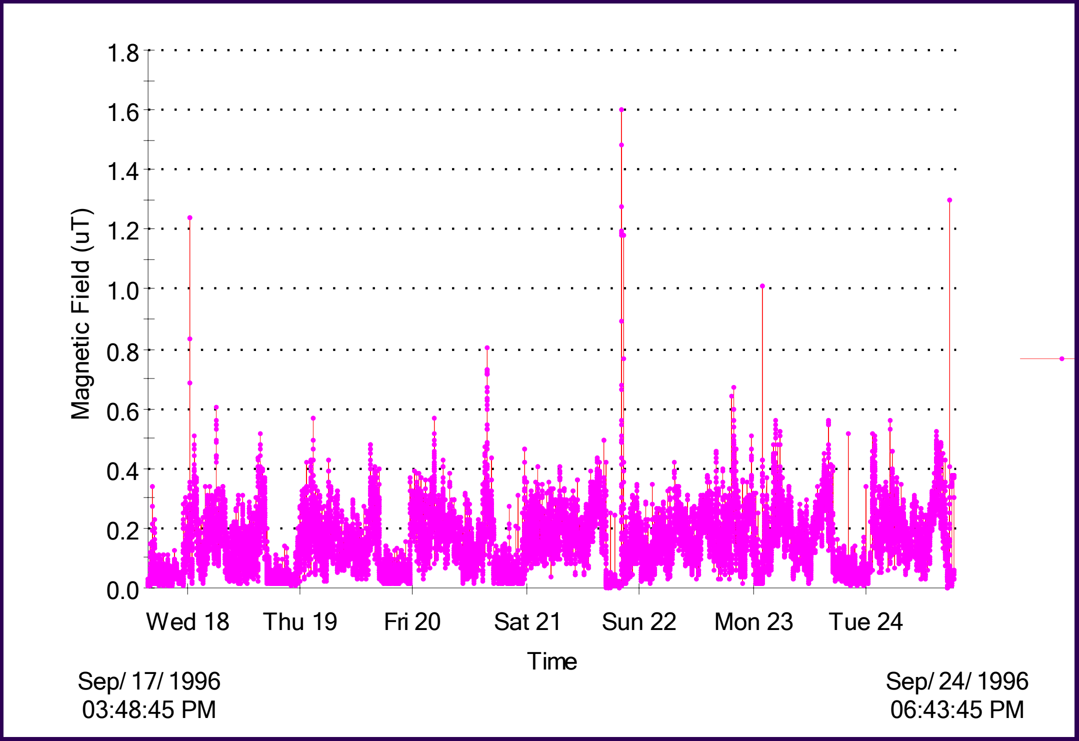
Lessons from Power Frequencies

Power frequency PEM

Magnetic fields

- Three orthogonal coils provide an isotropic response
- 40 to 800 Hz
- 10 nT resolution
- Measures up to 300 mT

Power Frequency Magnetic Field Trace



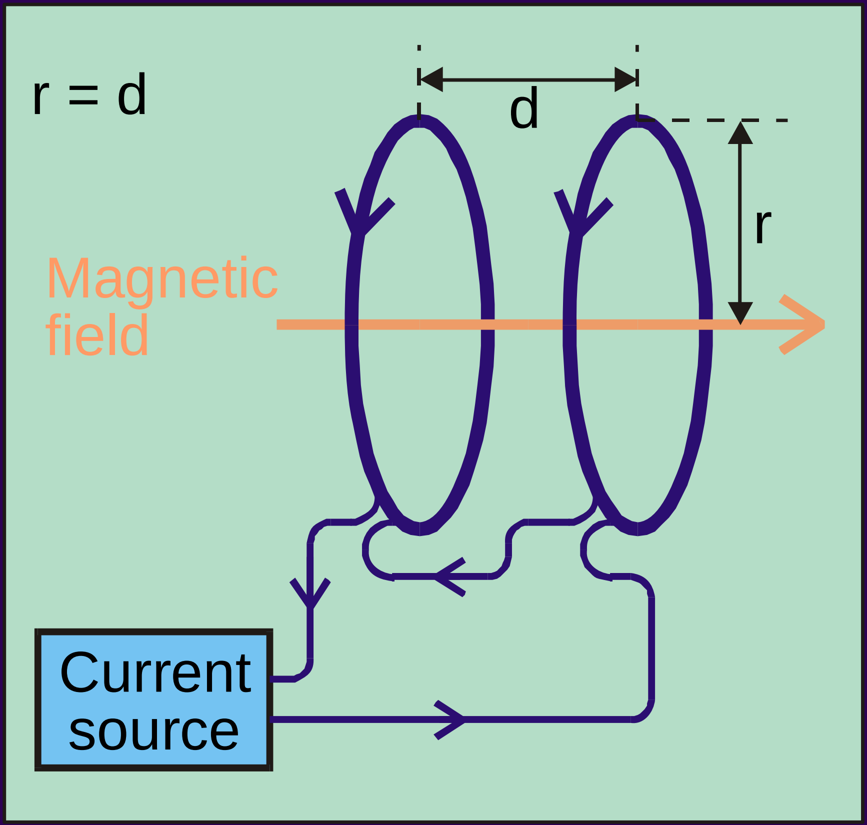
Typical range of magnetic fields for general public exposure:

- 10 nT - 10 μT (10 nT resolution)

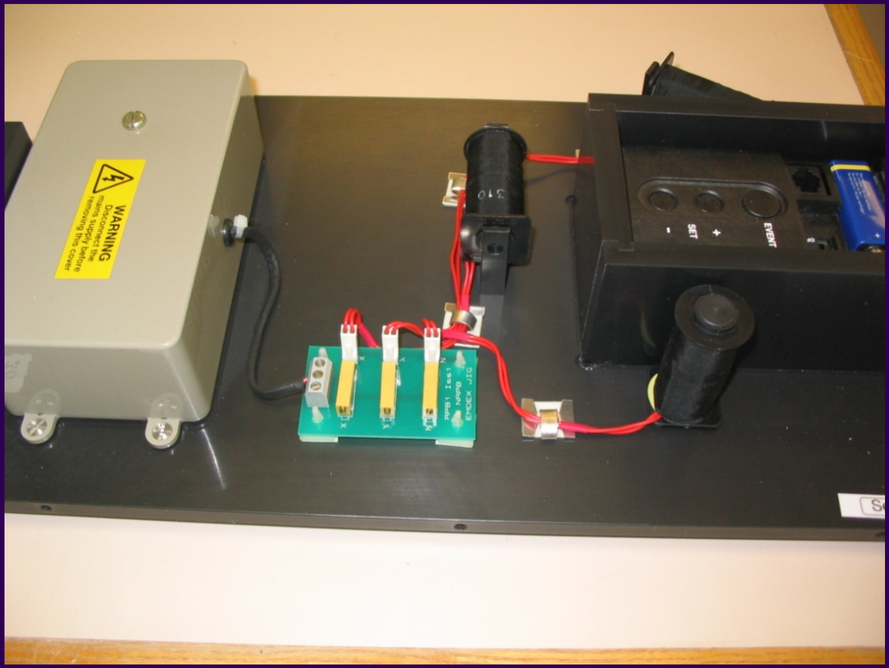
Dynamic range of 1000:1 is adequate

Frequency range: 50 Hz + first few harmonics

Helmholtz Coils for Magnetic Calibrations



Check Source for Power Frequency PEMs



Lessons for RF Assessments from ELF Work

Need to develop quality assurance (QA) procedures and standards for studies

- Independent verification of equipment performance
  - Acceptance tests
  - Check sources
- Periodic calibrations (yearly?)
- Protocols for measurements and data analysis

Standardised methods facilitate the pooling of data from different studies

Dosimetric Interactions at Low Frequencies

- Large wavelength in relation to distance from source
- Electric and magnetic field exposures considered separately

Current Density Induced by Magnetic Field

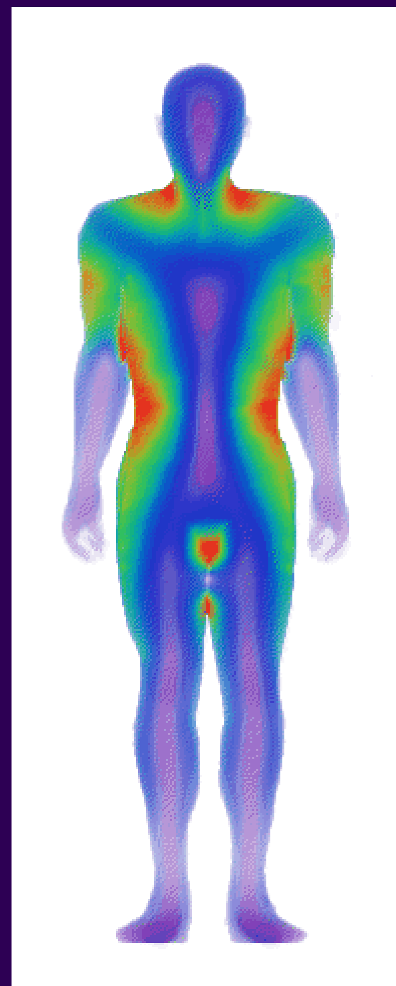
50 Hz magnetic field applied from front to back

The colour map is a standard rainbow spectrum going from red for the highest current density to violet for the lowest.

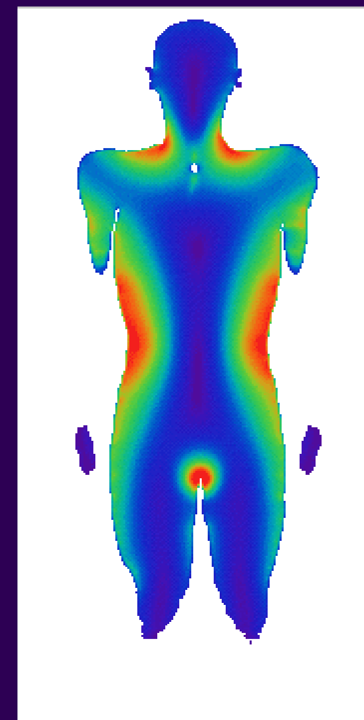
The highest values of current density will tend to be at the boundary of the section normal to the incident magnetic field

Also high current density where surface of body is concave, e.g where neck meets shoulders

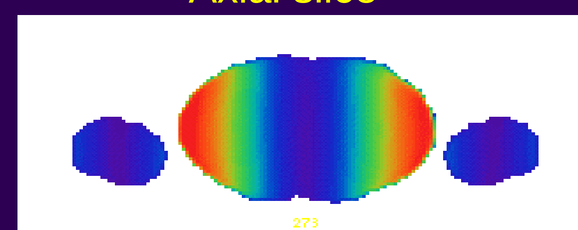
Volume rendered



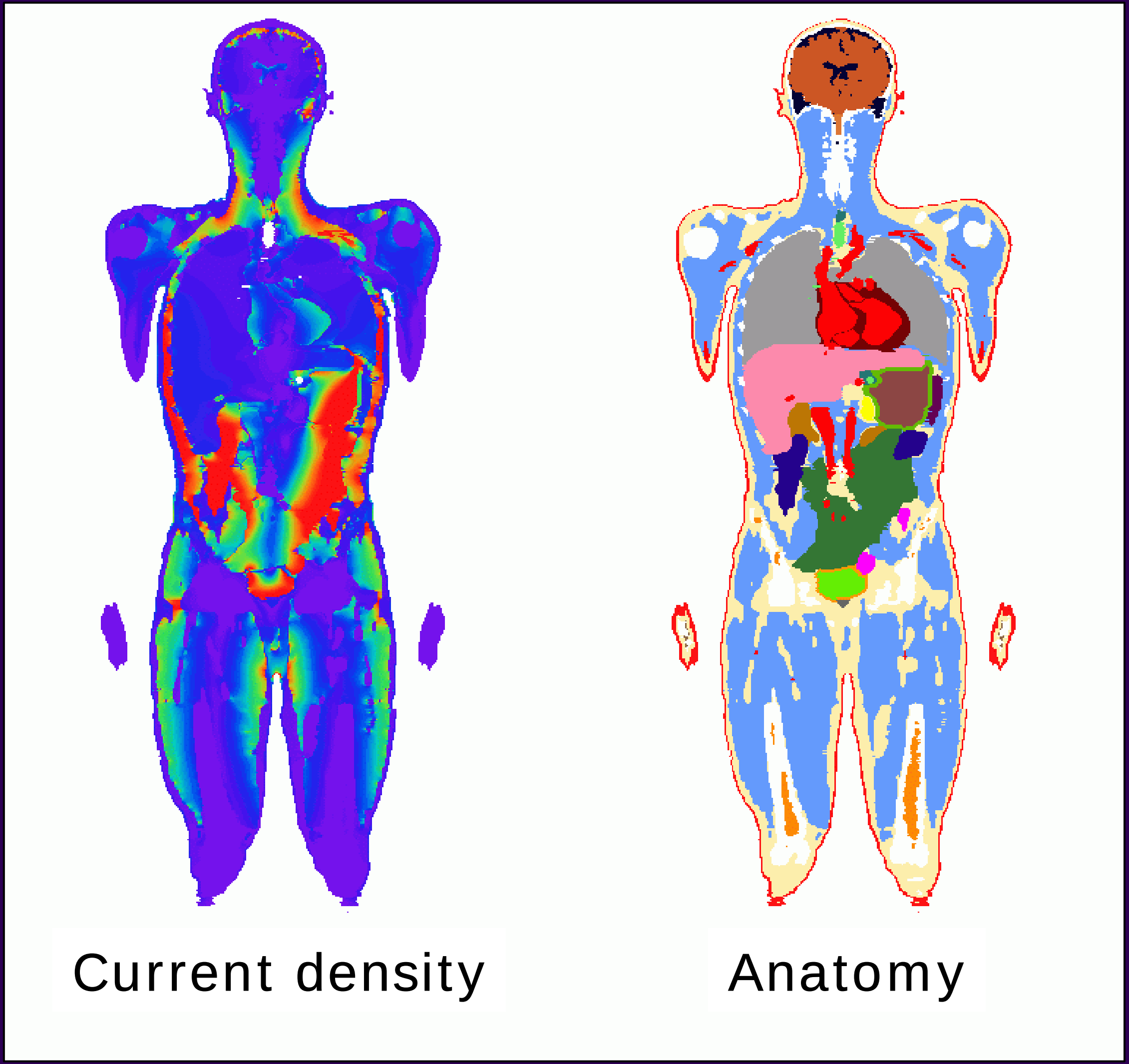
Coronal slice



Axial slice



Current Density Induced by Magnetic Field

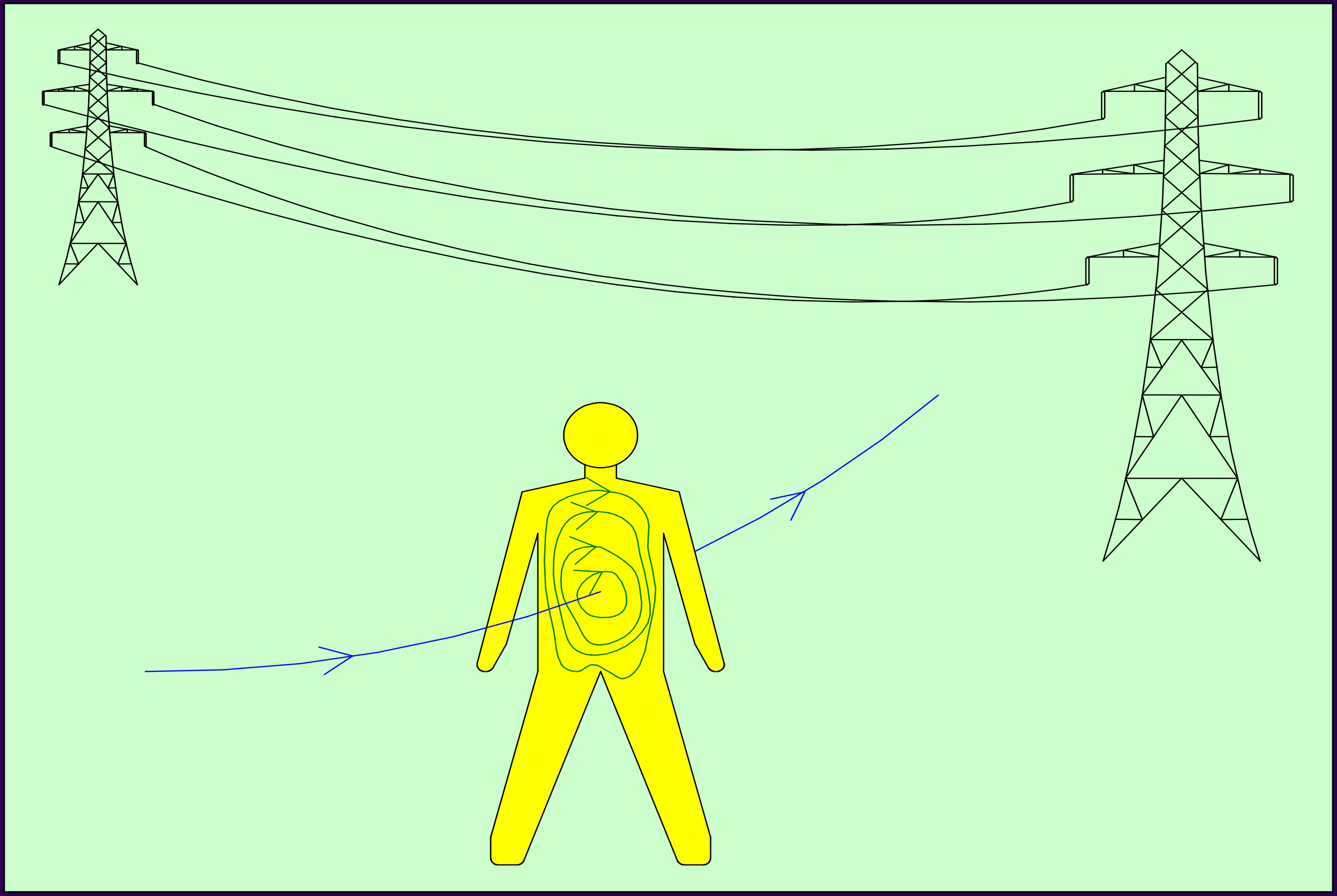


The current density (on left) in each voxel of a coronal plane through the centre of the body and the corresponding anatomy slice.

The irradiation is from the front, AP at a frequency of 50 Hz.

The colour map is a standard rainbow spectrum going from red for the highest current density to violet for the lowest. White indicates air.

Magnetic Field Interactions at Power Frequencies

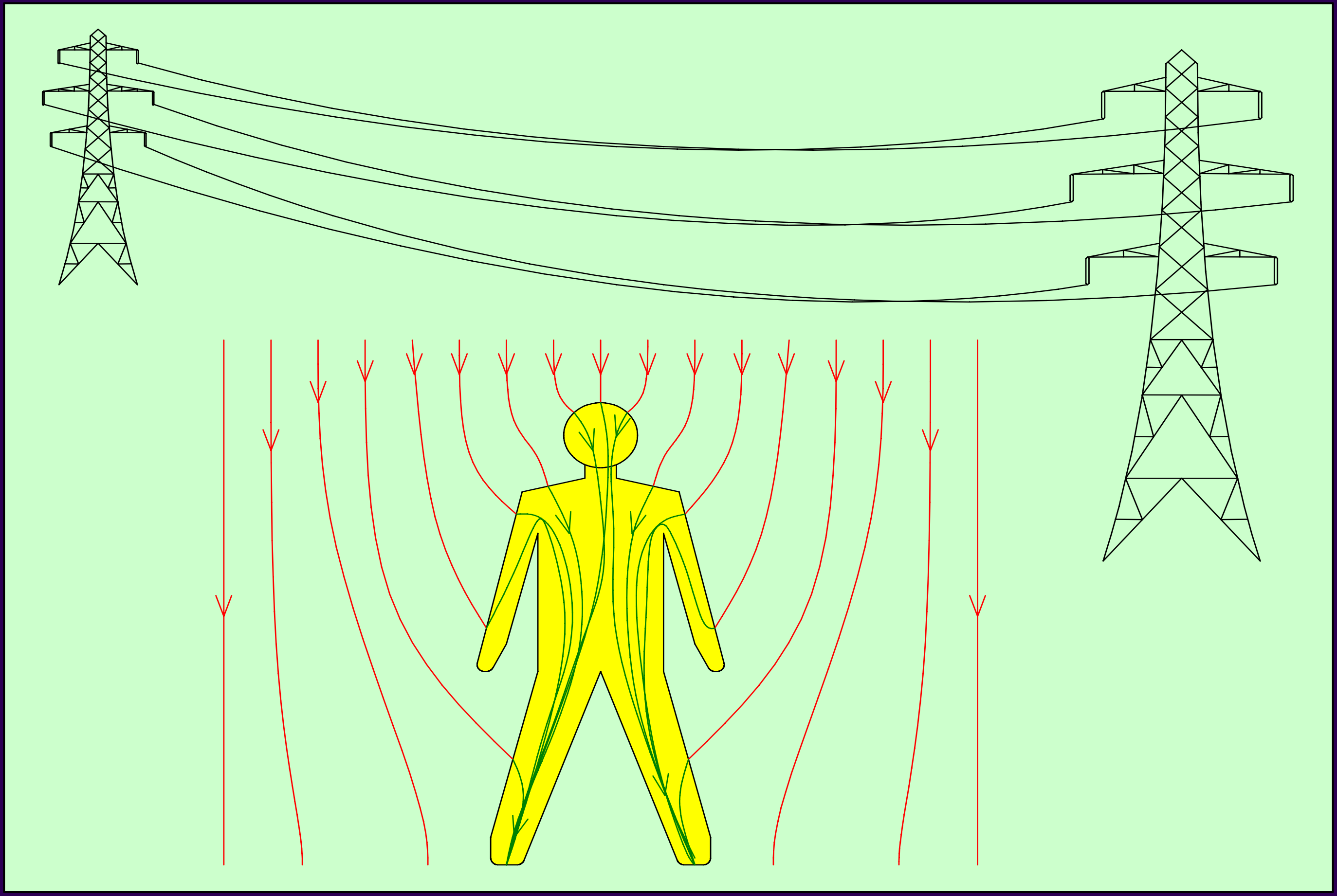


Current Density Induced by Electric Field

Vertical electric field in grounded person at 50 Hz

The colour map is a standard rainbow spectrum going from red for the highest current density to violet for the lowest.

Electric Field Interactions at Power Frequencies



Summary of Interactions at Low Frequencies

Wavelength is large in relation to distance from source so electric and magnetic fields are essentially independent

External Magnetic Field

- Weak interaction with body
- Field strength outside body is a good proxy for that inside
- Field can be at any angle to body surface
  - Need three axis sensor

External Electric Field

- Strong interaction with body
- Field strength is much lower inside body than outside
- Field direction is normal to body surface
  - Single axis sensor is fine

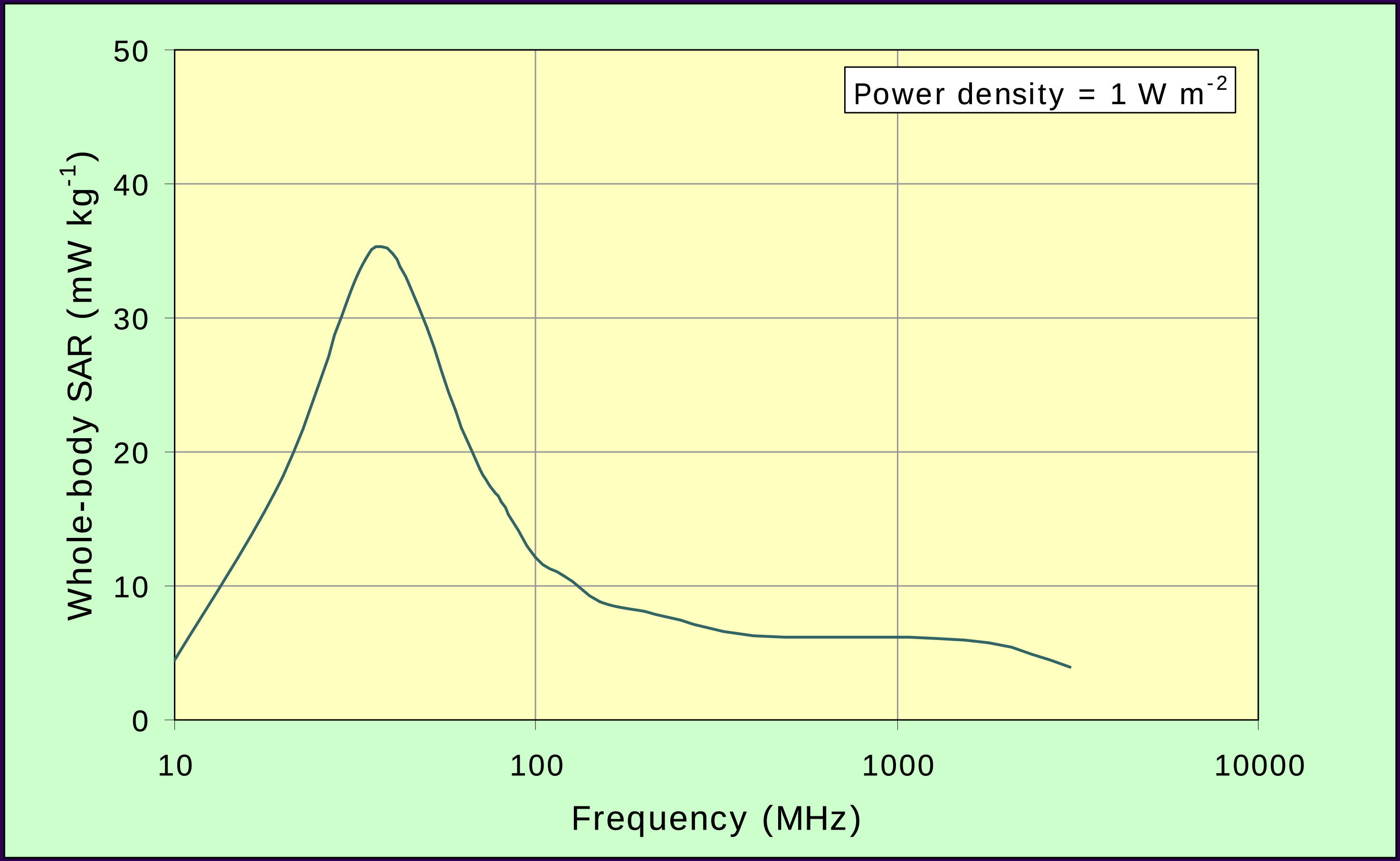
Dosimetric Interactions at High Frequencies

- Small wavelength in relation to distance from source
- Electric and Magnetic Fields have combined to form a wave

Common metric is whole body SAR

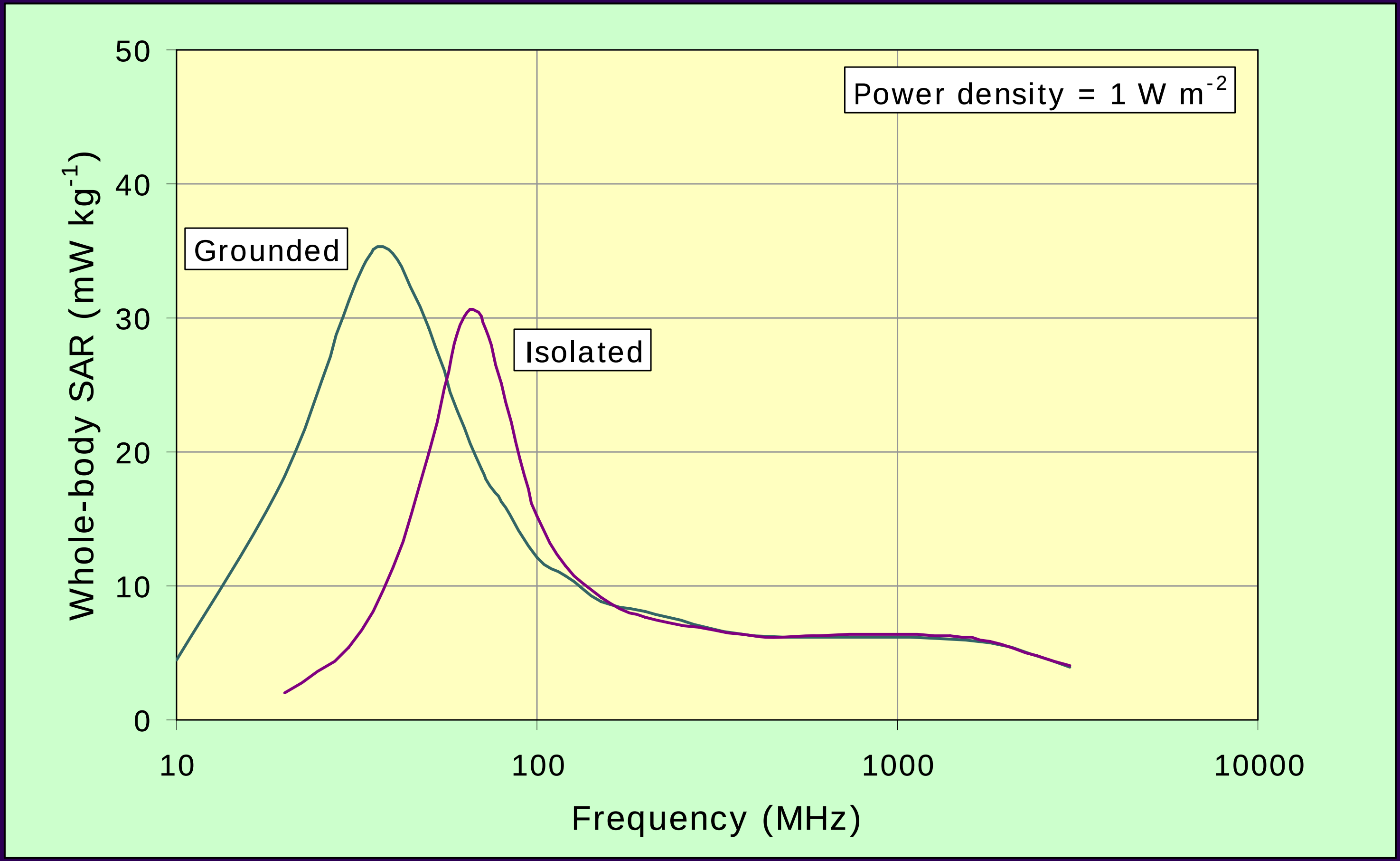
- Measures total absorption
- Says nothing about spatial distribution

SAR Variation with Frequency



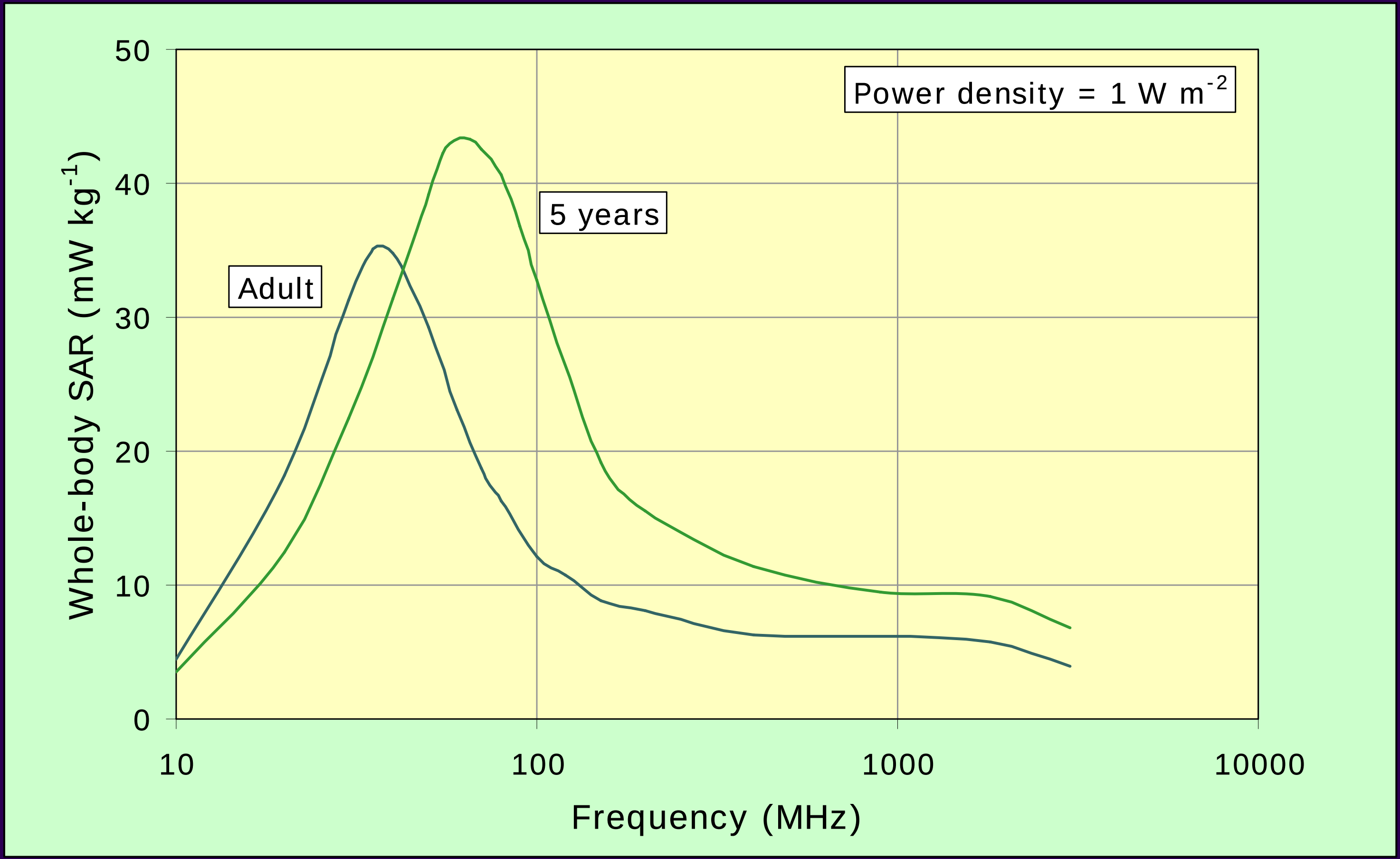
Resonance at ~40 MHz for a grounded adult standing in a vertical electric field (body height about 1/4 wavelength)

Effect of Grounding Conditions



Isolation from ground moves resonance up in frequency to where body height is about 1/2 wavelength

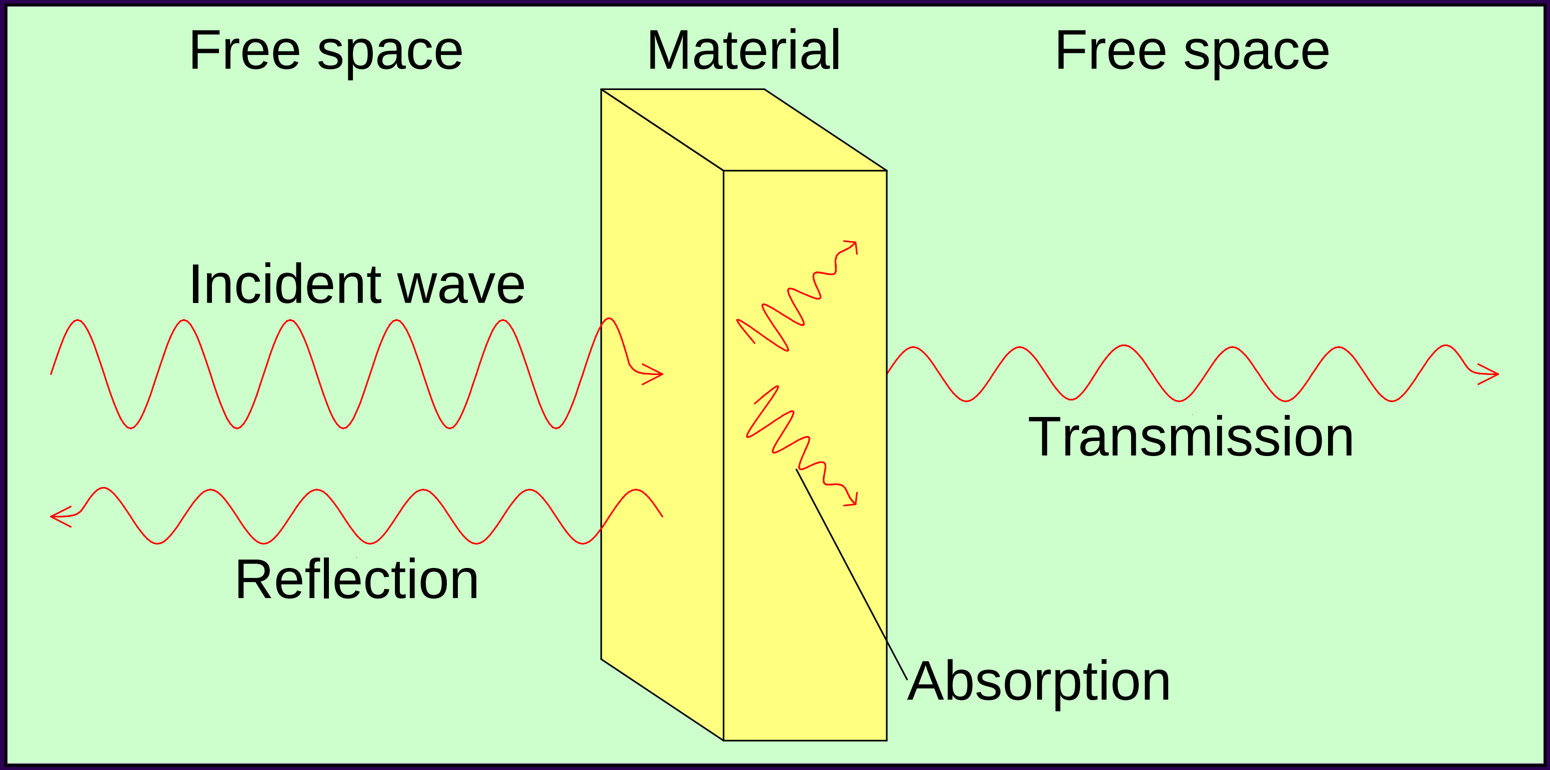
Effect of Body Size



Children have higher resonant frequency and WB SAR than adults

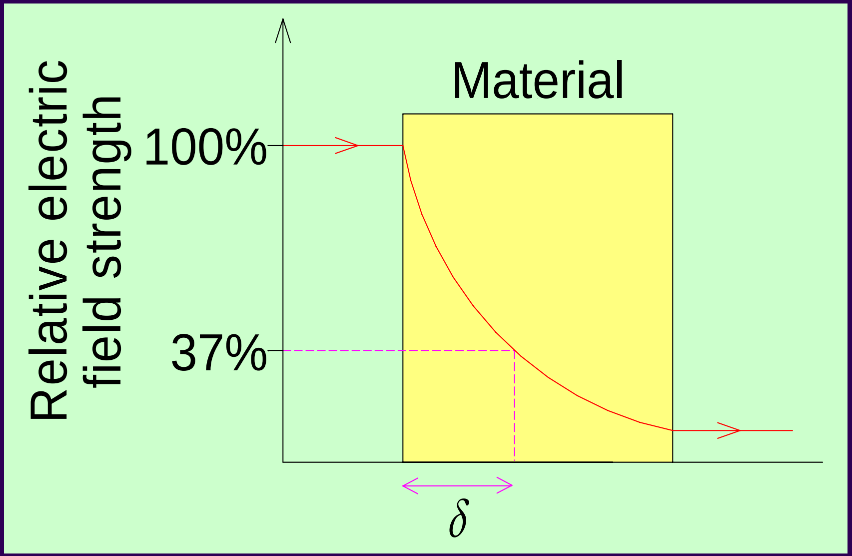
Different postures (sitting etc) also change absorption characteristic

Absorption of Energy at Radiofrequencies



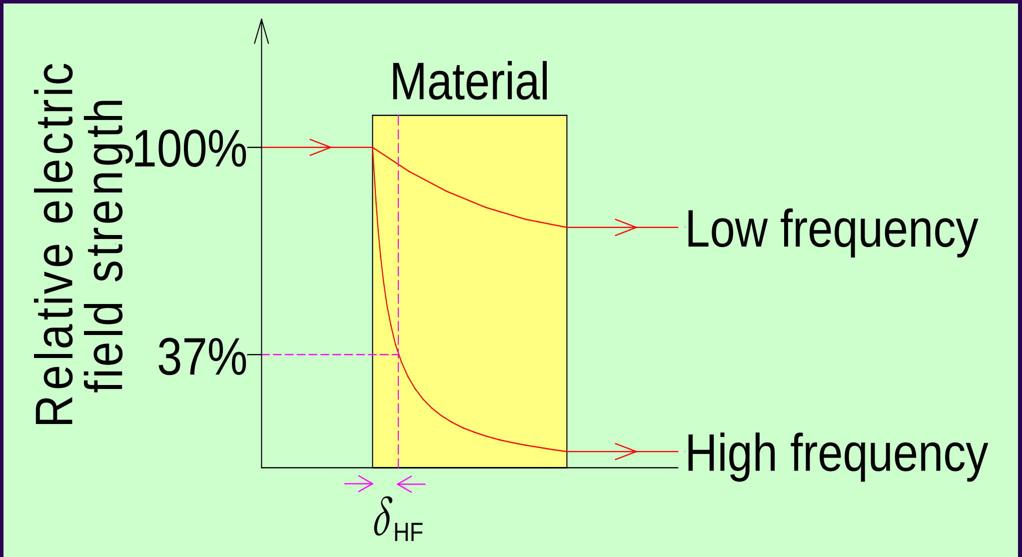
Amount of reflection and absorption depends on frequency of radio waves and properties of material

Penetration of Radio Waves into Tissue (Skin Depth)



Energy transmission decreases exponentially with thickness of material

Skin depth, *d*, is the thickness of material required to reduce *E* to 1/*e* (37%) of initial value



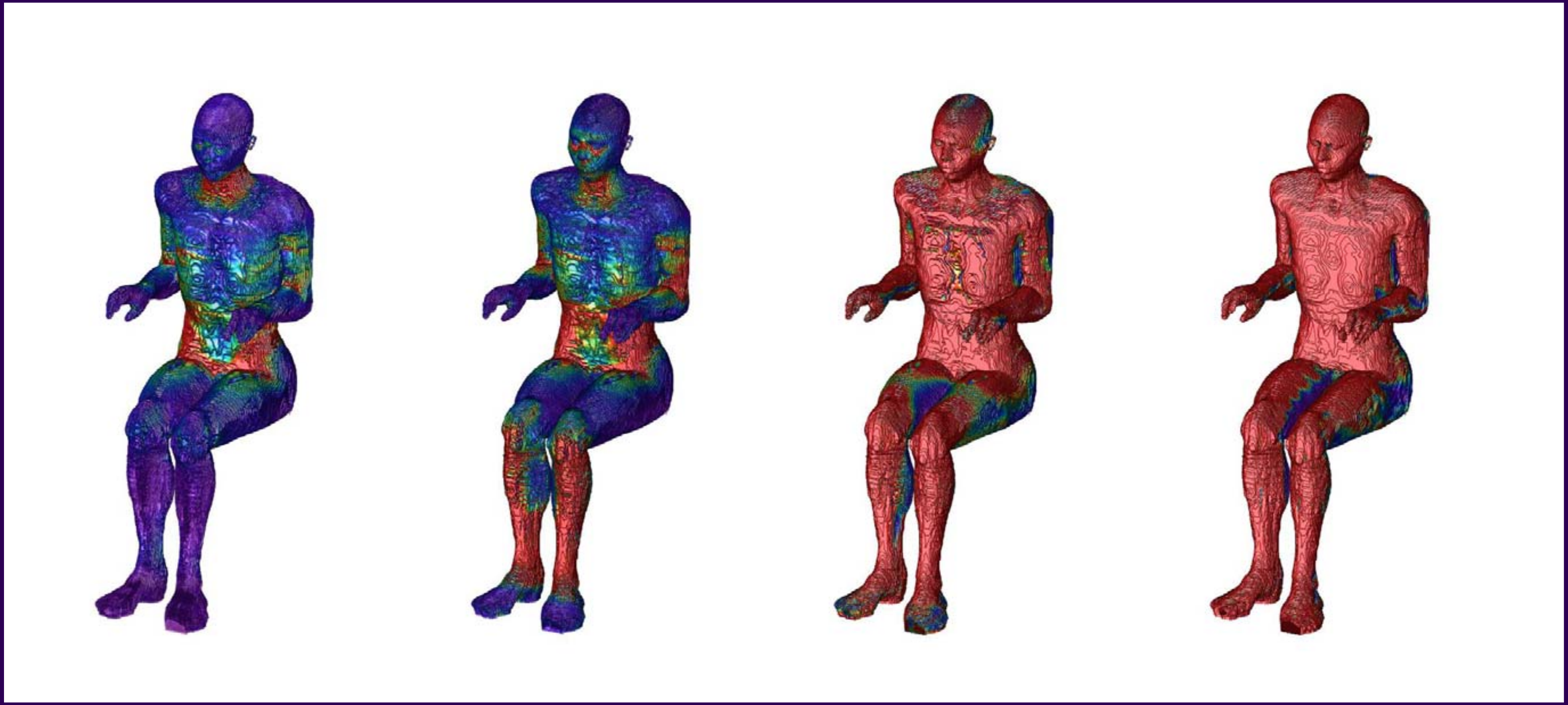
Low frequency: high skin depth

- **deep energy penetration**

High frequency: low skin depth

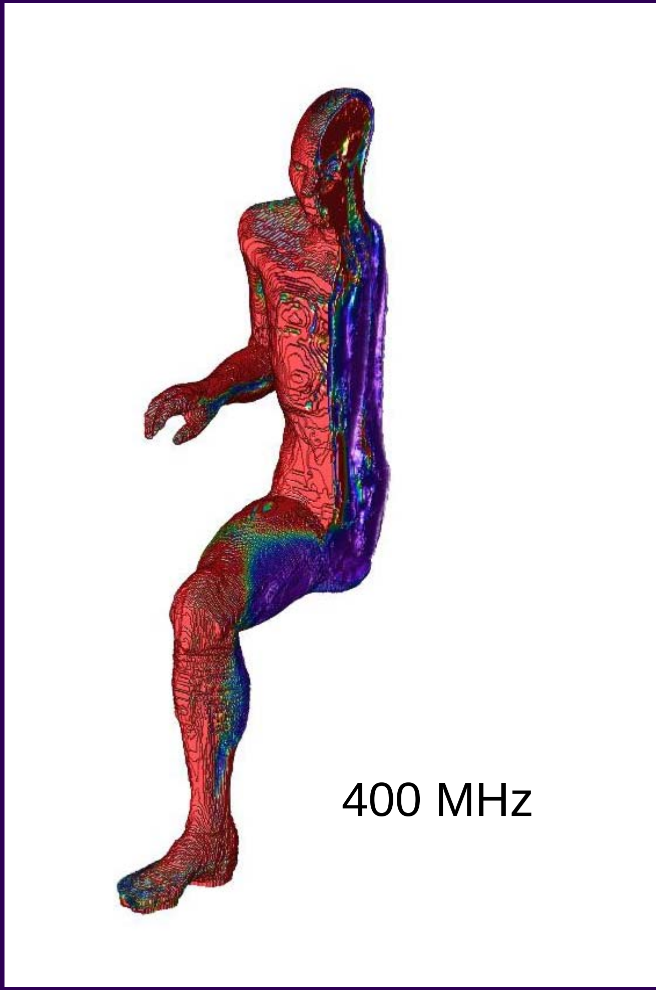
- **strong energy absorption**

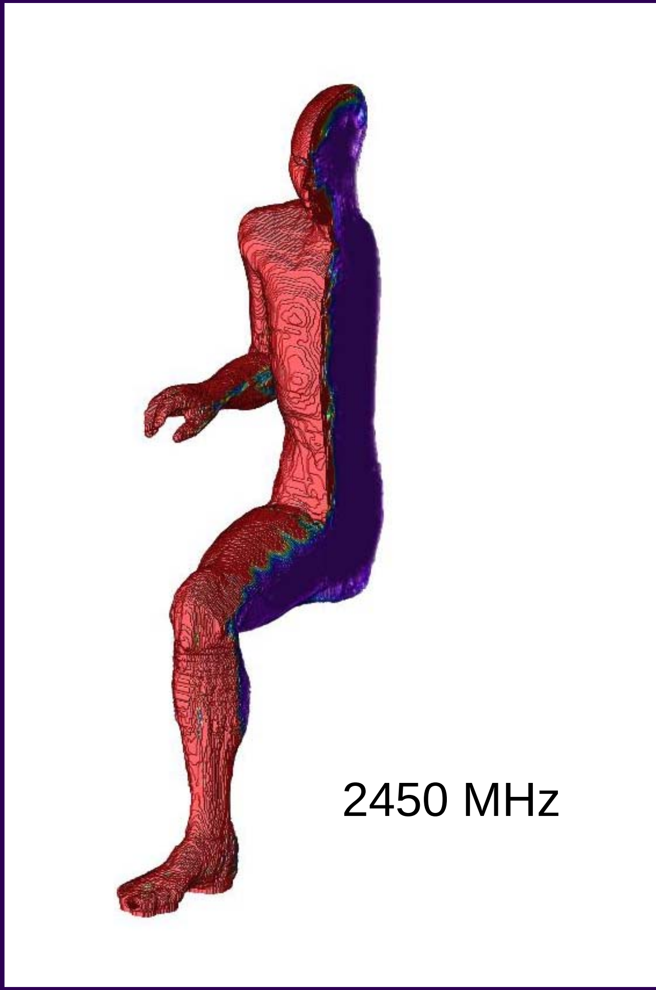
Variation in Absorbed Energy Distribution with Frequency



100 MHz 200 MHz 400 MHz 2450 MHz

Penetration into Body Tissues at Higher Frequencies





Implications of Dosimetry Studies

Magnitude and distribution of induced currents and SAR in the body depend on

- Frequency – skin depth and resonance
- Direction of incidence
- Polarisation (E-field parallel to body?)
- Posture (standing, sitting, arms up/out etc)
- Grounding conditions
- Morphological parameters of body (size, shape etc)
- Electrical parameters of body (conductivity, permittivity)

How to Account for Dosimetry?

- Need to sum exposure contributions
  - Varying incidence directions
  - Varying polarisations
  - Varying postures
- Need to account for different sizes of people
- Need weighting factors for different frequencies

- Aim to develop “average” interaction characteristics
  - Separate one(s) for children?

Sources close to the Body

Mobile phone exposures

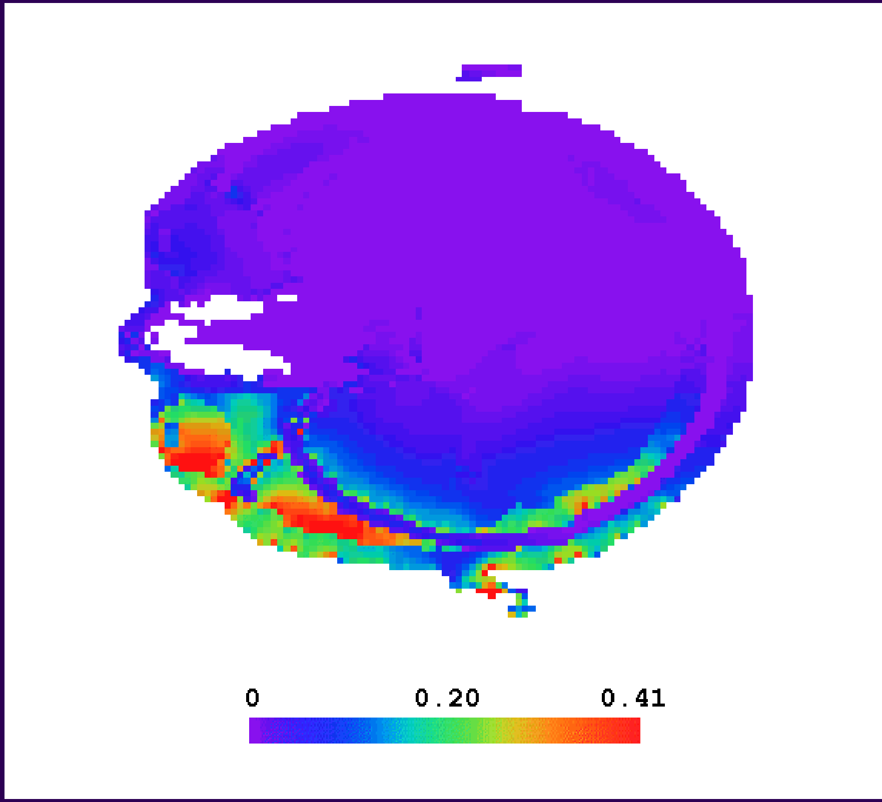
Mobile Phone Exposures

How to combine

- Whole-body exposures from distant sources
- Localised exposures from sources near the body

Is the phone near the head or elsewhere on the body?

Is it the PEM user's phone or that of the person sat next to them that has been measured?

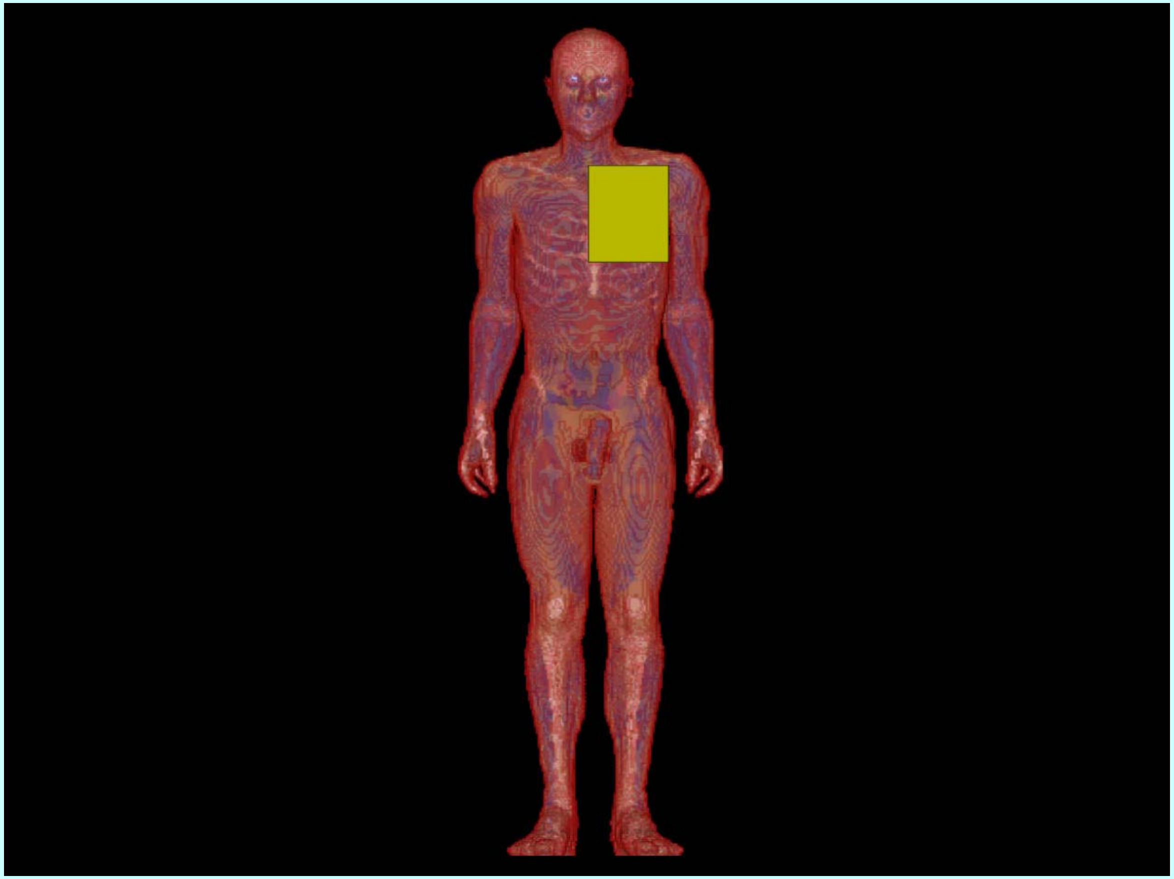


900 MHz

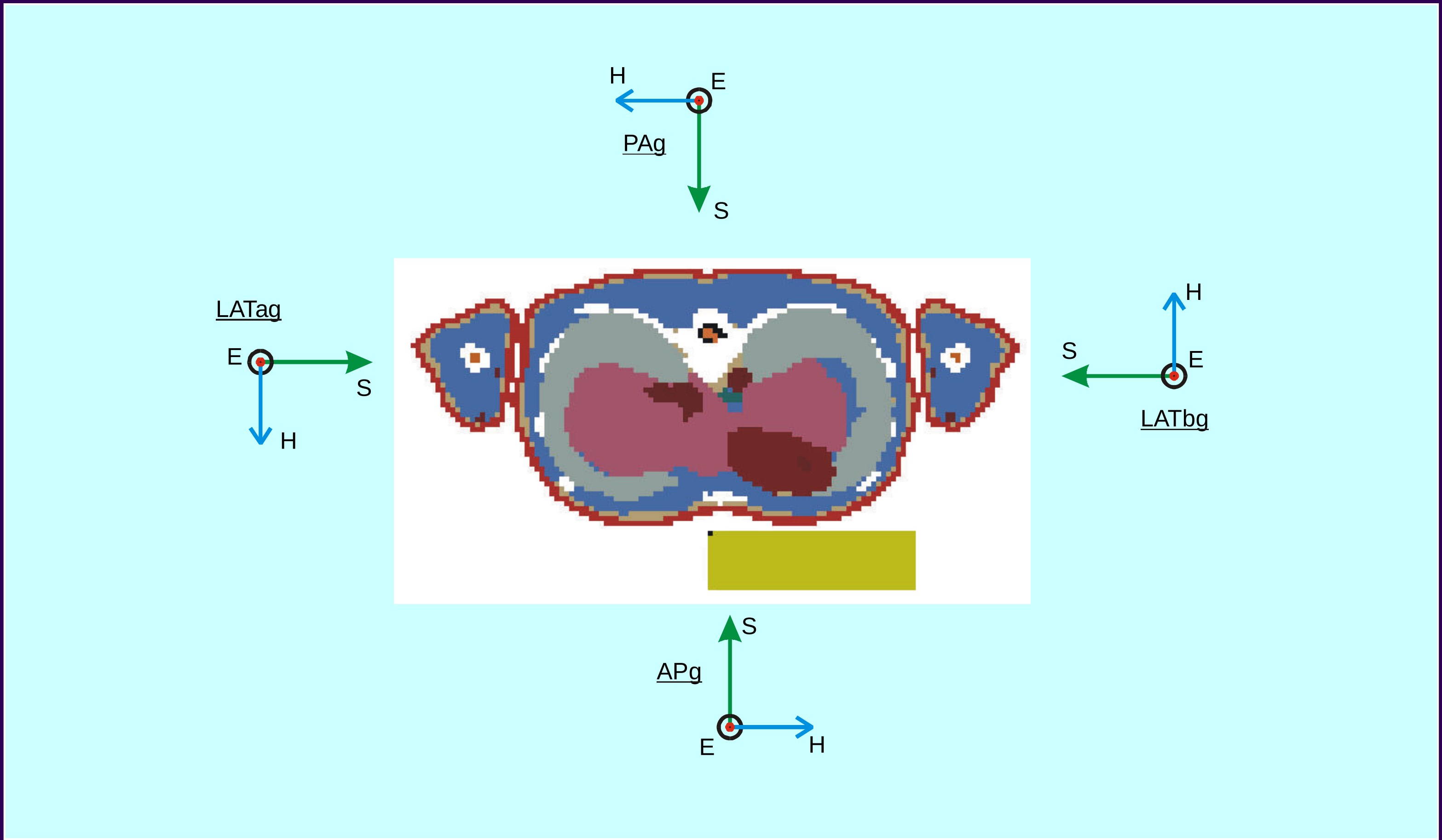
Shadowing Effect of Body

PEM Mounted on Chest

Volume of Interest Defined in Front of Chest



Plane-wave Exposure Directions



Analysis

Incidence: front, back and both sides

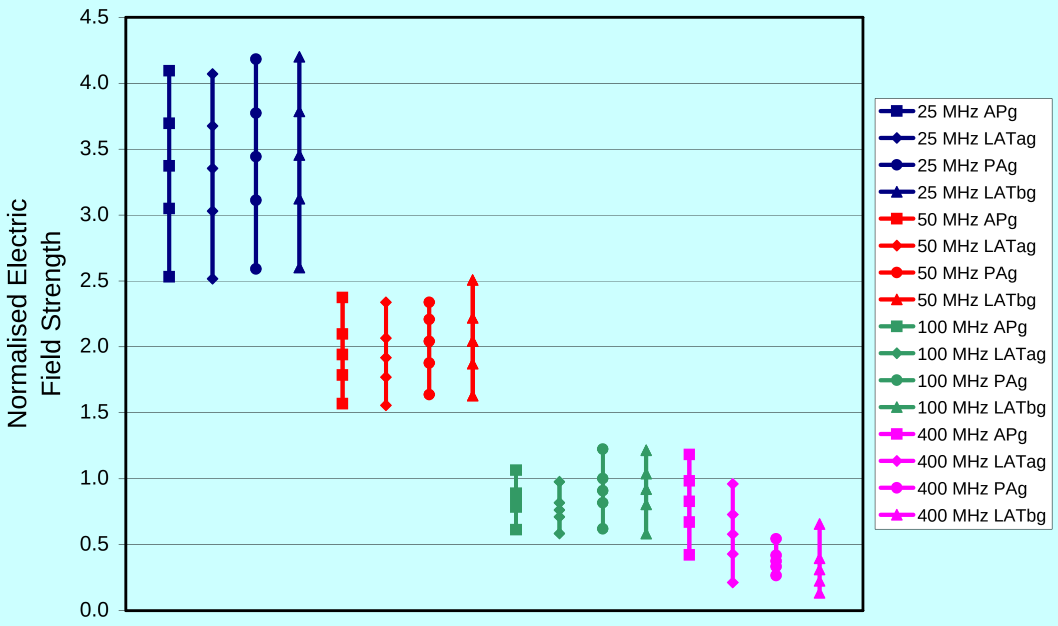
Frequencies: 25, 50, 100, 400 MHz

Calculated E and H fields in the VOI:

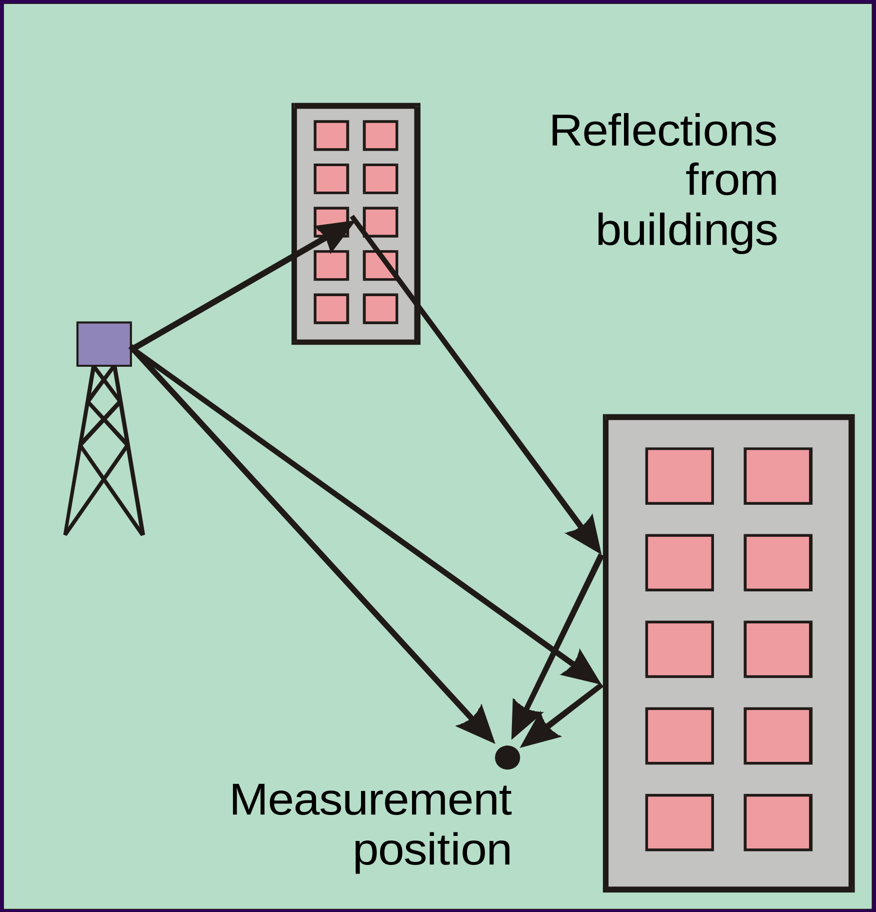
- Minimum, maximum, average
- Standard deviation

Normalise to incident field strengths

E-field Distribution in the VOI



Multipath / Fading



Field at a point is formed from

- Direct wave (not always present)
- Reflected wave contributions

Interference pattern formed

- Spatial fading of fields over distances comparable with the wavelength, i.e. 10s of centimetres

Can stabilise measurement by measuring at several points and averaging the results

- 3 heights: 1.1, 1.5, 1.7 m

Questions Arising from Shadowing

To what extent is shadowing effect offset by

- Multipath
- Movement

- Where is the best place to put the PEM when it is not being worn
    - Can guidelines be given to PEM users

Exposure Metrics

Defined in Context of a Health End-point

Exposure Metrics

External

- Unperturbed (body absent) field at a point
- Perturbed field at a point near the body
- Unperturbed field spatially averaged over volume occupied by body

Internal (field or specific absorption rate)

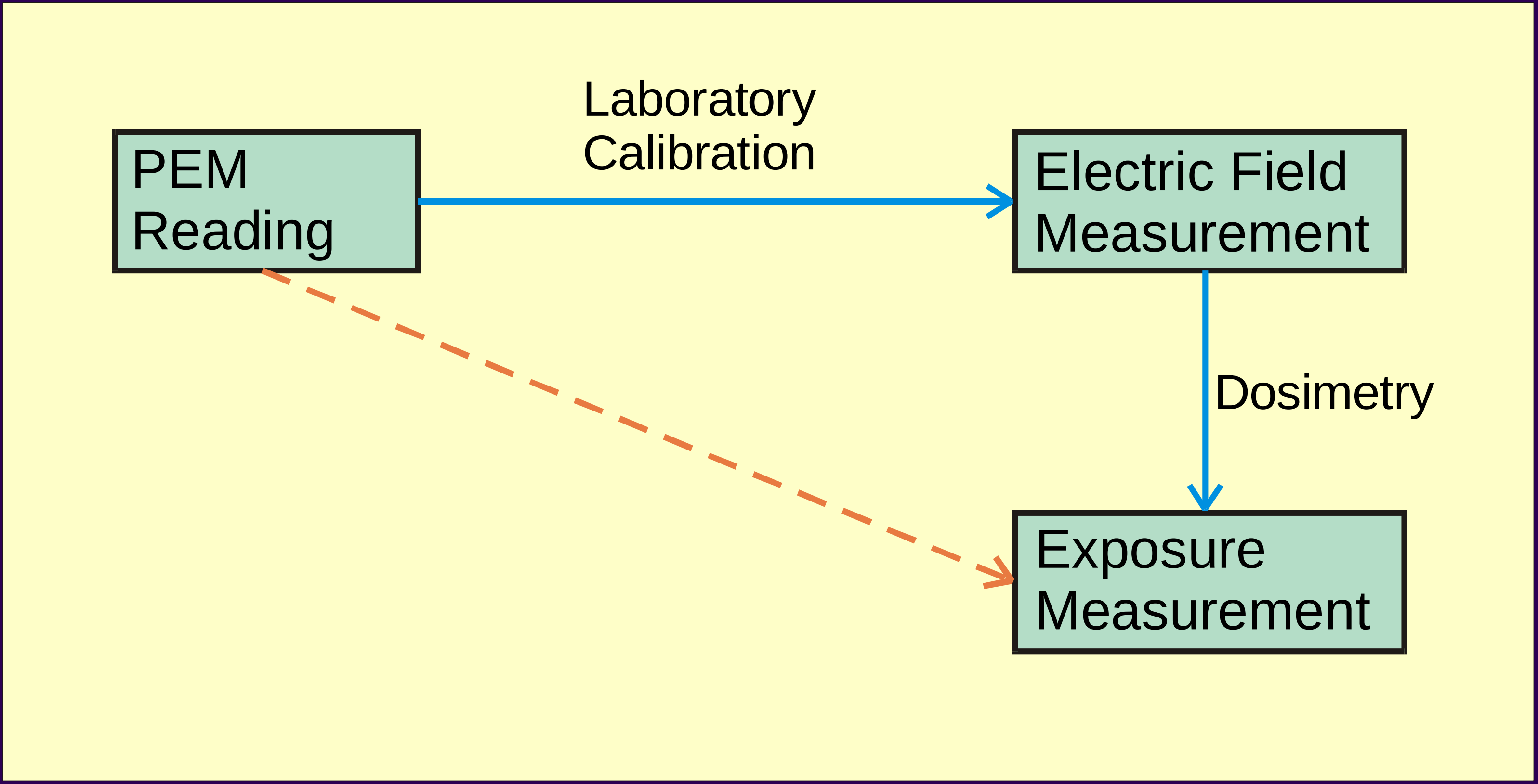
- At a point in the in the body (tumour location)
- Averaged over a region in the body (an organ, tissue type)
- Averaged over whole body

Metric usually involves averaging over time

Averaging can be in an RMS sense:

$$E_{RMS} = \sqrt{\frac{E_1^2 + E_2^2 + E_3^2 + \cdots + E_n^2}{n}}$$

Calibration Concepts



Exposure Metric

- Defining an exposure metric points the way to developing an interaction characteristic
  - How to sum exposure over a region of interest
  - How to sum exposure over time
- Requires
  - Laboratory calibrations of the PEM
  - Numerical dosimetry to define interactions with body

To Conclude ………..

What are the determinants of people's exposure and can a gradient be constructed without the need for personal measurements on the study subjects?

Conclusions
- Metrology Issues

- Independent verification of equipment performance
    - Acceptance tests
- Standardised procedures
    - Calibration
    - Data acquisition
    - Data analysis
- Instrument reliability – early detection of failures
    - Check sources

Conclusions
- Dosimetry Issues

Definition of health end-point and relevant tissues

Choice of appropriate exposure metric (energy absorption?)

- How to sum contributions at different frequencies
- How to account for variations in absorption due to body size, posture etc
- To what extent do multipath and movement offset the effect of shadowing
- How to combine exposure from a source near to the body (phone) with that from distant transmitters
- How to locate the PEM when not on the body (position, orientation)

Conclusions
- Statistical Issues

- Limits to the performance of ROS algorithm
  - What is maximum proportion of non-detects?
  - Can a measure of uncertainty be derived?
- Is there a problem in using the arithmetic mean to compare exposure scenarios, e.g. indoors vs outdoors?
  - The data are log-normally distributed
  - Means might be dominated by a few large values
  - Apparent differences in means might imply differences between maxima in different scenarios rather in than typical values