Evaluation of Human Exposure Levels around Radio Base Stations in Korea

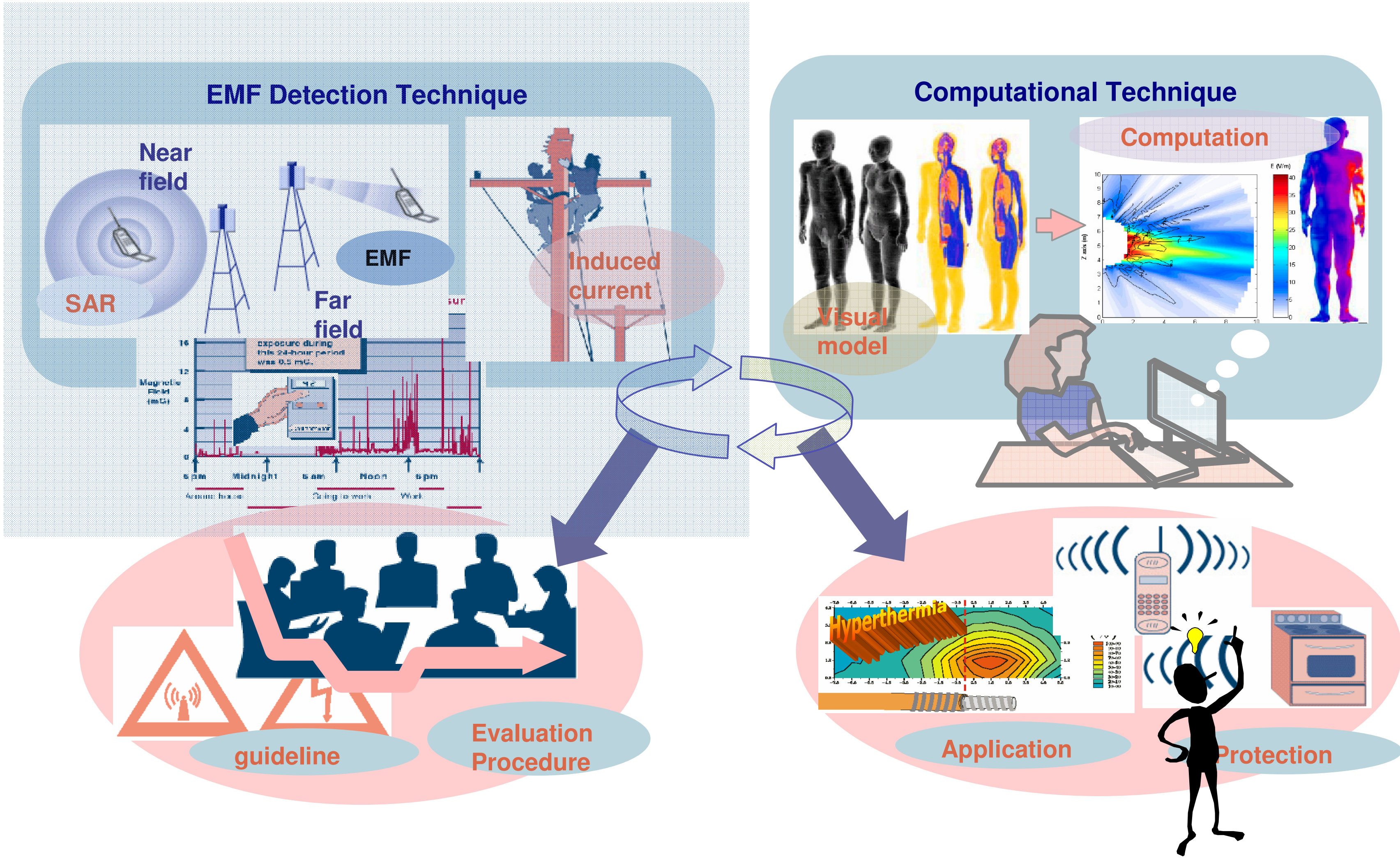
April 16, 2012

Byung Chan Kim, Ph.D.

bckima@etri.re.kr

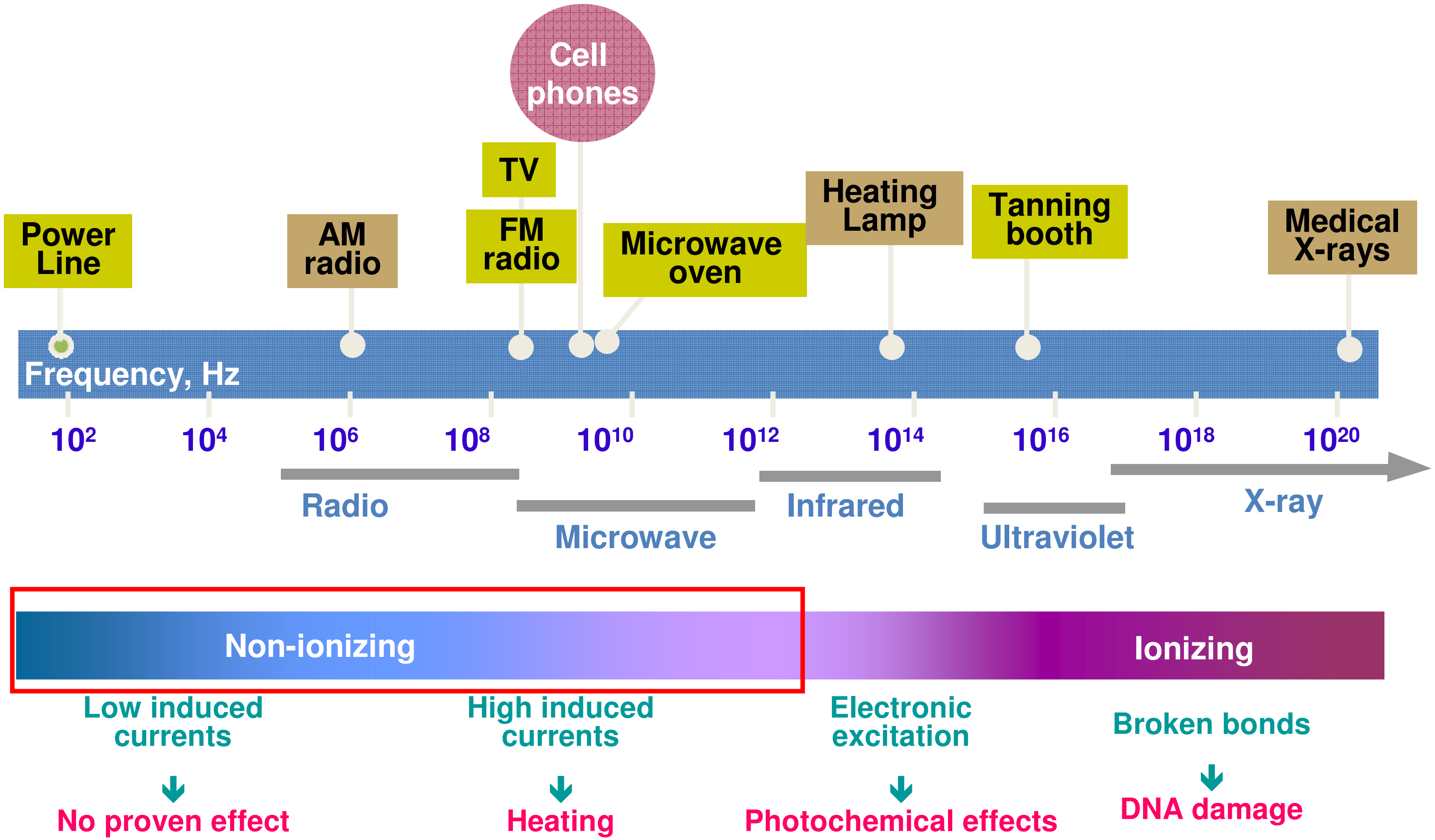
Contents

Background: Study on EMF & Health Effect



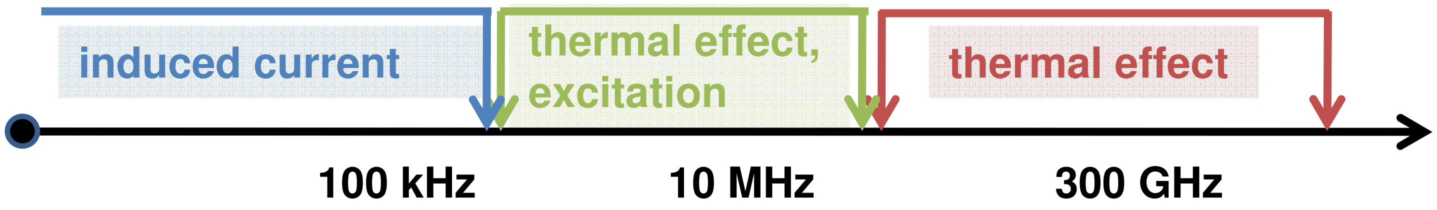
EMF: ElectroMagnetic Field

Background: Frequency Range

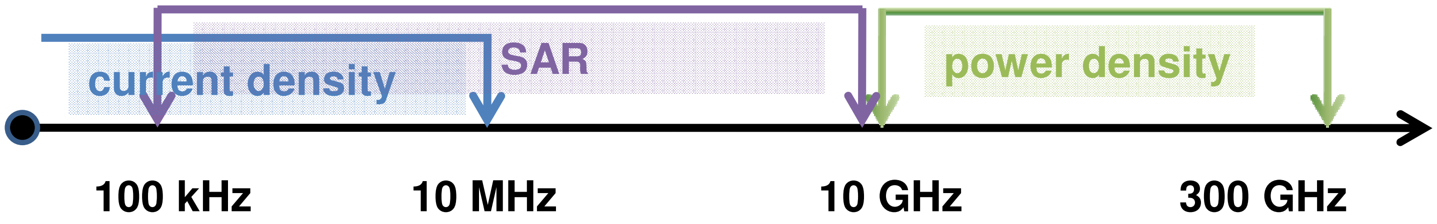


Background: Basis for Limiting Exposure

- Limiting Basis



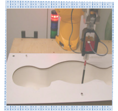
- Dosimetric Quantity



Dosimetry: Measurement or determination by calculation of internal electric field strength or induced current density or SAR in humans or animals exposed to EMFs

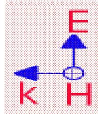
Background: Safety Limits-1

Basic Restriction



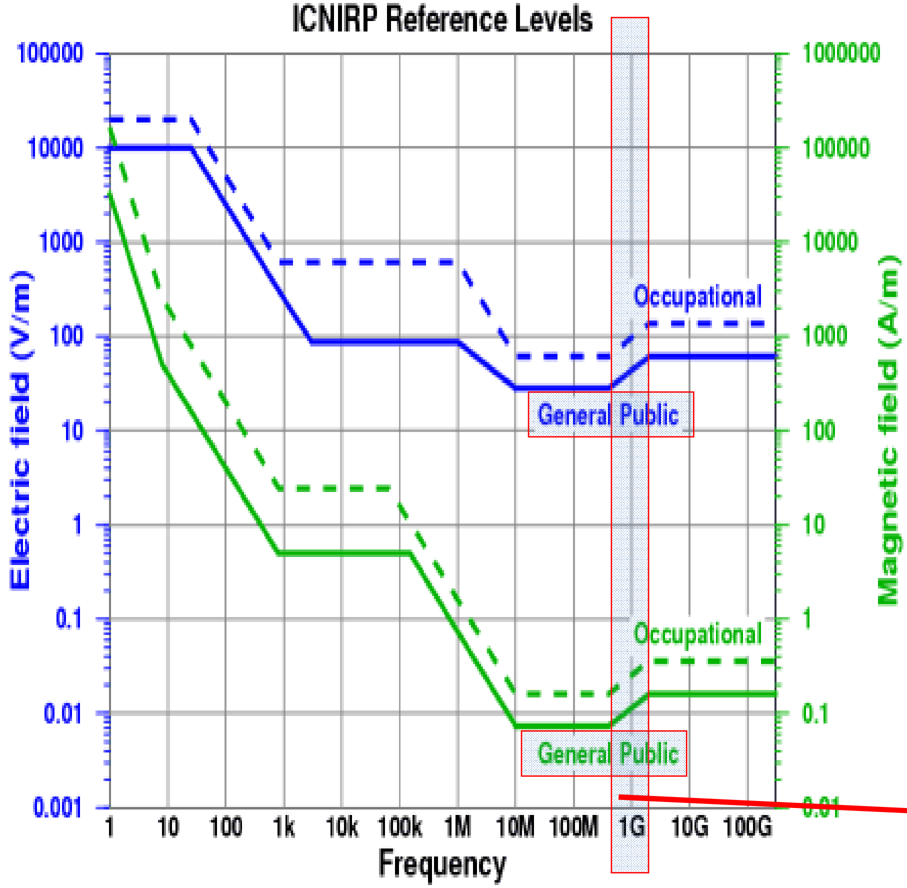
- The fundamental quantities that determine the physiological response of the human body to EMFs: Current density (J), Specific absorption ratio (SAR), Power density(S)
- It applies to a situation with *the body present in the field*

Reference Level



- Alternative means for determining compliance: Electric field strength (E), Magnetic field strength (H), Equivalent plane power density (S)
- It applies to a situation where the *electromagnetic field is not influenced by the presence of a body*

Background: Safety Limits-2



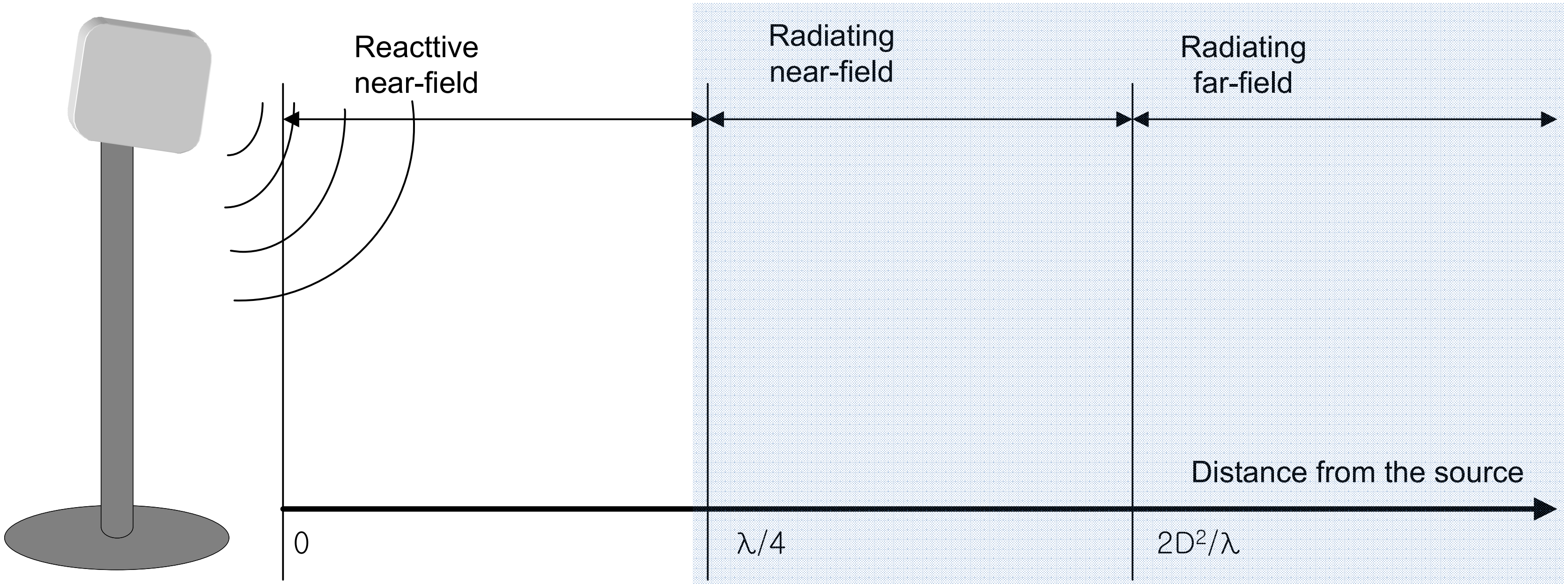
<Reference levels for GP>

Frequency range	E-field (V/m)*	H-field (A/m)*
- 1 Hz	-	3.2×10^4
1 Hz ~ 8 Hz	10,000	$3.2\times10^4/f^2$
8 Hz ~ 25 Hz	10,000	4,000/f
0.025 kHz ~ 0.8 KHz	250/f	4/f
0.8 kHz ~ 3 kHz	250/f	5
3 kHz ~ 150 kHz	87	5
0.15 MHz ~ 1 MHz	87	0.73/f
1 MHz ~ 10 MHz	$87/f^{1/2}$	0.73/f
10 MHz ~ 400 MHz	28	0.073
400 MHz ~ 2000 MHz	$1.375f^{1/2}$	$0.0037f^{1/2}$
2 GHz ~ 300 GHz	61	0.16

Note 1. Field value is rms and unit of frequency is same with leftmost column
2. The field strength are to averaged over any 6-min period

ICNIRP: International Committee on Non-Ionizing Radiation Protection

Background: Field Region

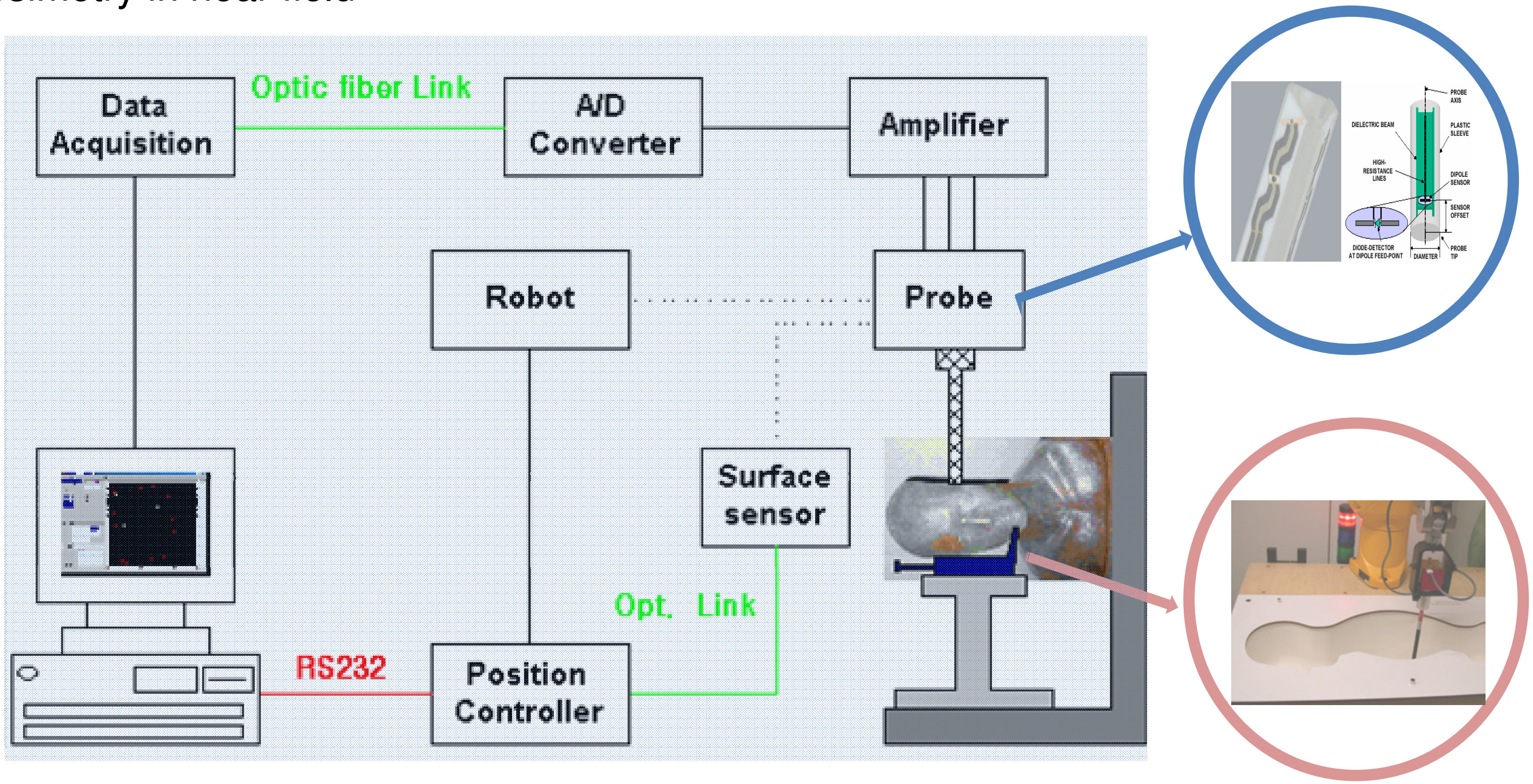


	Reactive near-field	Radiating near-field	Radiating far-field
E ⊥ H	No	Locally	Yes
Z = E/H	$\neq Z_0$	$\fallingdotseq Z_0$	$\fallingdotseq Z_0$
Measured quantity	SAR	E or H	E or H

Source: ITU-T Recommendation K.61, 2008

Background: Determine the Compliance-1

- Dosimetry in near field



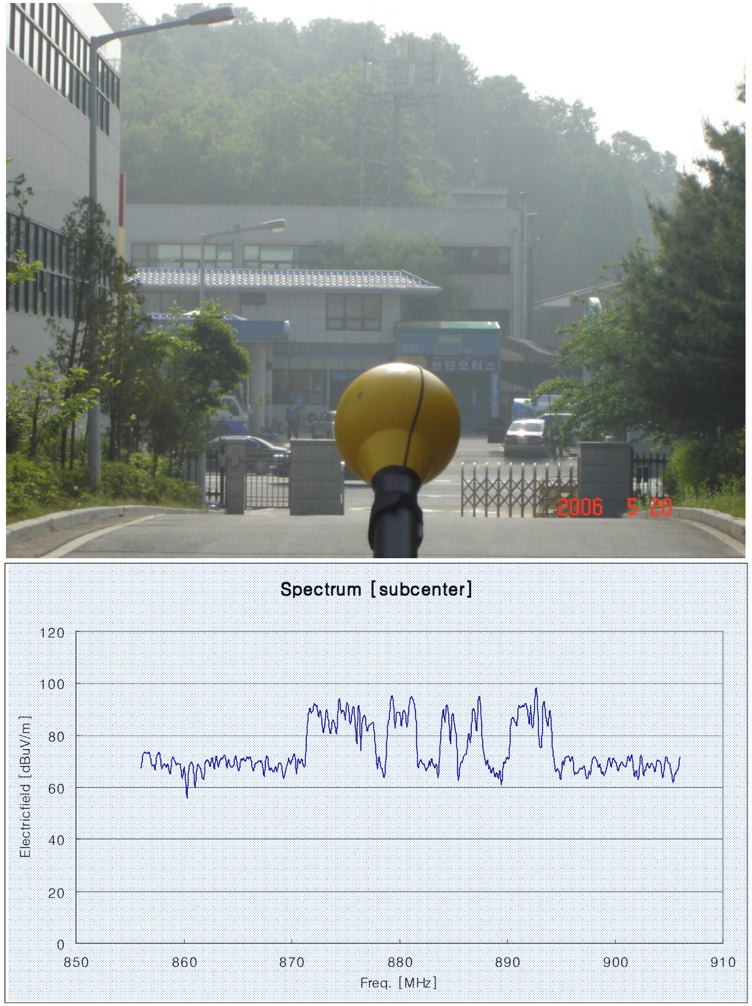
< Setups >

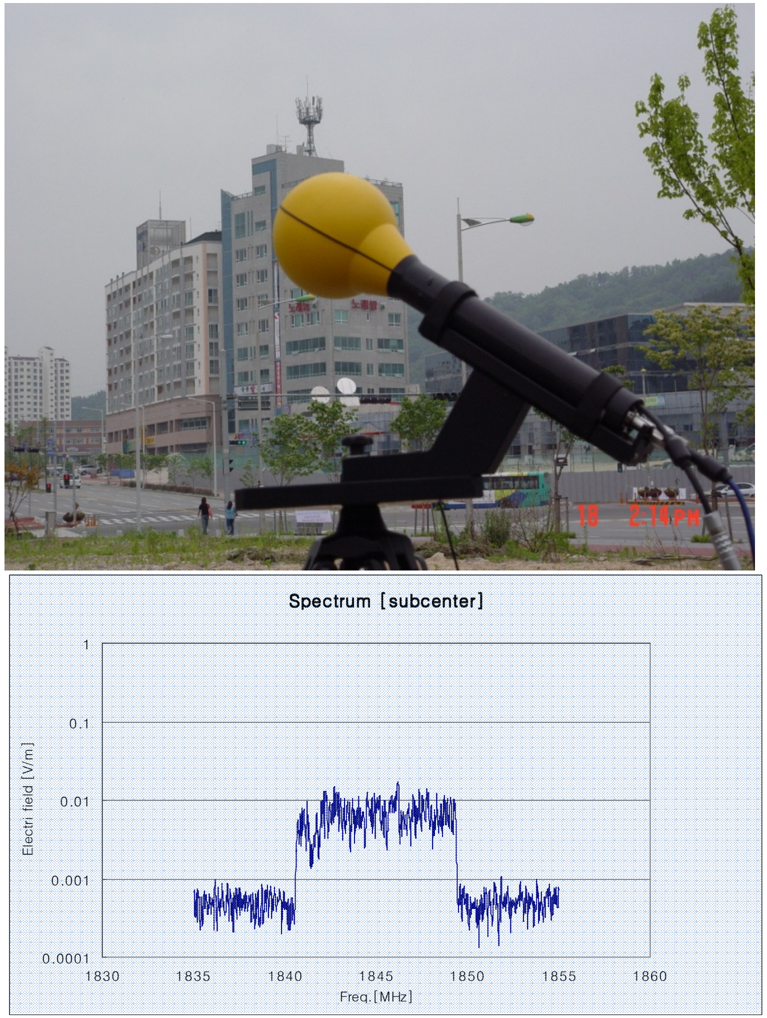
$$SAR = \frac{\sigma E_i^2}{\rho}$$

E_i: rms [V/m], σ: conductivity [S/m], ρ: density [kg/m^3]

Background: Determine the Compliance-2

- Evaluation of maximum permissible exposure in far field



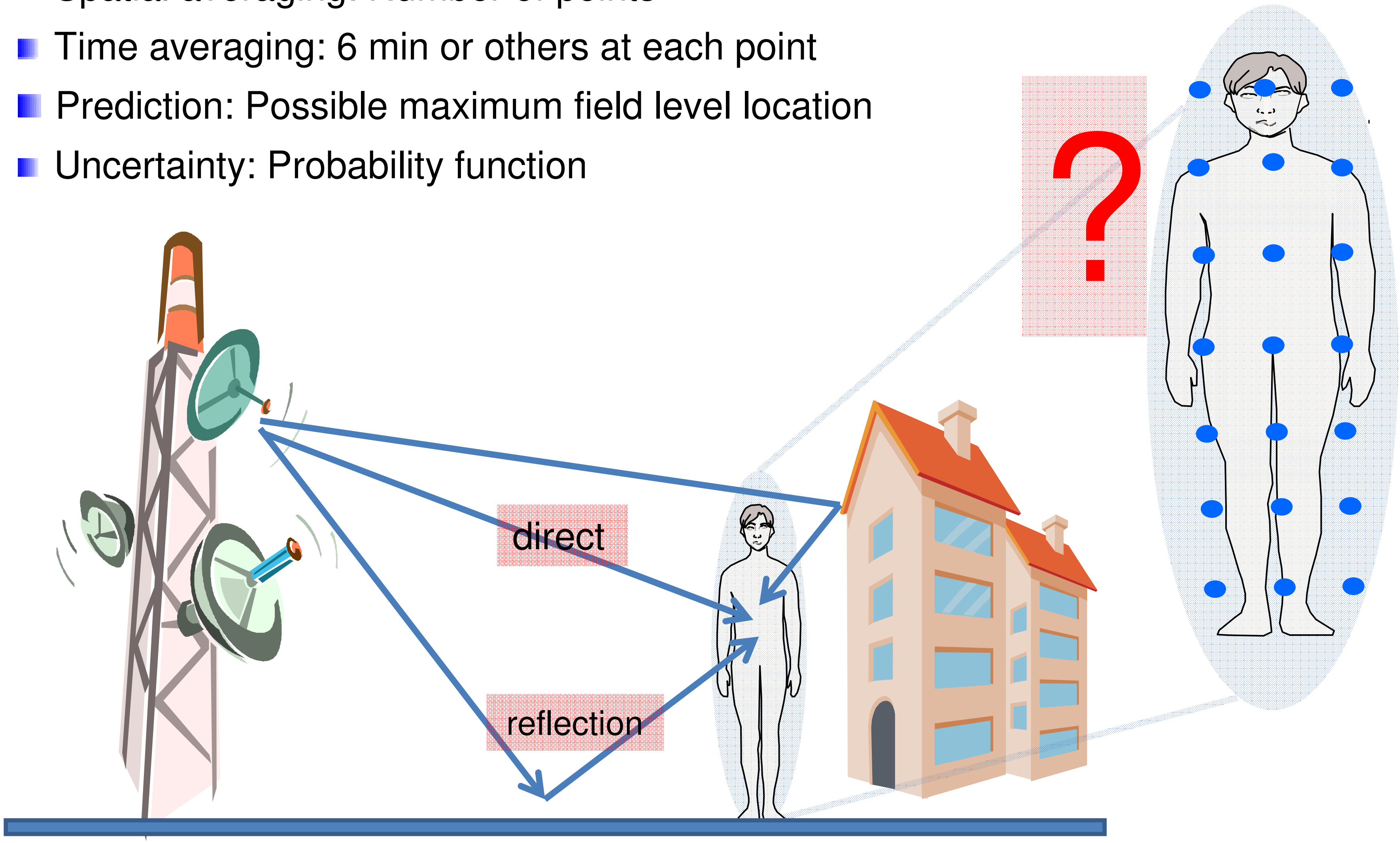


Motivation

- How can we evaluate reasonably the impact of EMF on the human body in far field ?
- What method should be used to measure the exposure practically ?

Research Issues in Korea

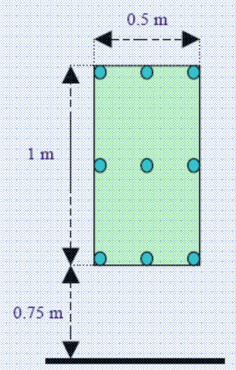
- Spatial averaging: Number of points
- Time averaging: 6 min or others at each point
- Prediction: Possible maximum field level location
- Uncertainty: Probability function

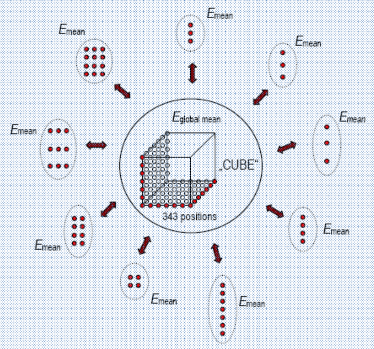


Spatial Averaging: Previous Status

- Multi-path reflections & Non uniform field distributions
- Natural and Man-made structures
- No global standard regarding number of points

	Australia	France	Portugal	Belgium	Italy	EN50383
Reference height[m]	1.5	0.75	1.1,1.5,1.7	-	1.1,1.5,1.9	-
No. of points	5	9	3	6	3	-
dimension [height*width, m]	1.0	1.0*0.5	-	1.2*0.4	-	0.7*0.4
Obtaining value	Max.	Ave.	Ave.	Ave.	Ave.	Ave.





$$Deviation = \frac{\overline{E}_{template} - \overline{E}_{global}}{\overline{E}_{global}} = \frac{\dfrac{\sum_{i=1}^{n_i} E_i}{n_i} - \dfrac{\sum_{j=1}^{n_j} E_j}{n_j}}{\dfrac{\sum_{j=1}^{n_j} E_j}{n_j}}$$

Spatial Averaging: Previous Study

- By small scale fading: N points have to be independent
- The correlation distance
- Theoretically 0.4 λ and empirically 0.8 λ
- Usually 0.5 λ

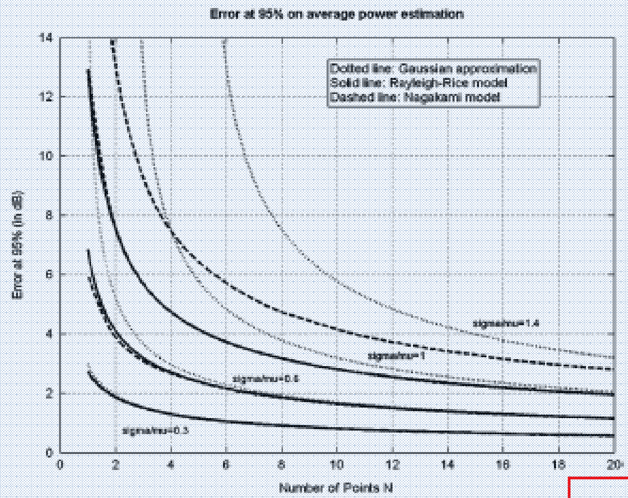
Error estimation

- Rayleigh model

$$p(\gamma) = e^{\frac{-N}{\gamma}} \sum_{j=0}^{N-1} \frac{1}{j!} \left(\frac{N}{\gamma} \right)^{j} - e^{-N\gamma} \sum_{j=0}^{N-1} \frac{1}{j!} (N\gamma)^{j}$$

- Rician model ($a^2 = \mu^2{}_X + \mu^2$, b :standard deviation)

$$p(\gamma) = Q_N\left(\sqrt{\frac{Na^2}{b^2}}, \sqrt{\frac{N}{\gamma}(2+\frac{a^2}{b^2})} \right) - Q_N\left(\sqrt{\frac{Na^2}{b^2}}, \sqrt{N\gamma(2+\frac{a^2}{b^2})} \right)$$

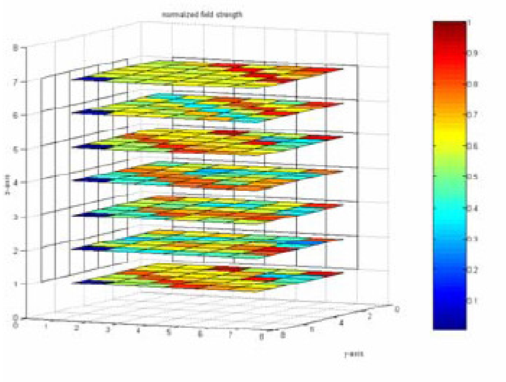


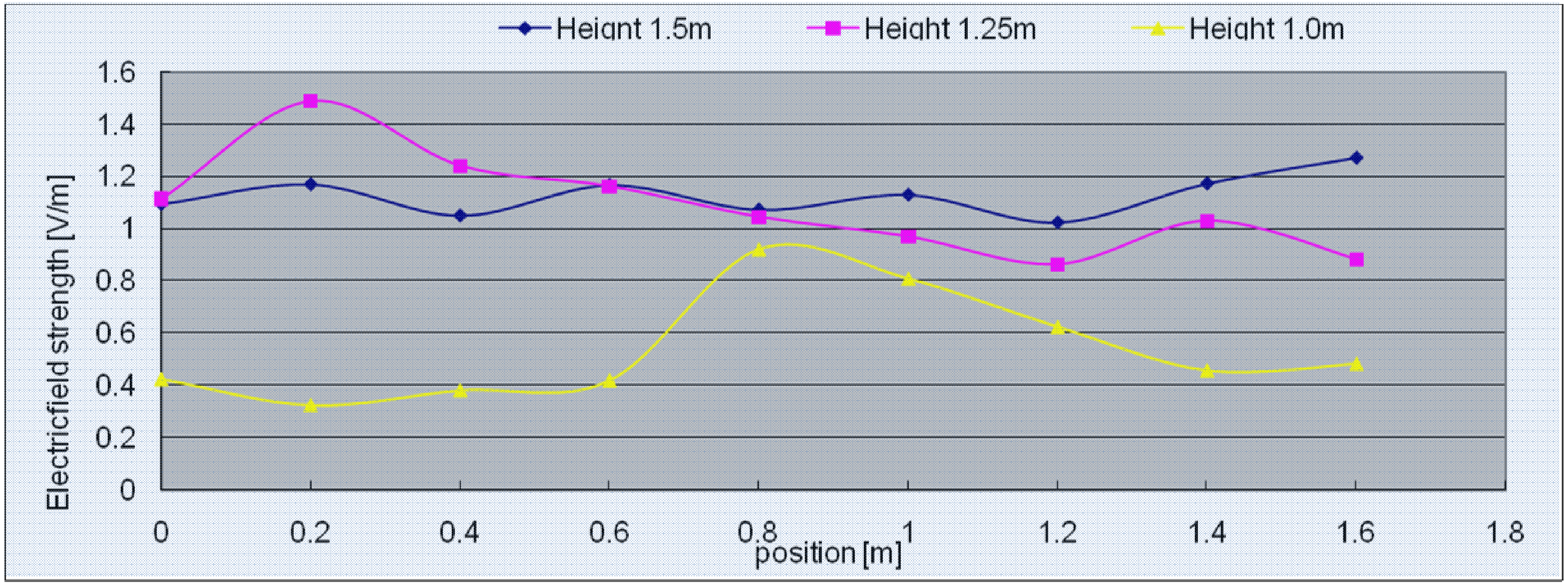
N	1	3	6	9
$\varepsilon_{95\%}$ (dB) for one-sided Gaussian ($\eta = 1.4$)	24.2	9.4	5.7	4.5
$\varepsilon_{95\%}$ (dB) for Rayleigh ($\eta = 1$)	12.9	5.7	3.8	3.0
$\varepsilon_{95\%}$ (dB) for Rice 1 ($\eta = 0.6$)	6.9	3.2	2.2	1.8
$\varepsilon_{95\%}$ (dB) for Rice 2 ($\eta = 0.3$)	2.8	1.5	1.1	0.9
$\varepsilon_{95\%}$ (dB) averaged	10.7	3.5	2.3	1.8

Source: E. Larcheveque et al., "Analysis of electric field averaging for in-situ radiofrequency exposure assessment," *IEEET Trans. on VTC*, vol.54, no.4, pp.1245-1250, 2005.

Spatial Averaging: Rationale

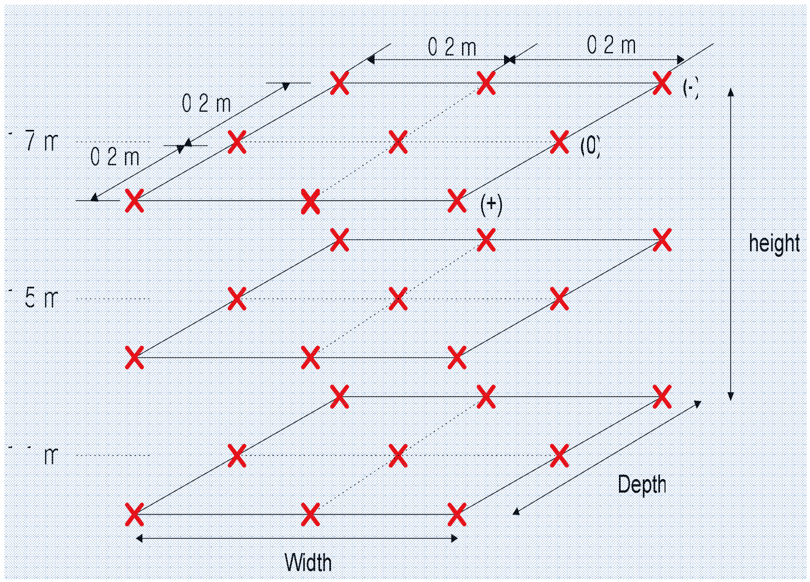
- Assessed quantity
  - Electric and magnetic field strength or equivalent plane wave power density
- At a given location
  - Diffraction and reflections
  - Different phases and amplitudes
- Spatial variations known as small-scale fading
  - It does not allow a repeatable exposure level
  - We should use an averaging scheme.

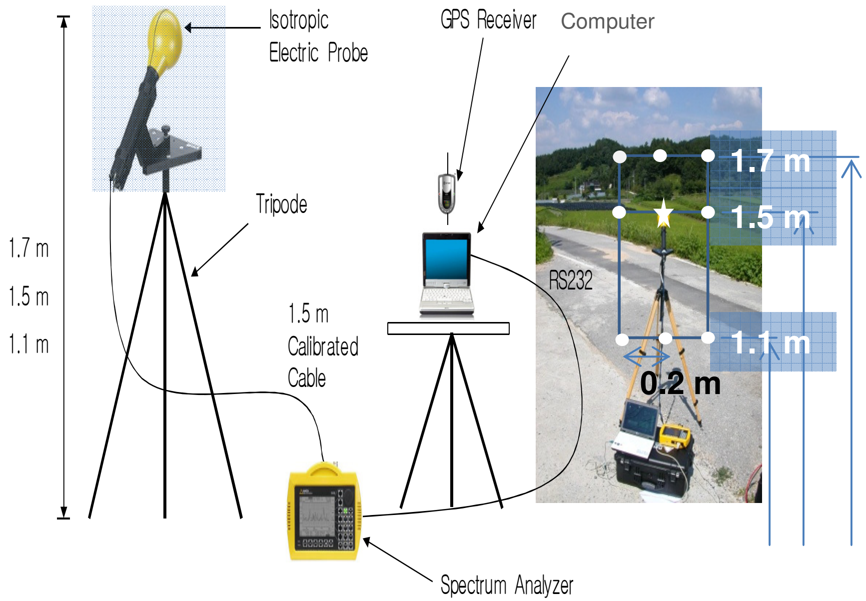




Spatial Averaging: Approach for New Method

- To determine the number of measurement points
  - Imitate the space occupied by human
  - Analysis the spatial variations of electric field strength
- To consider the effect of environments
  - Urban
  - Suburbs
  - Rural





Spatial Averaging: Analysis

- Maximum mean value occur when 6 or 9 points are used in averaging process.

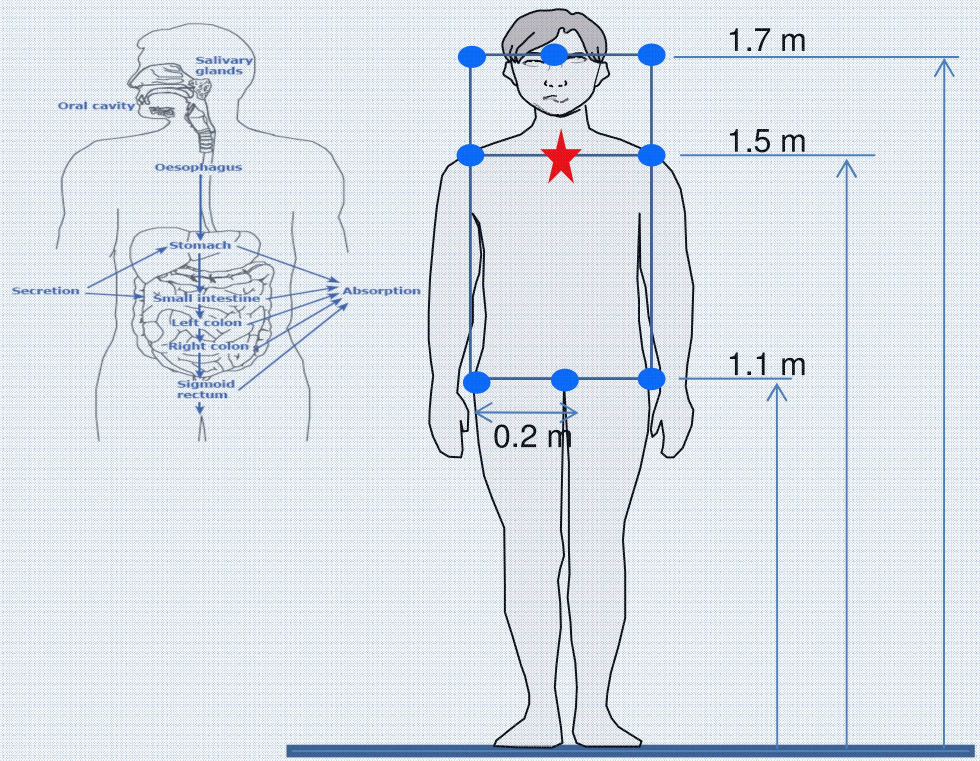
Unit : V/m

No. of points		BS1	BS2	BS3	BS4	BS5	BS6
27	Ave.	0.2866	0.2713	0.2308	0.3514	0.0299	0.0457
	Ave.(-)	0.2888	0.2714	0.2312	0.3616	0.0274	0.0477
9	Ave.(0)	0.2835	0.2712	0.2313	0.3511	0.0331	0.0424
	Ave.(+)	0.2874	0.2712	0.2312	0.3616	0.0274	0.0477
	Ave.(-)	0.2867	0.2716	0.2301	0.3457	0.0300	0.0461
6	Ave.(0)	0.2826	0.2709	0.2312	0.3590	0.0315	0.0440
	Ave.(+)	0.2881	0.2711	0.2309	0.3835	0.0275	0.0473
Number of Max. average point		9	6	9	6	9	9

- The more number of base stations we select, the better statistical meanings we can get. However, the purpose of these measurements does not determine the statistical significance (p-value estimation) between “an exposure to EMF from base station antenna” and “that’s impact on the human health” but check the levels of exposure.

Spatial Averaging: Korea's Method

- Location of the main organs of human and theoretical correlation distance
- Reliable and repeatable exposure assessment



$$\overline{E} = \sqrt{\frac{\sum_{i=1}^{N} (\hat{E}_i)^2}{N}} \quad or$$

$$\overline{H} = \sqrt{\frac{\sum_{i=1}^{N} (\hat{H}_i)^2}{N}} \quad or$$

$$\overline{S} = \frac{\sum_{i=1}^{N} \hat{S}_i}{N}$$

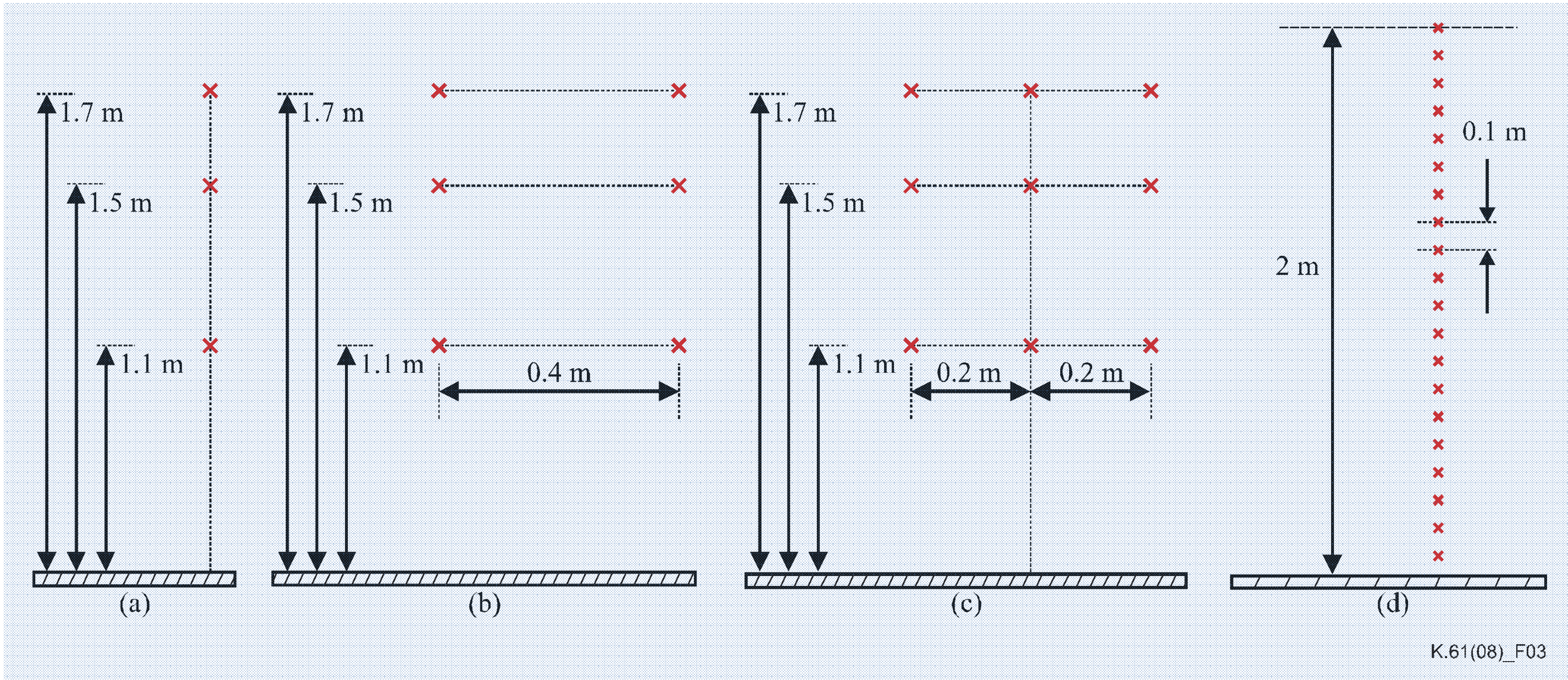
N: number of points

$\hat{E}_i$: root mean square

Source: Byung Chan Kim et al., "Methods of Evaluating Human Exposure to Electromagnetic Fields Radiated from Operating Base Stations in Korea," *Bioelectromagnetics*, vol. 29, no. 7, pp. 579-582, Oct. 2008.

Time Averaging: Previous Status

- Number of points for spatial averaging: 3, 6, 9, 20 points (ITU-T K.61 and IEC62232)
- Measurement time
- ICNIRP guidelines: Recommend averaged over any 6 min period
- Frequencies between 100 kHz and 10 GHz.



Source: ITU-T Recommendation K.61, 2008

Time Averaging: Previous Study

- Established biological and health effects
- Temperature (eyeball) rise of more than 1 degree

Tissue	Mass density (kg/m^3)	Thermal conductivity (W/m K)	Specific heat capacity (J/Kg K)	Volumetric perfusion (m^3/m^3s)	Equilibration time (min)	Conductivity (K kg/W)
Skeletal muscle	1050	0.50	3465	0.9	17	300
Kidney	1050	0.54	3700	61	0.27	4.4
Liver	1060	0.52	3600	15	1.1	18
Adipose tissue	950	0.27	3100	0.5	25	480
Brain	1040	0.54	3640	7.3	2.2	36
Blood	1060	0.51	3720	-	-	-

- Heat transfer model

$$\frac{\partial T(x,t)}{\partial t} - \alpha \frac{\partial^2 T(x,t)}{\partial x^2} + \beta (T(x,t) - T_a) = q(x,t)$$

$$Max\{\Delta T(t)\} = \sigma L_{SAR}[1 - \exp(-t/\tau)]$$

$L_{SAR} = (10 - 8r)$, *r:* exposed mass/total mass

Source: "Gunnar Brix, Martin Seebass, Gesine Hellwig, Jurgen Griebel, "Estimation of Heat Transfer and Temperature Rise in Partial-Body Regions during MR Procedures: An analytical approach with respect to safety considerations," *Magnetic Resonance Imaging*, vol. 20, pp. 65-76, 2002.

Time Averaging: Rationale of Time Reduction

The averaging time

- means the appropriate time over which exposure is averaged
- is 6 min at each point
- increases as the number of points increases
- increasing means an increase in cost
- is related to the time constant for partial body heating: present of a human body
- therefore, is not always necessary in all far field assessments

Reference levels at any point

- are evaluated in the absence of a human body
- are intended to be spatially averaged values body of the exposed individual

Time Averaging: Approach and Analysis

- Analyzed the eighteen periods of time from 180 to 10 sec: 10 sec interval

Unit : dBuV/m

Time (sec) / Base station	360	180	60	40	10
1	109.14	109.14	109.16	109.14	109.08
2	109.80	109.79	109.79	109.79	109.80
3	107.07	107.07	107.09	107.07	107.11
4	111.59	111.55	111.60	111.63	111.81
5	92.56	92.36	92.34	92.33	92.56
6	90.41	90.28	90.76	90.84	90.74
7	97.38	97.26	97.39	97.40	97.67

- The estimated standard uncertainties: 0.09 ~ 0.40 dB (t-distribution; $t_{.025}$=2.05, DoF=29)

Base station	1	2	3	4	5	6	7	8	9	10
Arithmetic average(dBuV/m)	110	117	106	109	114	100	93	107	110	99
Standard deviation (SD)	0.25	0.62	0.98	0.46	0.39	1.07	0.59	0.40	0.58	0.51
$T_{r/2}$(confidence level: 95%, DoF: 29)	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05
Standard uncertainty	0.09	0.23	0.36	0.17	0.15	0.40	0.22	0.15	0.22	0.19

DoF: Degree of Freedom

Time Averaging: Korea's Method

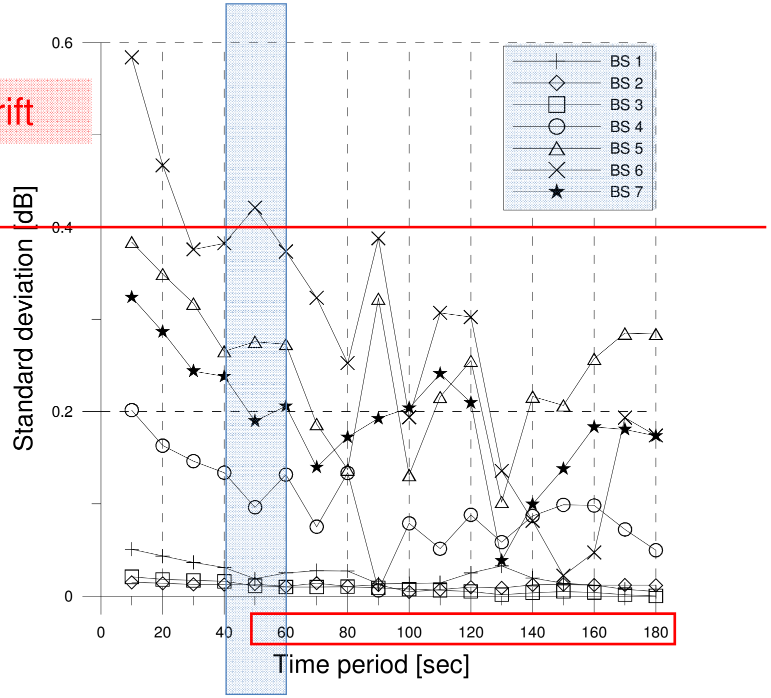
- Compare the SD with uncertainty of measurement drift
- Between the 360 sec average value and different time periods
- No overlapping time period: 1~60, 61~120, 121~180, 181~240, 241~300, 301~360 sec
- Maximum value of SD: 0.58 dB at 10 sec
- Uncertainty for repeated measurement: 0.4 dB

uncertainty for measurement drift

- Average: $\bar{q} = \frac{1}{n}\sum_{j=1}^{n} q_j$
- Standard deviations:

$$s(q_j) = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(q_j - \bar{q})^2}$$

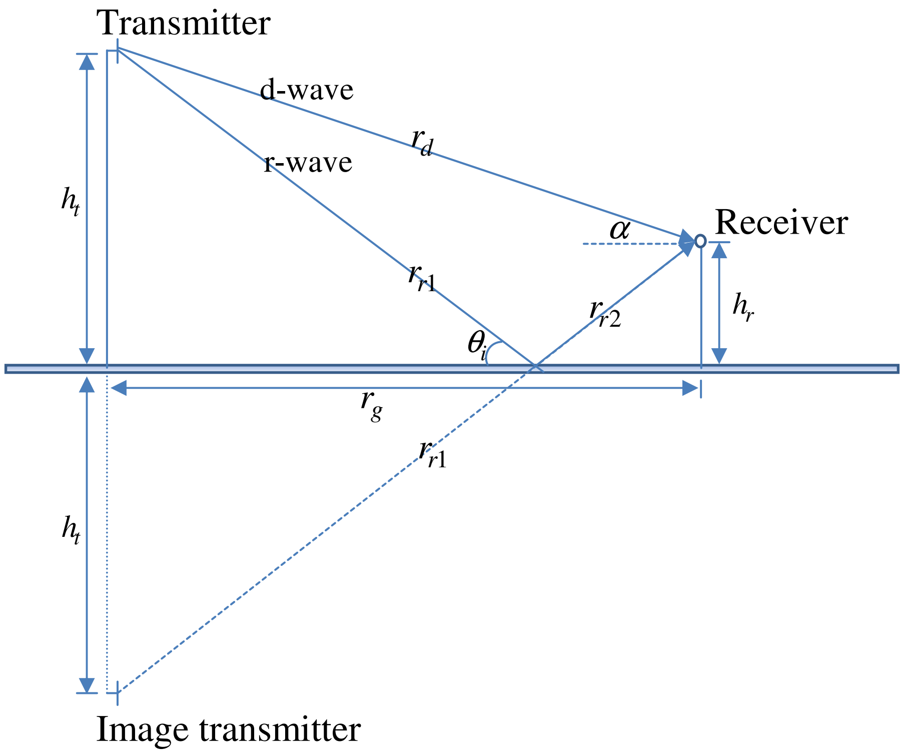
$$s(\bar{q}) = t_{r/2}\frac{s(q_j)}{\sqrt{n}} = t_{r/2}\frac{1}{\sqrt{n}}\sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(q-\bar{q})^2}$$



Source: Byung Chan Kim et al., "Reduction of averaging time for evaluation of human exposure to radiofrequency electromagnetic fields from cellular base stations," *IEICE Trans. on Communications,* vol. E93-B, no. 7, pp. 1862-1864, July 2010.

Predicting Formula: Korea's Method

- Need to predict the possible maximum exposure position



$$\vec{E}^t = \vec{E}^d + \vec{E}^r = (1+|\Gamma|)\,\vec{E}^d$$

$$\vec{E}^t = \hat{a}_\theta (1+|\Gamma|)\, j\eta \frac{I_0 e^{-j\beta r}}{2\pi r}\left[\frac{\cos(\frac{\beta l}{2}\sin\alpha) - \cos(\frac{\beta l}{2})}{\cos\alpha}\right]$$

$$G = 4\pi \frac{U(\theta,\phi)}{P_{in}},\quad P_{in} G = 4\pi U(\theta,\phi)$$

$$U(\theta,\phi) = r^2 W_{rad} = r^2 \frac{1}{2}\mathrm{Re}[\vec{E}\times\vec{H}^*] = r^2 \frac{|\vec{E}|^2}{2\eta}$$

$$U(\theta,\phi) = \frac{r^2}{2\eta}|E_\theta(r,\theta,\phi)|^2$$

$$|E_\theta|^2{}_{\max} = \eta^2 \frac{I_0{}^2}{4\pi r^2}$$

$$U_{\max}(\theta,\phi) = \frac{r^2}{2\eta}\times|E_\theta|_{\max} = \frac{\eta I_0{}^2}{8\pi^2}$$

$$\frac{\eta I_0{}^2}{2\pi} = P_{in} G,\quad I_0 = \sqrt{\frac{2\pi P_{in} G}{\eta}}$$

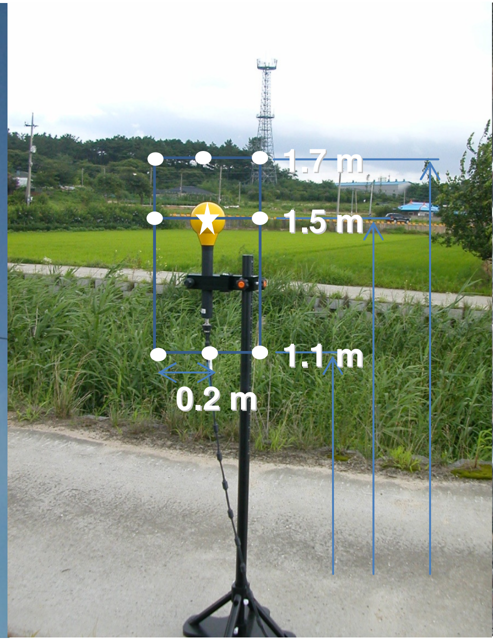
$$\vec{E}^t = \hat{a}_\theta (1+|\Gamma|)\frac{je^{-j\beta r}}{r}\sqrt{\frac{\eta P_{in} G}{2\pi}}\left[\frac{\cos(\frac{\beta l}{2}\sin\alpha) - \cos(\frac{\beta l}{2})}{\cos\alpha}\right]$$

$$\Gamma = \frac{-(\varepsilon_r' - j60\lambda\sigma)\sin\theta_i + \sqrt{(\varepsilon_r' - j60\lambda\sigma) - \cos^2\theta_i}}{(\varepsilon_r' - j60\lambda\sigma)\sin\theta_i + \sqrt{(\varepsilon_r' - j60\lambda\sigma) - \cos^2\theta_i}}$$

$$\theta_i = \sin^{-1}\left(\sin\alpha * \left(\frac{h_t + h_r}{h_t - h_r}\right)\right)$$

Evaluating Methods: Protocols and Status

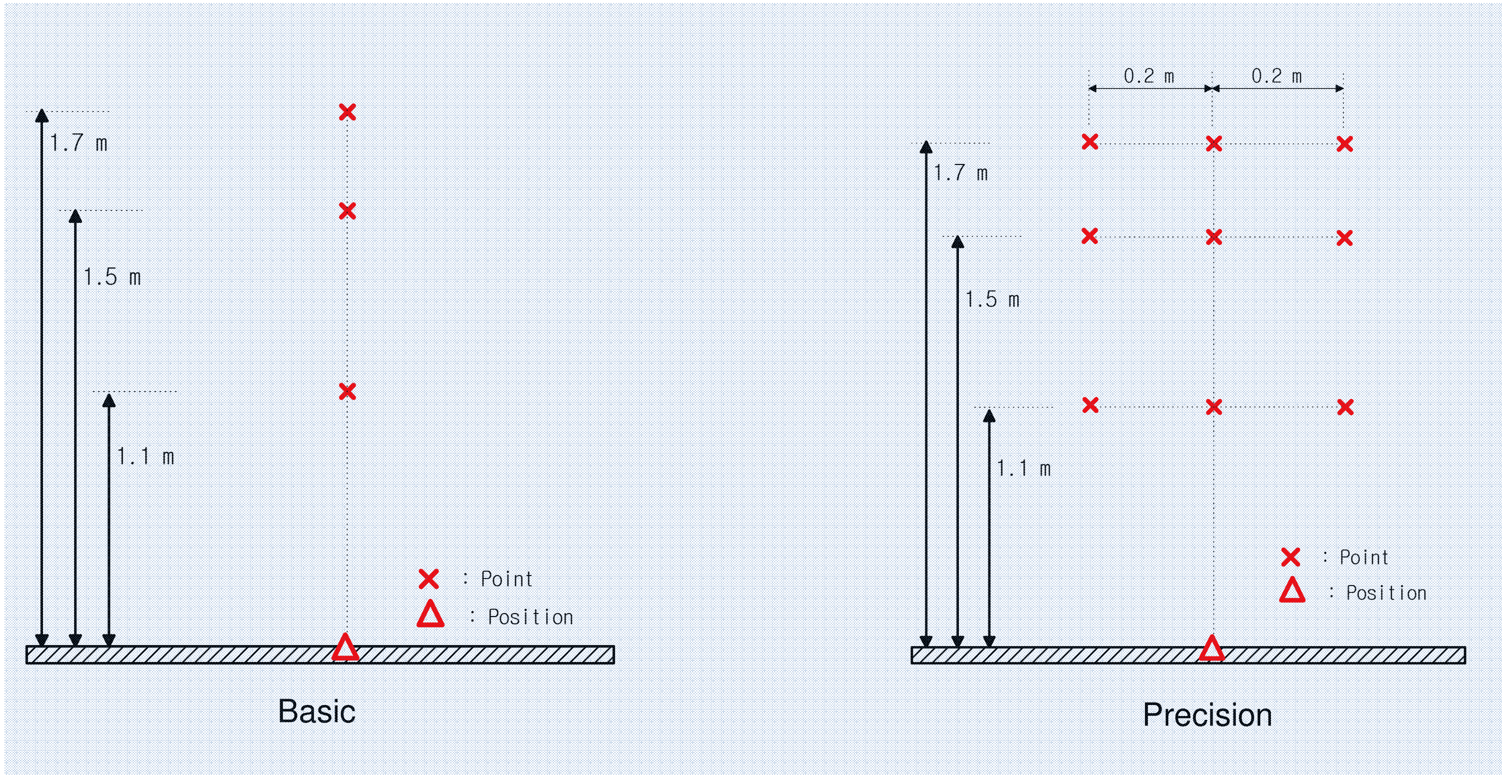
- Depending on the operation state,
- Put on the market: EN50383 (certification measurement)
- Put into service (EEM): RRL Notice 2010-64, EN50400
- Offer a service (In situ): TTAS.KO-06.0125, EN50492, IEC62232



EEM: Electromagnetic Environment Measurement

Evaluating Methods: Korea' method for In Situ

- Focused on human beings: human-centric
- Korean standard was established in December, 2006.
- Assume spatially averaged value / Take total exposure ratio (TER) of same frequency
- Only 1 point in any positions within space occupied by human body

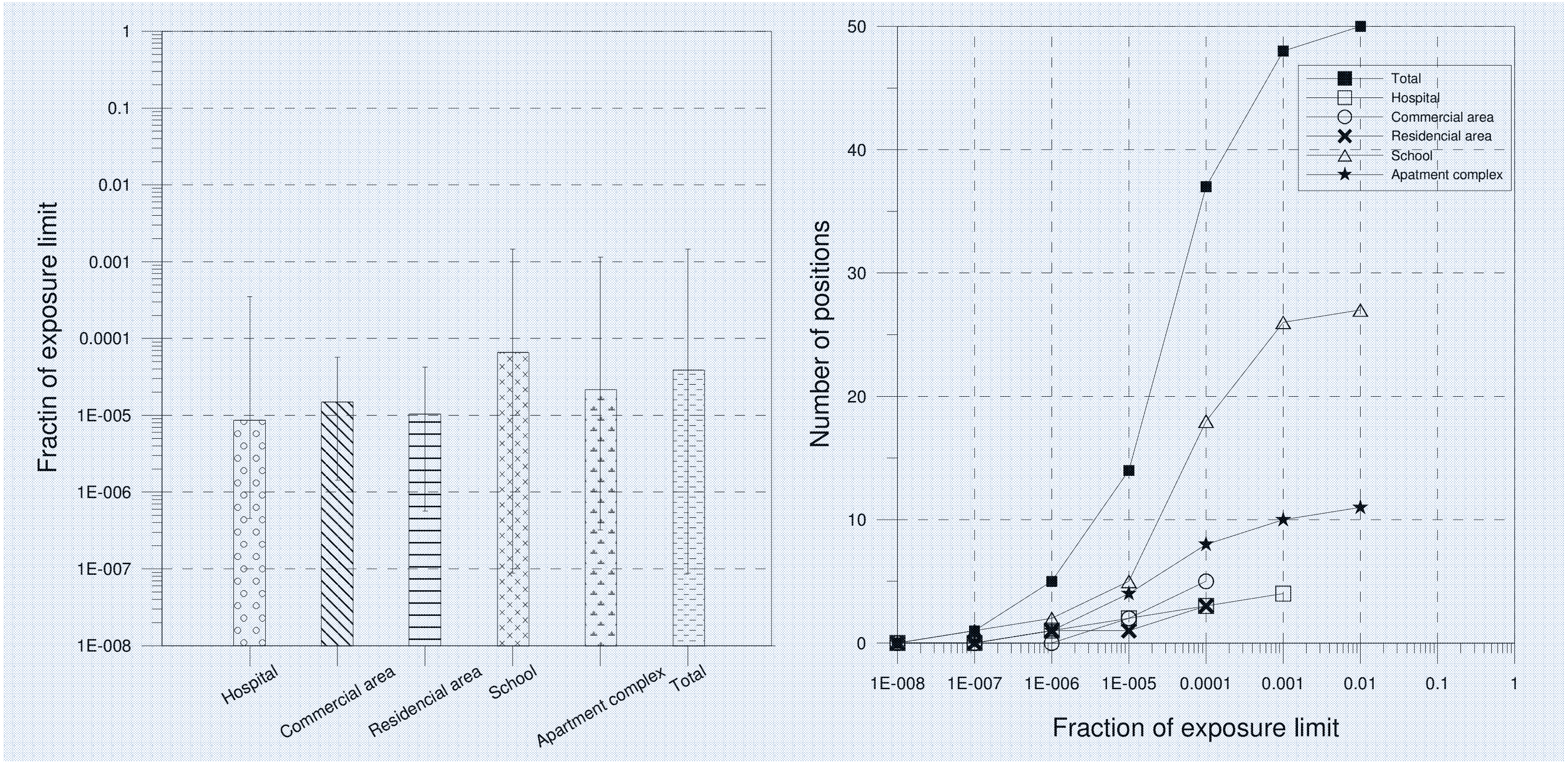


Evaluating Methods: Korea' method for In Situ

- Evaluation at place of concern

• Where the general public have voiced concerns about EMF

• Reference for the WHO in developing its anticipated Environmental Health Criteria (EHC) on radiofrequency



Source: Byung Chan Kim et al., "Methods of Evaluating Human Exposure to Electromagnetic Fields Radiated from Operating Base Stations in Korea," *Bioelectromagnetics*, vol. 29, no. 7, pp. 579-582, Oct. 2008.

Uncertainty: Previous study

- Several kinds of uncertainty sources exist
- The rationale of probability function is insufficient
- Divisor of U-shape probability function: $\sqrt{2}$, Rectangular: $\sqrt{3}$, Triangular: $\sqrt{6}$, Normal: 2.0

Budget	Uncertainty Source	Probability Function
Measurement equipment		
	Calibration	Normal
	Isotropy	Normal
	Linearity	Rectangular
	Measurement device	Normal
	Noise	Normal
	Power chain	Normal
Physical parameters		
	Drifts in output power of the EUT, probe, temperature and humanity	Rectangular
	Perturbation of the environment	Rectangular
	Influence of the body	
Post processing		
	Spatial averaging	Rectangular

Source: EN50492, 2008

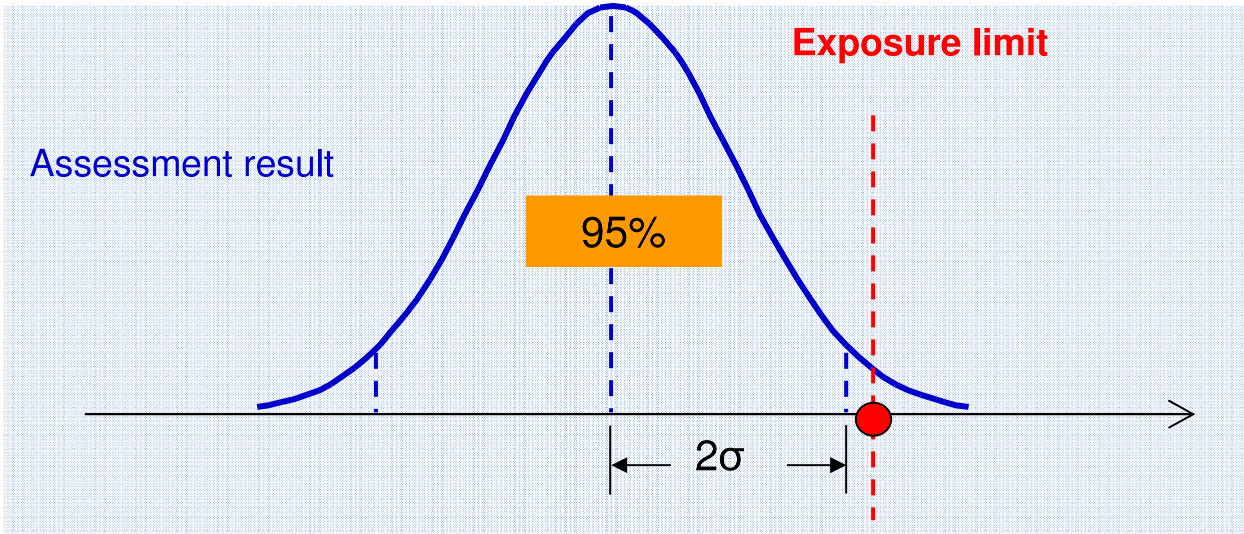
Uncertainty: Rationale

- A measured quantity is not measured directly, but is determined from other quantities through a functional relationship

$$Q = f(R_1, R_2, \cdots\cdots, R_N)\text{: measured quantity}$$
$$q = f(r_1, r_2, \cdots\cdots, r_N)\text{: estimate}$$

- Uncertainty: The variance of the mean

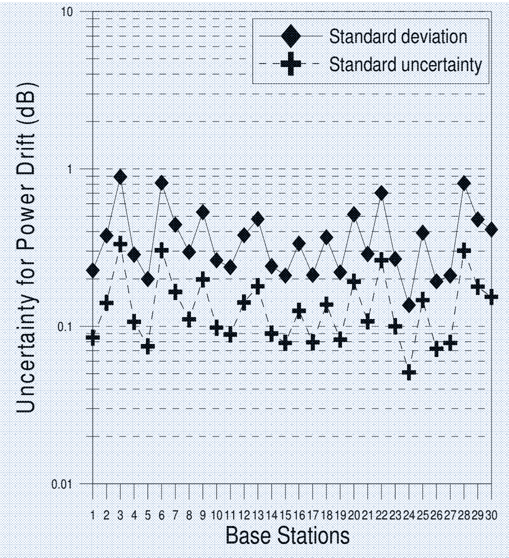
$$s(\bar{q}) = \frac{s(q_j)}{\sqrt{n}} = \frac{1}{\sqrt{n}}\sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(q - \bar{q})^2}, \qquad \bar{q} = \frac{1}{n}\sum_{j=1}^{n} q_j$$



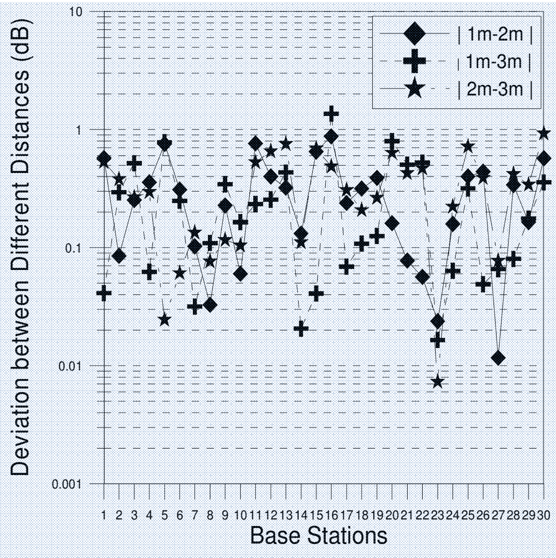
Uncertainty: Approach & Analysis

- Type A: Be obtained by repeated measurement
- Type B: Be estimated by the data on the calibration or specification sheet

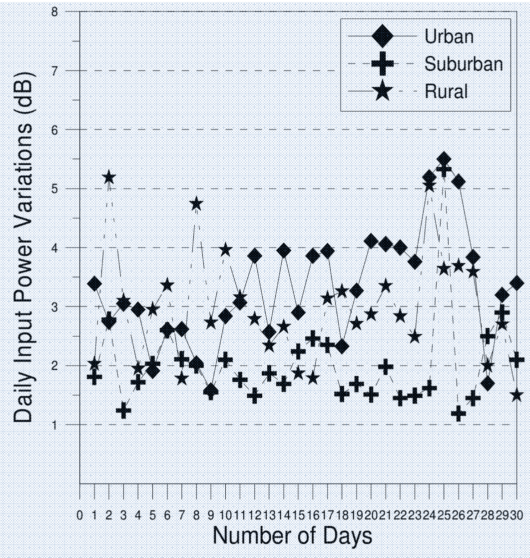
Type	Contribution components	Uncertainty sources
A	Physical parameters	Power drift (measurement drift), Body influence, noise
	Mechanical constraints	Tripod positioning, Mismatch between receiving antenna (or probe) and base station's antenna
	Post-processing	Spatial averaging
B	Measurement equipment	Calibration, Power receiver, Isotropy /linearity of probe, Cable, Power chain



Power drift



Body influence



Mismatches

Uncertainty: Krea's Methods

- The estimated uncertainty satisfy the recommendation by international standard (under 6 dB)

Evaluation type	Contribution components	Uncertainty sources	Probability function	Uncertainty value [dB]	Divisor	DoF	Rationale of distribution	Standard uncertainty [dB]
A	Physical parameter	Power drift	Student-t	0.67	2.05	29	Small sample, unknown population mean & variance	0.33
		Influence of body	Student-t	0.22	2.05	29	Small sample, unknown population mean & variance	0.11
	Mechanical constraint	Mismatches	Student-t	1.29	2.05	29	Small sample, unknown population mean & variance	0.63
	Post-processing	Spatial averaging	Student-t	0.99	2.26	9	Small sample, unknown population mean & variance	0.44
B	Measurement equipment	Calibration	Normal	3.00	2.00	∞	Data sheet	1.50
		Spectrum analyzer	Normal	0.34	2.00	∞	Calibration sheet	0.17
		Isotropy	Normal	1.50	2.00	∞	Calibration sheet	0.75
		Linearity	Normal	0.89	2.00	∞	Calibration sheet	0.45
		Cable	Normal	0.40	2.00	∞	Calibration sheet	0.20
	Combined uncertainty		Root Sum Square of all standard uncertainty ($\sqrt{\sum u^2}$)					1.95
	Expanded uncertainty		Student-t	1.95	1.96	1,447	DoF and t-distribution table	3.82

Source: Byung Chan Kim et al., "Uncertainty Estimation for Evaluating of Human Exposure Levels to RF Electromagnetic Fields from Cellular Base Stations," Accepted in *IEEE Trans. on EMC* and will publish soon.

Thank you and Questions ?