המשרד להגנת הסביבה

Ministry of Environmental Protection

Ministry of Communications

Technical limits of Human Exposure to RF from Cellular Base Stations and Handsets

Based on author's PhD thesis/book- An analysis of regulatory frameworks for wireless communications, societal concerns and risk: the case of Radio Frequency (RF) allocation and licensing and forthcoming Wiley book, to be published next year

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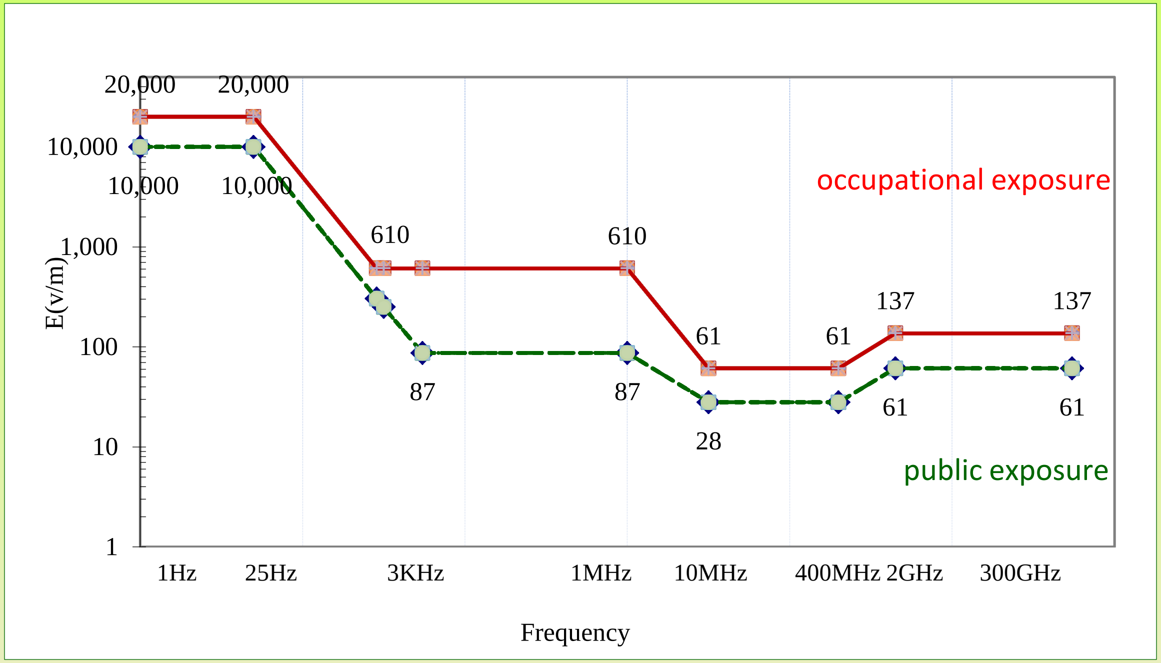
Physical Quantities and Units

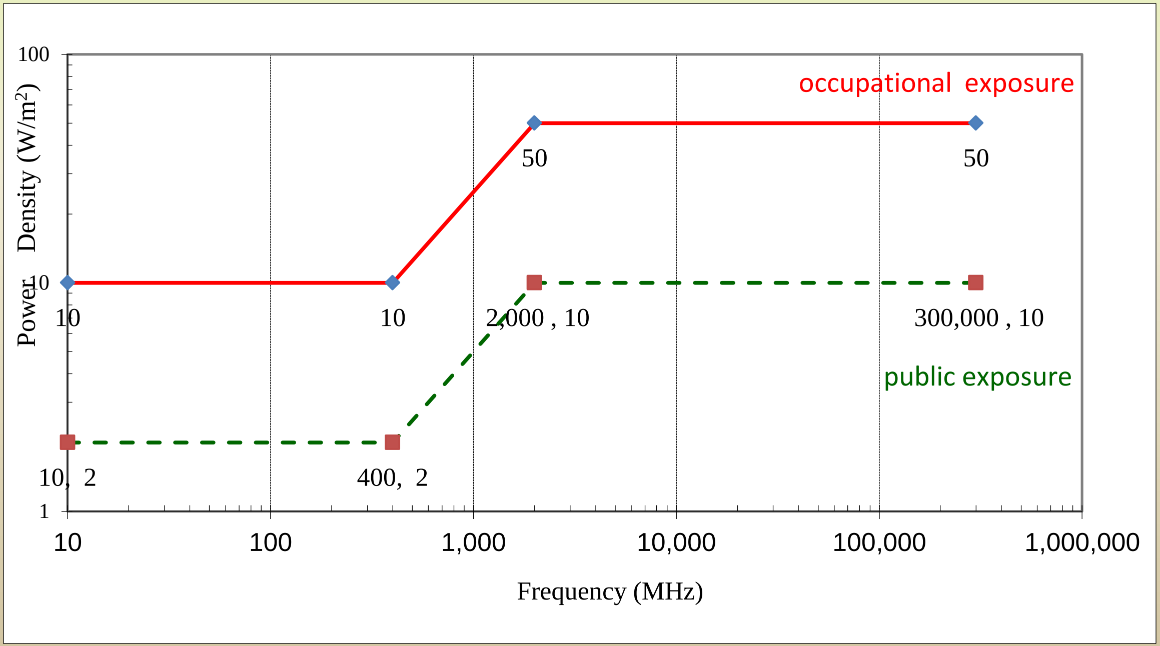
Quantity	Symbol	Unit	Symbol
Frequency	F	Hertz	Hz
Electric field strength	E	Volt per metre	V/m
Power	P	Watts	W
Power density or power flux density	S	Watt per square metre	W/m^2
		mWatt per square cm	mW/cm^2
Specific Absorption Rate	SAR	Watt per kilogram	W/kg
		mWatt per gram	mW/g

ICNIRP (1998:511) reference levels for occupational & general public exposure- table7

Frequency range	Electric field strength (V/m)		Equivalent plane wave power density S_{eq} (W/m^2)	
	general public	occupational	general public	Occupational
1-25 Hz	10,000	20,000	-	
0.025- 0.82 KHz	250/f(KHz)	500/f(KHz)	-	
0.82 -3 KHz	250/f(KHz)	610	-	
3-1000 KHz	87	610	-	
1-10 MHz	$87/f^{1/2}$ (MHz)	610/f (MHz)		
10-400 MHz	28	61	2	10
400-2000 MHz	$1.375f^{1/2}$ (MHz)	$3f^{1/2}$ (MHz)	f/200	f/40
2-300 GHz	61	137	10	50

ICNIRP (1998:511) reference levels for occupational & general public exposure- graphs





SAR is "the time derivative of the incremental energy (dW) absorbed by (dissipated in) an incremental mass (dm) contained in a volume element (dV) of a given mass density (ρ_m)" (ITU-T 2012 K.91:9) in W/kg

$$SAR = \frac{d}{dt}\left(\frac{dW}{dm}\right) = \frac{d}{dt}\left(\frac{dW}{\rho_m dV}\right)$$

SAR can be ascertained in three ways as indicated by the following equations:

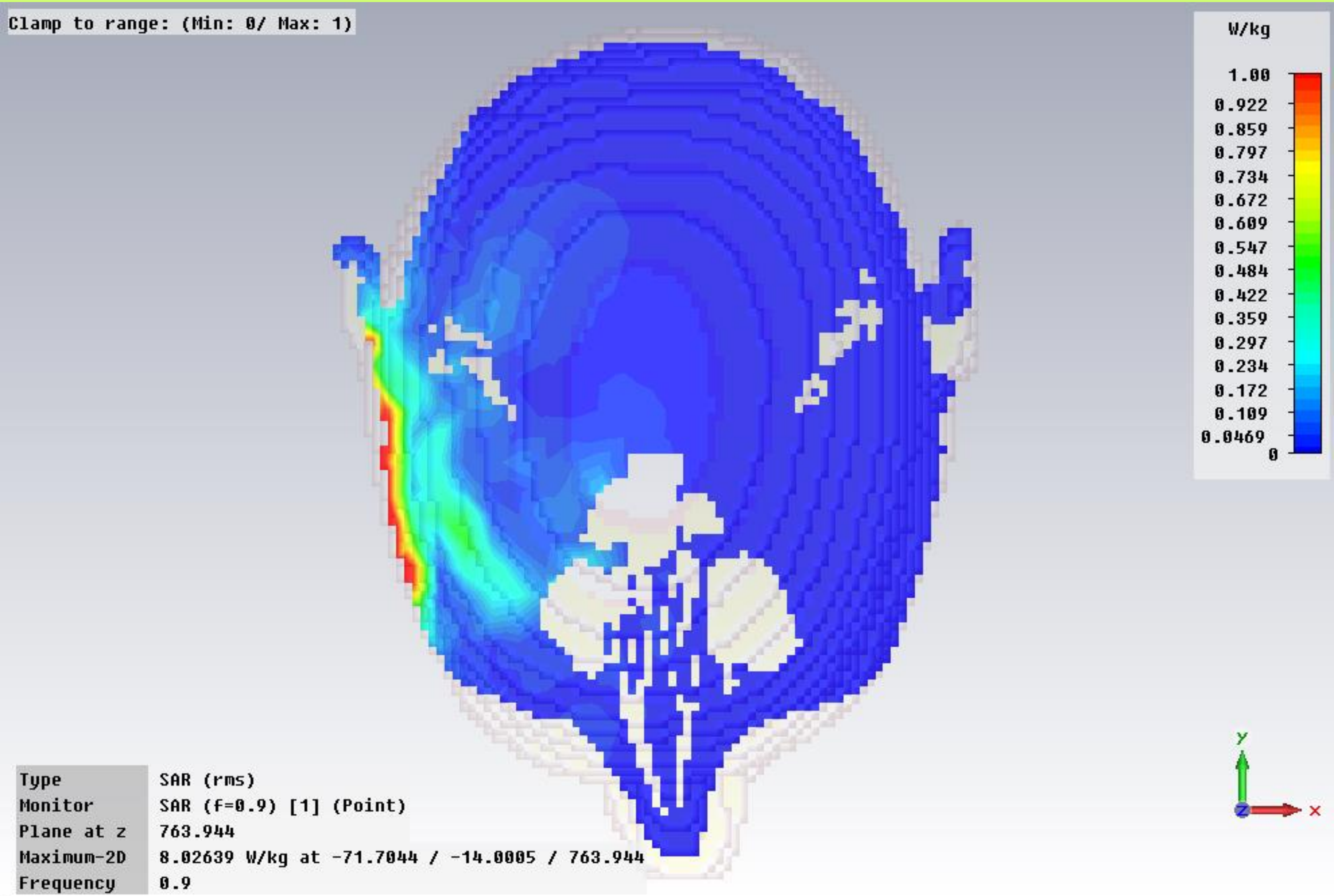
E : value of the internal electric field strength in the body tissue (V/m)
σ : conductivity of body tissue (S/m) (siemens per meter, or mho per meter)
ρ : mass density of body tissue (kg/m^3)
C_i : heat capacity of body tissue (J/kg °C)
dT/dt : time derivative of temperature in body tissue (°C/s)
J : value of the induced current density in the body tissue (A/m^2).

$$\mathrm{SAR} = \frac{\sigma E^2}{\rho} = C_i \frac{dT}{dt} = \frac{J^2}{\sigma\rho}$$

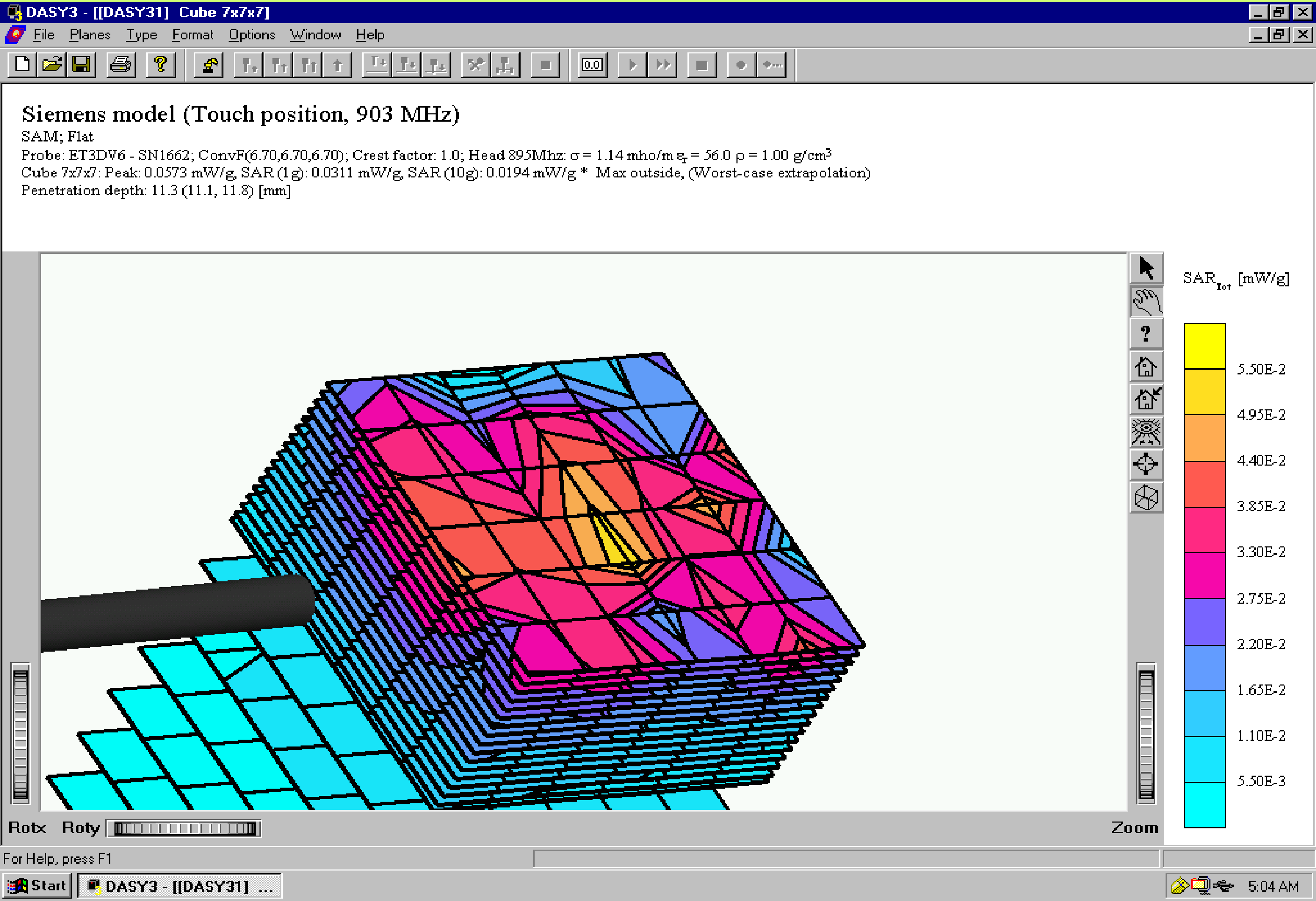
Maximal power from handsets: Specific Absorption Rate, SAR (W/kg)

ICNIRP	European Community	USA and Canada
From 10 MHz to 10 GHz; Localized SAR (Head and Trunk)		Portable Devices; General Population/ Uncontrolled
2.0; averaged over 10 g tissue (also IEEE 2005 level)		1.6; averaged over 1g tissue

SAR phantom simulation (Stefan Chulski & Stav Revich from HIT)



Measurements of SAR (Stefan Chulski & Stav Revich from HIT)



FCC 2013 Limits for Maximum Permissible Exposure (MPE)

[Reassessment of RF Exposure Limits & Policies, and Proposed Changes in the Rules Regarding Human Exposure to RF Fields]

Frequency range (MHz)	*Electric field strength (V/m)*	*Magnetic field strength (A/m)*	*Power density (mW/cm^2)*	*Averaging time (minutes)*
(A) Limits for Occupational/Controlled Exposure				
0.3 – 3.0	614	1.63	100 *	6
3.0 – 30	1842/f	4.89/f	$900/f^2$ *	6
30 – 300	61.4	0.163	1.0	6
300 – 1,500	–	–	f/300	6
1,500 – 100,000	–	–	5	6
(B) Limits for General Population/Uncontrolled Exposure				
0.3 – 1.34	614	1.63	100 *	30
1.34 – 30	824/f	2.19/f	$180/f^2$ *	30
30 – 300	27.5	0.073	0.2	30
300 – 1,500	–	–	f/1500	30
1,500 – 100,000	–	–	1.0	30

[1] FCC uses different units than ICNIRP for power density: mW/cm^2 and not W/m^2; $W/m^2 = 0.1\ mW/cm^2$

ICNIRP vs. N. America and Japan reference levels

ICNIRP 1998, EC (1999/519) and IEEE reference levels for public exposure

Frequency range	Electric field strength (V/m)	Equivalent plane wave power density S_{eq}(W/m^2)
10–400 MHz	28	2
400-2000 MHz	$1.375f^{1/2}$	$f/200$
2-300 GHz	61	10

North America and Japan Maximum Permissible Exposure for general population/uncontrolled

Frequency Range (MHz)	Electric Field (E) (V/m)	Power Density (S) (mW/cm^2)
30-300	27.5	0.2
300-1500	--	$f/1500$
1500-100,000	--	1

[1] FCC uses different units than ICNIRP for power density: mW/cm^2 and not W/m^2; W/m^2 = 0.1 mW/cm^2

Far-field free-space propagation loss

$$s = \frac{p_t g_t}{4\pi d^2} = \frac{eirp}{4\pi d^2}; d = \sqrt{\frac{eirp}{4\pi s}}$$

$$\vec{s} = \vec{e} \times \vec{h} = \frac{eirp}{4\pi d^2} \qquad \vec{h} = \frac{\vec{e}}{z_o} \qquad z_0 \equiv \mu_0 \times c_0 = \mu_0 \times \sqrt{\frac{1}{\varepsilon_0 \times \mu_0}} = \sqrt{\frac{\mu_0}{\varepsilon_0}} = \frac{1}{\varepsilon_0 \times c_0} = 120\pi$$

$$\vec{s} = \vec{e} \times \vec{h} = \frac{eirp}{4\pi d^2} = \frac{\vec{e} \times \vec{e}}{120\pi} \qquad |\vec{s}| = \frac{e^2}{z_o} = \frac{e^2}{120\pi} \qquad e = \frac{\sqrt{30\,eirp}}{d}; d = \frac{\sqrt{30\,eirp}}{e}$$

where:

p_t:	transmitter power (watts)
g_t :	transmitter antenna gain (numeric)
eirp:	equivalent isotropically radiated power (watts)
s:	power density (watts/m^2) (limit)
d:	distance (m)
e :	electric field strength (V/m) (limit)
z_0 :	impedance of free-space, 120π (Ohms)
M_0:	vacuum permeability (or magnetic constant)
ε_0 :	vacuum permittivity (or electric constant)
c_0 :	speed of light in vacuum

multiple-antenna emissions from the same site and same frequency

- at a frequency range whose limits are frequency independent (like 10–400 MHz and 2–300 GHz), the power density limits are equal for all transmitters emitting at the same frequency range, i.e. $s_{l1}= s_{l2}=\ldots =s_l$. The equivalent cumulative *eirp* is the power scalar sum of all the emitters; this equivalent *eirp* is used to calculate the safety-distance in ICNIRP 98 tables 6 and 7.

$$eirp_{eq} = \sum eirp_i \qquad d_{eq} = \sqrt{\frac{eirp_{\mathrm{eq}}}{4\pi s_l}} = \sqrt{\frac{\sum eirp_{\mathrm{i}}}{4\pi s_l}}$$

- the total field strength exposure ration w_t

$$w_t = \sum_i \left(\frac{e_i}{e_l} \right)^2 = \frac{\sum_i (e_i)^2}{(e_l)^2} \leq 1$$

Where

eirp$_{\mathrm{i}}$:	for each emitter	(watts)	
eirp$_{\mathrm{eq}}$:	equivalent cumulative *eirp*	(watts)	
d$_{\mathrm{i}}$:	safety-distance from each emitter	(m)	
d$_{\mathrm{eq}}$:	equivalent cumulative safety-distance	(m)	
s$_{\mathrm{i}}$:	power density from each emitter	(W/m²)	index i
s$_{\mathrm{li}}$:	power density limit from each emitter	(W/m²)	index i
e$_{\mathrm{i}}$:	electric field strength from each emitter	(V/m)	index i
e$_{\mathrm{li}}$:	electric field strength limit from each emitter	(V/m)	index i

Emissions transmitted from the same site: multiple-antenna installation

- ICNIRP 1998 limits are **RF dependent**; the equivalent cumulative safety-distance d_{eq}

$$d_{eq} = \sqrt{\sum_i d_i^{\,2}} \qquad d_i = \sqrt{\frac{eirp_{\mathrm{i}}}{4\pi s_i}}$$

- *eirp* is weighted by the inverse of its power density limit s_{li}

$$d_{eq} = \sqrt{\sum_i d_i^{\,2}} = \sqrt{\sum_i \frac{eirp_i}{4\pi s_{li}}} = \sqrt{\frac{eirp_1}{4\pi s_{l1}} + \frac{eirp_2}{4\pi s_{l2}} + \ldots + \frac{eirp_{\mathrm{n}}}{4\pi s_{\mathrm{ln}}}}$$

- check the limit compliance at each frequency band relative to the threshold s_{l} (or e_{l}); total exposure quotient (or cumulative exposure ratio) based on total cumulative weighted PD s_{t}

$$s_t = \sum_{i=1}^{n} \frac{s_i}{s_{li}} = \frac{s_1}{s_{l1}} + \frac{s_2}{s_{l2}} + \ldots + \frac{s_n}{s_{\mathrm{ln}}} \le 1$$

- total cumulative weighted field strength exposure ration w_{t}

$$w_t = \sum_i \left(\frac{e_i}{e_{li}} \right)^2 \le 1$$

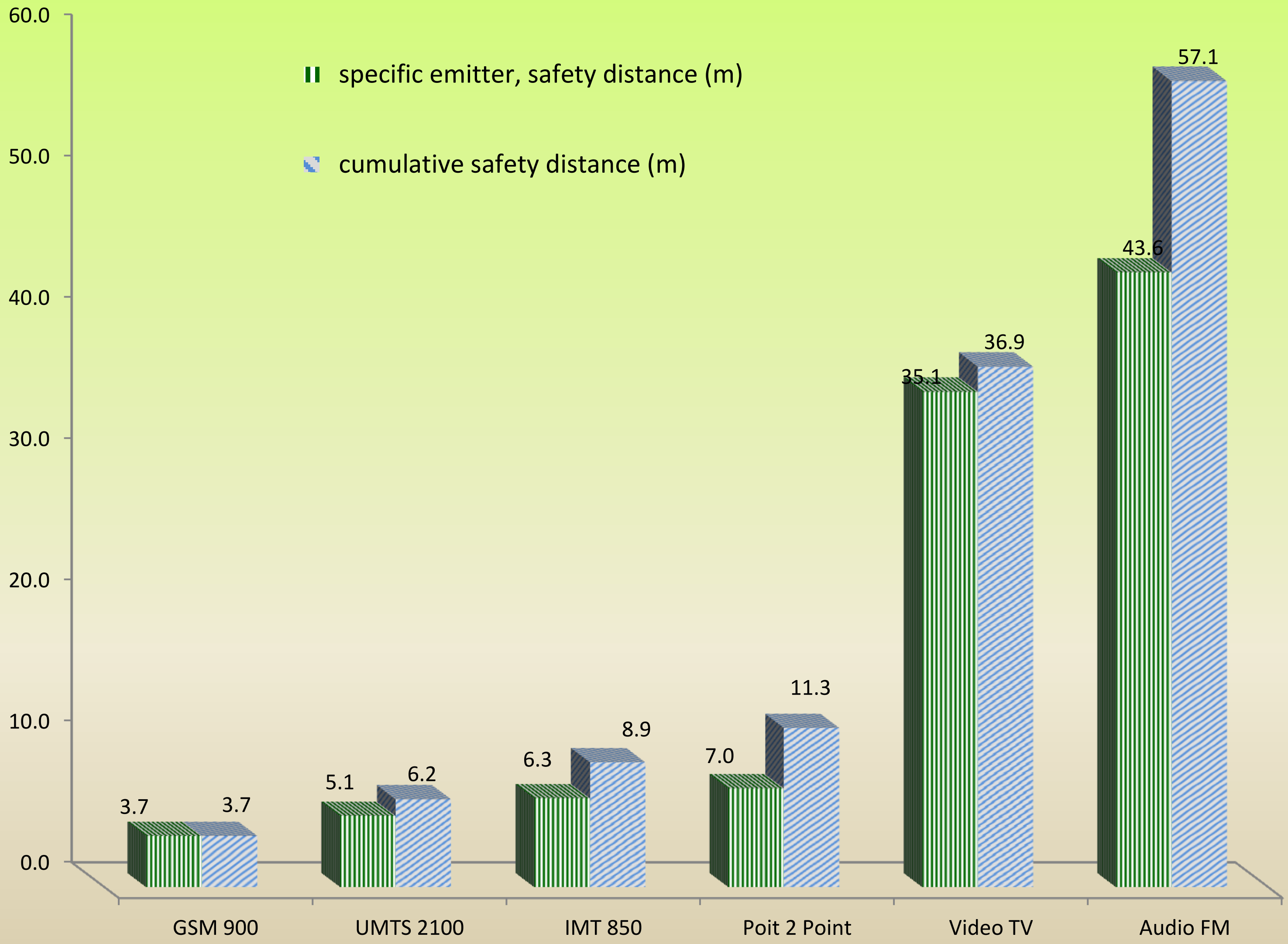
See table in next slide, and slide 19

Worst-case horizontal safety-distances & cumulative exposure; co-located site

Transmission System	GSM 900	UMTS 2100	IMT 850	point-to-point	Video TV	Audio FM
Frequency (MHz)	891	2100	800	514	514	100
ICNIRP limit, power density (W/m^2)	4.75	10.00	4.00	2.57	2.57	2.00
Antenna Gain (dBi)	16	18	18	23	17	10
Antenna elevation model or real pattern	742 265	TBXLHA	80010302_0824	ITU-R [F.1336]()	ITU-R [F.699]()	ITU-R [F.699]()
Antenna Altitude above ground level (m)	32	45	15	25	60	60
Cable Loss (dB)	0	1	1	1	1	1
Power (Watt)	20	64	40	10	1,000	6,000
EIRP (Watt)	800	3,210	2,000	1,580	39,810	47,660
Specific safety distance (m)	3.7	5.1	6.3	7.0	35.1	43.6
Cumulative safety distance (m)	3.7	6.3	8.9	11.3	36.9	57.1
ICNIRP limit, field strength (V/m)	41.30	61.00	38.89	31.17	31.17	28.00
Specific field strength at 50m, ICNIRP ratio	0.08	0.10	0.13	0.14	0.70	0.85
Cumulative field strength ration (mV/m)	0.08	0.13	0.18	0.23	0.74	1.13

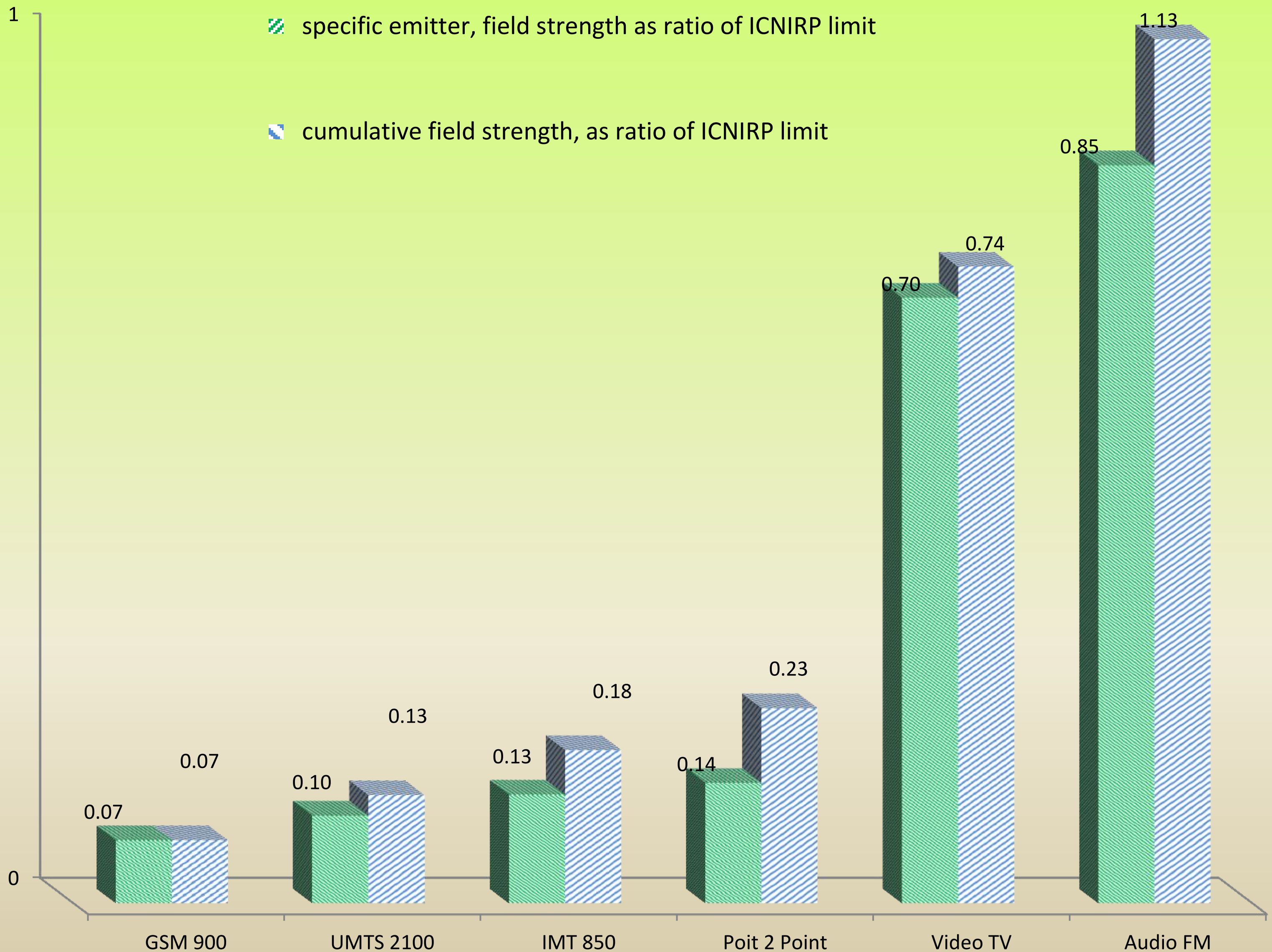
calculated by author

Cumulative horizontal safety-distance, co-located site; y axis (m)



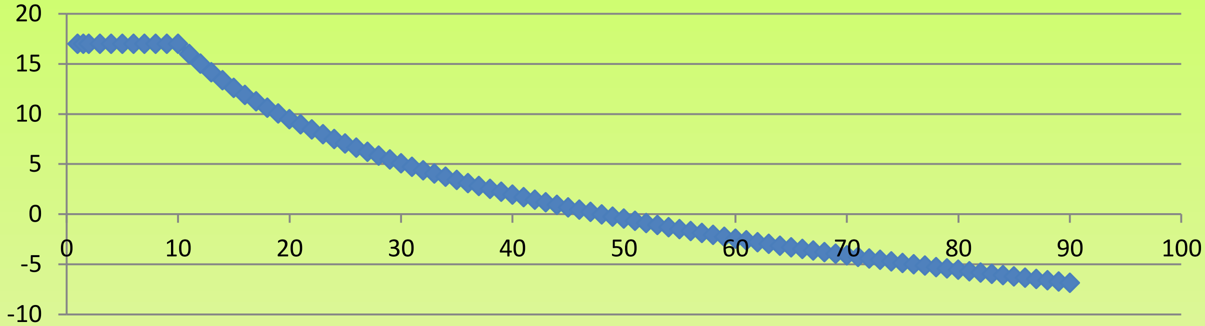
calculated by author

Cumulative field strength exposure ratio , co-located site; point of investigation at 50 meter

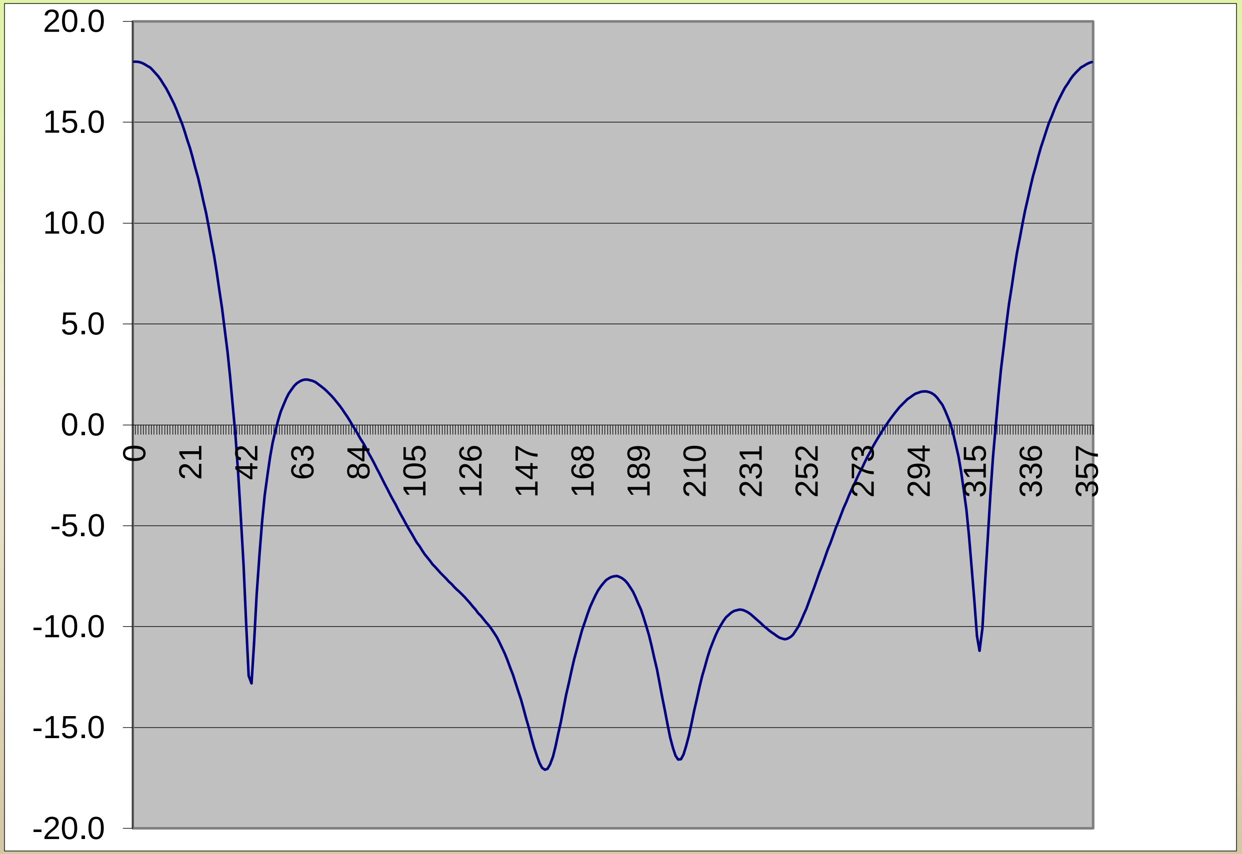


calculated by author

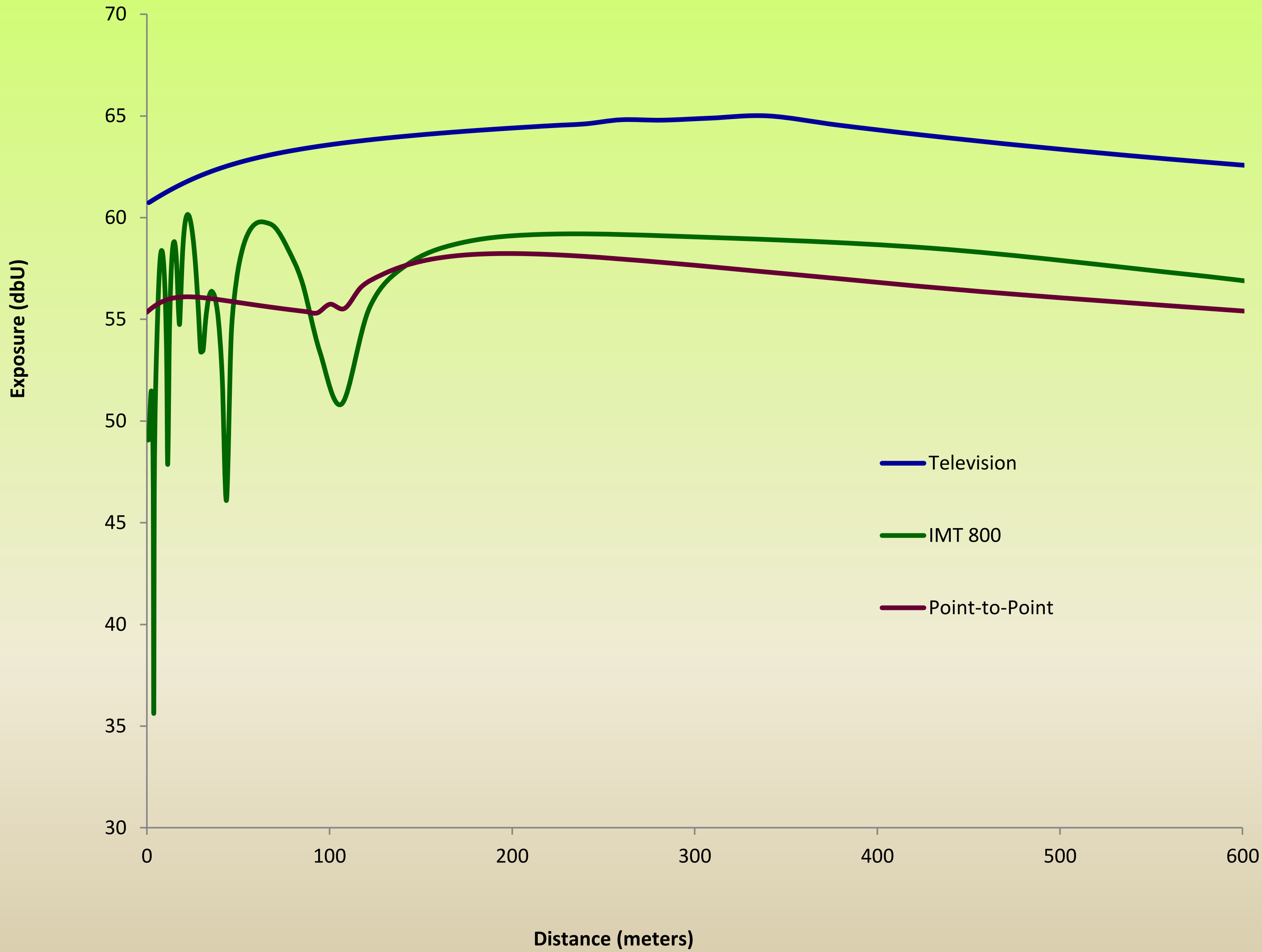
Vertical pattern of TV antenna 17 dBi calculated by ITU-R Rec. [F.699]



Vertical pattern of 80010302_0824_X_CO_M45_00T; Anatel

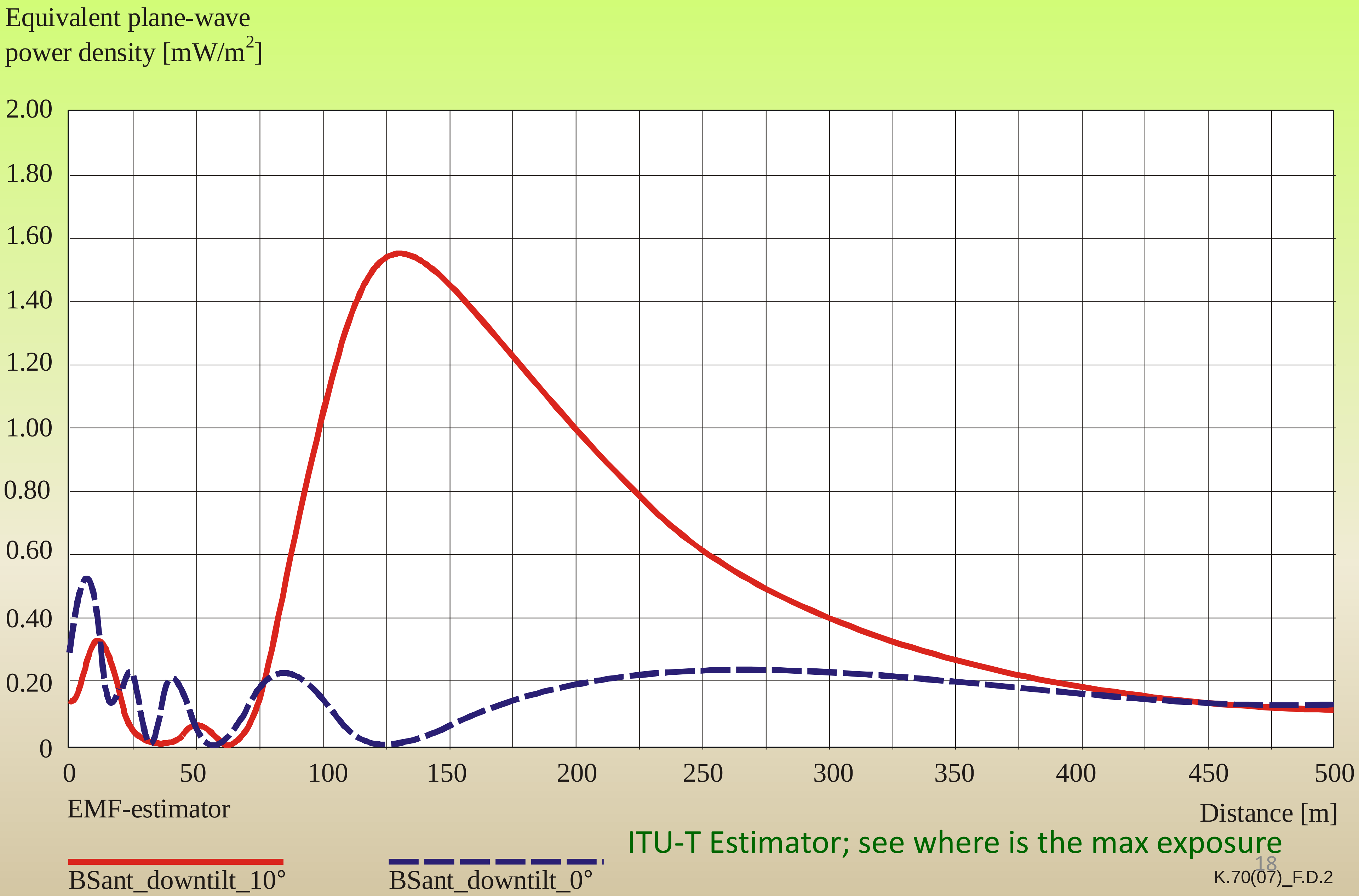


Field Strength (dBµV/m) vs. distance (m), co-located site TV, IMT 850 & Point 2 Point



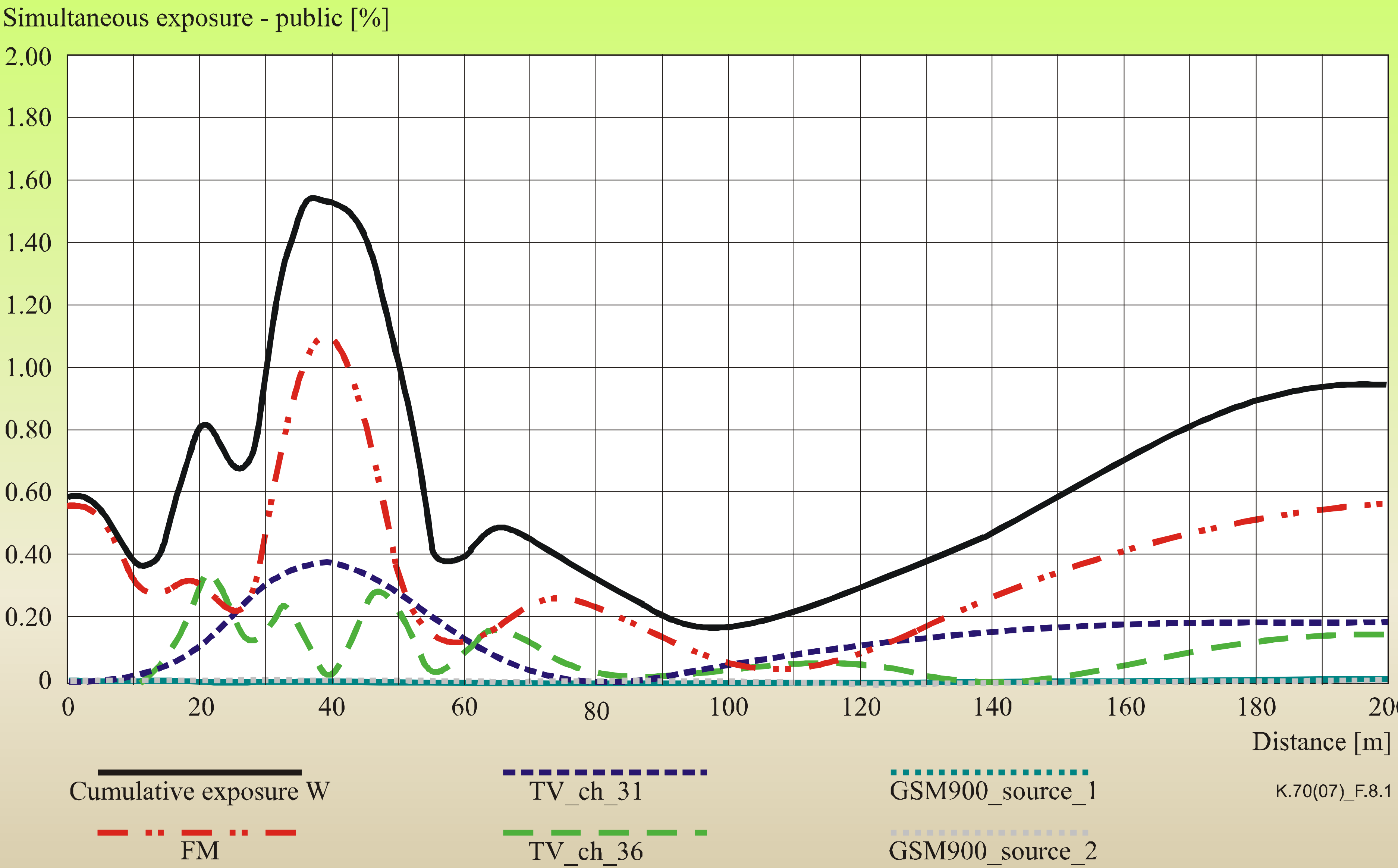
calculated by author; see where is the max exposure

Power density vs. horizontal distance at co-located site near-field & far-field



ITU-T Estimator; see where is the max exposure

Coefficient W_t vs. distance for co-located site with FM, TV & GSM 900

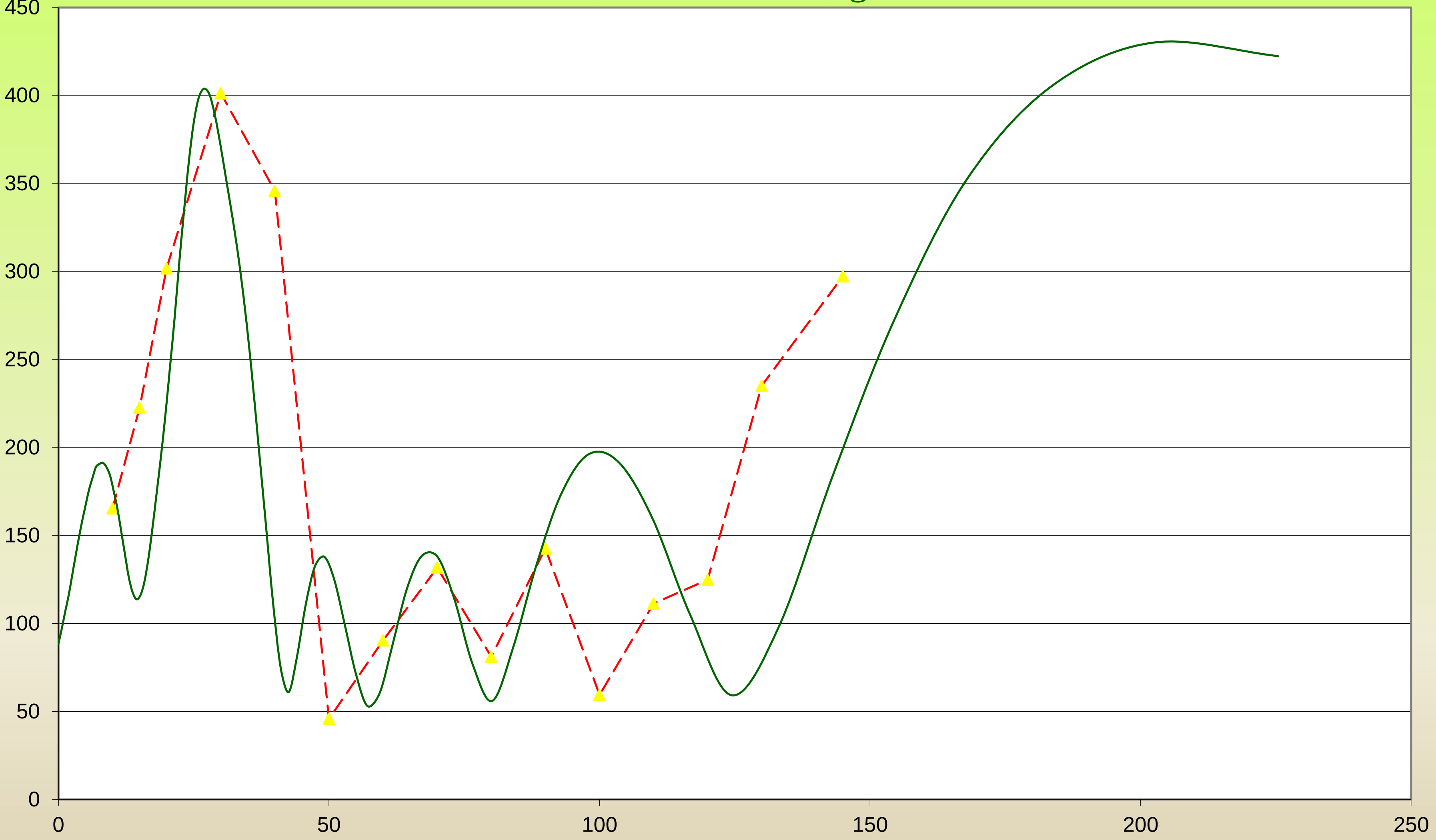


black solid line: cumulative exposure ratio W_t
dotted coloured lines: contribution from each transmission component

calculated by author; see where is max exposure

Field Strength (mV/m) vs. distance (m)

RF = 1875.8 MHz; red- measured, green- calculated



Measured and calculated by ANATEL 2012, Eng . Agostinho Linhares de Souza Filho

RF Hazards limits & their impact on network planning

Excessive exposure limits affect network planning

- Co-location and MIMO increase the safety distance and restrict mast construction near buildings
- Countries (e.g. Switzerland) reduce by 100 (and Salzburg by 9,000) the power density level and restrict the cellular BTS planning and location
- Lower RF exposure limits enforce to decrease the EIRP (in order to reduce the power density and field strength near the station) or to extend the distance of the mast from the public
- Handling low exposure thresholds by additional cellular antennas or RF Spectrum

Mitigation techniques to decrease the radiation level

- Restrict access to areas where the exposure limits are exceeded. Physical barriers, lockout procedures and adequate signs are essential; workers can use protective clothing (ITU-T 2004 K.52:19)
- Increase the antenna height. The distances to all points of investigation are increased and the radiation level is reduced. Moreover, additional attenuation to the radiation is achieved due to the increase of elevation angle and decrease of transmitting antenna sidelobe (ITU-T 2007 K.70:22)
- Increase the antenna gain (mainly by reducing the elevation beam width), and consequently decrease the radiation in the direction accessible to people. The vertical beam width may be used to reduce the radiation level in close proximity to the antenna. Moreover, the same value of the EIRP can be achieved by a low power transmitter feeding high gain antenna or by high power transmitter feeding low gain antenna. As far as the protection against radiation is concerned, a much better choice is to use the low power transmitter feeding the high gain antenna. (ITU-T 2007 K.70:22)
- Minimize exposure to the minimum needed to maintain the quality of the service, as quality criterion. Decrease the transmitter power and consequently decrease linearly the power density in all the observation points. As it reduces the coverage area, it is used only if other methods cannot be applied (2007 K.70:22)

Myths and Realities

- *Myth*: The construction of a site antenna in one's neighborhood should be of RF human exposure concern to people of that neighborhood
- *Reality*: Quite the opposite. As use the handsets is total, the limiting factor in terms of EMF exposure is the transmissions from the handset (uplink). This is the case in view of its physical proximity to the user's body. The handset transmissions are power controlled, such that the handset does not transmit higher power than what is necessary to maintain reliable communications. Closer to the site the handset transmits less power
- *Myth*: The higher the number of site antennas in a given area the higher the EMF exposure
- *Reality*: Not true. In reference to the exposure from the handset see the above; due to the profusion of sites, the handsets are closer to their corresponding base station and emit less. For radiation from the site antenna, the transmission levels are such that they should allow quality of service at the cell boundaries. The power density attenuates as the square of distance in free space and with a higher exponent resulting in higher levels at the inner areas of the cell. The smaller the cells the smaller is that extra exposure levels in the inner parts of the cell
- *Myth*: The larger the dimensions of the cell site and antennas, the higher the exposure
- *Reality*: Not true: Antennas are made big in order to get higher gains of main beams. As a result the field strength (and power density) in the area close to the antenna is reduced; achieved due to the sidelobe in elevation
- *Myth*: An antenna erected on the roof causes maximum exposure inside the building underneath
- *Reality*: Not true. Antenna transmits horizontally (or some small downtilt) such that directly underneath the transmissions are much reduced. Moreover, a concrete roof is a quite strong attenuator of EMF

Technical Thresholds of Human Exposure to RF from Cellular Base Stations and Handsets

Many Thanks
Any Qs?

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