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Ministry of Communications

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מכון טכנולוגי חולון
Holon Institute of Technology

Israel IEEE EMC Chapter

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

Presentation at IEEE/ EMC 2014

Holon Institute of Technology

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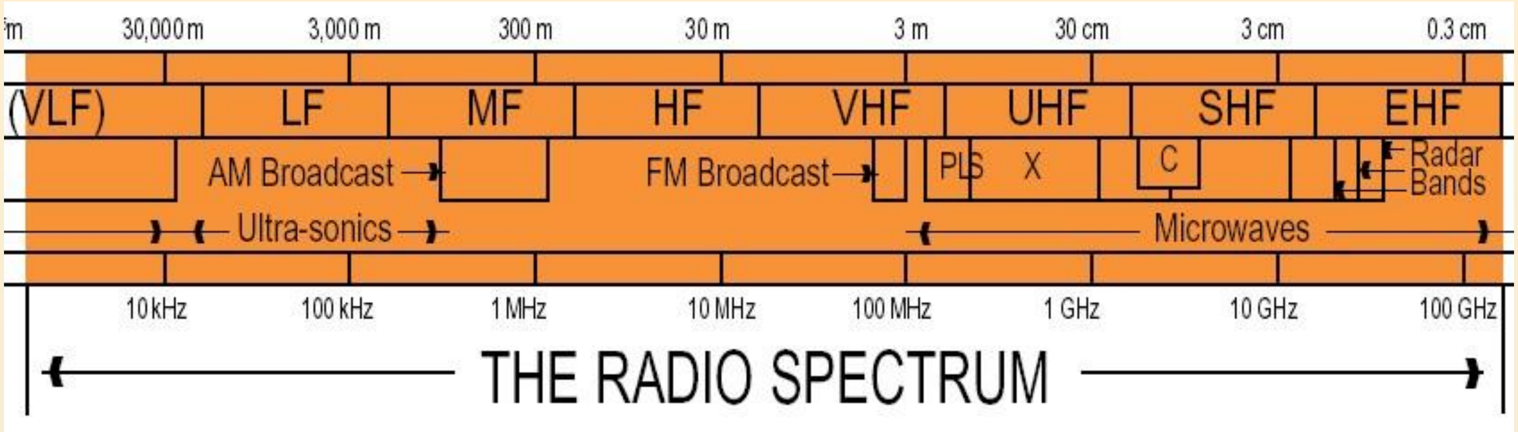
MoC RF Spectrum Management and Licensing

The RF Spectrum: including ITU symbols



Symbols	Frequency range	metric subdivision	Metric abbreviations
VLF	3 to 30 kHz	Myriametric waves	B.Mam
LF	30 to 300 kHz	Kilometric waves	B.km
MF	300 to 3 000 kHz	Hectometric waves	B.hm
HF	3 to 30 MHz	Decametric waves	B.dam
VHF	30 to 300 MHz	Metric waves	B.m
UHF	300 to 3 000 MHz	Decimetric waves	B.dm
SHF	3 to 30 GHz	Centimetric waves	B.cm
EHF	30 to 300 GHz	Millimetric waves	B.mm
	300 to 3 000 GHz	Decimillimetric waves	

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

Electromagnetic Hyper-Sensitivity; electro-phobia

Subjective phobia, phantom risk (?!)

Precautionary Principle: billions of cellular users phones and millions of base-stations worldwide

Type I error imposes regulatory restrictions on factors that turn out to be harmless.

Type II error : acceptance of a null hypothesis that turns out to be false

Source:???

There is no evidence of causality between pains and RF exposure

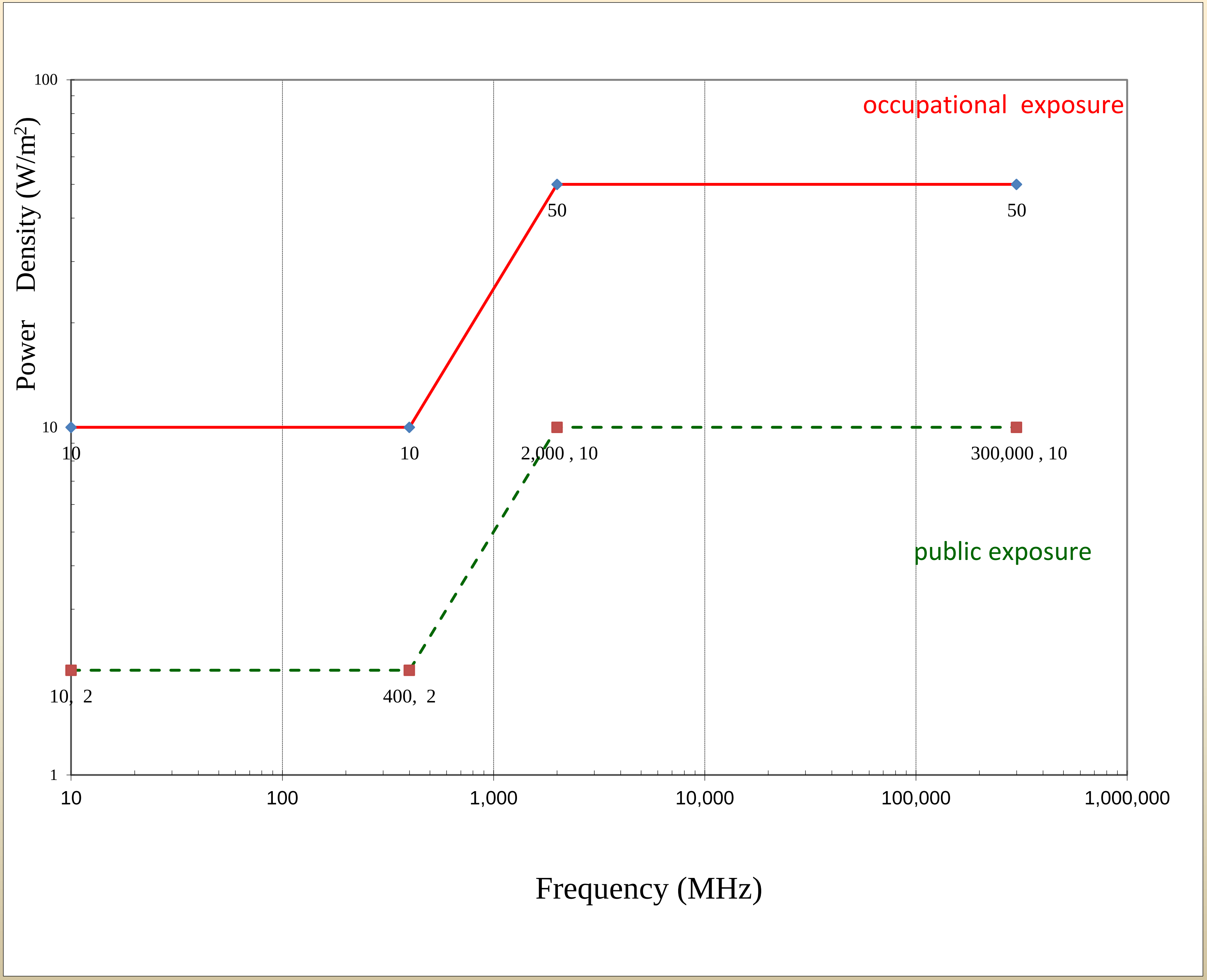
Hillel (ex) Radio Antenna

Although all thresholds were kept, the station was closed

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



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

RF (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; $W/m^2 = 0.1\ mW/cm^2$

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:

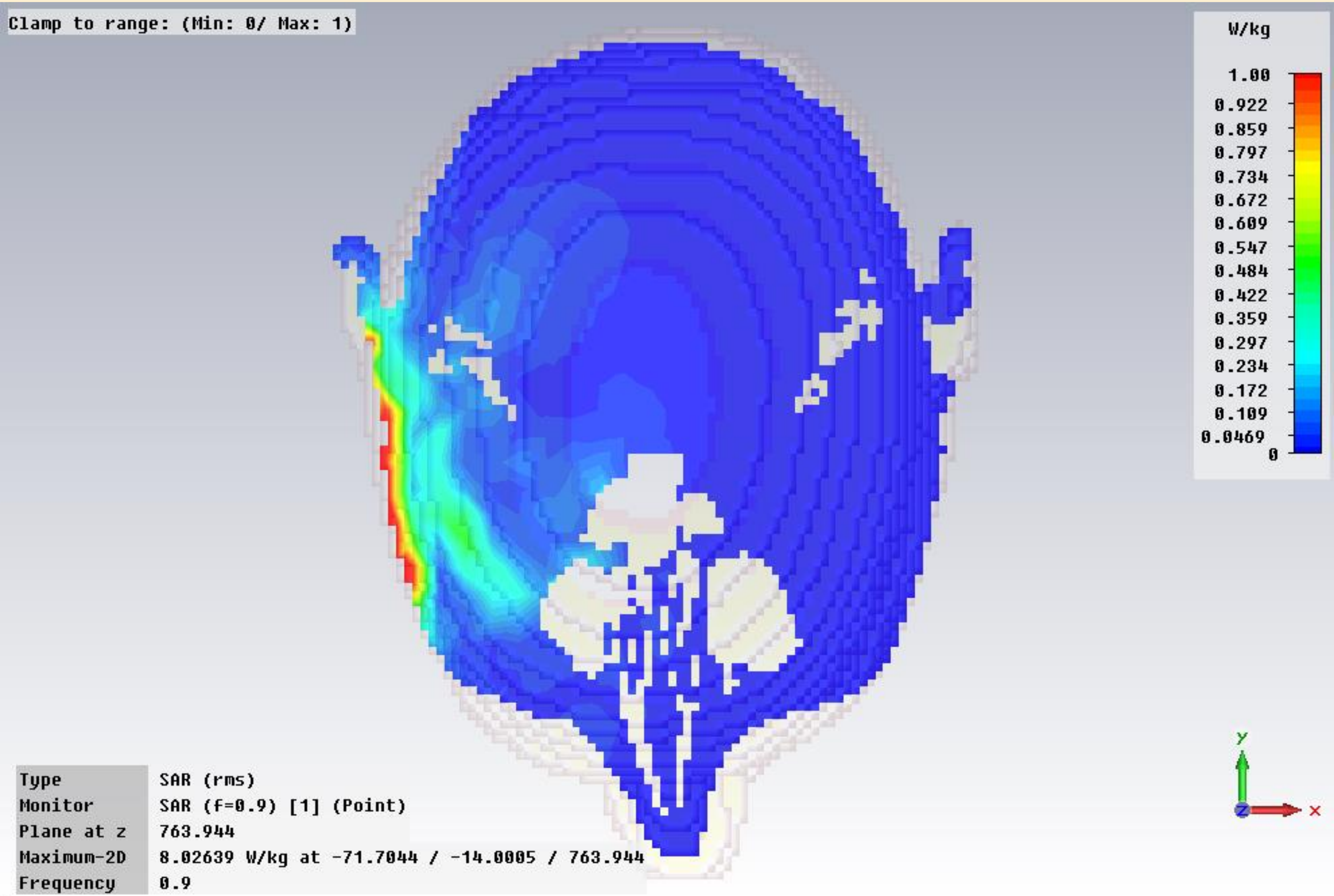
$$\mathrm{SAR} = \frac{\sigma E^2}{\rho} = C_i \frac{dT}{dt} = \frac{J^2}{\sigma\rho}$$

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).

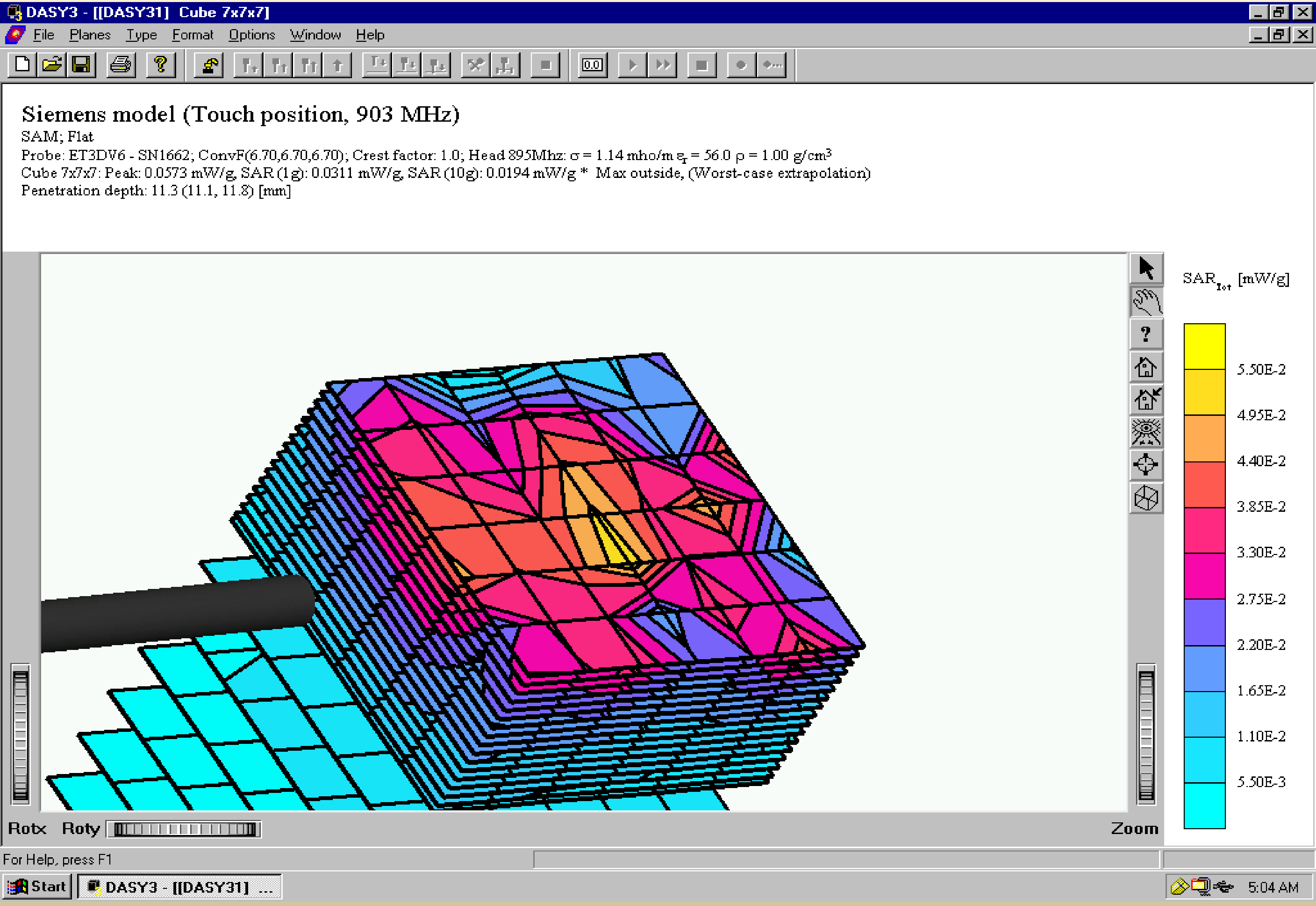
Maximal power from handsets: Specific Absorption Rate, SAR (W/kg)

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)



Far-field free-space propagation loss

$$s = \frac{p_{\mathrm{t}}\,\mathrm{g}_{\mathrm{t}}}{4\pi d^2} = \frac{eirp}{4\pi d^2}; d = \sqrt{\frac{eirp}{4\pi s}}$$

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

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

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

$eirp_i$:	for each emitter	(watts)
$eirp_{eq}$:	equivalent cumulative *eirp*	(watts)
d_i:	safety-distance from each emitter	(m)
d_{eq}:	equivalent cumulative safety-distance	(m)
s_i :	power density from each emitter	(W/m²) index i
s_{li} :	power density limit from each emitter	(W/m²) index i
e_i :	electric field strength from each emitter	(V/m) index i
e_{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}

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

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

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

See table in next slide, and

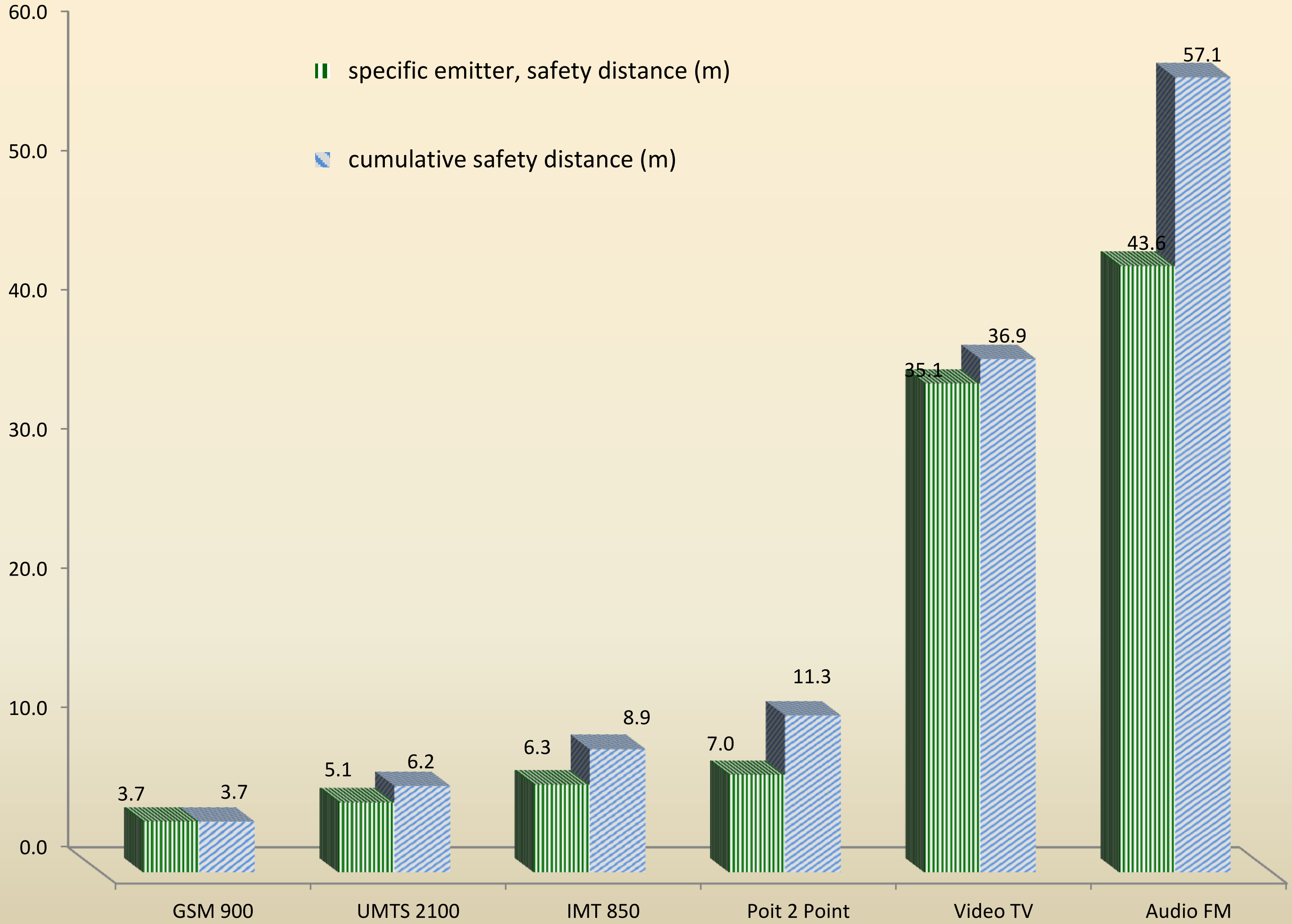
Coefficient Wt vs. distance for co-located site with FM

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/m²)	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)



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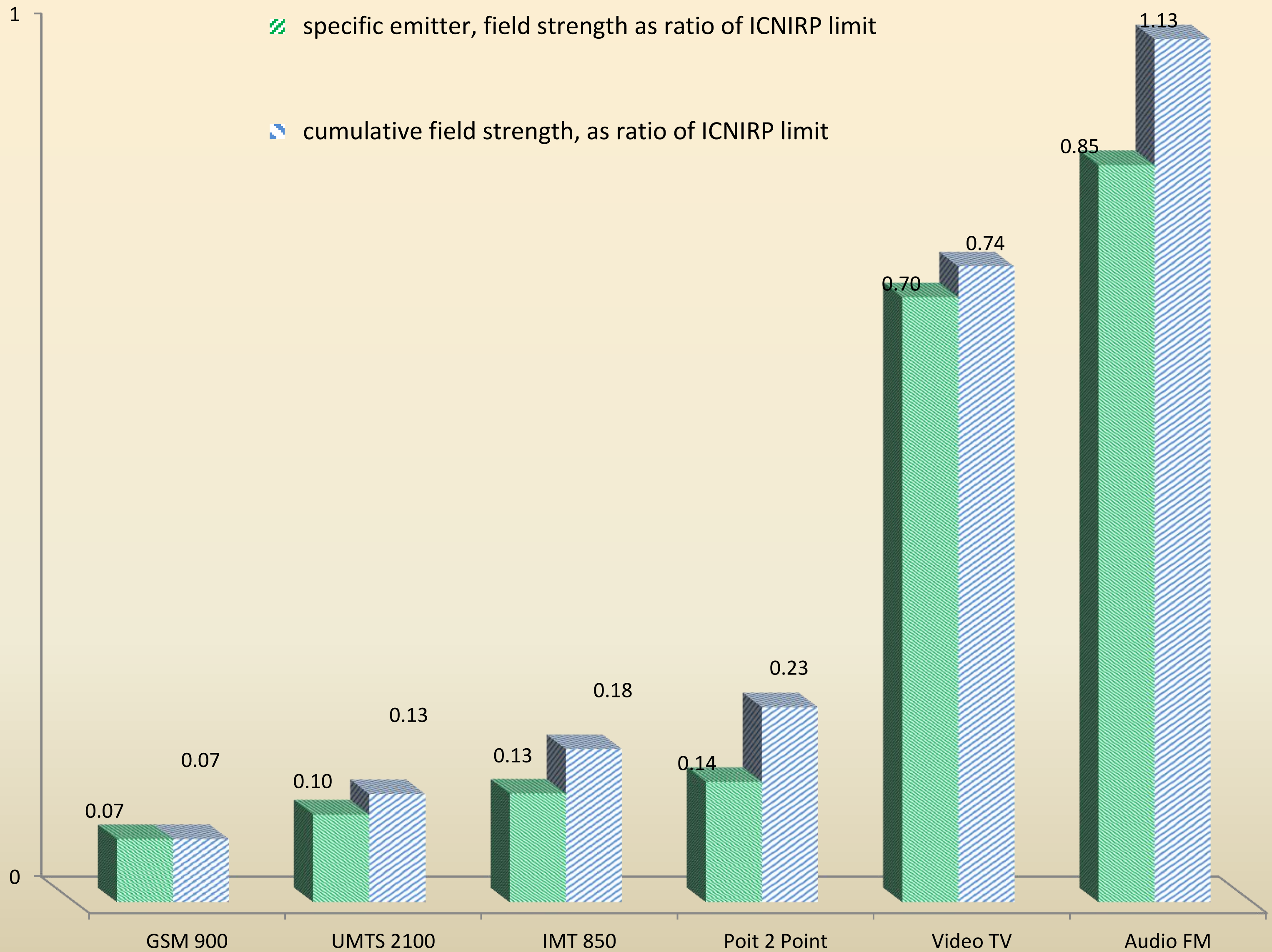
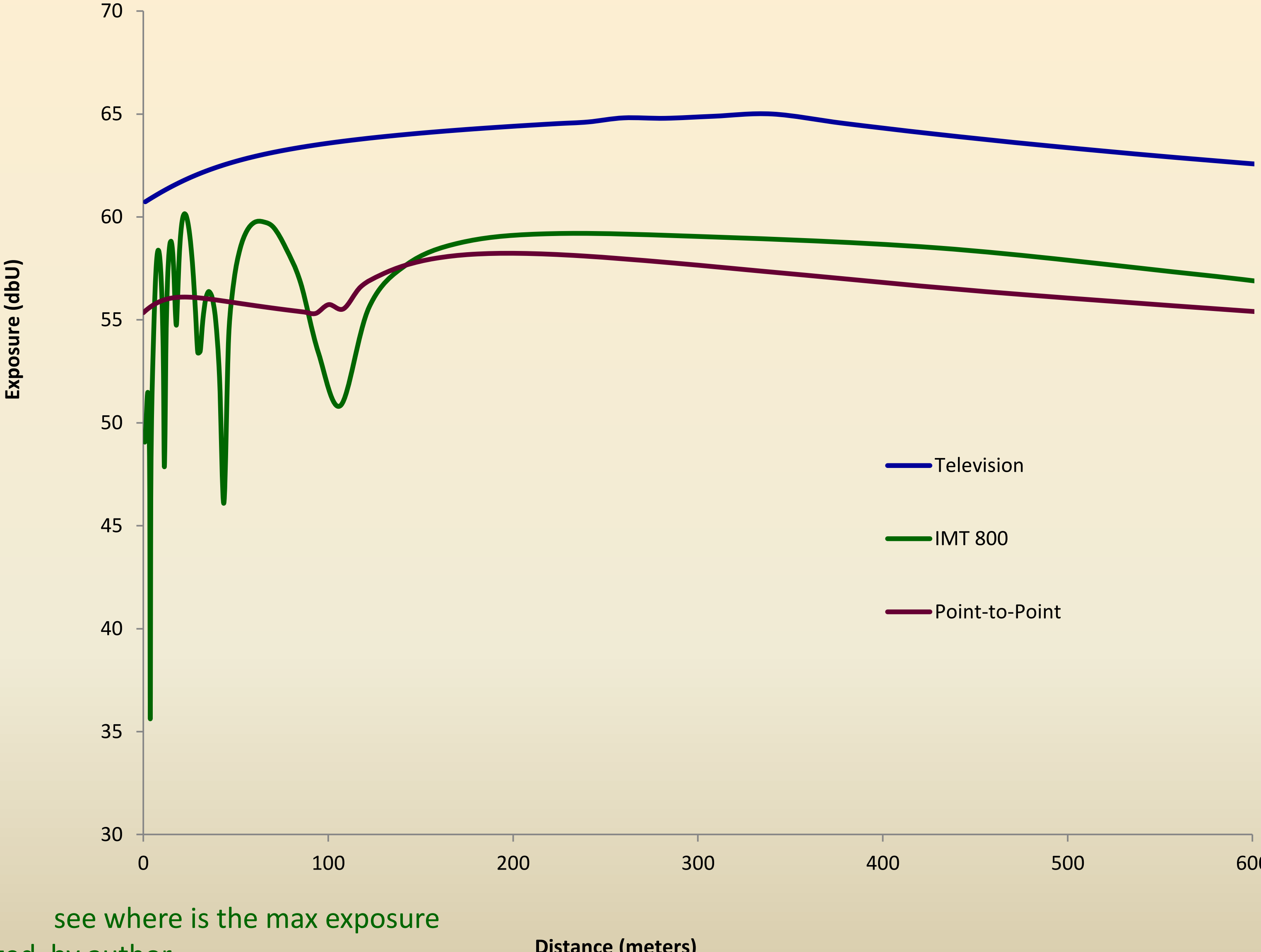
Cumulative field strength exposure ratio , co-located site; point of investigation at 50 meter



calculated by author

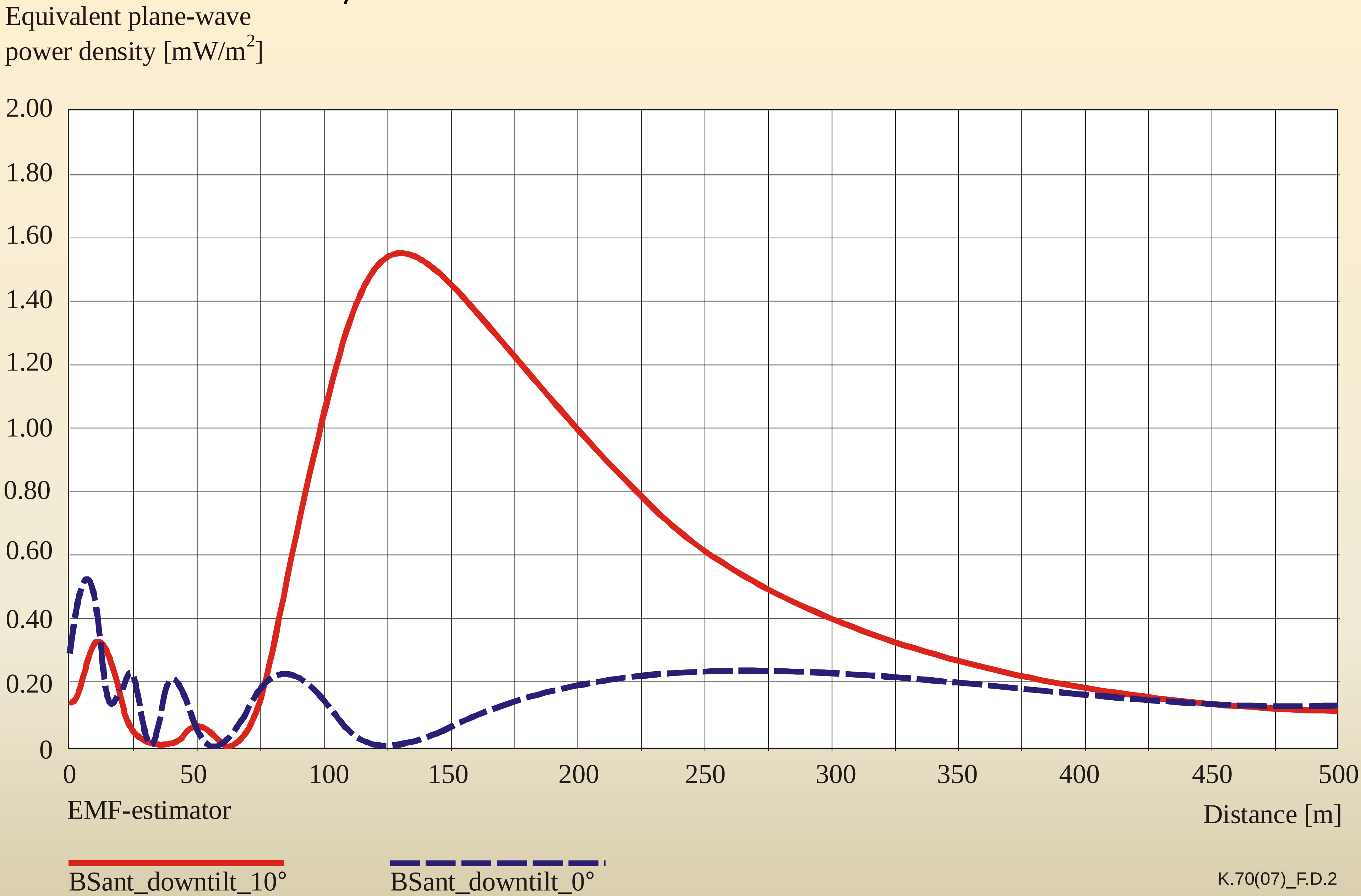
Field Strength (dBµV/m) vs. distance (m), co-located site TV, IMT 850 & Point 2 Point



see where is the max exposure

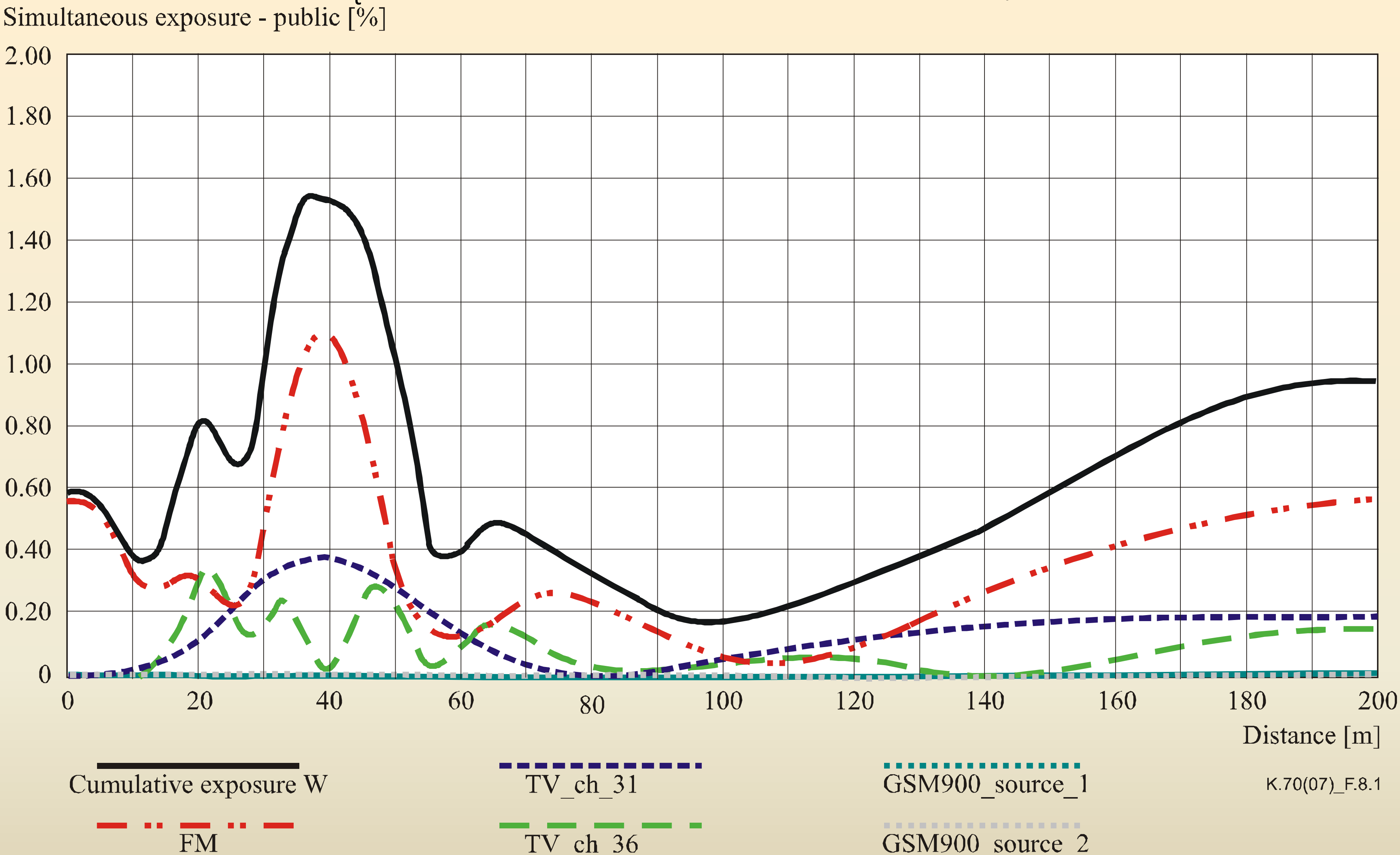
calculated by author

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



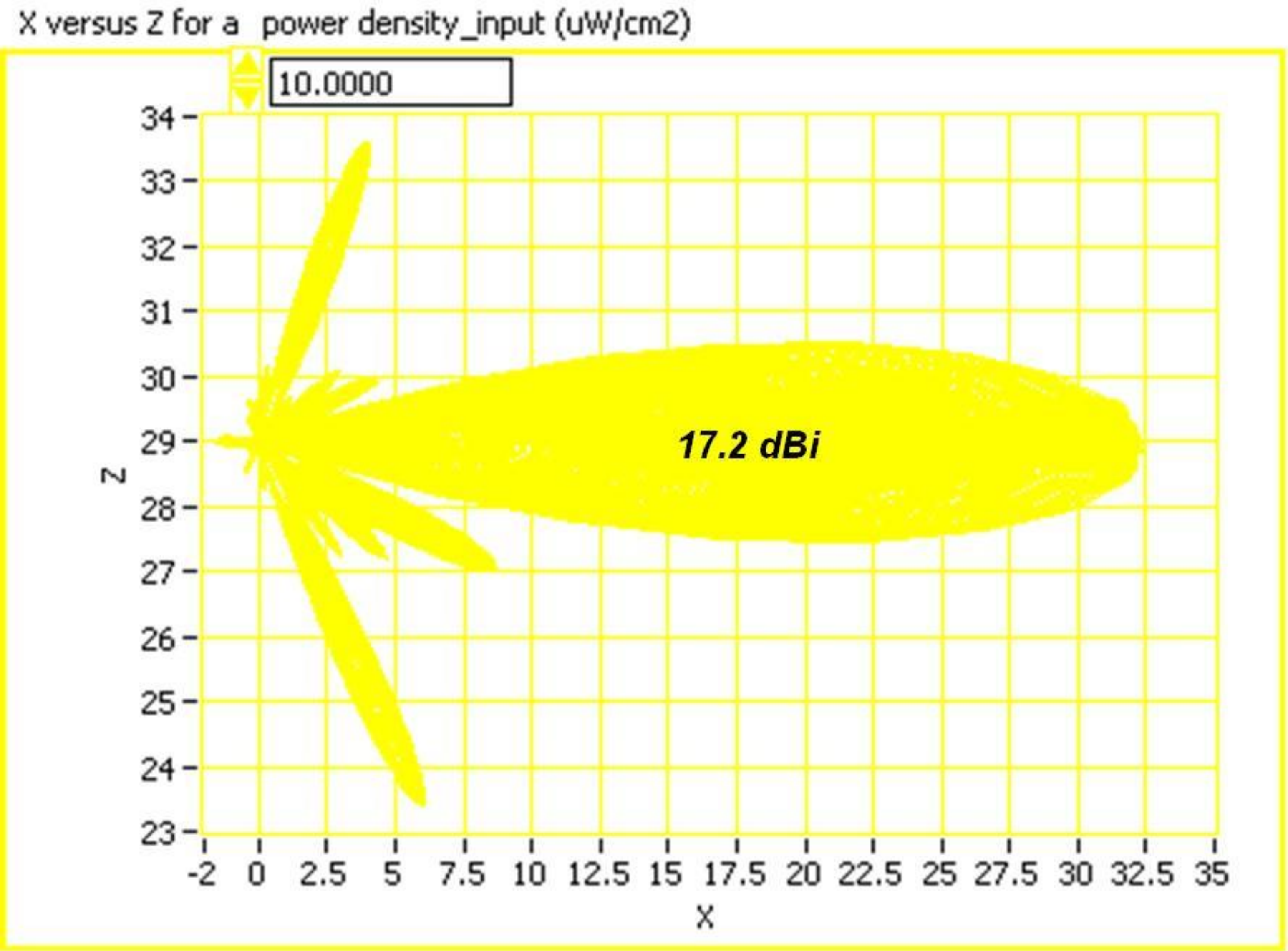
black solid line: cumulative exposure ratio W_t

see where is the max exposure

dotted coloured lines: contribution from each transmission component

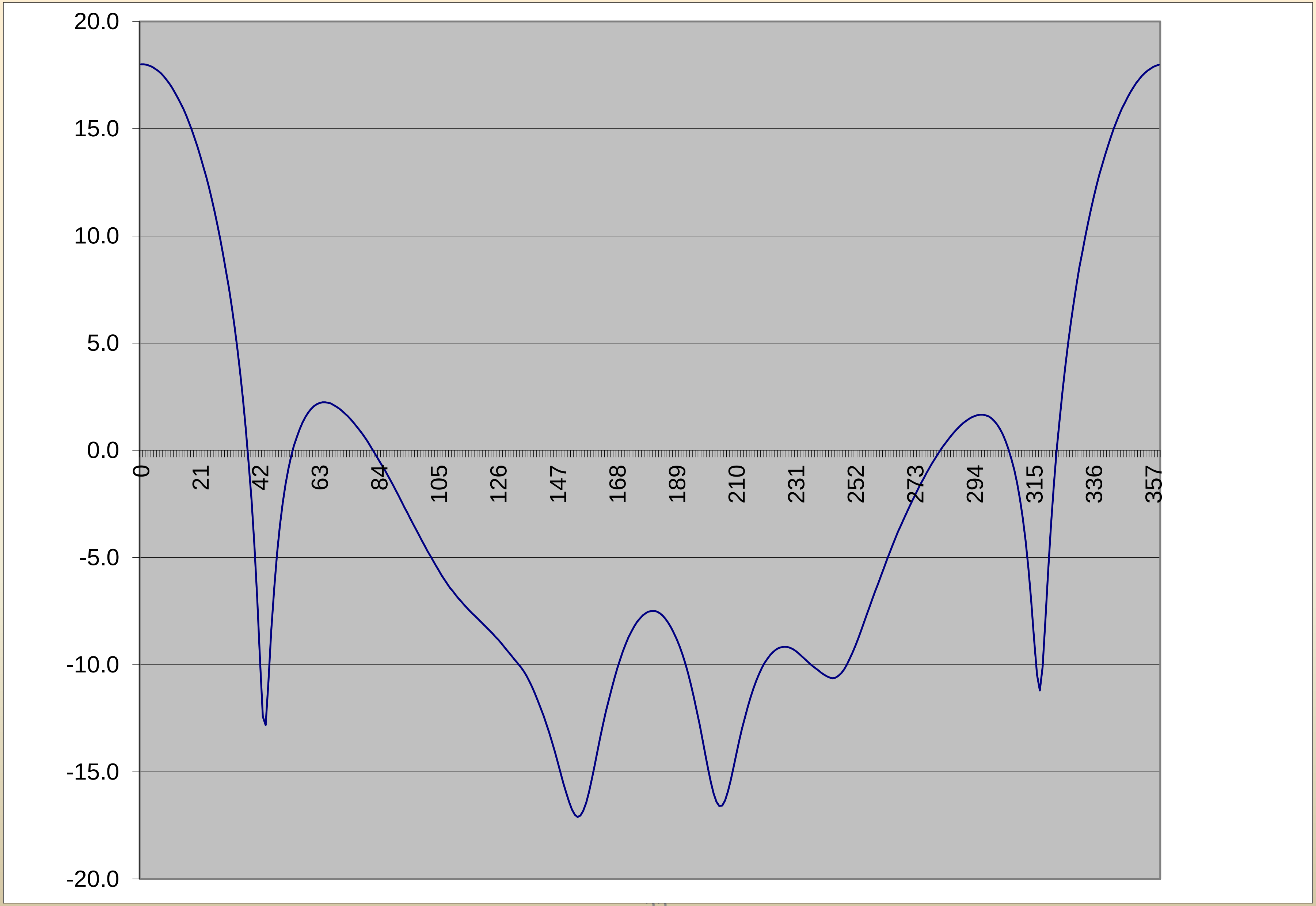
calculated by author

Typical Sectorial Antenna



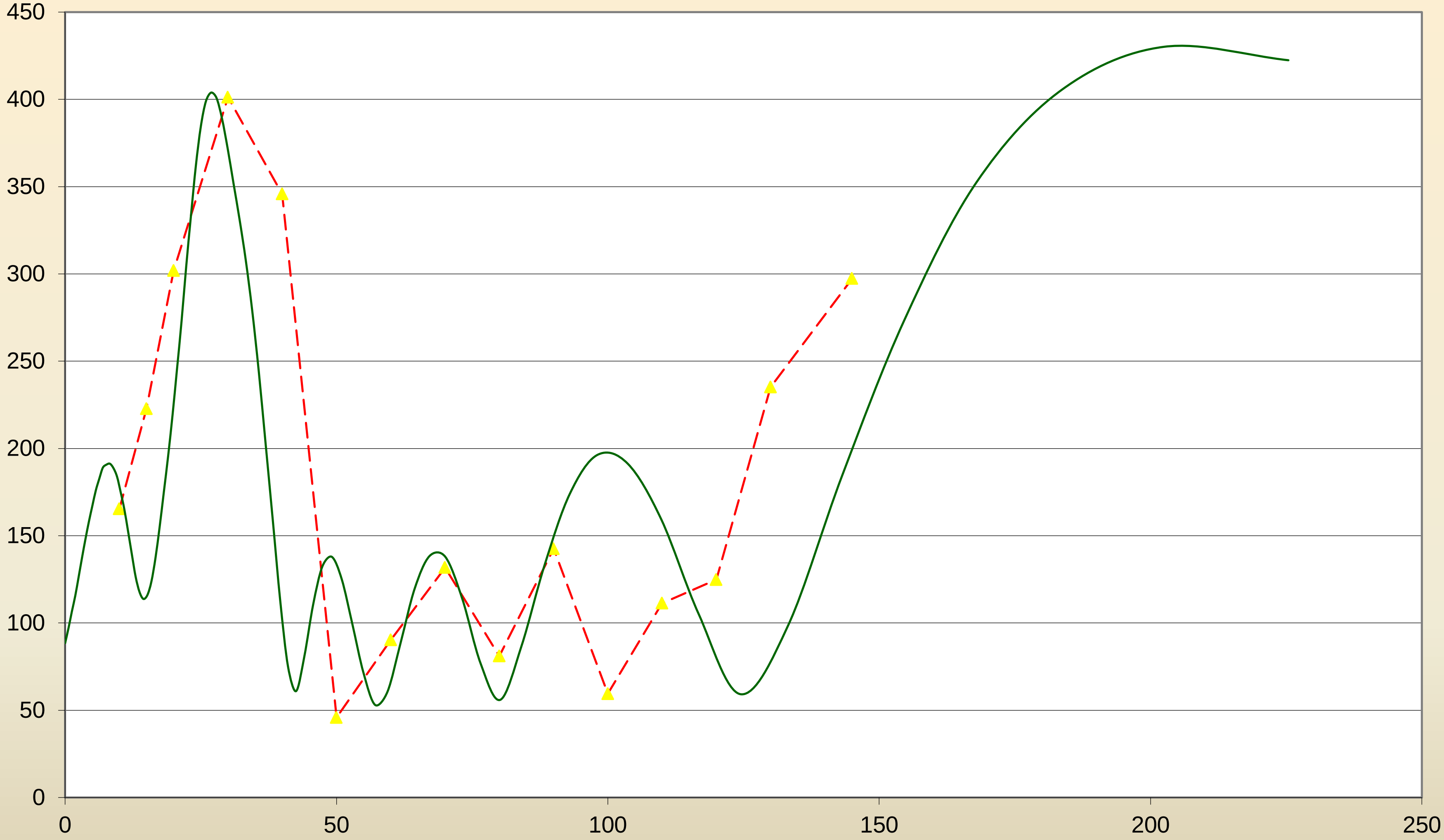
אנטנה מסוג 739686, עבור תדר 850 מגא-הרץ, בשימוש במתקנים רגילים

Vertical pattern of 80010302_0824_X_CO_M45_00T; Anatel



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

Monitoring of human exposure around the world reveals that the levels are very low, relative to ICNIRP reference levels

- 2001 to 2004 (WHO 2007:30), **UK conducted radio surveys at 289 schools** with base stations on or near them. The highest compliance factor measured anywhere was 3.5 x 10^{-3} (= 12.2 x 10^{-6} of the power density), with the 90% of the schools having a highest compliance factor below 2.9 x 10^{-4} (**8.4 x 10^{-8}** power density) – which are very low values indeed.
- See also IARC 2013:58, fig. 1.11 specifies a cumulative distribution of exposure quotients corresponding to 3321 spot measurements made by **OFCOM at 499 sites** where public concern had been expressed about nearby base stations; the quotient values are median 8.1×10^{-6} of ICNIRP power density, ranging from the **5th percentile 3.0×10^{-8} to 95th percentile 2.5×10^{-4}**.
- Two hundred randomly selected people in urban, sub-urban, and rural subgroups have measured on 2005–2006 in **France** (Viel et al. 2009; see also IARC 2013:114) for 24 hours a day, 184 daily measurements. At the GSM 900/1800 bands most of the time, the recorded field strength was below detection level (**0.05 V/m); 0.05 V/m is 3.63%** of the ICNIRP level at 900 MHz. 12.3% of measurements at the FM band indicate field strength above the detection threshold; the mean field strength was 0.17 V/m (Viel et al. 2009:552), the maximum field strength was always lower than 1.5 V/m. ANFR 2007 reveals that at 2004-2007, the average measurements are less than 2% of the field strength limit (less than 0.04 % of power density); more than 75% of the measurements were less than 2% of the field strength limit, regardless of the frequency band considered.

Questions to be raised

Why do we need to make so many measurements?

May be ICNIRP reference levels are too high?

RF Hazards limits & their impact on network planning

- Excessive exposure limits affect network planning
- Co-location and MIMO increase the safety distance & 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 or to extend the distance of the mast from the public
- Handling low exposure thresholds by additional cellular antennas or RF Spectrum; but societal concerns limit the construction

Mitigation techniques to decrease the radiation level

- **Restrict access to areas where the exposure limits are exceeded**: Physical barriers, lockout procedures & adequate signs are essential; workers can use protective clothing (ITU-T 2004 K.52:19)
- **Increase the ant height**: Distances are increased & the radiation level is reduced. Additional attenuation is achieved due to the increase of elevation angle & decrease of transmitting ant sidelobe (ITU-T 2007 K.70:22)
- **Increase the ant gain** (mainly by reducing the elevation beam width), & 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 ant. Same value of EIRP can be achieved by a low power transmitter feeding high gain antenna; (ITU-T 2007 K.70:22)
- Minimize the transmission to the min. needed to maintain the quality of the service, as quality criterion. Decrease the Tx 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)

Low exposure thresholds by additional cellular antennas or RF Spectrum

Operators install additional sites to increase capacity and throughput; how to quantify: more sites more capacity? or the inverse- reduce sites by adding RF to the operat?

For a given network (technology, number of sites, RF spectrum, quality of service), better coverage is achieved by transmitting at higher effective power (for both downlink and uplink channels), installing base stations at higher altitude above ground level (less signal attenuation) and using lower RF.

Max. channel capacity for each communications link in a given network is derived from Shannon Hartley monumental paper (**Shannon 1948:43, theorem 17**), relating c̲apacity (bit/s), RF b̲andwidth (Hz) and the s̲ignal to n̲oise (dimensionless) ratio

$$c = b \times log_2\left(1 + s/n\right)$$

In urban scenario *s/n* is small. LTE RSRQ (Reference Signal Received Quality) quantifies the capacity; UE measures this parameter as reference signal. Values higher than −9dB guarantee the best subscriber experience; the range between −9 and −12dB can be seen as neutral with a slight degradation of Quality of Service. So for *s/n* very small relative to 1, capacity aims to:

$$c = b \times log_2\left(1 + s/n\right) \approx b \times \frac{s/n}{\ln 2} \approx 1.44 \times b \times s/n$$

Therefore, staying with the same *capacity*- less sites (reduced *s*) can be compensated by more frequency *band* (*b*), or active sharing (including RF) by operators.

Additional files are found at:

http://mazar.atwebpages.com/Downloads
http://www.moc.gov.il/138-en/MOC.aspx

Hyperlink to **PhD Thesis**

Hyperlink to the **Book**

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