Advanced Wireless Communications, 2024

Sami Shamoon College of Engineering

המכללה האקדמית להנדסה ע"ש סמי שמעון

Main seminar course reference- Mazar Wiley book 2016 'Radio Spectrum Management: Policies, Regulations, Standards and Techniques' The Book is already published in Chinese

1. RF Engineering identifier DOI 10.13140/RG.2.2.11529.80488

2. Radio Services identifier DOI 10.13140/RG.2.2.35017.90722

3. RF: Regulation, RFI and Human Hazards identifier DOI 10.13140/RG.2.2.29984.74247

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11 June 2024

Not all slides will be presented during the academic course

The man who asks a question is a fool for a minute, the man who does not ask is a fool for life—Confucius
Share your knowledge. It is a way to achieve immortality—Dalai Lama
A good teacher is a teacher whose students surpass him, Janusz Korczak מורה טוב אינו אלא מורה שתלמידיו עולים עליו בגדולתם,יאנוש קורצ'אק

https://mazar.atwebpages.com/Downloads/Academic_Course_Advanced_Wireless_Communications_Mazar1_Engineering_2024.pdf

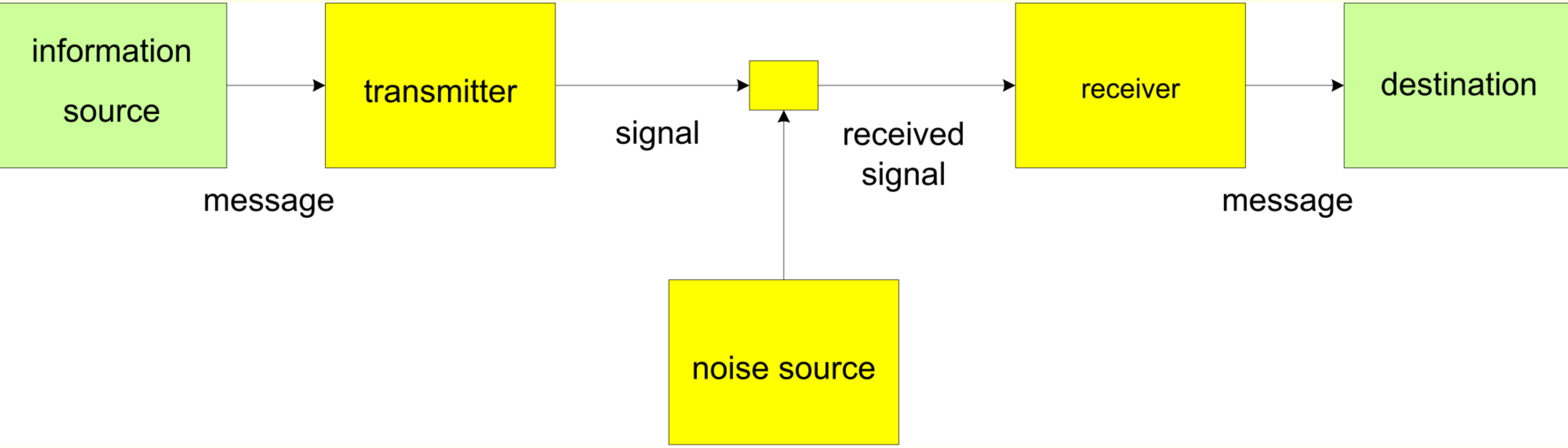
Dr. Haim Mazar (Madjar), ITU & World-Bank expert. At Radio Assembly Nov.2023, elected vice-chair ITU-Radio Study Group 3 (radiowave propagation)

Table of Content: RF Engineering;

The DOI identifier of this 2020 section is 10.13140/RG.2.2.11529.80488

End-to-end wireless communication

Shannon's 1949 (Communication Theory of Secrecy Systems) Schematic diagram of a general communication

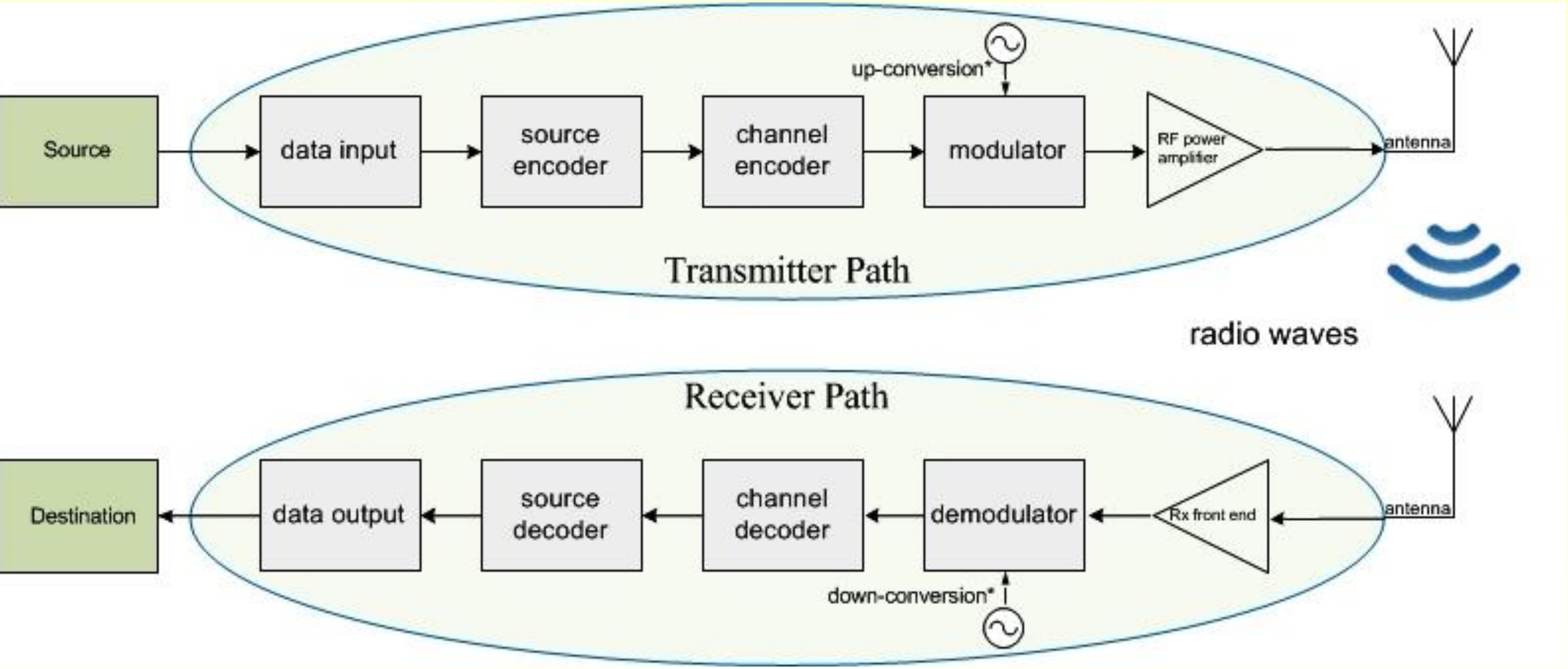


This figure is Figure 1.1 at Mazar's Wiley book on RF regulation

The material in this paper appeared originally in a confidential report "A Mathematical Theory of Cryptography" dated Sept. 1, 1945. Shannon, C. E., "A Mathematical Theory of Communication," Bell System Technical Journal, July 1948, p, 379; Oct. 1948, p. 623Claude Elwood Shannon (April 30, 1916 – February 24, 2001).

Till the invention of the Fax, military technology lead also the civilian market

Schematic diagram of wireless communication



The modulation, and the up-conversion and down-conversion are not always merged; there are many structures where a signal, that is already modulated, is up-converted in a separate (mixer-based) stage.

This diagram is Figure 5.1 at Mazar's Wiley book on RF regulation

Physical Quantities and their Units (1) International System of Units SI

Quantity	Symbol	Unit	Symbol	Remarks
Angle	θ (elevation); φ (azumuth) Ω (solid angle)	radian	rad	1rad≡180/π ^{0}≈57.3^0 Ω unit is steradian
		degrees	^{0}	
(effective) Area	A_e	square metre	(m^2)	
Bandwidth	b	Hertz	Hz	
Boltzmann's constant	K	Joule per Kelvin	J/K	
Capacity	c	bit per second	bit/s	
Carrier to Noise	c/n	dimensionless		interchangeable with s/n and c/n ratio
logarithmic term	C/N, CNR	dB		
Conductivity	σ	Siemens per meter	S/m	
		mho per meter	Ω^{-1}/m	
(antenna) Directivity	d_0	dimensionless		
logarithmic term	D	dBi		
Distance	d	metre	m	
Efficiency (antenna)	η	dimensionless		η (antenna)≡g/d_0
Frequency	f	Hertz	Hz	
Electric field strength	*e*	Volt per metre	V/m	vector; μV/m and dB(μV/m) are practical E=20 log e
logarithmic term	E	dB(V/m)		
(antenna) Gain	g	dimensionless		
logarithmic term	G	dBi		dBd is also used
Impedance, resistance	r	Ohm	Ω	
Impedance (free-space intrinsic)	z_0	Ohm	Ω	≈ 120π

Physical Quantities and their Units (2) International System of Units SI

Quantity	Symbol	Unit	Unit symbol	Remarks
Magnetic field strength		Ampere per metre		vector; μA/m and dB(μA/m) are practical $H = 20 \log h$
logarithmic term	H $\vec{h}$	dB(A/m)		
Noise factor	nf	dimensionless		
logarithmic term	NF	dB		also termed Noise Figure
Phase	φ	Radian	^{0}	
Phase rate	w	radian/second	^{0}/s	w=2πf
Permeability	μ	Henry/meter		at vacuum (free-space) $\mu_0 \equiv 4\pi \times 10^{-7}$
relative Permeability	μ_r	dimensionless		$\mu = \mu_r \mu_0$
Permittivity	ε	Farad/meter		at vacuum (free-space) $\varepsilon_0 \approx 8.854 \times 10^{-12}$
relative Permittivity	ε_r	dimensionless		$\varepsilon = \varepsilon_r \varepsilon_0$
Power	p	Watts	W	kW is practical
logarithmic term	P $\vec{s}$	dBW		dBm is practical
Power density or power flux density		Watt per square metre	W/m²	Poynting vector; term pd also used for power density
		mWatt per square cm	mW/cm²	
Reflection coefficient (Return Loss)	Γ	dimensionless		$\lvert\Gamma\rvert = \rho$; $\rho = \frac{vswr - 1}{vswr + 1}$
logarithmic term		dB		$20 \log \lvert\Gamma\rvert = 20 \log \rho$

Physical Quantities and their Units (3) International System of Units SI

Quantity	Symbol	Unit	Unit Symbol	Remarks
Sensitivity	s	Watts	W	μW, nanoW are used μV used, as power= $\frac{v^2}{r}$
logarithmic term	S	dBW		dBm is more practical
signal to noise	s/n	dimensionless		interchangeable with c/n and signal to noise ratio
logarithmic term	S/N, SNR	dB		
Skin depth	δ	metre	m	
Temperature	t_0	Kelvin	K	
Time	t	second	s	
Velocity of light	c_0	metre / second	m/s	c_0=299 792 458≈ ≈ 300 10^6
Voltage standing wave ratio	vswr	dimensionless		$vswr=\frac{1+\rho}{1-\rho}$ $\lvert\frac{v_r}{vf}\rvert$ =ρ
logarithmic term	VSWR	dB		VSWR=20 log vswr
Wave length	λ	metre	m	
Wavenumber	K	1/metre	1/m	k≡ $\sqrt{\mu\varepsilon}$

Vector presentation of the e^{jx} ; relations between sine, cosine & exponent

exponent $e = (1+1/n)^n$ for n_∞

https://en.wikipedia.org/wiki/Euler%27s_formula

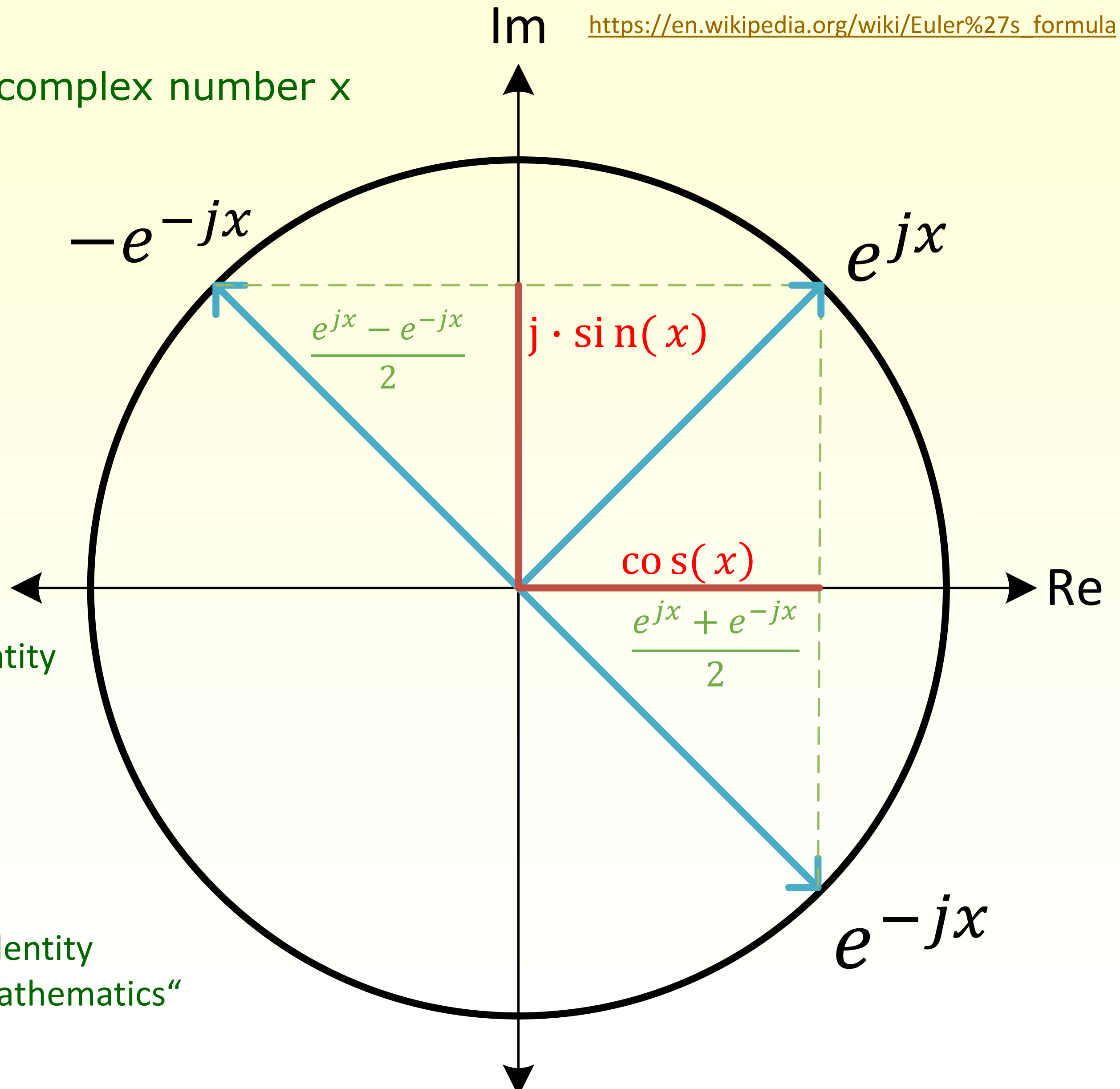
Euler formula, for any real or complex number x

$e^{jx} = \cos(x) + j\sin(x)$

$e^{-jx} = \cos(x) - j\sin(x)$

$$\cos(x) = \frac{e^{jx} + e^{-jx}}{2}$$

$$\sin(x) = \frac{e^{jx} - e^{-jx}}{2j}$$

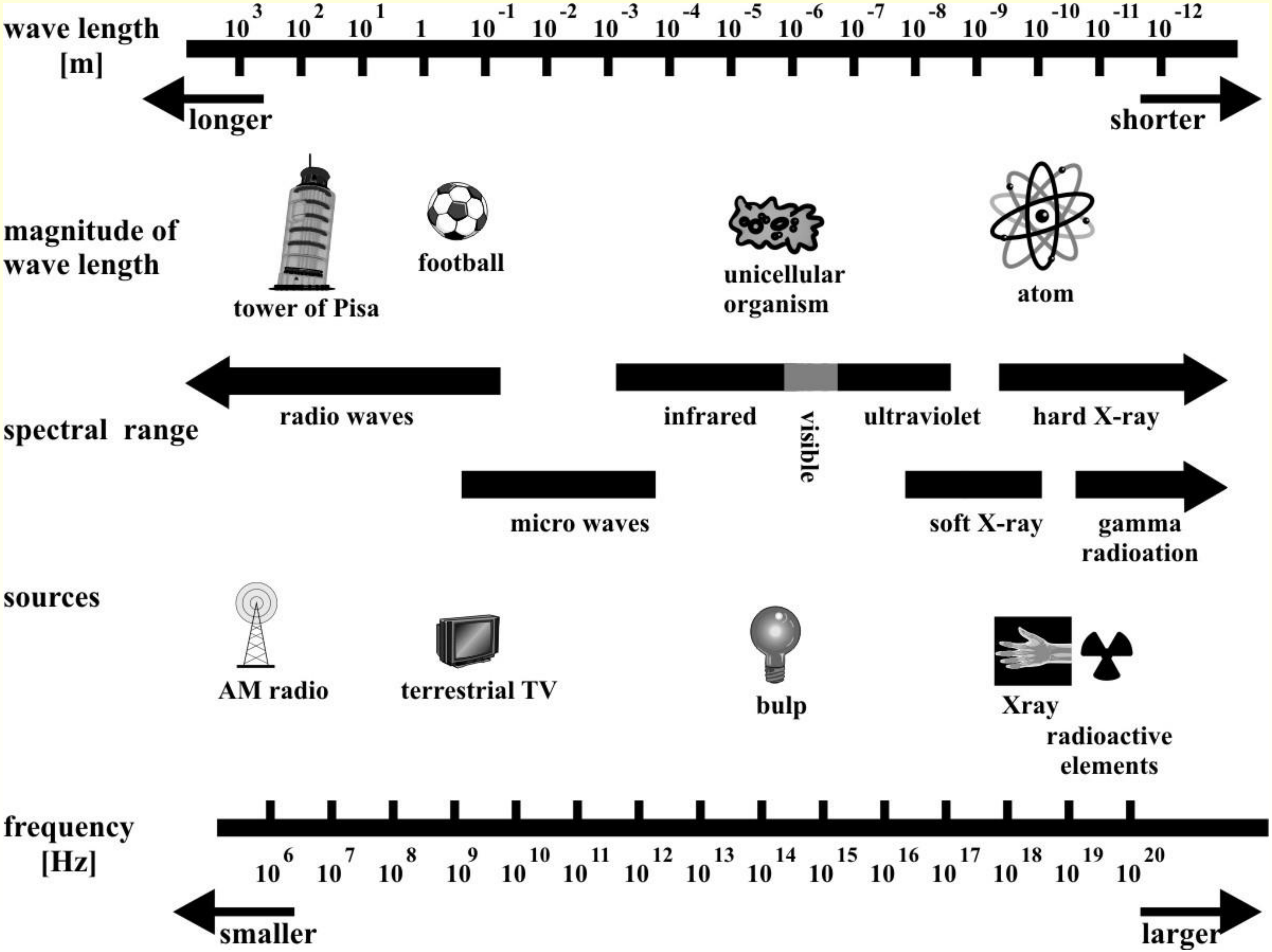


Substituting x = π, we get Euler's identity

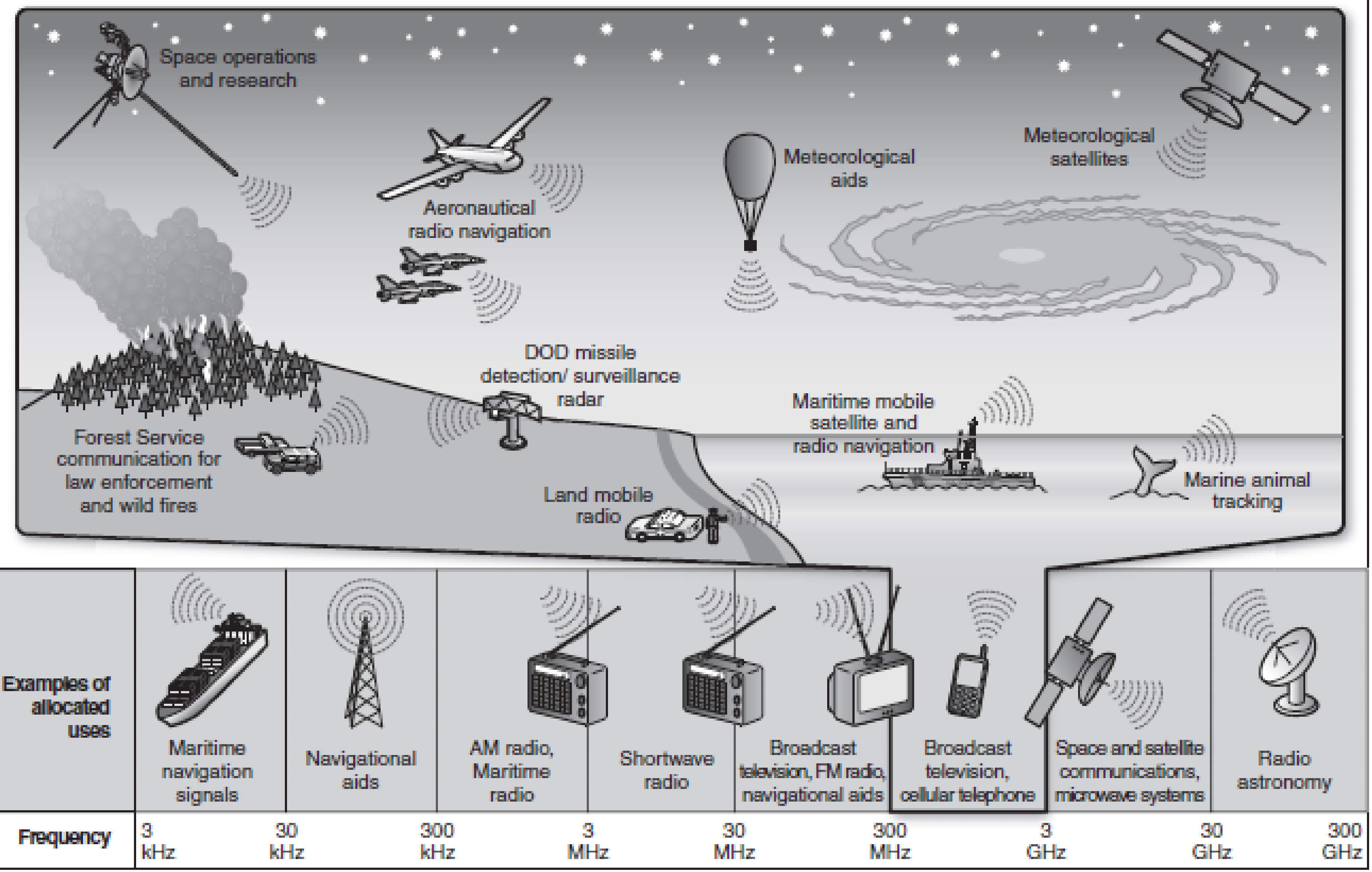
$$e^{j\pi} \equiv -1$$

Richard Feynman called the Euler identity
"the most remarkable formula in mathematics"

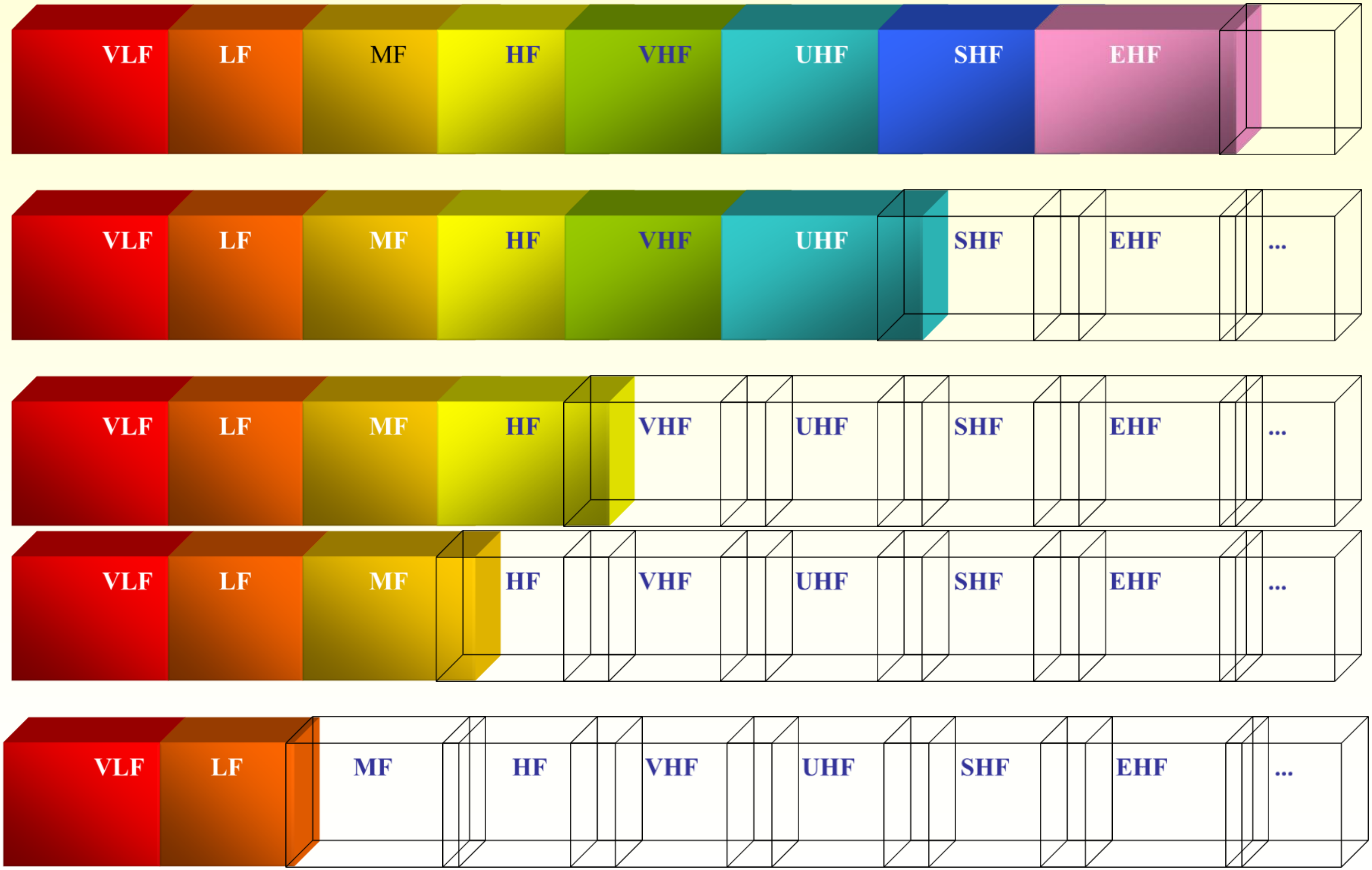
The RF Spectrum



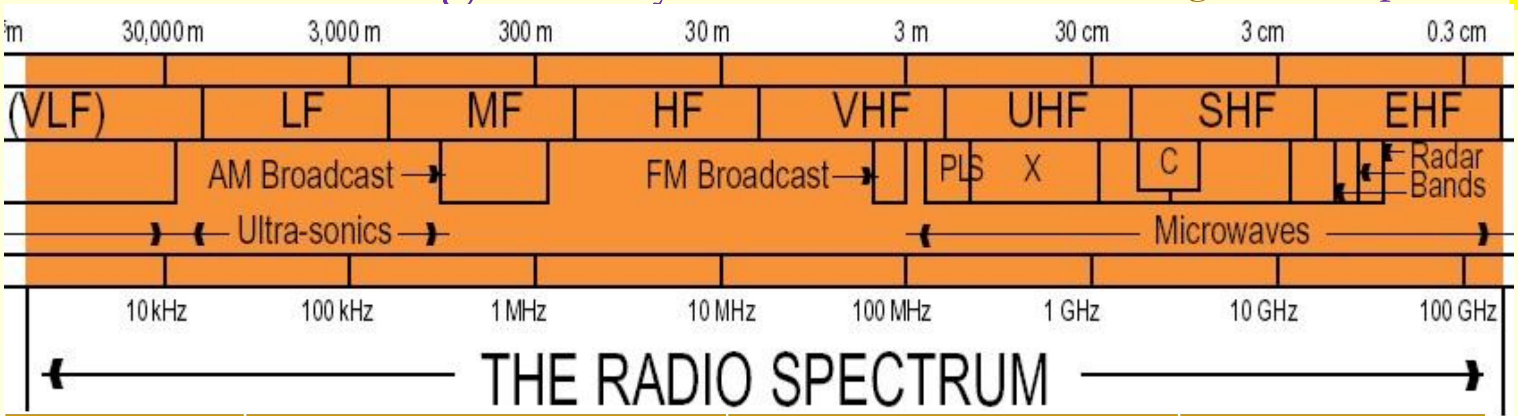
NTIA 2011; Allocated Spectrum Uses



Scarcity of RF increases in time (ITU-D Resolution 9 report, Fig. 1)



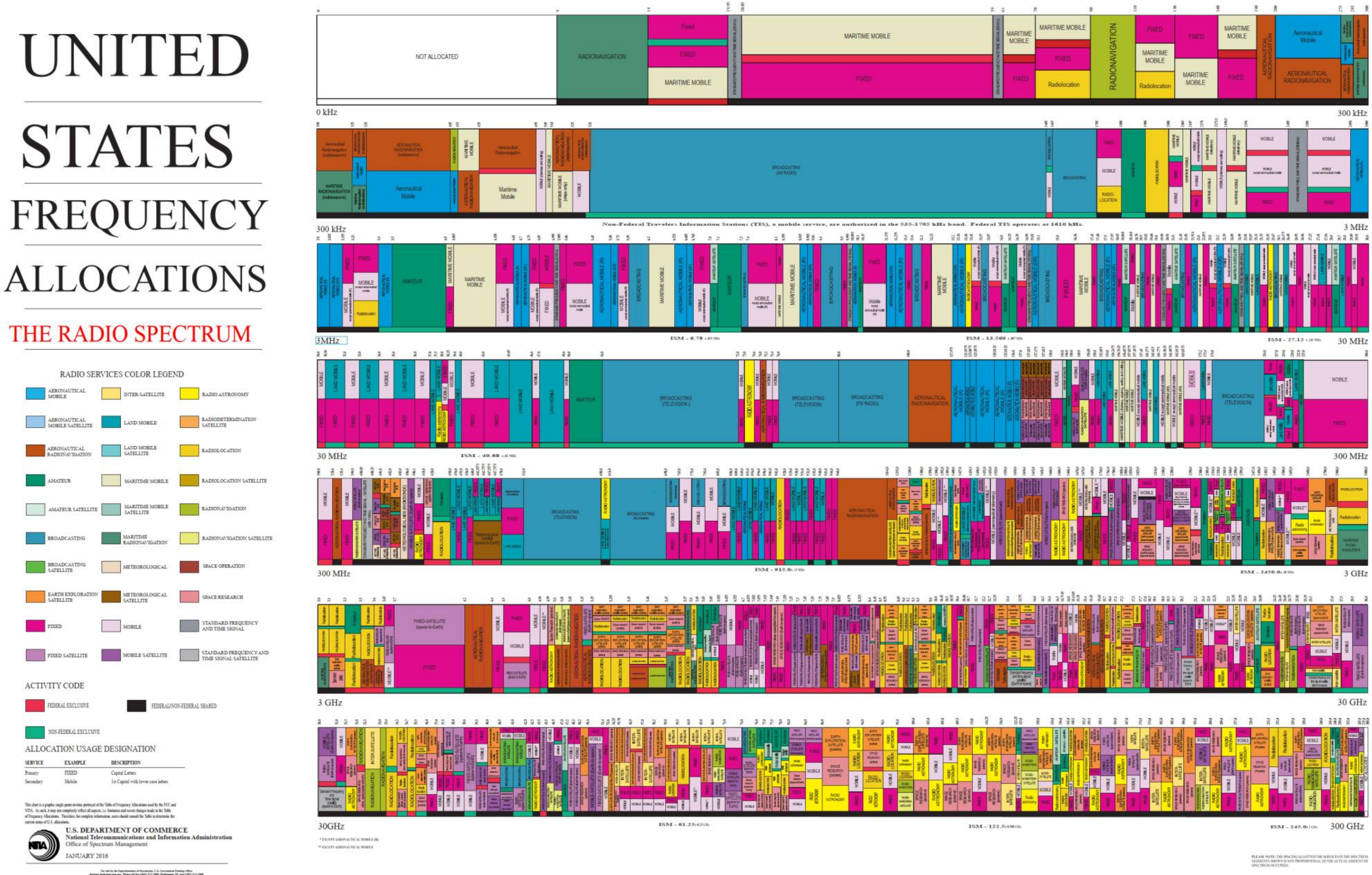
RF Spectrum: including ITU symbols; see ITU Radio Regulations updated 28/03/24



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
THF*	300 to 3 000 GHz	Decimillimetric waves	

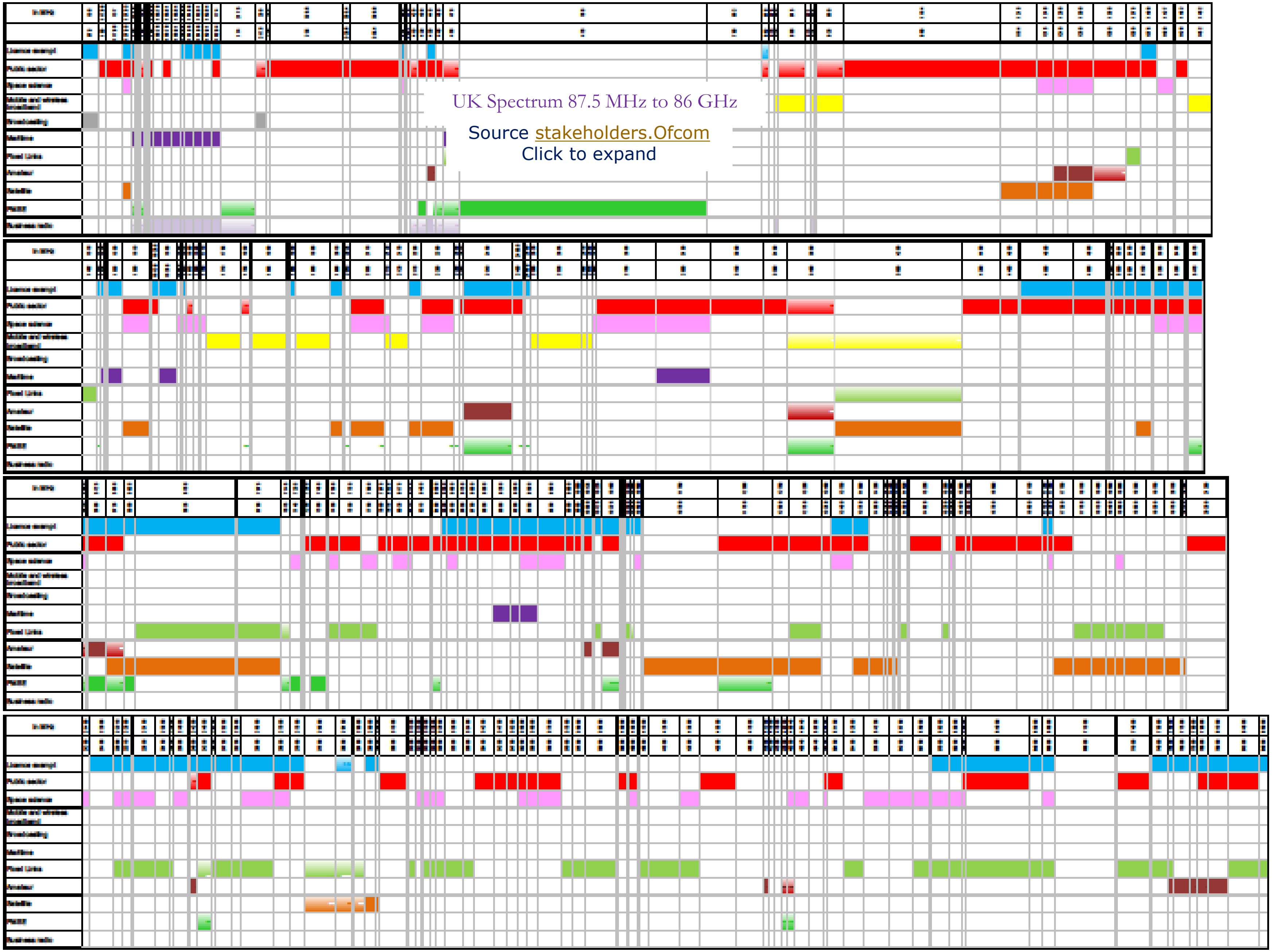
* Symbol THF was proposed by the Author to ITU CCT/CCV Study Groups , to insert in Rec ITU-R V.431-6 'Nomenclature of the frequency and wavelength bands used in telecommunications

US RF Allocations 2016

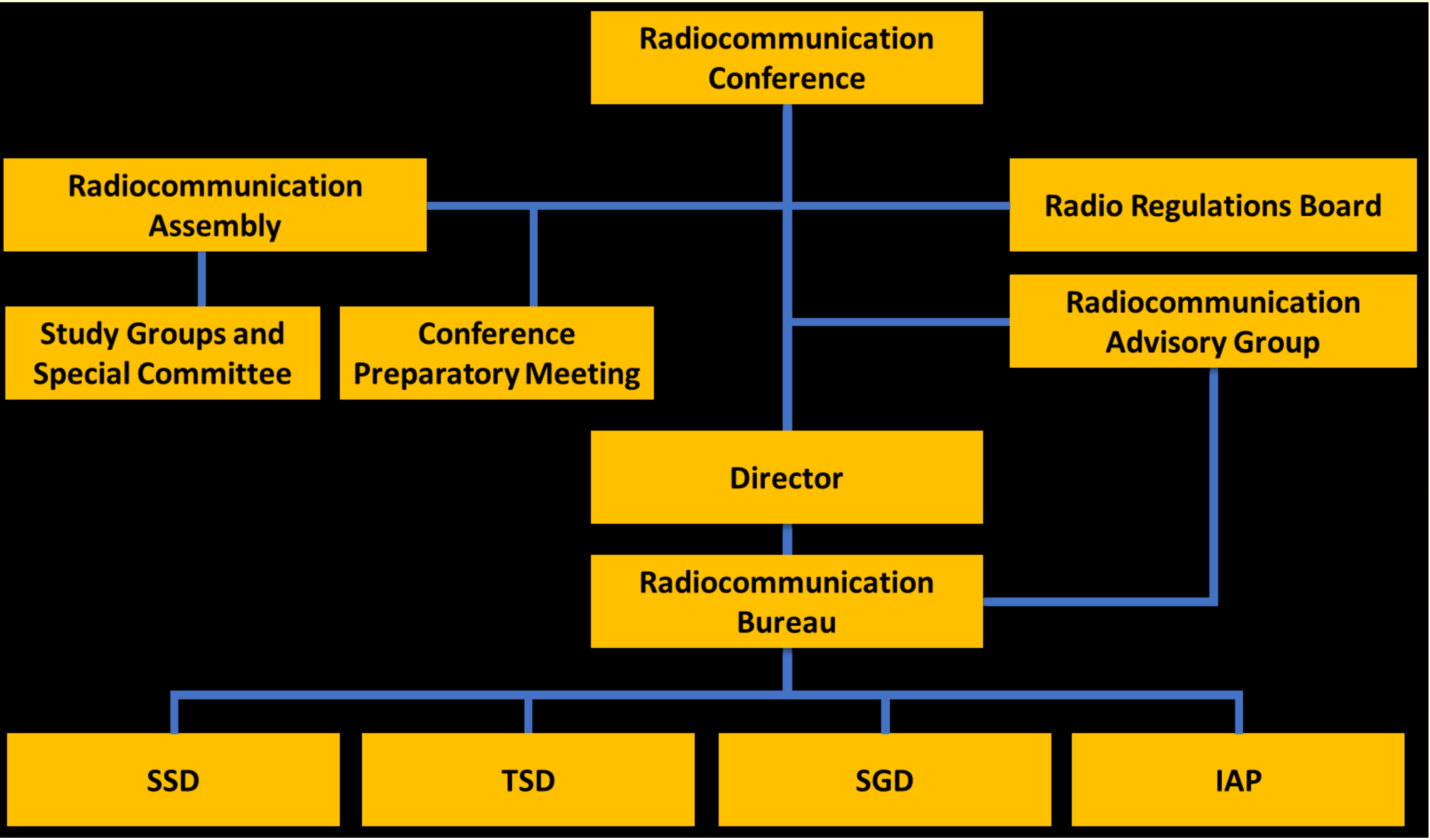


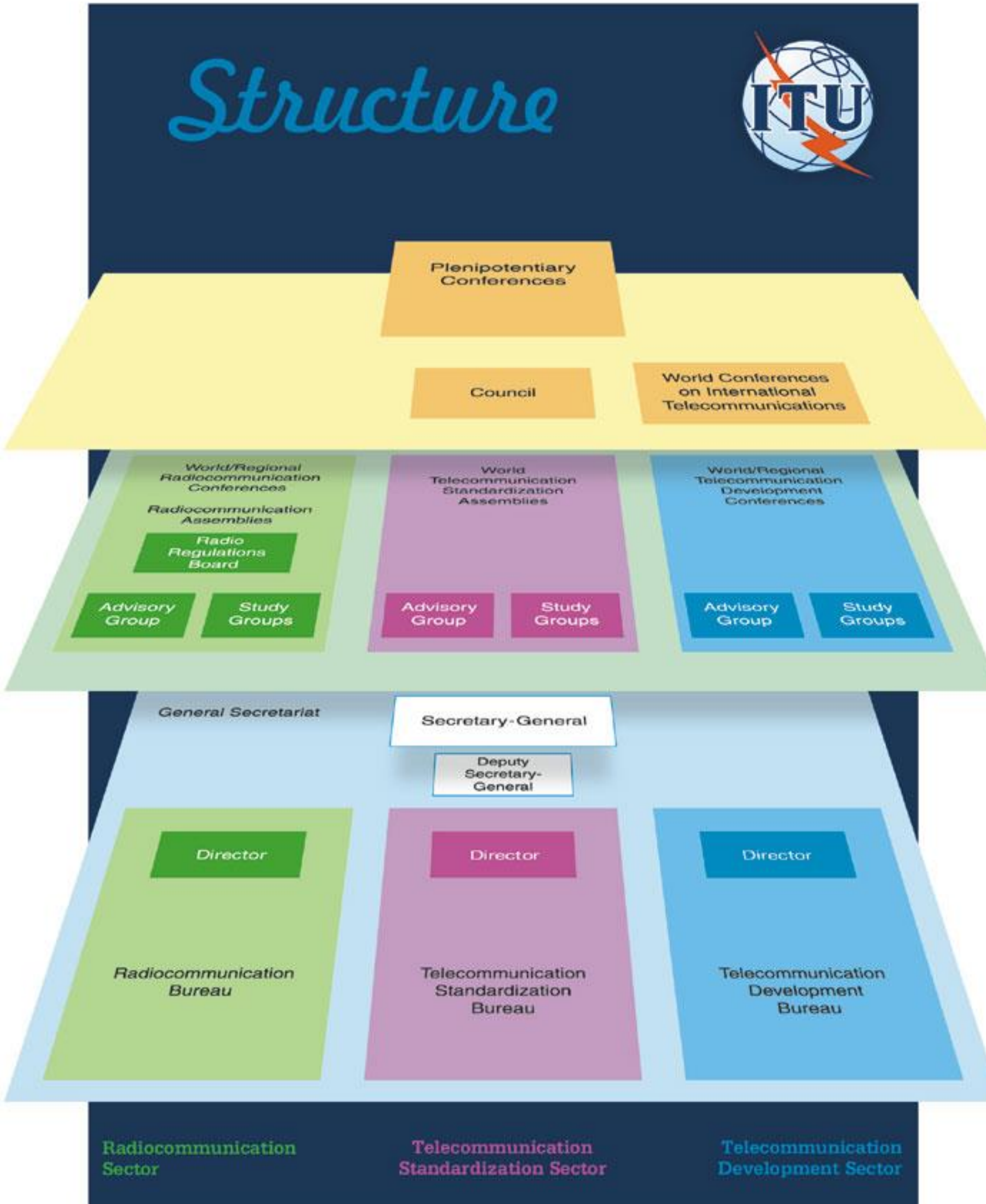
https://www.ntia.doc.gov/files/ntia/publications/january_2016_spectrum_wall_chart.pdf

Spectrum map: 87.5MHz to 86GHz

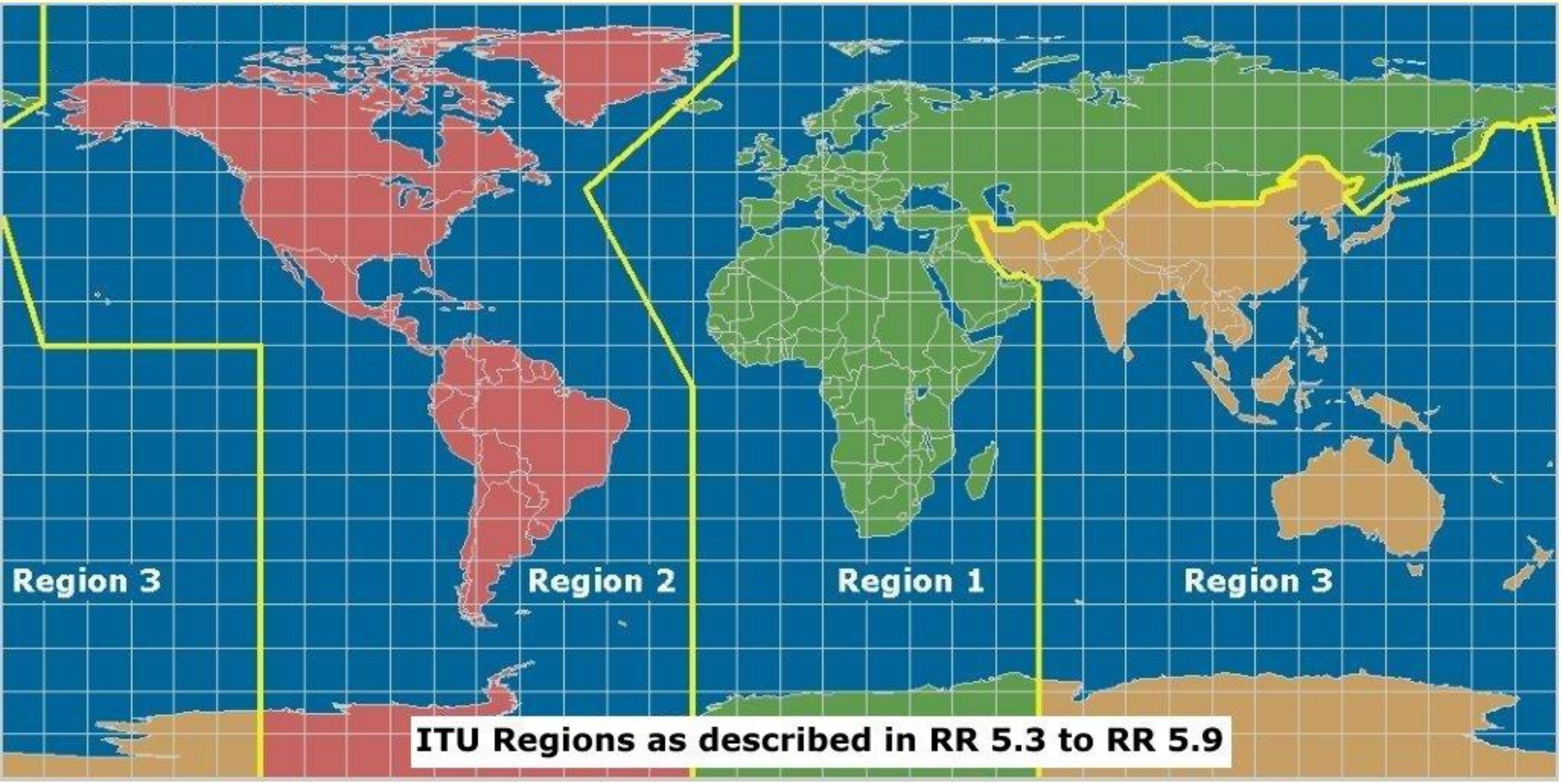


ITU structure




Structure
ITU
Plenipotentiary Conferences
Council
World Conferences on International Telecommunications
World/Regional Radiocommunication Conferences
Radiocommunication Assemblies
Radio Regulations Board
Advisory Group
Study Groups
World Telecommunication Standardization Assemblies
Advisory Group
Study Groups
World/Regional Telecommunication Development Conferences
Advisory Group
Study Groups
General Secretariat
Secretary-General
Deputy Secretary-General
Director
Radiocommunication Bureau
Director
Telecommunication Standardization Bureau
Director
Telecommunication Development Bureau
Radiocommunication Sector
Telecommunication Standardization Sector
Telecommunication Development Sector

Three ITU Regions



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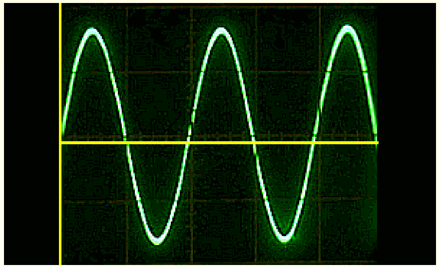


Propagation

http://mazar.atwebpages.com/

Maxwell Equations Wikipedia

Formulation in International System of Units (SI) convention

Name	Integral equations	Differential equations
Gauss's law	$\oint\!\!\!\oint_{\partial\Omega} \mathbf{E}\cdot \mathrm{d}\mathbf{S} = \frac{1}{\varepsilon_0}\iiint_{\Omega}\rho\,\mathrm{d}V$	$\nabla\cdot\mathbf{E} = \frac{\rho}{\varepsilon_0}$
Gauss's law for magnetism	$\oint\!\!\!\oint_{\partial\Omega} \mathbf{B}\cdot \mathrm{d}\mathbf{S} = 0$	$\nabla\cdot\mathbf{B} = 0$
Maxwell–Faraday equation (Faraday's law of induction)	$\oint_{\partial\Sigma} \mathbf{E}\cdot \mathrm{d}\boldsymbol{\ell} = -\frac{\mathrm{d}}{\mathrm{d}t}\iint_{\Sigma}\mathbf{B}\cdot\mathrm{d}\mathbf{S}$	$\nabla\times\mathbf{E} = -\frac{\partial\mathbf{B}}{\partial t}$
Ampère's circuital law (with Maxwell's addition)	$\oint_{\partial\Sigma} \mathbf{B}\cdot \mathrm{d}\boldsymbol{\ell} = \mu_0\left(\iint_{\Sigma}\mathbf{J}\cdot\mathrm{d}\mathbf{S} + \varepsilon_0\frac{\mathrm{d}}{\mathrm{d}t}\iint_{\Sigma}\mathbf{E}\cdot\mathrm{d}\mathbf{S}\right)$	$\nabla\times\mathbf{B} = \mu_0\left(\mathbf{J} + \varepsilon_0\frac{\partial\mathbf{E}}{\partial t}\right)$

Formulation in Gaussian units (SI) convention

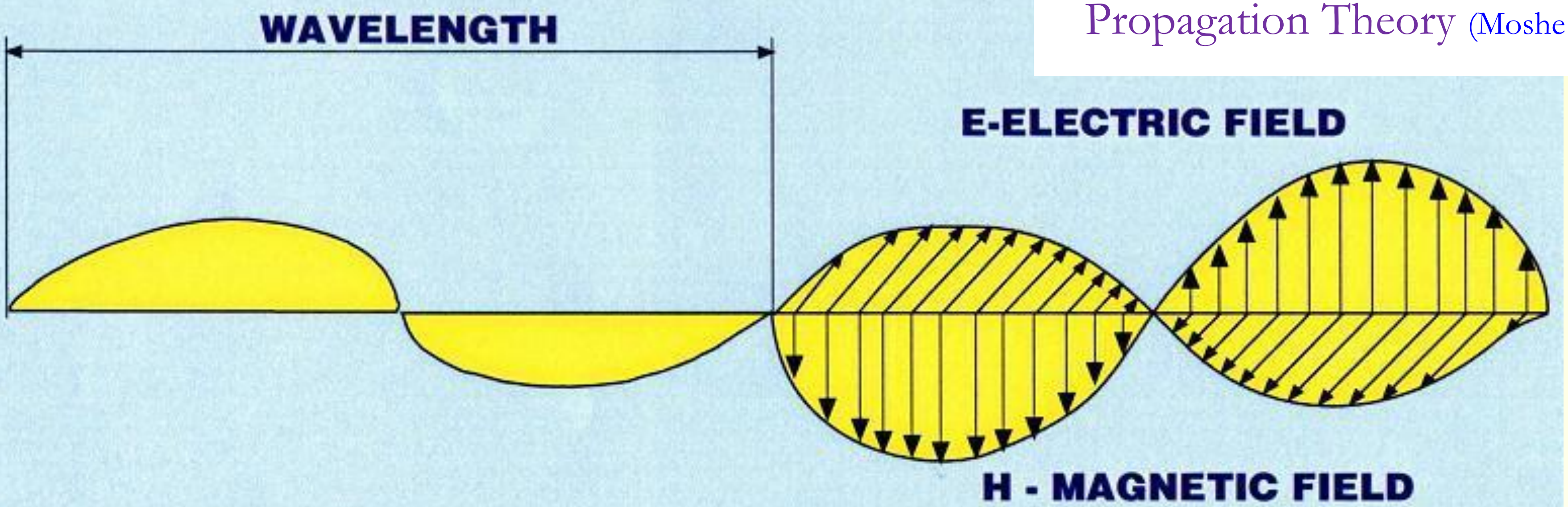
Name	Integral equations	Differential equations
Gauss's law	$\oint\!\!\!\oint_{\partial\Omega} \mathbf{E}\cdot \mathrm{d}\mathbf{S} = 4\pi\iiint_{\Omega}\rho\,\mathrm{d}V$	$\nabla\cdot\mathbf{E} = 4\pi\rho$
Gauss's law for magnetism	$\oint\!\!\!\oint_{\partial\Omega} \mathbf{B}\cdot \mathrm{d}\mathbf{S} = 0$	$\nabla\cdot\mathbf{B} = 0$
Maxwell–Faraday equation (Faraday's law of induction)	$\oint_{\partial\Sigma} \mathbf{E}\cdot \mathrm{d}\boldsymbol{\ell} = -\frac{1}{c}\frac{\mathrm{d}}{\mathrm{d}t}\iint_{\Sigma}\mathbf{B}\cdot\mathrm{d}\mathbf{S}$	$\nabla\times\mathbf{E} = -\frac{1}{c}\frac{\partial\mathbf{B}}{\partial t}$
Ampère's circuital law (with Maxwell's addition)	$\oint_{\partial\Sigma} \mathbf{B}\cdot \mathrm{d}\boldsymbol{\ell} = \frac{1}{c}\left(4\pi\iint_{\Sigma}\mathbf{J}\cdot\mathrm{d}\mathbf{S} + \frac{\mathrm{d}}{\mathrm{d}t}\iint_{\Sigma}\mathbf{E}\cdot\mathrm{d}\mathbf{S}\right)$	$\nabla\times\mathbf{B} = \frac{1}{c}\left(4\pi\mathbf{J} + \frac{\partial\mathbf{E}}{\partial t}\right)$

In the case of electromagnetic-wave , the current density J=0; in materials with permittivity ε_0, & permeability μ_0, the phase velocity of light is c_o . If we equalize the two red arrows, we get

$$c_0 \equiv \frac{1}{\sqrt{\varepsilon_0\mu_0}}$$

$\mu_0 \times \varepsilon_0 = 1/c_0$; click here

EM WAVE PROPERTIES



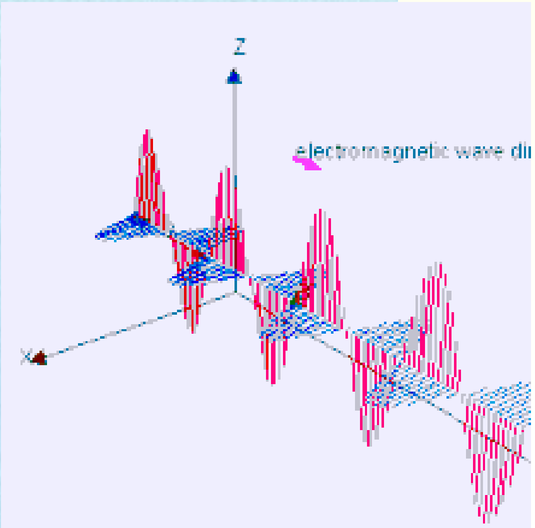
LIGHT VELOCITY = 300,000Km/ sec

ELECTRIC FIELD UNITS - V/m

MAGNETIC FIELD UNITS - A/m

POINTING VECTOR UNITS - W/ m^2 $[\vec{P} = \vec{E} \times \vec{H}]$

$$f = (\text{MHz}) = \frac{300}{\lambda\,(\text{m})}$$



Friis transmission equation & free-space propagation loss: power

Using the international system of units (SI):

p_t = transmitter output power (Watts)
g_t = transmitter antenna gain (dimensionless, with no units)
d = observation distance from transmitter to receiver (m)
p_d = incident power density at the receiver (W/m2)
A_e = effective area of receiver's antenna (m^2)
λ = wave length (m)
g_r = receiver antenna gain (dimensionless)
p_r = received power (Watts)
p_l = propagation loss (dimensionless)

$$p_d = \frac{p_t g_t}{4\pi d^2} \qquad A_e = \frac{g_r \lambda^2}{4\pi}$$

$$p_r = \frac{p_t g_t}{4\pi d^2} \times A_e = \frac{p_t g_t}{4\pi d^2} \times \frac{g_r \lambda^2}{4\pi}$$

Free-space propagation loss- power (cont.)

Friis transmission equation relates the power delivered to the receiver antenna p_r to the input power of the transmitting antenna p_t. Expressing p_r and p_t in the same units, the *Friis transmission equation* expressed numerically looks

$$\frac{p_r}{p_t} = \frac{\frac{p_t g_t}{4\pi d^2} \times \frac{g_r \lambda^2}{4\pi}}{p_t} = g_t \times g_r \left(\frac{\lambda}{4\pi d} \right)^2$$

This equation is valid also for g_t & g_p equal 1

$\left(\frac{4\pi d}{\lambda} \right)^2$ is independent of antenna gains; it is called the *free-space loss factor*. Where *d* (distance) and λ (wave length) are expressed in the same unit

$$p_l = \left(\frac{4\pi d}{\lambda} \right)^2 = \left(\frac{4\pi df}{c_0} \right)^2$$

The free-space path loss expressed logarithmically by wavelength or frequency, where c_o(velocity of light)≡λx*f*

$$P_l(\mathrm{dB}) = 20\ log\left(4\pi d / \lambda\right) = 20\ log\left(4\pi df / c_0\right) = 20\ log\left(4\pi df\right) - 20\ log c_0$$

$$\boxed{P_l(\mathrm{dB}) = 32.45 + 20\ log\ d\ (\mathrm{km}) + 20\ log\ f\ (\mathrm{MHz})}$$

Elements Influencing Propagation Loss (ITU-R P.1812 2019)

1. line-of-sight (need of 3 Fresnel zones to get free space loss; see National Bureau of Standards NBS 101 *
2. diffraction (embracing smooth-Earth, irregular terrain and sub-path cases)
3. tropos-pheric scatter
4. anomalous propagation (ducting and layer reflection/refraction)
5. height-gain variation in clutter
6. location variability
7. building entry losses
8. Earth Radius =6,371 km

* Transmission loss predictions for tropospheric communication circuits. P.L.Rice, A.G. Longley, K.A.Norton, and A.P. Barsis. National Bureau of Standards Technical Note 101; issued May 7 1965; revised May 1966; revised January 1 1967; Volume 1; June 1 1965 Volume 2

Free Space loss, **Electric** Field-Strength

(see also next slides)

p_t= t_x power, g= antenna gain d=distance, p_t x g- *e.i.r.p.* *e*= field strength *h*= magnetic field

$$PoyntingVector = \frac{p_t g_t}{4\pi d^2} = (\vec{e} \times \vec{h}) = \frac{e^2}{z_o}$$

Where *e* (V/m), *h* (A/m), the impedance the impedance Z_0 (Ω) relates the magnitudes of electric and magnetic fields travelling through free space. $Z_0 \equiv |E|/|H|$. From the plane wave solution to Maxwell's equations click here, the impedance of free space equals the product of the vacuum permeability (or magnetic constant) μ_0 and the speed of light c_0 in a free space.
The numerical equivalent isotropically radiated power is *e.i.r.p.* (W) and logarithmic *E.I.R.P.* (dBW)

$$\vec{e} = \frac{\sqrt{30 \times p_t \times g_t}}{d} = \frac{\sqrt{30 \times e.i.r.p.}}{d}$$

$$d = \frac{\sqrt{30 \times e.i.r.p.}}{\vec{e}}$$

Following Maxwell equations; see slide $\quad c_0 \equiv \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$ we may define Z_0

$$z_0 \equiv \mu_0 c_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} = \frac{1}{\varepsilon_0 c_0} \approx 120\pi \approx 376.730\,313\,461 \approx 377\,Ohm$$

$$e.i.r.p. = \frac{e^2 \times d^2}{30}$$

Free Space loss, Magnetic Field-Strength (numerical)

(see next slides)

p_t=t_x power, g= antenna gain d=distance, p_t x g- *e.i.r.p.* e=field strength h=magnetic field

$$PoyntingVector = \frac{p_t g_t}{4\pi d^2} = \frac{e.i.r.p.}{4\pi d^2} = (\vec{e} \times \vec{h}) = \frac{e^2}{z_o} = h^2 \times z_o = h^2 \times 120\pi$$

As the impedance Z_0 (Ω) relates the magnitudes of electric and magnetic fields travelling through free space. $Z_0 \equiv |E|/|H| \approx 120\pi \approx 377$Ohm

$$\frac{e.i.r.p.}{4\pi d^2} = h^2 \times 120\pi$$

$$e.i.r.p. = h^2 \times 120\pi \times 4\pi d^2$$

$$h^2 = \frac{e.i.r.p.}{480\pi^2 d^2}$$

$$|\vec{h}| = \sqrt{\frac{e.i.r.p.}{480\pi^2 d^2}} = \frac{\sqrt{e.i.r.p.}}{\sqrt{480} \times \pi d}$$

or

$$|\vec{h}| = \frac{e}{120\pi} = \frac{\sqrt{30 \times e.i.r.p.}}{120\pi \times d} = \frac{\sqrt{e.i.r.p.}}{\sqrt{480}\pi \times d}$$

and

$$e.i.r.p. = 480\pi^2 \times h^2 \times d^2$$

Free Space loss, electric field-strength (numeric to log scale) (see next slide)

$$|\vec{e}| = \frac{\sqrt{30 \cdot e.i.r.p.}}{d} \quad 20\log|\vec{e}| = E = 10\log 30 + E.I.R.P. - 20\log d = 14.8 + E.I.R.P. - 20\log d$$

E (dBV/m) = *E.I.R.P.* (dB(W) - 20 log *d* (m) +14.8, and changing units,

E (dBμV/m)-120= *E.I.R.P.* (dB(W) - 20 log *d* (km) - 60 + 14.8, thus

***E* (dBμV/m) = *E.I.R.P.* (dB(W) -20 log *d* (km) + 74.8 and**

***E.I.R.P.* (dB(W)= *E* (dBμV/m) +20 log *d* (km) – 74.8**

See, isotropically P_r received power for a given field strength; see Rec. ITU-R P.525 equation (7)

Received isotropically P_r (dB(W) = *E* (dBμV/m) - 20 log *f* (GHz) - 167.2; see P.525 equation (8)

Free-space basic transmission loss for a given isotropically transmitted power and field strength:

Lbf (dB) = P_t (dB(W) - *E* (dBμV/m) + 20 log *f* (GHz) + 167.2; see P.525 equation (9)

Power flux-density for a given field strength: *S*(dB(W/m^2) = *E* (dBμV/m –145.8 P.525 equation (10)

P_t :	isotropically transmitted power	(dB(W))
P_r :	isotropically received power	(dB(W))
E :	electric field strength	(dB(μV/m))
f :	frequency	(GHz)
d :	radio path length	(km)
Lbf :	free-space basic transmission loss	(dB)
S :	power flux-density	(dB(W/m^2))

Free-space *E* relative to half-wave dipole for 1 kW e.r.p. is : *E* dB(μV/m)= 106.9 – 20 log *d* (km)

Free Space loss, magnetic field-strength (numeric to log scale)

$$|\vec{h}| = \frac{e}{120\pi} = \frac{\sqrt{30 \times e.i.r.p.}}{120\pi \times d} = \frac{\sqrt{e.i.r.p.}}{\sqrt{480}\pi \times d}$$

and

$$e.i.r.p. = 480\pi^2 \times h^2 \times d^2$$

H (dBA/m) = *E.I.R.P.* (dB(W) - 20 log *d* (m) - 20 log (sqrt 480 x *π)*=
=*E.I.R.P.* (dB(W) - 20 log *d* (m) – 36.8, and changing units,
H (dBμA/m)-120= *E.I.R.P.* (dB(W) - 20 log *d* (km) - 60 - 36.8, thus
***H* (dBμA/m) = *E.I.R.P.* (dB(W) - 20 log *d* (km) + 23.2** and
***E.I.R.P.* (dB(W) = *H* (dBμA/m) +2 0 log *d* (km) - 23.2**

P_t :	isotropically transmitted power	(dB(W))
P_r :	isotropically received power	(dB(W))
H :	electric field strength	(dB(μA/m))
f :	frequency	(GHz)
d :	radio path length	(km)
Lbf :	free-space basic transmission loss	(dB)

For example: assuming free-space loss, given *H*=68 dBμA/m @ 10 m, P_t dB(W) = *H* (dBμA/m) +20 log *d* (km) – 23.2= 68 (dBμA/m) +20 log 0.01 (km) – 23.2= 68-40-23.2=4.8 dB(W), equivalent to 3 W.

Interesting to compare

E.I.R.P. (dB(W) = *H* (dBμA/m) +2 0 log *d* (km) - **23.2** and
E.I.R.P. (dB(W)= *E* (dBμV/m) +20 log *d* (km) – **74.8**
As h=120πx*e, 20log e/h= 20log(*120π)=51.52 ~ (64.8-23.2)

Radar Free-Space Basic Transmission Loss Equation

σ: radar target cross-section, *d*: distance from the radar to the target, λ: wave length

$$p_{target} = pfd \cdot A_e = \left(\frac{p_t g_t}{4\pi d^2}\right) \times \sigma$$

$$P_{received} = \left(\frac{p_t g_t}{4\pi d^2}\right) \times \sigma \times \left(\frac{1}{4\pi d^2}\right) \times \left(\frac{g_r \lambda^2}{4\pi}\right) = p_{transmit} g^2 \times \sigma \times \left(\frac{\lambda}{4\pi d^2}\right)^2 \frac{1}{4\pi}$$

$$p_{received} = p_{transmit} \times g^2 \times \sigma \times \frac{\lambda^2}{(4\pi)^3 d^4}$$

σ:radar target cross-section (m²); *d*: distance from radar to target (km)
f : transmission frequency (MHz)

$PL = 10\log(p_t/p_r) = 103.4 + 20\log f + 40\log d - 10\log\sigma - 2G$ (dB)

(from web)

Voltage or current ratio	Power ratio	Decibels	Voltage or current ratio	Power ratio
1.00	1.000	0	1.000	1.000
0.989	0.977	0.1	1.012	1.022
0.977	0.955	0.2	1.023	1.047
0.966	0.933	0.3	1.035	1.072
0.955	0.912	0.4	1.047	1.096
0.944	0.891	0.5	1.059	1.122
0.933	0.871	0.6	1.072	1.148
0.912	0.832	0.8	1.096	1.202
0.891	0.794	1.0	1.122	1.259
0.841	0.708	1.5	1.189	1.413
0.794	0.631	2.0	1.259	1.585
0.750	0.562	2.5	1.334	1.778
0.708	0.501	3.0	1.413	1.995
0.668	0.447	3.5	1.496	2.239
0.631	0.398	4.0	1.585	2.512
0.596	0.355	4.5	1.679	2.818
0.562	0.316	5.0	1.778	3.162
0.501	0.251	6.0	1.995	3.981
0.447	0.200	7.0	2.239	5.012
0.398	0.159	8.0	2.512	6.310
0.355	0.126	9.0	2.818	7.943
0.316	0.100	10	3.162	10.00
0.282	0.0794	11	3.55	12.6
0.251	0.0631	12	3.98	15.9
0.224	0.0501	13	4.47	20.0
0.200	0.0398	14	5.01	25.1
0.178	0.316	15	5.62	31.6
0.159	0.0251	16	6.31	39.8
0.126	0.0159	18	7.94	63.1
0.100	0.0100	20	10.00	100.0
3.16×10^{-2}	10^{-3}	30	3.16×10	10^{3}
10^{-2}	10^{-4}	40	10^{2}	10^{4}
3.16×10^{-3}	10^{-5}	50	3.16×10^{2}	10^{5}
10^{-3}	10^{-6}	60	10^{3}	10^{6}
3.16×10^{-4}	10^{-7}	70	3.16×10^{3}	10^{7}
10^{-4}	10^{-8}	80	10^{4}	10^{8}
3.16×10^{-5}	10^{-9}	90	3.16×10^{4}	10^{9}
10^{-5}	10^{-10}	100	10^{5}	10^{10}
3.16×10^{-6}	10^{-11}	110	3.16×10^{5}	10^{11}
10^{-6}	10^{-12}	120	10^{6}	10^{12}

Correspondance e.i.r.p., e.r.p.; field-strength; pfd

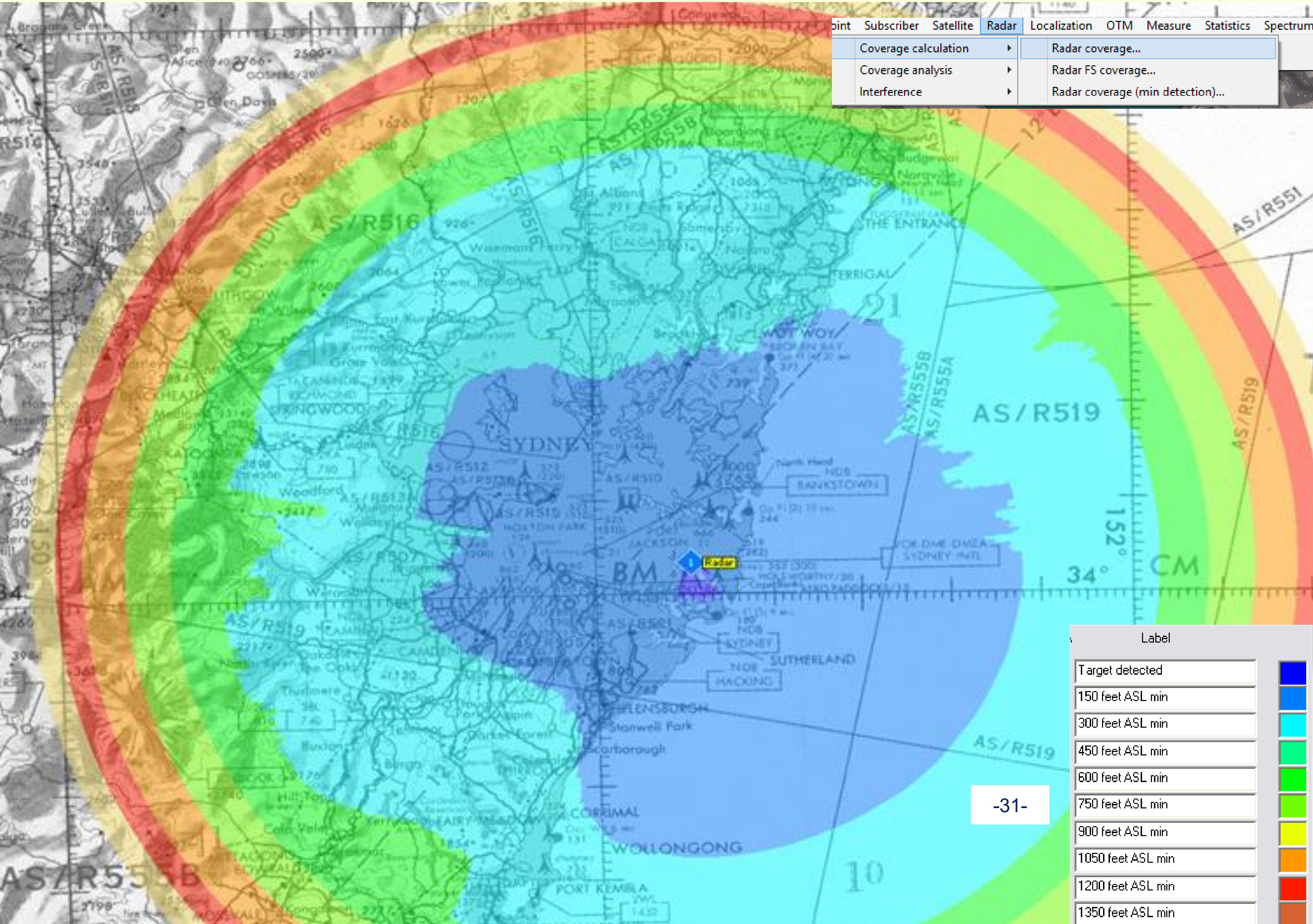
E.I.R.P. (dBm)	**e.i.r.p. (nW)**	**E.I.R.P. (dB(pW))**	**E.I.R.P. (dBW)**	**E.R.P. (dBm)**	***E* field free space (dB(μV/m)) at 10 m**	**E_{max} OATS (dB(μV/m)) at 10 m**	**pfd free space (dB(W/m²)) at 10 m**	**pfd maximum OATS (dB(W/m²)) at 10 m**
–90	0.001	0	–120	–92.15	–5.2	–1.2	–151.0	–147.0
–80	0.01	10	–110	–82.15	4.8	8.8	–141.0	–137.0
–70	0.1	20	–100	–72.15	14.8	18.8	–131.0	–127.0
–60	1	30	–90	–62.15	24.8	28.8	–121.0	–117.0
–50	10	40	–80	–52.15	34.8	38.8	–111.0	–107.0
–40	100	50	–70	–42.15	44.8	48.8	–101.0	–97.0
–30	1 000	60	–60	–32.15	54.8	58.8	–91.0	–87.0
–20	10 000	70	–50	–22.15	64.8	68.8	–81.0	–77.0
–10	100 000	80	–40	–12.15	74.8	78.8	–71.0	–67.0
0	1 000 000	90	–30	–2.15	84.8	88.8	–61.0	–57.0

(Table from web)

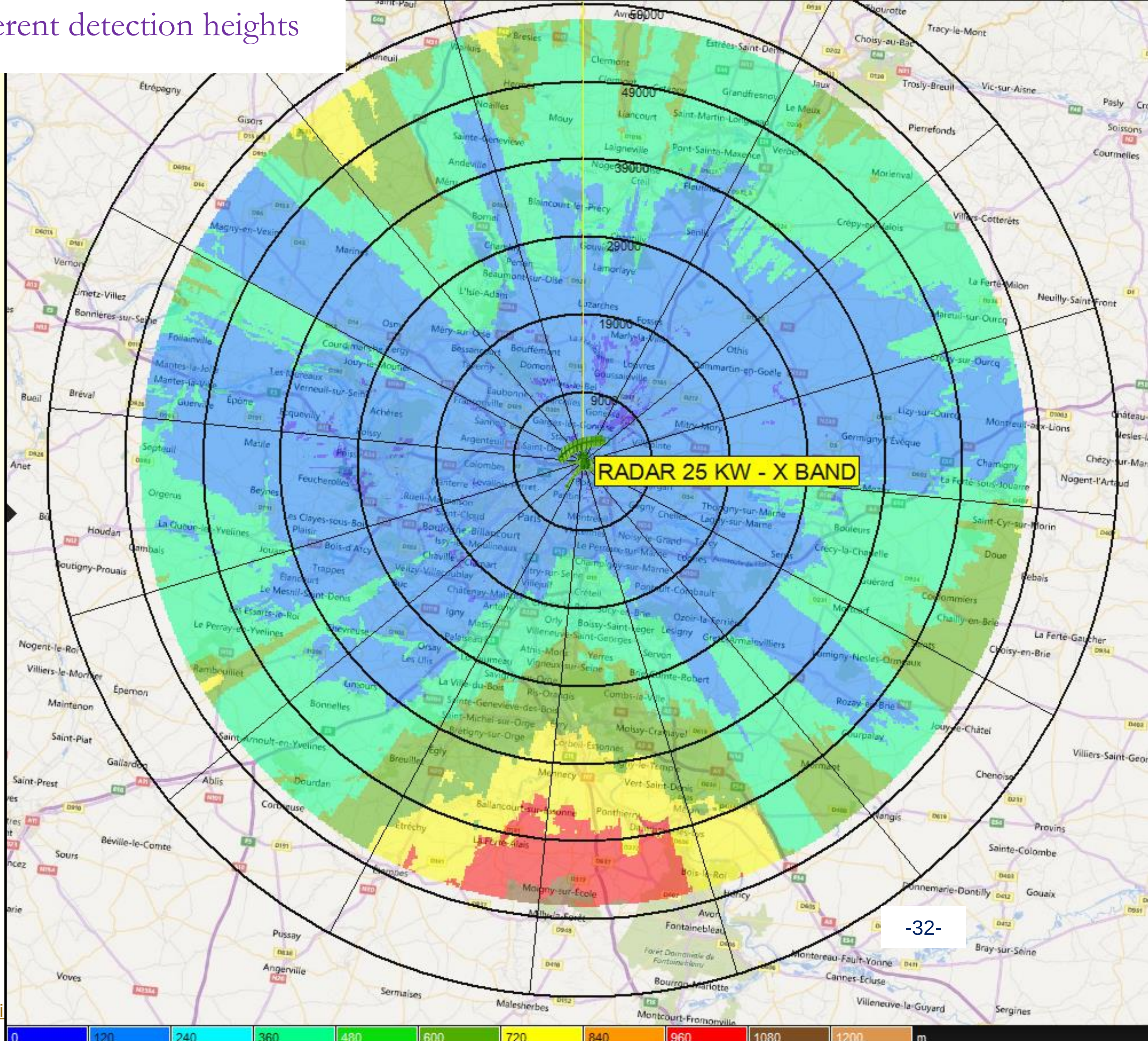
The table is based on $$e_0 = \frac{\sqrt{30 \times p_t \times g_t}}{d} = \frac{\sqrt{30 \times eirp}}{d} = \frac{\sqrt{30 \times erp \times 1.64}}{d}$$

For d=10 m Open Area Test Site (OATS) $$e_0 = \frac{\sqrt{30 \times eirp}}{10} = \sqrt{0.30 \times eirp} = \frac{\sqrt{30 \times erp \times 1.64}}{10} = \sqrt{0.30 \times erp \times 1.64} = \sqrt{0.492 \times erp}$$

Simulating radar, coverage for different detection heights

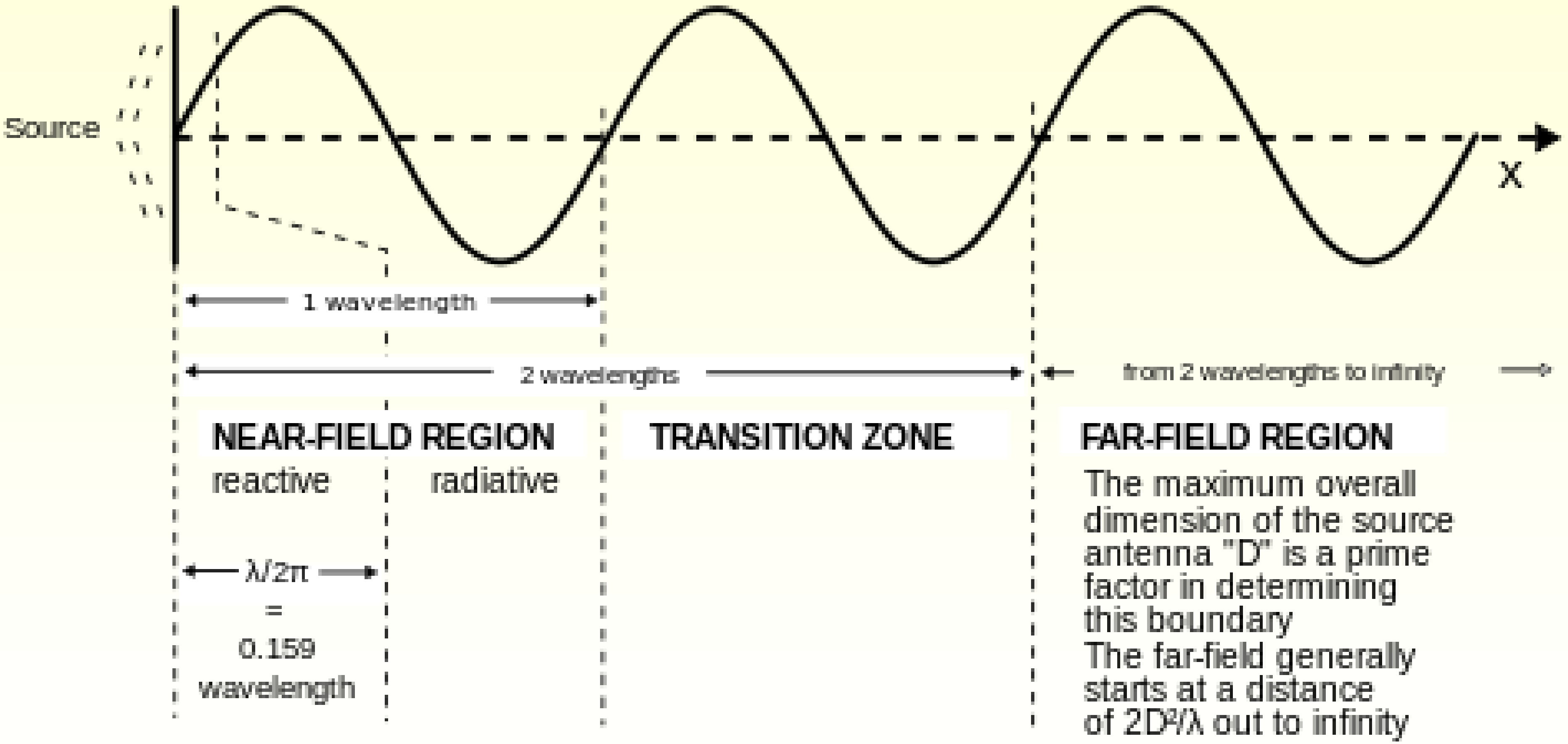


Coverage for different detection heights



Far-Field, Near-Field (1)

Wiki

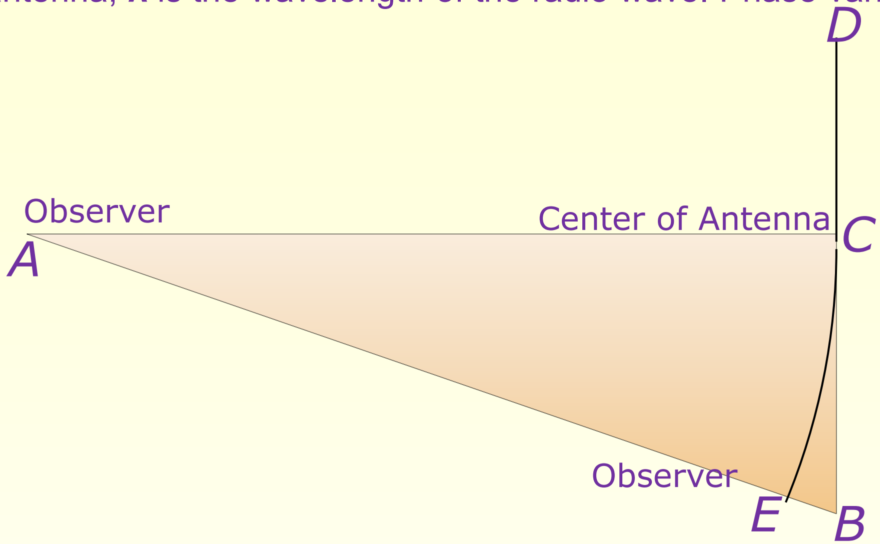


Far-Field, Near-Field (2)

- Near-field region:
  - Angular distribution of energy depends on distance from the antenna אנטנה = מְשׂוּשָׂה; reactive-field components dominate (L,C)
  - In the reactive near-field (very close to the antenna), the relationship between the strengths of the E and H fields is often too complex to predict
  - The energy in the radiative near-field is all radiant energy, although its mixture of magnetic and electric components are still different from the far field
- Far-field region:
  - Angular distribution of energy is independent on distance
  - Radiating field component dominates (R)

Far-Field, Near-Field (3)

Fraunhofer distance: value of 2 $\mathbf{D}^2/\boldsymbol{\lambda}$, where **D** is the largest dimension of the radiator (or the cross-sectional diametre of the antenna; **λ** is the wavelength of the radio wave. Phase variation over the ant. aperture is less than π/8 radians



AB = Tx/Rx distance

BC = **D**/2

BD = **D**, largest dimension of Ant
rectangular in this case

AC = X, limit far/near field

AE = *AC*; *EB*= λ/16

λ = wavelength of the radio wave

Phase difference 2∏ is equivalent to λ; phase diff ∏/8 equivalent to λ/16.

$x^2 + (\mathbf{D}/2)^2 = (x + \lambda/16)^2 = x^2 + x\lambda/8 + (\lambda/16)^2$

$(\lambda/16)^2$ is relatively small to $x\lambda/8$ (as $x >> \lambda/32$), so $X^2 + (\mathbf{D}/2)^2 \approx X^2 + x\lambda/8$

and $(D/2)^2 \approx X\lambda/8$, $D^2 \approx x\lambda/2$ and $\mathbf{x \approx 2D^2/\lambda}$ *QED*

If $x >= 2\mathbf{D}^2/\lambda$, **far-field** region

If $2\mathbf{D}^2/\lambda > X > \lambda/2\Pi$ **radiating** near-field region

If $\lambda/2\Pi > X$ **reactive** near-field region

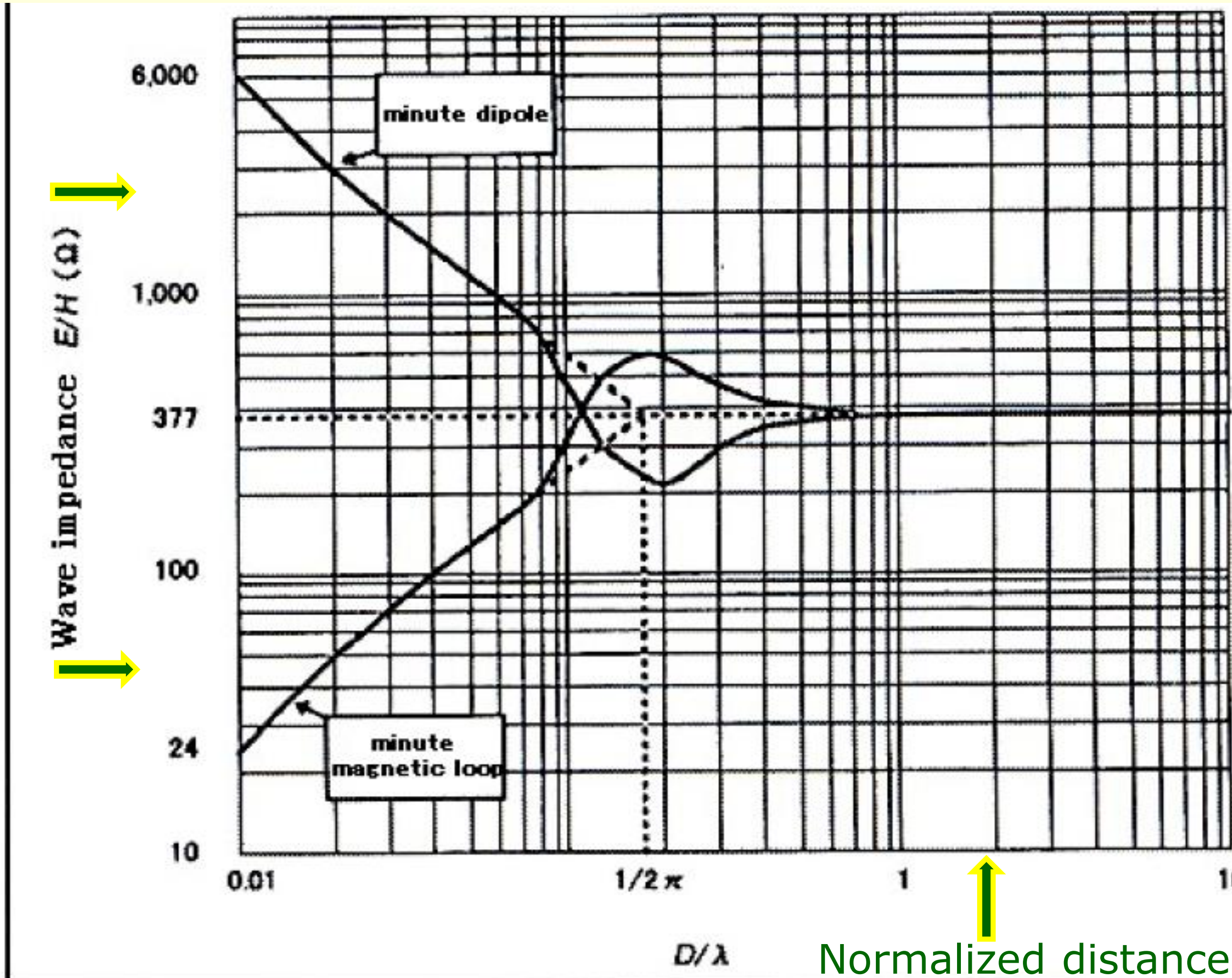
For non directive antenna, far field is beyond 3 λ

Wave Impedance (z)of minute dipole & minute magnetic dipole

$$PoyntingVector = \frac{p_t g_t}{4\pi d^2} = (\vec{e} \times \vec{h}) = \frac{e_o^2}{z} = h^2 z$$ relevant for far & near field

Source, Dipole Antenna - electric field is dominant

Source, Loop Dipole- magnetic field is dominant

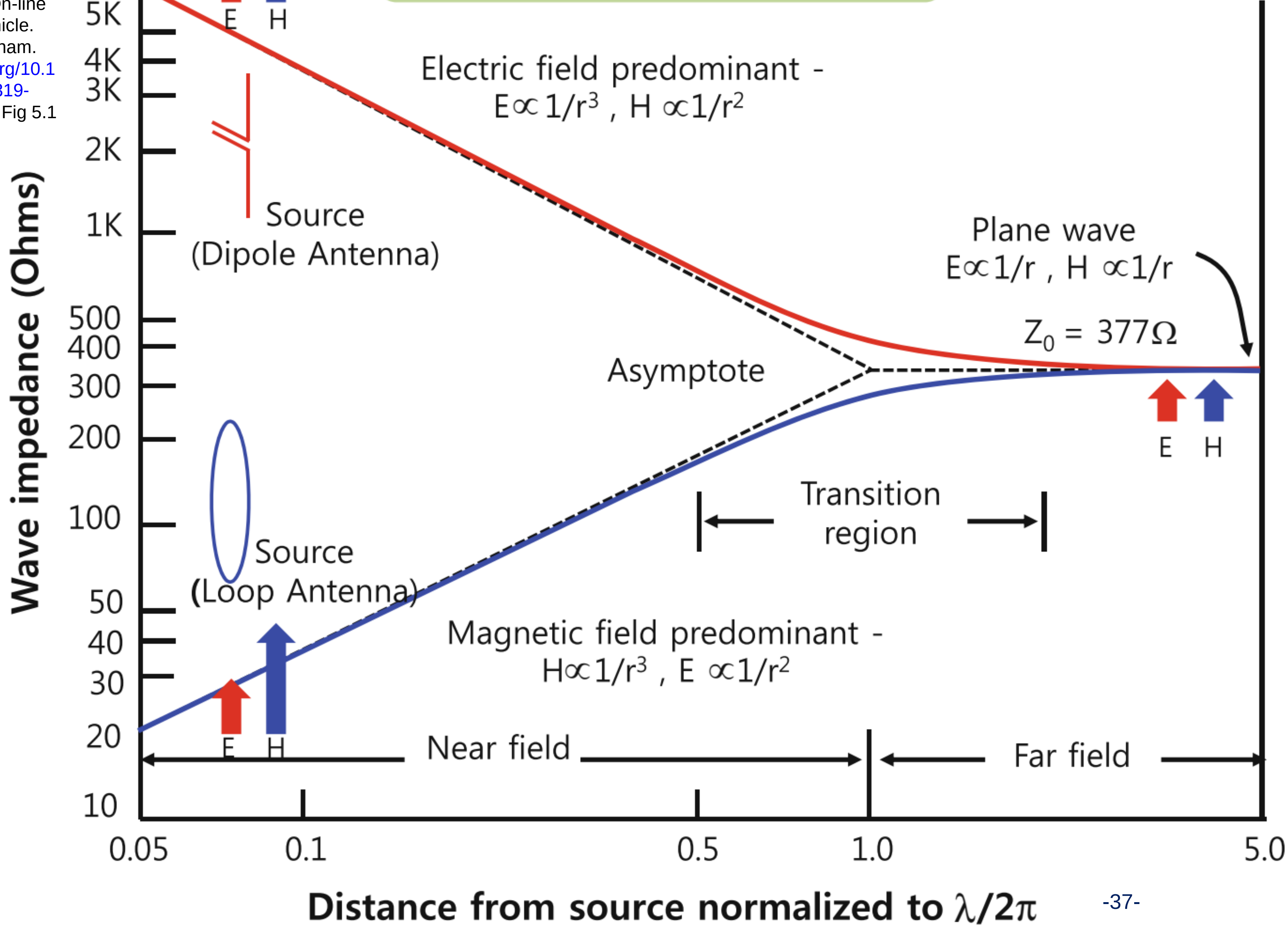


Normalized distance

Source: Ahn S. (2017) Magnetic Field Generation. In: Suh N., Cho D. (eds) The On-line Electric Vehicle. Springer, Cham. https://doi.org/10.1007/978-3-319-51183-2_5; Fig 5.1

Wave impedance versus distance

$$\frac{E}{H} = Z_w \; (Wave\ Impedance)$$



Near Field Measurements

Fresnel Zones

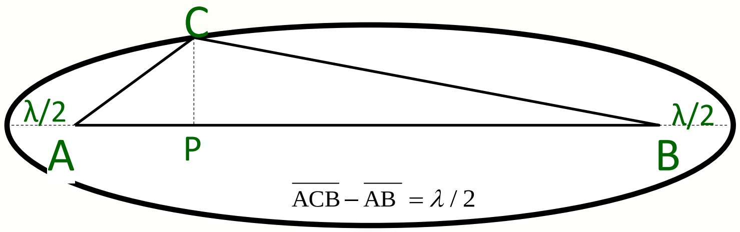
- The Fresnel zone is the ellipsoid that stretches between the two antennas; locus of points such that the difference between the direct path $\overline{AB}$ and the indirect path $\overline{ACB}$ is half the wavelength. λ = The wavelength of the transmitted signal F_n is the n^{th} Fresnel zone radius d ($\overline{AB}$)= d_1 ($\overline{PA}$)+ d_2 ($\overline{PB}$), *F* gets the same unit as λ, d_1 and d_2 (e.g. meter). Units: d_1 , d_2 , λ in metres

$$F_n = \sqrt{\frac{n\lambda d_1 d_2}{d_1 + d_2}} \qquad F_n = F_1\sqrt{n}$$

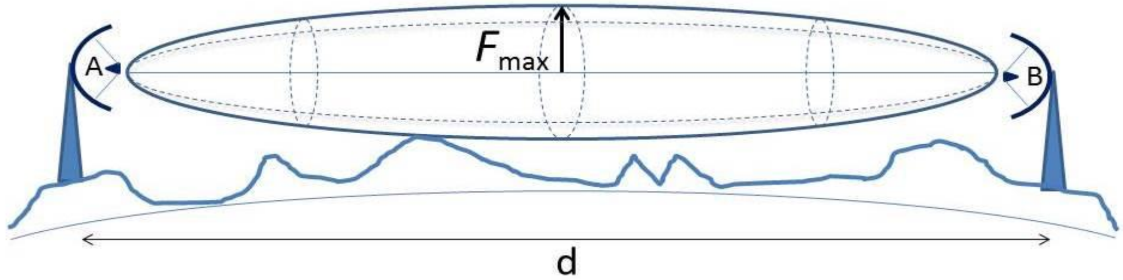
- By deriving *Fn*, and equating to 0, the max value of F_n , ***b***, is for d_1 = d_2= d/2 & equals $b = \sqrt{\frac{n\lambda d}{4}}$

When d (kM) and f (GHz), F (m) $F_1 = 17.3\sqrt{\frac{d_1\, d_2}{f d}}$ $F_3 = 30\sqrt{\frac{d_1\, d_2}{fd}}$

The First Fresnel zone



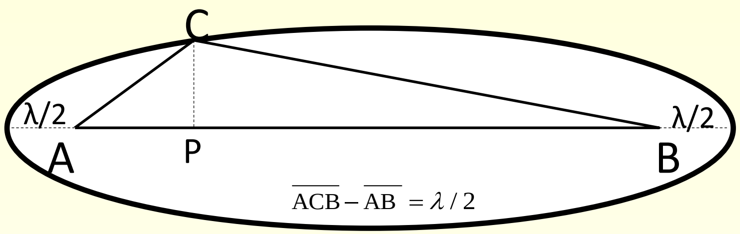
The Fresnel Ellipsoid



Calculating the Fresnel Zones, to show

$$F_n = \sqrt{\frac{n\lambda d_1 d_2}{d_1 + d_2}} = \sqrt{\frac{n\lambda d_1 d_2}{d}} \qquad F_n = F_1\sqrt{n}$$

The First Fresnel zone: for $\overline{PA} = d_1$, $\overline{PB} = d_2$ and $\overline{AB} = d_1 + d_2 = d$



$$\overline{ACB} - \overline{AB} = \frac{\lambda}{2} \qquad \overline{AC} = \sqrt{(d_1)^2 + (F_1)^2} \qquad \overline{CB} = \sqrt{(d_2)^2 + (F_1)^2}$$ therefore

$$\sqrt{(d_1)^2 + (F_1)^2} + \sqrt{(d_2)^2 + (F_1)^2} - d = d_1\sqrt{1 + \left(\frac{F_1}{d_1}\right)^2} + d_2\sqrt{1 + \left(\frac{F_1}{d^2}\right)^2} - d = \frac{\lambda}{2}$$

Using Taylor series expansion of a function about 0: Maclaurin series

$$\sqrt{1 + \left(\frac{F_1}{d_1}\right)^2} \approx 1 + \frac{1}{2}\left(\frac{F_1}{d_1}\right)^2$$ and $$\sqrt{1 + \left(\frac{F_1}{d_2}\right)^2} \approx 1 + \frac{1}{2}\left(\frac{F_1}{d_2}\right)^2$$ so $$d_1\sqrt{1 + \left(\frac{F_1}{d_1}\right)^2} + d_2\sqrt{1 + \left(\frac{F_1}{d_2}\right)^2} - d \approx d_1 + \frac{1}{2}\frac{(F_1)^2}{d_1} + d_2 + \frac{1}{2}\frac{(F_1)^2}{d_2} - d = \frac{1}{2}\frac{(F_1)^2}{d_1} + \frac{1}{2}\frac{(F_1)^2}{d_2} = \frac{\lambda}{2}$$

$$\frac{(F_1)^2}{d_1} + \frac{(F_1)^2}{d_2} = \lambda \qquad (F_1)^2 = \frac{\lambda d_1 d_2}{d_1 + d_2} = \frac{\lambda d_1 d_2}{d}$$ and $$F_1 = \sqrt{\frac{\lambda d_1 d_2}{d_1 + d_2}} = \sqrt{\frac{\lambda d_1 d_2}{d}}$$

Quod Erat Demonstrandum QED

Assuming $\overline{ACB} - \overline{AB} = n\frac{\lambda}{2}$ nλ replaces λ, to get

$$F_n = \sqrt{\frac{n\lambda d_1 d_2}{d_1 + d_2}} = \sqrt{\frac{n\lambda d_1 d_2}{d}} = \sqrt{n}\sqrt{\frac{\lambda d_1 d_2}{d}} = \sqrt{n}F_1$$

Fresnel Zones (cont.)

$F_n = \sqrt{\frac{n\lambda d_1 d_2}{d_1 + d_2}}$ near the 2 sites, $d_1 << d_2$ and $d_1 + d_2 \approx d_2$

$\frac{F_1}{d_1}$ is still small , in order to keep the approximation $\sqrt{1+\left(\frac{F_1}{d_1}\right)^2} = 1 + \frac{1}{2}\left(\frac{F_1}{d_1}\right)^2$

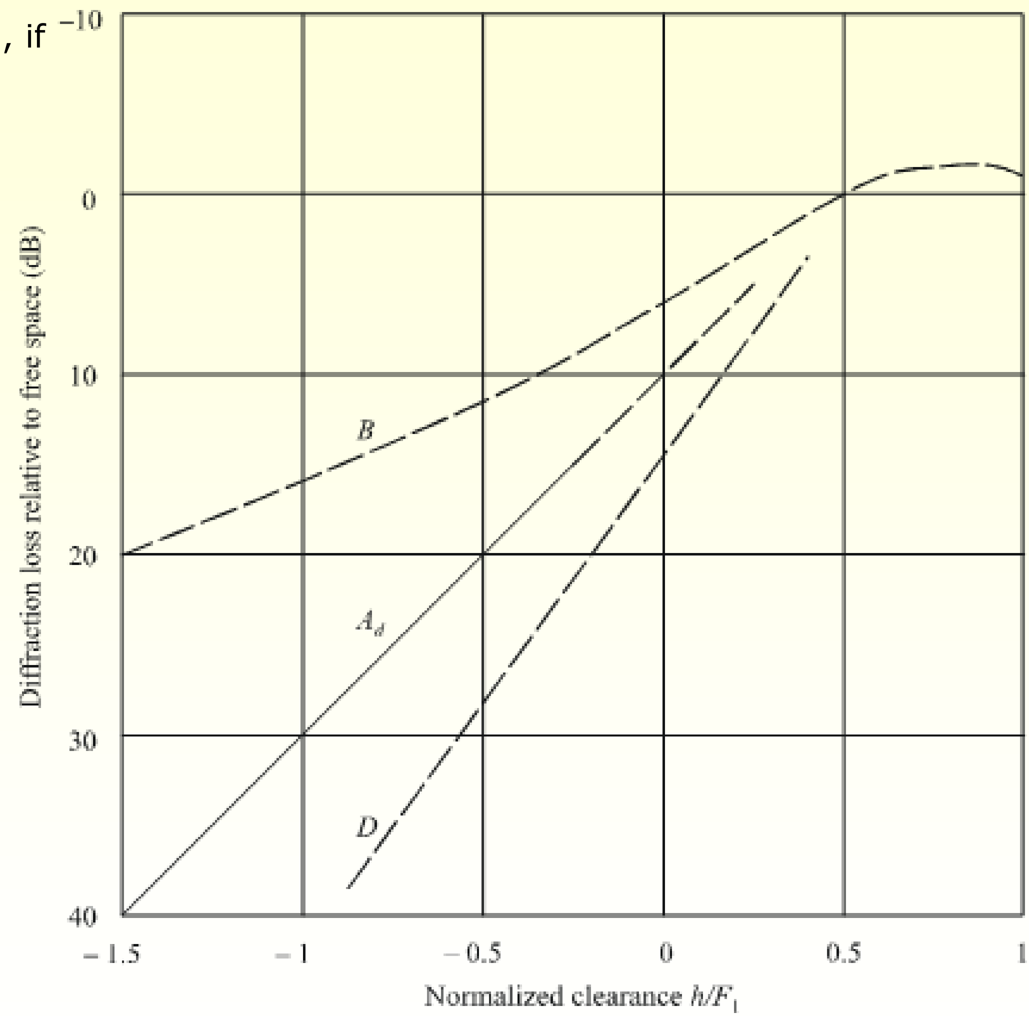
$$F_n = \sqrt{\frac{n\lambda d_1 d_2}{d_1 + d_2}} \approx \sqrt{\frac{n\lambda d_1 d_2}{d_2}} = \sqrt{n\lambda d_1}$$

Diffraction loss for obstructed LoS μwave radio paths (Rec ITU-R P.530)

Propagation is assumed to occur in line-of-sight (LoS), i.e. with negligible diffraction phenomena, if there is no obstacle within the first Fresnel ellipsoid; see Rec. ITU-R P.526

h is the height difference (m) between most significant path blockage and the path trajectory; amount of path clearance
F_1 is the radius of the first Fresnel ellipsoid given by: (see units other slide)

$$F_1 = 17.3\sqrt{\frac{d_1 d_2}{f d}}$$

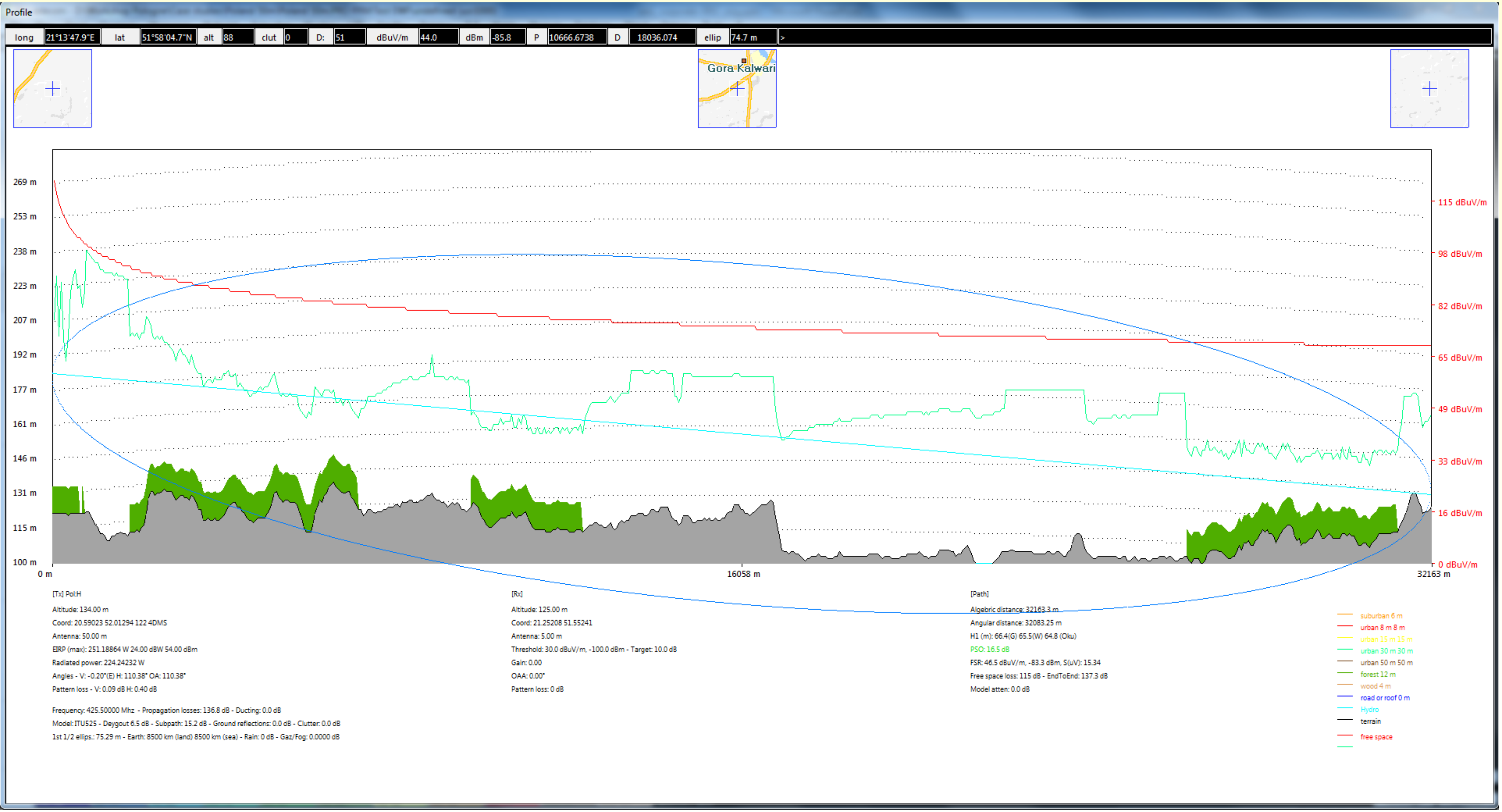


B: Theoretical knife-edge curve
D: Theoretical smooth spherical earth loss curve at 6.5 GHz
k_r = 4/3
A_d : empirical diffraction loss for intermediate terrain

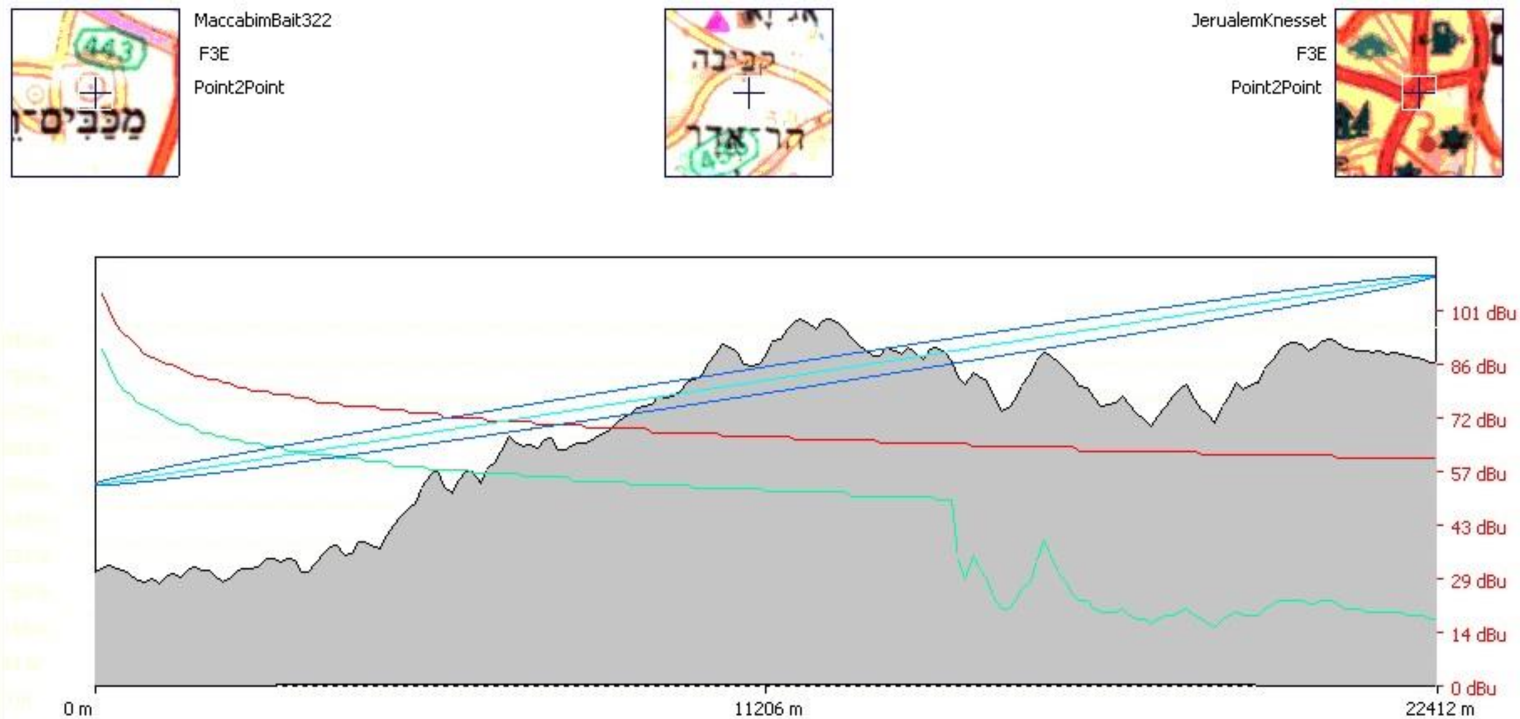
$$A_d = -20\, h / F_1 + 10$$

Fresnel; profile influenced from topography

ATDI , HTZ



Profile P2P Maccabim-Jerusalem (ATDI , HTZ)



Altitude - Tx: 271 meters, Rx: 760 meters

Antennas - Tx: 200.00 meters, Rx: 200.00 meters, H1: -139.04(G) -89.31(W) -70.42 (Oku)

FSR: 18.2 dBµV/m, -117.7 dBm (gain=17.00) - FS: 61 dBµV/m, Model att: 3.8 dB - Rx ant: 10.53 dB - IRF+XPD: 0 dB

EIRP (max): 20.04749 Watts , 13.02 dBW 43.021 dBm

FREQUENCY: 1800.00000 Mhz - Radiated power: 1.77499 Watts - Losses: 152.9 dB

Deygout - Attenuation: 28.3 dB - Ground reflections: 0.0 dB - Clutter: 0.0 dB

Distance: 22416 meters - Atmospheric fade margin (0.1 %): 1.87 dB / S2=25.00(*)

Tx: 35.01469 31.53380 271 4DMS

Rx: 35.13442 31.47024 760 4DMS

V-angle: 1.17°, H-angle: 122.98° - loss: 10.53 dB - FSL: 125 dBi

1st 1/2 ellips.: 30.56 m - Earth radius: 8500 km (land) 8500 km (sea) - Rain att.: 0 dB, Gaz. att.: 0.0000 dB

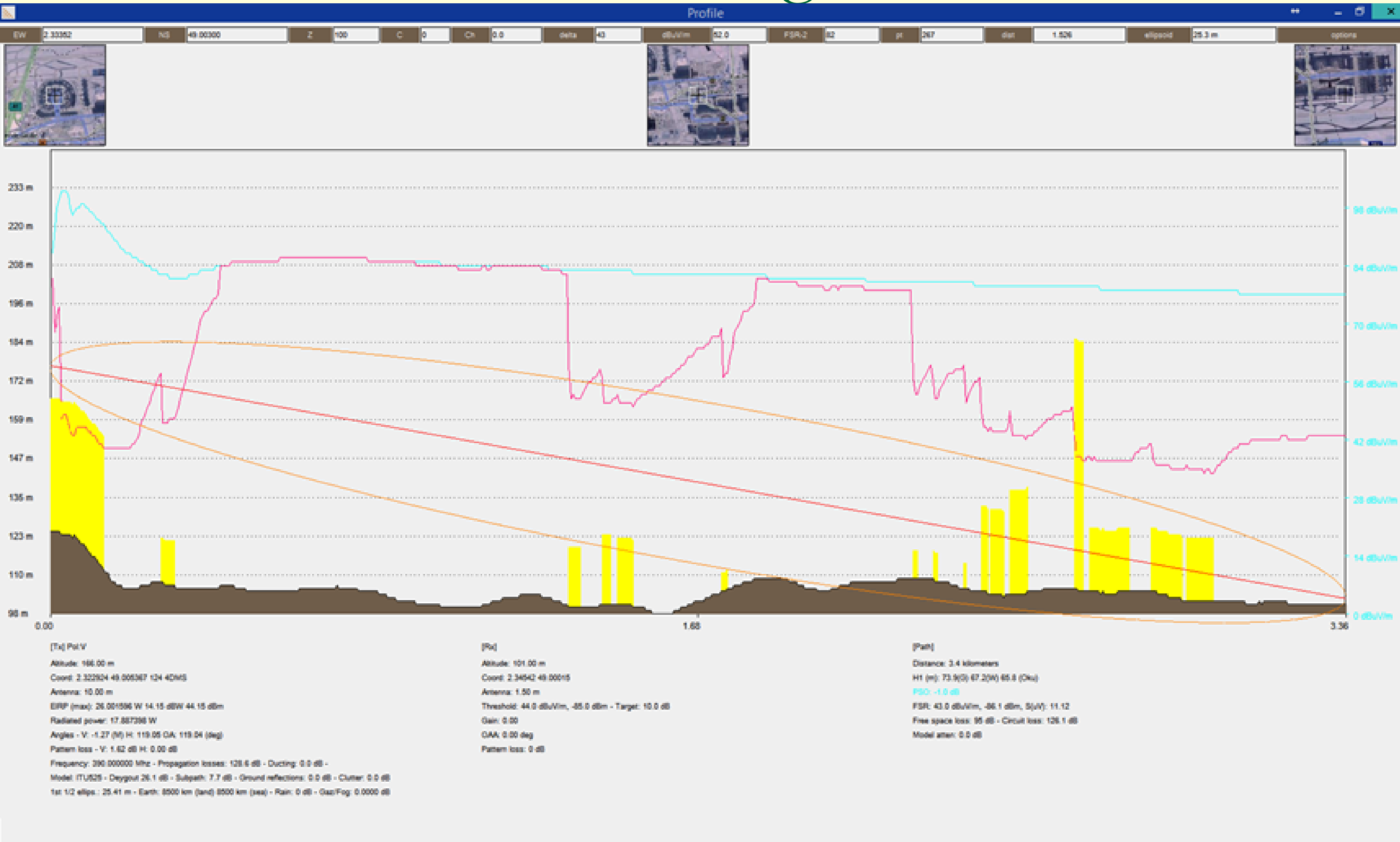
Conversion Formulae

$$p_r = \frac{e^2}{120\pi} \times \frac{g_r \lambda^2}{4\pi}$$

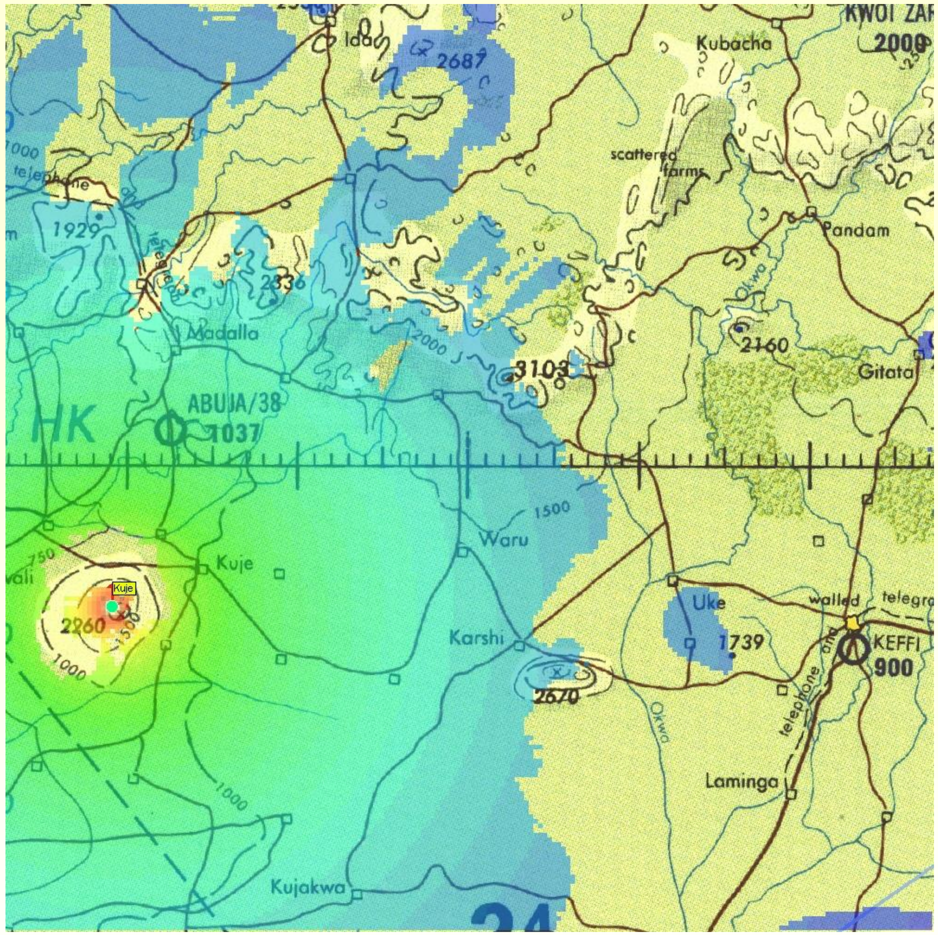
$$p_r(\mathrm{W}) = \frac{e^2}{120\pi} \times \frac{(c_o)^2 \times g_r}{4\pi f^2(\mathrm{MHz}) 10^{-12}} = \frac{89{,}987.551 \times e^2 \times g_r}{480\pi^2 f^2(\mathrm{MHz})} = \frac{18.97 \times e^2(\mathrm{V/m}) \times g_r}{f^2(\mathrm{MHz})}$$

$$p_r(\mathrm{mW}) = \frac{18.97 \times e^2(\mu\mathrm{V/m}) \times g_r}{f^2(\mathrm{MHz})} 10^{-9}$$

Profile for Coverage Prediction (ATDI , HTZ)

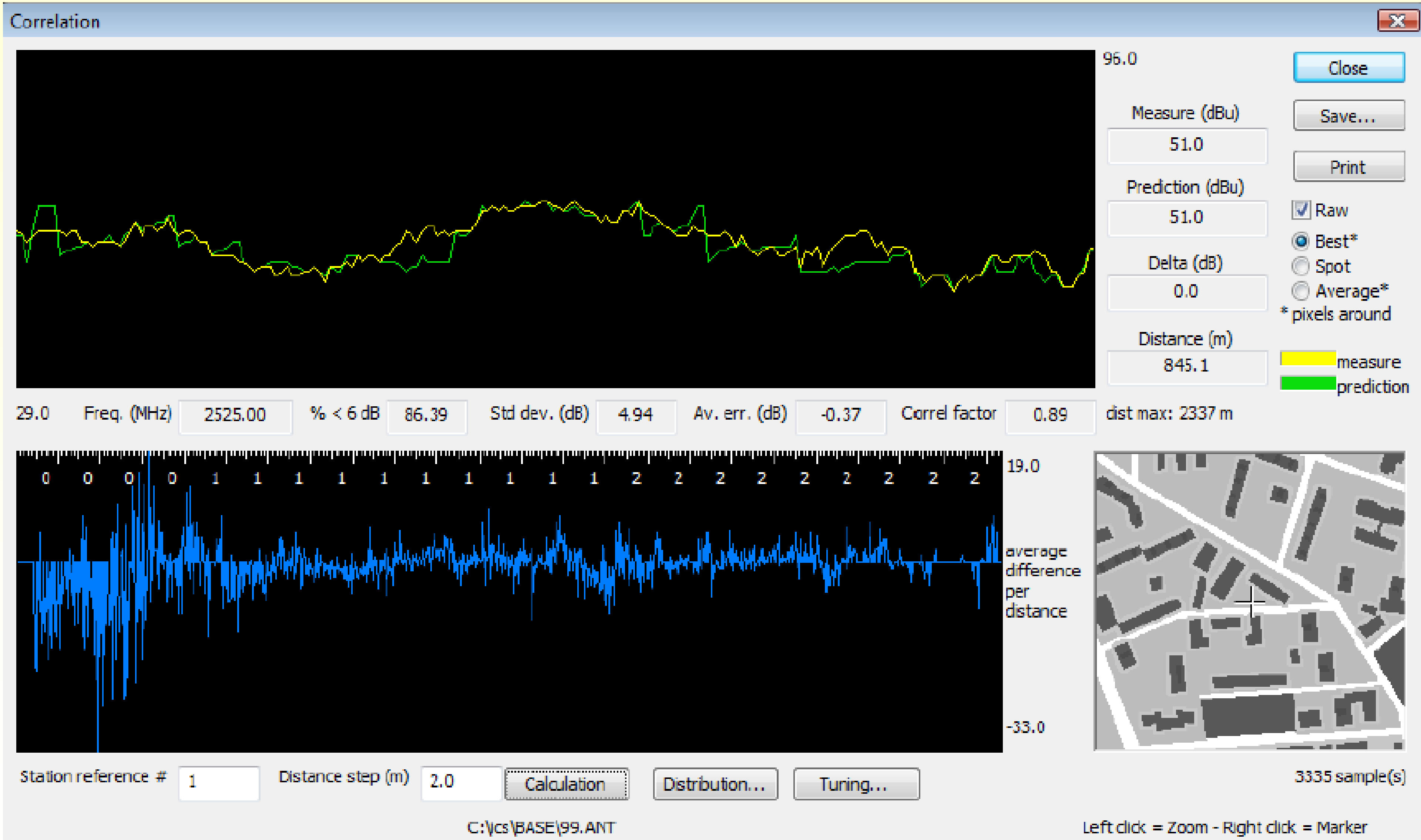


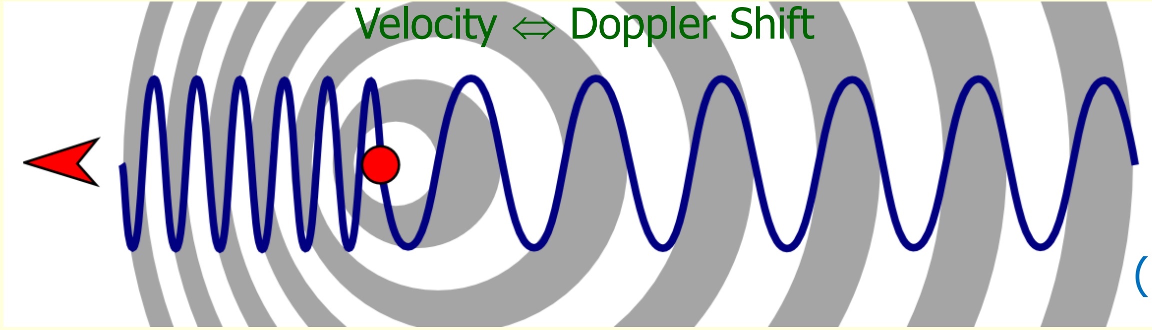
Coverage of an FM transmitter: topography influences



Enclosed a useful link to retrieve the Digital Terrain Elevation Data (DTED): http://gcmd.nasa.gov/records/GCMD_DMA_DTED.html; this is the link to meteorological parameters: http://weather.uwyo.edu/upperair/sounding.html

Measurement vs Prediction; WiMAX (Russia); 3.5 GHz; 2m resolution 3D building data input. Average error: -0.37 dB, standard deviation 4.94 dB; correlation percentage: 86.39%





(figure from web)

$$f_D \approx -\frac{\dot{R}}{\lambda}$$

- Range rate: $\dot{R}$
- Wavelength: λ
- Doppler shift: f_D

$$f_D \approx -2\frac{\dot{R}}{\lambda}$$

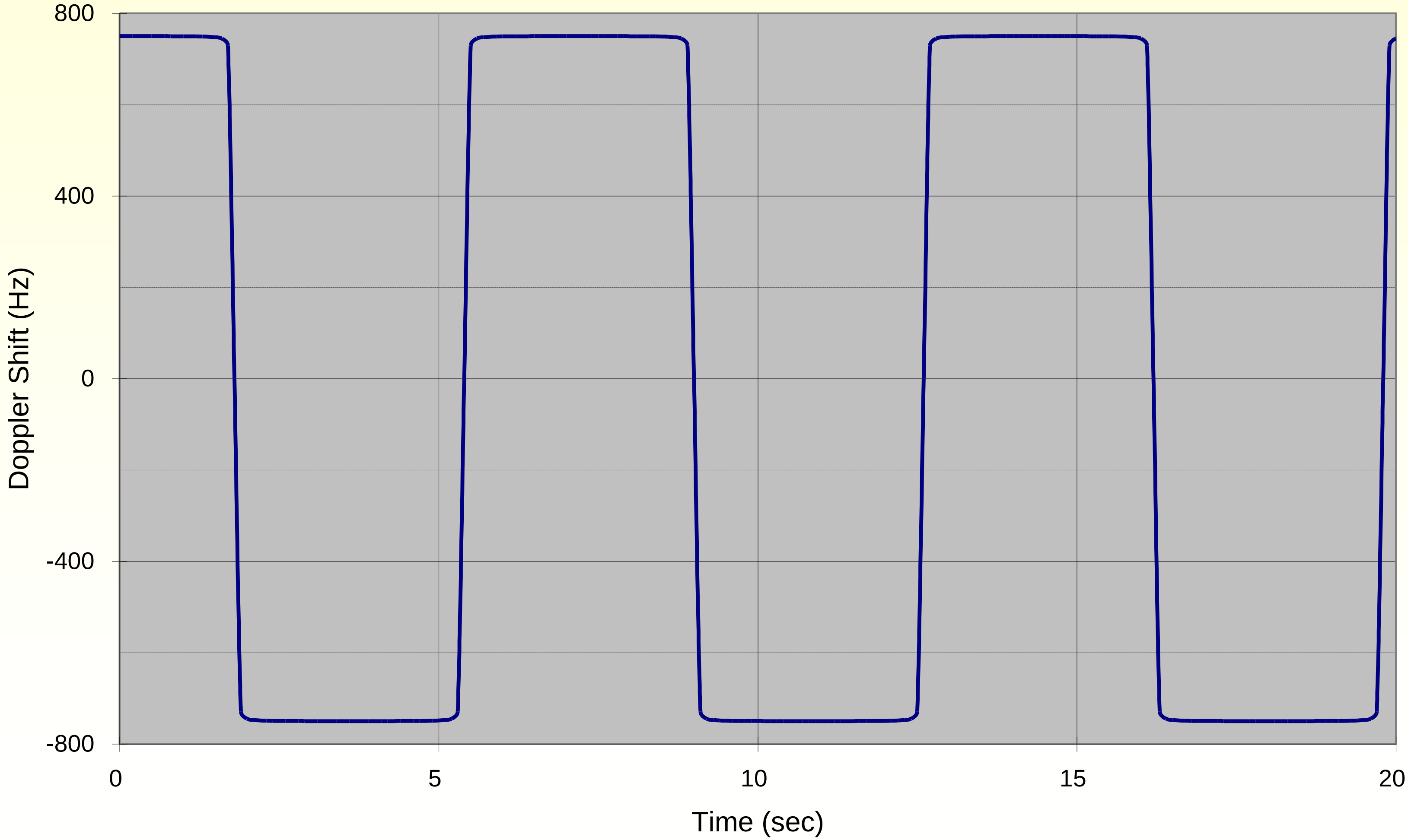
for radars and proximity fuses

$$\lambda = \frac{C_p}{f_0}$$

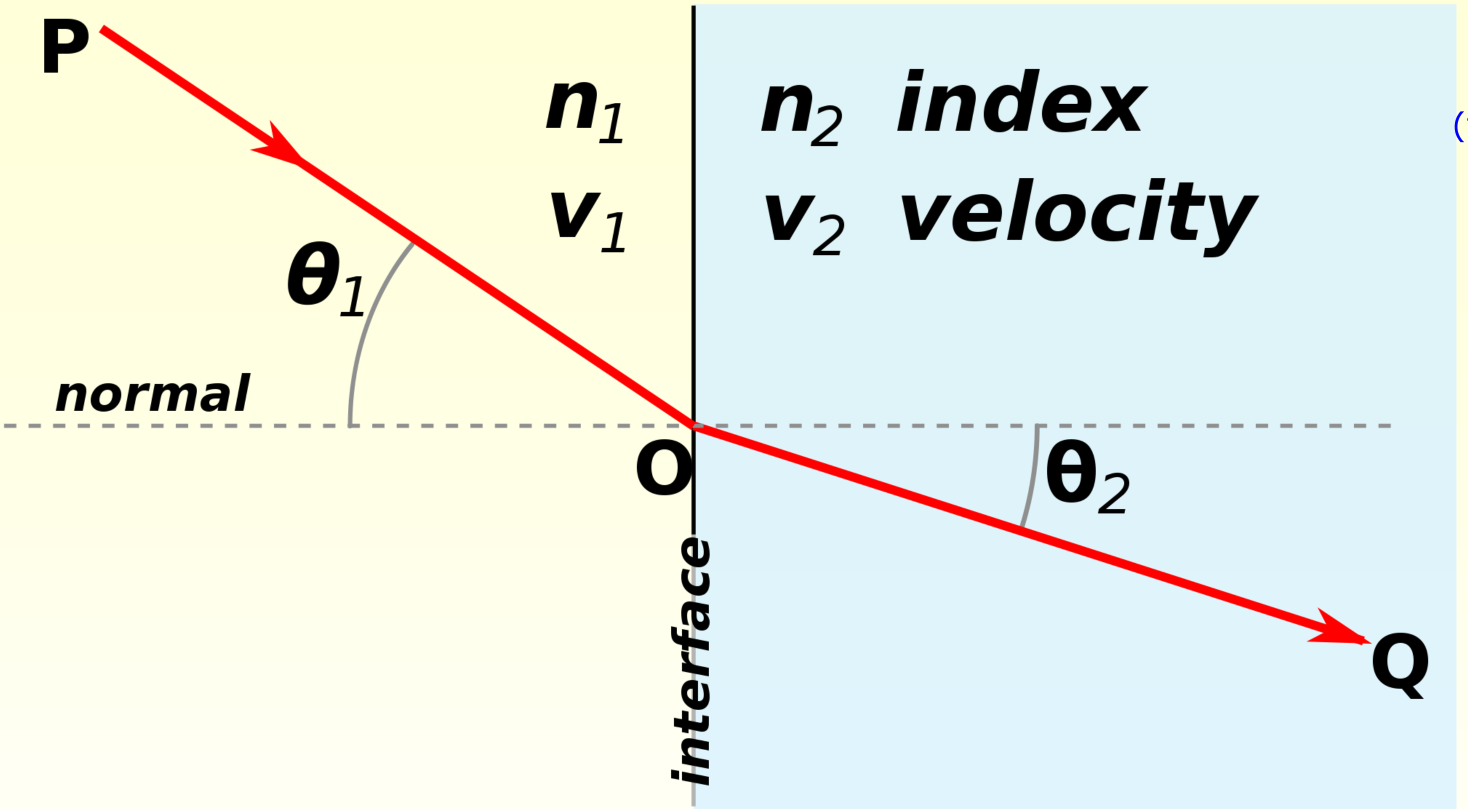
- Velocity of propagation: C_p
- Carrier frequency: f_0

Doppler shift trajectory in LTE (GPP TS 36.101 V12.1.0 (2013-09); release 12

Given the initial distance of the **crossing train** from eNodeB is 300 m , and d_{min} is 2 m eNodeB Railway track distance; the velocity of the train is 300 km/h, t is time in seconds f_d max at 2.6 GHz is 750 Hz



Radio Horizon as a Function of Ant Height; Snell's law



(figure from web)

n = velocity of light in a vacuum / velocity of light in medium

ε_r is the material's relative permittivity, and μ_r is its relative permeability.

μ_r is very close to 1 at optical frequencies.

$$n = \frac{c}{v_p}$$

$$c \equiv \frac{1}{\sqrt{\varepsilon_0 \mu_0}} \qquad v_p = \frac{1}{\sqrt{\varepsilon_r \varepsilon_0 \mu_r \mu_0}} \qquad n = \frac{\sqrt{\varepsilon_r \varepsilon_0 \mu_r \mu_0}}{\sqrt{\varepsilon_0 \mu_0}} = \sqrt{\varepsilon_r \mu_r}$$

Effective Radius of the Earth (Rec. ITU-R P. 310)

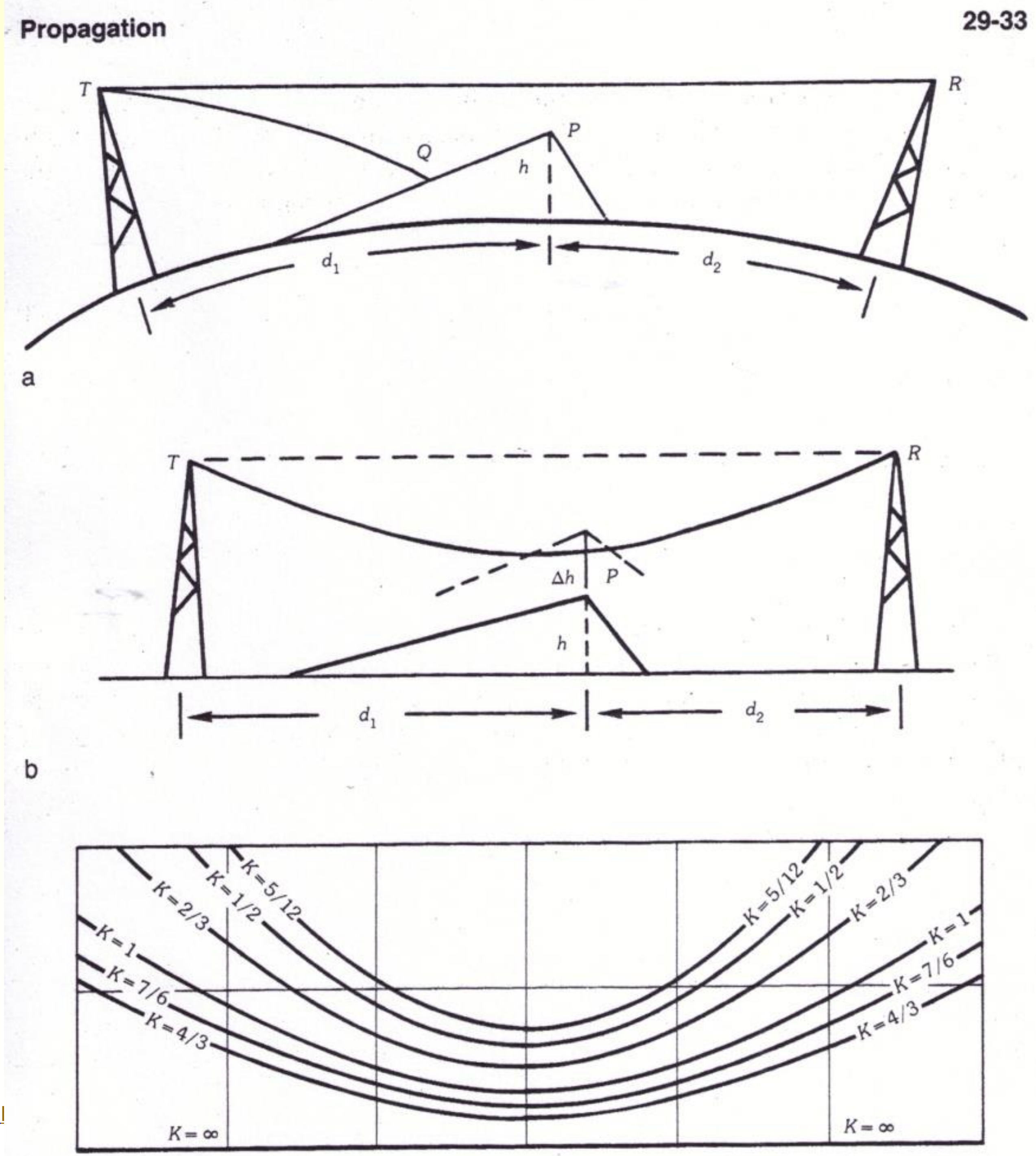
- ***Effective radius of the Earth: a*** Radius of a hypothetical spherical Earth, without atmosphere, for which propagation paths are along straight lines, the heights and ground distances being the same as for the actual Earth in an atmosphere with a constant vertical gradient of refractivity. *Note* – For an atmosphere having a standard refractivity gradient, the effective radius of the Earth is about **4/3 t**hat of the actual radius, which corresponds to approximately **8 500 km**
- ***Refractive index n*** *Ratio of the speed of radio waves in vacuo to the speed in the medium under consideration*
- ***Refractivity**; **N*** One million times the amount by which the refractive index *n* in the atmosphere exceeds unity: $N = (n - 1)10^6$
- **Effective Earth-radius factor, k** Ratio of the effective radius of the Earth to the actual Earth radius. Note 1 – This factor k is related to the vertical gradient dn/dh of the refractive index n and to the actual Earth radius a by the equation:

$$k = \frac{1}{1 + a\frac{dn}{dh}}$$

Geometry of radio wave propagation

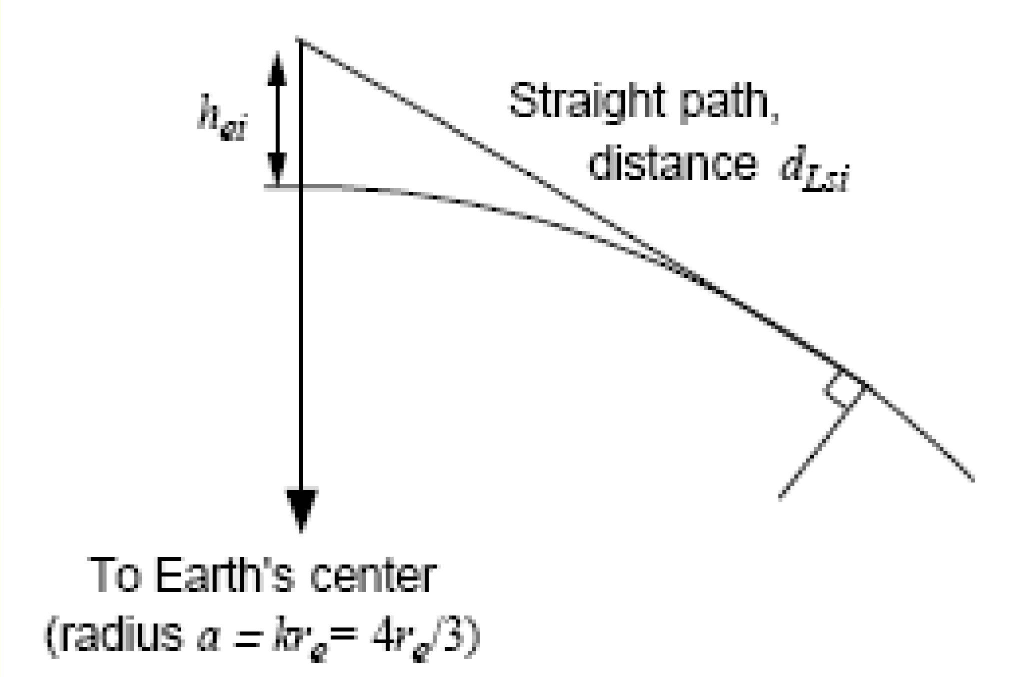
a:propagation in the troposphere;
b: path profile construction
c: standard K curves

Lo/Lee Antenna Handbook



Dr. Haim Mazar (Madjar) haimma1@ac.sce.ac.il

Radio Horizon for a Smooth Earth, function of ant height



$(a+h)^2 = a^2 + 2ha + h^2 = x^2 + a^2$; $2ha + h^2 = x^2$

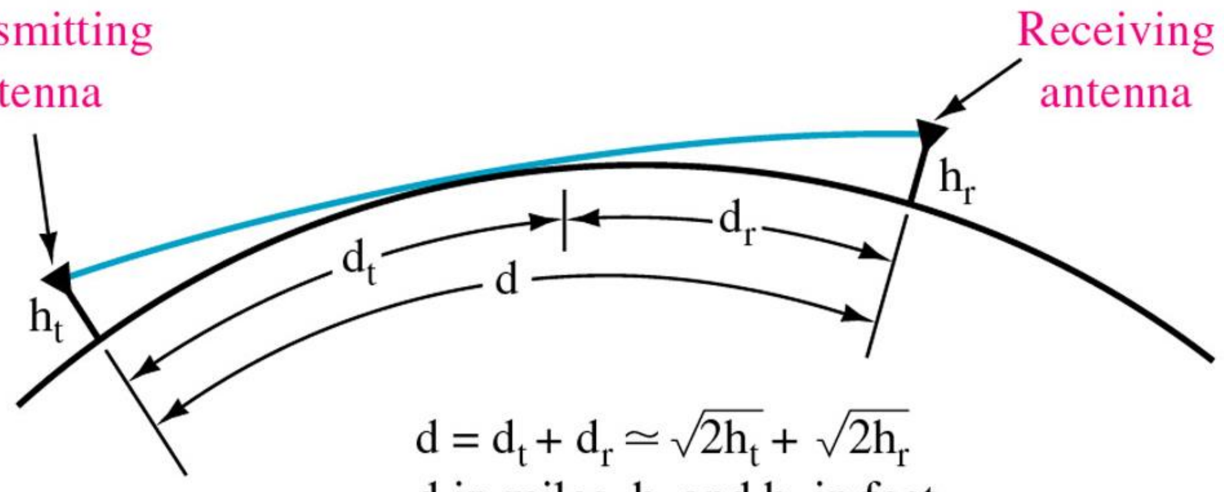
$$x = \sqrt{2ha + h^2}$$

$$x(when\_h << a) \approx \sqrt{2ha}$$

$$d_{los} \approx \sqrt{2a}\left(\sqrt{h_1} + \sqrt{h_2}\right)$$

For k= 1 (*Earth Radius* =6,371 *k*m), horizon (miles) $x \approx \sqrt{height_{feet}}$

Radio horizon Tx & Rx Antennas



$(a+h_1)^2 = a^2 + 2h_1a + h_1^2 = x^2 + a^2 \quad ; \; 2h_1a + h_1^2 = x^2$

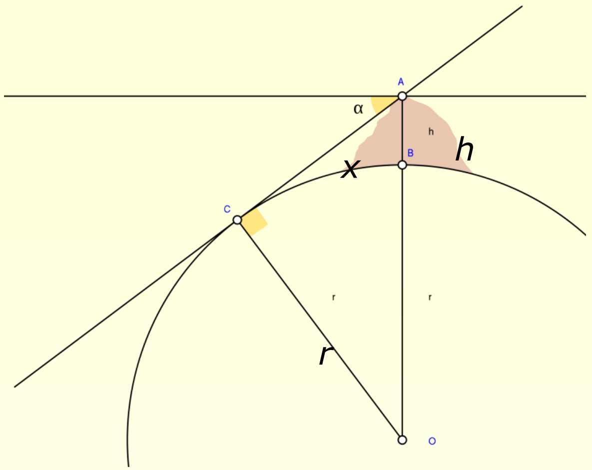
$(a+h_2)^2 = a^2 + 2h_2a + h_2^2 = x^2 + a^2 \quad ; \; 2h_2a + h_2^2 = x^2$

$$x = \sqrt{2h_1a + h_1^{\;2}} + \sqrt{2h_2a + h_2^{\;2}} \approx \sqrt{2h_1a} + \sqrt{2h_2a}$$

$$x = \sqrt{2h_1a} + \sqrt{2h_2a} \quad \text{when x << a}$$

Calculating radio horizon for a smooth Earth, as function of ant height

$$x \approx \sqrt{2hr}$$



Calculate the radio horizon x (N. miles), k=4/3 (*Earth Radius* =8500 *k*m), for h in feet

$$x_m \approx \sqrt{2h_m r_m} = \sqrt{2h_{feet} \times 0.3048 \times 8500 \times 10^3} = \sqrt{518 \times 10^4 h_{feet}} = 2{,}277\sqrt{h_{feet}}$$

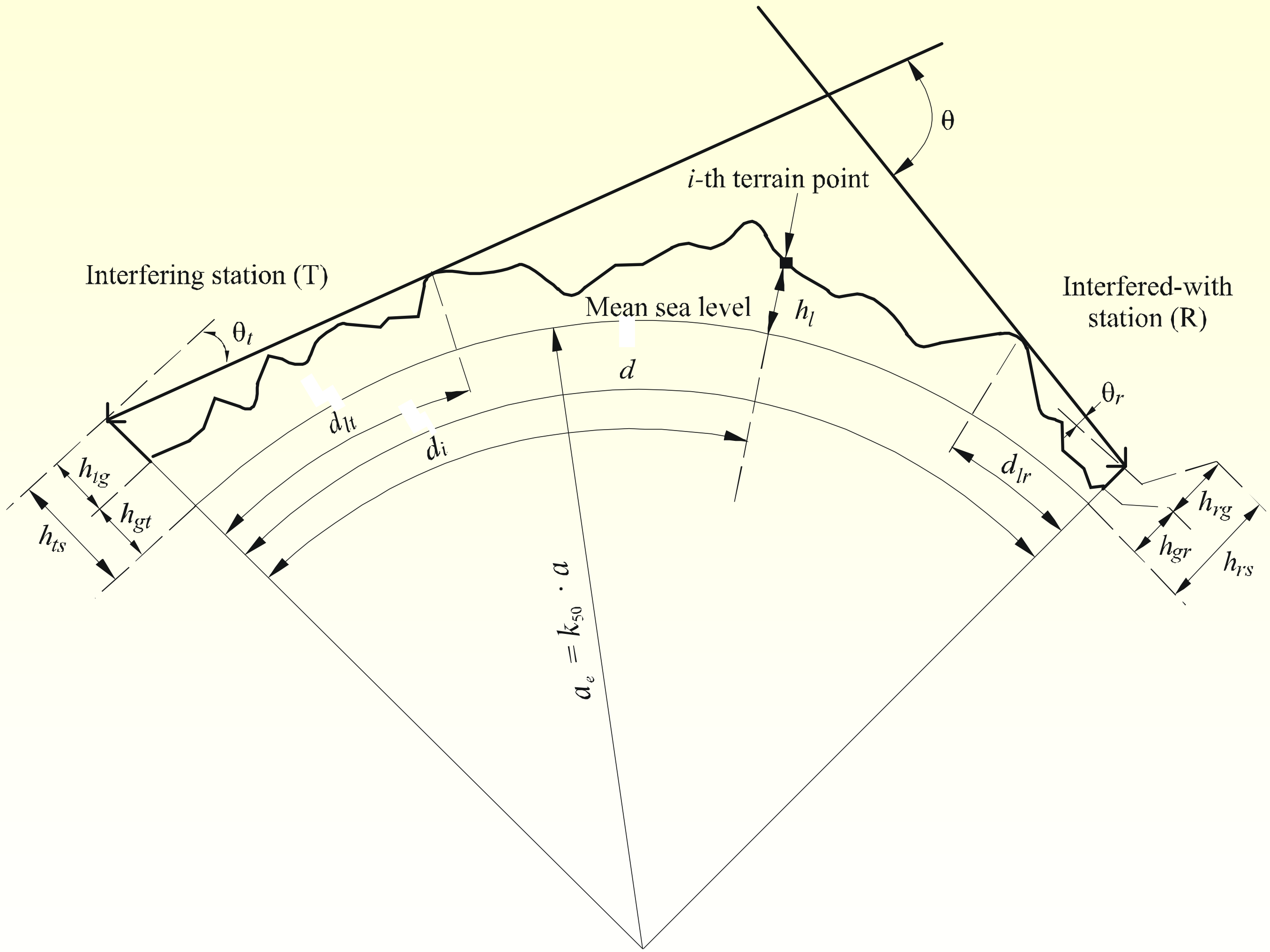
$$for\ h = 28{,}000\ _{feet} \quad x_m = 2{,}277 \times \sqrt{28{,}000} = 381{,}015\ _m = 381{,}015/1{,}852 = 206.7\ _{NM}$$

Prove that for k= 1 (*Earth Radius* =6,371 *k*m), horizon (miles) $x_{NM} \approx \sqrt{height_{feet}}$

$$x_m \approx \sqrt{2h_m r_m} = \sqrt{2h_{feet} \times 0.3048 \times 6371 \times 10^3} = \sqrt{3{,}884 \times 10^3 h_{feet}} = 1{,}970\sqrt{h_{feet}}$$

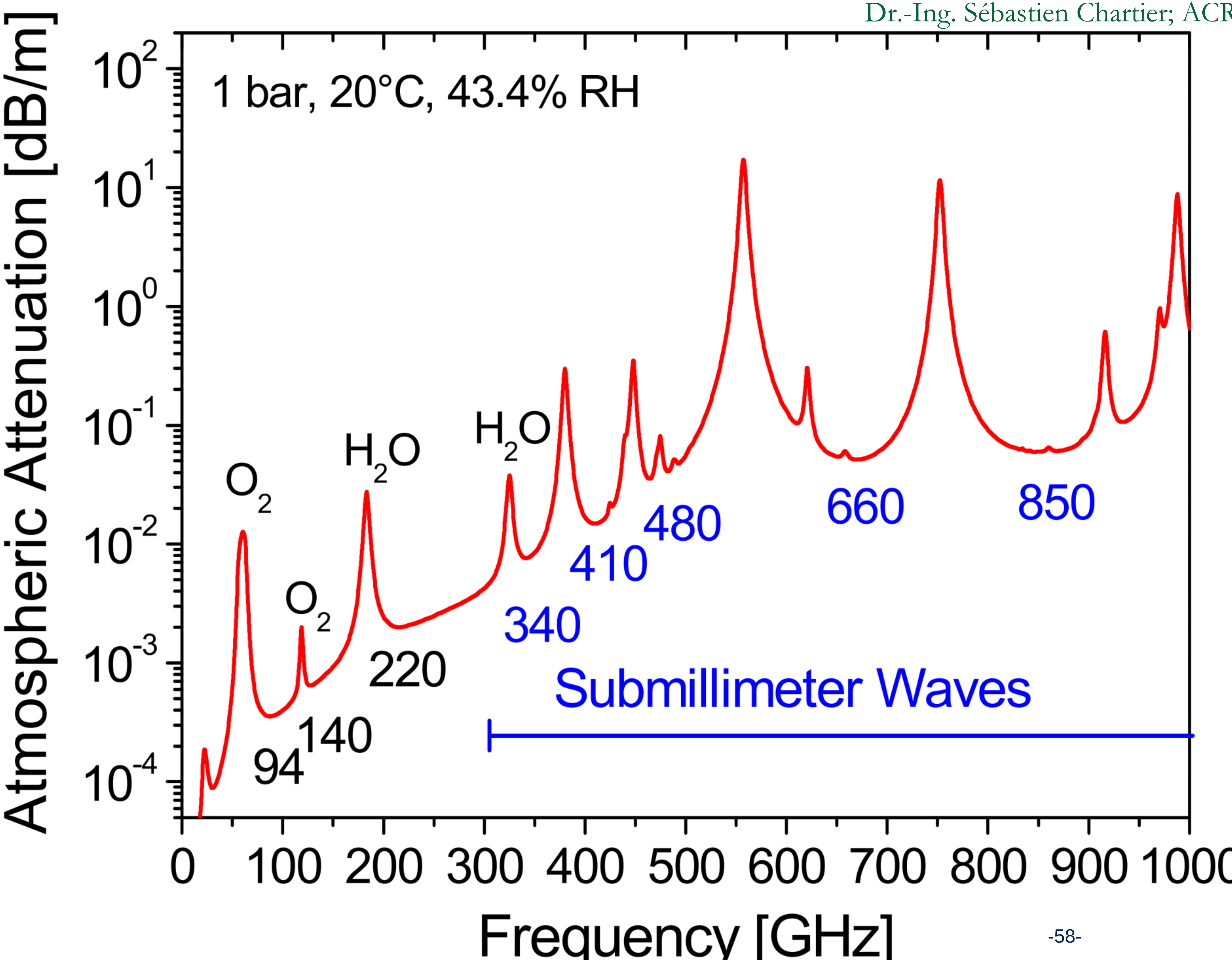
$$x_{NM} = 1{,}970/1{,}852\sqrt{h_{feet}} = 1.07\sqrt{h_{feet}} \approx \sqrt{h_{feet}} \qquad QED$$

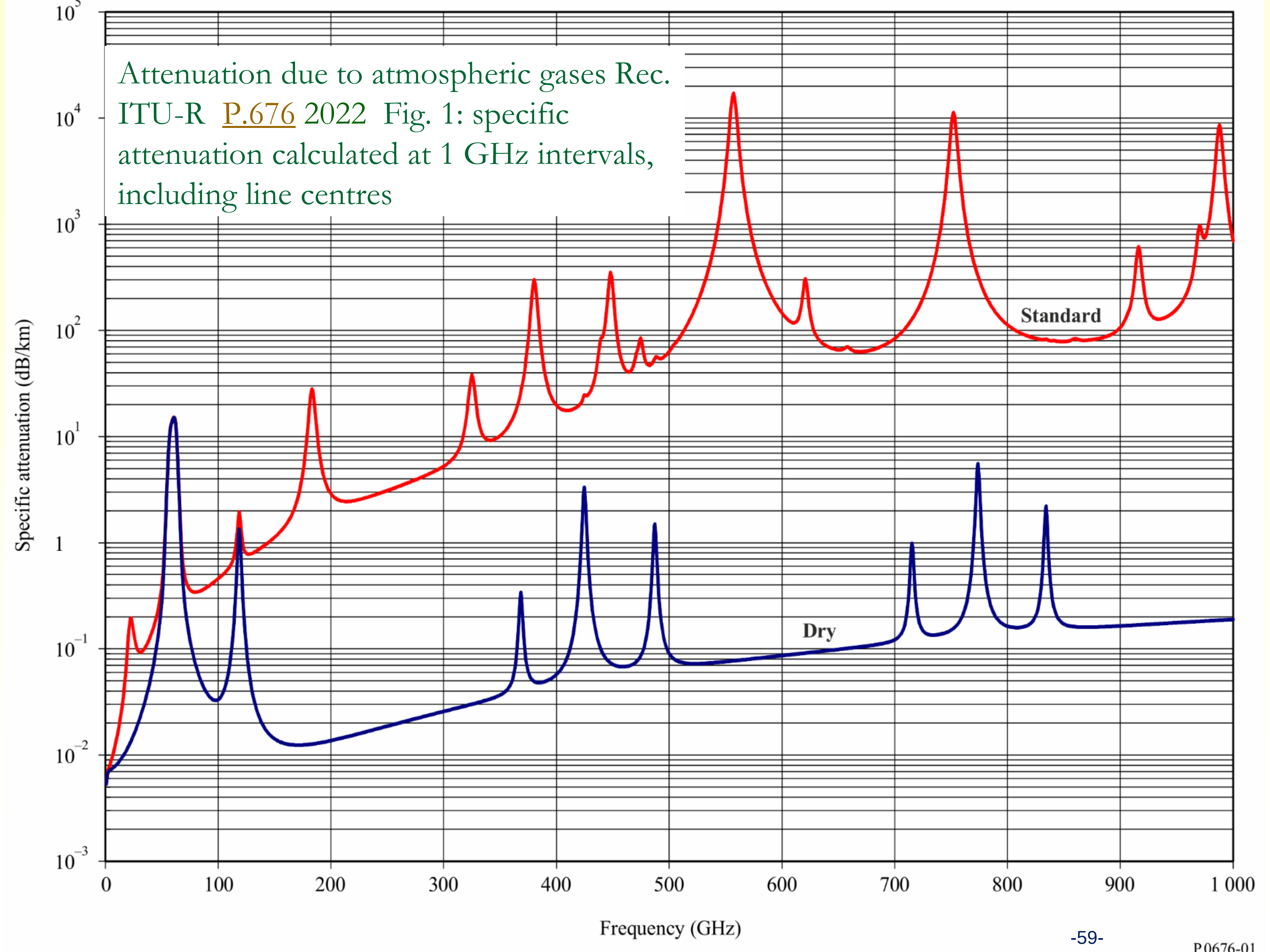
Example of trans-horizon path profile (ITU-R P.1812 2019)

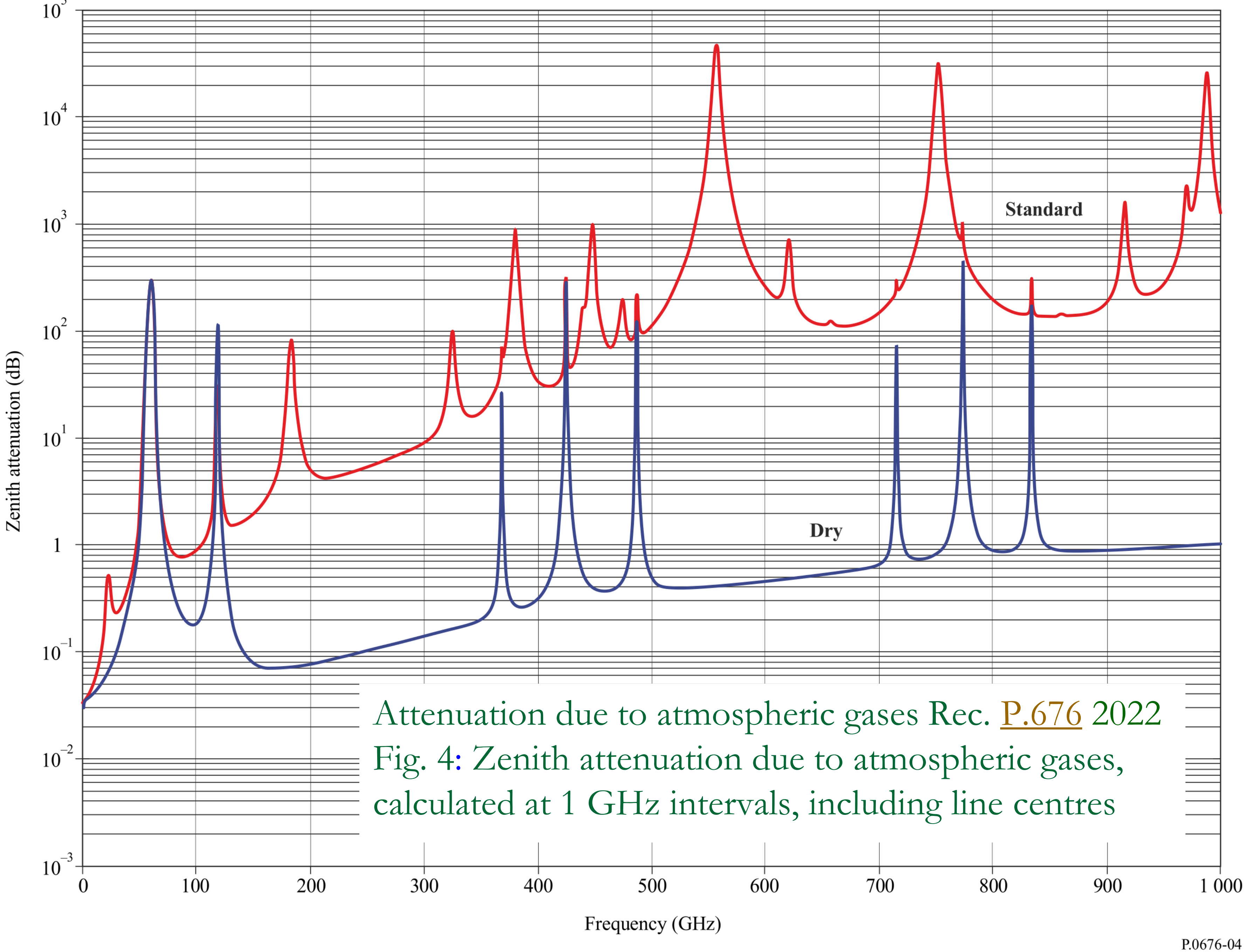


Millimeter-wave to Submillimeter-wave MMICs & Systems for Sensing and Communications; Dr.-Ing. Sébastien Chartier; Advanced Circuits Research Center (ACRC)

- Millimetre and submillimeter waves penetrate dust, smoke, fog, clouds, clothes
- Atmospheric windows at 94, 140, 220, 340, 410, 480, 660, 850 GHz
- Millimeter and submillimeter waves enable superior spatial resolution; reconnaissance, camp protection;
- Small dimensions, therefore UAV applications
- High data rate, such as for point-to-point data links

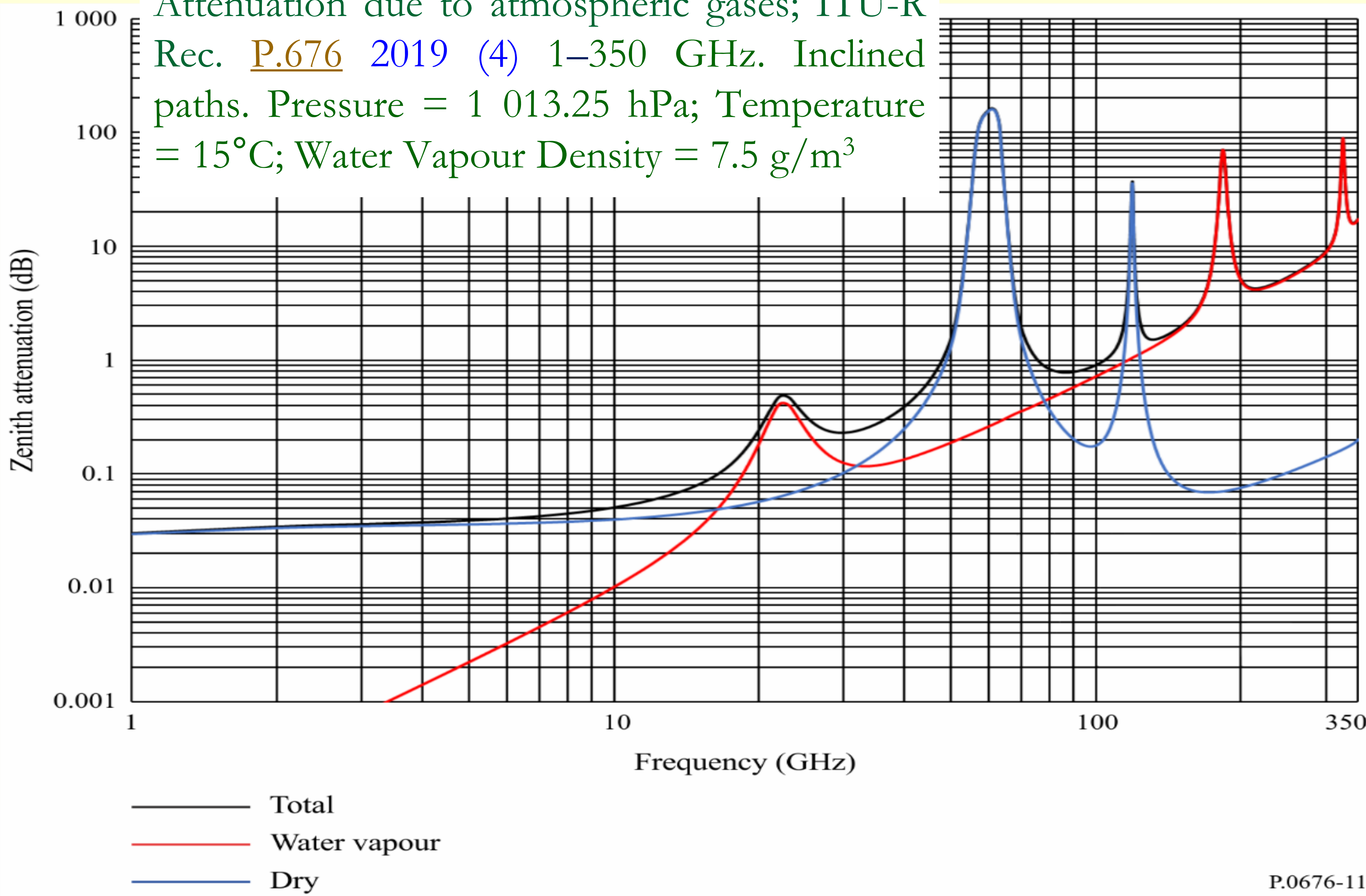

1 bar, 20°C, 43.4% RH
Atmospheric Attenuation [dB/m]
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
O_2
O_2
H_2O
H_2O
94
140
220
340
410
480
660
850
Submillimeter Waves
0
100
200
300
400
500
600
700
800
900
1000
Frequency [GHz]

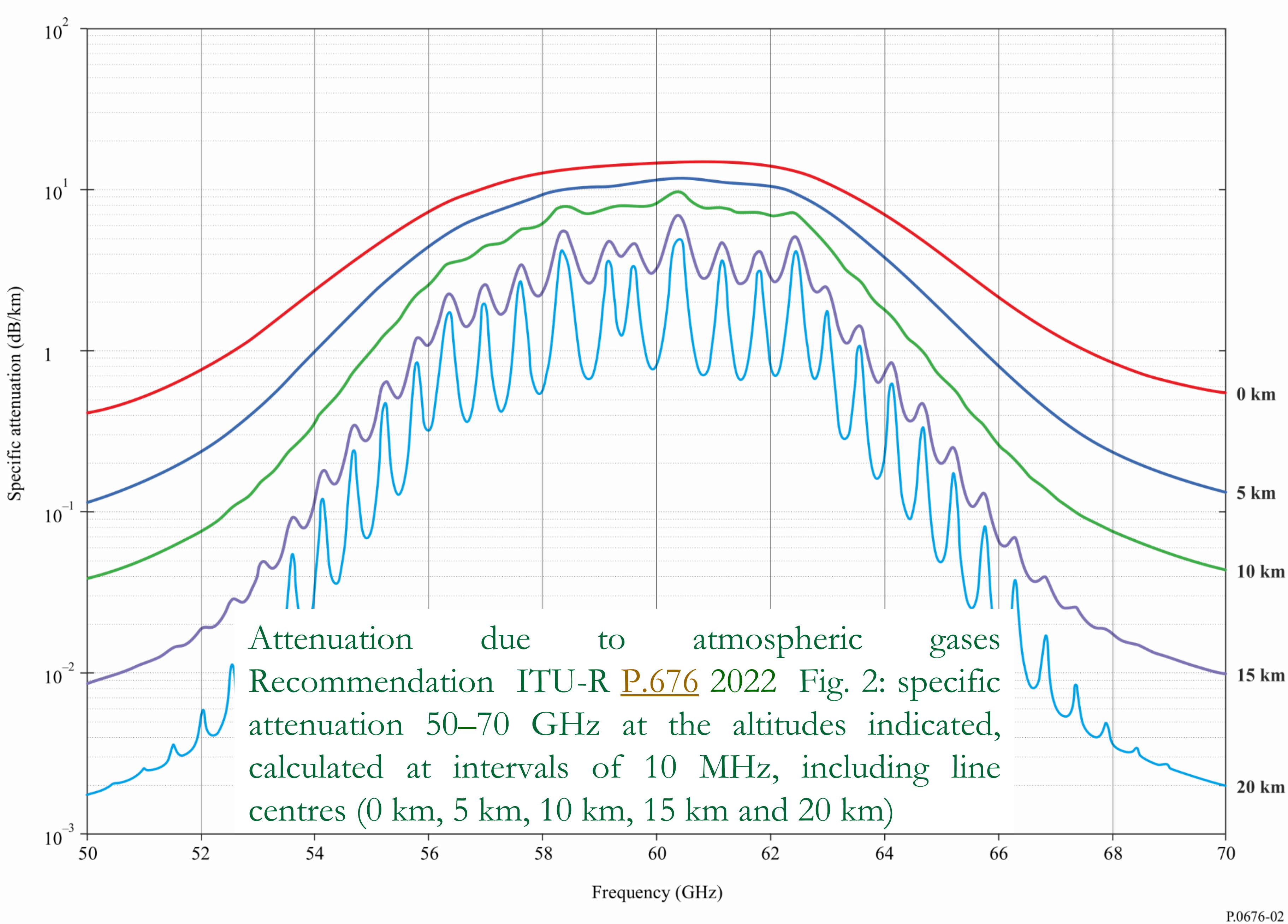

Attenuation due to atmospheric gases Rec. ITU-R P.676 2022 Fig. 1: specific attenuation calculated at 1 GHz intervals, including line centres
Specific attenuation (dB/km)
Frequency (GHz)
Standard
Dry
P.0676-01



Attenuation due to atmospheric gases Rec. P.676 2022
Fig. 4: Zenith attenuation due to atmospheric gases, calculated at 1 GHz intervals, including line centres

Attenuation due to atmospheric gases; ITU-R Rec. P.676 2019 (4) 1–350 GHz. Inclined paths. Pressure = 1 013.25 hPa; Temperature = 15°C; Water Vapour Density = 7.5 g/m^3

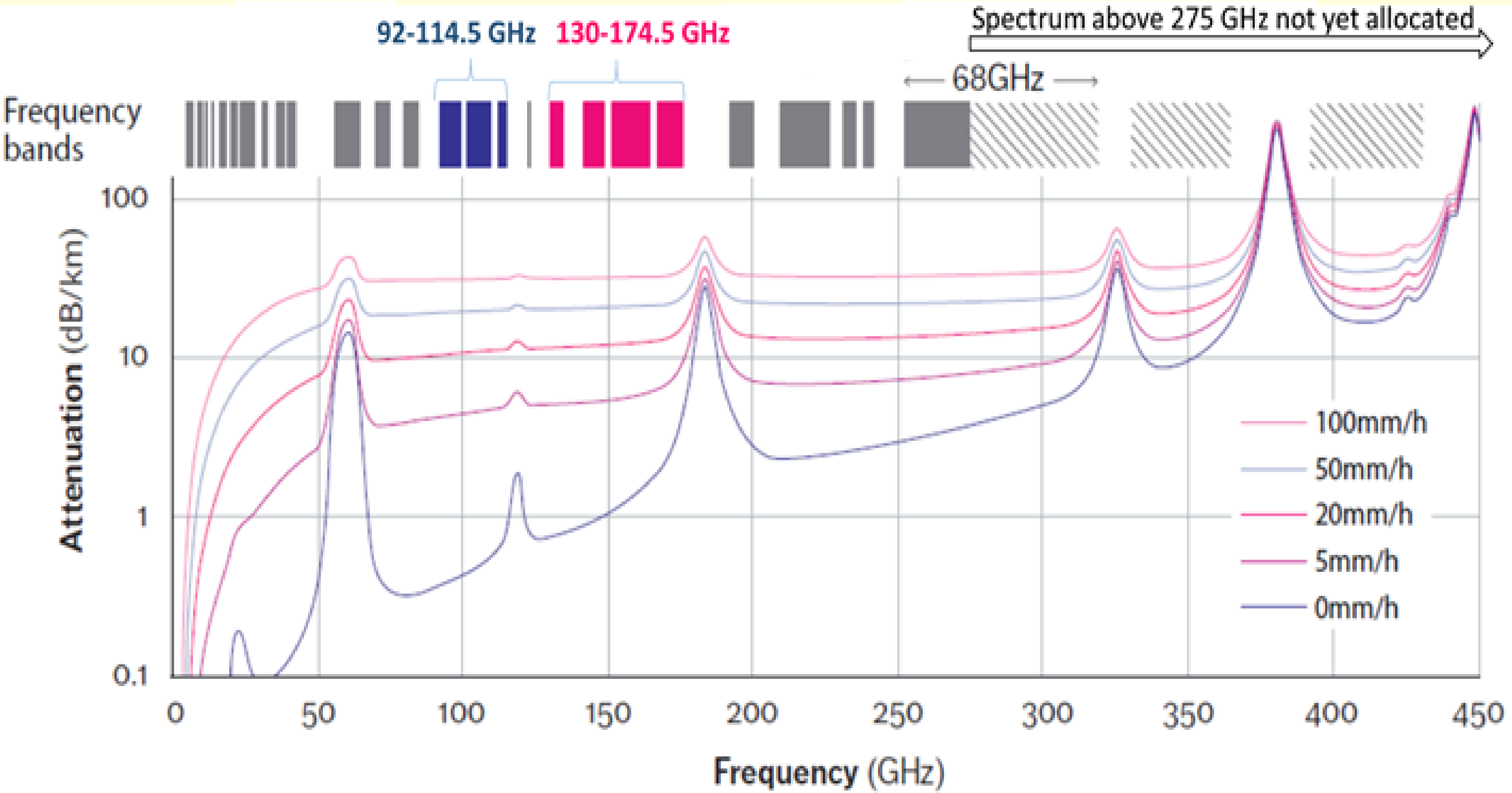




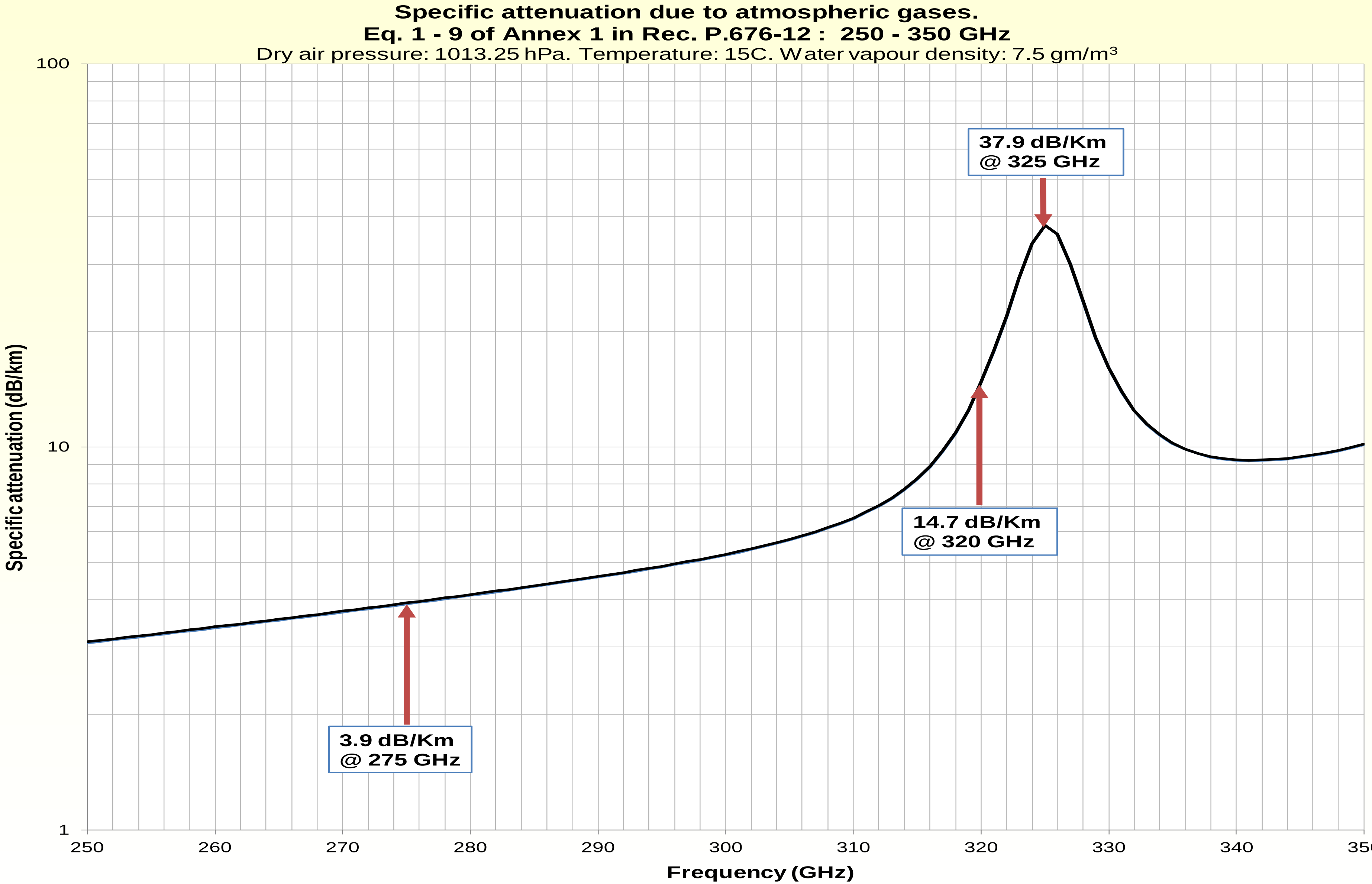
Attenuation due to atmospheric gases Recommendation ITU-R P.676 2022 Fig. 2: specific attenuation 50–70 GHz at the altitudes indicated, calculated at intervals of 10 MHz, including line centres (0 km, 5 km, 10 km, 15 km and 20 km)

Attenuation from atmospheric gases and rain

Report F.2416 (2018) Fig. 2

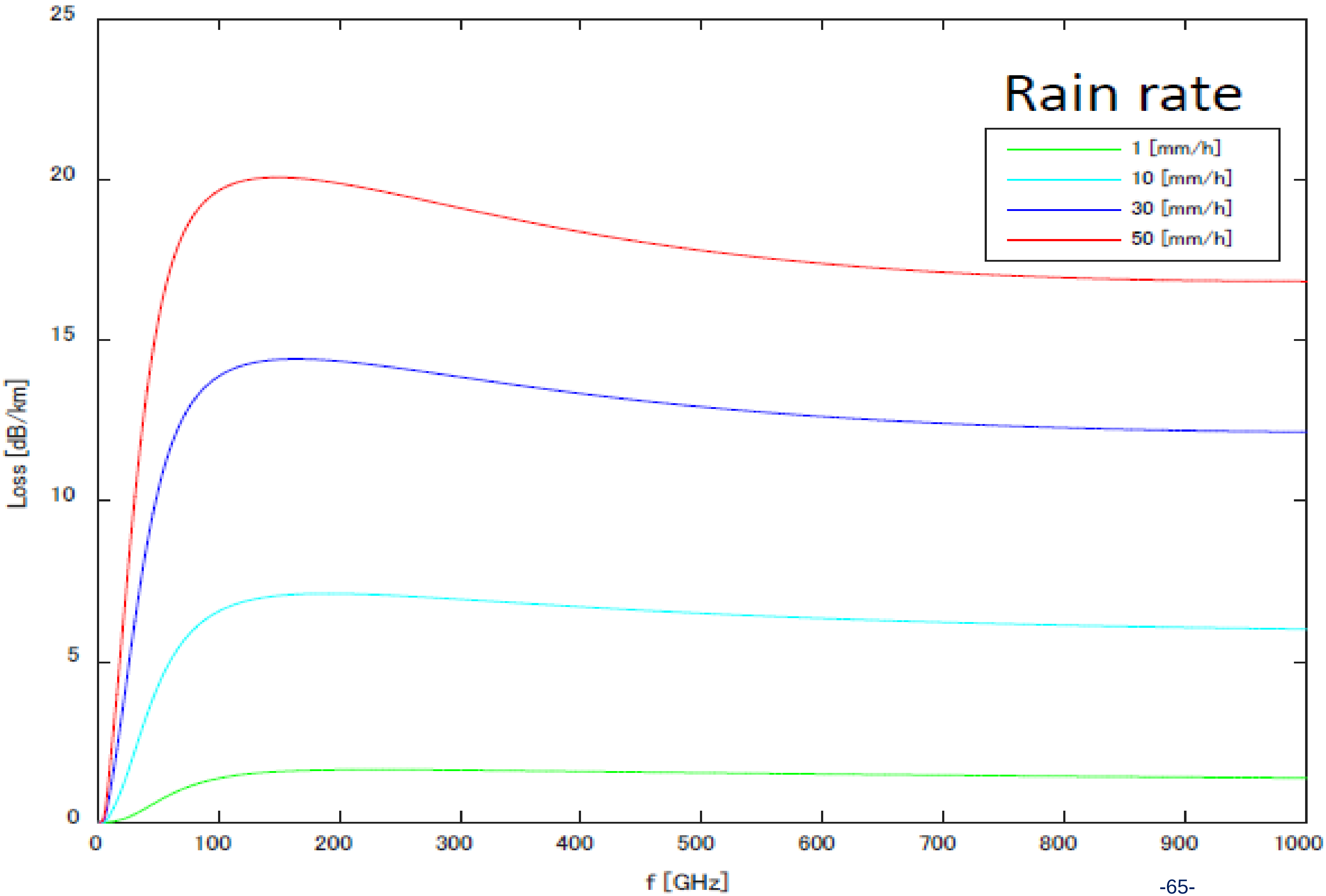


Attenuation characteristics by atmospheric gases Revised Report F.2416 (2022) Fig. 4

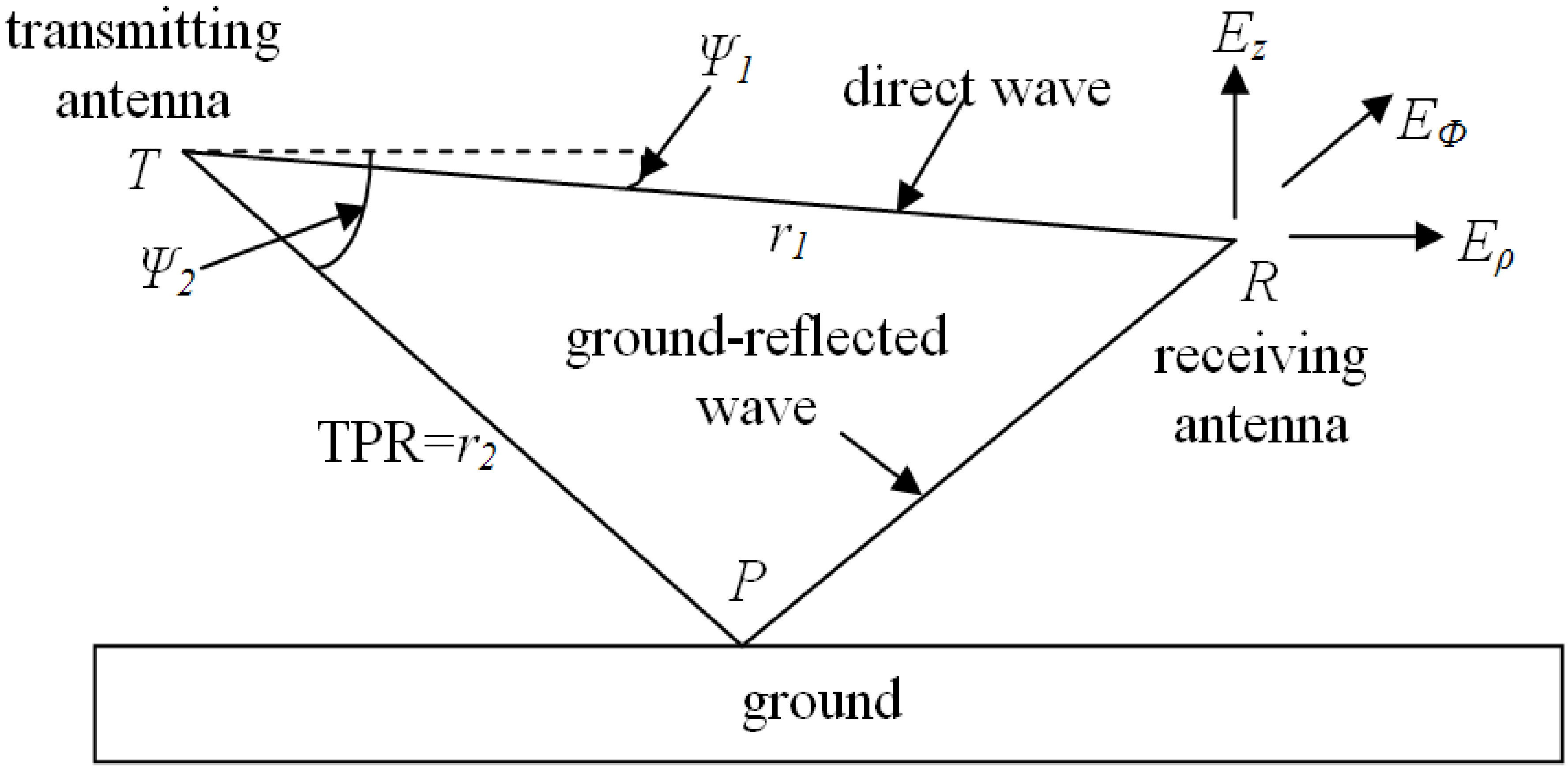


Attenuation characteristics by rain rate

Rep. F.2416 (2018) Fig. 5



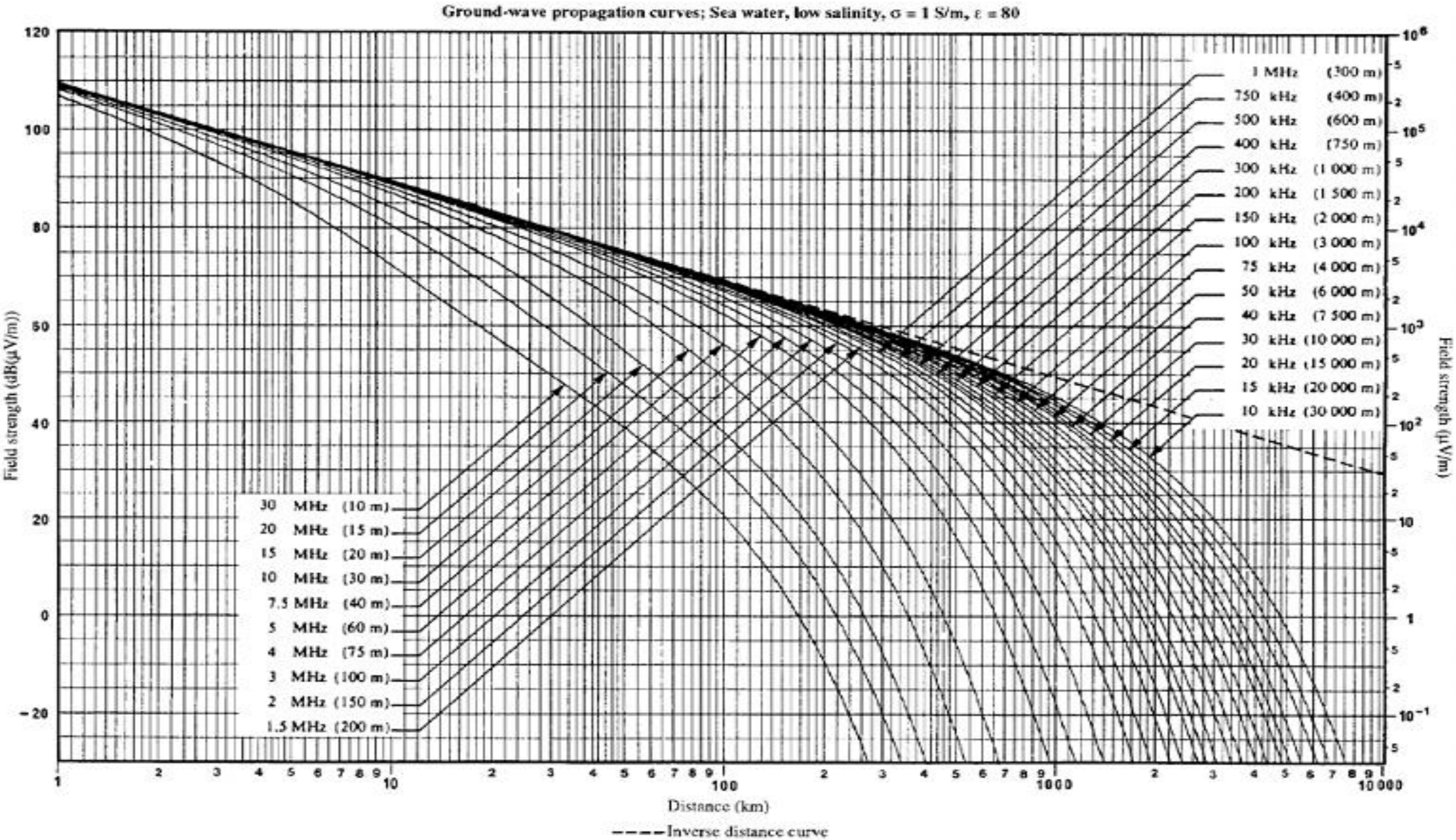
Ground Wave Propagation [Ground Wave propagation handbook]



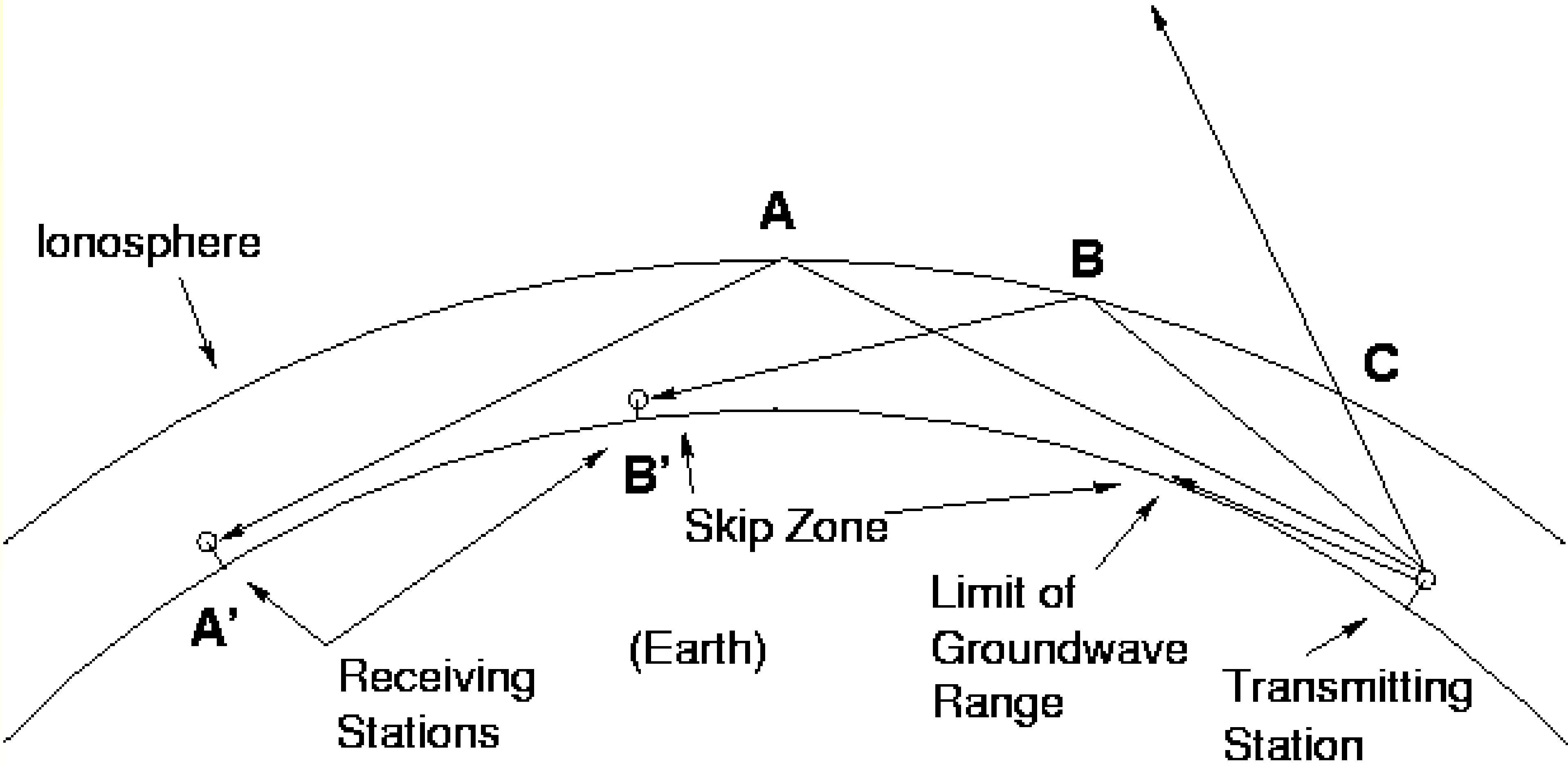
GRWAVE generates propagation curves; calculation of ground-wave field strength in an exponential atmosphere as a function of frequency, antenna heights and ground constants; approximate frequency range 10 kHz-10 GHz. GRWAVE is most useful for RF 10 kHz to 30 MHz

Ground Wave Propagation (2) Ground Wave propagation handbook

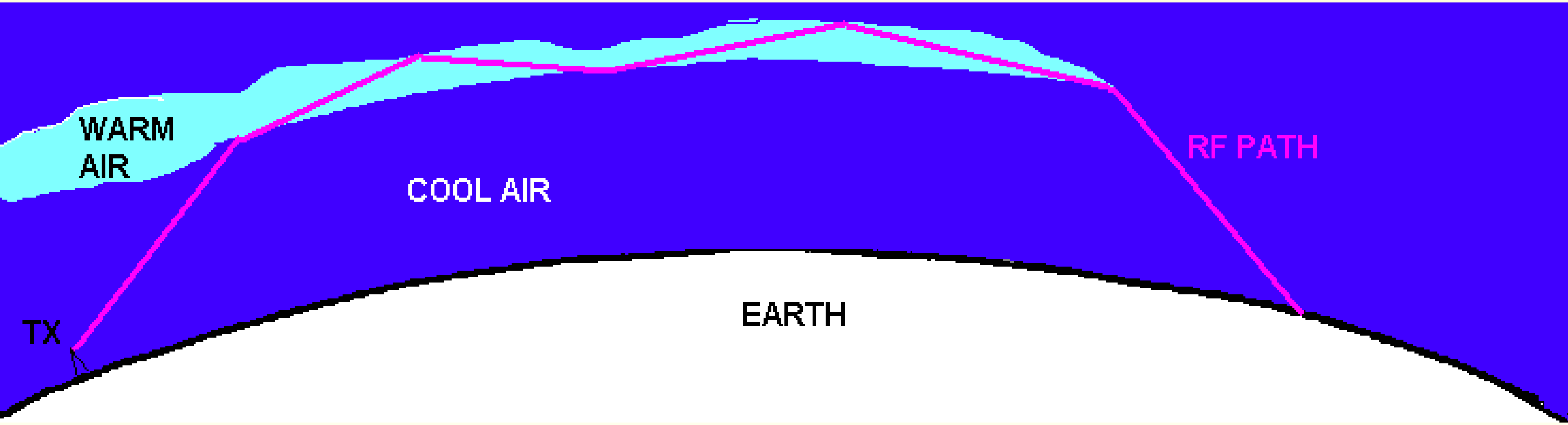
ITU-R P.368 Fig 1-11 contains field-strength curves as a function of distance with RF as a parameter; this example ε= 80; σ= 1 s/m



Propagation Modes (Ray Grimes, Motorola)



Duct: Temperature Inversion / Troposphere Ducting

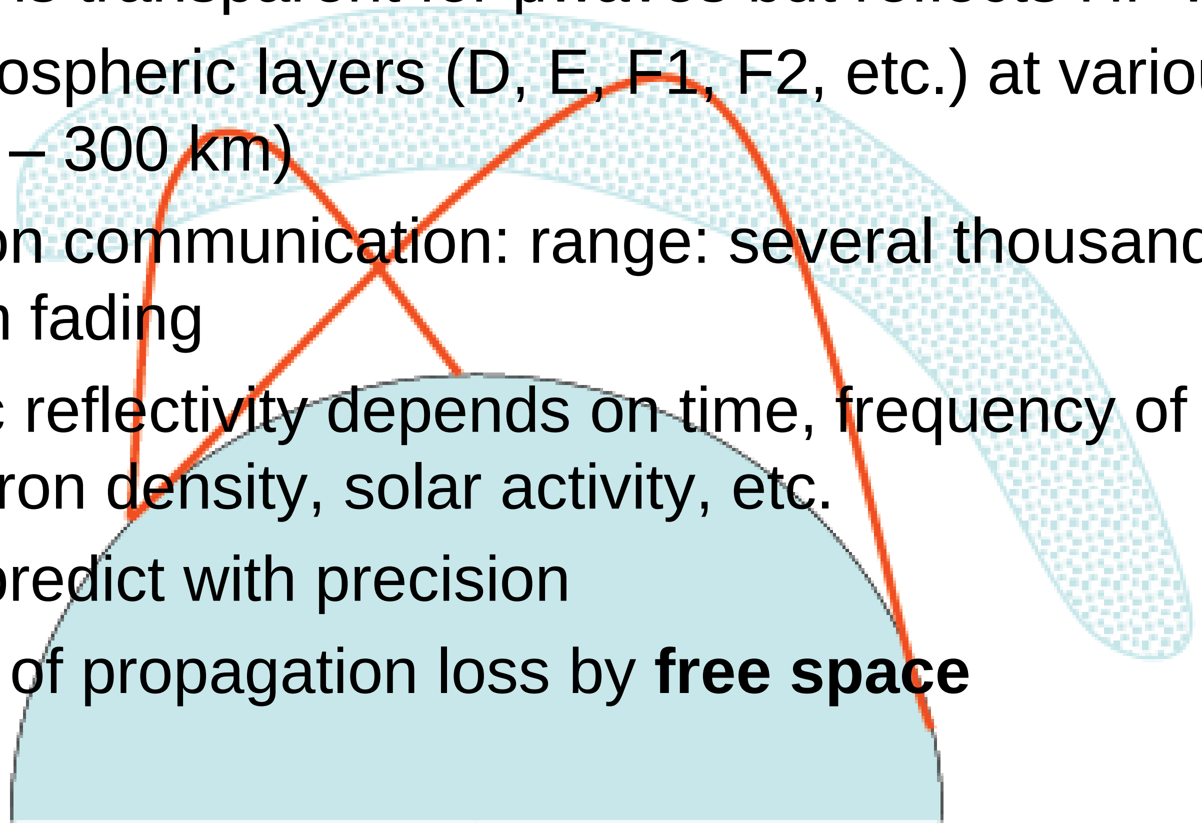


1. **Certain weather conditions** produce a layer of air in the Troposphere that will be at a higher temperature than the layers of air above & below it.
2. Such a layer **will provide a "duct"** creating a path through the warmer layer of air
3. These ducts occur over relatively long distances and at varying heights from almost ground level to several hundred meters above the earth
4. This propagation takes place when hot days are followed by rapid cooling at night. Signals can propagate hundreds of kM up to about 2,000 km

סטרופינסקי

HF Propagation

- Ionospheric “reflections”
- Ionosphere is transparent for µwaves but reflects HF waves
- Various ionospheric layers (D, E, F1, F2, etc.) at various heights (50 – 300 km)
- Over-horizon communication: range: several thousand km; suffers from fading
- Ionospheric reflectivity depends on time, frequency of incident wave, electron density, solar activity, etc.
- Difficult to predict with precision
- Calculation of propagation loss by **free space**



Propagation Loss HF (P. 533)

$$PL(dB) = 20\log\left(\frac{4\pi d}{\lambda}\right) \qquad PL(dB) = 32.44 + 20\log d_{kM} + 20\log f_{MHz}$$

P. 533 5.2.2 Field strength determination

the median field strength is given by:

E_w = 136.6 + P_t + G_t + **20 log *f*** – L_b dB (μV/m) (17)

where:

f : transmitting frequency (MHz)

P_t : transmitter power (dB(1 kW))

G_t : Tx ant gain at the required azimuth & elevation angles relative to an isotropic ant (dB)

L_b : ray path basic transmission loss for the mode under consideration given by:

L_b = 32.45 + **20 log *f*** + 20 log p' + L_i + L_m + L_g + L_h + L_z (18)

P' : virtual slant range (km)

L_i : absorption loss (dB) for an *n*-hop mode given by

L_m: "above-the-MUF" loss.

L_g: summed ground-reflection loss at intermediate reflection points

L_h: factor to allow for auroral and other signal losses

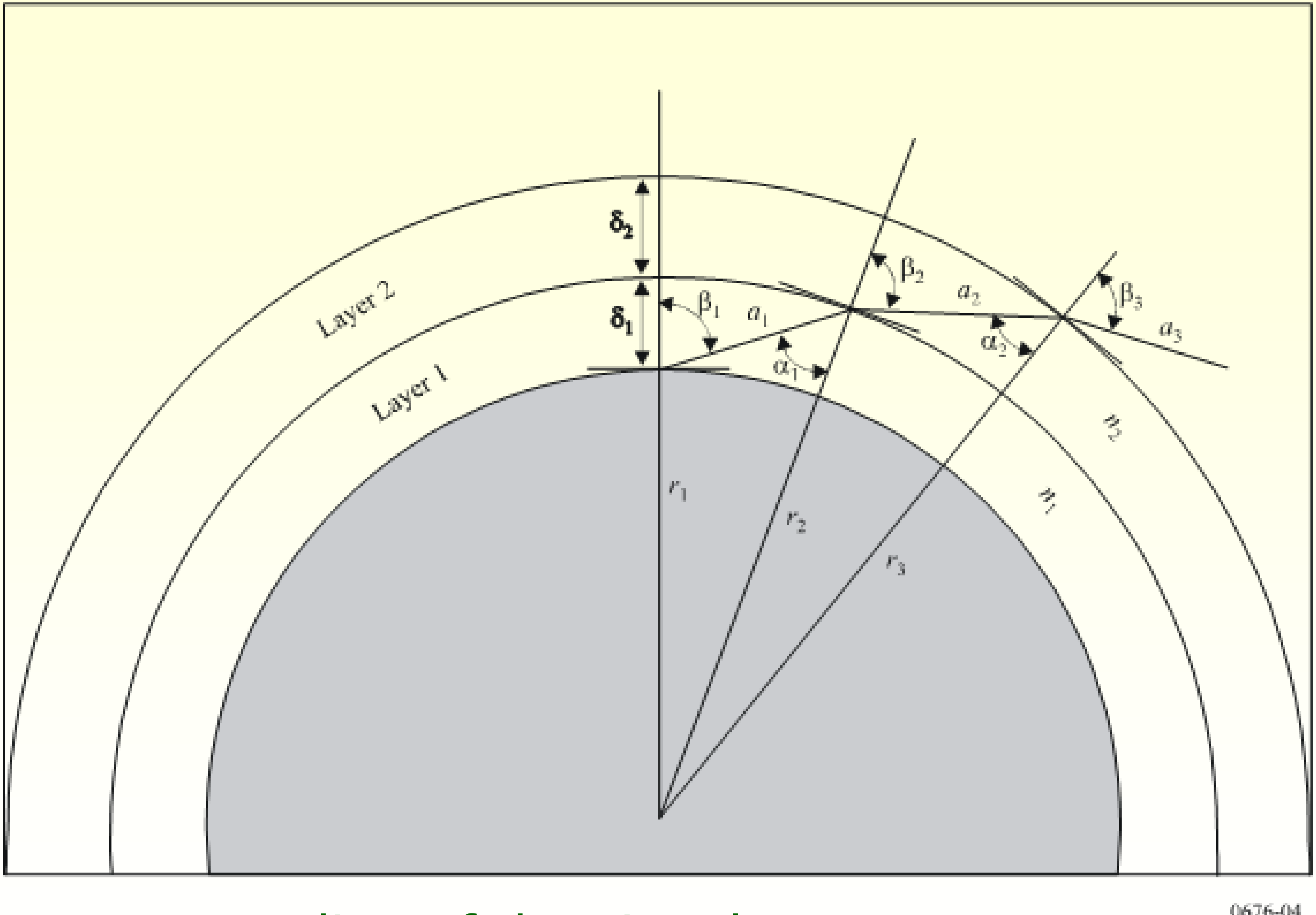
L_z: term containing those effects in sky-wave propagation

Note: **20 log *f*** of E_w is subtracted by **20 log *f*** at L_b

HF Propagation; Definitions

1. *basic MUF* is the highest frequency by which a radiowave can propagate between given terminals, on a specified occasion, by ionospheric refraction alone
2. *Optimum working frequency (OWF)*: the lower decile of the daily values of operational MUF at a given time over a specified period, usually a month. That is, it is the frequency that is exceeded by the operational MUF during 90% of the specified period
3. *Highest probable frequency (HPF)*: the upper decile of the daily values of operational MUF at a given time over a specified period, usually a month. That is, it is the frequency that is exceeded by the operational MUF during 10% of the specified period
4. *Lowest usable frequency (LUF)*: the lowest frequency that would permit acceptable performance of a radio circuit by signal propagation via the ionosphere between given terminals at a given time under specified working conditions

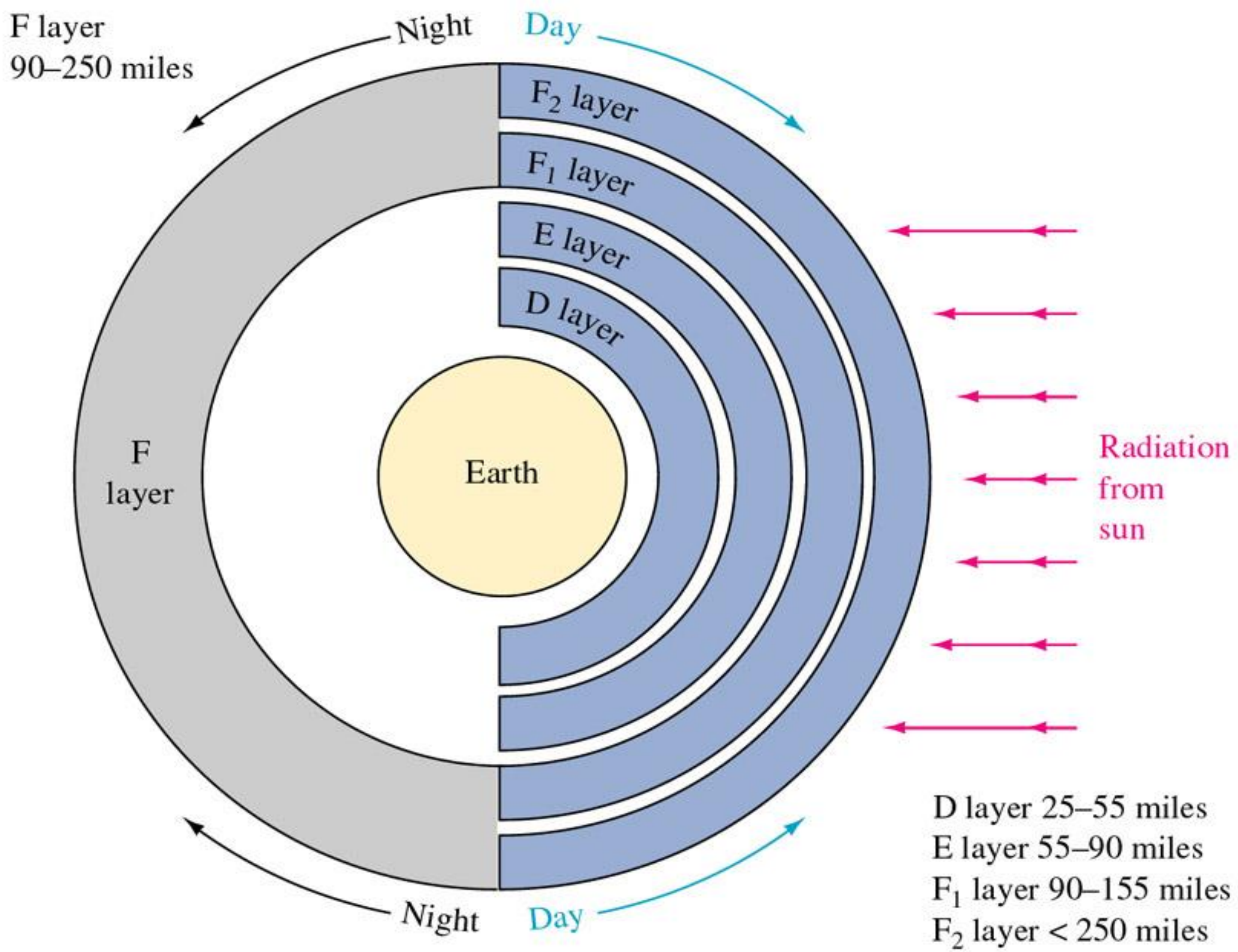
HF Layers



Bending of the signal (ITU-R P. 676 Fig. 4)

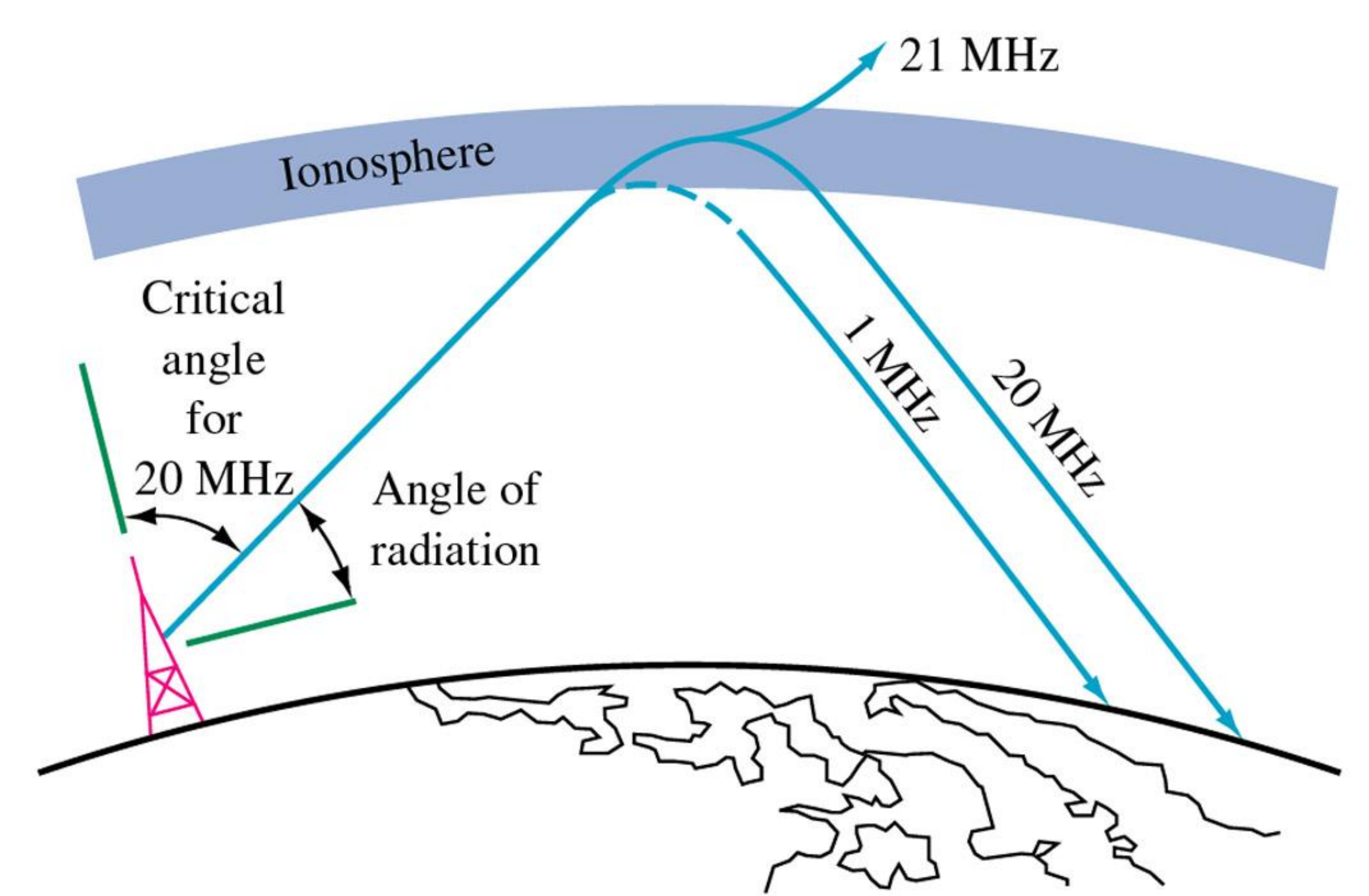
Ionospheric Layers (cont'd)

(from web)



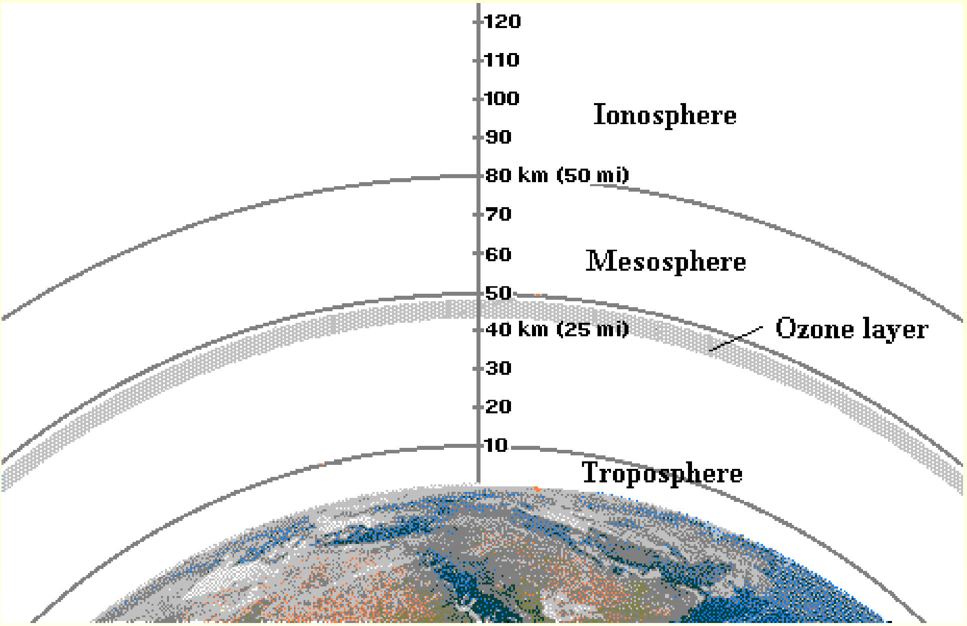
Ionospheric Layers (cont'd)

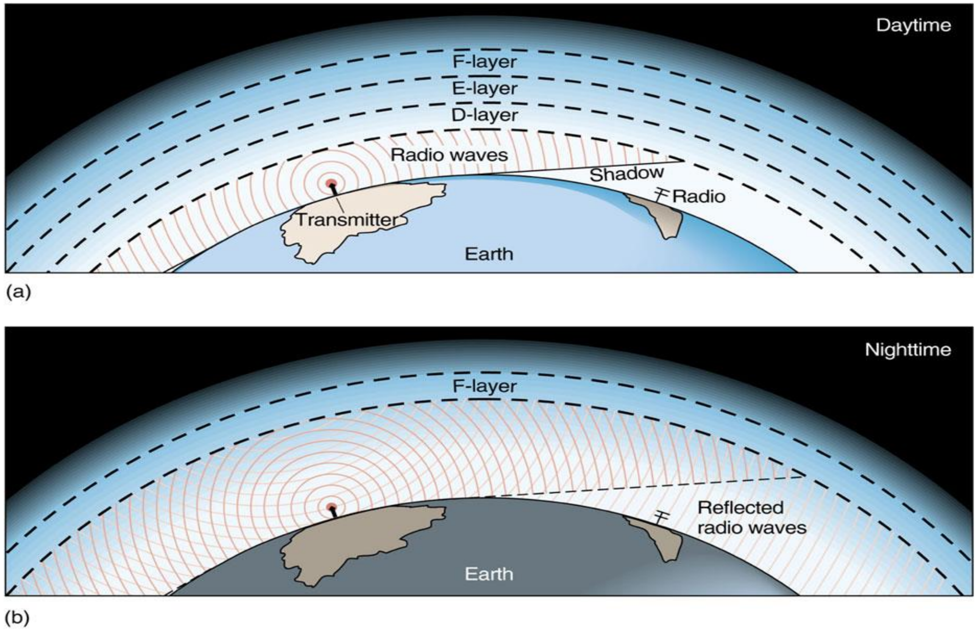
(from web)

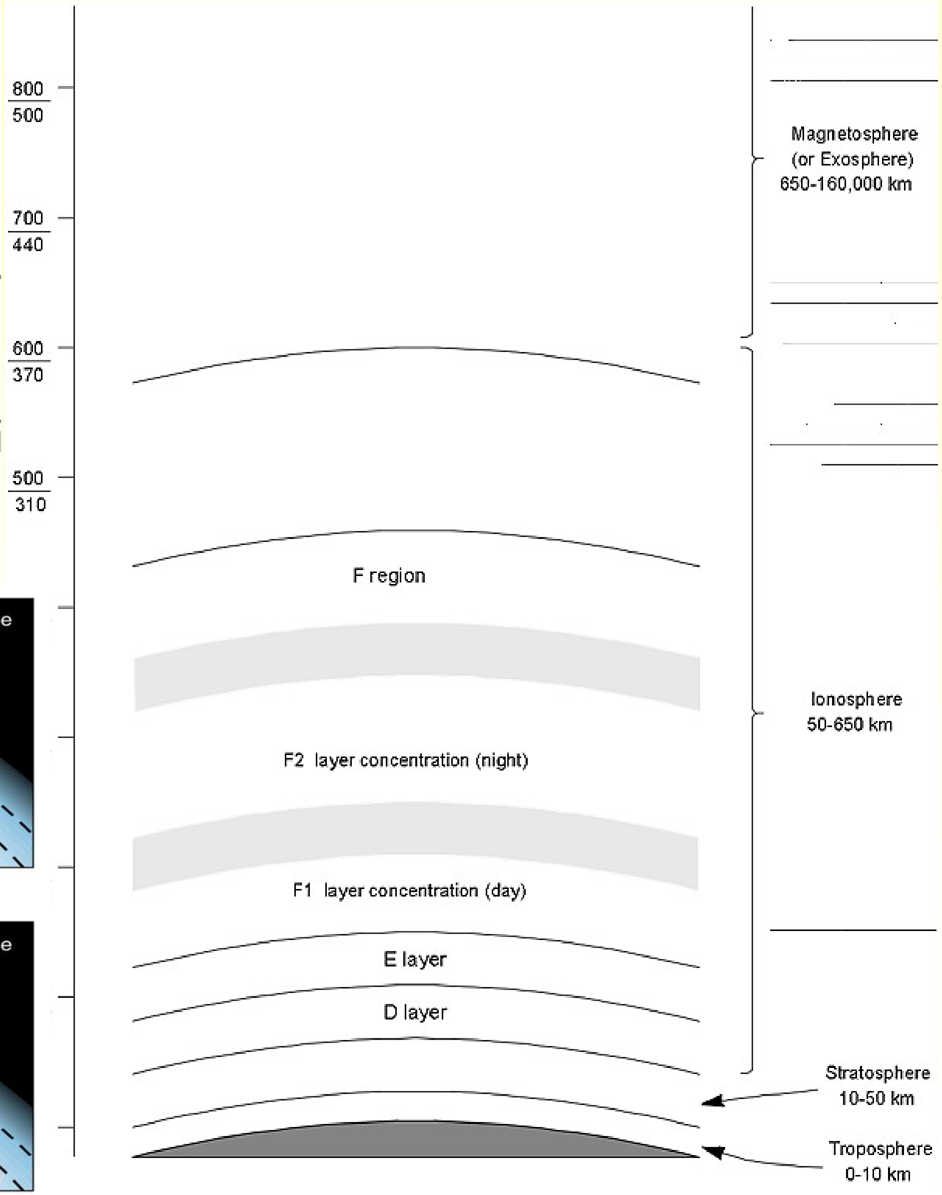


Ionosphere Regions

(from web)

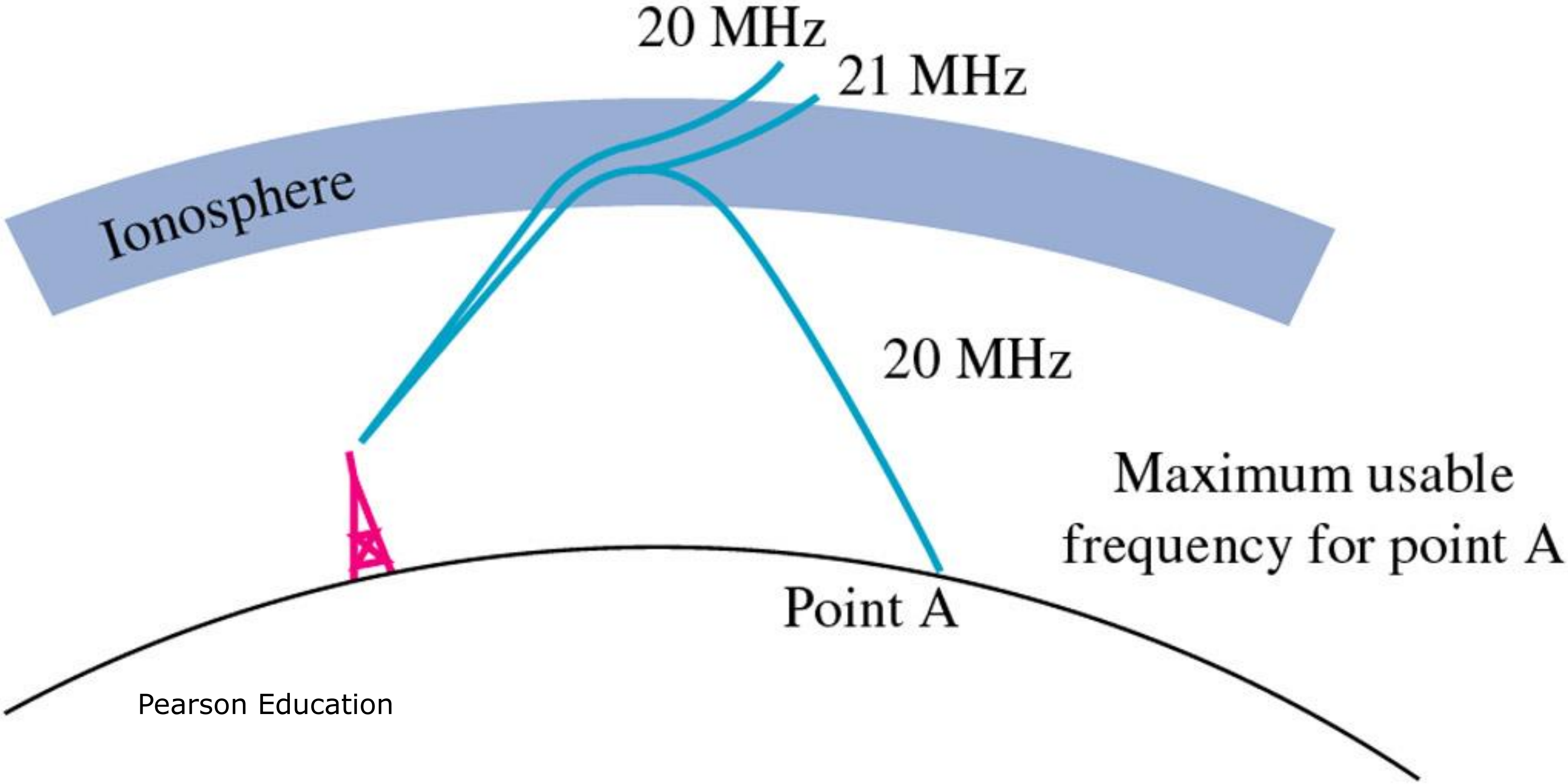






Ionospheric Layers (cont'd)

(from web)



Pearson Education

Figure 2.2 Hop lengths based on an antenna elevation angle of 4º and E and F region refraction heights of 100 km and 300 km, respectively

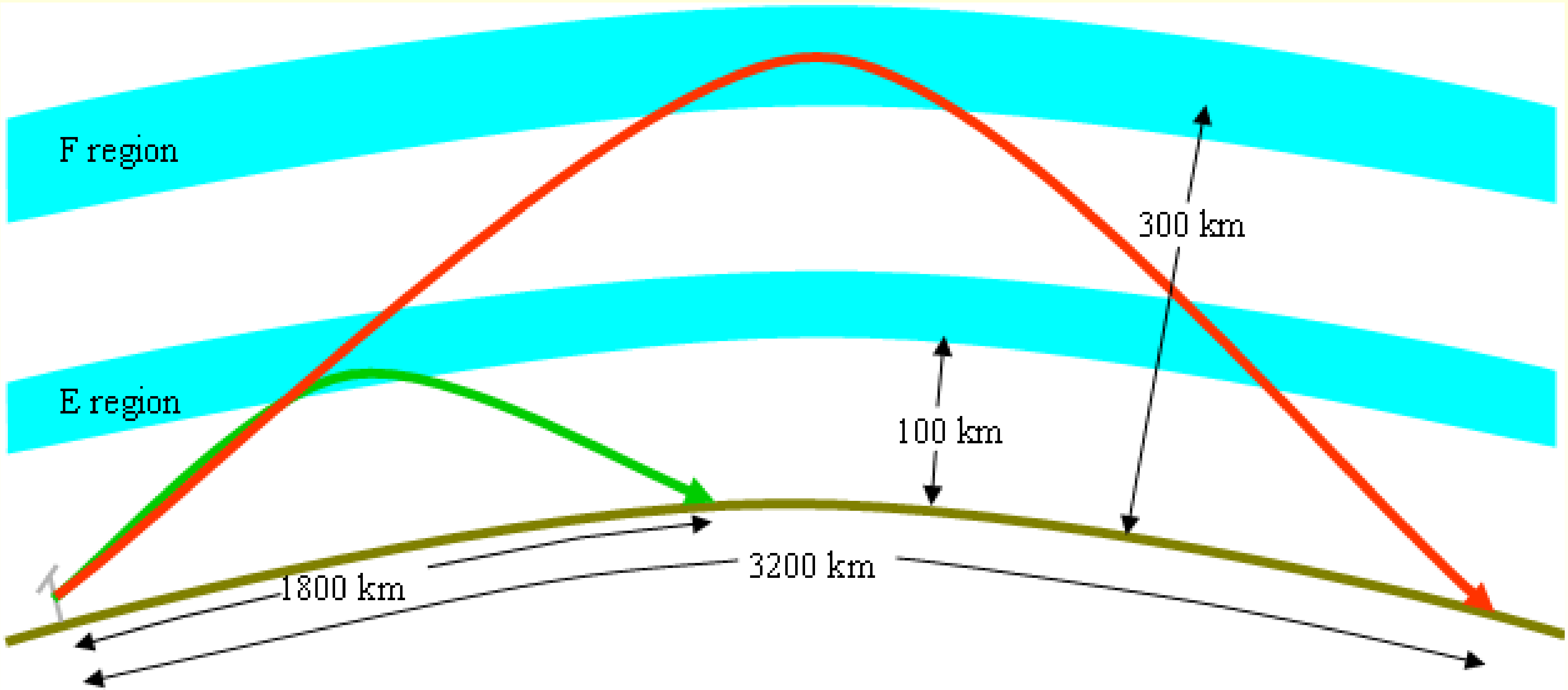
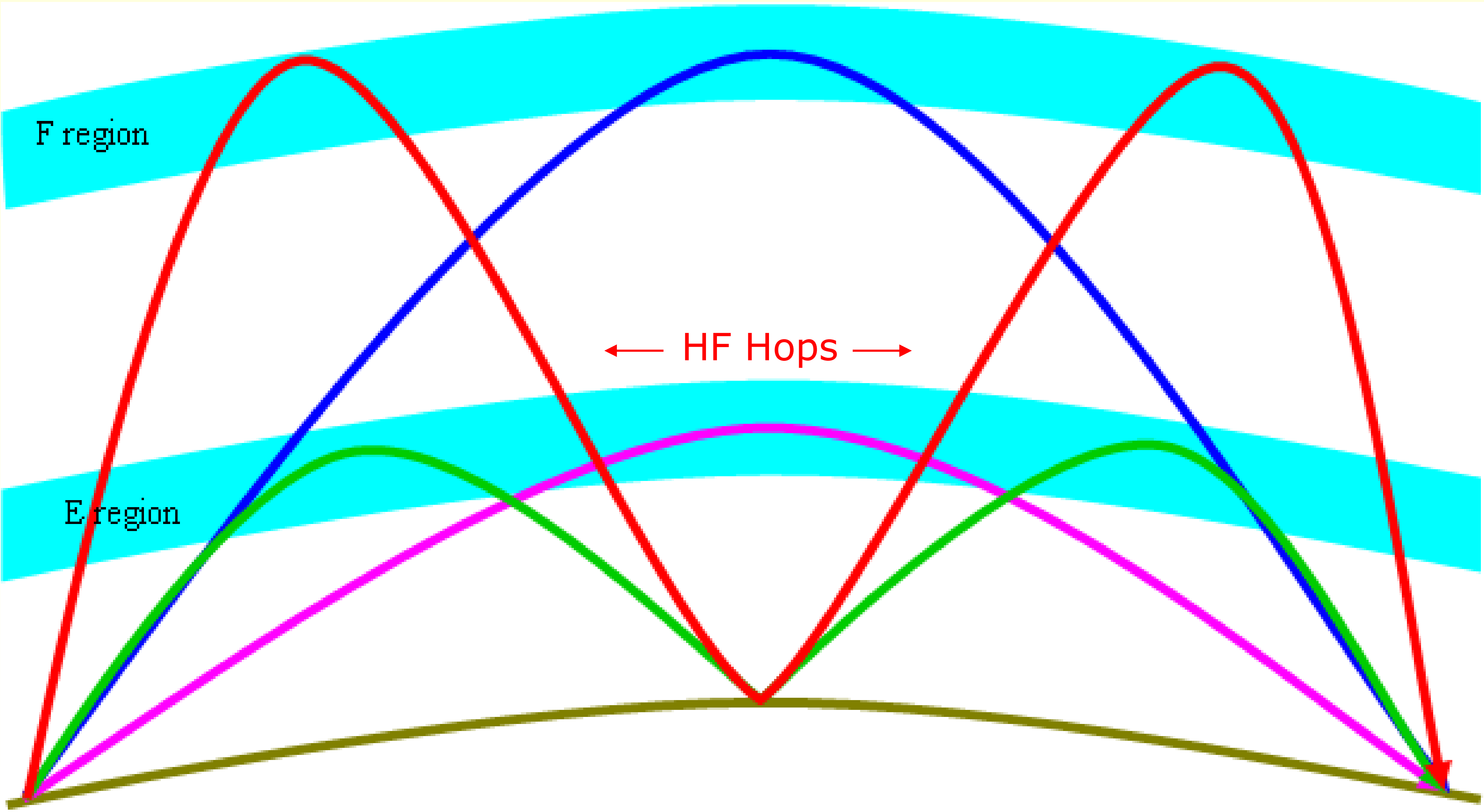
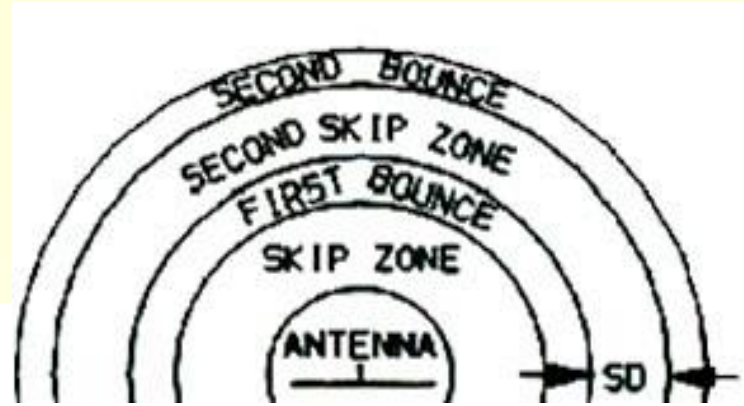
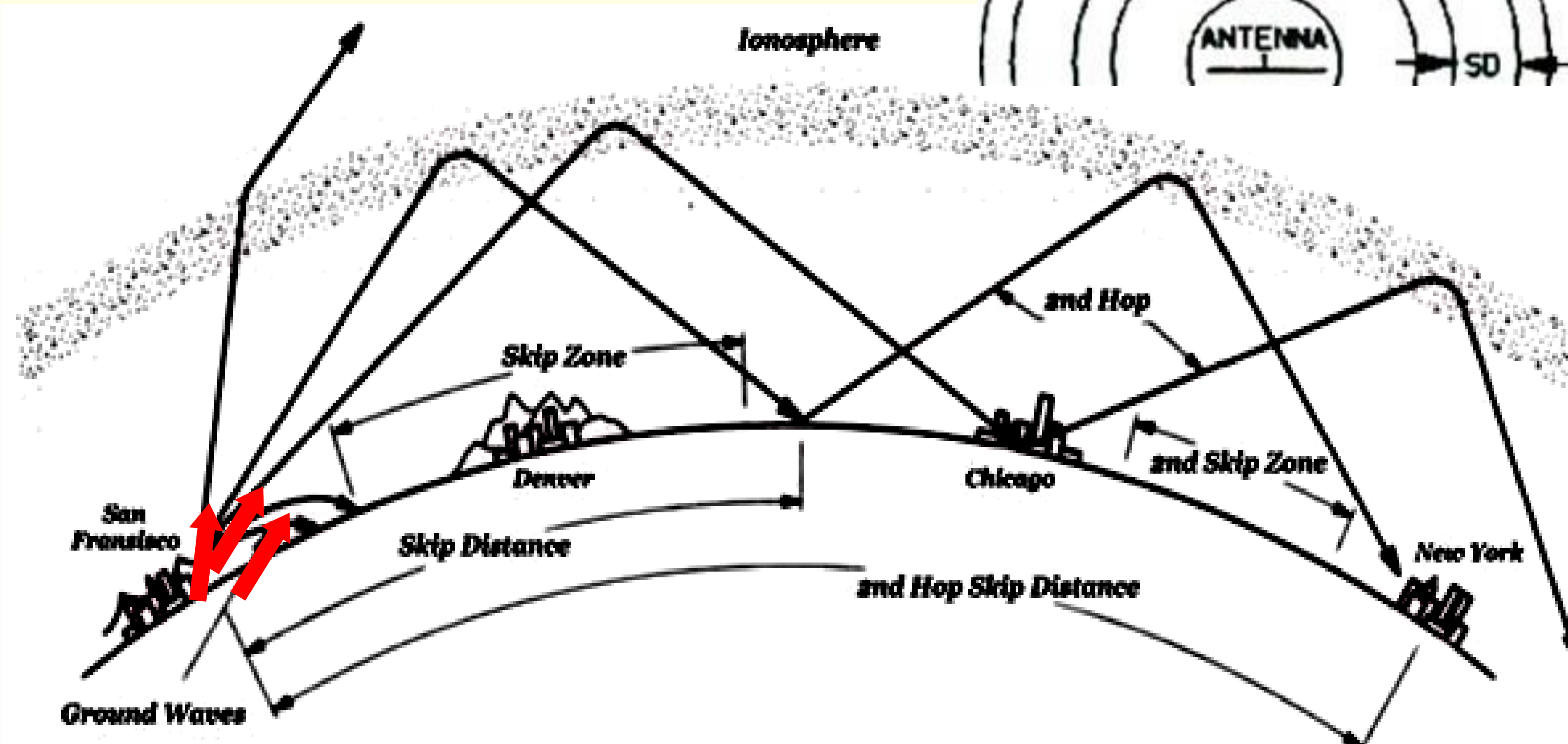


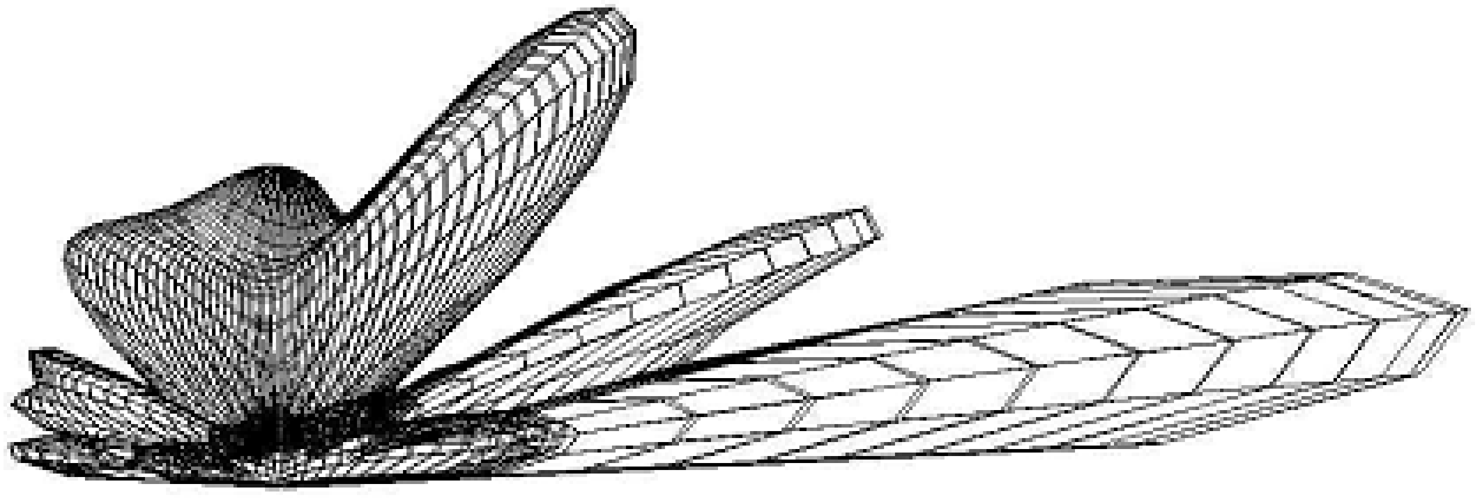
Figure 2.2 Hop lengths based on an antenna elevation angle of 4º and E and F region refraction heights of 100 km and 300 km, respectively



HF Propagation; Hops, Skips Zones (from web)



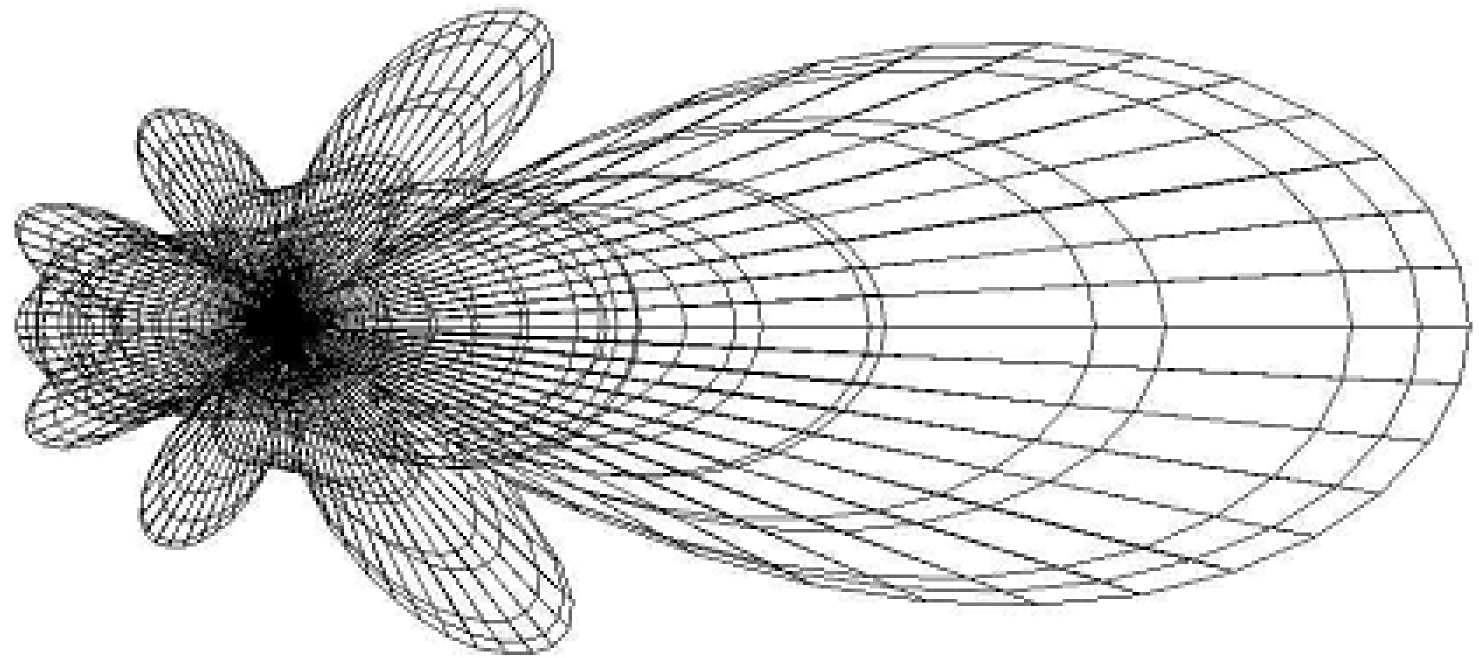




ITU-R BS.1698_2005

Typical HF antenna patterns

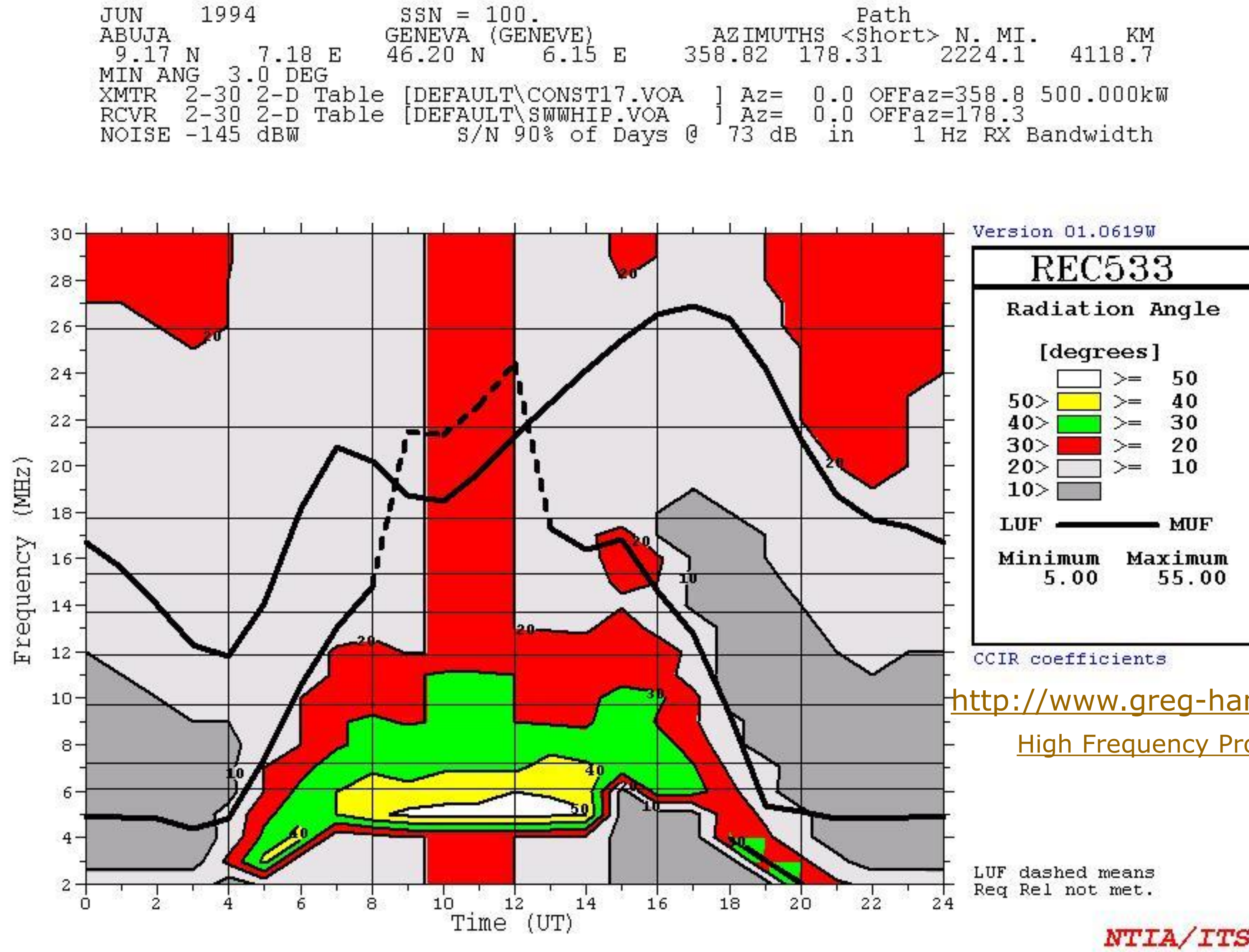
1698-25



Horizontal

1698-24

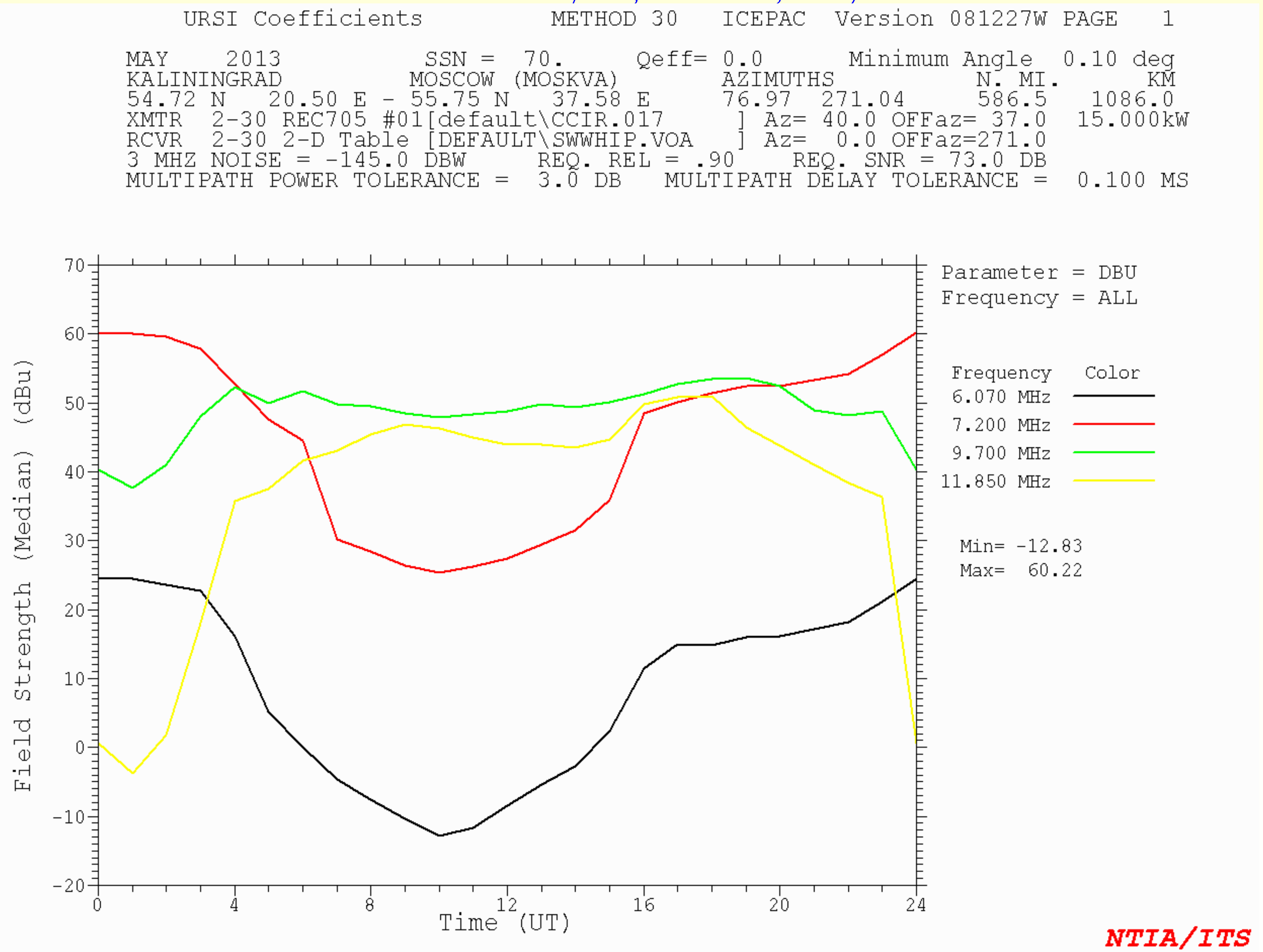
HF Propagation; Abuja-Geneva, IONCAP



http://www.greg-hand.com/hf.html

[High Frequency Propagation Models](http://www.greg-hand.com/hf.html)

Calculated field strength (within 24 hours) in the measuring point in Moscow region Kaliningrad; Tx (NTIA@ ITU-R doc 6A/360, Transition; 2013)



Advanced Wireless Communications

Academic Course for Eng. Students

Antennas- performance

Gain, Beamwidth, Pattern, Polarization and VSWR

Sami Shamoon College of Engineering

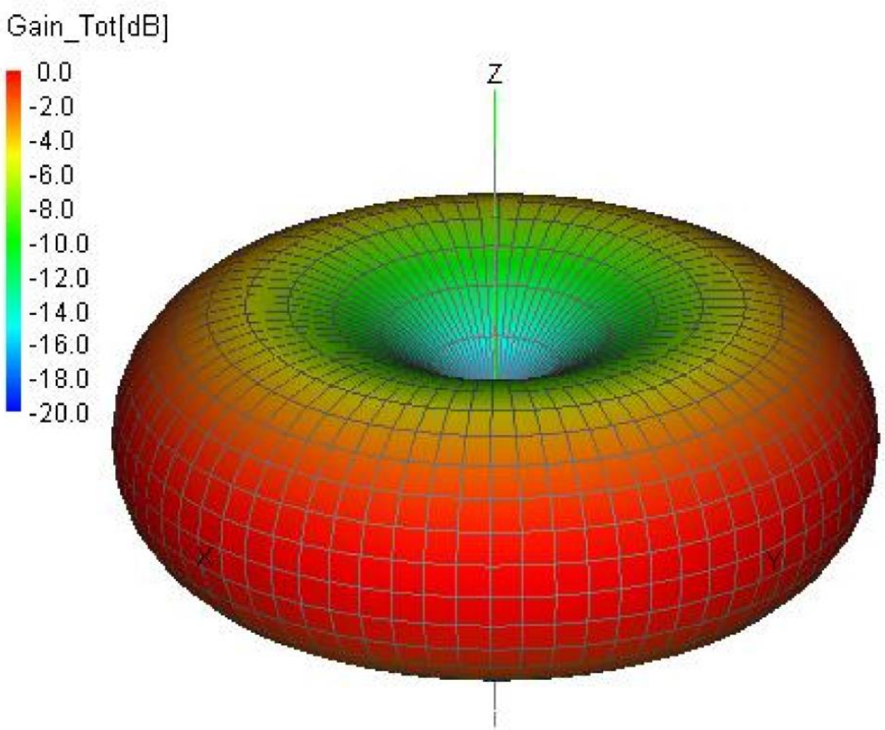
http://mazar.atwebpages.com/

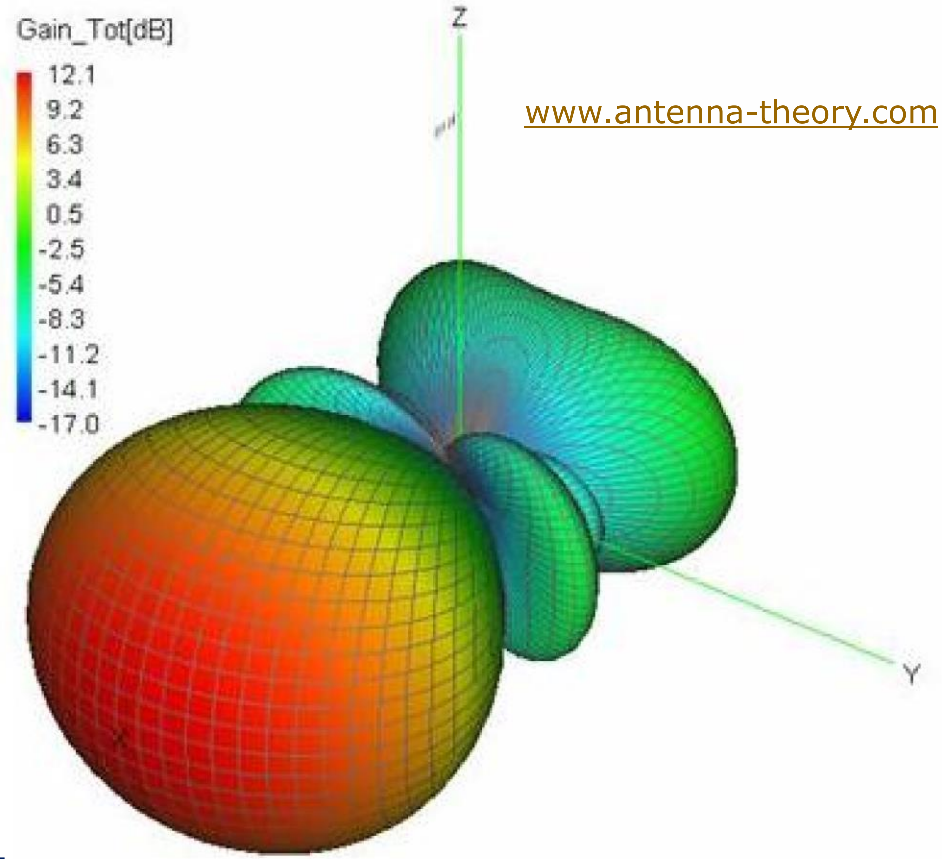
Definitions; Isotropic, Omni and Directional

- Isotropic = equal radiation in all angles (4π steradian)
- Omni Directional = equal radiation in one plane
- Directional = the radiation goes to a narrow sector

Left sketch: 3-D radiation pattern of a dipole **omni-directional antenna**
right sketch: 3-D radiation pattern of a Yagi directional antenna

Aerial Collective Systems

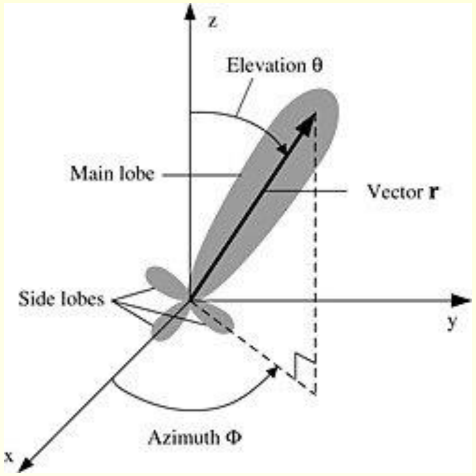




www.antenna-theory.com

Antenna is the interface between **electro-magnetic waves** propagating through space and electric currents moving in metal conductors, used with a **transmitter** or **receiver**

https://www.researchgate.net/profile/Hong-Ning_Dai



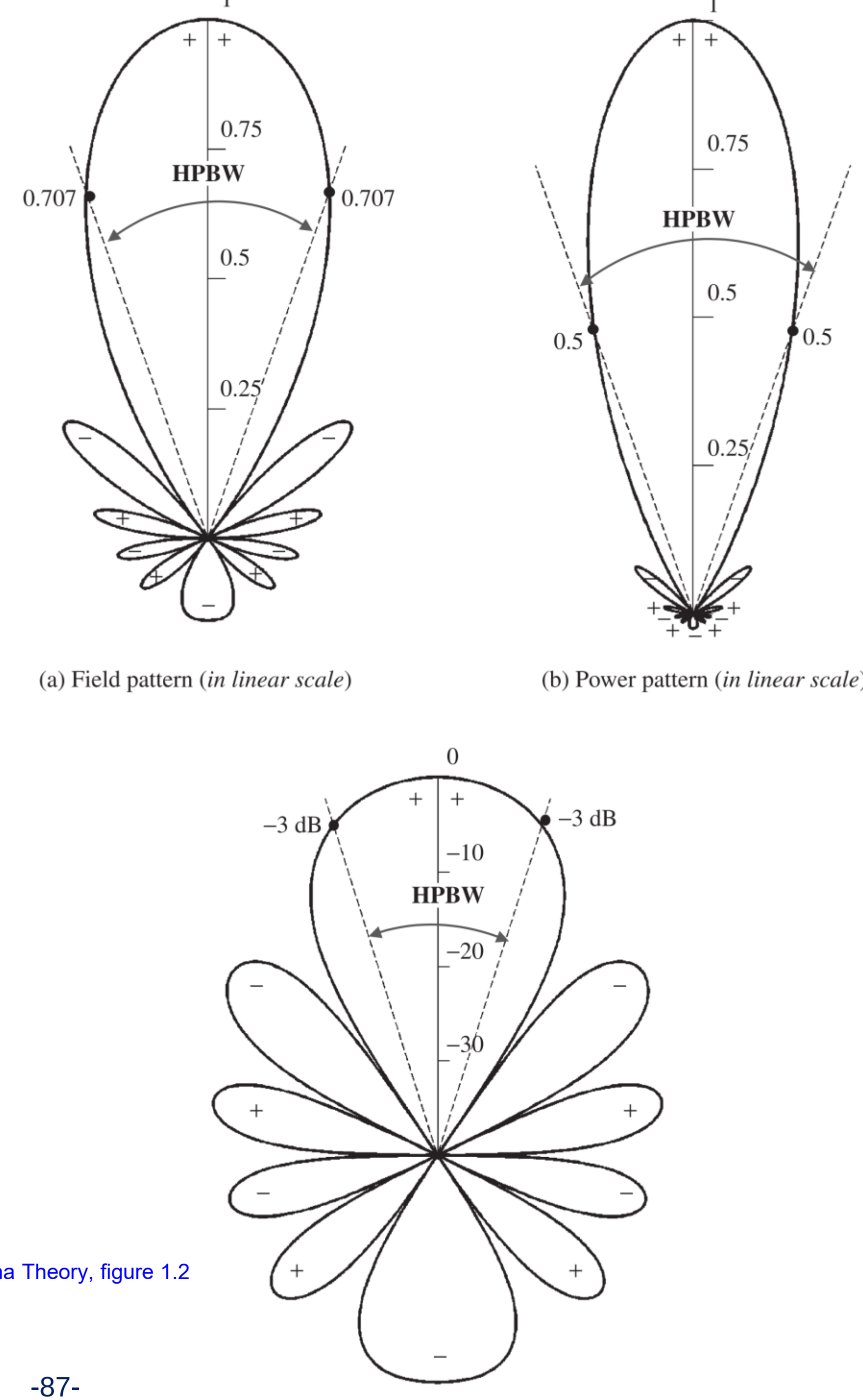
Graf, Rudolf F., ed. (1999) "Antenna"

- Isotropic =
  equal radiation in all angles (4π steradian)
- Omni Directional =
  equal radiation in one plan

- Directional =
  radiation goes to a narrow sector

Two-dimensional normalized *field* pattern (*linear scale*), *power* pattern (*linear scale*), and *power* pattern (in *dB*) of a 10-element linear array with a spacing of $d = 0.25\lambda$

half-power beamwidth (*HPBW*): "In a plane containing the direction of the maximum of a beam, the angle between the two directions in which the radiation intensity is one-half value of the beam; see IEEE Std 145-1983 Definitions of Terms for Antennas



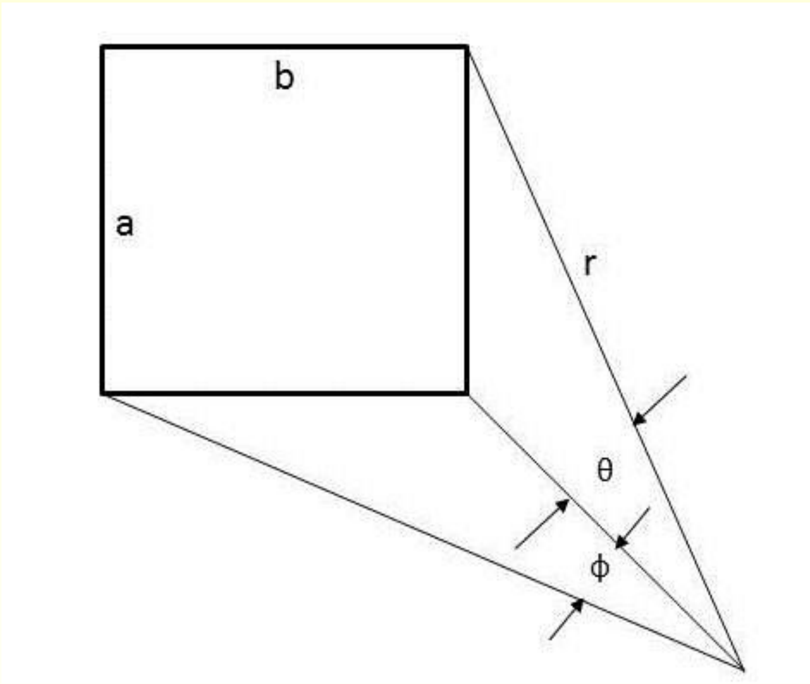
(a) Field pattern (*in linear scale*)

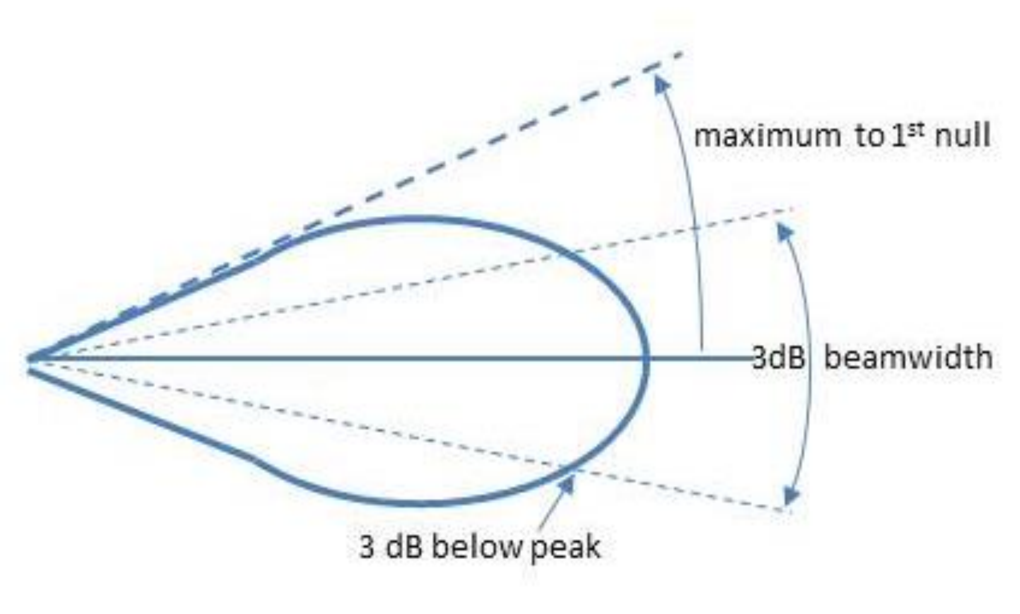
(b) Power pattern (*in linear scale*)

(c) Power pattern (*in dB*)

Balanis,2008 Antenna Theory, figure 1.2

Antenna Apertures and Beamwidths

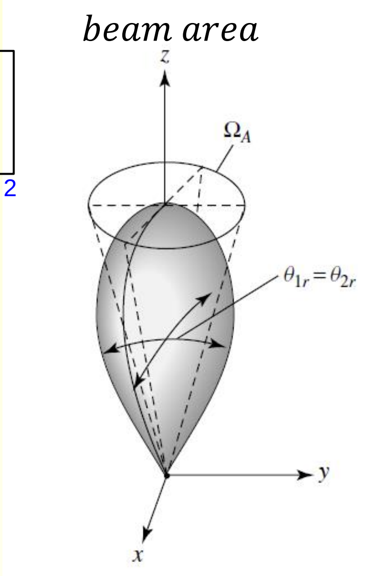




Antenna aperture (a) and beamwidths (b)

Antenna Directivity & Gain

see Author's: Mazar H. 2016 Wiley Radio Spectrum Management; pp. 177-198



Directivity ($d(\theta, \phi)$) : "the ratio of the **radiation intensity in a given direction** from the antenna to the radiation intensity **averaged** over all directions".

Balanis, Antenna Theory, 3rd ed., Ch. 2

$$d_{(\theta,\phi)} = \frac{P(\theta,\phi)}{P_{ave}} = \frac{4\pi}{\Omega_A}$$

$\Omega_A = beam\ area(steradians)$

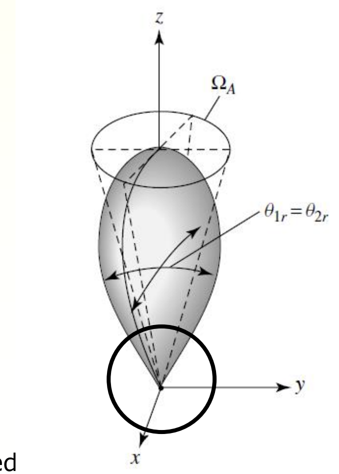
P= $power\ density\ [{}^{watt}/_{m^2}]$

$$d_0 = d_{max}(\theta,\phi)$$

For isotropic antenna: $d(\theta,\phi) = d_0 = 1 = 0dBi$

Gain ($g(\theta, \phi)$) : "the ratio of the **actual intensity**, in a given direction, to the radiation intensity that would be obtained if the power accepted by the antenna were radiated **isotropically**".

$$g_0 = \eta d_0 \quad \eta = \frac{P_{rad}}{P_{input}} \qquad \eta = antena\ efficency, 0 < \eta < 1$$



For: **η** = Aperture efficiency; ***A*** = Physical aperture area, $\mathbf{A_e}$ = Effective aperture area
$\mathbf{d_0}$= max directivity; $\mathbf{g_0}$= max Ant Gain , **G**= Ant Gain (dBi), **Gd** =Gi-2.15; **λ**= wavelength **BW**= Ant beamwidth, **θ**= BW_{elv} **φ**= Bw_{az}

Effective Capture Area

Effective aperture (A_e): "the ratio of the available power at the terminals of a receiving antenna to the power flux density of a plane wave incident on the antenna".

Balanis, Antenna Theory, 3rd ed., Ch. 2

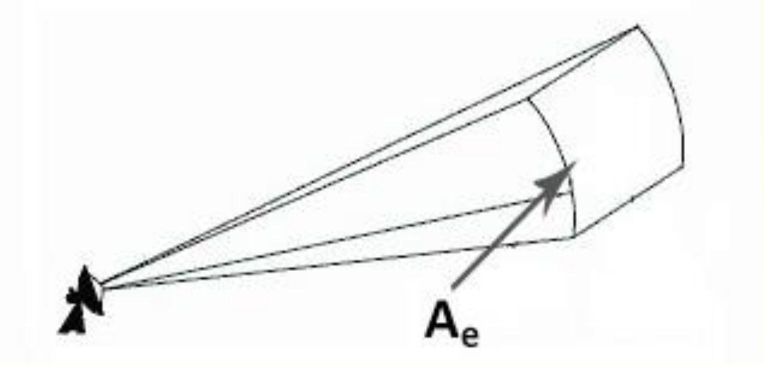
$$A_e = \frac{P_{tot}}{P_{max}(\theta, \phi)}$$

$P_{tot} = power\ delivered\ to\ the\ load\ [watt]$

$P_{max}(\theta, \phi) = power\ density\ [{}^{watt}/_{m^2}]$

$$A_e = \eta A_{physical}$$

For aperture antennas



$$A_e = \frac{g\lambda^2}{4\pi}$$

$$g_0 = 4\pi \frac{A_e}{\lambda^2}$$

$$A_{e\ isotropic} = \frac{\lambda^2}{4\pi}$$

The same equation serves to calculate the gain of a passive reflector

Effective Capture Area (2)

Kraus 'Antennas' 1988 p. 25 equation (6), for Ω_A solid angle (steradian, sr), θ and φ azimuth and elevation angles(radian);

$$\Omega_A = \theta_{HP}\varphi_{HP}$$

p. 27 equation (1), for g gain (dimensionless), k efficiency factor (dimensionless) and d directivity (dimensionless);

$g = kd$ and p. 28 equation (4); $d = 4\pi/\Omega_A$

p. 36 equation (1), for ε_{ap} *efficiency* (dimensionless), A_e effective aperture (m^2) and A_p physical aperture (m^2); $\varepsilon_{ap} = A_e / A_p$

Derived from the Poynting Vector, p. 46 equation (5), for A_{em} maximum effective aperture (losses=0) and λ wavelength (m);

$$\lambda^2 = A_{em}\,\Omega_A$$

p. 47, for simplicity $A_{em} = A_{em}$ and using p. 28 equation (4), we get equation (10)

$$g_0 = 4\pi \frac{A_e}{\lambda^2}$$

See also Kraus 'Antennas' 1988 pp. 410-413 'reciprocity theorem of antennas':
antennas work equally well as transmitters or receivers, and specifically that an antenna's radiation and receiving patterns are identical; see next slide

Effective Capture Area (3)

Just as energy conservation implies that all lossless transmitting antennas have the same average power gain, all lossless receiving antennas have the same average collecting area. Nyquist: $$B\nu = \frac{2kT}{\lambda^2}$$

US National Radio Observatory https://public.nrao.edu/

Many antenna properties are the same for both transmitting and receiving. Thus this receiving/transmitting "reciprocity" greatly simplifies antenna calculations and measurements. Reciprocity can be understood via Maxwell’s equations or by thermodynamic arguments. Burke & Smith (1997) state the electromagnetic case for reciprocity clearly: "An antenna can be treated either as a receiving device, gathering the incoming radiation field and conducting electrical signals to the output terminals, or as a transmitting system, launching electromagnetic waves outward. These two cases are equivalent because of time reversibility: the solutions of Maxwell's equations are valid when time is reversed.“

Thus energy conservation and the weak reciprocity theorem imply

$$\mathrm{A_e} = \frac{g\lambda^2}{4\pi}$$

Practical Formulas, for ant. Gain

For η=0.7

$$g=\eta\frac{4\pi}{\varphi\theta(radians)}=\eta\frac{4\pi}{\varphi\theta(^0)}\left(\frac{360}{2\pi}\frac{360}{2\pi}\right)=\eta\frac{41,253}{\varphi\theta(^0)}=\eta\frac{41,253}{\varphi\theta(^0)}\approx\frac{28,800}{\varphi\theta(^0)}$$

$$\theta_e(\text{radian})=\sqrt{\frac{1}{\eta}}(\lambda/b)$$

$$\varphi_e(\text{radian})=\sqrt{\frac{1}{\eta}}(\lambda/a)$$

G=44.6 dBi -10logθ^0 –10logφ^0;

G=44.6 dBi -20log θ^0 for circular Ant

For circular antennas, where λ/l is not given, this ratio may be estimated; inserting:

$$\theta(\text{degrees})\approx 70\frac{\lambda}{l}$$

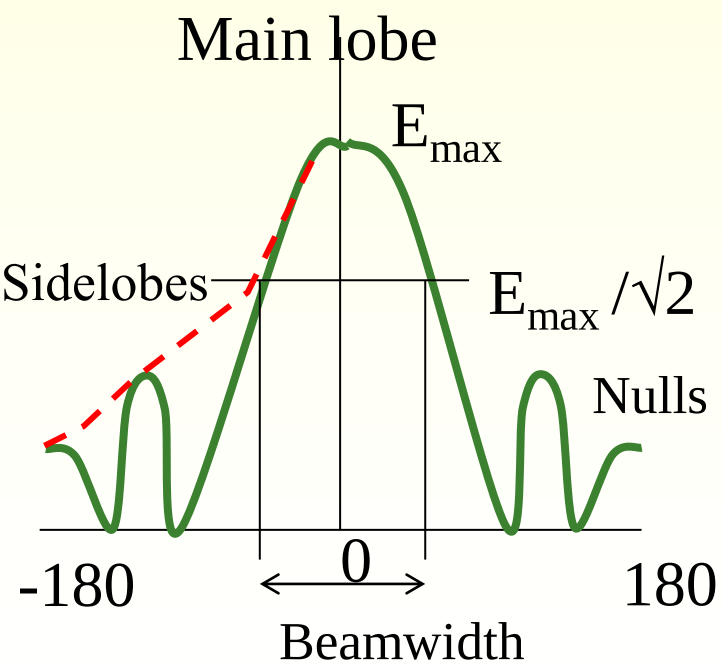
G=44.6 dBi -20log $(70\frac{\lambda}{l})$

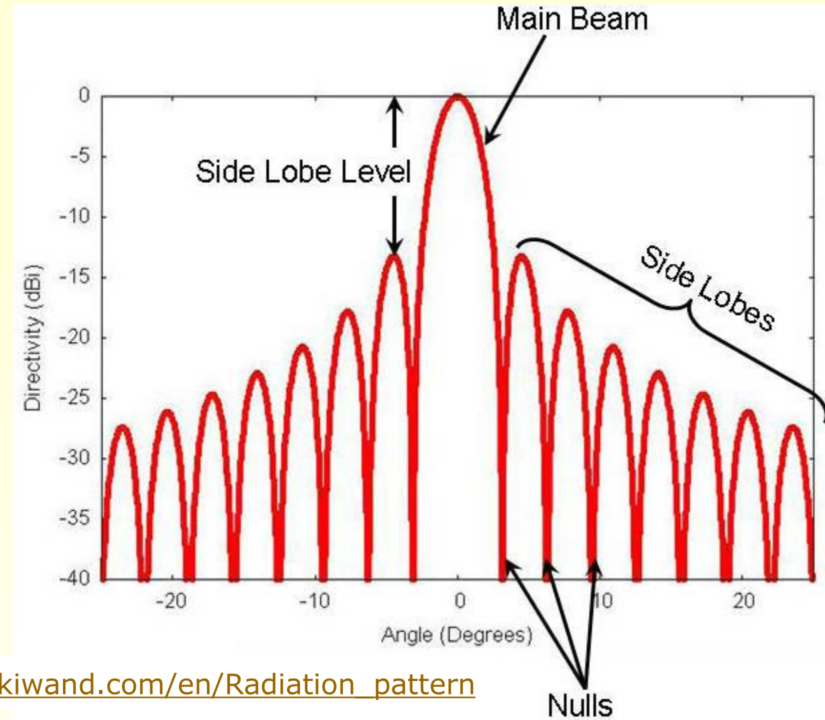
G= 7.7 - 20log $(70\frac{\lambda}{l})$

Elements of Radiation Pattern

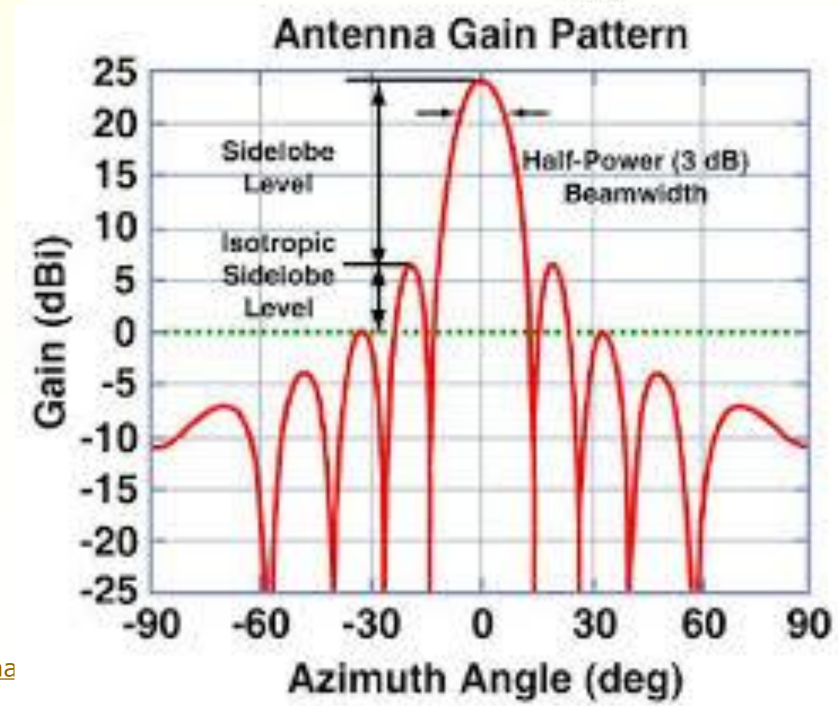
(Struzak)

- Gain
- Beam width
- Nulls (positions)
- Side-lobe levels
- Front-to-back ratio



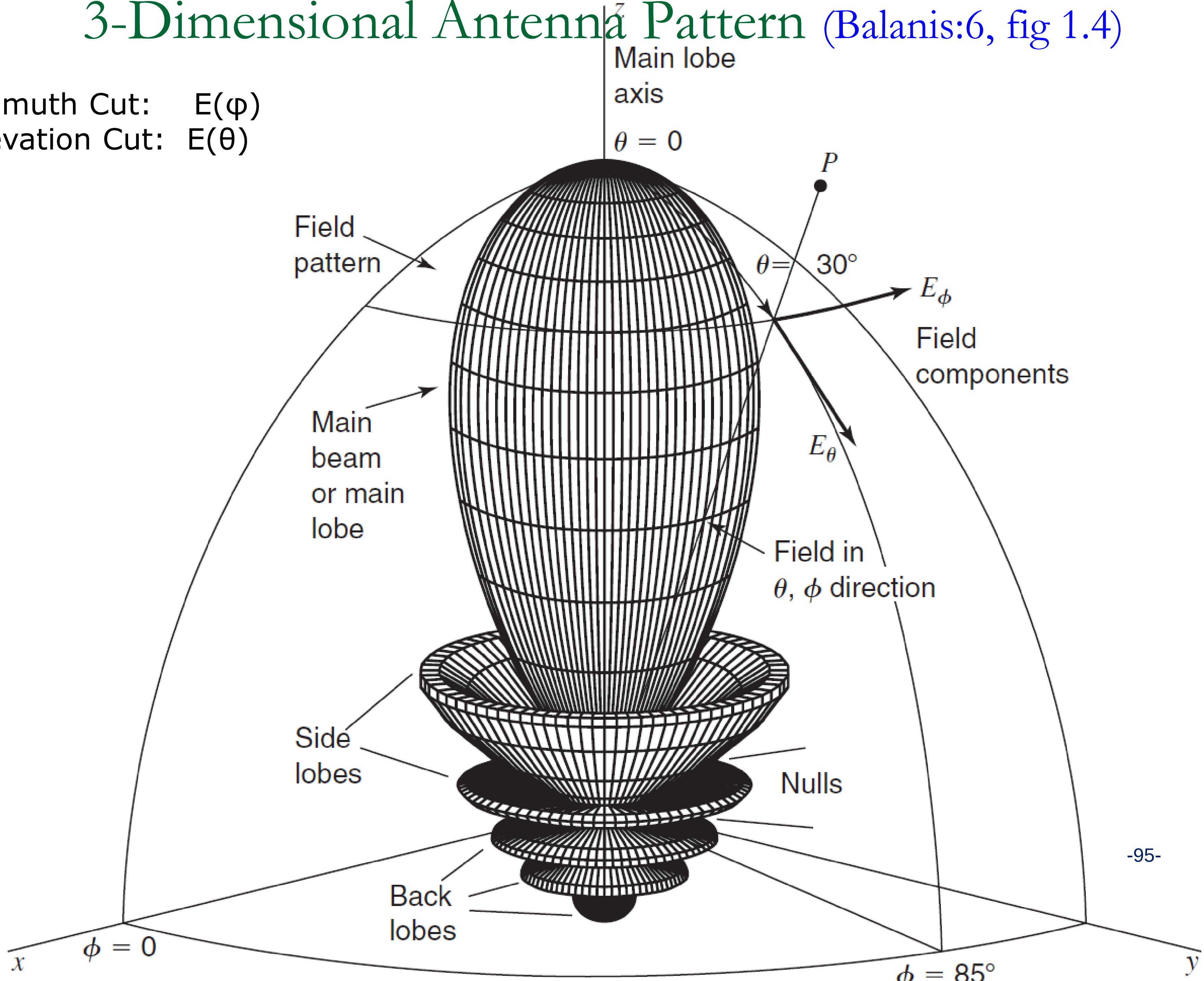


https://www.wikiwand.com/en/Radiation_pattern

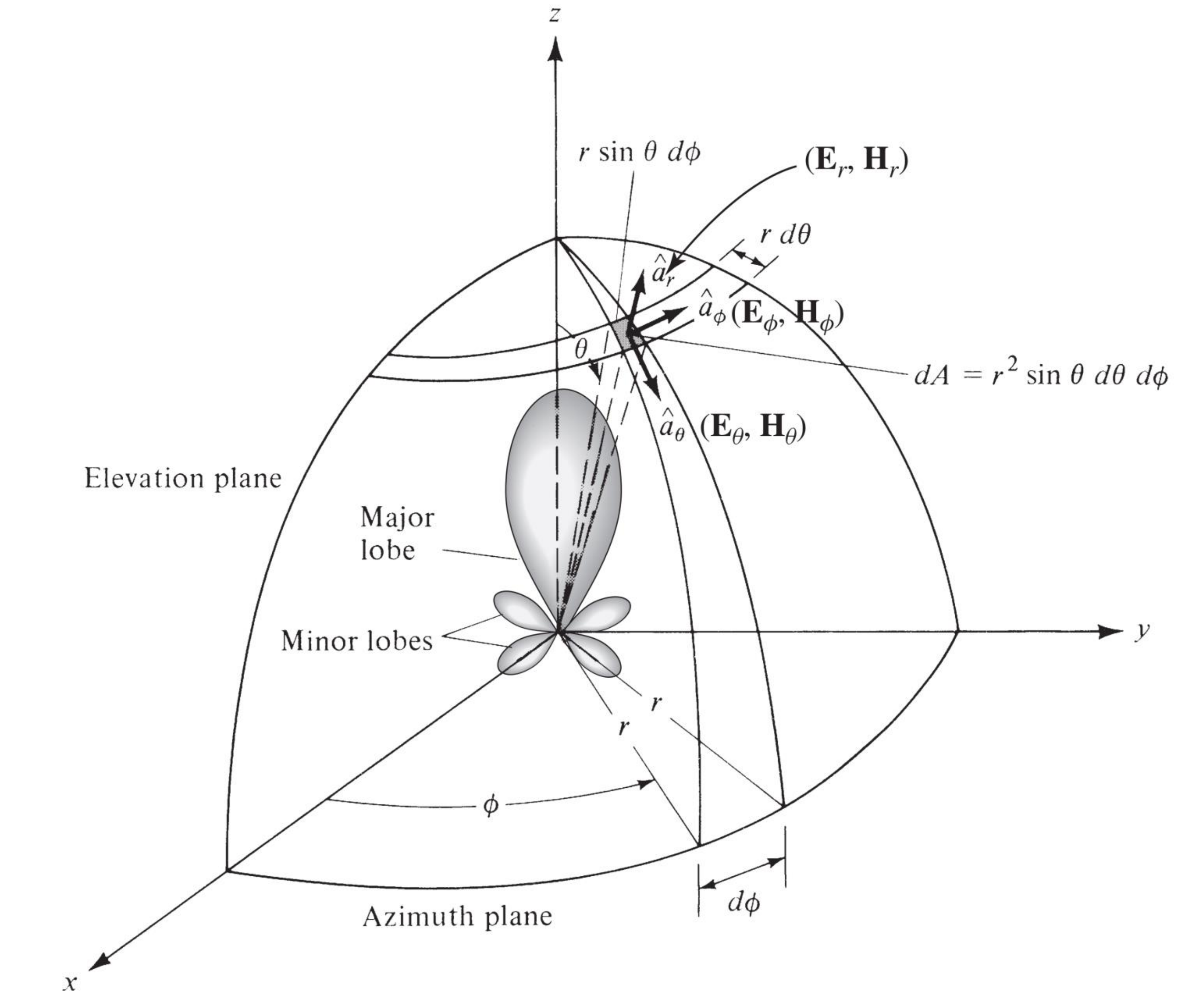


3-Dimensional Antenna Pattern (Balanis:6, fig 1.4)

Azimuth Cut: E(φ)
Elevation Cut: E(θ)

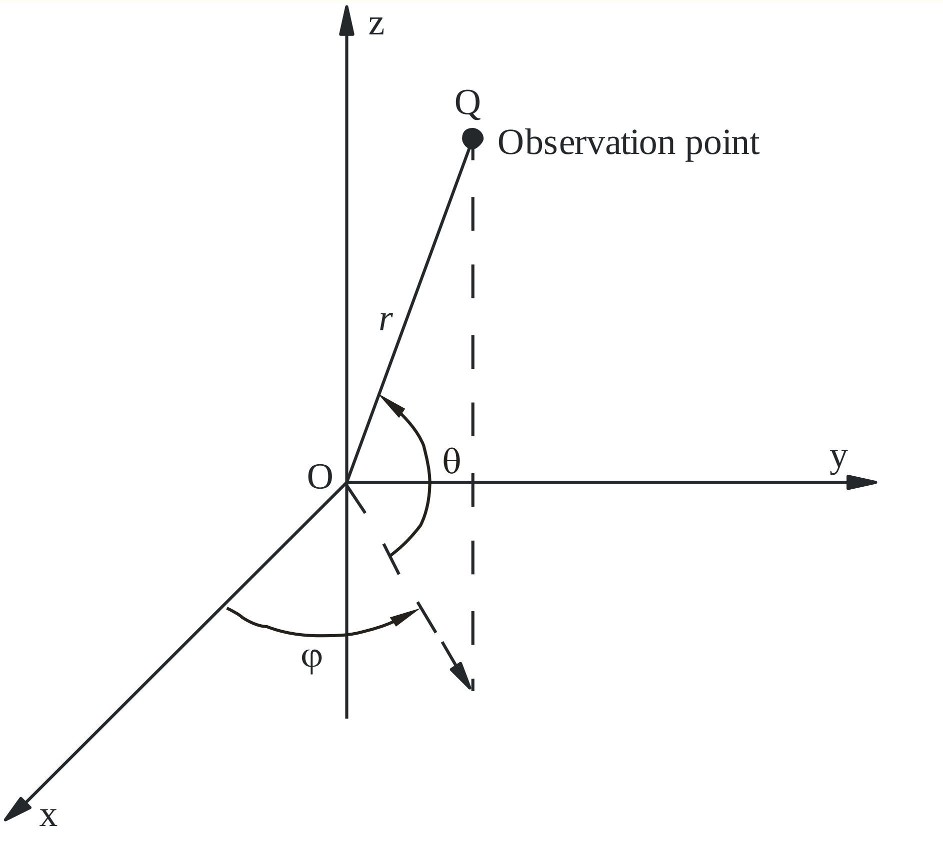


Coordinate system for antenna analysis (Balanis 2008, Fig 1.1.)



Geometrical representation of ant patterns (Rec. ITU-R BS. 1195)

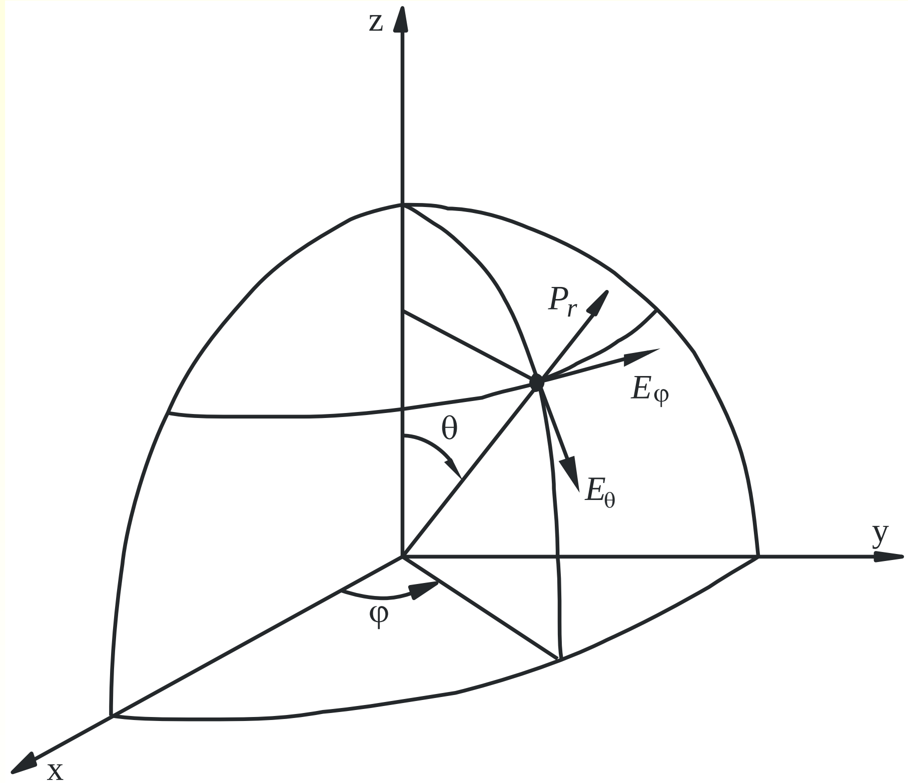
θ : elevation angle from the horizontal (0° ≤ θ ≤ 90°)
φ : azimuthal angle from the x-axis (0° ≤ φ ≤ 360°)
r : distance between the origin and the observation point
Q : observation point.



The reference coordinate system

BS.1195-01

Relation of the Poynting vector and the electrical far field components



BS.1195-02

Geometrical Representation of Patterns (cont'd)

The **antenna directivity *d (g)*** is defined as the ratio of its maximum radiation intensity to the radiation intensity (or power flux-density) of an isotropic source radiating the same total power; see BS.1195 and also Balanis (2008:18) (the directions of θ are different in Balanis and BS.1195); the maximum directivity d_0 (g) can be expressed:

$$g = \frac{4\pi \left| e(\theta, \varphi) \right|^2_{max}}{\int_0^{2\pi} \int_0^{\pi} \left| e(\theta, \varphi) \right|^2 \sin\theta \, d\theta \, d\phi}$$

$e(\theta, \varphi)$: vector of the source electrical field; expressed in spherical coordinate system;

$|e(\theta, \varphi)|$: magnitude of the electrical field ;

$|e(\theta, \varphi)| = \sqrt{\left|e_\theta(\theta, \varphi)\right|^2 + \left|e_\varphi(\theta, \varphi)\right|^2}$

Due to the **law of conservation of energy**, the total directivity integral equals 1

The equation specifies ant. *gain* as a function of the source radiation pattern.

For a **lossless isotropic source**, by definition its ant. radiation *e* (q,j)≡1; setting *e* (θ, φ))=1:

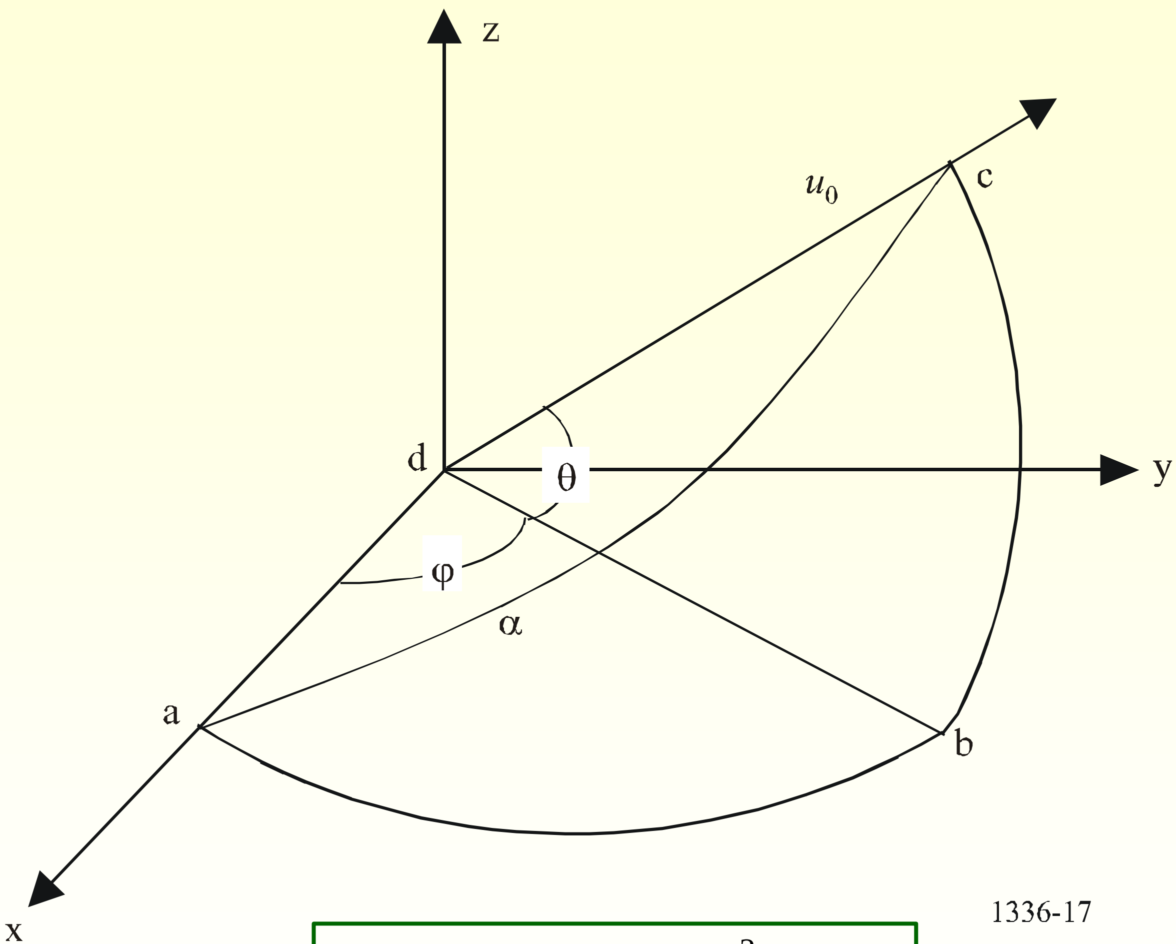
$$g = \frac{4\pi}{\int_0^{2\pi} \int_0^{\pi} \sin\theta \, d\theta \, d\phi} = \frac{4\pi}{\int_0^{2\pi} \left[-\cos(\pi) + \cos(0) \right] d\phi} = \frac{4\pi}{2\int_0^{2\pi} d\phi} = \frac{4\pi}{4\pi} = 1$$

Attenuation Pattern

Dividing directivity *d* by the maximum directivity d_0 merely normalizes the directivity (and radiation intensity) and it makes its maximum value unity. This is the relative antenna pattern, it equals d/d_0

$$\frac{\dfrac{4\pi\, e(\theta,\varphi)^2}{\int_0^{2\pi}\int_0^{\pi}\left|e(\theta,\varphi)\right|^2 \sin\theta\, d\theta\, d\phi}}{\dfrac{4\pi\left|e(\theta,\varphi)\right|^2_{max}}{\int_0^{2\pi}\int_0^{\pi}\left|e(\theta,\varphi)\right|^2 \sin\theta\, d\theta\, d\phi}} = \frac{e(\theta,\varphi)^2}{\left|e(\theta,\varphi)\right|^2_{max}}$$

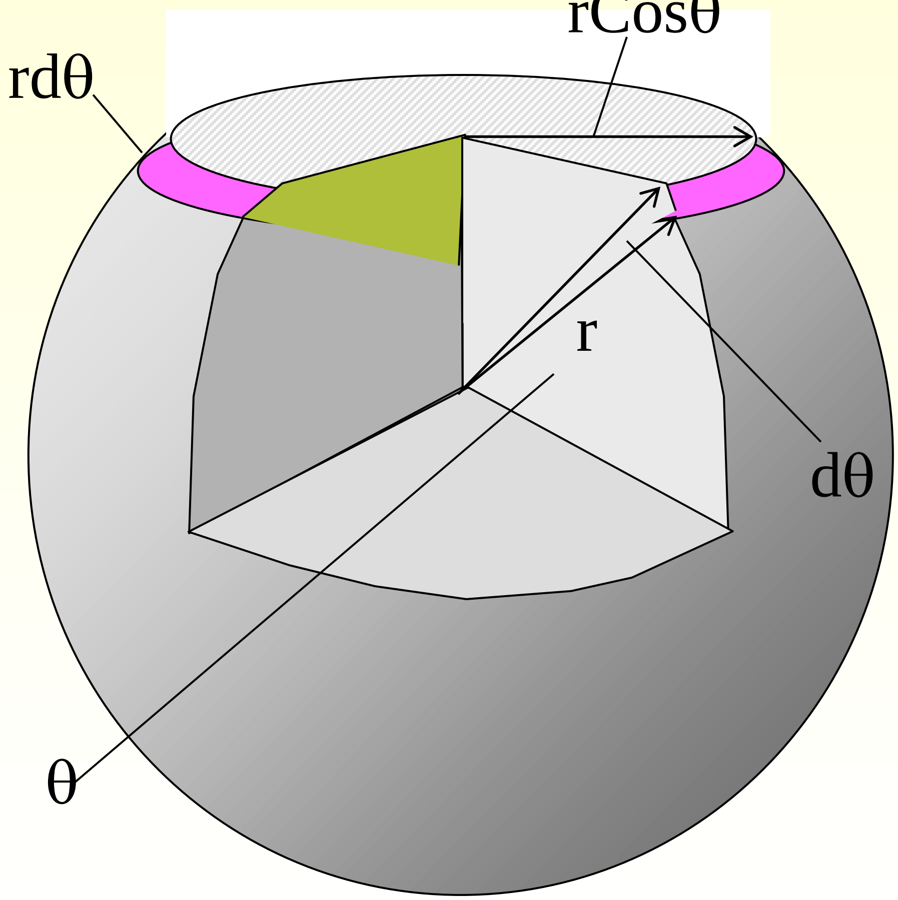
Off-Boresight Gain, given azimuth and elevation angles (F1336)



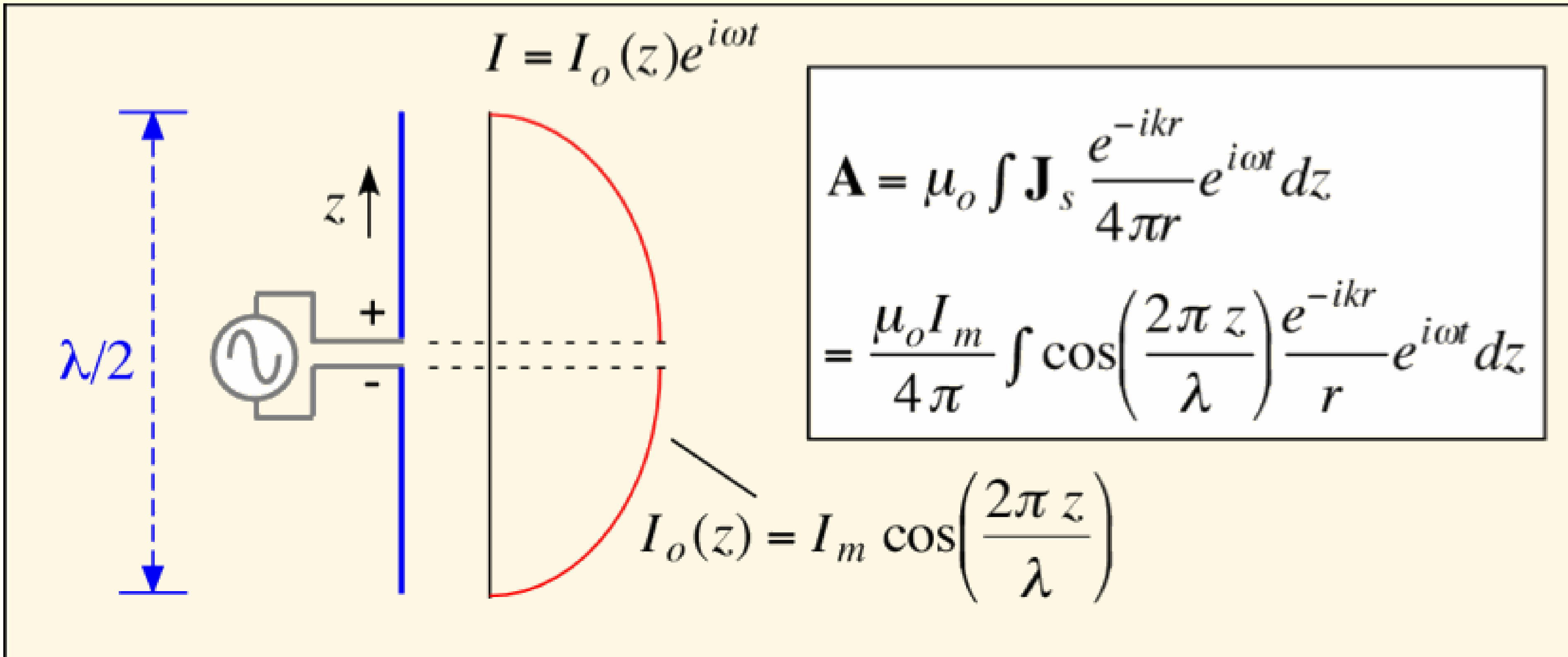
$$g = \frac{4\pi \left|E(\theta,\varphi)\right|^2_{max}}{\int_0^{2\pi}\int_{-\pi/2}^{\pi/2} \left|E(\theta,\varphi)\right|^2 \cos\theta \, d\theta \, d\varphi}$$

Off-Boresight Gain, given azimuth and elevation angles (web)

$$dS = 2\pi r^2 \cos(\theta) d\theta$$



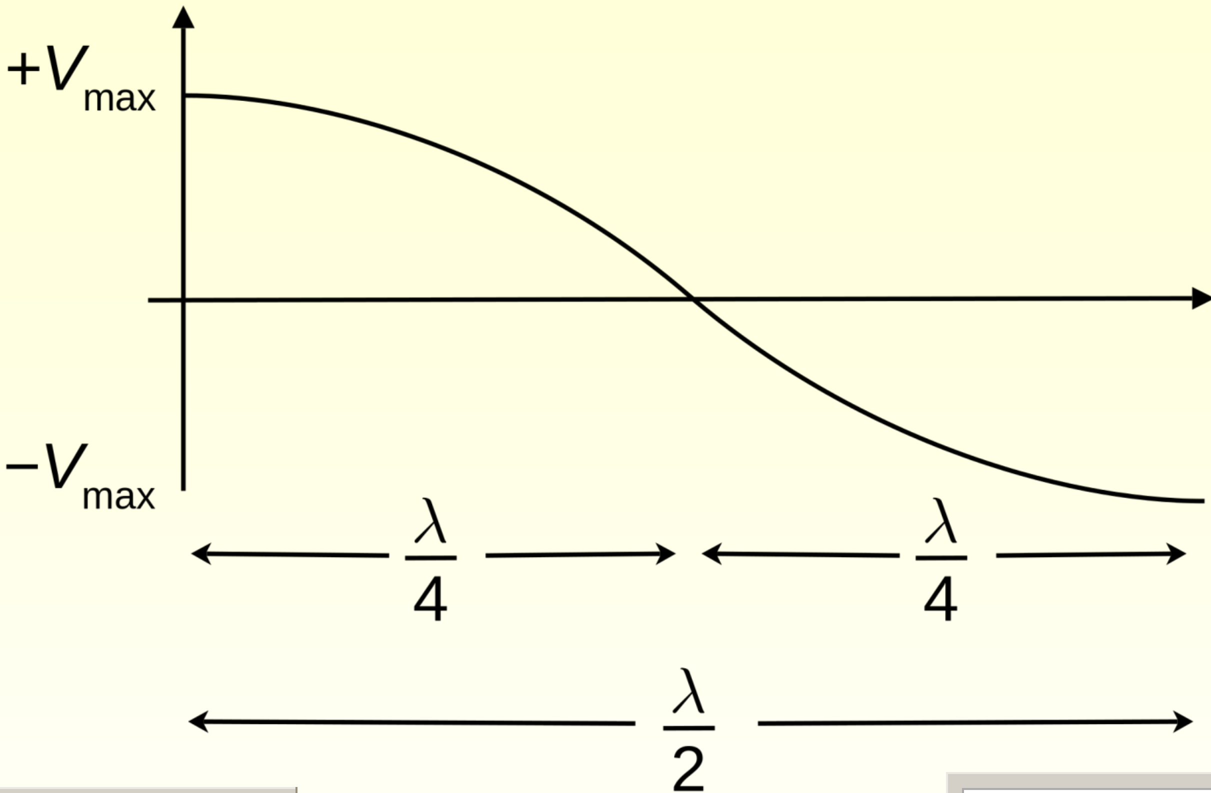
Half wave Dipole Radiation pattern and gain (web)



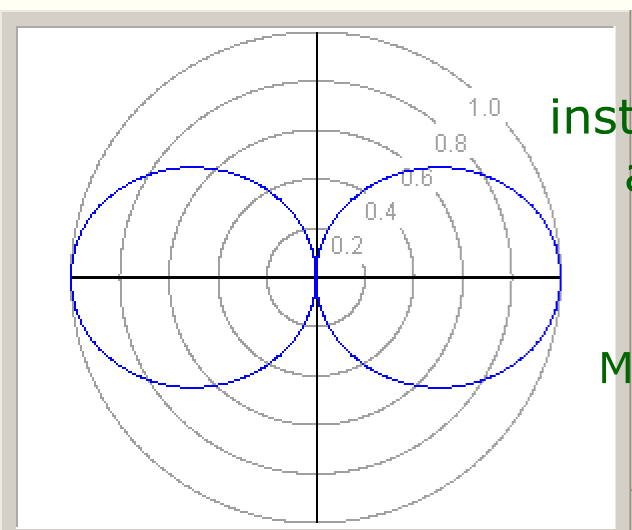
Dr. Haim Mazar (Madjar) haimma1@ac.sce.ac.il h.mazar@atdi-group.com

Half wave Dipole Radiation Pattern and Gain

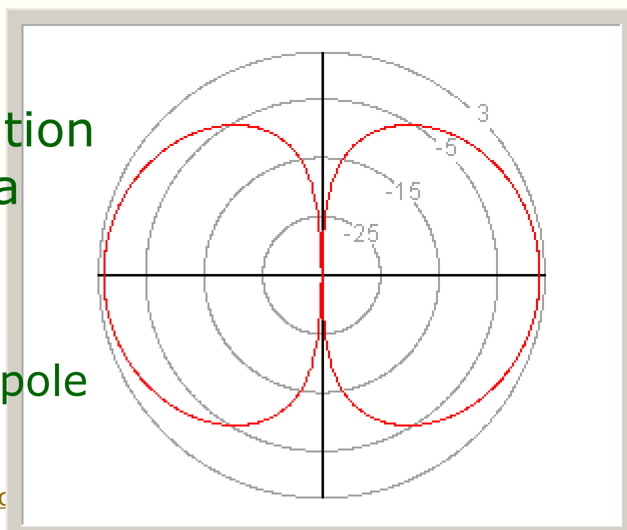
Wiki



Linear scale



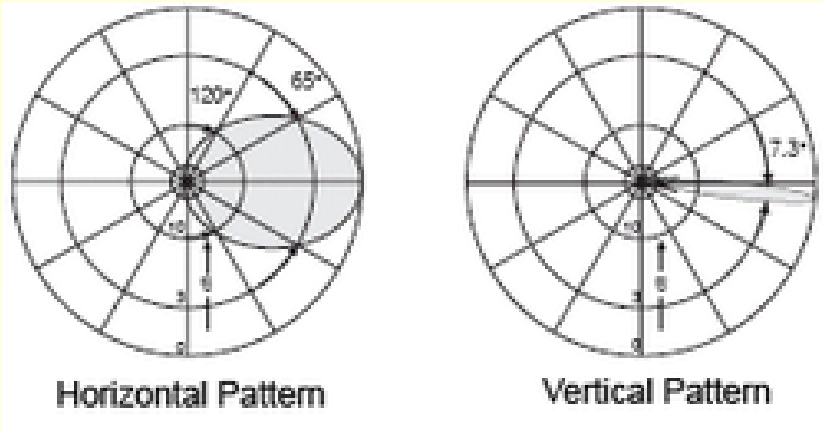
dBi scale



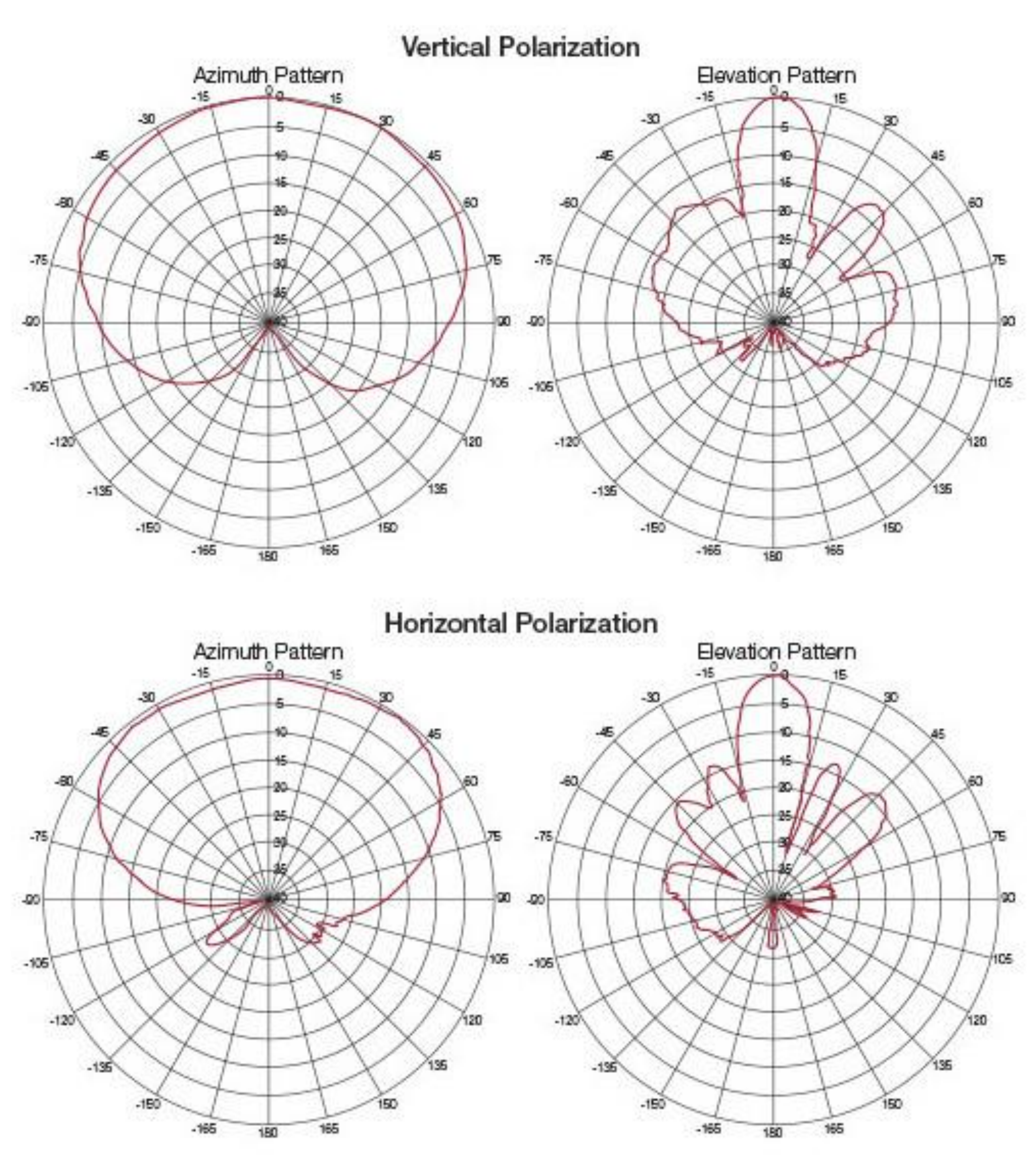
instantaneous voltage distribution across a λ/2 dipole antenna

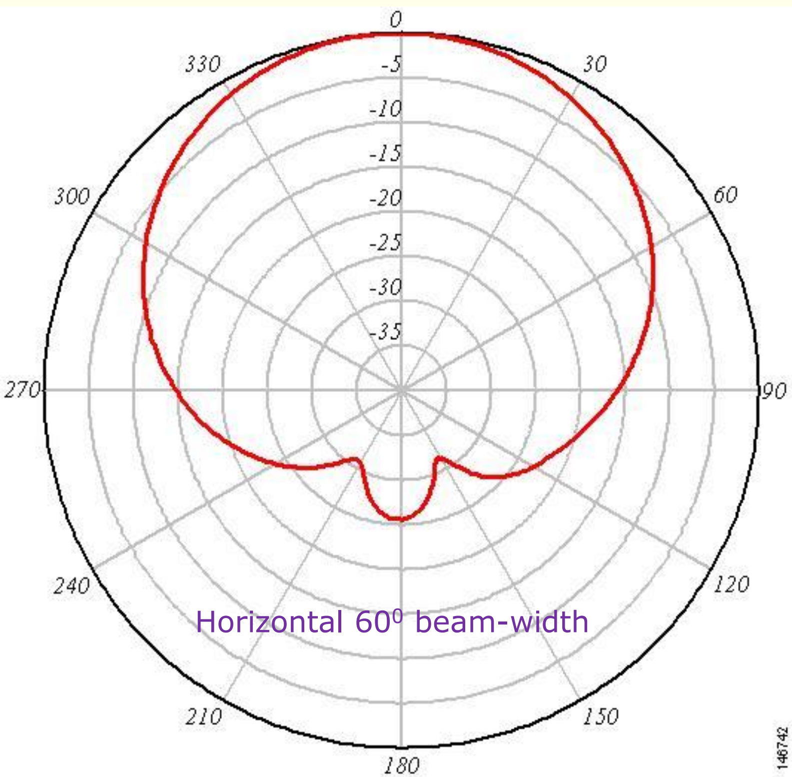
Max theoretical gain of a λ/2-dipole is 10 log 1.64 or 2.15 dBi

Typical 3-sector antenna patterns of cellular base-stations (from web)



Theoretical vs. measured base-station cellular patterns





Mathematical Models: Antenna Patterns (Rec. ITU-R M.1851)

the Author contributed the Rec's revisions of 2018, and the following figures

To simplify the analysis, ant. current distribution is considered as a function of either the elevation or azimuth. Patterns are correct only in the case where the current distribution amplitude at the edge of the ant. aperture is equal to zero & stays within the bounds of the main lobe and first two antenna side lobes.

The **directivity pattern**, $F(\mu)$, of a given space distribution is found from the **finite Fourier transform** as:

$$F(\mu) = \frac{1}{2}\int_{-1}^{+1} f(x) \cdot e^{j\mu x} dx$$

$f(x)$= relative shape of field distribution

$\mu = \pi\left(\frac{l}{\lambda}\right)\sin(\alpha)$

l = overall length of aperture

λ = wavelength

α = angle relative to aperture normal

θ = $(\alpha-\omega)$ angle relative to aperture normal and pointing angle; later main beam at 0 , ω= 0 and $\theta = \alpha$

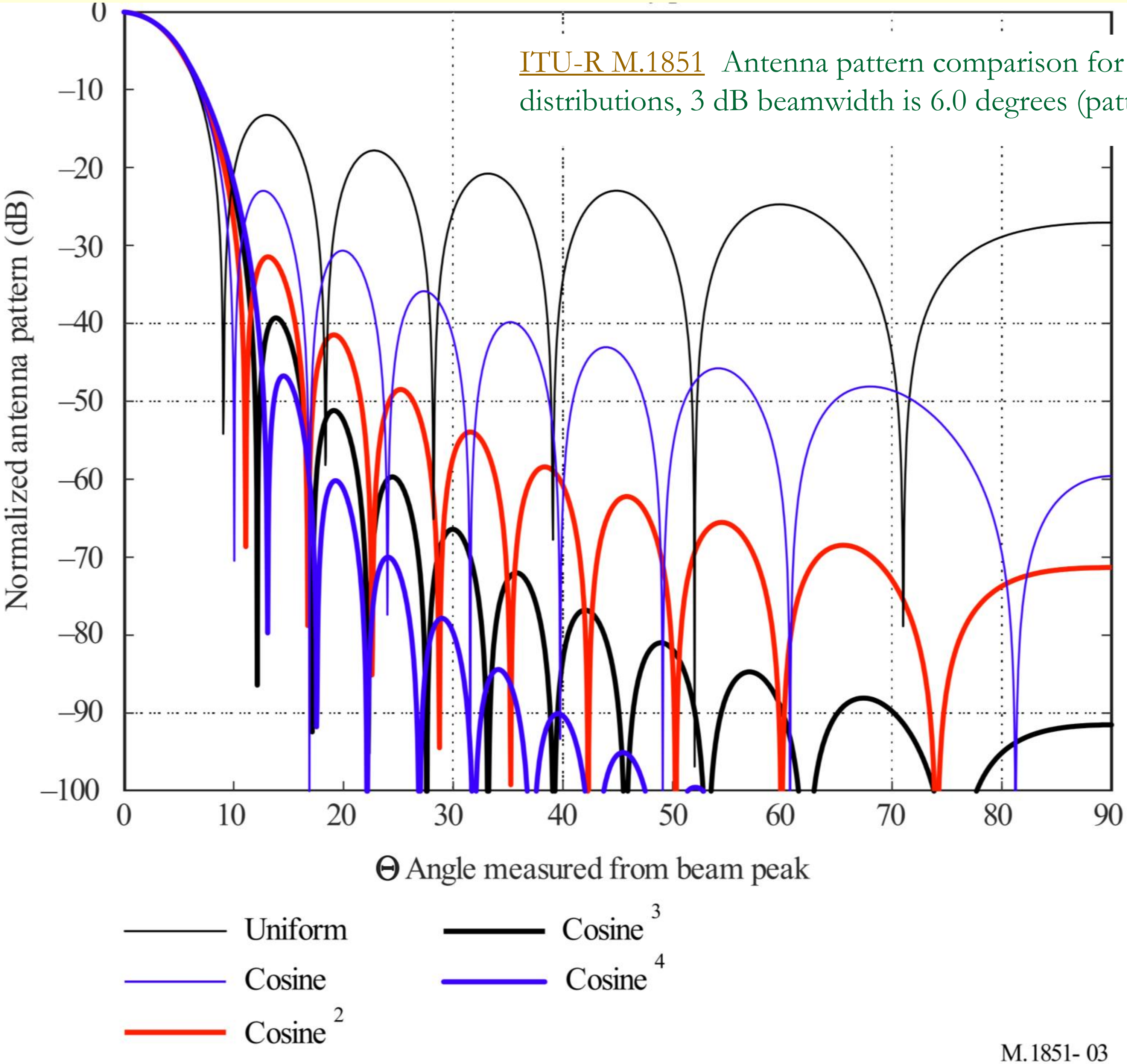
x = normalized distance along aperture $-1 \le x \le 1$

j = complex number notation.

Theoretical antenna directivity parameters (Rec. M.1851 Table 2)

Relative shape of field distribution $f(x)$ where $-1 \le x \le 1$	**Directivity pattern $F(\mu)$**	**θ_3 half power beam-width (degrees)**	**μ as a function of θ_3**
Uniform value of 1	$\frac{\sin(\mu)}{\mu}$	$50.8\left(\frac{\lambda}{l}\right)$	$\frac{\pi \cdot 50.8 \cdot \sin(\theta)}{\theta_3}$
COS(π*x/2)	$\frac{\pi}{2}\left[\frac{\cos(\mu)}{\left(\frac{\pi}{2}\right)^2-\mu^2}\right]$	$68.8\left(\frac{\lambda}{l}\right)$	$\frac{\pi \cdot 68.8 \cdot \sin(\theta)}{\theta_3}$
COS ^{2}(π*x/2)	$\frac{\pi^2}{2\cdot\mu}\left[\frac{\sin(\mu)}{(\pi^2-\mu^2)}\right]$	$83.2\left(\frac{\lambda}{l}\right)$	$\frac{\pi \cdot 83.2 \cdot \sin(\theta)}{\theta_3}$
COS ^{3}(π*x/2)	$\frac{3\cdot\pi\cdot\cos(\mu)}{8}\left[\frac{1}{\left(\frac{\pi}{2}\right)^2-\mu^2}-\frac{1}{\left(\frac{3\cdot\pi}{2}\right)^2-\mu^2}\right]$	$95\left(\frac{\lambda}{l}\right)$	$\frac{\pi \cdot 95 \cdot \sin(\theta)}{\theta_3}$
COS ^{4}(π*x/2)	$\frac{3\pi^4\sin(\mu)}{2\mu\left(\mu^2-\pi^2\right)\left(\mu^2-4\pi^2\right)}$	$106\left(\frac{\lambda}{l}\right)$	$\frac{\pi \cdot 106 \cdot \sin(\theta)}{\theta_3}$

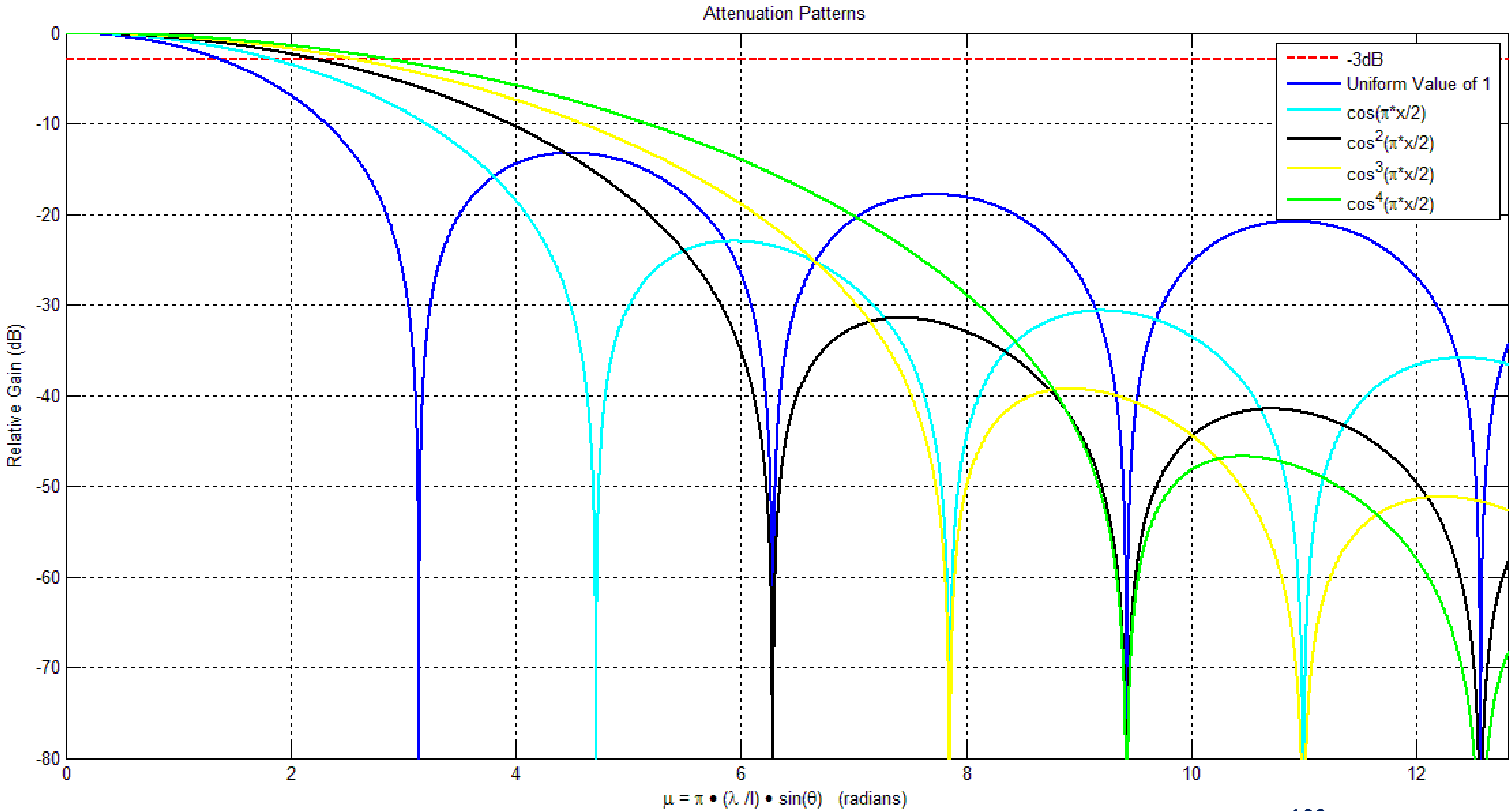
ITU-R M.1851 Antenna pattern comparison for various linear aperture distributions, 3 dB beamwidth is 6.0 degrees (pattern is symmetric)



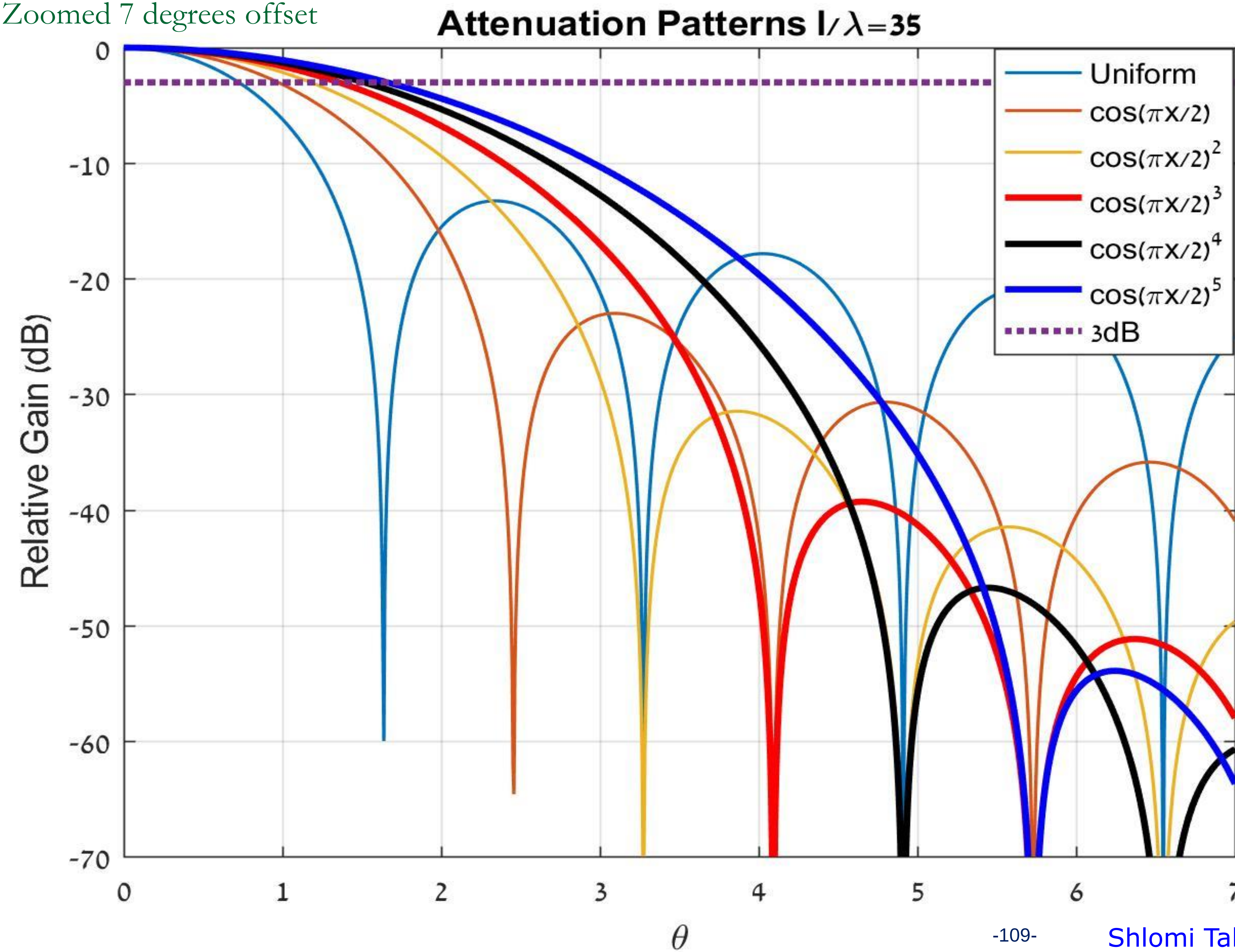
Ant attenuation patterns; different distribution functions

Tamir Lugassi

For l antenna =20λ



Zoomed 7 degrees offset

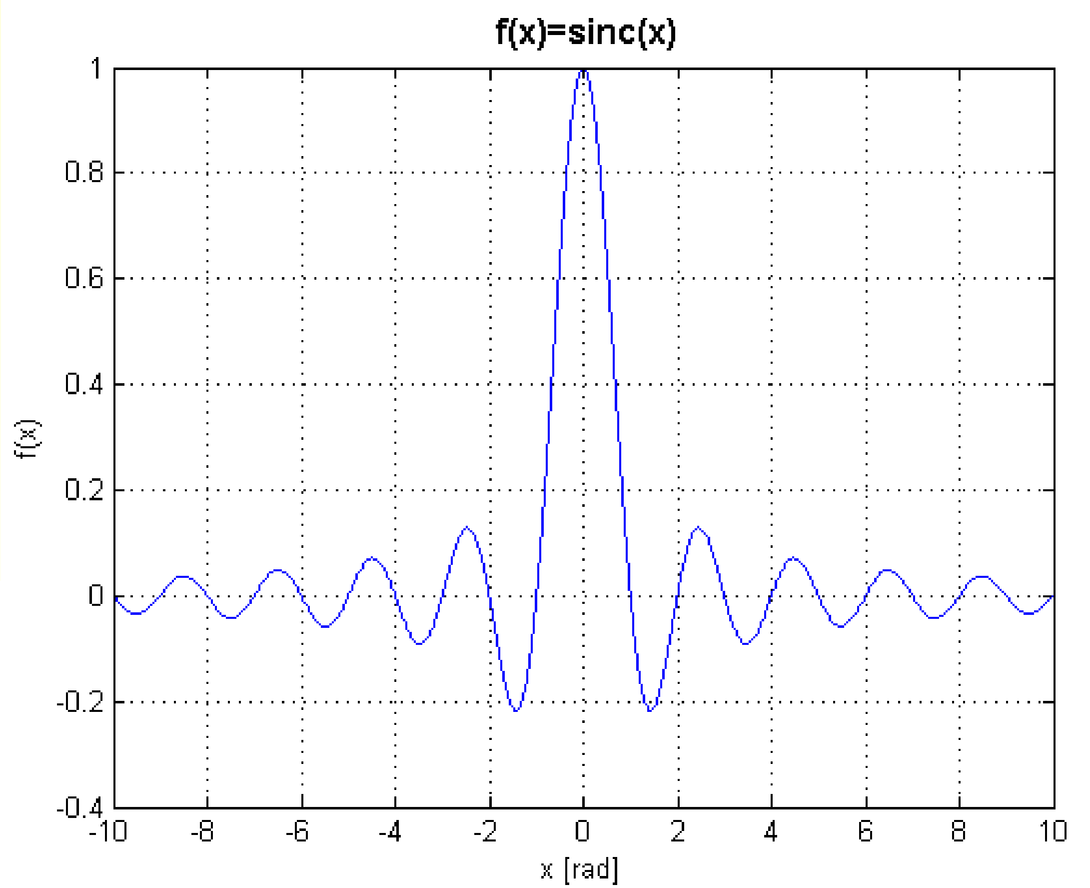


Shlomi Talala

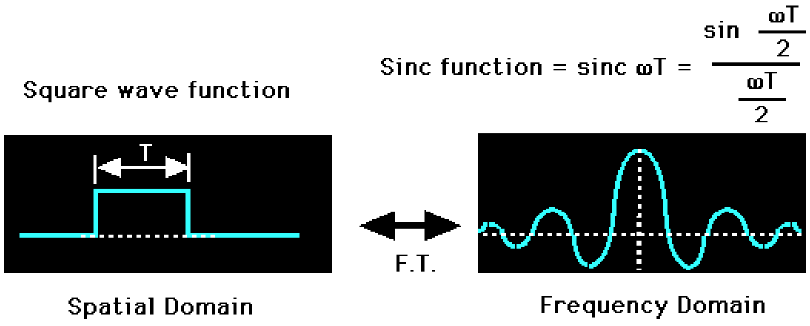
Spatial and Time domain; square wave (Fourier) transformed to sincx

$$f(x) = \text{sinc}(x) = \frac{\sin x}{x}$$

Engineering examples:
Pulse radar and uniform illumination of a reflector



f(t)=1 for 0<t<T
f(t)=0 for t<0 or T<t



laser.physics.sunysb.edu

+10>x>-10 radians

Sinc (x): minima and maxima lobes

Uniform illumination case:

x (normalized distance along aperture) equals 1 in $-1 \le x \le 1$ and 0 outside

- **Ant. pattern is actually a spatial Fourier transform**, converting two orthogonal θ (elevation) and φ (azimuth) pulse waves ('1' inside, '0' outside the rectangular) to two Sinc functions (sinθ/θ) and (sinφ/φ), respectively.

- Next figure is the numerical attenuation pattern for the uniform distribution on **rectangular reflector**; it depicts off boresight (axes in radians) absolute relative attenuation: the three dimensional isometric projection pattern.

- Sinc 'square' as the directivity and attenuation in the far-field depend on the square of field strength.

$$F(\mu) = \frac{1}{2}\int_{-1}^{+1} f(x)\cdot \mathrm{e}^{j\mu x}\mathrm{d}x = \frac{1}{2}\int_{-1}^{+1} \mathrm{e}^{j\mu x}\mathrm{d}x = \frac{1}{2j\mu}(\mathrm{e}^{j\mu} - \mathrm{e}^{-j\mu}) \equiv \frac{\sin\mu}{\mu}$$

Using Euler function $$\frac{1}{2j}(\mathrm{e}^{j\mu} - \mathrm{e}^{-j\mu}) \equiv \sin\mu$$

Cosine illumination case $f(x)=\cos\left(\pi x/2\right)$

$$F(\mu)=\frac{1}{2}\int_{-1}^{1} f(x)\cdot e^{j\mu x}dx$$

$$F(\mu)=\frac{1}{2}\int_{-1}^{1}\cos\left(\frac{\pi x}{2}\right)\cdot e^{j\mu x}dx=$$

$$=\frac{1}{2}\int_{-1}^{1}\left(\frac{e^{j\pi x/2}+e^{-j\pi x/2}}{2}\right)\cdot e^{j\mu x}dx=\frac{1}{4}\int_{-1}^{1}e^{j\pi x/2+j\mu x}+e^{-j\pi x/2+j\mu x}dx$$

$$=\frac{1}{4}\left[\left(\frac{e^{j(\mu+0.5\pi)}}{j(\mu+0.5\pi)}+\frac{e^{j(\mu-0.5\pi)}}{j(\mu-0.5\pi)}\right)-\left(\frac{e^{-j(\mu+0.5\pi)}}{j(\mu+0.5\pi)}+\frac{e^{-j(\mu-0.5\pi)}}{j(\mu-0.5\pi)}\right)\right]$$

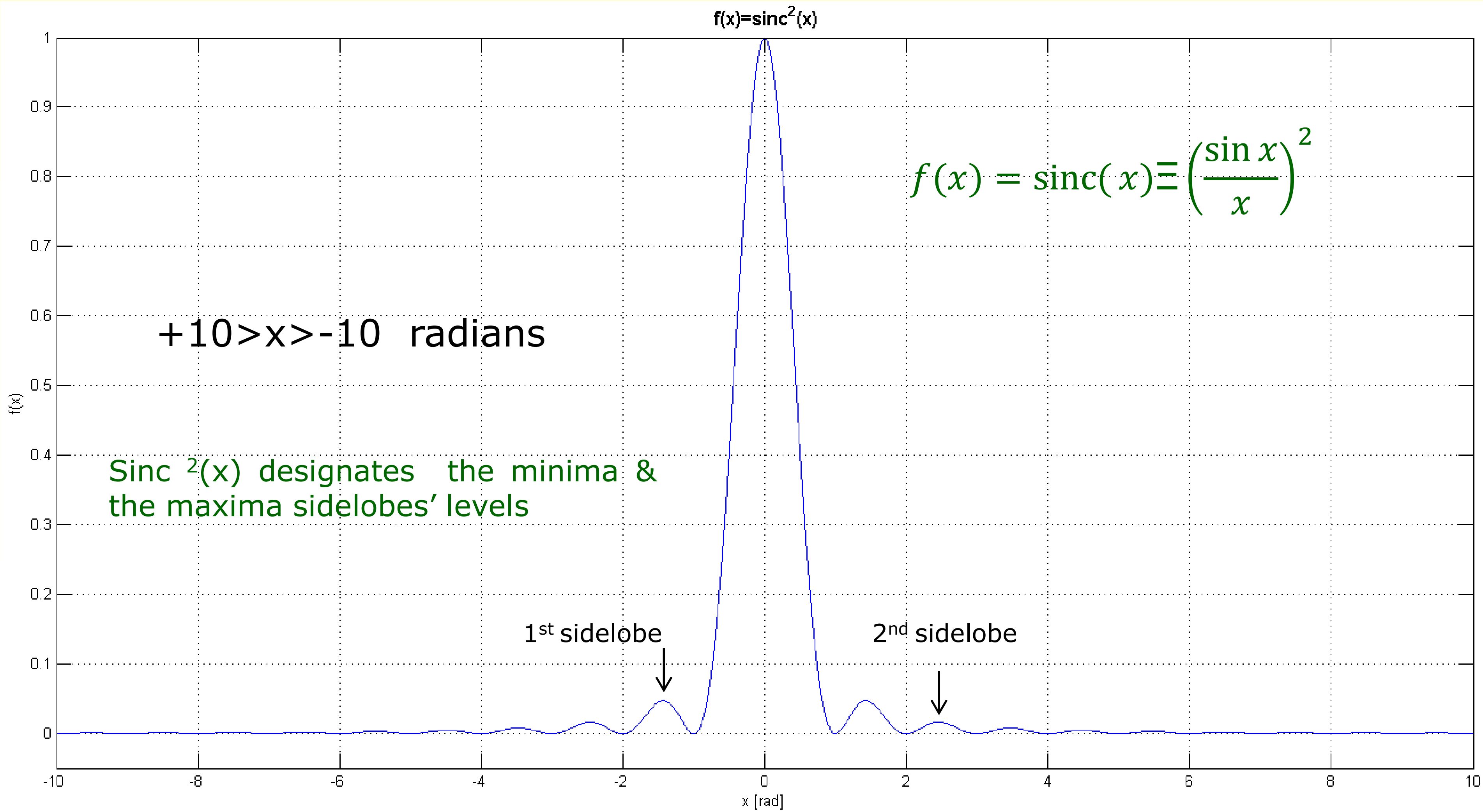
$$=\frac{1}{2}\left[\frac{e^{j(\mu+0.5\pi)}-e^{-j(\mu+0.5\pi)}}{2j(\mu+0.5\pi)}+\frac{e^{j(\mu-0.5\pi)}-e^{-j(\mu-0.5\pi)}}{2j(\mu-0.5\pi)}\right]$$

$$=\frac{1}{2}\left[\frac{\sin(\mu+0.5\pi)}{\mu+0.5\pi}+\frac{\sin(\mu-0.5\pi)}{\mu-0.5\pi}\right]$$

$$=\frac{1}{2}\left[\frac{\cos(\mu)}{\mu+0.5\pi}-\frac{\cos(\mu)}{\mu-0.5\pi}\right]=\frac{1}{2}\left[\frac{-\pi\cos(\mu)}{\mu^2-(0.5\pi)^2}\right]=\frac{\pi}{2}\left[\frac{\cos(\mu)}{(0.5\pi)^2-\mu^2}\right]$$

Numerical (non logarithmic) $\mathrm{sinc}^2 x$

In the far-field the antenna pattern is relative to square electric field-strength



Calculating local extremum of ant. pattern

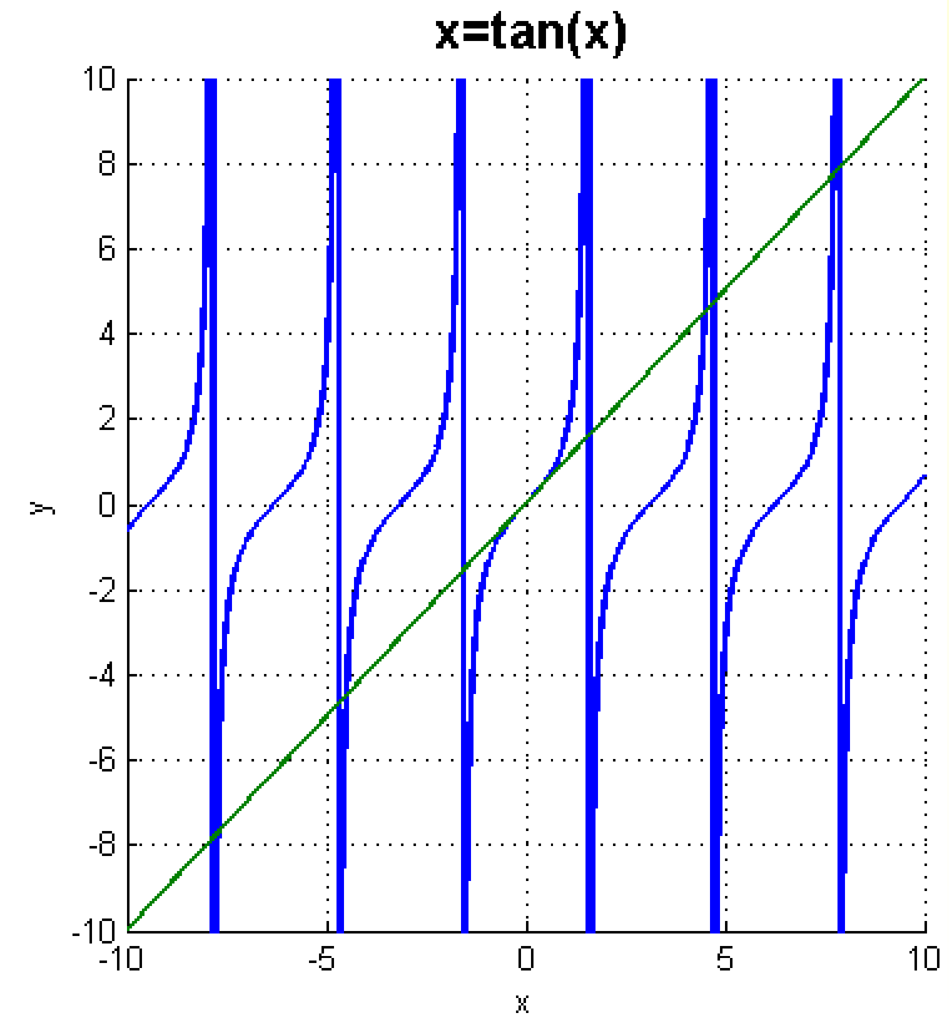
$$f(x) = \mathrm{sinc}^2(x) = \left(\frac{\sin x}{x}\right)^2$$

$$f'(x) = \left(\frac{x^2 \times 2\sin x\cos x - 2x\sin^2 x}{x^4}\right) = 0$$

X (radians)=0 is maximal (main beam);

and xcosx=sinx;

for x≠ п/2; x=tanx



Numerical solutions :

x=0,+/- **4.49** (≈1.5 Π, 4.71);

+/-7.72 (≈2.5 Π, 7.85) …

At x= +/- 4.49; 10 log (sinc x)^2=

-13.26: first sidelobe attenuation

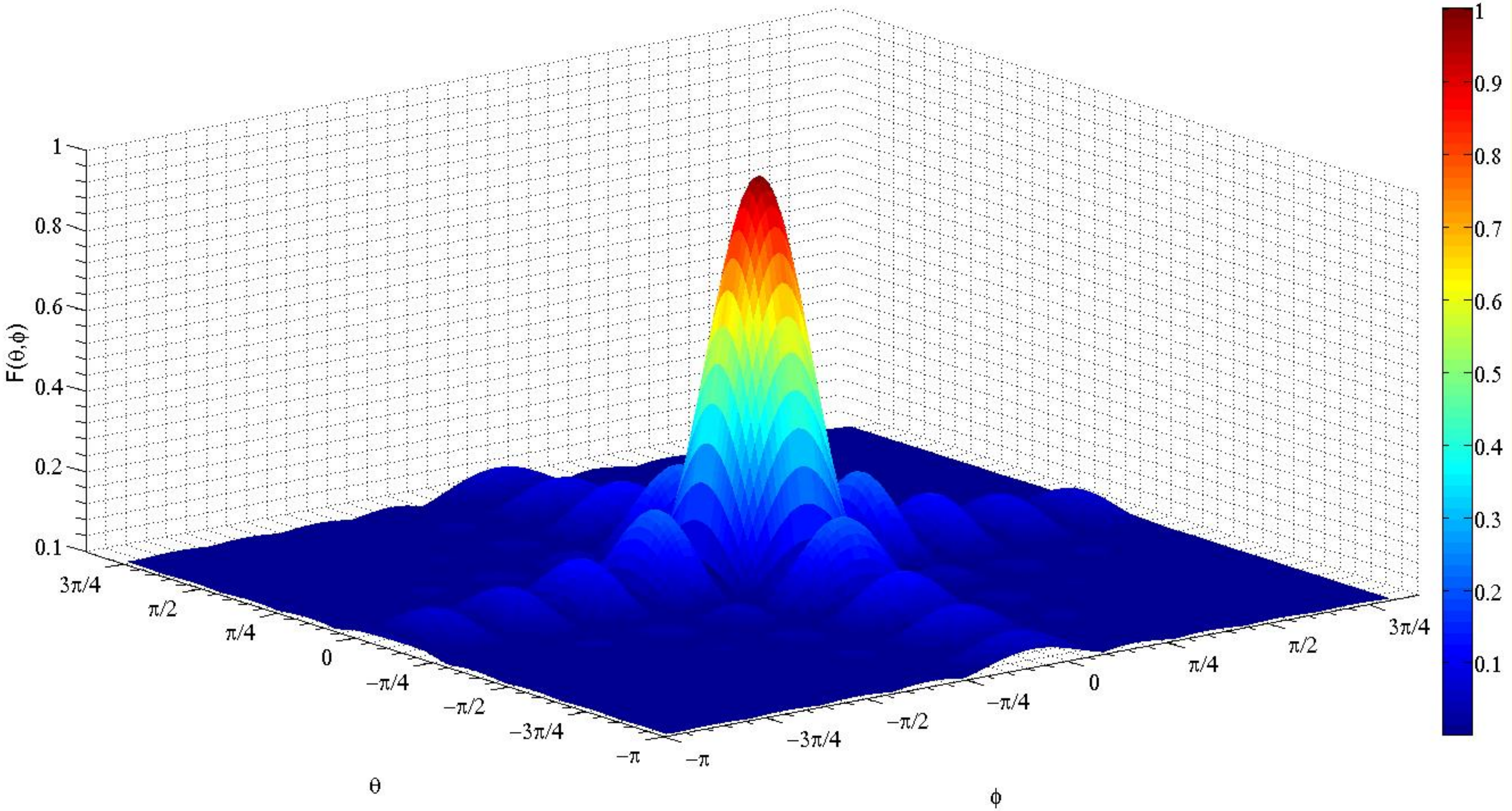
+10>x>-10 radians

Series' expansion of tan(x) is inappropriate as tan(x) and its derivatives are not continuous for x= +/- Π /2 +nx Π

—— y=x —— y=tan(x)

Matlab 3D rectangular reflector illuminated $e(\theta,\varphi)=1$, relative pattern $[(\sin u)/u]^2$

Kobi Aflalo; 25 Nov 2014
Rec. M.1851, fig. 15



Rec. ITU-R F699 radiation patterns 100 MHz –86 GHz
the Author contributed the Rec's revisions of 2018

$$\left.\begin{array}{ll} D: & \text{antenna diameter} \\ \lambda: & \text{wavelength} \end{array}\right\} \text{expressed in the same units}$$

$$20\log\frac{D}{\lambda} \approx G_{max} - 7.7 \qquad G_{max} \approx 20\log\frac{D}{\lambda} + 7.7$$

$$\boxed{D/\lambda \approx 70/\theta^{0}} \qquad \boxed{G_{max}(\text{dBi}) \approx 44.5 - 20\log\theta^{0}}$$

where θ is the beamwidth (−3 dB) (degrees) (& η = 0.7)

Rec. ITU-R F699 Patterns for 70 GHz to 86 GHz, where D/λ ≥100

D= Ant length or diameter; formulas are the 2018, above 70 GHz, **appropriate also 1–70 GHz**

$G(\varphi) = G_{max} - 2.5 \times 10^{-3} \left(\frac{D}{\lambda} \varphi \right)^2$	for	$0° < \varphi < \varphi_m$
$G(\varphi) = G_1$	for	$\varphi_m \le \varphi < \varphi_r$
$G(\phi) = 32 - 10 \log \frac{D}{\lambda} - 25 \log \phi$	for	$\varphi_r \le \varphi < 120°$
$G(\phi) = -20$	for	$120° \le \varphi \le 180°$

$G(\varphi)$: gain relative to an isotropic antenna; φ : off-axis angle (degrees)

D : antenna diameter
λ : wavelength
} expressed in the same units

G_1 : gain of the first side-lobe $= 2 + 15 \log D/\lambda$

$$\varphi_m = \frac{20\lambda}{D} \sqrt{G_{max} - G_1} \quad \text{degrees}$$

$$\phi_r = 15.85 \left(\frac{D}{\lambda} \right)^{-0.6} \quad \textit{degrees}$$

Rec. ITU-R F699 Patterns for 1 GHz to 86 GHz, where D/λ ≤100

D= Ant length or diameter; formulas are the 2018, above 70 GHz, **appropriate also 1–70 GHz**

$$G(\varphi) = G_{max} - 2.5 \times 10^{-3} \left(\frac{D}{\lambda} \varphi \right)^2 \quad \text{for} \quad 0^\circ < \varphi < \varphi_m$$

$$G(\varphi) = G_1 \quad \text{for} \quad \varphi_m \le \varphi < 100 \frac{\lambda}{D}$$

$$G(\varphi) = 52 - 10 \log \frac{D}{\lambda} - 25 \log \varphi \quad \text{for} \quad 100 \frac{\lambda}{D} \le \varphi < 120^\circ$$

$$G(\phi) = -10 \log \frac{D}{\lambda} \quad \text{for} \quad 120^\circ \le \varphi \le 180^\circ$$

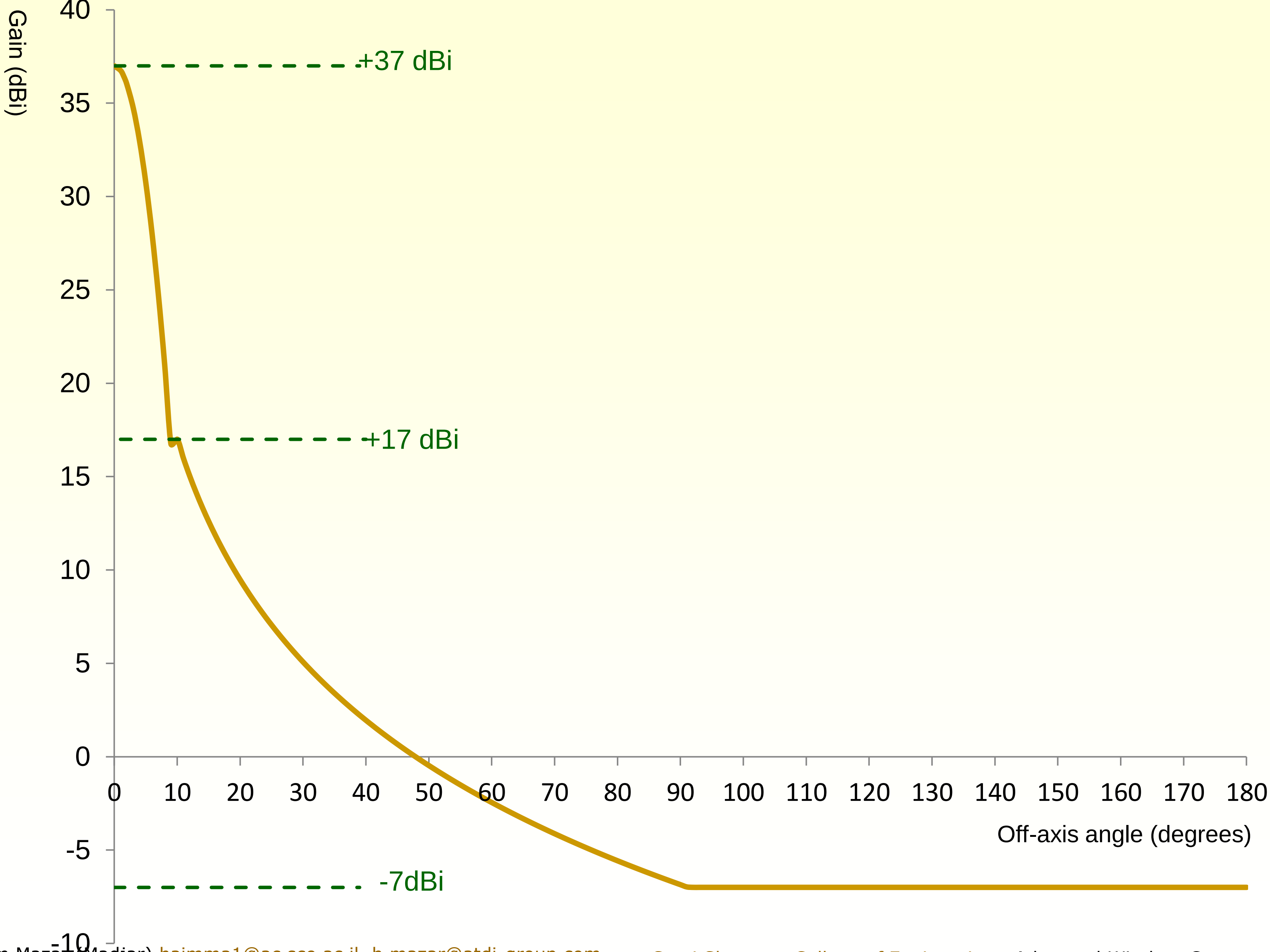
$G(\varphi)$: gain relative to an isotropic antenna; φ: off-axis angle (degrees)

D: antenna diameter
λ: wavelength
} expressed in the same units

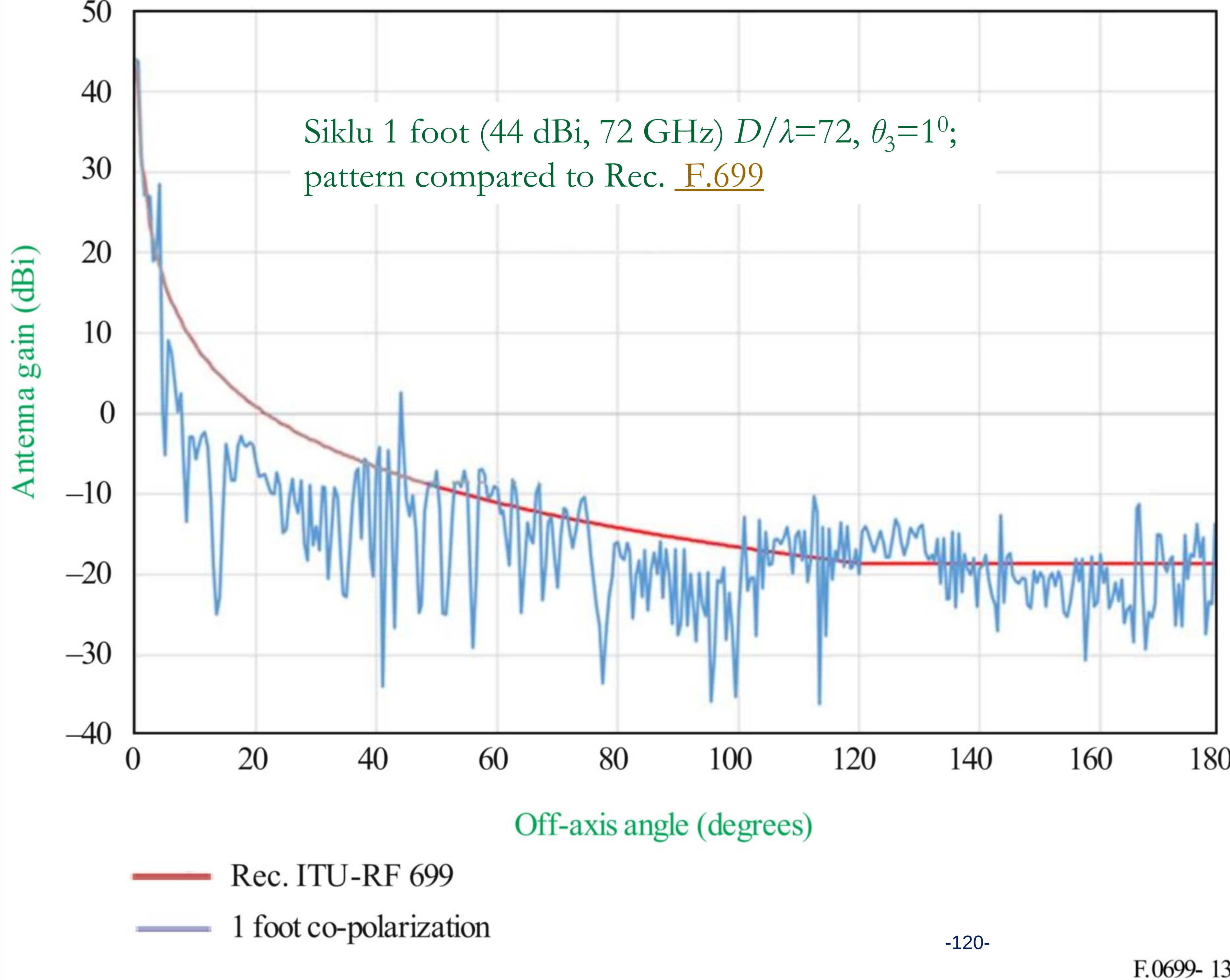
G_1: gain of the first side-lobe $= 2 + 15 \log D/\lambda$

$$\varphi_m = \frac{20\lambda}{D} \sqrt{G_{max} - G_1} \quad \text{degrees}$$

Vertical pattern of TV ant. 17 dBi calculated by ITU-R Rec. F.699



Siklu 1 foot (44 dBi, 72 GHz) D/λ=72, $\theta_3=1^0$;
pattern compared to Rec. F.699



Pattern approximation by powers of Cosine

Many aperture-type antennas have a single major lobe and the backward is negligible; their far-field patterns can be approximated by simple and useful analytical functions; see Lo YT and Lee SW 1988:1-28 and Balanis 1997:48.

The **normalised/relative numeric gain** for elevation (el) 0≤ θ ≤2π & azimuth (az) 0≤φ≤2π equals:

$$g(\theta) = \left|(\cos\theta)^{q_{el}}\right| \text{ and } g(\varphi) = \left|(\cos\varphi)^{q_{az}}\right|$$

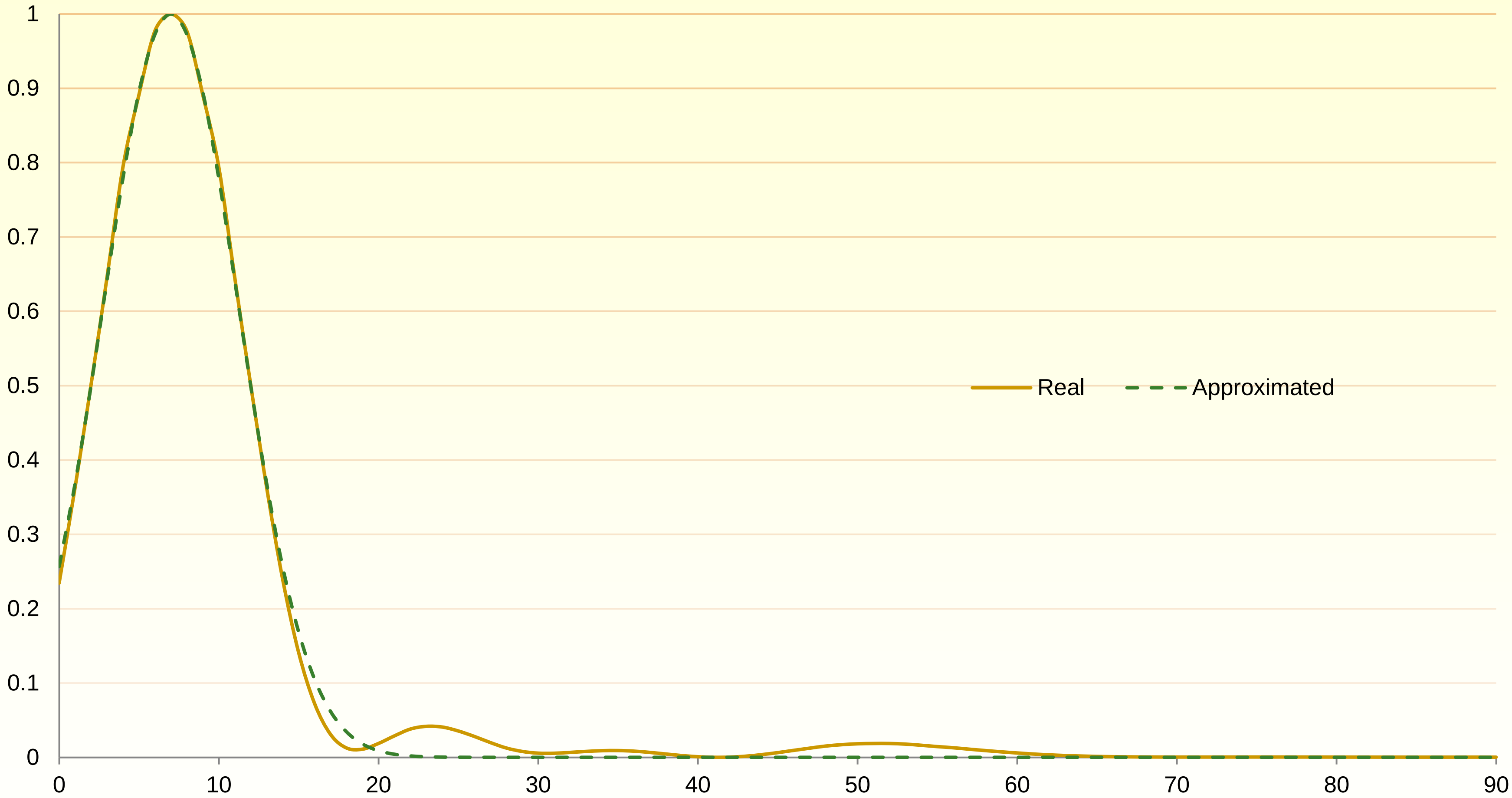
At the half-power angles (antenna beamwidths) ½ θ_{3db} and ½ φ_{3db}, the numeric gains $g(\theta)$ and $g(\varphi)$ equal 0.5; therefore, the exponents $\boldsymbol{q}_{\mathbf{el}}$ and $\boldsymbol{q}_{\mathbf{az}}$ can be calculated:

$$g(\frac{1}{2}\theta_{3db}) = \cos^{q_{el}}(\frac{1}{2}\theta_{3db}) = 0.5 \text{ and } g(\frac{1}{2}\varphi_{3db}) = \cos^{q_{az}}(\frac{1}{2}\varphi_{3db}) = 0.5$$

$$g(\frac{1}{2}\varphi_{3db}) = \cos^{q_{az}}(\frac{1}{2}\varphi_{3db}) = 0.5 \qquad q_{el} = \frac{\log 0.5}{\log(\cos\frac{1}{2}\theta_{3db})} \; and \; q_{az} = \frac{\log 0.5}{\log(\cos\frac{1}{2}\varphi_{3db})}$$

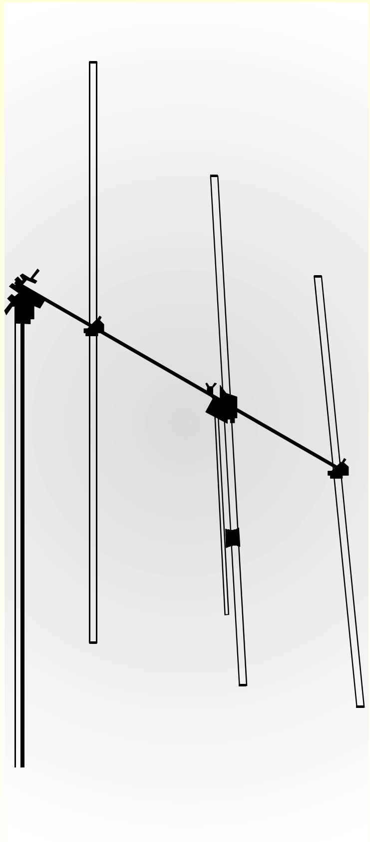
Actually, cosine patterns are the envelope of the antenna sidelobes

Real elev. pattern vs. calculated $\cos^n(\theta\text{-}a)$ for a tilt of 7^0

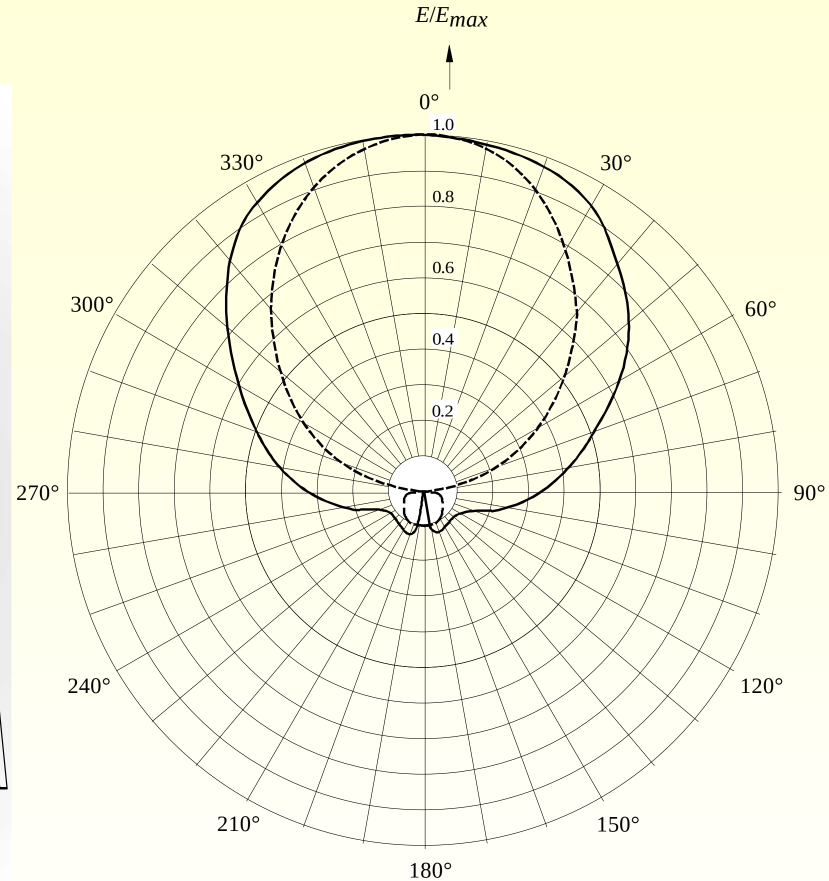


See ITU-T Recommendation K.52 p. 35, prepared by Agostinho Linhares de Souza Filho, ANATEL, Brazil, 2013

Typical TV ant (ITUR Rec. BS. 1195 2013)



a) Typical Yagi antenna for
full Band II coverage



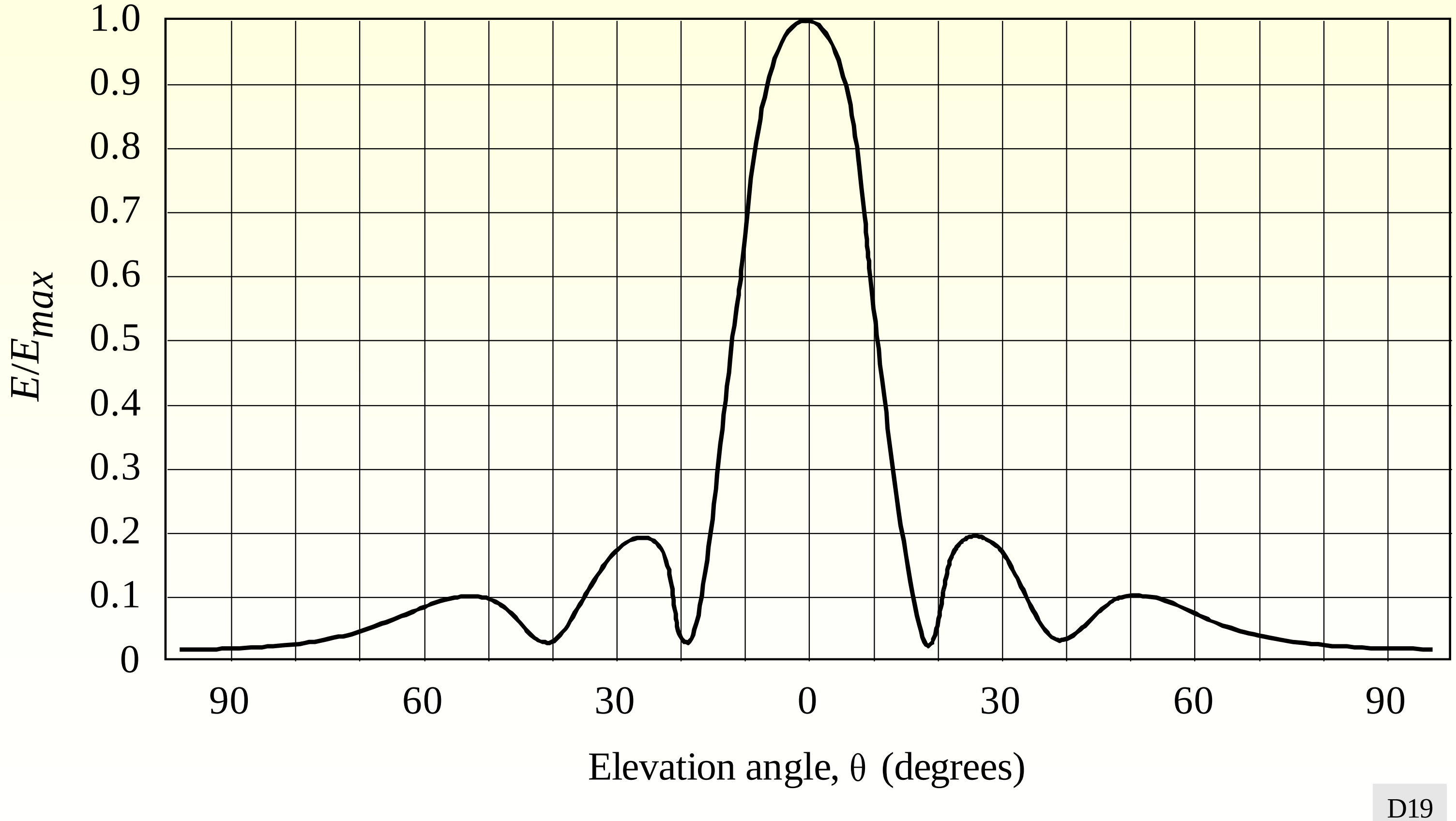
b) Typical radiation pattern

—— Pattern in the plane orthogonal to dipoles

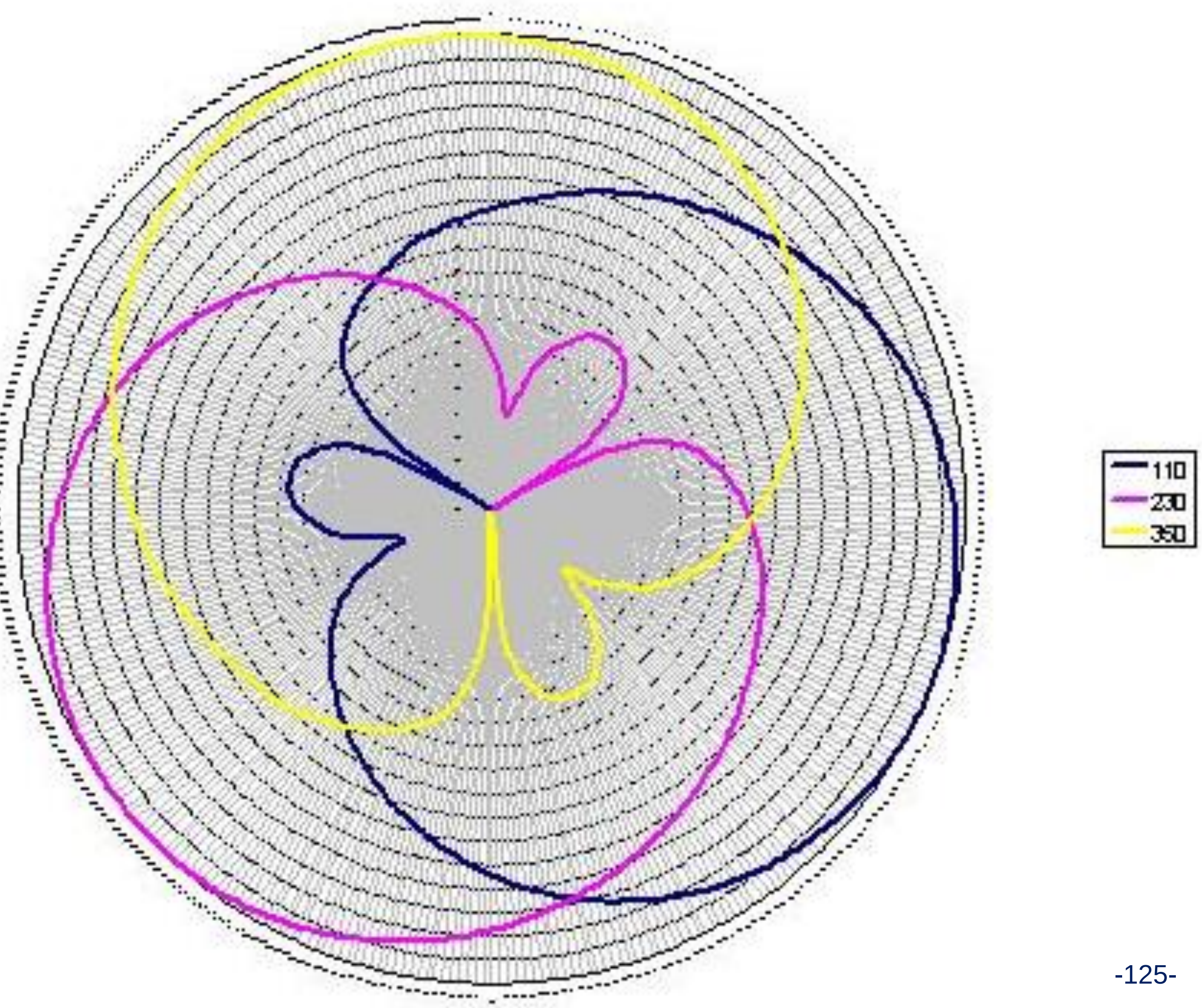
- - - - - Pattern in the plane of dipoles

TV elev. Pattern (ITU-R Rec. BS. 1195 2013)

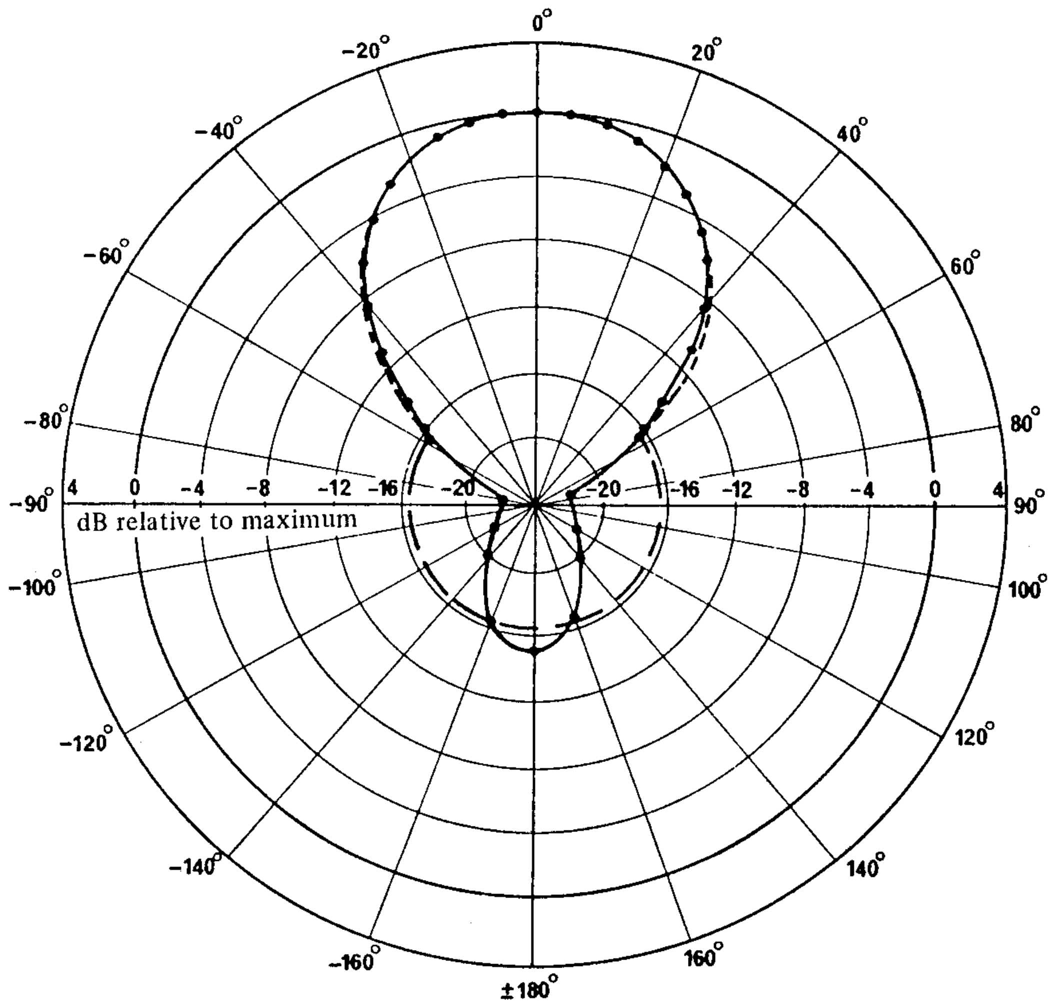
Vertical radiation pattern for an array of 5 vertical 0.5 λ spaced radiating elements having equal current and phase



Typical mast and horizontal pattern of a typical cellular antenna

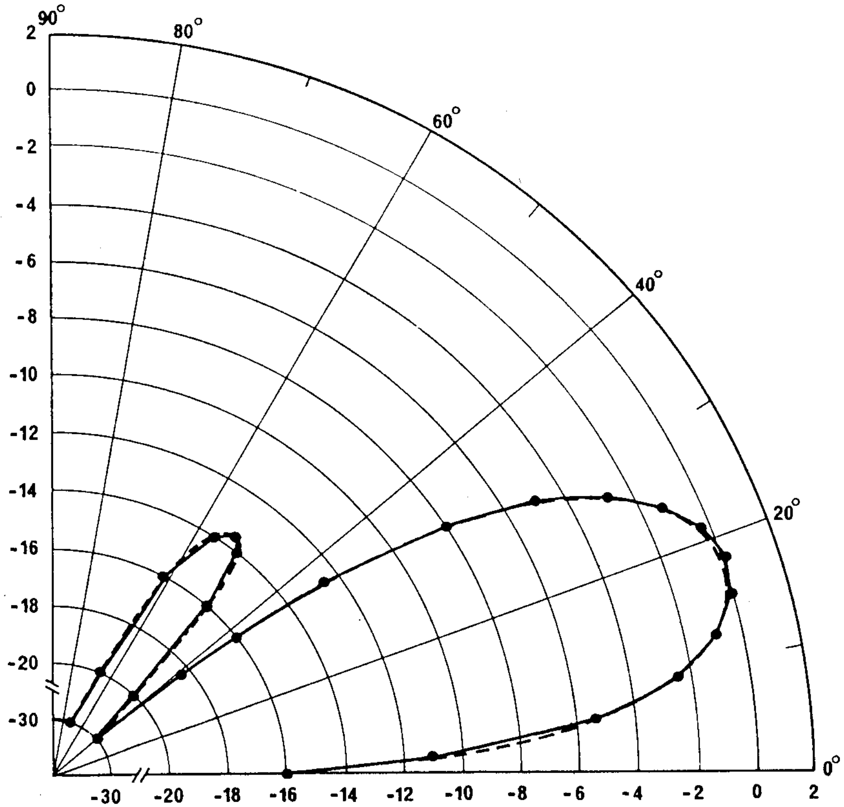


Typical HF Antenna Pattern (Rec. ITU-R BS. 80)

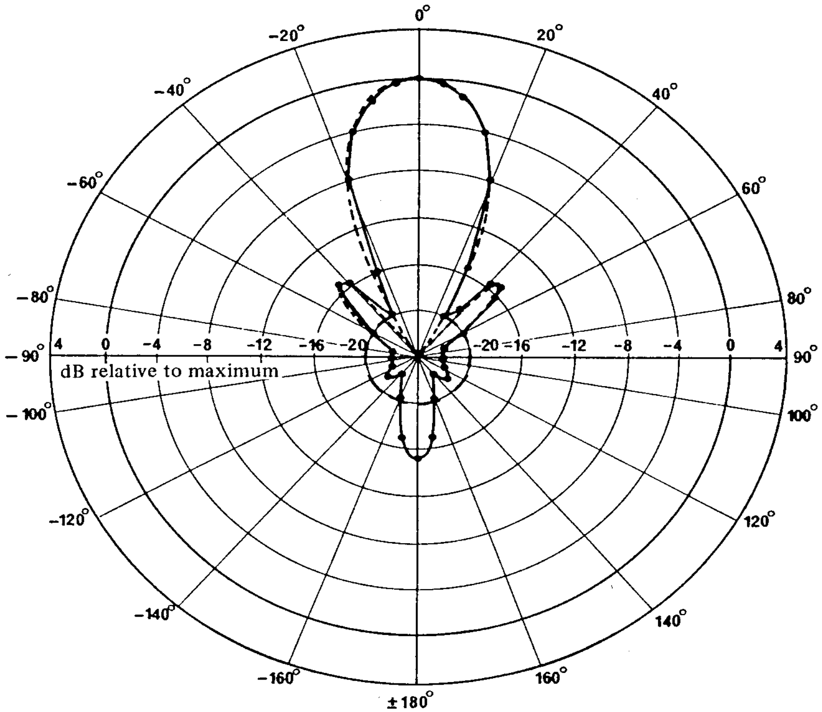


a) Azimuthal pattern HR 2/4/0.5, maximum gain 19 dBi

Az. and Elev. Patterns of Tx HF Ant. (BS. 80)



a) Vertical pattern HR *m*/2/0.5



b) Azimuthal pattern HR 4/4/1, maximum gain 22 dBi

FIGURE 2 — *Azimuthal patterns*

Representative data

ITU-R data

Recommendation ITU-R BS.80

0080-02

Antenna RF Bandwidth

Balanis (2008 p. 26) defines the **ant bandwidth** as 'the range of frequencies within which the performance of the antenna, with respect to some characteristic, conforms to a specified standard'. Those parameters may shape the bandwidth: input impedance, gain, radiation pattern, beamwidth, polarization, side-lobe level, radiation efficiency, etc. For f_o center frequency, the bandwidth for broadband antenna FBW_{bb} and narrowband FBW_{nb} equal:

$$FBW_{bb} = \frac{f_{\max}}{f_{\min}}$$

$$FBW_{nb} = \frac{f_{\max} - f_{\min}}{f_0} 100\%$$

Polarizations (ITU-R Recommendation BS. 1195)

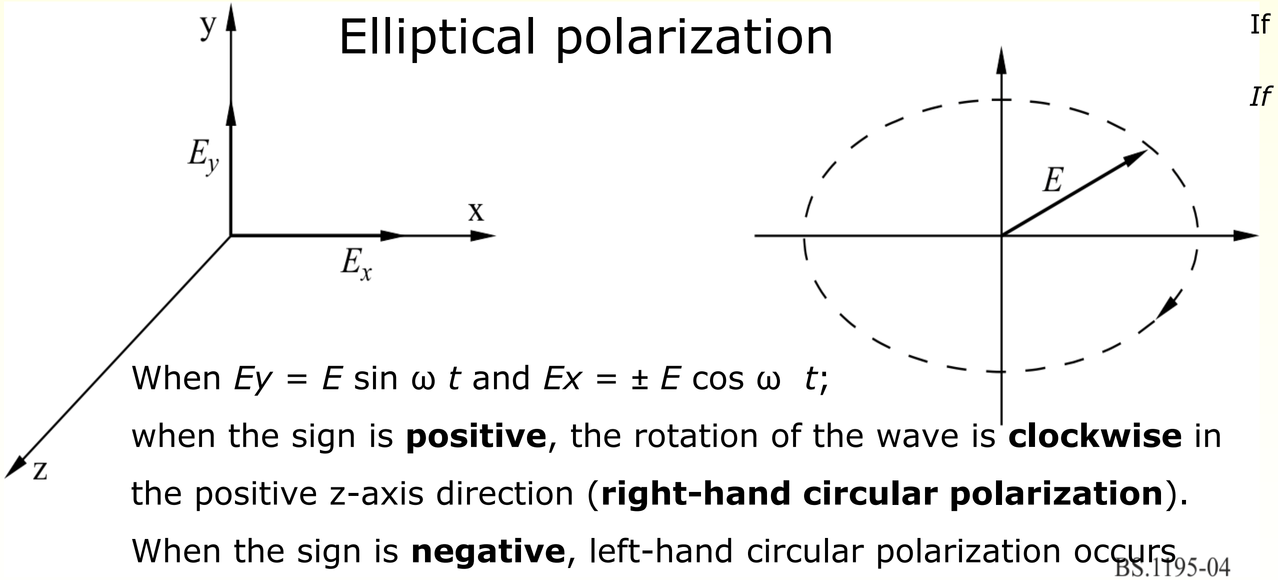
- **Polarization** is the orientation of the electrical field vector, which may be in a fixed direction or may change in time. Polarization is defined in the far-field.
- The different forms of wave polarization (**linear and circular**) are special cases of the more general case of **elliptical polarization**.
- The field strength vector describes an ellipse whose semi-axes are given by E_1 and E_2

$$E_x = E_1 \sin \omega t \; ; \quad E_y = E_2 \sin (\omega t + \varphi)$$

If $E_1 = E_2$ and $\varphi = 0$, 45° slant polarization

If $E_1 = 0$, Vertical Pol; If $E_2 = 0$, Horizontal Pol

Antenna patterns differ for cross polarization



When $E_y = E \sin \omega t$ and $E_x = \pm E \cos \omega t$;

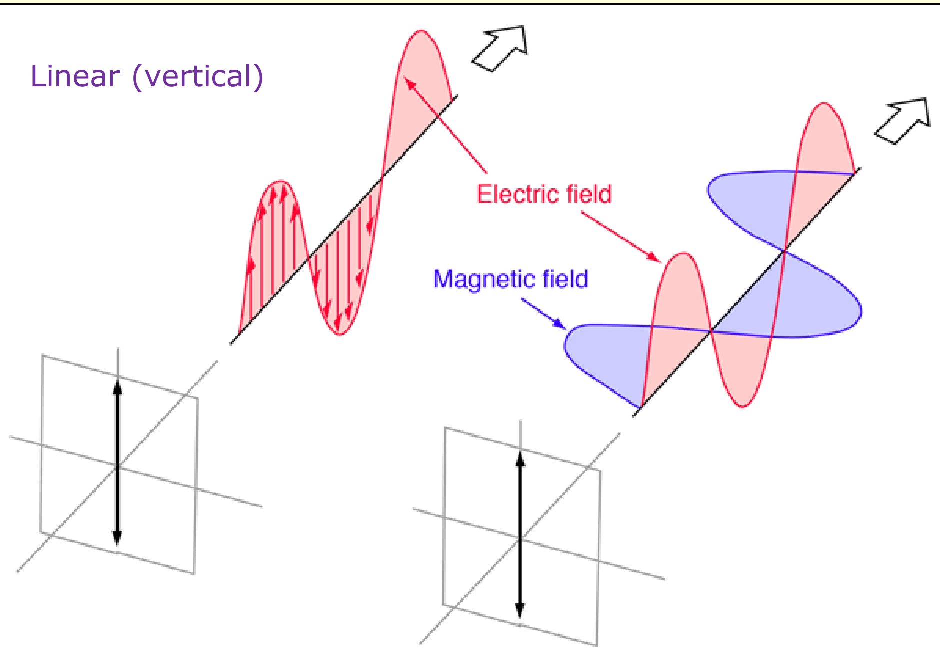
when the sign is **positive**, the rotation of the wave is **clockwise** in the positive z-axis direction (**right-hand circular polarization**).

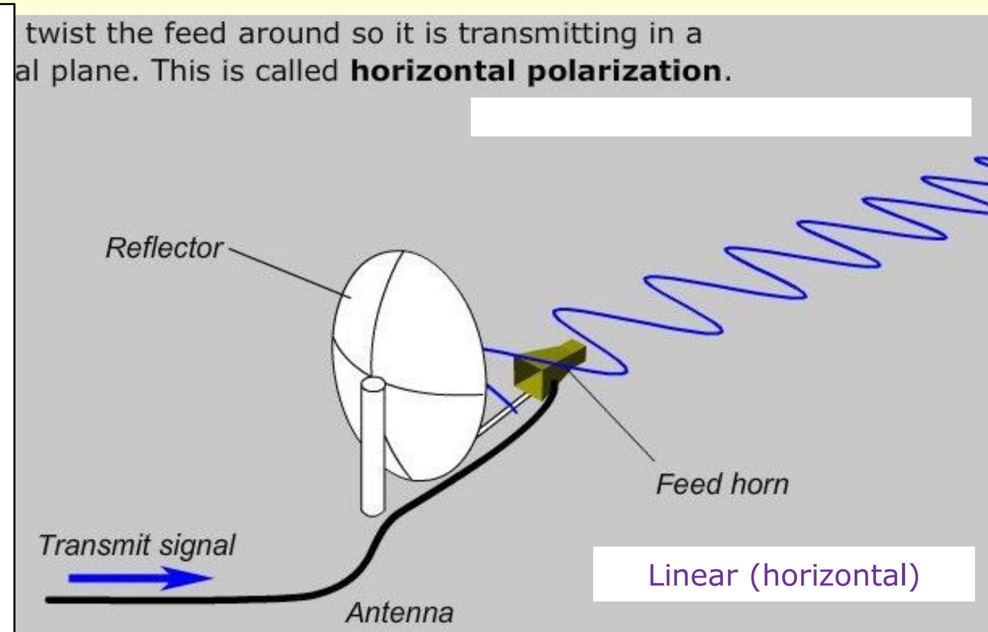
When the sign is **negative**, left-hand circular polarization occurs.

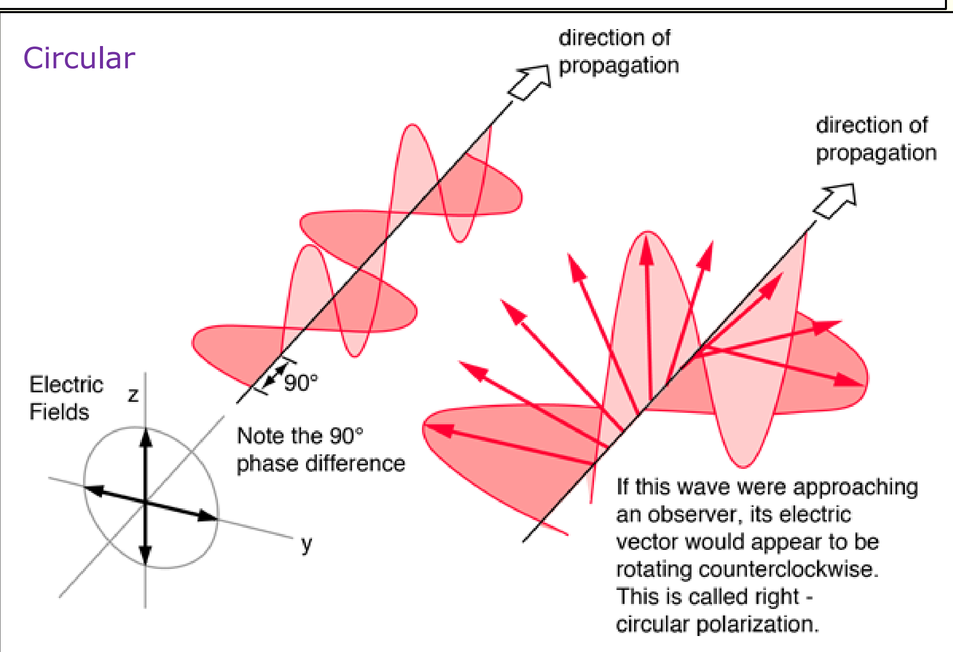
Two arrays of receiving **cross-polarized base station** antenna improve the up-link cellular signal **up to 6 dB;** this receiver polarization diversity also decreases the link un-balance, derived from higher down-link transmitting power, relative to the handset up-link power

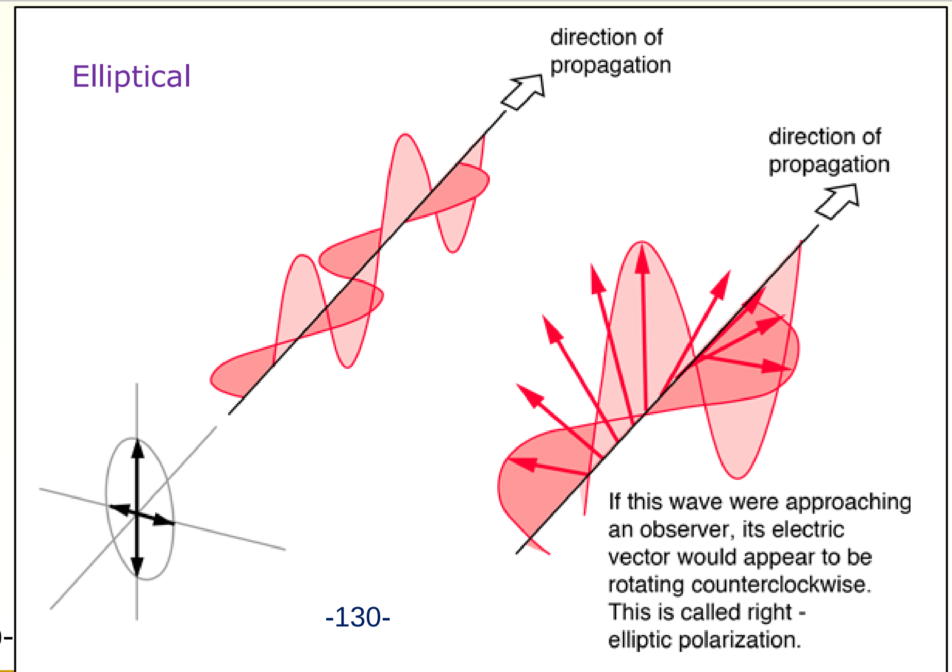
Polarization

http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/polclas.html; https://www.linksystems-uk.com/vsat-polarization/

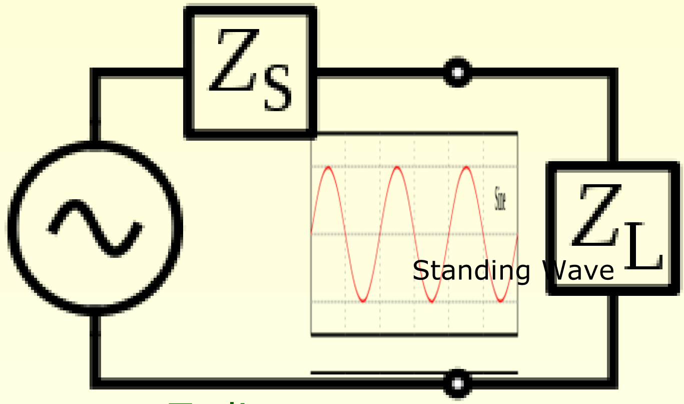








Impedance, Return Loss and VSWR



- At this equivalent circuit, Z_S represents Tx and Z_L the ant impedance, a complex number.

  $$\mathbf{Z= R + jX= |Z|e^{j\theta} \quad Z_L = Z_a = R_{losses} + R_{radiation} + j\,X_L}$$

- At resonance $Z_a = R_r$ (Radiation Resistance). Max power is transferred to the antenna, when the generator is conjugately matched to the antenna.
- The ant impedance can be viewed as a load connected to a transmission line with characteristic impedance of Z_l
- The reflection coefficient Γ is the ratio of reflected voltage to incident voltage waves at the ant terminals
- Γ is related to the impedances at resonance by: $\mathbf{\Gamma=(R_r-Z_0)/(R_r+Z_0)}$
- The returned power from the ant to the generator is the Power Loss (PL) or Return Loss :

  $$\mathbf{PL=RL= |\Gamma|^2=\rho^2}$$

VSWR: Voltage Standing Wave Ratio

- The voltage component of a standing wave consists of the forward wave (with amplitude V_f) superimposed on the reflected wave (with amplitude V_r).

- The voltage reflection coefficient $\Gamma \equiv V_r / V_f$ $\rho \equiv |\Gamma|$ Return Loss $\equiv \rho^2$

- $V_{max} = V_f + V_r = V_f + \rho V_f = V_f (1+\rho)$ $V_{min} = V_f - V_r = V_f - \rho V_f = V_f (1-\rho)$

$$\text{VSWR} = \frac{V_{max}}{V_{min}} = \frac{1+\rho}{1-\rho} \qquad \rho = \frac{VSWR - 1}{VSWR + 1}$$

- ρ always falls in the range [0,1], so the VSWR is always ≥ +1

- SWR is also defined as the ratio of the maximum amplitude of the electric field to its minimum amplitude E_{max} / E_{min}

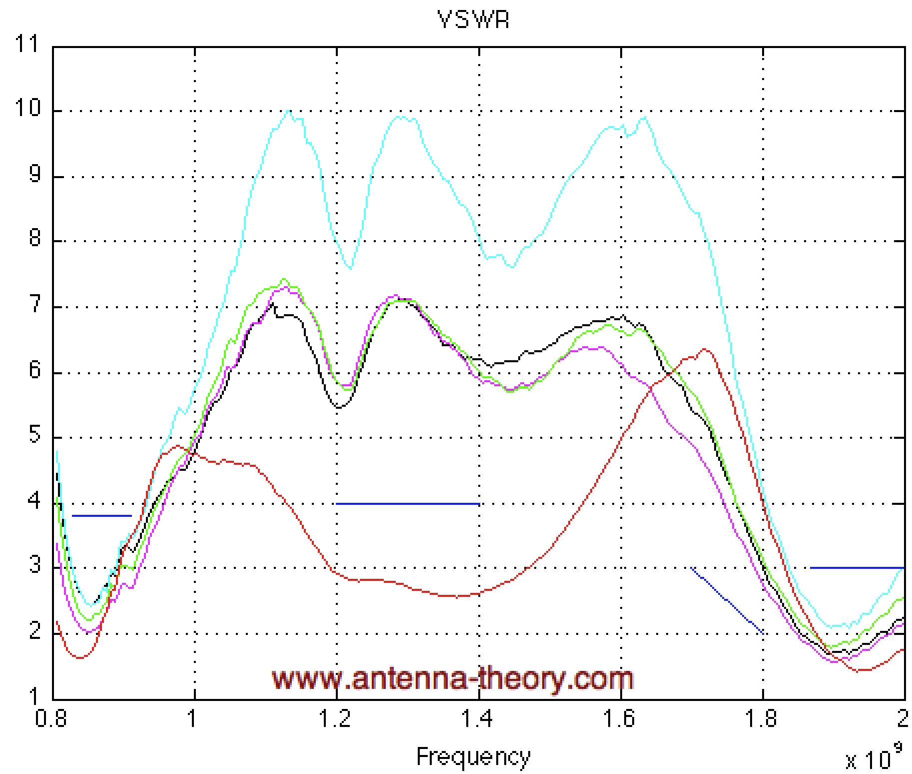
$$\text{SWR} = \frac{E_{max}}{E_{min}} = \frac{1+\rho}{1-\rho}$$

The bandwidth is a measure of how much the frequency can be varied while still obtaining an acceptable VSWR (2:1 or less) and minimizing losses in unwanted directions. A 2:1 VSWR corresponds to a 9.5dB (or 10%) return loss

The Return Loss (RL) =

20 log ρ=20 log (VSWR-1) - 20 log (VSWR+1)

Mismatch loss (ML) is the ratio of incident power to the difference between incident and reflected power; ML (dB) = -10 log (1- ρ^2)



return loss Vs. VSWR

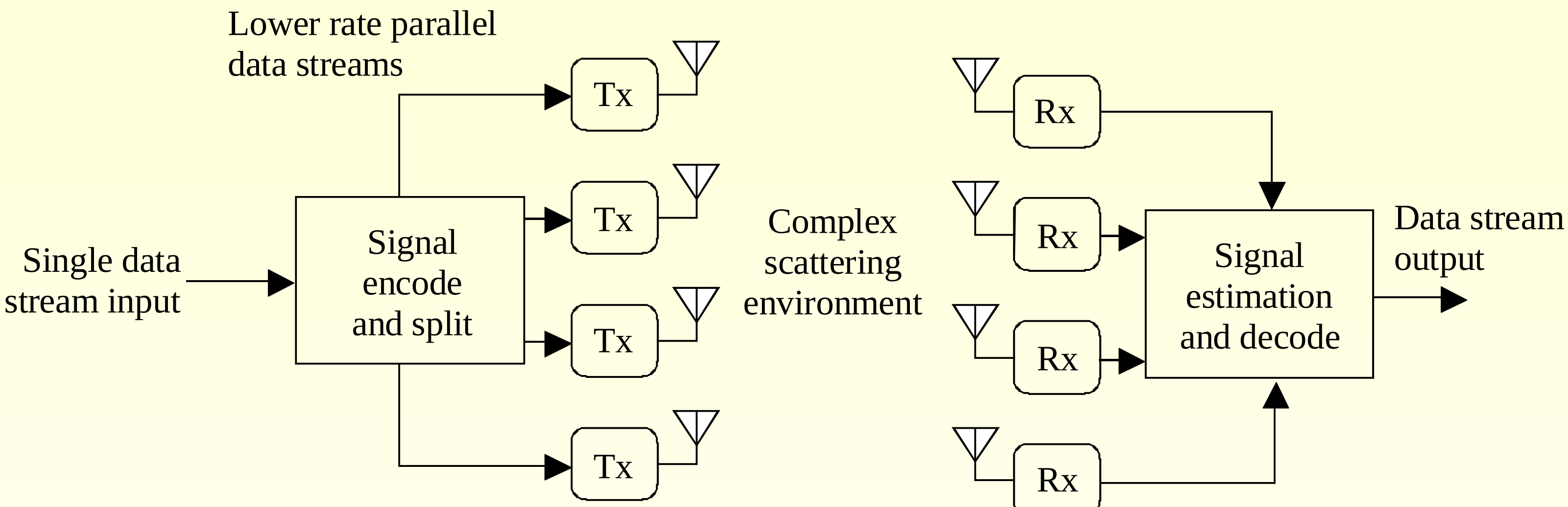
table of return loss vs. voltage standing wave ratio

RETURN LOSS (dB)	VSWR	RETURN LOSS (dB)	VSWR	RETURN LOSS (dB)	VSWR	RETURN LOSS (dB)	VSWR	RETURN LOSS (dB)
46.064	1.01	13.842	1.51	9.485	2.01	7.327	2.51	5.999
40.086	1.02	13.708	1.52	9.428	2.02	7.294	2.52	5.970
36.607	1.03	13.577	1.53	9.372	2.03	7.262	2.53	5.956
34.151	1.04	13.449	1.54	9.317	2.04	7.230	2.54	5.935
32.256	1.05	13.324	1.55	9.262	2.05	7.198	2.55	5.914
30.714	1.06	13.201	1.56	9.208	2.06	7.167	2.56	5.893
29.417	1.07	13.081	1.57	9.155	2.07	7.135	2.57	5.872
28.299	1.08	12.964	1.58	9.103	2.08	7.105	2.58	5.852
27.318	1.09	12.849	1.59	9.051	2.09	7.074	2.59	5.832
26.444	1.10	12.736	1.60	8.999	2.10	7.044	2.60	5.811
25.658	1.11	12.625	1.61	8.949	2.11	7.014	2.61	5.791
24.943	1.12	12.518	1.62	8.899	2.12	6.984	2.62	5.771
24.289	1.13	12.412	1.63	8.849	2.13	6.954	2.63	5.751
23.686	1.14	12.308	1.64	8.800	2.14	6.925	2.64	5.732
23.127	1.15	12.207	1.65	8.752	2.15	6.896	2.65	5.712
22.607	1.16	12.107	1.66	8.705	2.16	6.867	2.66	5.693
22.120	1.17	12.009	1.67	8.657	2.17	6.839	2.67	5.674
21.664	1.18	11.913	1.68	8.611	2.18	6.811	2.68	5.654
21.234	1.19	11.818	1.69	8.565	2.19	6.783	2.69	5.635
20.828	1.20	11.725	1.70	8.519	2.20	6.755	2.70	5.617
20.443	1.21	11.634	1.71	8.474	2.21	6.728	2.71	5.598
20.079	1.22	11.545	1.72	8.430	2.22	6.700	2.72	5.579
19.732	1.23	11.457	1.73	8.386	2.23	6.673	2.73	5.561
19.401	1.24	11.370	1.74	8.342	2.24	6.646	2.74	5.542
19.085	1.25	11.285	1.75	8.299	2.25	6.620	2.75	5.524
18.783	1.26	11.202	1.76	8.257	2.26	6.594	2.76	5.506
18.493	1.27	11.120	1.77	8.215	2.27	6.567	2.77	5.488
18.216	1.28	11.039	1.78	8.173	2.28	6.541	2.78	5.470
17.949	1.29	10.960	1.79	8.138	2.29	6.516	2.79	5.452
17.690	1.30	10.881	1.80	8.091	2.30	6.490	2.80	5.435
17.445	1.31	10.804	1.81	8.051	2.31	6.465	2.81	5.417
17.207	1.32	10.729	1.82	8.011	2.32	6.440	2.82	5.400
16.977	1.33	10.654	1.83	7.972	2.33	6.415	2.83	5.383
16.755	1.34	10.581	1.84	7.933	2.34	6.390	2.84	5.365
16.540	1.35	10.509	1.85	7.894	2.35	6.366	2.85	5.348
16.332	1.36	10.437	1.86	7.856	2.36	6.341	2.86	5.331
16.131	1.37	10.367	1.87	7.818	2.37	6.317	2.87	5.315
15.936	1.38	10.298	1.88	7.781	2.38	6.293	2.88	5.298
15.747	1.39	10.230	1.89	7.744	2.39	6.270	2.89	5.281
15.563	1.40	10.163	1.90	7.707	2.40	6.246	2.90	5.265
15.385	1.41	10.097	1.91	7.671	2.41	6.223	2.91	5.248
15.211	1.42	10.032	1.92	7.635	2.42	6.200	2.92	5.232
15.043	1.43	9.968	1.93	7.599	2.43	6.177	2.93	5.216
14.879	1.44	9.904	1.94	7.564	2.44	6.154	2.94	5.200
14.719	1.45	9.842	1.95	7.529	2.45	6.131	2.95	5.184
14.564	1.46	9.780	1.96	7.494	2.46	6.109	2.96	5.168
14.412	1.47	9.720	1.97	7.460	2.47	6.086	2.97	5.152
14.264	1.48	9.660	1.98	7.426	2.48	6.064	2.98	5.137
14.120	1.49	9.601	1.99	7.393	2.49	6.042	2.99	5.121
13.979	1.50	9.542	2.00	7.360	2.50	6.021	3.00	5.105

Dr. Haim Mazar (Madjar) haimma1@ac.sce.ac.il h.mazar@atdi-group.com Sa

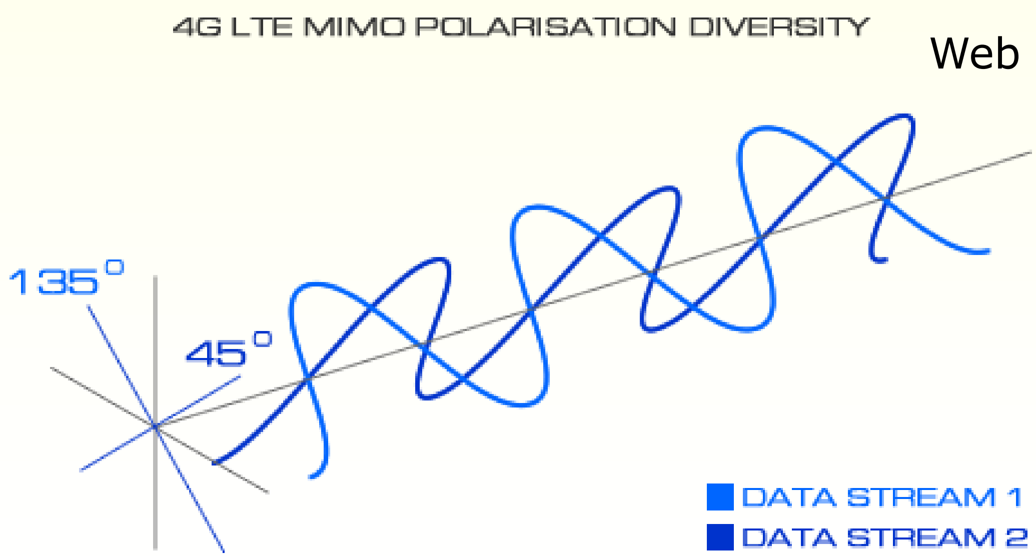
MIMO (Multiple-input multiple-output) (ITU-Report M.2038 2004)

MIMO transmitter-receiver concept



MIMO increases system throughput data rate for the same total radiated power & channel bandwidth 2038-01

Array gain to concentrate the signal to one or more directions, in order to serve multiple users simultaneously, so called MIMO (Multiple-Input and Multiple-Output): increase gain; spatial multiplexing gain to transmit multiple signal streams to a single user. MIMO DL may differ from UL MIMO



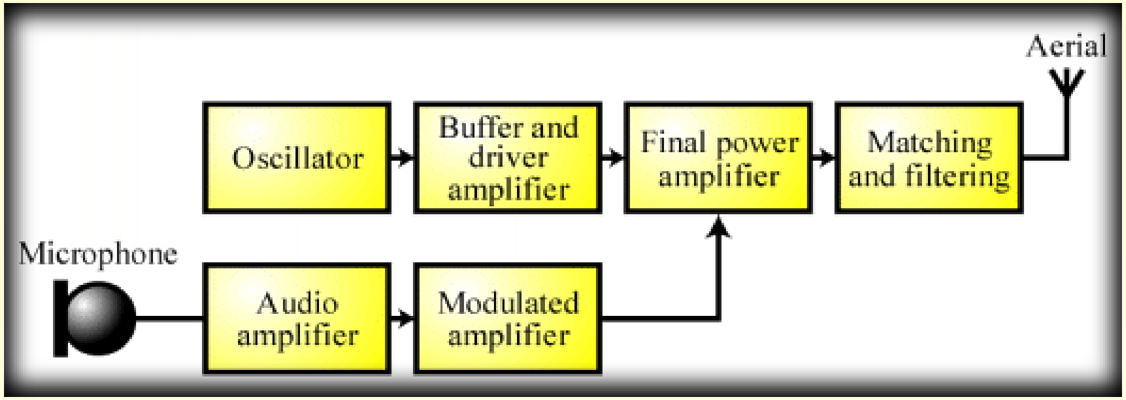
Transmitters and Receivers

http://mazar.atwebpages.com/

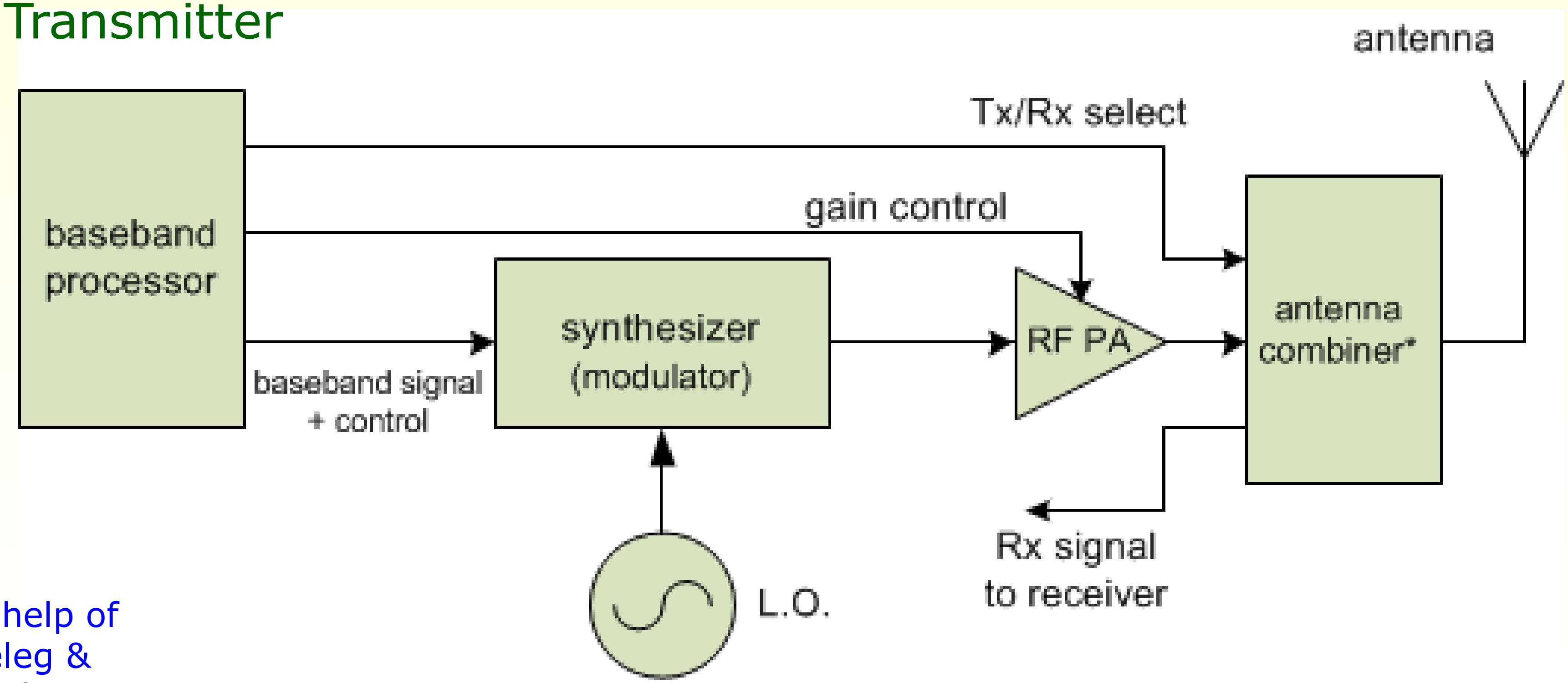
Only part of this section will be presented

Analog FM Transmitter (Ray Grimes, Motorola)

Oscillator	Fundamental x 1
Multipliers	Multiply to F_0
Mid-Amplifier	Low=Level Amplify F_0
Final Amplifier	High=Level Amplify F_0
Modulator	Modulates the Carrier



Digital Transmitter



With the help of Ehoud Peleg & Dr. Oren Eliezer

* antenna combiner is a switch for TDD systems or duplexer for FDD

Quadrature Transmitters: Representation of the modulated signal

s = modulated signal; *a* = amplitude of carrier; f_c = frequency of carrier; *t* = time; *b* = bandwidth of modulated signal; *φ* = phase of modulated signal; *f* = frequency of the modulated signal= $\frac{d\varphi}{dt}$

Polar representation: $s(t) = a(t)\ cos\ [2\pi\ f_c\ t + \ \varphi(t)]$

Cartesian (or quadrature) representation:

$$s(t) = a(t) cos\ \varphi(t) cos\ (2\pi\ f_c t) - a(t)\ sin\ \varphi(t)\ sin\ (2\pi\ f_c t)$$

$$s(t) = \ x(t)\ cos\ (2\pi\ f_c\ t) - y(t)\ \sin\ (2\pi\ f_c\ t)$$

a(t) cos φ(t)= x(t) and *a(t) sin φ(t)= y(t)*. Low-frequency signal components *x (t)* & *y (t)* may be viewed as amplitude modulations impressed on the carrier components *cos (2π* f_c *t)* and *sin (2π* f_c *t)*. *x (t)* and *y (t)* are the in-phase **I** (x axis) and quadrature-phase **Q** (y axis) components of the baseband signal.

The phase *φ* and the amplitude *a* of the signal *s(t)* may be represented as functions of the quadrature components of the complex envelope:

$$a(t) = \sqrt{x^2(t) + y^2(t)} \qquad \varphi(t) = \arctan\frac{y(t)}{x(t)}$$

a(*t*) and φ(*t*) are non-linear conversions that expand the bandwidth

Dr. Oren Eliezer
24 November 2014

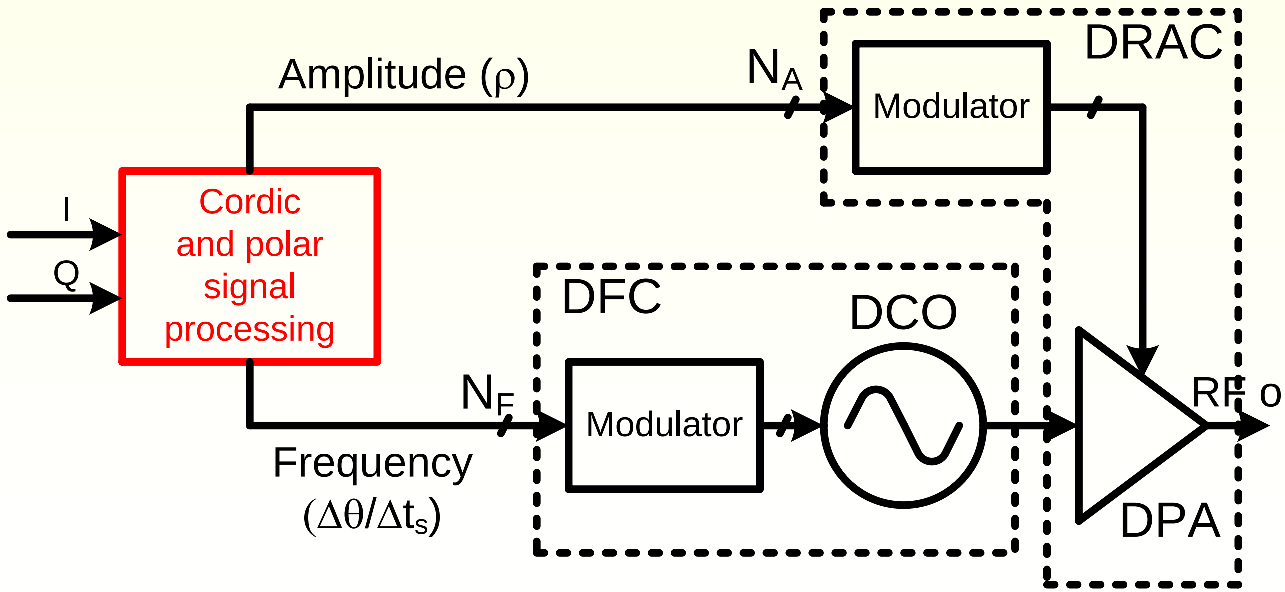
The CORDIC Operation

Cartesian to Polar Conversion

- **The CORDIC's coordinate conversion operations are non-linear**
- **Amplitude:** $\rho = \sqrt{I^2 + Q^2}$
- **Phase:** $\theta = arctan\frac{Q}{I}$

Bandwidth expansion!

- **The polar signals are much wider in bandwidth**



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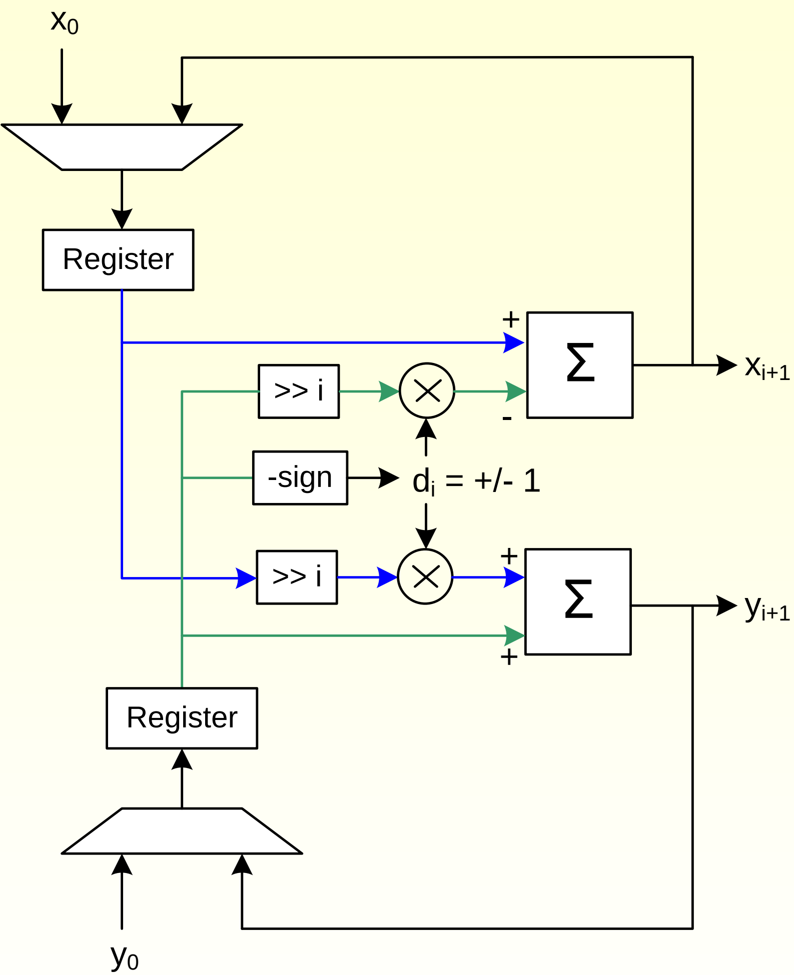
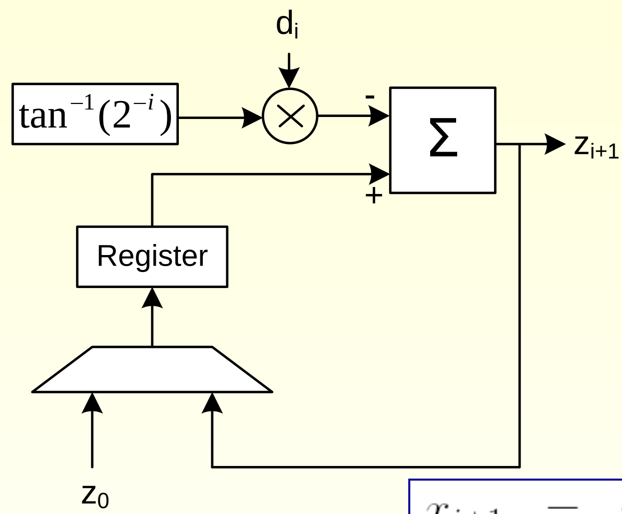
Cartesian to Polar Conversion (CORDIC)



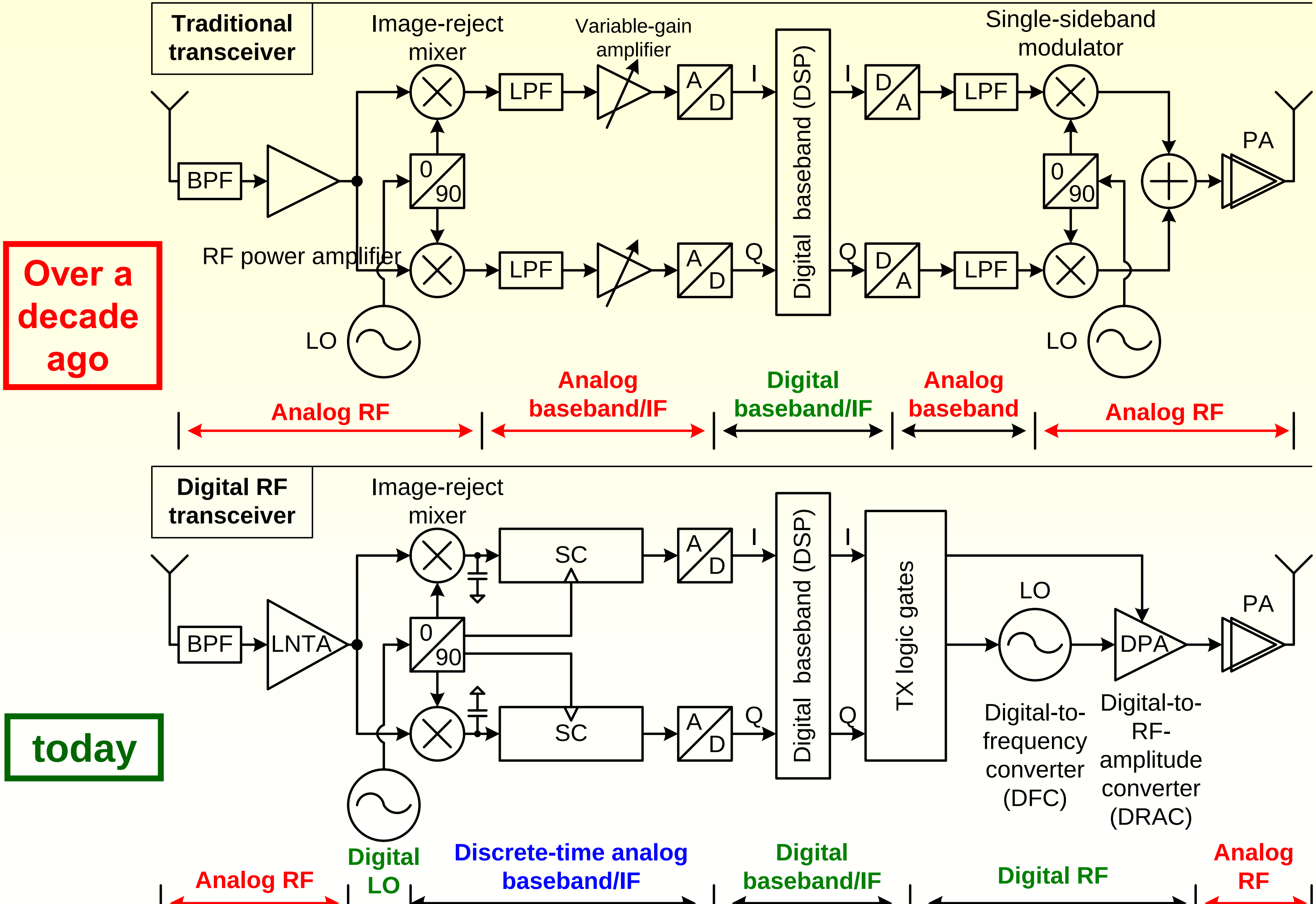


$$
\begin{aligned}
x_{i+1} &= x_i - (y_i \times d_i \times 2^{-i}) \\
y_{i+1} &= y_i + (x_i \times d_i \times 2^{-i}) \\
z_{i+1} &= x_i - [z_i \times \tan^{-1}(2^{-i})] \\
d_i &= +1 \text{ if y} < 0, \\
&= -1 \text{ otherwise}
\end{aligned}
$$

- No multiplier used
- Iterative operation using adders and shifters

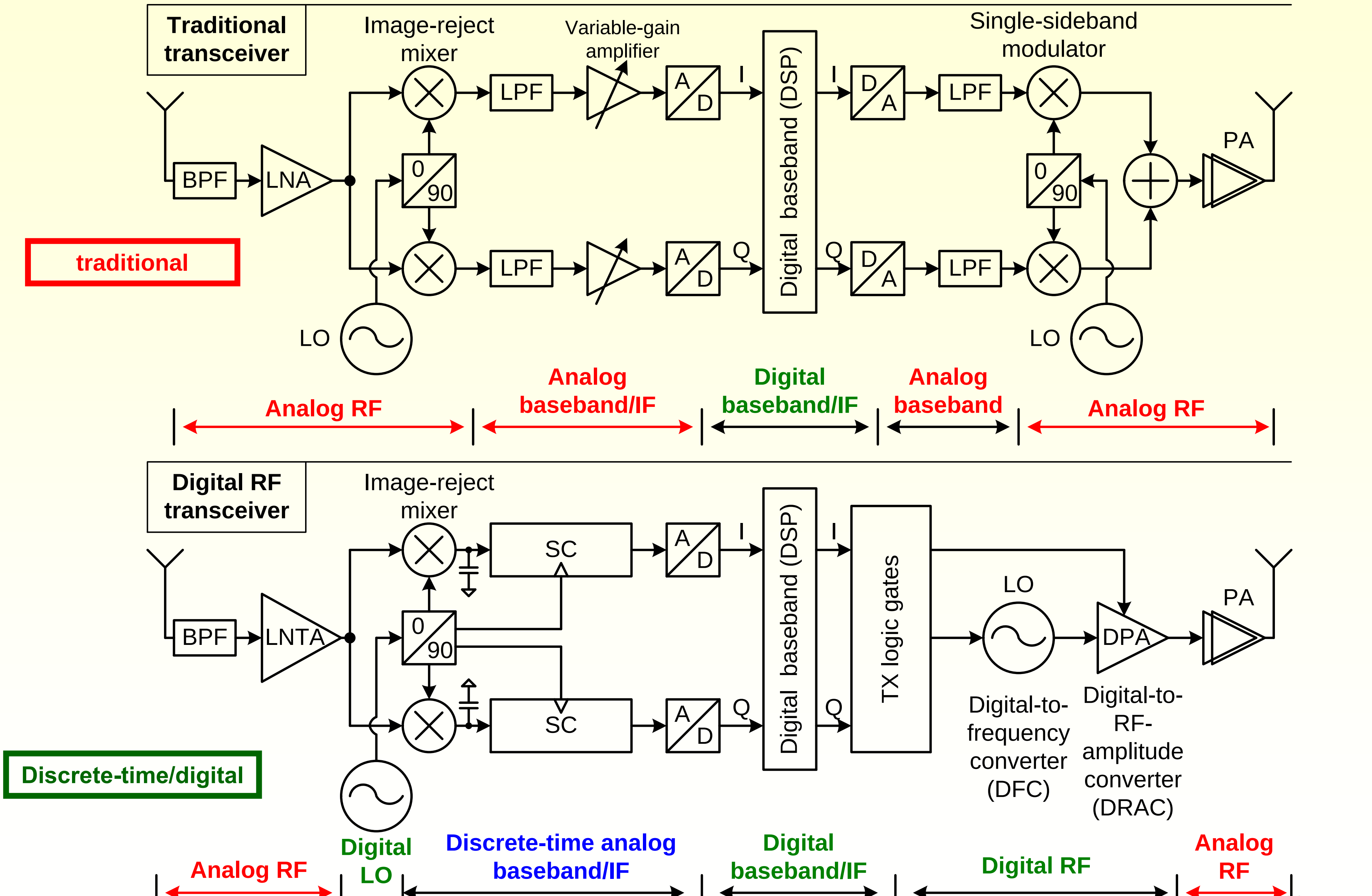
Dr. Oren Eliezer
24 November 2014

From Analog RF to Digital RF



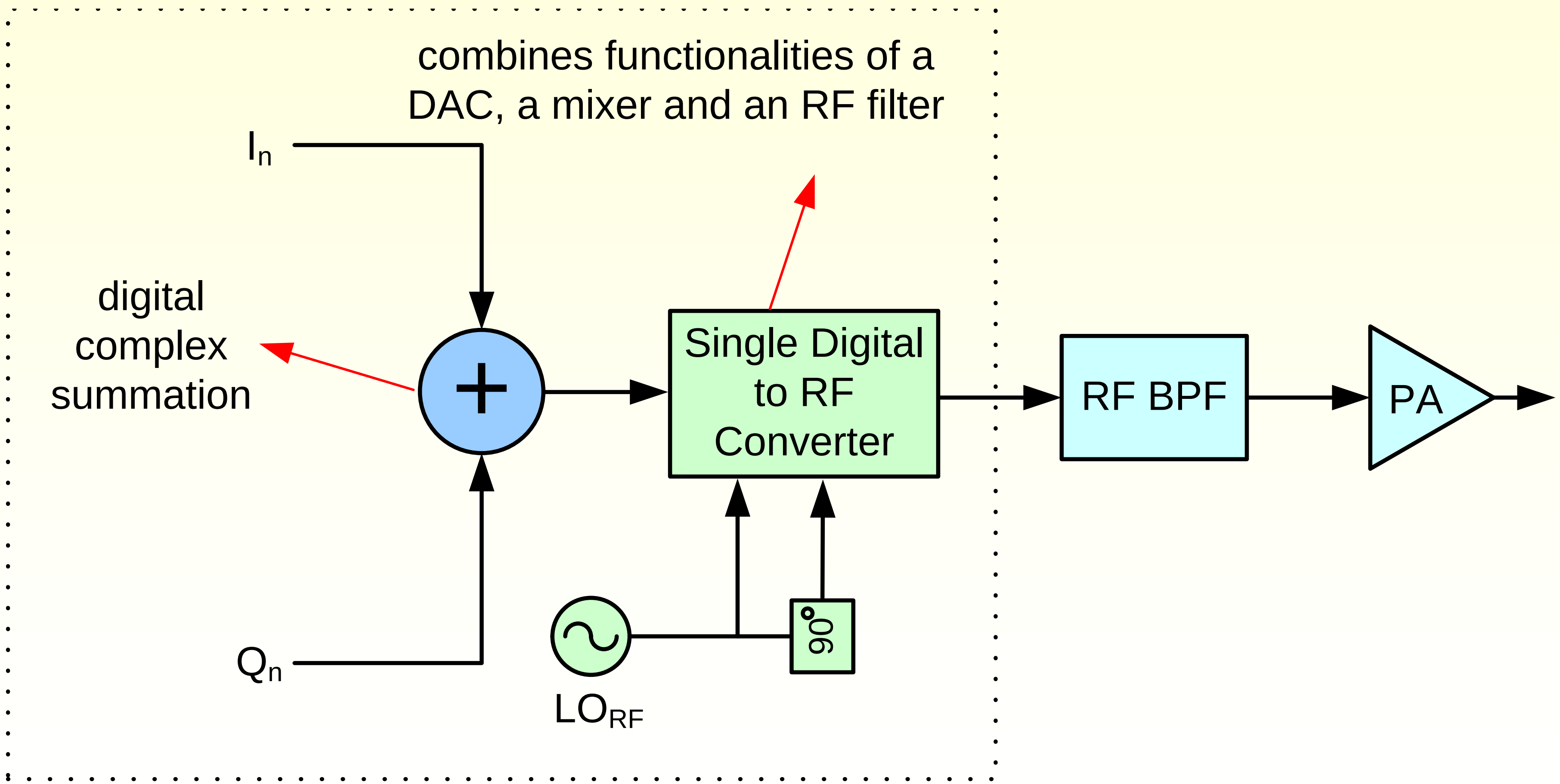
From Analog RF to Digital RF

Dr. Oren Eliezer, 2 Dec. 2022



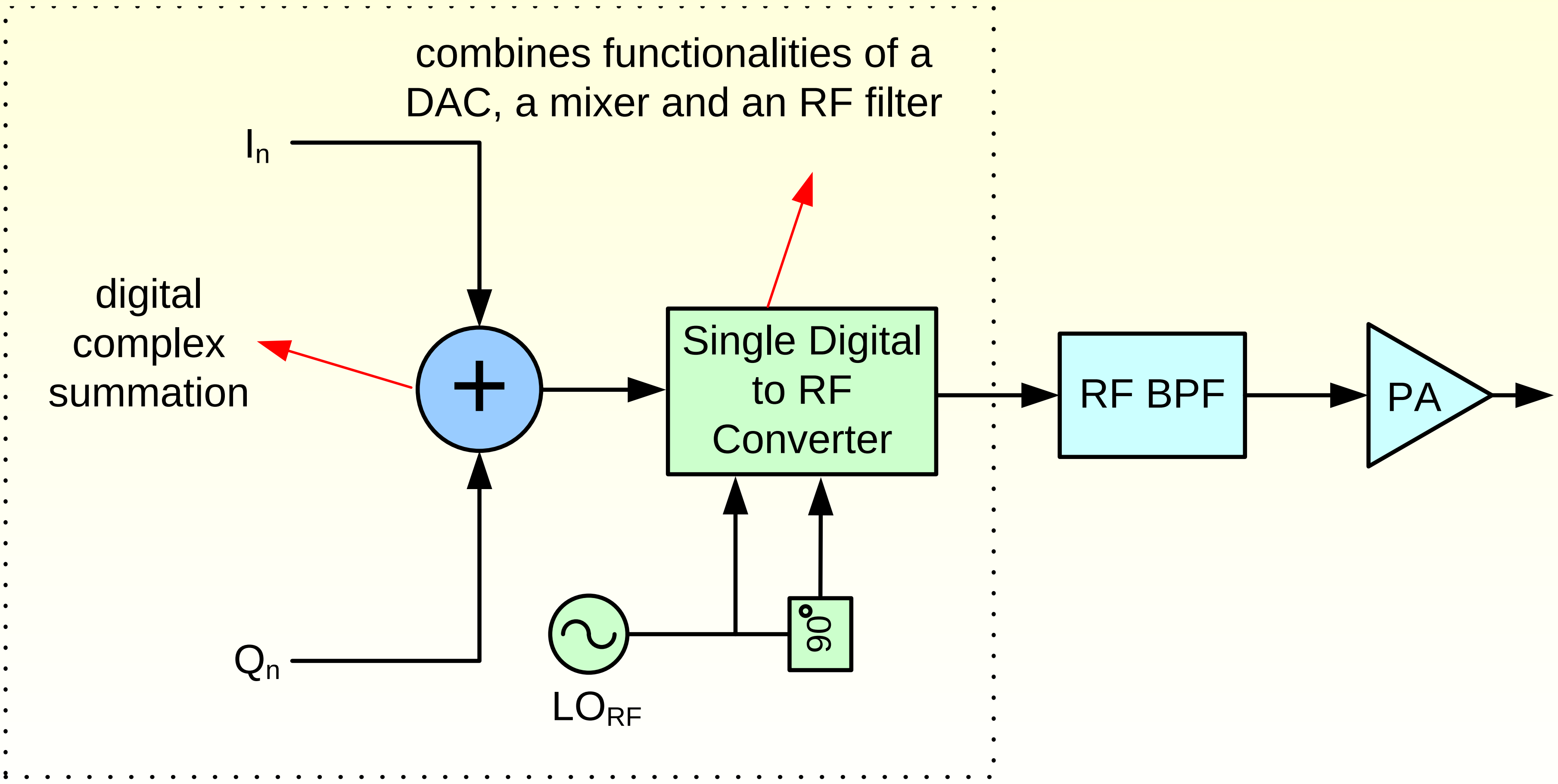
The Fully Digital Quadrature Tx

- A single Digital-to-RF converter is used to realize $I+j\cdot Q$
- Summation operation realized in digital domain



Quadrature Transmitter

Dr. Oren Eliezer
24 November 2014

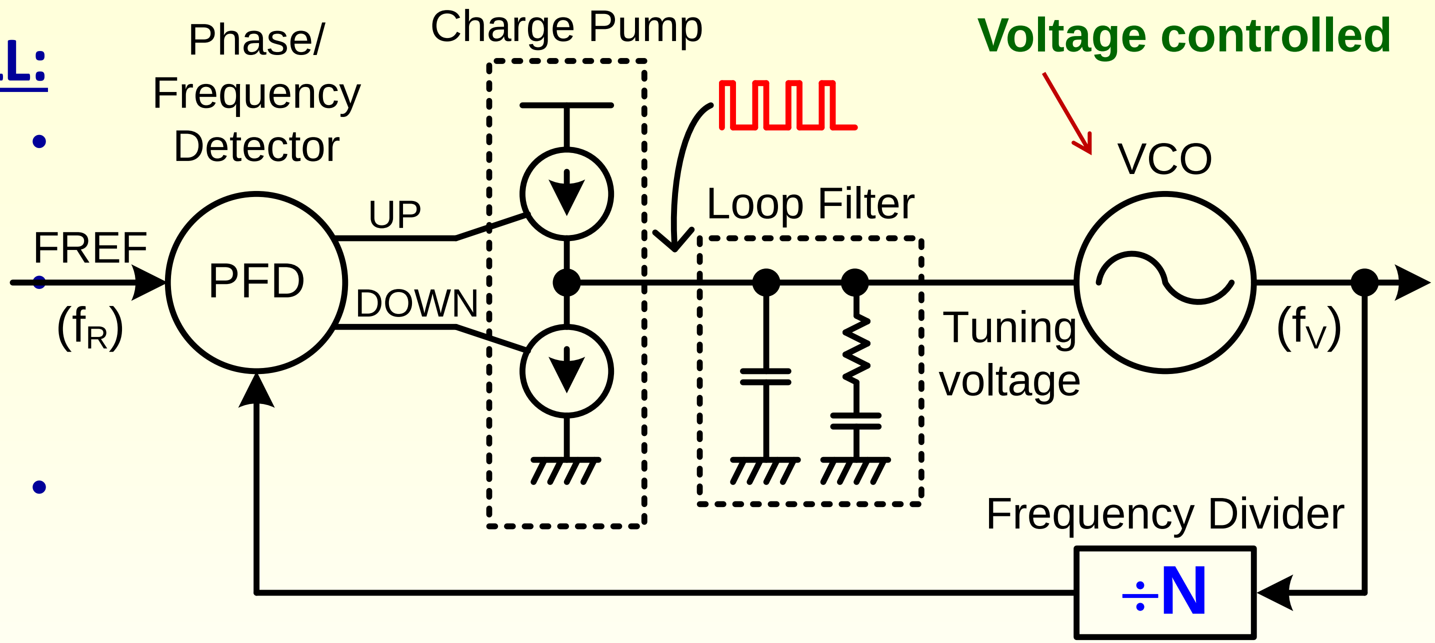


All-Digital vs. Conventional phase locked loop (PLL)

Dr. Oren Eliezer, 2 Dec. 2022

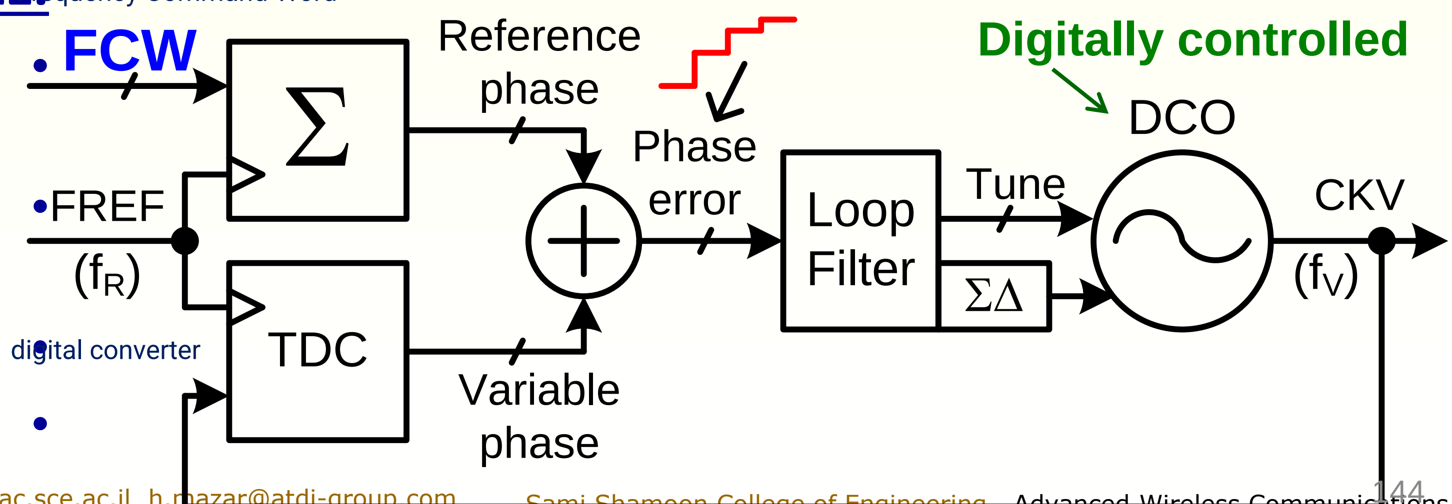
Charge-pump PLL:

- Suffers from f_R spurs
- Tradeoff: bandwidth against spur level
- Requires large capacitors



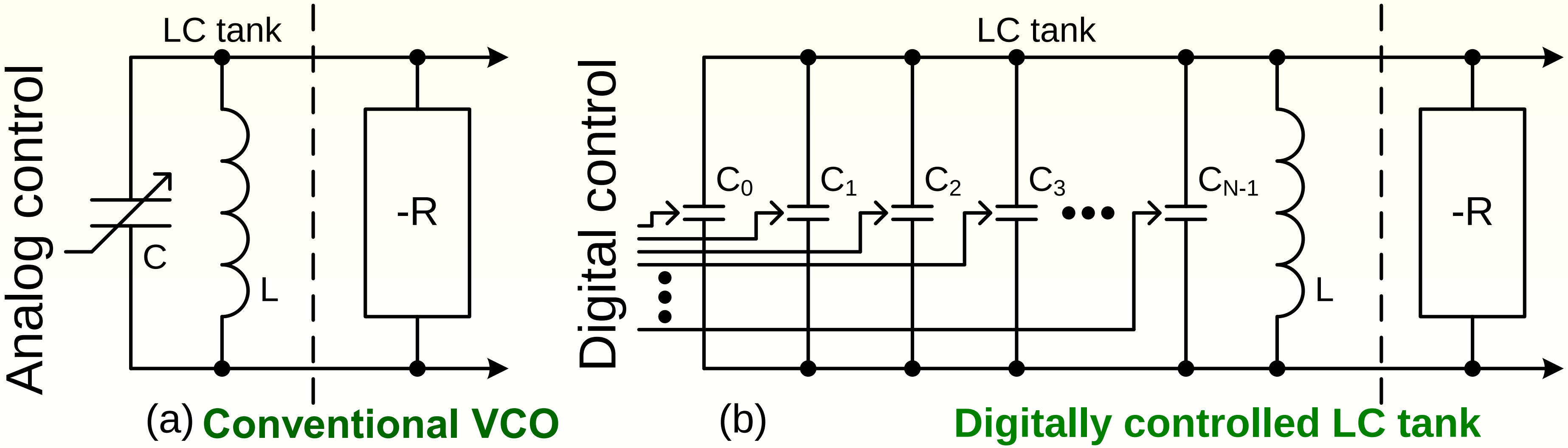
All-digital PLL:

- True phase domain operation
- Digital signal processing
- Noise immunity
- Configurable



DCO Capacitor Banks (MOS Varactors)

- The loop operation is fully digital including the frequency tuning
- Linear varactor of conventional Voltage Controlled Oscillator (VCO) replaced with a large number of binary-controlled varactors in the digitally-controlled oscillator (DCO)
- Smallest varactor size: tens of atto-Farad (aF=10^{-18}F)



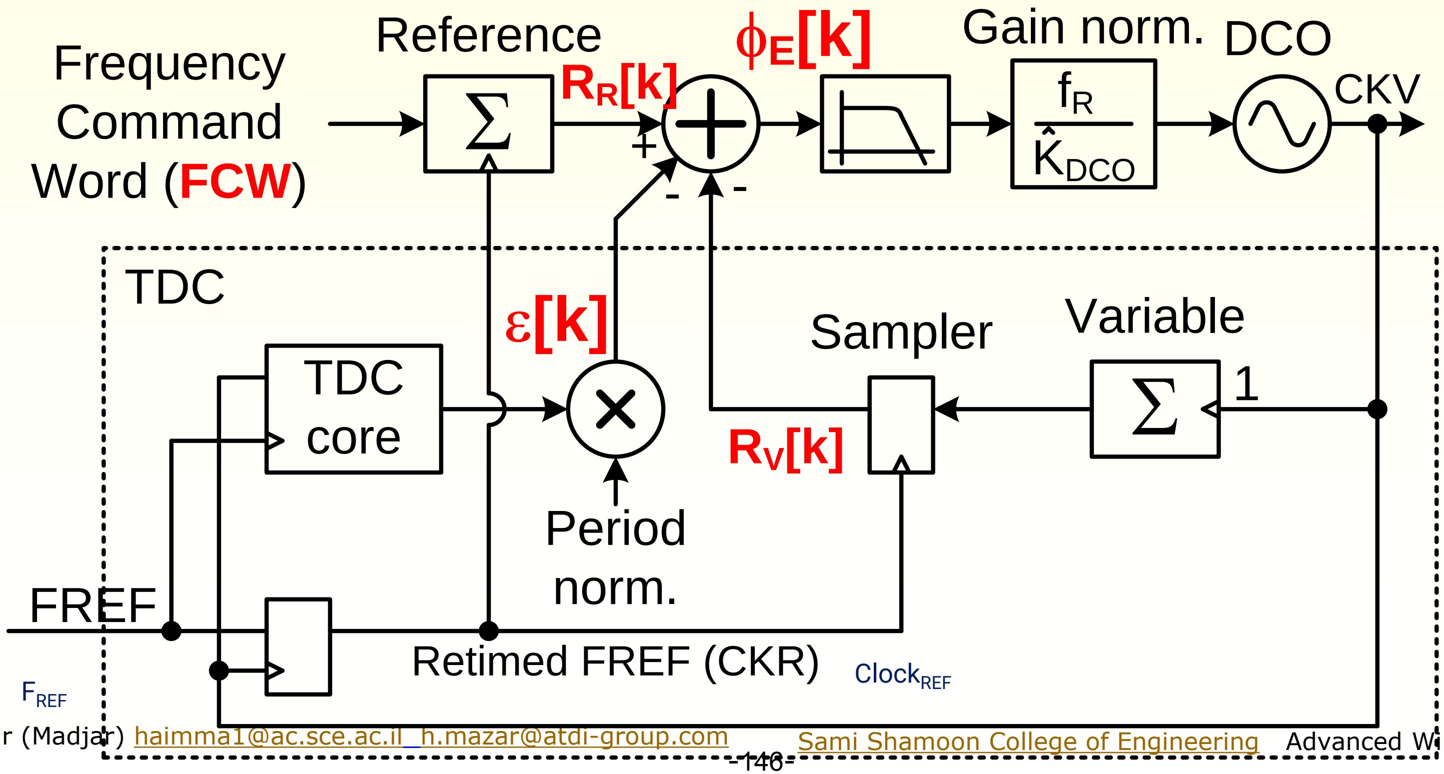
ADPLL Operating in Phase Domain

Dr. Oren Eliezer, 2 Dec. 2022

- Phase of DCO at output is compared against the desired reference to produce a phase error that needs to be corrected
- Digitally synchronous fixed-point arithmetic
- Phase signals cannot be corrupted by noise

fractional part

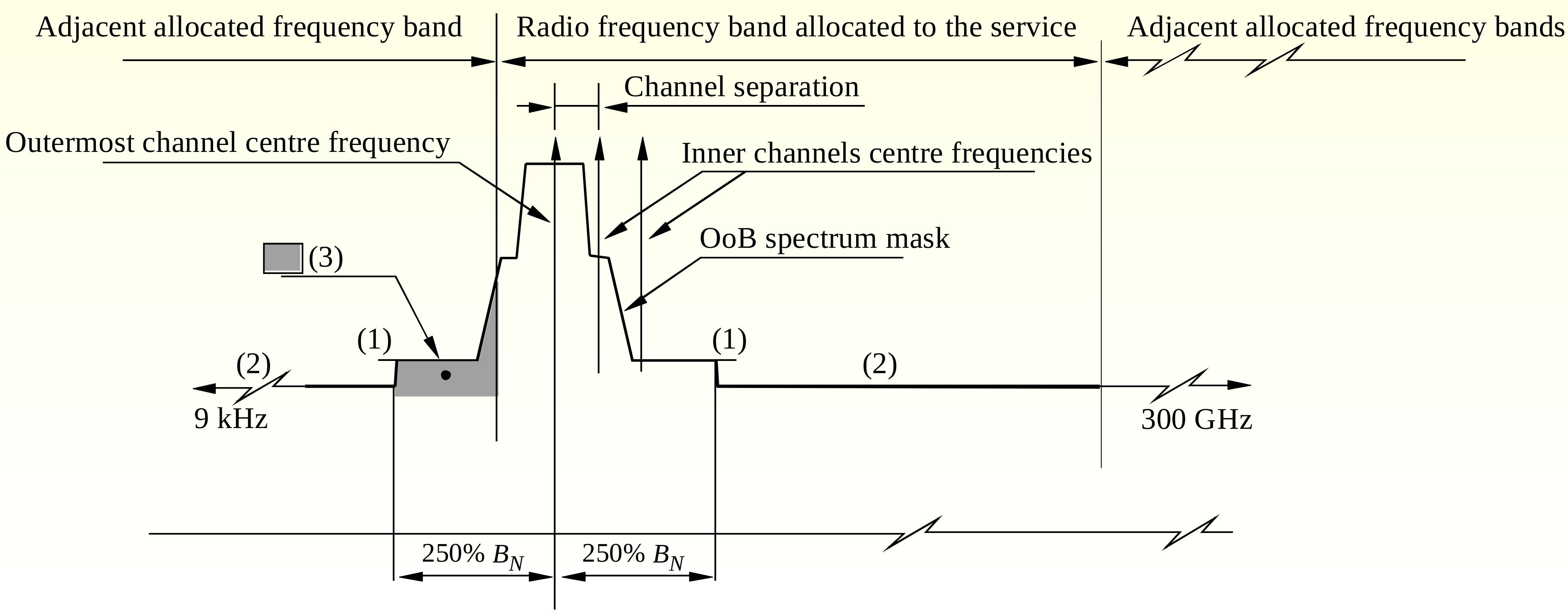
$$\varphi_E = R_R[k] - (R_V[k] + \varepsilon[k])$$



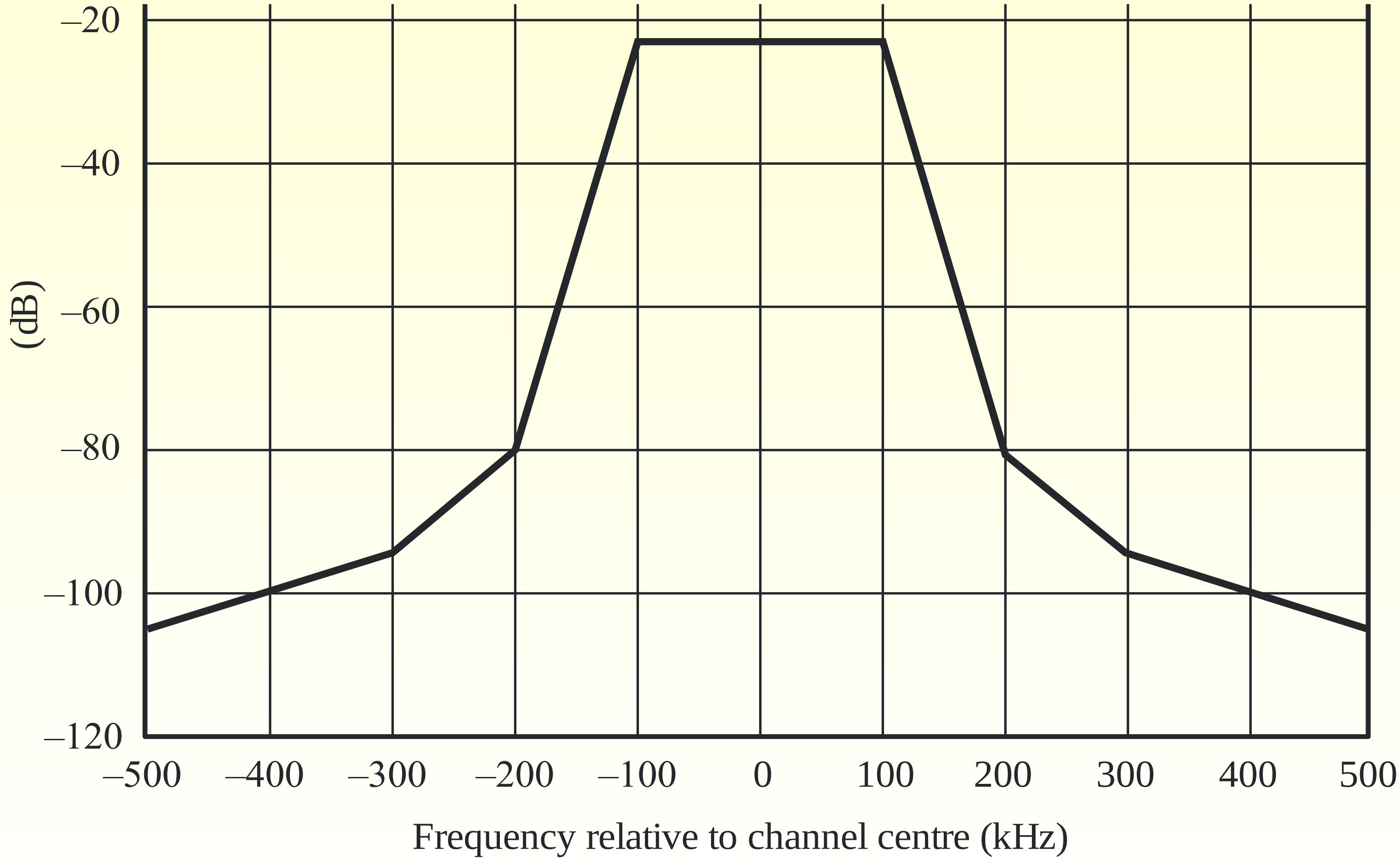
-146-

Transmitters: Unwanted Emissions (Rec. SM.1540, fig 1)

1. The frequency, output power, the bandwidth and unwanted emissions, consisting of spurious emissions and out-of-band Emissions; ITU Radio Regulations RR **1.146** detail the important parameters of Tx
2. The ITU RR Article defines *spurious emission* (RR **1.145**), *out-of-band emission* (**RR 1.144**), *occupied bandwidth* (**RR 1.153**), *necessary bandwidth* (RR **1.152**), *assigned frequency band (*RR **1.147**) and *assigned frequency* (**RR 1.148**).

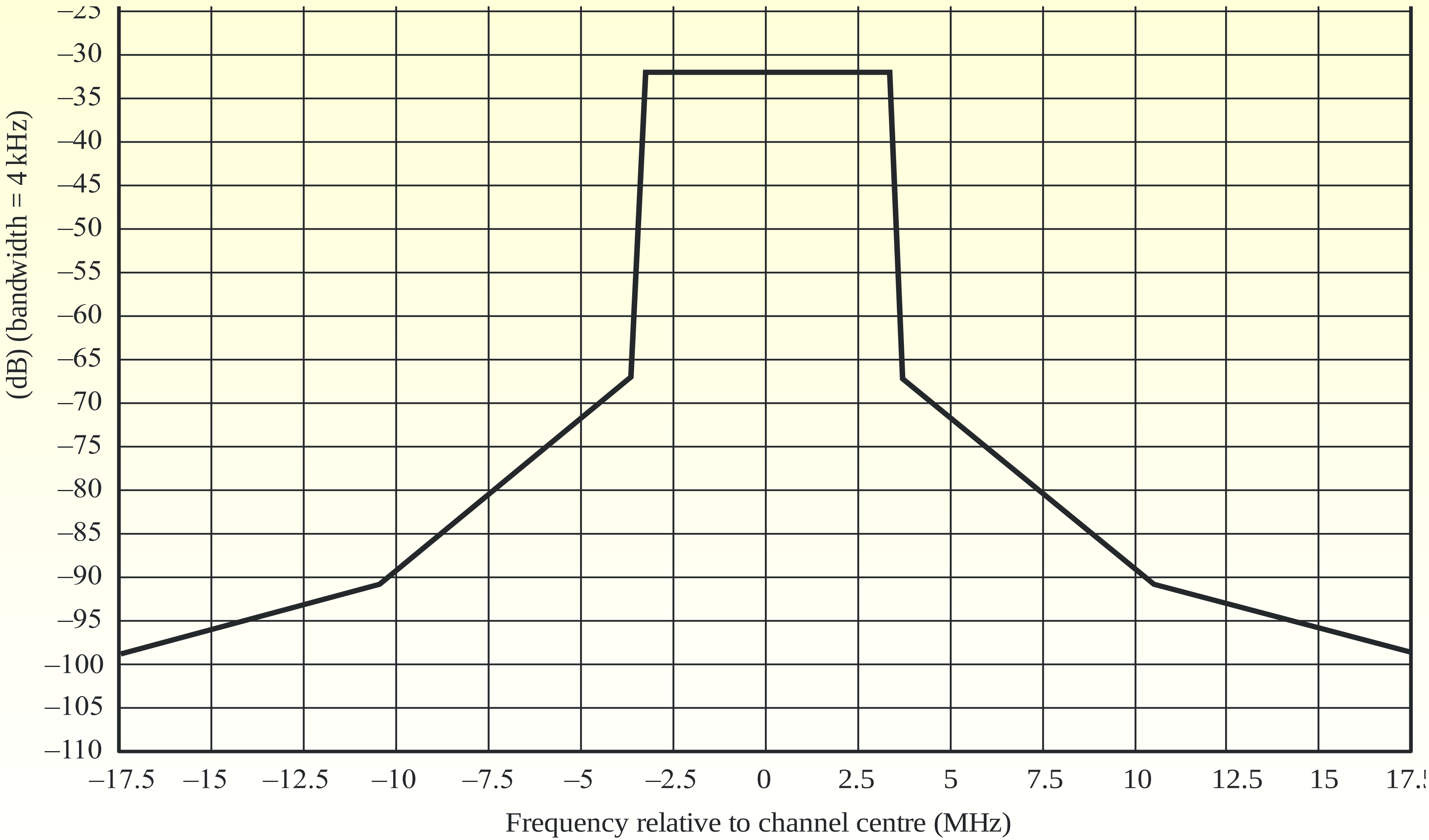


Spectrum Limit VHF FM sound (Rec. ITU-R SM.1541)



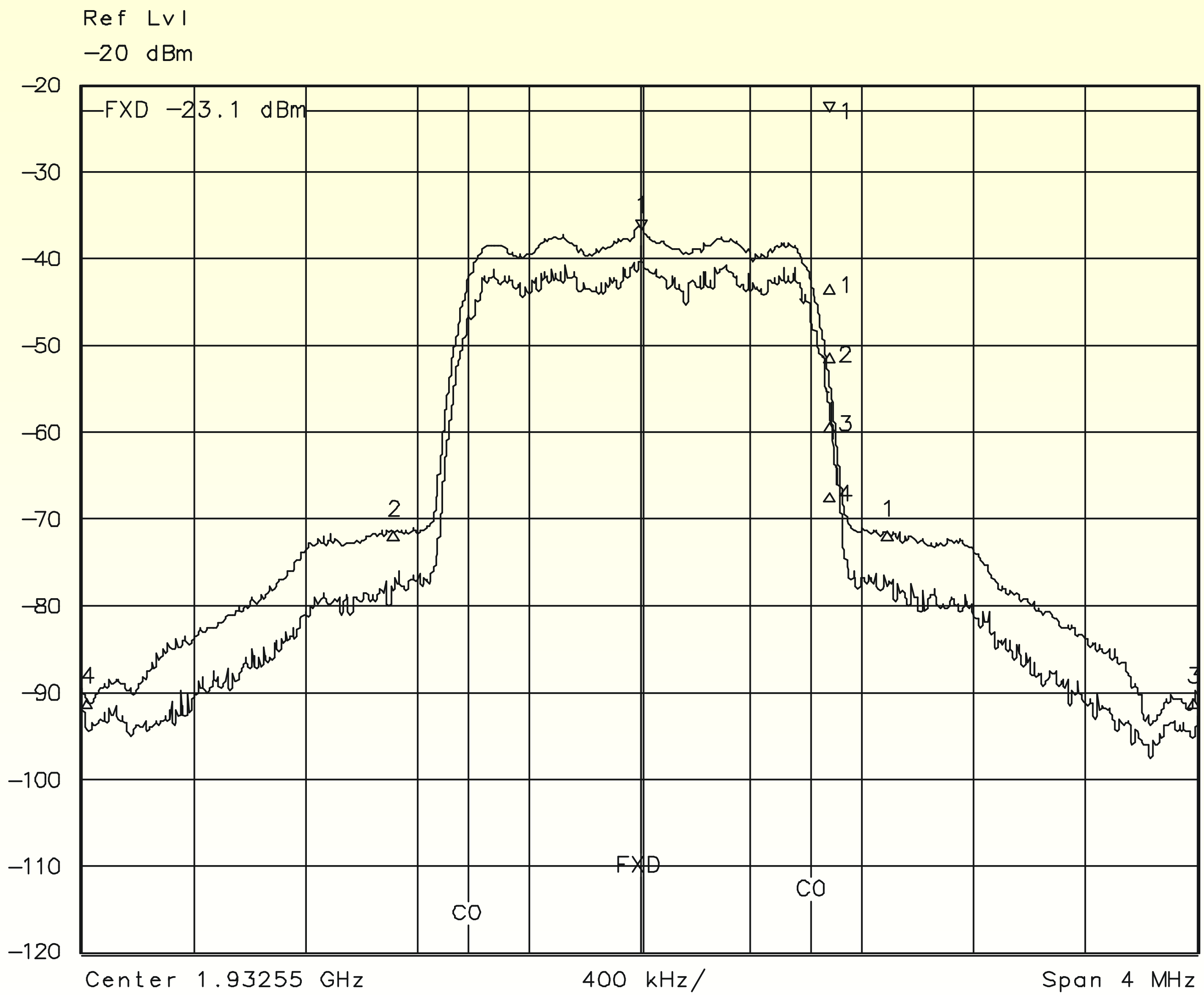
Limit mask for VHF FM sound broadcasting transmitters, 200 kHz channeling

Spectrum for 7 MHz DVB-T (Rec SM.1541)

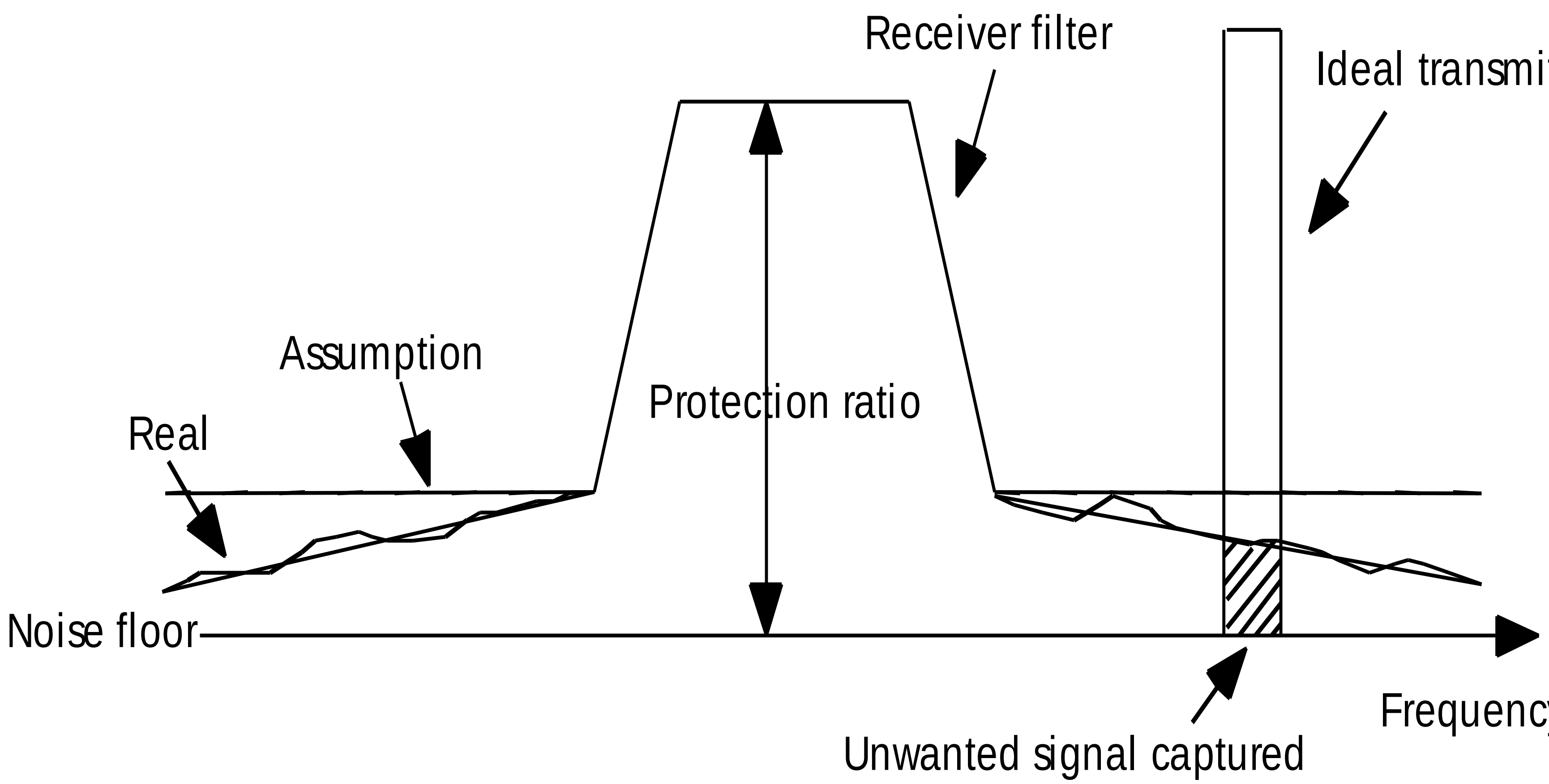


Spectrum limit mask for 7 MHz DVB-T systems

CDMA IS95 1,932.55 MHz Ch. Spacing 1.25 MHz

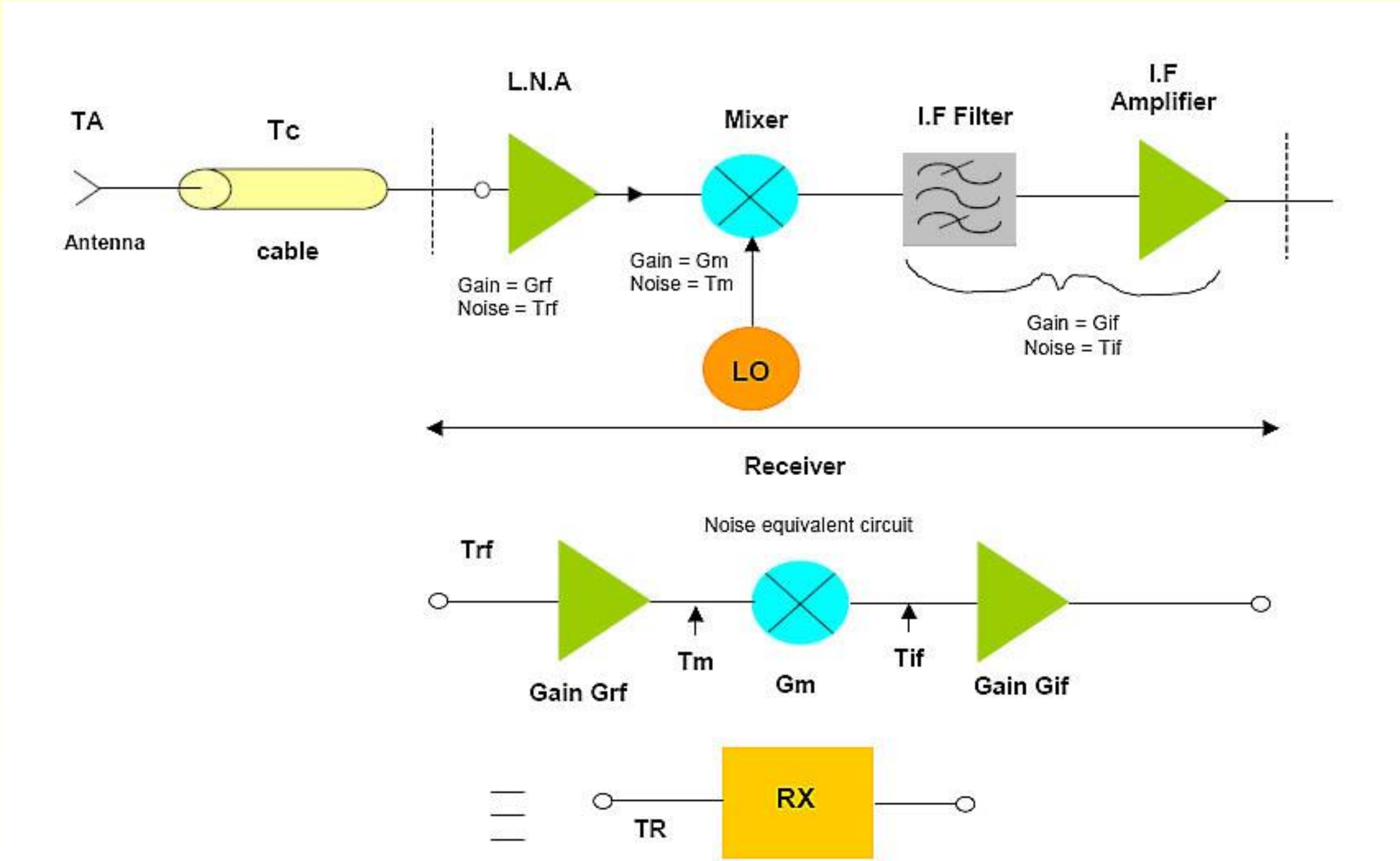


Receiving Conditions



Receiver concept and selectivity (Report ITU-R SM.2028 2017 Fig. 9)

Typical Rx Schematics (Rami Neuderfer)



Receiver Sensitivity (Watts)

s_{min} : sensitivity (W)

k : Boltzmann's constant = $1.38 x 10^{-23}$ J/K

t_0 : reference temperature (K) (absolute degrees, ^{0}Celsius + 273.15), taken as 290 K

b : power bandwidth of the receiving system (Hz)

The nominal receiver bandwidth equals the channel spacing, such as 12.5 kHz for simplex, 100 kHz for FM, 6-8 MHz for TV

nf : noise factor of the receiver

s/n: required signal to noise ratio;

s/n is interchanged with c/n: carrier to noise ratio

$$s_{min} = k \cdot t_0 \cdot b \cdot nf \cdot (s/n)$$

Receiver Sensitivity Expressed logarithmically

S_{min}: sensitivity (dBW)

K : Boltzmann's constant = 10log(1.38 ´ 10^{-23})=-228.6 dB J/K

T_0 : reference temperature (K) taken as 10 log (290) dB K

B : RF bandwidth of the receiving system 10log b(Hz) dB Hz

NF : noise figure of the receiver 10 log nf dB

SNR, S/N: signal to noise ratio 10 log (*s/n*) dB

CNR, C/N: carrier to noise ratio 10 log (*c/n*) dB

SNR, S/N, CNR and *C/N* are interchanged

$$S_{min}=K+T_0+B+NF+SNR$$

Thermal noise power density @ 290 K (16.85 °C)= -204 dBW/Hz= =-174 dBm/Hz =-144 dBm/kHz=-144 dBW/MHz=**-114dBm/MHz**

SINAD and SNIR

- Signal-to-noise and distortion ratio (*sinad)* relates to the quality of a signal: the ratio of the total received power to the noise-plus-distortion power.

sinad= $$\frac{signal + noise + distortion}{noise + distortion}$$ SINAD≡10log *sinad*

- The coverage of wireless communication systems is noise-limited; in contrast, the urban cellular networks are interference-limited. Thus, for a given quality, cellular systems operate at the minimum signal-to-noise-plus-interference ratio (SNIR) or signal-to-interference-plus-noise ratio (SINR) possible. For a particular receiver:

- *snir*= $$\frac{signal}{noise + \text{int}\,erference}$$ =*sinr*= $$\frac{signal}{\text{int}\,erference + noise}$$

SNIR≡SINR≡10log *snir*≡10log *sinr*

Noise Figure and Terms to specify noise intensity and inter-relationship

- *Noise Figure (and Noise Factor) is defined as the ratio of the output noise power to the portion attributed to thermal noise in the input termination at standard noise temperature t_c (usually 290 K)*

$$nf = \frac{snr_{in}}{snr_{out}} = \frac{cnr_{in}}{cnr_{out}}$$

- If devices are cascaded use with Friis' Formula: where Fn is the noise factor for the n-th device and Gn is the power gain (linear, not in dB) of the n-th device. Overall cascading :

$$nf = nf_1 + \frac{nf_2 - 1}{g_1} + \frac{nf_3 - 1}{g_1 g_2} + \frac{nf_4 - 1}{g_1 g_2 g_3} + \ldots + \frac{nf_n - 1}{g_1 g_2 g_3 \cdots g_{n-1}}$$

- In a well designed receive chain, only the noise factor of the first amplifier is significant

f_a : the external noise factor is defined as

$$f_a = \frac{p_n}{k\, t_0\, b}$$

p_n: available noise power from an equivalent lossless ant

Logarithm $F_a = 10 \log f_a$ dB

$$\boldsymbol{f = f_a - 1 + f_c\ f_t\ f_r}$$

Given $t_c = t_t = t_0$

t_o : reference temperature (K) taken as 290 K

t_c: actual temperature (K) of the antenna and nearby ground

t_t: actual temperature (K) of the transmission line

k : Boltzmann's constant = 1.38×10^{-23} J/K

b : noise power bandwidth of the receiving system (Hz)

f_r : noise factor of the receiver

Noise Figure (cont'd)

k : Boltzmann's constant = 1.38 x 10^{-23} J/K

b : noise power bandwidth of the receiving system (Hz)

f_r : noise factor of the receiver

$$f_a = \frac{p_n}{k\, t_0\, b} \qquad\qquad f_a = \frac{t_a}{t_0}$$

external noise factor can be expressed as a temp t_a, where, by definition of f_a:

t_a is the effective antenna temperature due to external noise

p_n from f_a in dB: $P_n = F_a + B - 204$ dBW

P_n = 10 log p_n available power (W)

B = 10 log b

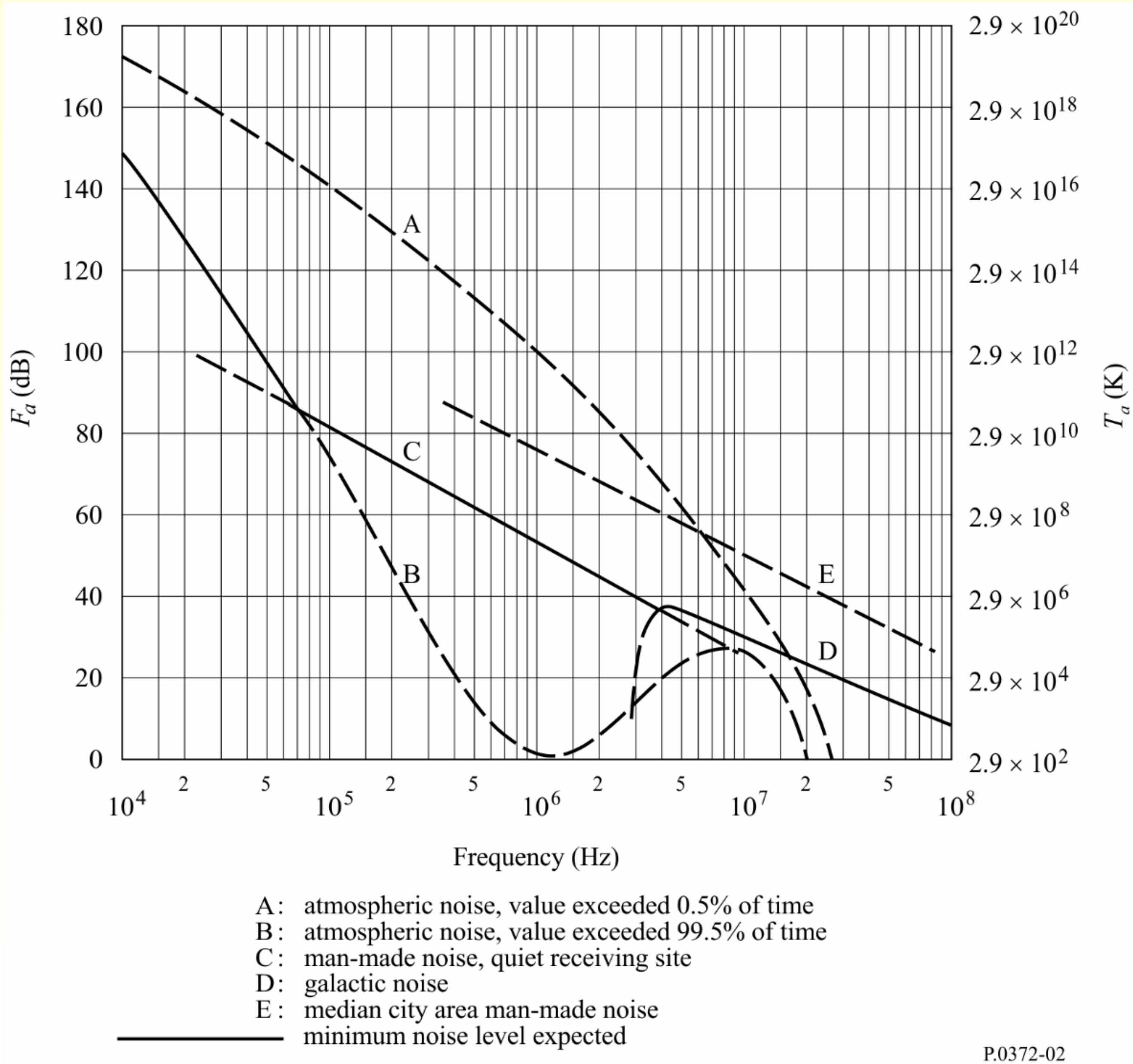
–204 =10 log k t_o (1.38 x 290 = 400.2)

for a half-wave dipole in free space:

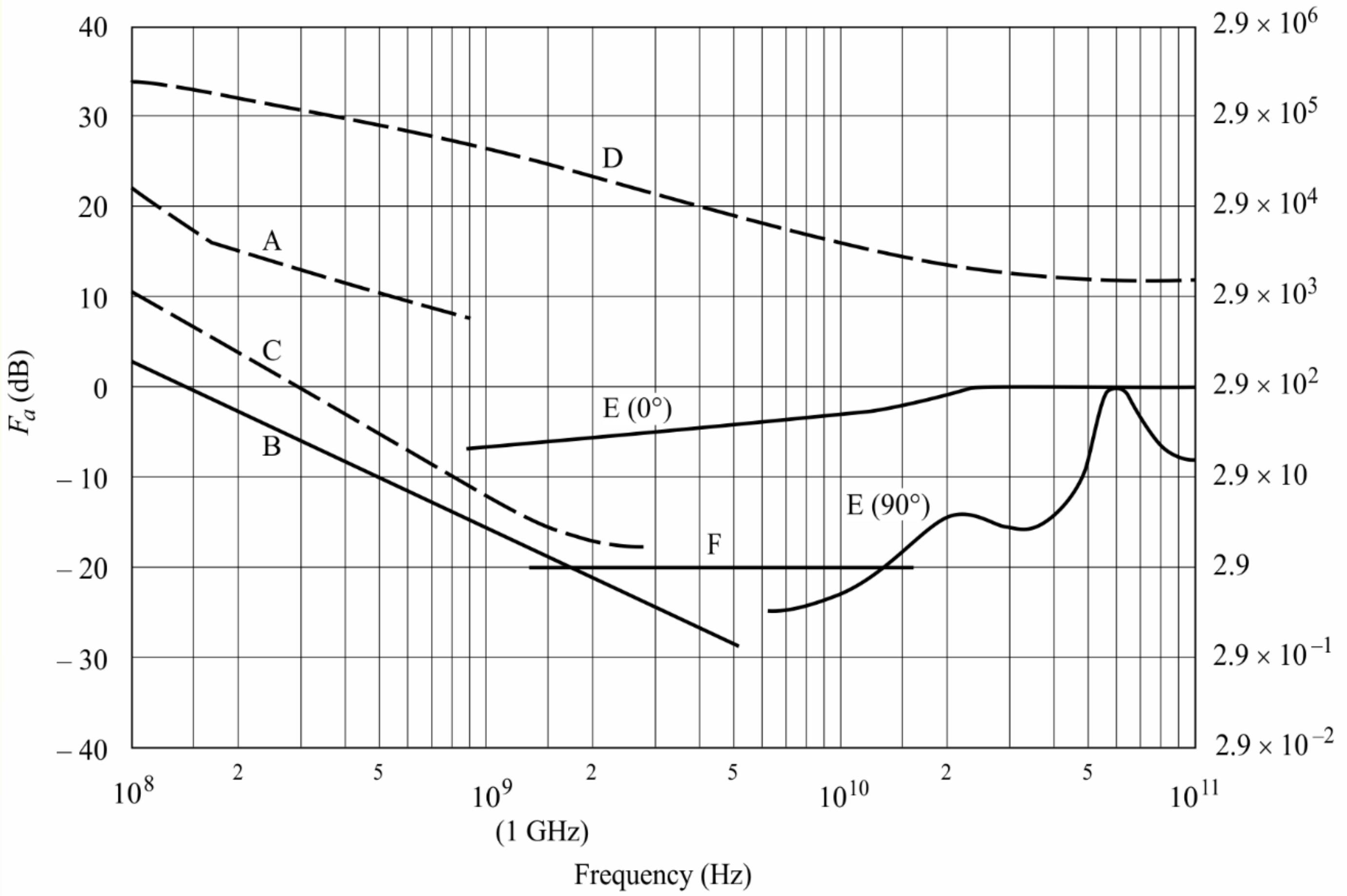
$$p_r = \frac{e^2 g \lambda^2}{z_0 4\pi} = \frac{e^2 g c^2}{480\pi^2 f^2}$$

E_n = Fa + 20 log f(MHz) + B (MHz) – 98.9 dB(μ V/m)

Radio Noise: F_a vs RF Rec. ITU-R P. 372 Fig. 2; 10 kHz to 100 MHz



Radio Noise: F_a vs RF ITU-R P. 372 Fig. 3; 100 MHz to 100

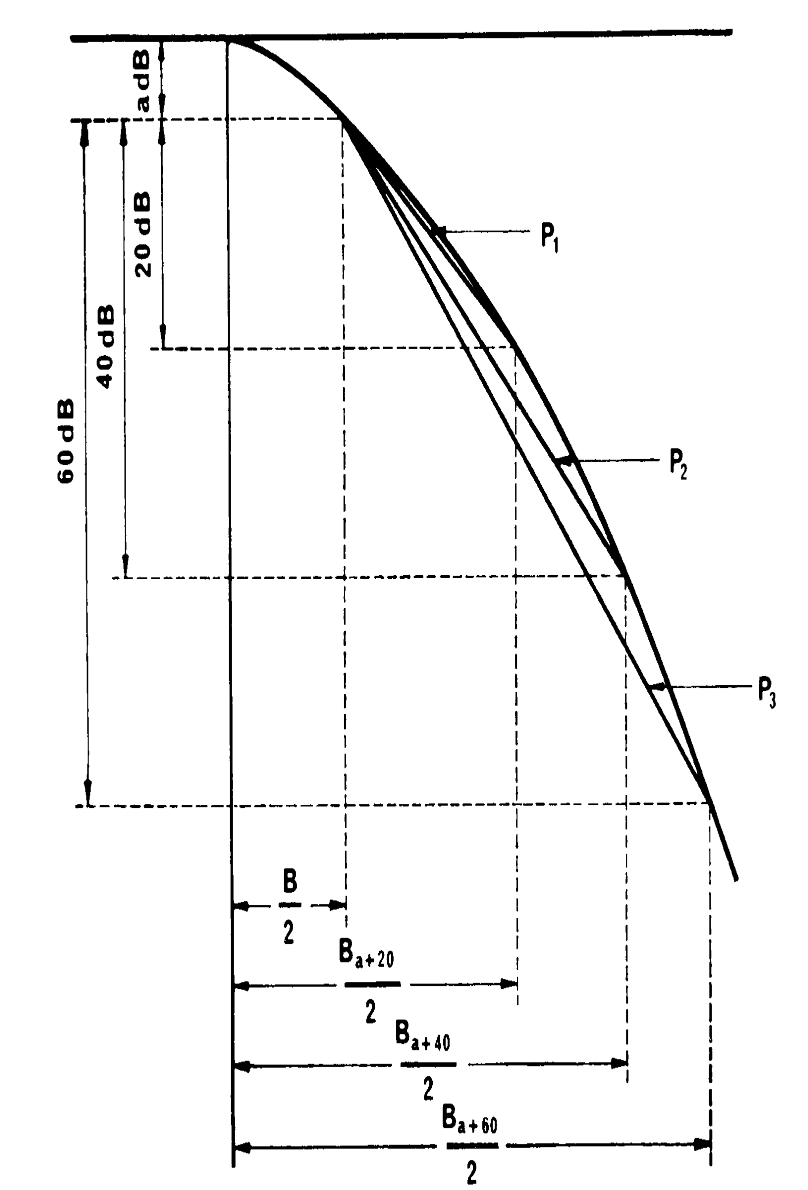


A: estimated median city area man-made noise
B: galactic noise
C: galactic noise (toward galactic centre with infinitely narrow beamwidth)
D: quiet Sun (½° beamwidth directed at Sun)
E: sky noise due to oxygen and water vapour (very narrow beam antenna); upper curve, 0° elevation angle; lower curve, 90° elevation angle
F: black body (cosmic background), 2.7 K

minimum noise level expected

P.0372-03

Signal Selectivity (Rec. ITU-R SM 332)



Second and third files of the course are found at:

- https://mazar.atwebpages.com/Downloads/Academic_Course_Advanced_wireless_communications_Mazar2_Services_2024.pdf 2020 version identifier DOI 10.13140/RG.2.2.35017.90722
- _Mazar3_Regulation_EMC_HumanHazards_2024.pdf 2020 version identifier DOI 10.13140/RG.2.2.29984.74247

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More info in my Wiley book 2016 'Radio Spectrum Management: Policies, Regulations, Standards and Techniques' : policies, regulations, standards and techniques'

http://mazar.atwebpages.com/