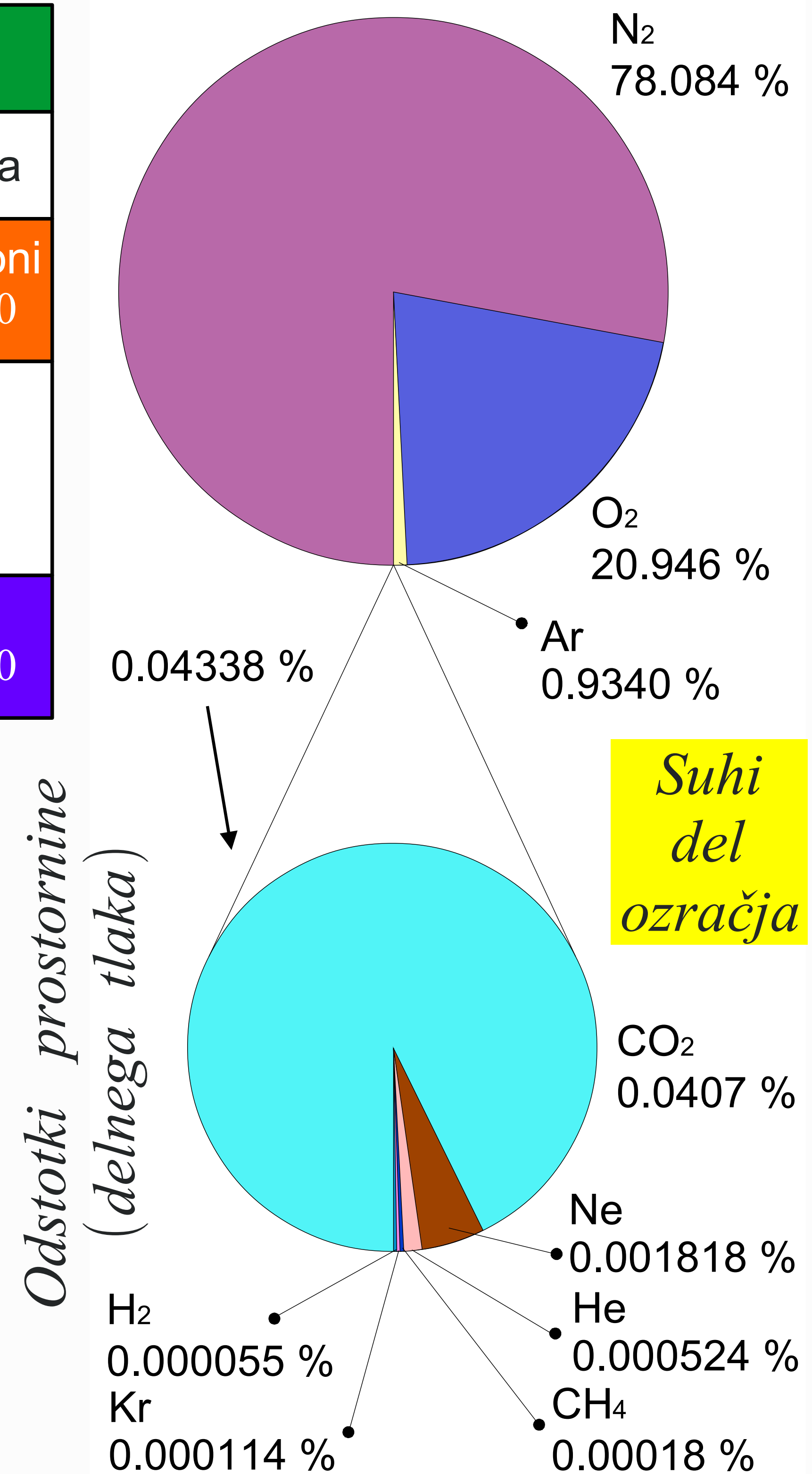
Ozračje

Plast ozračja	Višina *h*	Temperatura	EM učinek
Eksosfera	>700km	dT/dh≈0	Praznina vesolja
Termosfera	80km−700km	dT/dh>0	Ionosfera elektroni $\varepsilon_r(\omega)<1$ $\gamma(\omega)>0$
Mezosfera	50km−80km	dT/dh<0	Brez večjega učinka (O_3)
Stratosfera	12km−50km	dT/dh>0	
Troposfera	0−12km	dT/dh<0	Nevtralni plini $\varepsilon_r(\omega)>1$ $\gamma(\omega)>0$

Mokri del ozračja

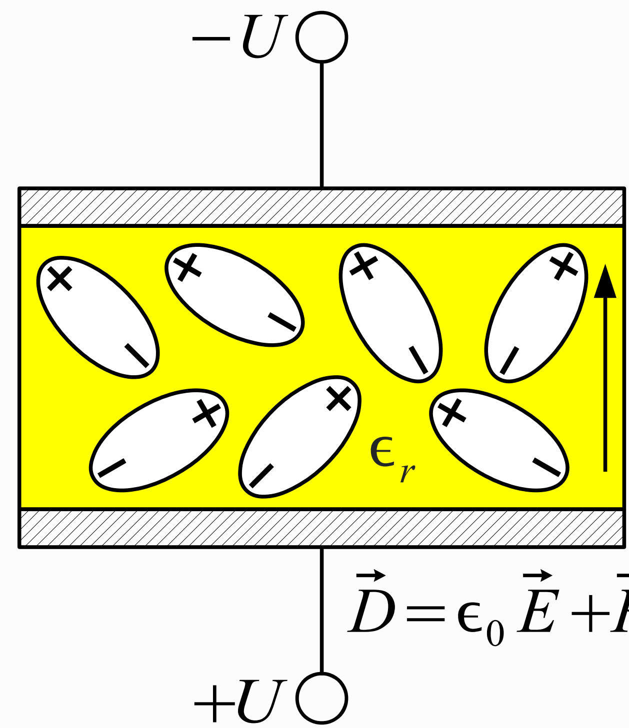
0.4 % vodne pare v povprečju
1 % vodne pare ob gladini morja
5 % vodne pare v vročih tropskih krajih

vsebnost vodne pare hitro upada s temperaturo/višino

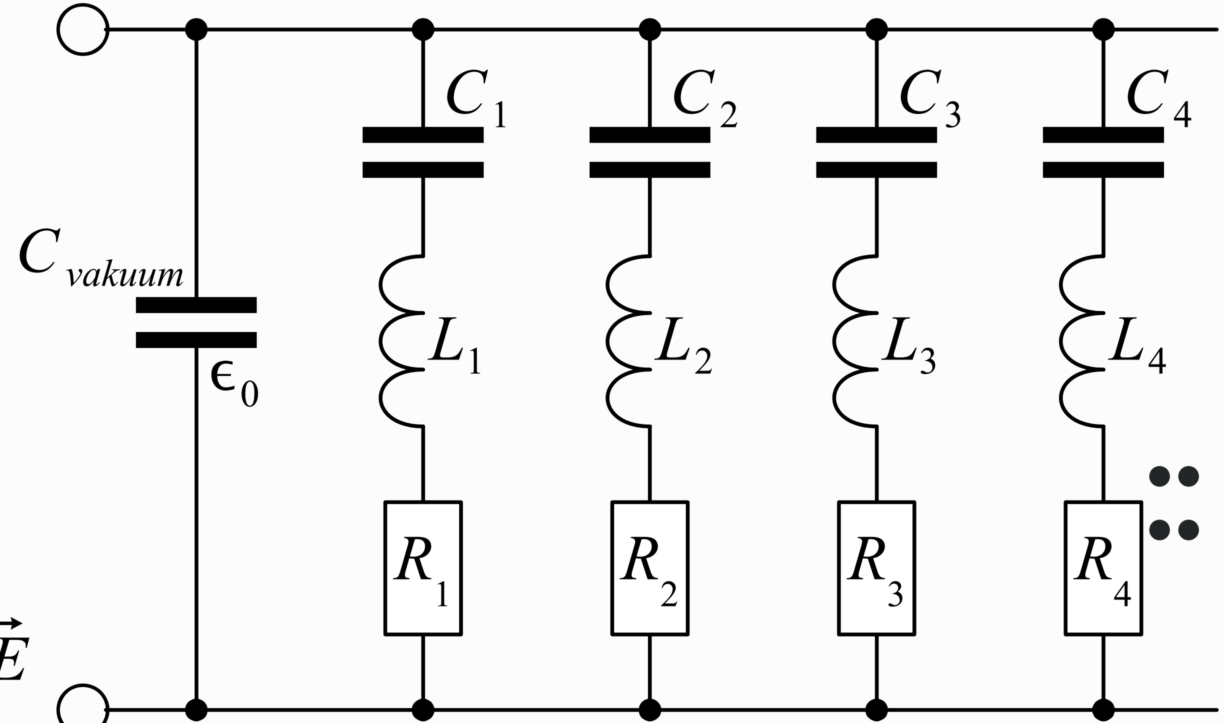


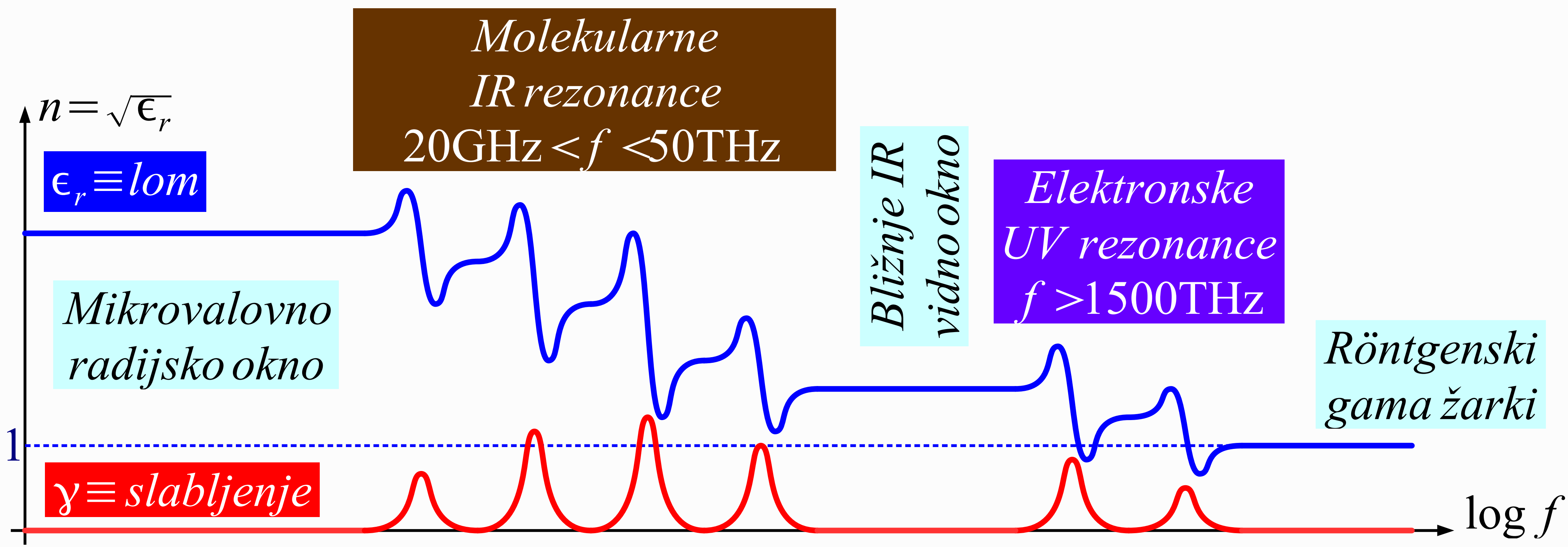
<u>Sestava zemeljskega ozračja</u>

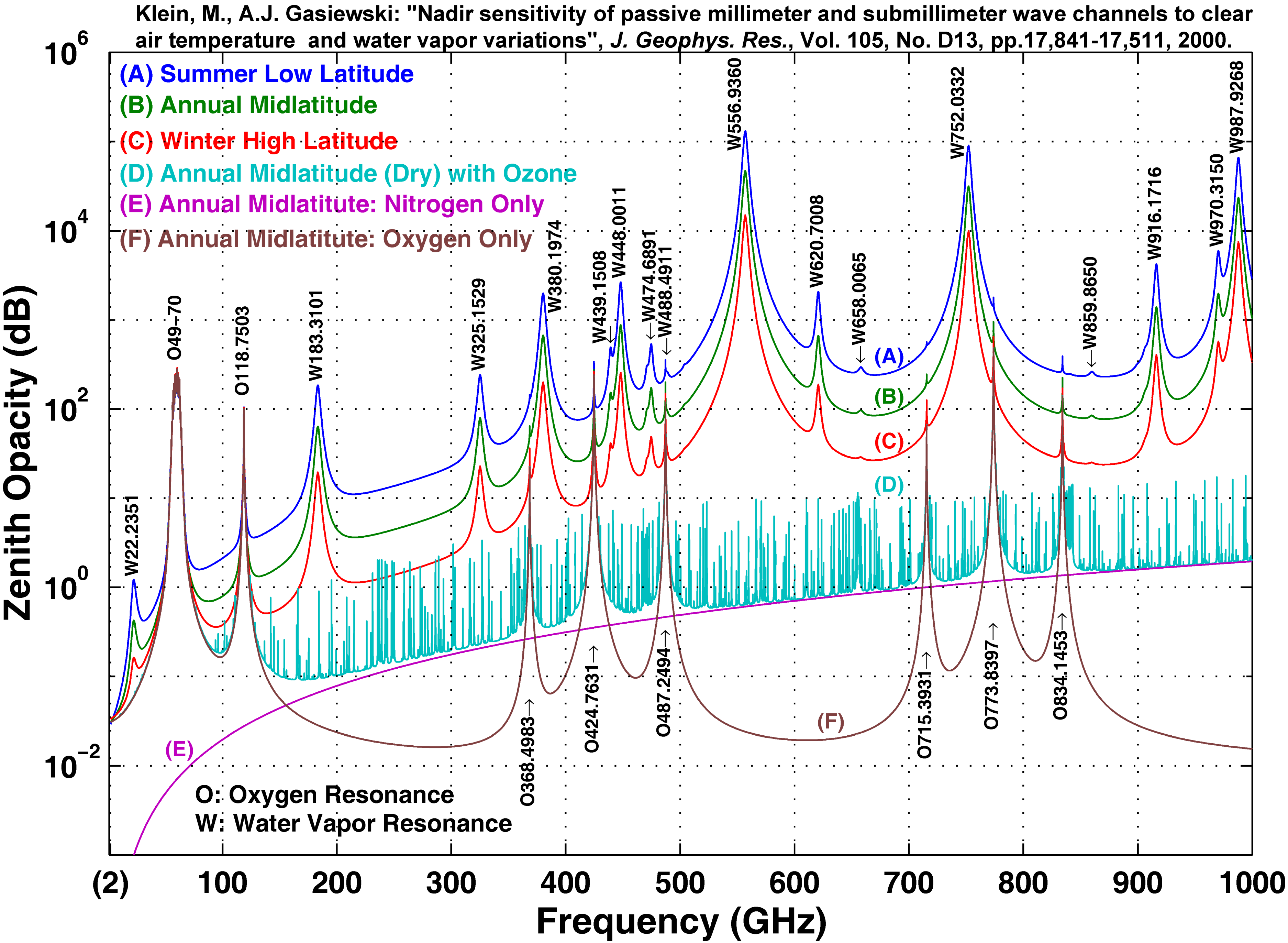
Nadomestno vezje dielektrika



$$\vec{D} = \epsilon_0 \vec{E} + \vec{P} = \epsilon_0 \epsilon_r \vec{E}$$

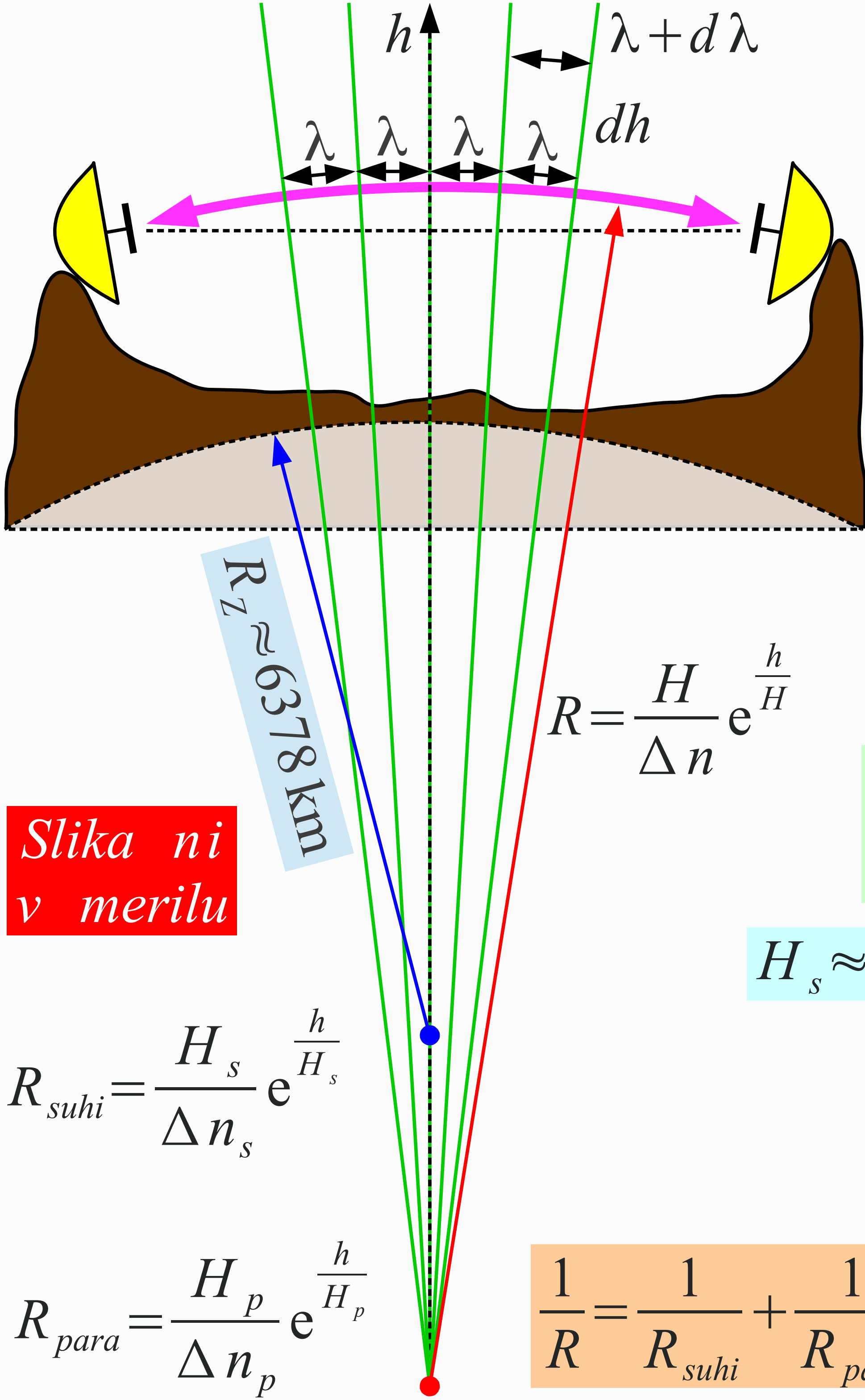






Zenitno slabljenje zemeljskega ozračja

Lom radijskih valov v troposferi



$$R=\frac{H}{\Delta n}e^{\frac{h}{H}}$$

$$R_{suhi}=\frac{H_s}{\Delta n_s}e^{\frac{h}{H_s}}$$

$$R_{para}=\frac{H_p}{\Delta n_p}e^{\frac{h}{H_p}}$$

$$\frac{1}{R}=\frac{1}{R_{suhi}}+\frac{1}{R_{para}}$$

Dobro premešano ozračje

$$n(h)=\sqrt{\epsilon_r(h)}\approx 1+\Delta n\, e^{-\frac{h}{H}}$$

Suhi del

$$H_s\approx\begin{cases}9\text{km} & poleti\\ 8\text{km} & pozimi\end{cases}$$

$$\Delta n_s\approx\begin{cases}0.0003 & radio\\ 0.00015 & vidna\ \ svetloba\end{cases}$$

Podobni trikotniki $\frac{\lambda}{R}=\frac{\lambda+d\lambda}{R+dh}=\frac{d\lambda}{dh}$

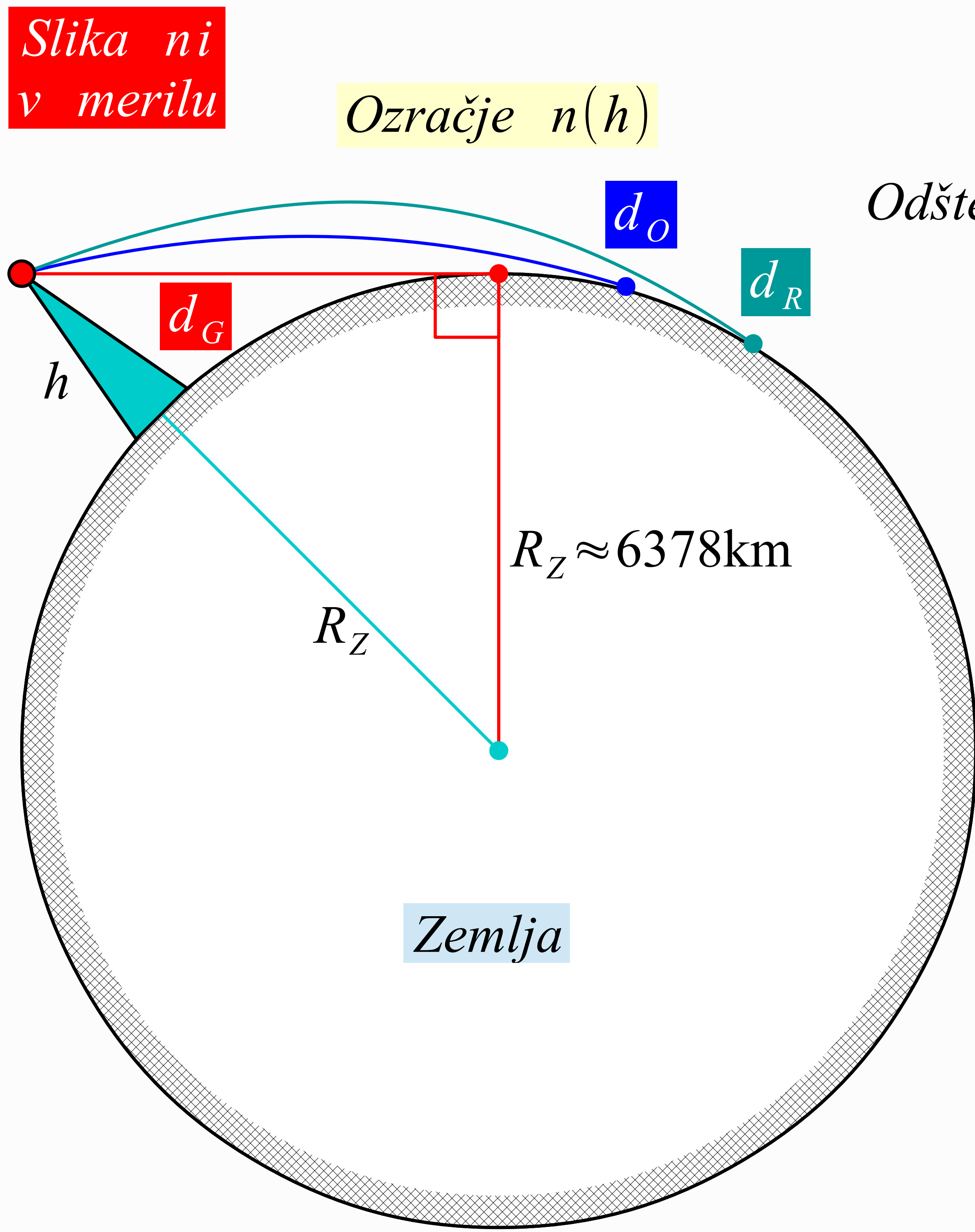
$$\lambda(h)=\frac{\lambda_0}{n(h)}\rightarrow\frac{d\lambda}{dh}=-\frac{\lambda_0}{n^2}\frac{dn}{dh}\approx\lambda\frac{\Delta n}{H}e^{-\frac{h}{H}}$$

$$H_s\approx 8.5\text{km}\rightarrow R_{suhi}(h=0)\approx 28300\text{km}\ \ (radio)$$

Upoštevanje vodne pare $H_p\approx 1.5\text{km}$

$$n(h)\approx 1+\Delta n_s e^{-\frac{h}{H_s}}+\Delta n_p e^{-\frac{h}{H_p}}$$

$$R(h=0)\approx\begin{cases}25000\text{km} & radio\\ 50000\text{km} & vidna\ \ svetloba\end{cases}$$



$$R \approx \begin{cases} 25000\text{km} & \textit{radio} \\ 50000\text{km} & \textit{vidna svetloba} \end{cases}$$

Odštevanje ukrivljenosti $\dfrac{1}{R_{eff}} = \dfrac{1}{R_Z} - \dfrac{1}{R}$

$$R_{eff} \approx \begin{cases} 8560\text{km} & \textit{radio} \\ 7310\text{km} & \textit{vidna svetloba} \end{cases}$$

$$K = \frac{R_{eff}}{R_Z} \approx \frac{4}{3} \quad (\textit{radio})$$

$$N = \Delta n \cdot 10^6 \approx 300 \quad (\textit{radio})$$

Geometrijska vidljivost

$$d_G = \sqrt{(R_Z + h)^2 - R_Z^2} \approx \sqrt{2 R_Z h}$$

Zgled $h = 100\text{m} \rightarrow d_G \approx 35.7\text{km}$

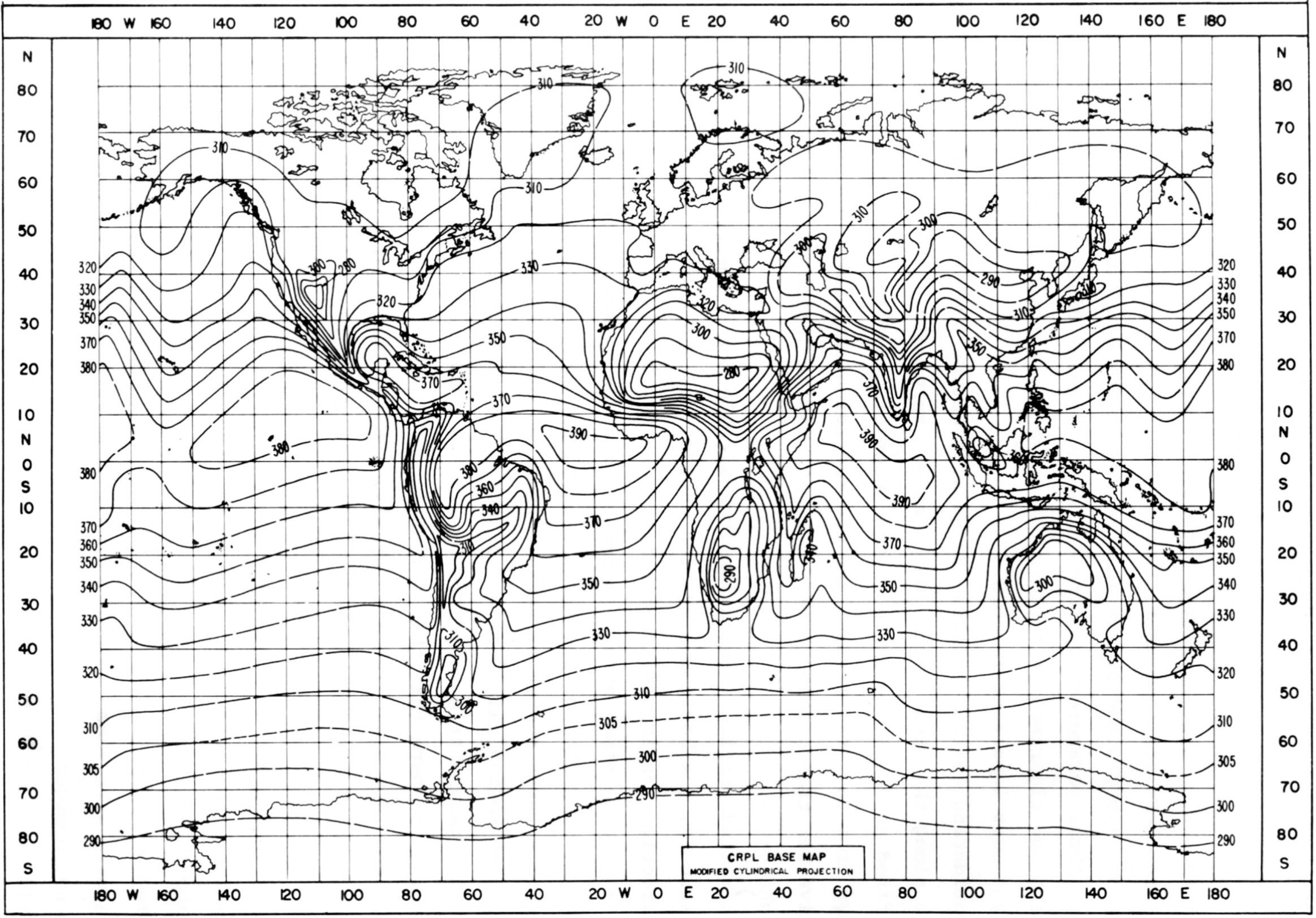
Optična/radijska vidljivost

$$d = \sqrt{(R_{eff} + h)^2 - R_{eff}^2} \approx \sqrt{2 R_{eff} h}$$

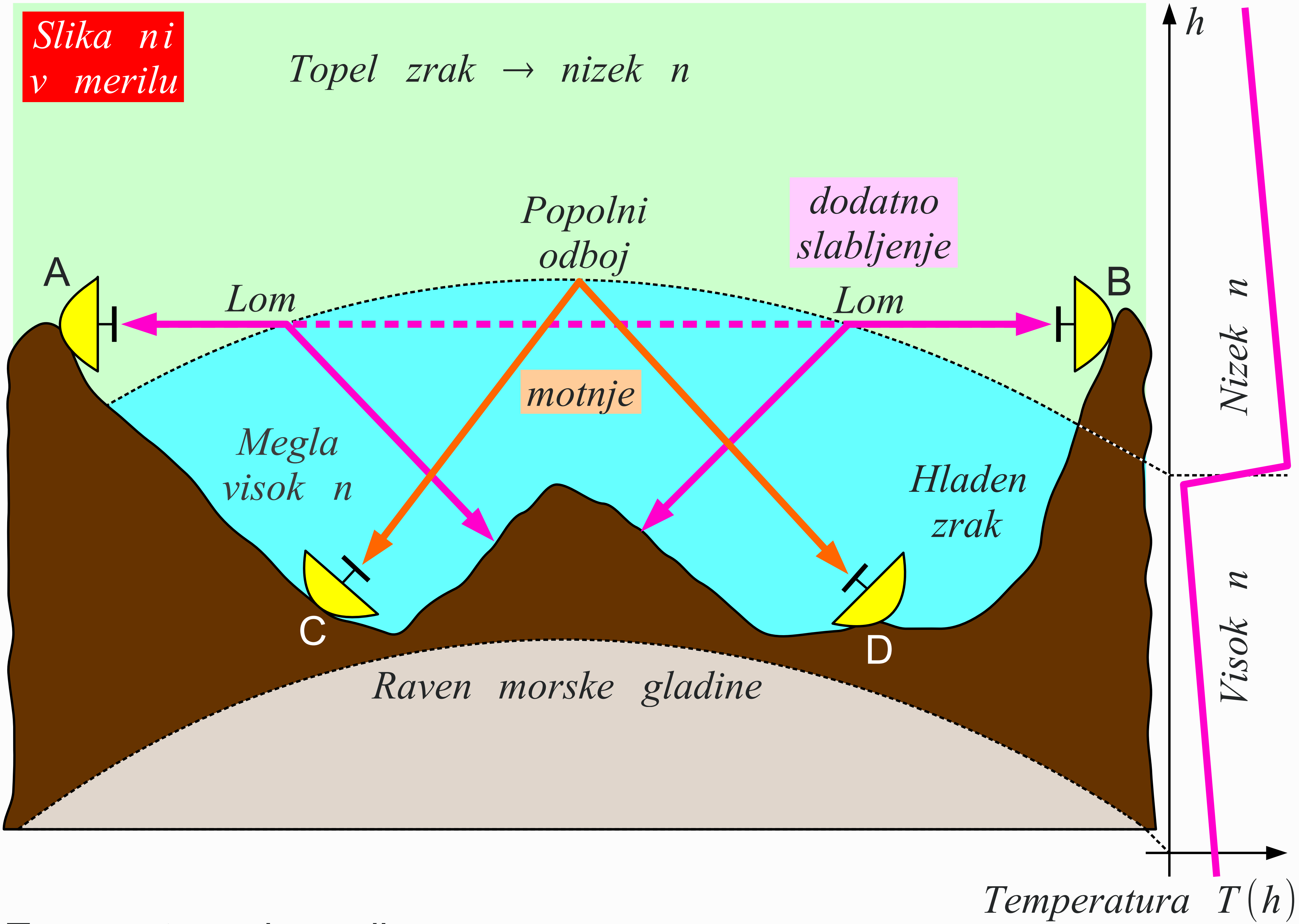
Zgled $h = 100\text{m} \rightarrow$

$$d \approx \begin{cases} 41.4\text{km} & \textit{radio} \\ 38.2\text{km} & \textit{vidna svetloba} \end{cases}$$

Geometrijska, optična in radijska vidljivost

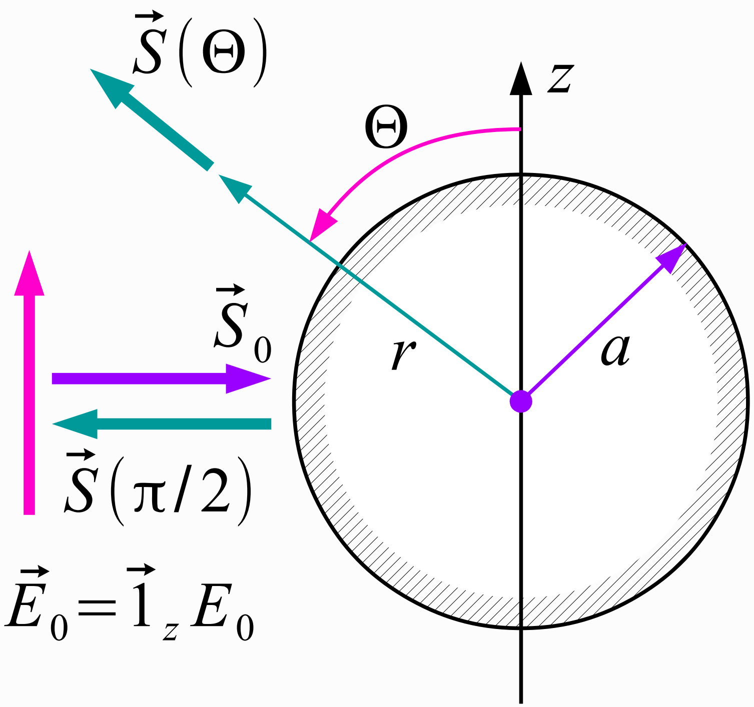


Svetovna porazdelitev najnižje srednje vrednosti $N=\Delta n \cdot 10^6$



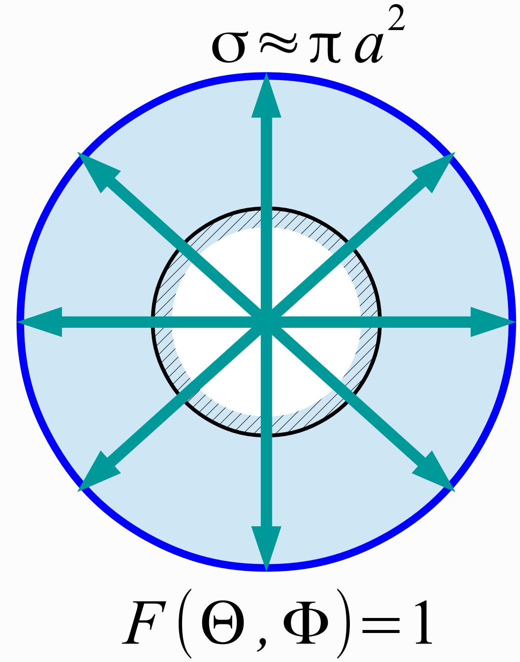
Temperaturna inverzija

Odboj od prevodne krogle



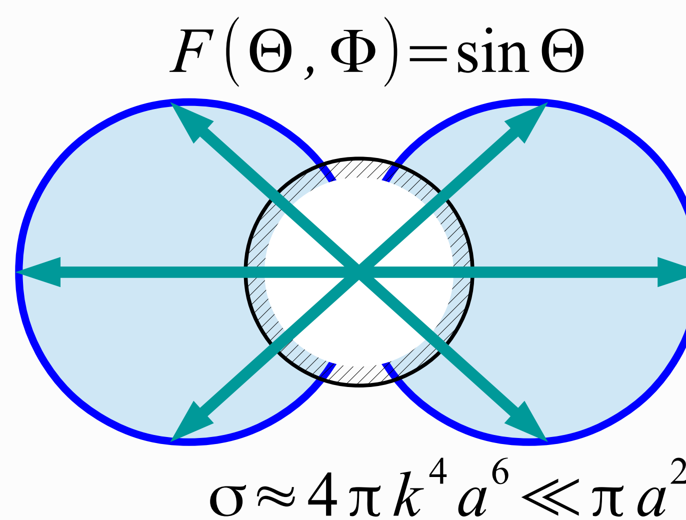
Kovinska kroglica

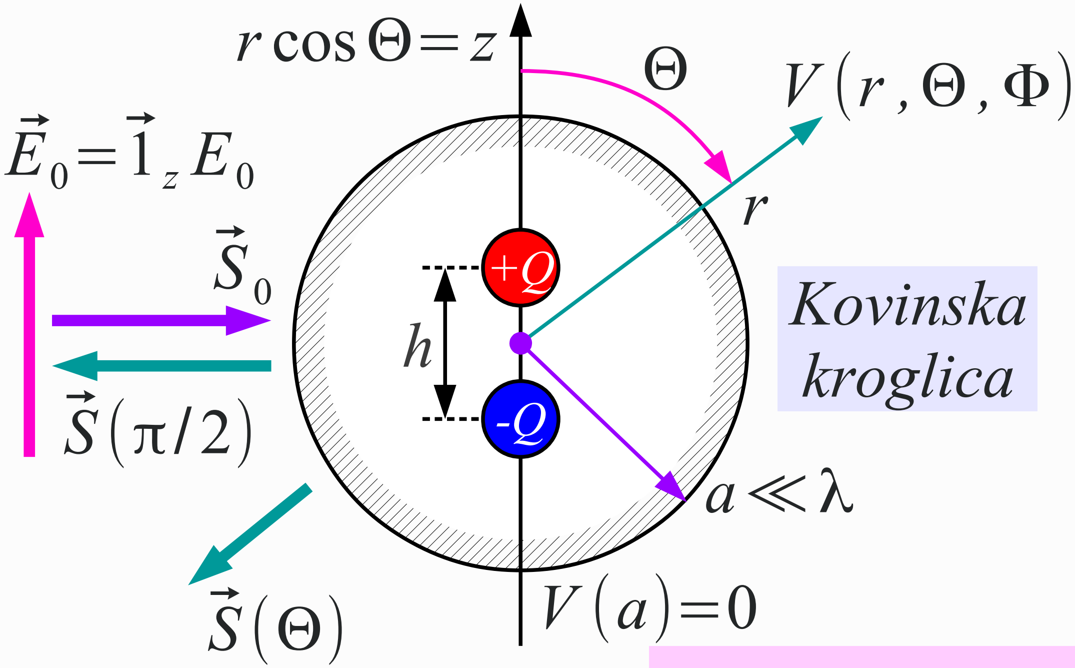
$a \gg \lambda$
neodvisno od frekvence ter polarizacije (bel oblak)



Rezonance (Mie)
$a \approx \lambda$

Rayleigh
$a \ll \lambda$
polarizacijsko ter frekvenčno odvisno (modro nebo)





Kovinska kroglica

Prazen prostor $\Delta V + k^2 V = 0$

$a \ll \lambda \;\rightarrow\;$ *Statika* $\Delta V \approx 0$

Pogoja $V(a)=0$ *in* $V(\infty) = -E_0 z$

$$V(r,\Theta,\Phi) = E_0\left(-r + \frac{a^3}{r^2}\right)\cos\Theta$$

Statika $V_{dipol}(r,\Theta,\Phi) = \frac{Q\,h}{4\pi\epsilon_0}\frac{\cos\Theta}{r^2}$

Zveznost $I = j\omega Q$

Sevanje točkastega dipola $\vec{E} \approx \vec{1}_\Theta \frac{jkZ_0}{4\pi} I\,h \frac{e^{-jkr}}{r}\sin\Theta$

$$Q\,h = 4\pi\epsilon_0 a^3 E_0 \;\rightarrow\; I\,h = 4\pi\epsilon_0 j\omega a^3 E_0 \;\rightarrow\; \vec{E} \approx -\vec{1}_\Theta k^2 a^3 E_0 \frac{e^{-jkr}}{r}\sin\Theta$$

Gostota sevane moči $\vec{S}(\Theta) = \vec{1}_r \frac{|\vec{E}|^2}{2Z_0} = \vec{1}_r k^4 a^6 \frac{|E_0|^2}{2Z_0}\frac{\sin^2\Theta}{r^2} = \vec{1}_r k^4 a^6 |\vec{S}_0| \frac{\sin^2\Theta}{r^2}$

$$\vec{S}(\Theta) = \vec{1}_r \frac{|\vec{S}_0|\sigma}{4\pi r^2} \;\;\&\;\; \sin\Theta = 1 \;\rightarrow\; \sigma = 4\pi r^2 \frac{|\vec{S}(\pi/2)|}{|\vec{S}_0|} = 4\pi k^4 a^6 = 64\pi^5 \frac{a^6}{\lambda^4}$$

Dielektrična kroglica $\sigma = 64\pi^5 \frac{a^6}{\lambda^4}\left|\frac{\epsilon_r - 1}{\epsilon_r + 2}\right|^2$

Odmevna površina majhne krogle

Dežna kapljica $\sigma = \frac{\pi^5}{\lambda^4}\left|\frac{\epsilon_r - 1}{\epsilon_r + 2}\right|^2 (2a)^6$

$\left|\frac{\epsilon_r - 1}{\epsilon_r + 2}\right|^2 = |K|^2 \equiv dielektrični \quad faktor$

$$\left|\frac{\epsilon_r - 1}{\epsilon_r + 2}\right|^2 \approx \begin{cases} 0.93 & (voda \quad \epsilon_r \approx 80) \\ 0.21 & (led \quad \epsilon_r \approx 3.5) \\ 1 & (kovina \quad \epsilon_r \to \infty) \end{cases}$$

Naključna faza $\rightarrow \sigma = \sum_i \sigma_i$

$$Z = \frac{1}{\Delta V} \sum_i (2a_i)^6 \equiv faktor \quad odboja$$

$$\eta = \frac{d\sigma}{dV} = \frac{\pi^5}{\lambda^4}\left|\frac{\epsilon_r - 1}{\epsilon_r + 2}\right|^2 Z \leftarrow Z[\mathrm{m}^3]$$

Dež $\sigma = V\eta = V\frac{\pi^5}{\lambda^4}\left|\frac{\epsilon_r - 1}{\epsilon_r + 2}\right|^2 Z$

Odmevna površina padavin

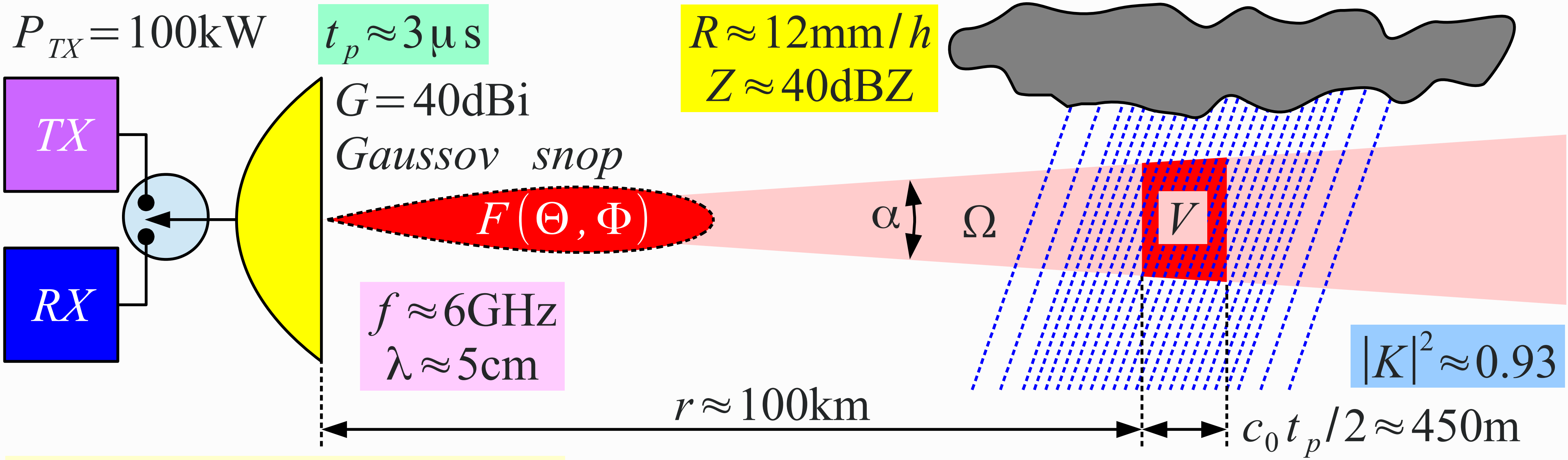
J. S. Marshall & W. M. Palmer 1948

$$R\left[\frac{mm}{h}\right] \equiv jakost \quad padavin$$

$$Z\left[\frac{mm^6}{m^3}\right] = 200\,R^{1.6} \qquad R = \left(\frac{Z}{200}\right)^{0.625}$$

$$Z_{\mathrm{dBZ}} = 10\log_{10}\frac{Z}{Z_0} \qquad Z_0 = \frac{1\,\mathrm{mm}^6}{1\,\mathrm{m}^3} = 10^{-18}\,\mathrm{m}^3$$

Padavine	R[mm/h]	Z[dBZ]	Z[m^3]	*Barva*
Toča	205mm/h	60dBZ	$10^{-12}\mathrm{m}^3$	
	100mm/h	55dBZ	$3\cdot10^{-13}\mathrm{m}^3$	
Naliv	49mm/h	50dBZ	$10^{-13}\mathrm{m}^3$	
	24mm/h	45dBZ	$3\cdot10^{-14}\mathrm{m}^3$	
Dež	12mm/h	40dBZ	$10^{-14}\mathrm{m}^3$	
	5.6mm/h	35dBZ	$3\cdot10^{-15}\mathrm{m}^3$	
	2.7mm/h	30dBZ	$10^{-15}\mathrm{m}^3$	
Rosenje	1.3mm/h	25dBZ	$3\cdot10^{-16}\mathrm{m}^3$	
	0.6mm/h	20dBZ	$10^{-16}\mathrm{m}^3$	



$$\vec{S}_0=\vec{1}_r\frac{P_{TX}G}{4\pi r^2}\frac{|F(\Theta,\Phi)|^2}{|F(\Theta_{MAX}=0)|^2}$$

$$dV=\frac{c_0 t_p}{2}r^2 d\Omega$$

$$\eta=\frac{d\sigma}{dV}=\frac{\pi^5}{\lambda^4}|K|^2 Z$$

$$40\text{dBZ}==10^{-14}\text{m}^3$$

$$dP_{RX}=\frac{G\lambda^2}{4\pi}\frac{|F(\Theta,\Phi)|^2}{|F(\Theta_{MAX}=0)|^2}|d\vec{S}|$$

$$d\vec{S}=\frac{-\vec{S}_0}{4\pi r^2}\eta\, dV$$

Stožčast snop

$$F(\Theta)=\begin{cases}1 & (\Theta<\alpha/2)\\ 0 & (\Theta>\alpha/2)\end{cases}$$

$$I=\Omega\approx\frac{4\pi}{G}$$

$$P_{RX}=\frac{P_{TX}G^2\lambda^2}{(4\pi)^3 r^2}\eta\frac{c_0 t_p}{2}I \qquad I=\oiint_{4\pi}\left(\frac{|F(\Theta,\Phi)|^2}{|F(\Theta_{MAX}=0)|^2}\right)^2 d\Omega$$

$$P_{RX}\approx\frac{P_{TX}G\lambda^2}{64\pi^2 r^2}\eta c_0 t_p=\frac{P_{TX}G\pi^3 c_0 t_p|K|^2}{64 r^2\lambda^2}Z\approx 1.62\cdot 10^{-10}\text{W}$$

Gaussov snop

$$|F(\Theta)|^2=e^{-(\Theta/\Theta_{-3\text{dB}})^2\ln 2}$$

$$I\approx\frac{\pi\Theta_{-3\text{dB}}^2}{2\ln 2}\approx\frac{2\pi}{G}$$

$$P_{RX}\approx 162\text{pW}\approx -67.9\text{dBm}$$

Vremenski radar

$$I=\oiint_{4\pi}\left(\frac{|F(\Theta,\Phi)|^2}{|F(\Theta_{MAX}=0)|^2}\right)^2 d\Omega$$

Gaussov snop $|F(\Theta,\Phi)|^2=e^{-(\Theta/\Theta_{-3dB})^2\ln 2}$

Rotacijsko$-$simetričen snop $\alpha_E=\alpha_H=2\Theta_{-3dB}$

$$I=\int_0^{\pi}\int_0^{2\pi}\left(e^{-(\Theta/\Theta_{-3dB})^2\ln 2}\right)^2\sin\Theta\, d\Theta\, d\Phi$$

$$D=\frac{4\pi|F(\Theta_{MAX}=0)|^2}{\oiint_{4\pi}|F(\Theta,\Phi)|^2 d\Omega}$$

Kraussov približek $D\approx\frac{\pi}{\Theta^2_{-3dB}}$

$$I=2\pi\int_0^{\pi}e^{-2(\Theta/\Theta_{-3dB})^2\ln 2}\sin\Theta\, d\Theta$$

$$D=\frac{4\pi}{\int_0^{\pi}\int_0^{2\pi}e^{-(\Theta/\Theta_{-3dB})^2\ln 2}\sin\Theta\, d\Theta\, d\Phi}$$

$\Theta_{-3dB}\ll 1$

$\sin\Theta\approx\Theta$

$$I\approx 2\pi\int_0^{\infty}e^{-2(\Theta/\Theta_{-3dB})^2\ln 2}\Theta\, d\Theta$$

$$D\approx\frac{2}{\int_0^{\infty}e^{-(\Theta/\Theta_{-3dB})^2\ln 2}\Theta\, d\Theta}$$

$u=(\Theta/\Theta_{-3dB})^2$

Brezizgubna antena $G\approx D$

$$I\approx\pi\Theta^2_{-3dB}\int_0^{\infty}e^{-2u\ln 2}du=\frac{\pi\Theta^2_{-3dB}}{2\ln 2}$$

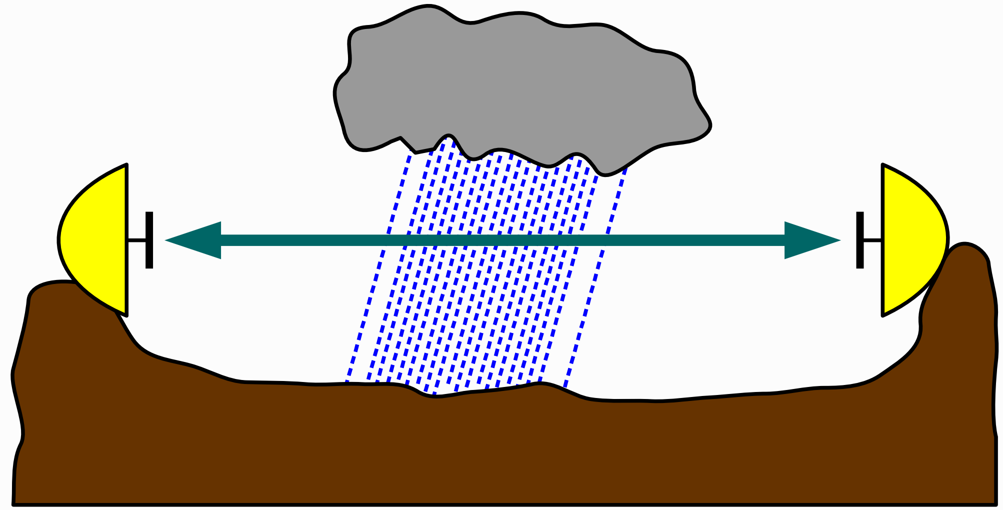
$$G\approx\frac{4}{\Theta^2_{-3dB}\int_0^{\infty}e^{-u\ln 2}du}=\frac{4\ln 2}{\Theta^2_{-3dB}}\approx\frac{2.77}{\Theta^2_{-3dB}}$$

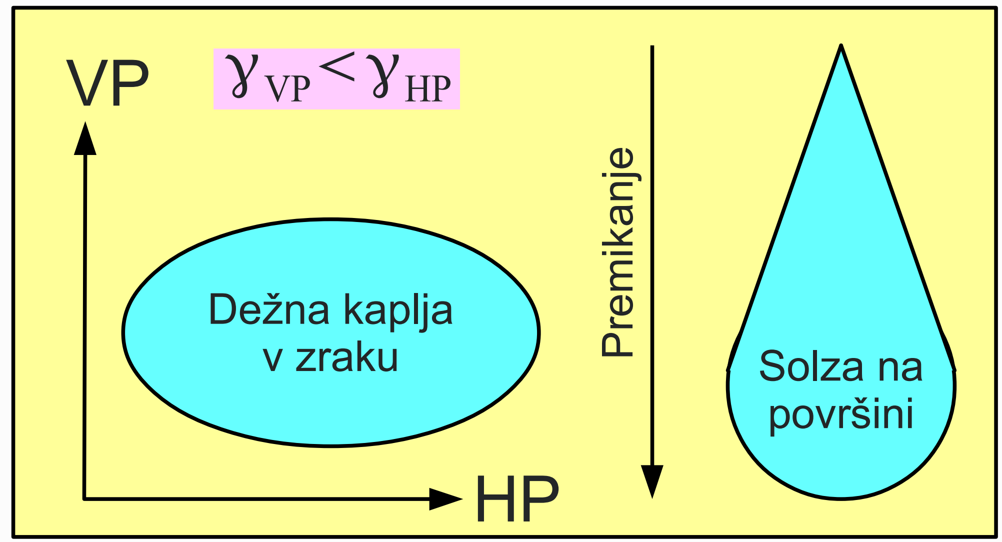
$$I\approx\frac{\pi\Theta^2_{-3dB}}{2\ln 2}\approx\frac{2\pi}{G}$$

$$\Theta^2_{-3dB}\approx\frac{4\ln 2}{G}\approx\frac{2.77}{G}$$

Gaussov snop

Dielektrične lastnosti vode		
f	$\varepsilon_r = \varepsilon_r' - j\varepsilon_r''$	$n = \sqrt{\varepsilon_r}$
300GHz	$5.81 - j4.85$	$2.59 - j0.94$
150GHz	$6.75 - j9.57$	$3.04 - j1.57$
100GHz	$8.26 - j14.07$	$3.50 - j2.01$
60GHz	$12.69 - j22.00$	$4.36 - j2.52$
30GHz	$26.40 - j34.22$	$5.90 - j2.90$
18.5GHz	$42.54 - j35.62$	$7.00 - j2.54$
16GHz	$50.00 - j37.50$	$7.50 - j2.50$
11GHz	$61.16 - j32.12$	$8.07 - j1.99$
6GHz	$73.72 - j20.84$	$8.67 - j1.20$
4GHz	$76.08 - j16.05$	$8.77 - j0.92$
3GHz	$78.30 - j11.14$	$8.87 - j0.63$
2GHz	$79.32 - j7.53$	$8.92 - j0.42$
1.43GHz	$80.92 - j4.95$	$9.00 - j0.28$





Slabljenje padavin

Priporočilo ITU-R P.838-3

$$\gamma[\mathrm{dB/km}] \approx k(f)(R[\mathrm{mm/h}])^{\alpha(f)}$$

Enačbe/tabele za $k(f)$ & $\alpha(f)$ *posebej za* HP *oziroma za* VP

$$\gamma = -a_{\mathrm{dB}}/l$$

f (GHz)	k_{HP}	α_{HP}	k_{VP}	α_{VP}
3.5	0.0001155	1.4189	0.0002346	1.1387
6	0.0007056	1.5900	0.0004878	1.5728
11	0.01772	1.2140	0.01731	1.1617
18	0.07078	1.0818	0.07708	1.0025
30	0.2403	0.9485	0.2291	0.9129
50	0.6600	0.8084	0.6472	0.7871
80	1.1704	0.7115	1.1668	0.7021

Koeficienti priporočila ITU-R P.838-3

FIGURE 1

***k* coefficient for horizontal polarization**

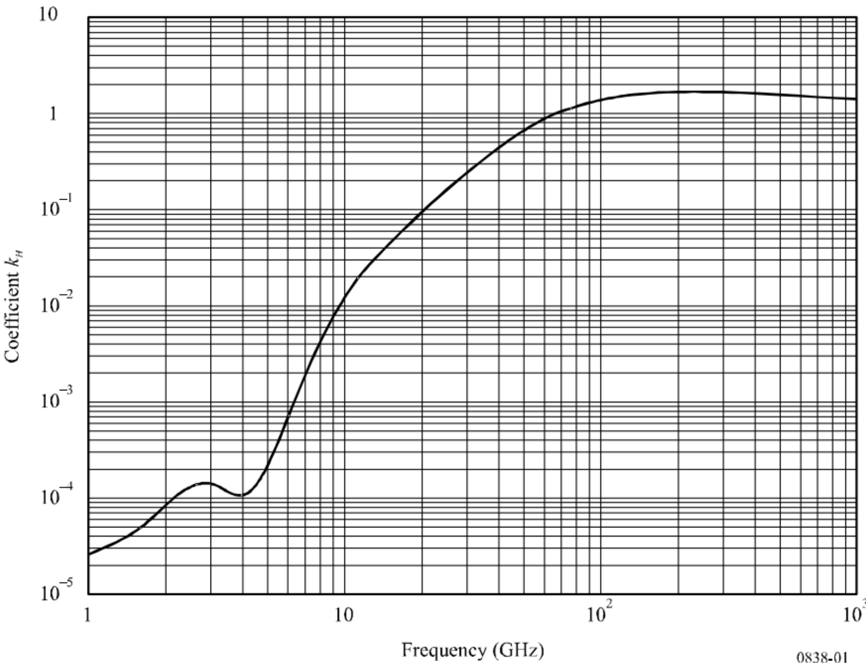


FIGURE 2

α coefficient for horizontal polarization

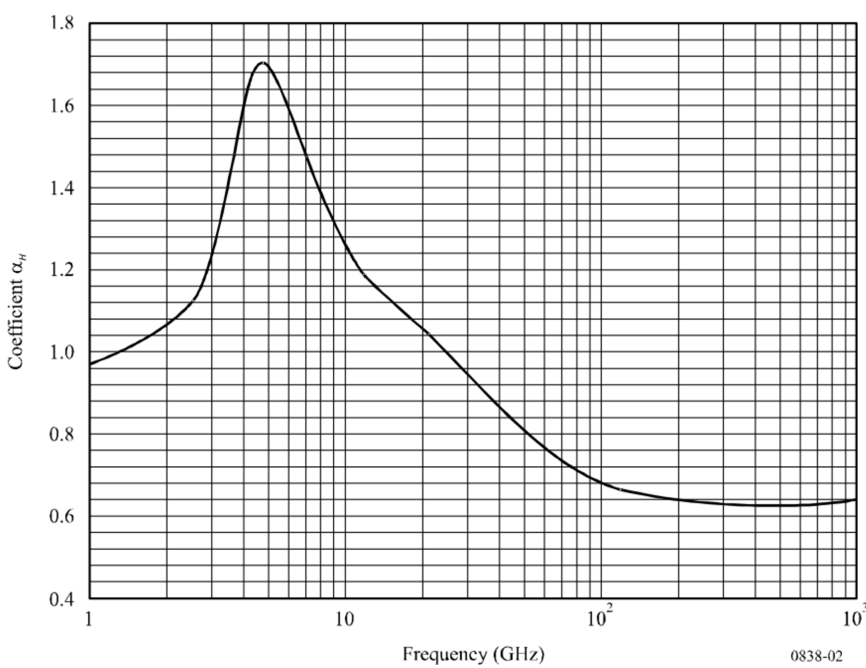


FIGURE 3

***k* coefficient for vertical polarization**

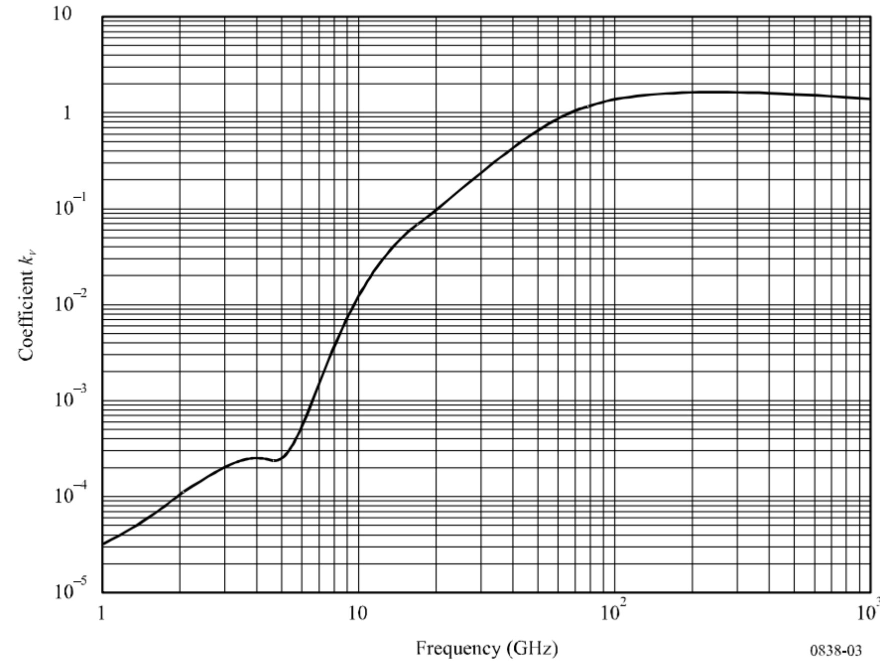
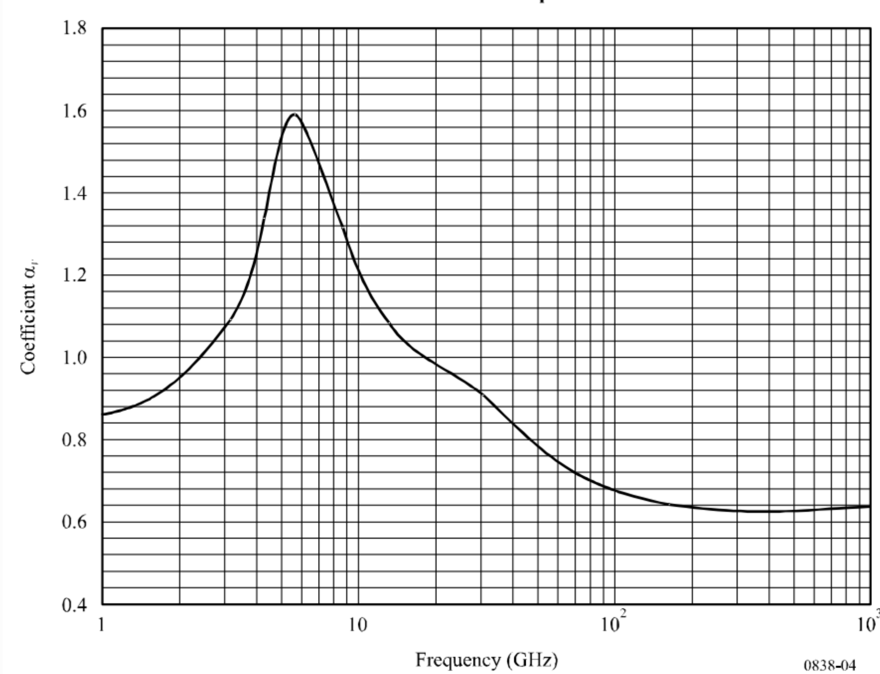
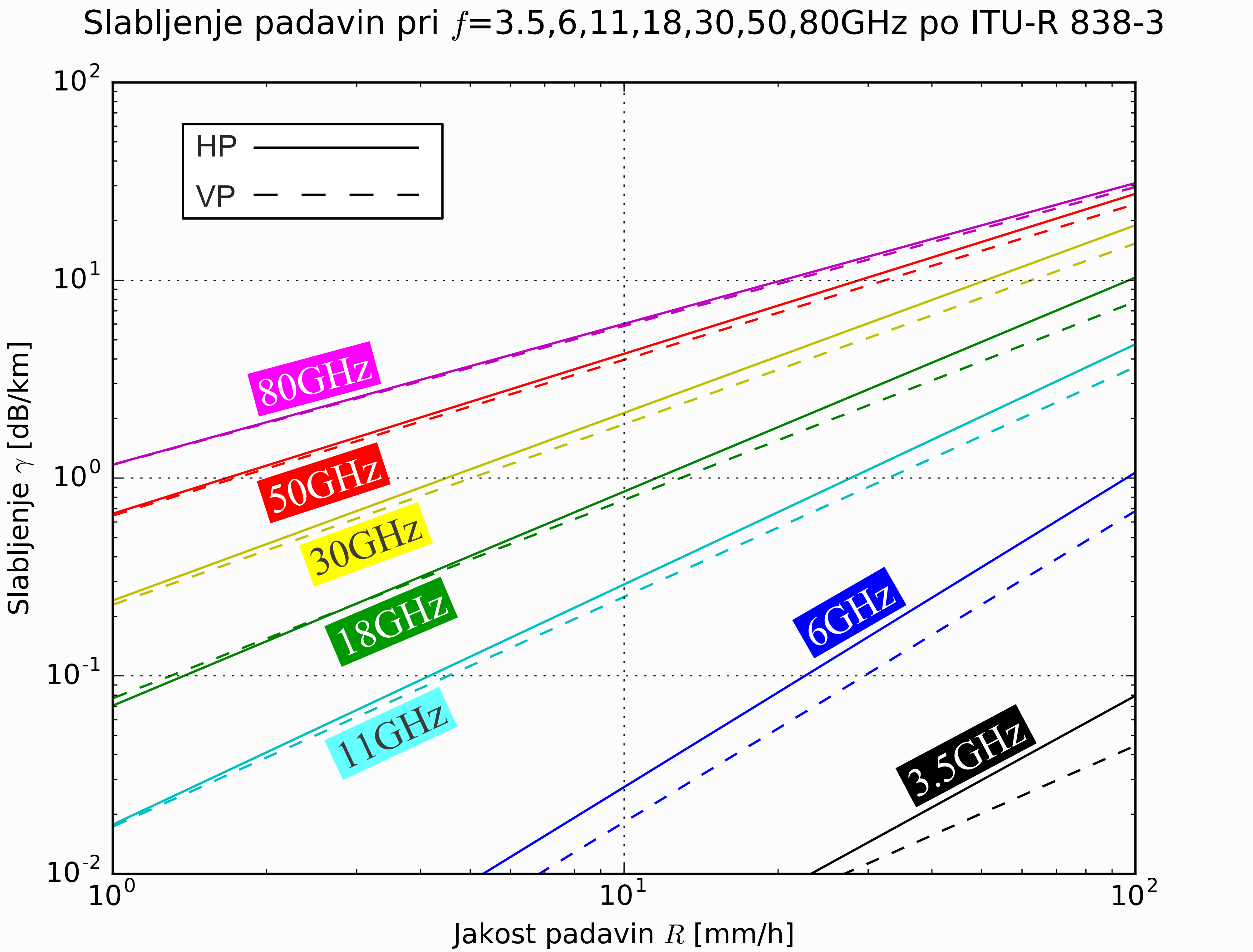


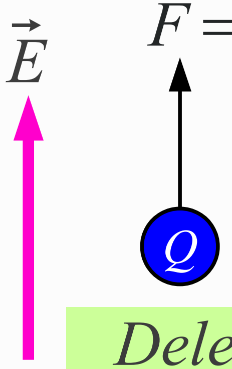
FIGURE 4

α coefficient for vertical polarization





Slabljenje padavin pri f=3.5,6,11,18,30,50,80GHz po ITU-R 838-3
Slabljenje γ [dB/km]
Jakost padavin R [mm/h]
HP
VP
80GHz
50GHz
30GHz
18GHz
11GHz
6GHz
3.5GHz
10^2
10^1
10^0
10^{-1}
10^{-2}



$$\vec{F} = Q\,\vec{E} = m\,\vec{a} = m\frac{d\vec{v}}{dt} = j\,\omega\, m\,\vec{v} \;\rightarrow\; \vec{v} = \frac{Q}{j\,\omega\, m}\vec{E}$$

Delec
masa m

$$\vec{J}_{konvektivni} = N\,Q\,\vec{v} \qquad N\,[\mathrm{m}^{-3}] \equiv gostota \;\; delcev \;\; v \;\; prostoru$$

$$\vec{J}_{konvektivni} = \sum_i \frac{N_i Q_i^2}{j\,\omega\, m_i}\vec{E} \qquad \left(\begin{matrix} različni \\ delci \;\; i \end{matrix}\right)$$

Elektron
$$Q_e \approx -1.6\cdot 10^{-19}\,\mathrm{As}$$
$$m_e \approx 9.1\cdot 10^{-31}\,\mathrm{kg}$$

$$Ionosfera:\;\; \vec{J}_{konvektivni} = \frac{N_e Q_e^2}{j\,\omega\, m_e}\vec{E} + \frac{N_p Q_p^2}{j\,\omega\, m_p}\vec{E} + \ldots \left(\begin{matrix} težji \\ delci \end{matrix}\right)$$

Proton
$$Q_p \approx 1.6\cdot 10^{-19}\,\mathrm{As}$$
$$m_p \approx 1.67\cdot 10^{-27}\,\mathrm{kg}$$

Ampère:

$$\mathrm{rot}\,\vec{H} = \vec{J} + j\,\omega\,\epsilon_0\vec{E} \approx \frac{N_e Q_e^2}{j\,\omega\, m_e}\vec{E} + j\,\omega\,\epsilon_0\vec{E} = j\,\omega\,\epsilon_0\left(1 - \frac{N_e Q_e^2}{\omega^2\epsilon_0 m_e}\right)\vec{E} = j\,\omega\,\epsilon_0\,\epsilon_r\,\vec{E}$$

$$\epsilon_r = 1 - \frac{N_e Q_e^2}{\omega^2\epsilon_0 m_e} = 1 - \left(\frac{\omega_p}{\omega}\right)^2 = 1 - \left(\frac{f_p}{f}\right)^2$$

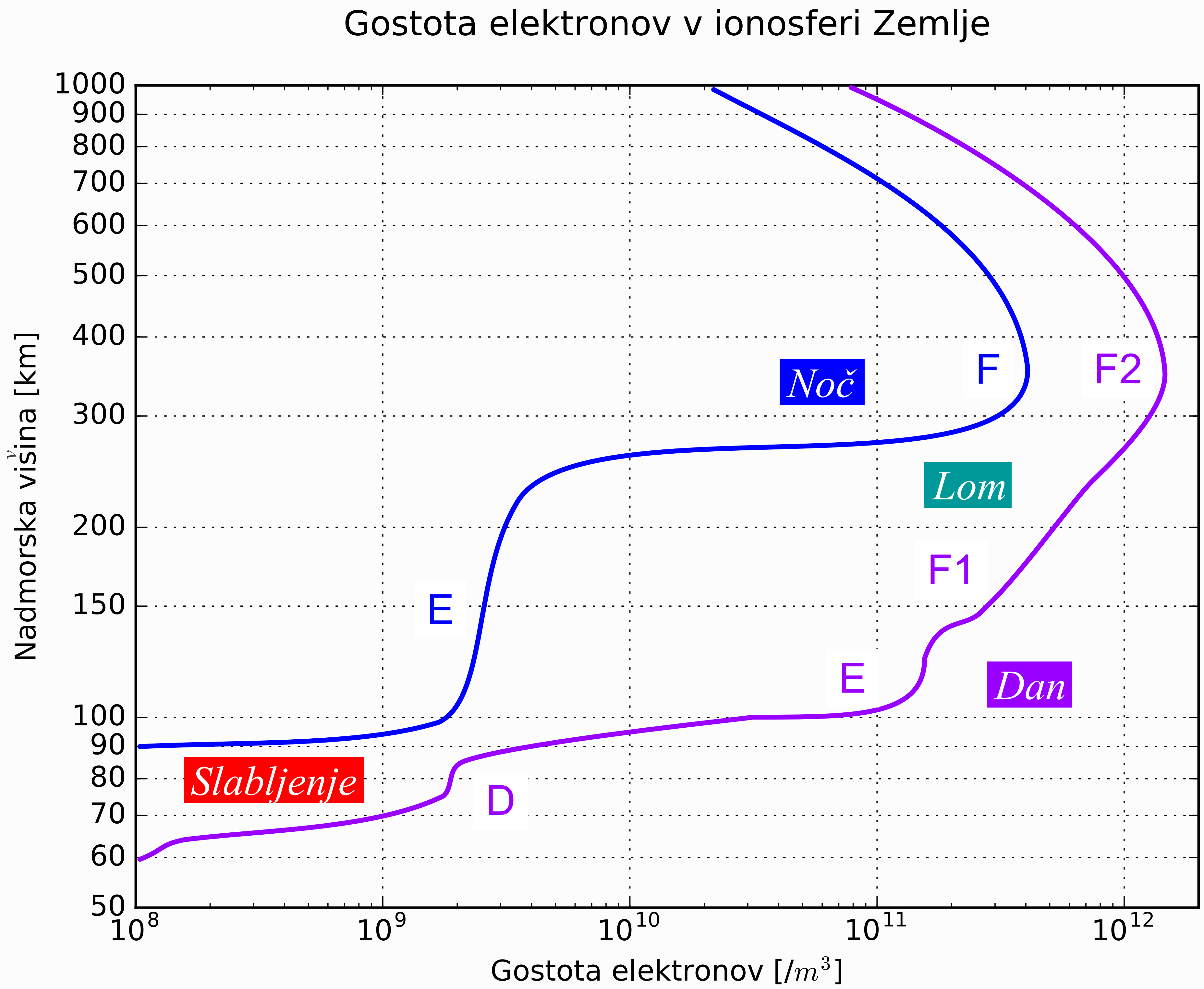
$$f < f_p \;\rightarrow\; prevodnik$$

$$f_p \equiv frekvenca \;\; plazme$$

$$f_p = \frac{1}{2\pi}\sqrt{\frac{N_e Q_e^2}{\epsilon_0 m_e}} \approx \sqrt{80.6\,\frac{\mathrm{m}^3}{\mathrm{s}^2}N_e} \approx \left\{\begin{matrix} 11\,\mathrm{MHz} & dan \\ 5\,\mathrm{MHz} & noč \end{matrix}\right\}$$

$$f > f_p \;\rightarrow\; dielektrik$$
$$n = \sqrt{1 - \left(\frac{f_p}{f}\right)^2} < 1$$

Dielektričnost in lomni količnik ionosfere



Gostota elektronov v ionosferi Zemlje
1000
900
800
700
600
500
400
300
200
150
100
90
80
70
60
50
Nadmorska višina [km]
10^8
10^9
10^{10}
10^{11}
10^{12}
Gostota elektronov [$/m^3$]
Noč
Lom
Dan
Slabljenje
F
F2
F1
E
E
D

Radijska zveza preko ionosfere

$$n(h)=\sqrt{1-\left(\frac{f_p(h)}{f}\right)^2}<1$$

Popolni odboj

$$n=\sin\Theta\approx\frac{R_Z}{R_Z+h}$$

$$\frac{R_Z}{R_Z+h}=\sqrt{1-\left(\frac{f_p}{f}\right)^2}$$

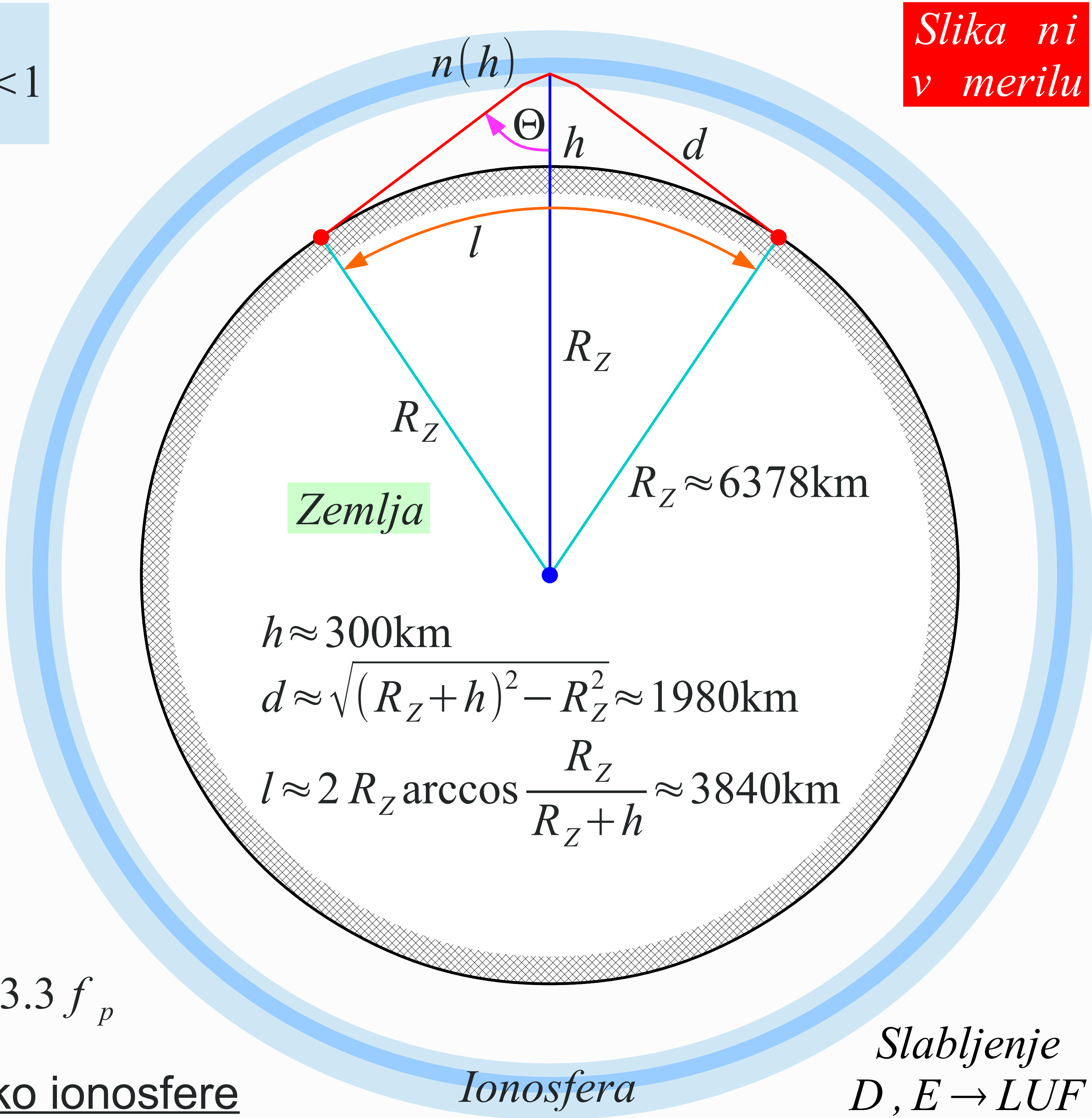
$$\left(\frac{f}{f_p}\right)^2=\frac{(R_Z+h)^2}{(R_Z+h)^2-R_Z^2}$$

$$h\ll R_Z$$

$$f\approx f_p\sqrt{\frac{R_Z}{2h}}$$

$$h_{MAX}\approx 300\text{km}$$

$$MUF\approx f_p\sqrt{\frac{R_Z}{2h_{MAX}}}\approx 3.3 f_p$$



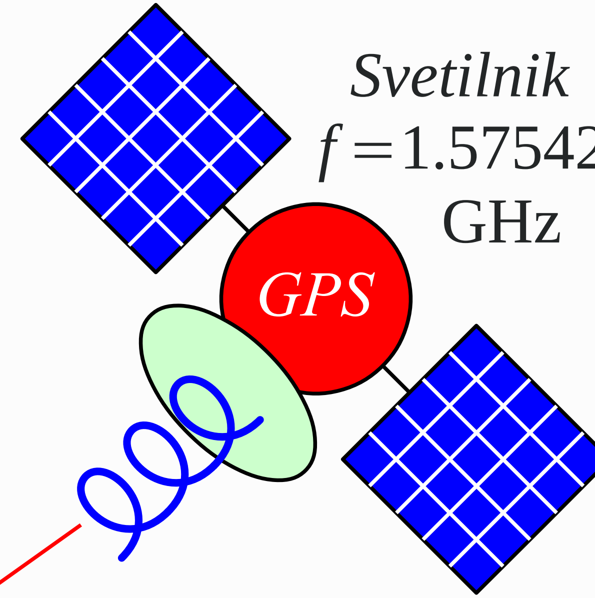
Hitrosti valovanja v ionosferi

$$\beta=\frac{\omega}{c_0}\sqrt{1-(\omega_p/\omega)^2}=\frac{1}{c_0}\sqrt{\omega^2-\omega_p^2}$$

$$\frac{d\beta}{d\omega}=\frac{1}{c_0}\frac{\omega}{\sqrt{\omega^2-\omega_p^2}}$$

Svetilnik

$f=1.57542$ GHz



Fazna hitrost $v_f=\frac{\omega}{\beta}=\frac{c_0}{\sqrt{1-(\omega_p/\omega)^2}}>c_0$

$$f_p^2=\frac{N_e(s)Q_e^2}{4\pi^2\epsilon_0 m_e}$$

Skupinska hitrost $v_g=\frac{d\omega}{d\beta}=c_0\sqrt{1-(\omega_p/\omega)^2}<c_0$

$$f\gg f_p \rightarrow \begin{matrix} v_f\approx c_0+\Delta v \\ v_g\approx c_0-\Delta v \end{matrix} \quad \Delta v=\frac{c_0}{2}(f_p/f)^2$$

$$TEC[m^{-2}]=\int_s N_e(s)ds$$

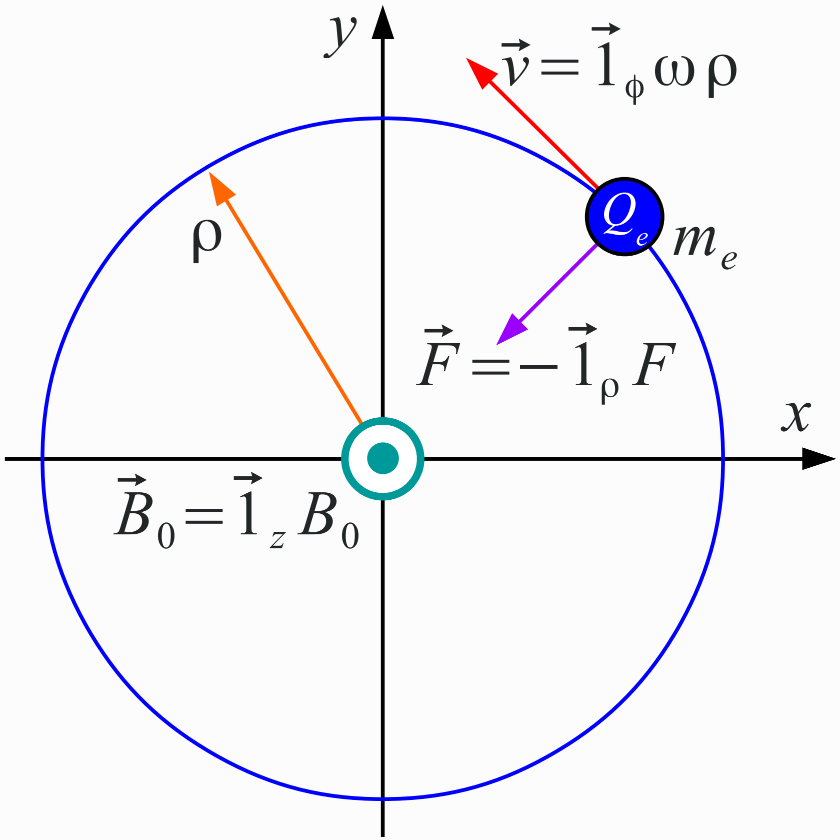
Ionosfera $n<1$ s $f_p\approx 11\text{MHz}$

Slika ni v merilu

$$t=\int_s\frac{ds}{v(s)}=\int_s\frac{ds}{c_0\pm\Delta v}\approx\frac{s}{c_0}\mp\int_s\frac{\Delta v}{c_0^2}ds=\frac{s}{c_0}\mp\int_s\frac{(f_p/f)^2}{2c_0}ds$$

$$\Delta r=c_0\Delta t\approx\int_s\frac{\mp N_e(s)Q_e^2}{8\pi^2\epsilon_0 m_e f^2}ds=\frac{\mp Q_e^2 TEC}{8\pi^2\epsilon_0 m_e f^2}\approx\mp 40.3\frac{\text{m}^3}{\text{s}^2}\frac{TEC}{f^2}$$

$$TEC\approx 10^{18}\,\text{m}^{-2} \rightarrow \Delta r\approx\mp 16.2\text{m}$$



Kroženje $\vec{a}=\dfrac{d\vec{v}}{dt}=-\vec{1}_\rho \omega \rho \dfrac{d\phi}{dt}=-\vec{1}_\rho \omega^2 \rho$

$$\vec{F}=m_e \vec{a}=-\vec{1}_\rho m_e \omega^2 \rho$$

Elektron
$Q_e \approx -1.6\cdot 10^{-19}\,\mathrm{As}$
$m_e \approx 9.1\cdot 10^{-31}\,\mathrm{kg}$

Lorentzova sila $\vec{F}=Q\left(\vec{E}+\vec{v}\times\vec{B}\right)$

$$\vec{F}=Q_e \vec{v}\times\vec{B}_0=\vec{1}_\rho Q_e \omega \rho B_0$$

$$\vec{\omega}_g=\frac{-Q_e \vec{B}_0}{m_e}$$

Zemlja $H_0 \approx 40\,\mathrm{A/m}$

$$f_g=\frac{|Q_e|\mu_0 H_0}{2\pi m_e}\approx 1.4\,\mathrm{MHz}$$

Povečano slabljenje @ f_g
Dvolomnost !

Žiromagnetna rezonanca v ionosferi

$$\text{Lorentzova sila} \quad \vec{F} = m_e \vec{a} = j\omega m_e \vec{v} = Q_e(\vec{E} + \vec{v} \times \vec{B}_0)$$

$$\text{Enosmerni} \quad \vec{B}_0 = \vec{1}_z B_0$$

$$\text{Preprosta rešitev} \quad \vec{1}_K = \frac{\vec{1}_V \pm j\vec{1}_H}{\sqrt{2}}$$

$$\vec{v} = \vec{1}_K v_0 e^{-j\beta z} \qquad \vec{E} = \vec{1}_K E_0 e^{-j\beta z}$$

$$\vec{1}_K \times \vec{1}_z = \frac{-\vec{1}_H \pm j\vec{1}_V}{\sqrt{2}} = j\frac{j\vec{1}_H \pm \vec{1}_V}{\sqrt{2}} = \pm j\vec{1}_K$$

$$j\omega m_e \vec{v} = Q_e(\vec{E} \pm jB_0 \vec{v}) \rightarrow \vec{v} = \frac{\vec{E}}{\frac{j\omega m_e}{Q_e} \mp jB_0}$$

$$\vec{J} = N_e Q_e \vec{v} = \frac{N_e Q_e \vec{E}}{\frac{j\omega m_e}{Q_e} \mp jB_0}$$

$$\omega_p^2 = \frac{N_e Q_e^2}{\epsilon_0 m_e}$$

$$\epsilon_r = 1 + \frac{N_e Q_e}{j\omega\epsilon_0\left(\frac{j\omega m_e}{Q_e} \mp jB_0\right)} = 1 - \frac{N_e Q_e^2}{\omega^2 \epsilon_0 m_e \left(1 \mp \frac{Q_e B_0}{\omega m_e}\right)} = 1 - \left(\frac{\omega_p}{\omega}\right)^2 \frac{1}{1 \pm \frac{\omega_g}{\omega}}$$

$$\omega_g = \frac{-Q_e B_0}{m_e}$$

$$n = \sqrt{1 - \left(\frac{\omega_p}{\omega}\right)^2 \frac{1}{1 \pm \frac{\omega_g}{\omega}}}$$

$$\omega \gg \omega_p, \omega_g$$

$$n \approx 1 - \frac{1}{2}\left(\frac{\omega_p}{\omega}\right)^2 \frac{1}{1 \pm \frac{\omega_g}{\omega}} \qquad \Delta n = n_L - n_D \approx \left(\frac{\omega_p}{\omega}\right)^2 \frac{\omega_g}{\omega}$$

Krožna dvolomnost

$$\Delta\phi=\int_s \Delta n(s)\, k_0\, ds\approx\frac{\omega}{c_0}\int_s\left(\frac{\omega_p(s)}{\omega}\right)^2\frac{\omega_g}{\omega}ds=\frac{\omega_g}{c_0}\int_s\frac{N_e(s)Q_e^2}{\epsilon_0 m_e\omega^2}ds=\frac{Q_e^2 f_g TEC}{2\pi c_0\epsilon_0 m_e f^2}$$

$$TEC\approx 10^{18}\,\mathrm{m}^{-2}\quad f_g\approx 1.4\mathrm{MHz}\quad f=1\mathrm{GHz}\ \rightarrow\ \Delta\phi\approx 2.36\mathrm{rd}$$

Radijska zveza preko ionosfere $f<MUF$:

(1) *presih zaradi hitrega sukanja polarizacije*

(2) *nerecipročna zveza zaradi nerecipročnega sukanja*

Radijska zveza do satelita v vesolju:

(1) $f<100\mathrm{MHz}$ → *neprozorna ionosfera*

(2) $100\mathrm{MHz}<f<3\mathrm{GHz}$ → *RHCP / LHCP zaradi krožne dvolomnosti ionosfere*

(3) $3\mathrm{GHz}<f<10\mathrm{GHz}$ → *uporaba poljubne polarizacije*

(4) $f>10\mathrm{GHz}$ → *VP / HP zaradi dvolomnosti dežnih kapljic*

Faradayevo sukanje