Odboj

Prazen prostor

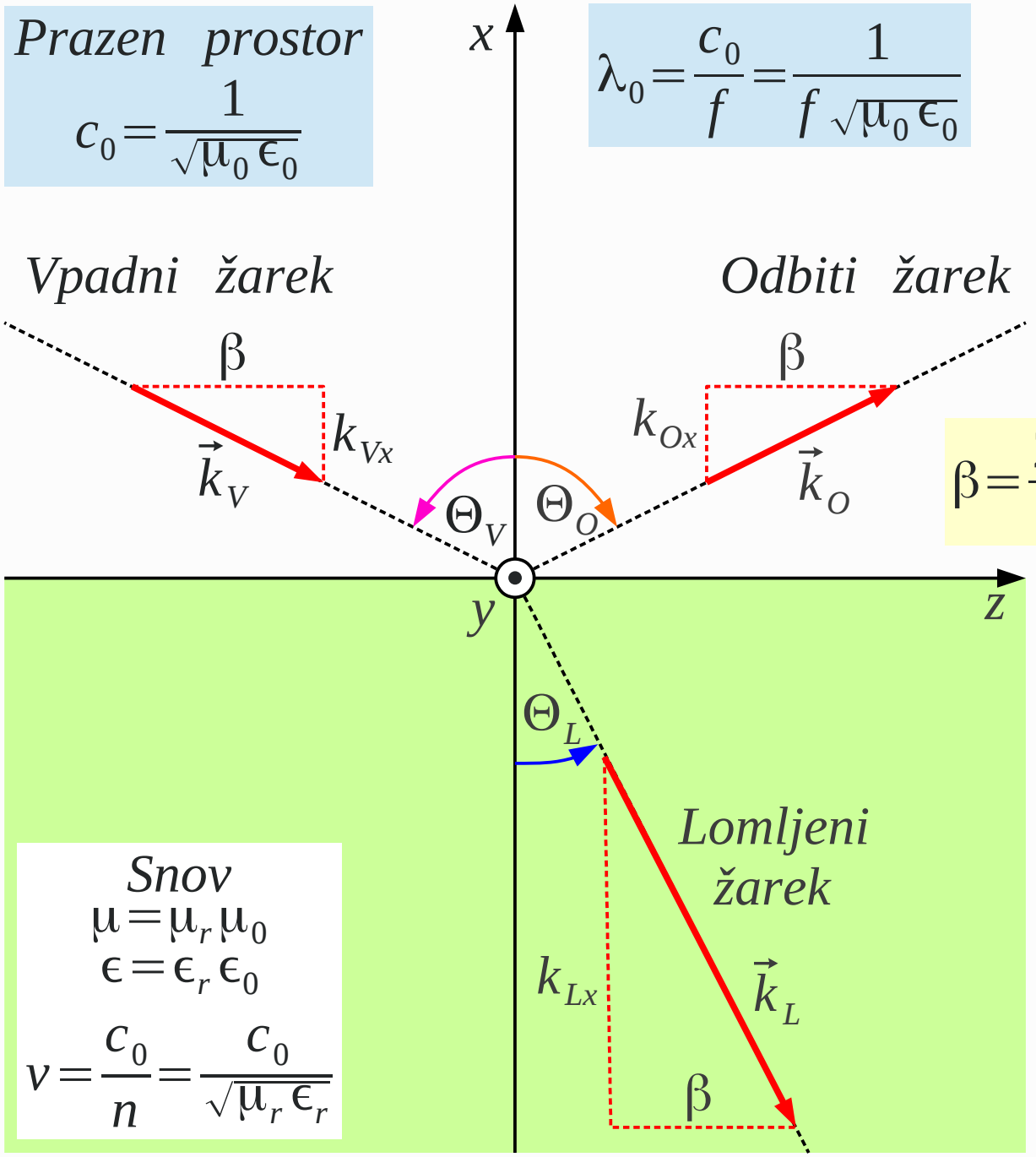
$$c_0 = \frac{1}{\sqrt{\mu_0 \epsilon_0}}$$

$$\lambda_0 = \frac{c_0}{f} = \frac{1}{f\sqrt{\mu_0 \epsilon_0}}$$

$$\vec{k}_V = \vec{1}_V \frac{2\pi}{\lambda_0} = \vec{1}_x k_{Vx} + \vec{1}_z \beta$$

$$\vec{k}_O = \vec{1}_O \frac{2\pi}{\lambda_0} = \vec{1}_x k_{Ox} + \vec{1}_z \beta$$

Odbojni zakon $\Theta_O = \Theta_V$



$$\beta = \frac{2\pi}{\lambda_0}\sin\Theta_V = \frac{2\pi}{\lambda_0}\sin\Theta_O = \frac{2\pi}{\lambda}\sin\Theta_L$$

$$\vec{k}_L = \vec{1}_L \frac{2\pi}{\lambda} = \vec{1}_x k_{Lx} + \vec{1}_z \beta$$

$$\lambda = \frac{\lambda_0}{n} = \frac{\lambda_0}{\sqrt{\mu_r \epsilon_r}}$$

Snov

$$\mu = \mu_r \mu_0$$

$$\epsilon = \epsilon_r \epsilon_0$$

$$v = \frac{c_0}{n} = \frac{c_0}{\sqrt{\mu_r \epsilon_r}}$$

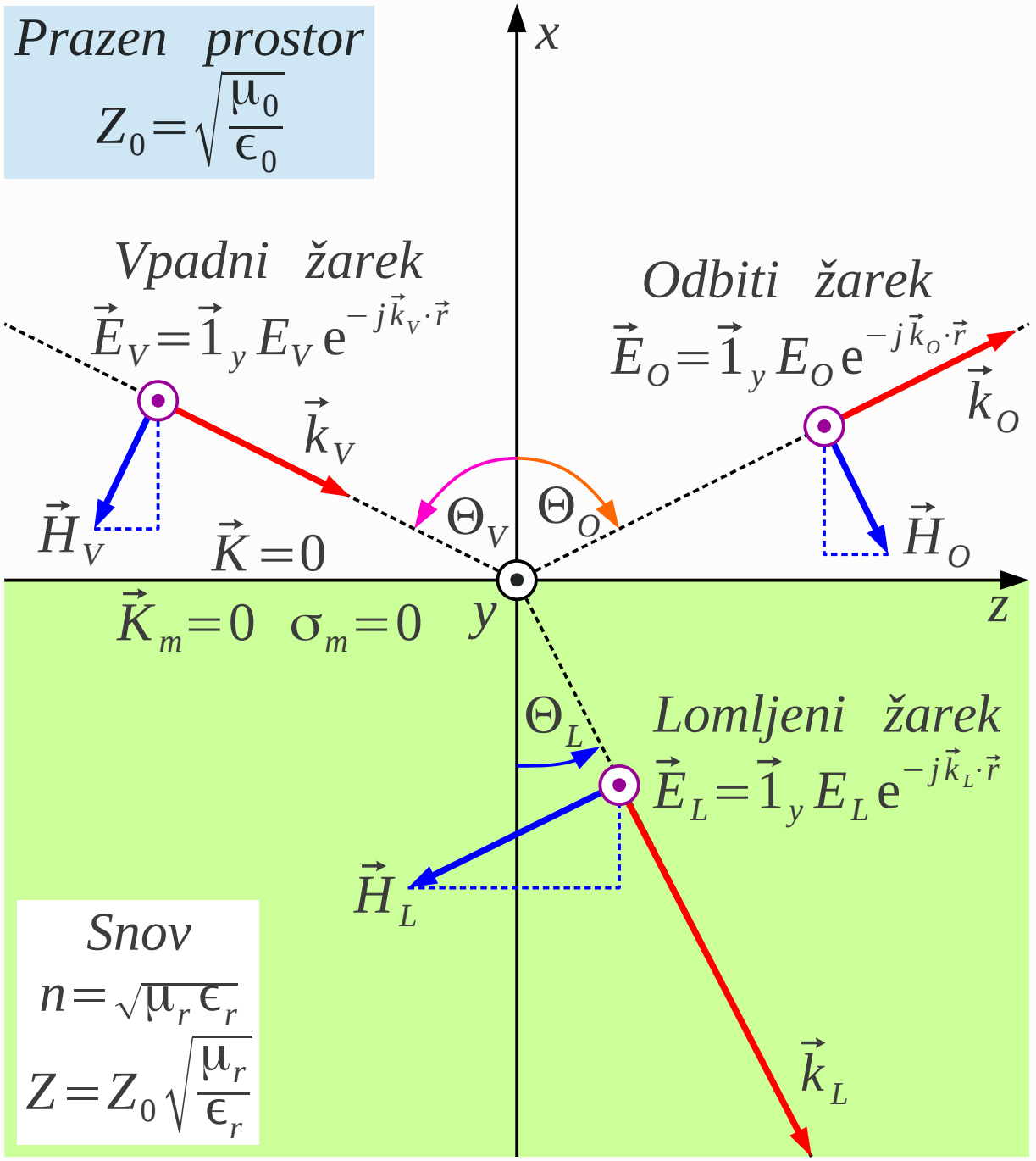
Lomni zakon

Ibn Sahl 984

$$\sin\Theta_V = n \sin\Theta_L$$

$$\sin\Theta_L = \frac{\sin\Theta_V}{\sqrt{\mu_r \epsilon_r}}$$

Odboj in lom na površini snovi



Prazen prostor

$$Z_0 = \sqrt{\frac{\mu_0}{\epsilon_0}}$$

Snov

$$n = \sqrt{\mu_r \epsilon_r}$$

$$Z = Z_0 \sqrt{\frac{\mu_r}{\epsilon_r}}$$

Prestopni pogoji

$$(1)\quad E_{Vy} + E_{Oy} = E_{Ly}$$

$$(2)\quad H_{Vz} + H_{Oz} = H_{Lz}$$

$$(3)\quad B_{Vx} + B_{Ox} = B_{Lx}$$

$$(1)\quad E_V + E_O = E_L$$

$$(2)\quad (E_V - E_O)\frac{\cos\Theta_V}{Z_0} = E_L \frac{\cos\Theta_L}{Z}$$

$$(1-\Gamma_{HP})\frac{\cos\Theta_V}{Z_0} = (1+\Gamma_{HP})\frac{\cos\Theta_L}{Z}$$

Odboj

$$\Theta_O = \Theta_V$$

Odbojnost

$$\Gamma_{HP} = \frac{E_O}{E_V}$$

$$\Gamma_{HP} = \frac{Z\cos\Theta_V - Z_0\cos\Theta_L}{Z\cos\Theta_V + Z_0\cos\Theta_L}$$

Lom

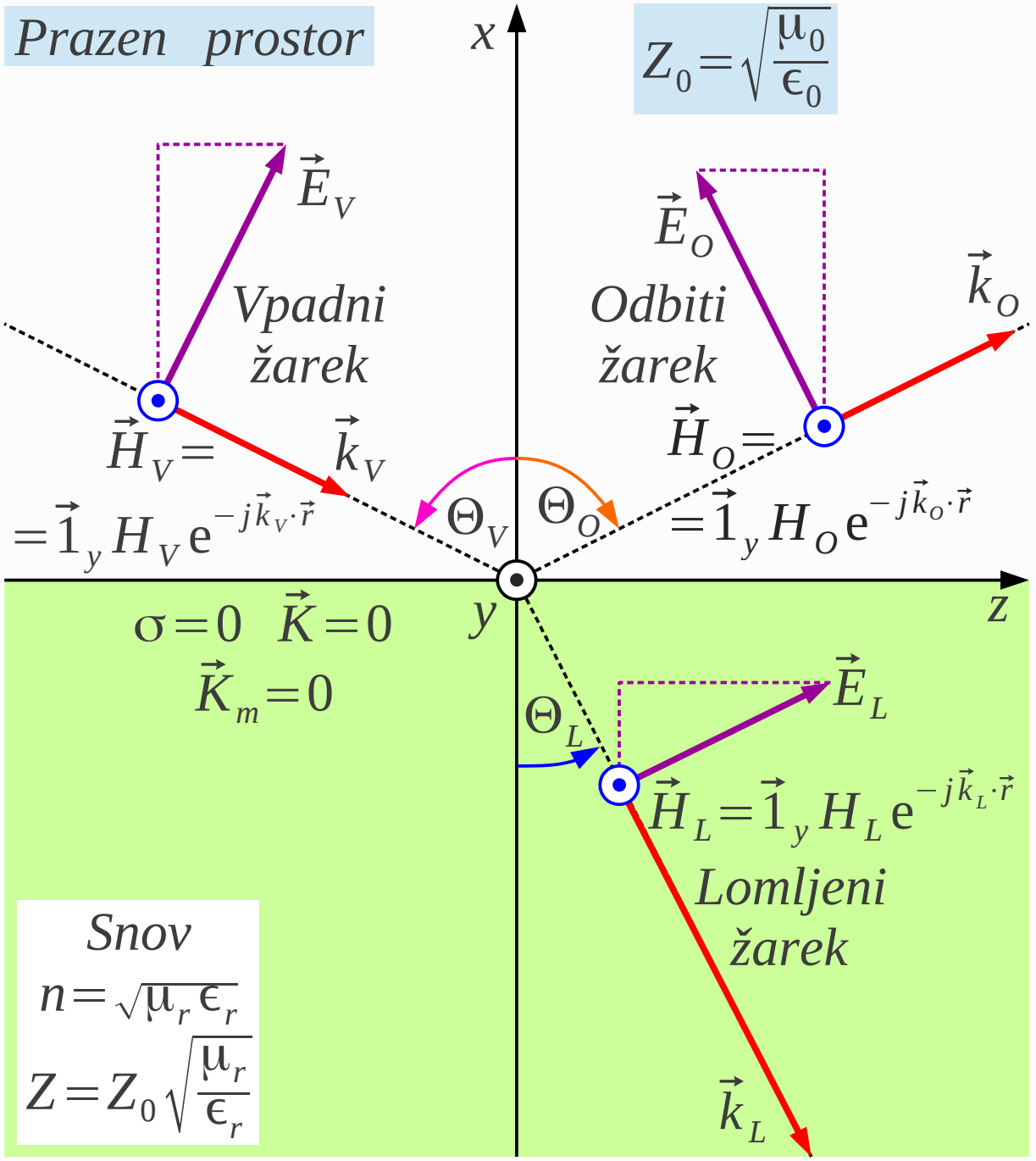
$$\cos\Theta_L = \sqrt{1 - \left(\frac{\sin\Theta_V}{n}\right)^2}$$

Dielektrik $\mu_r = 1 \quad n = \sqrt{\epsilon_r}$

$$\Theta = \Theta_V$$

$$\Gamma_{HP} = \frac{\cos\Theta - \sqrt{\epsilon_r - \sin^2\Theta}}{\cos\Theta + \sqrt{\epsilon_r - \sin^2\Theta}}$$

Odboj vodoravne polarizacije (HP ali TE)



Prestopni pogoji

(1) $H_{Vy}+H_{Oy}=H_{Ly}$

(2) $E_{Vz}+E_{Oz}=E_{Lz}$

(3) $D_{Vx}+D_{Ox}=D_{Lx}$

Odboj

$\Theta_O=\Theta_V$

Odbojnost

$$\Gamma_{VP}=\frac{E_O}{E_V}$$

$$(1)\quad \frac{E_V+E_O}{Z_0}=\frac{E_L}{Z}$$

$$(2)\quad (E_V-E_O)\cos\Theta_V=E_L\cos\Theta_L$$

$$(1-\Gamma_{VP})\frac{\cos\Theta_V}{Z}=(1+\Gamma_{VP})\frac{\cos\Theta_L}{Z_0}$$

$$\Gamma_{VP}=\frac{Z_0\cos\Theta_V-Z\cos\Theta_L}{Z_0\cos\Theta_V+Z\cos\Theta_L}$$

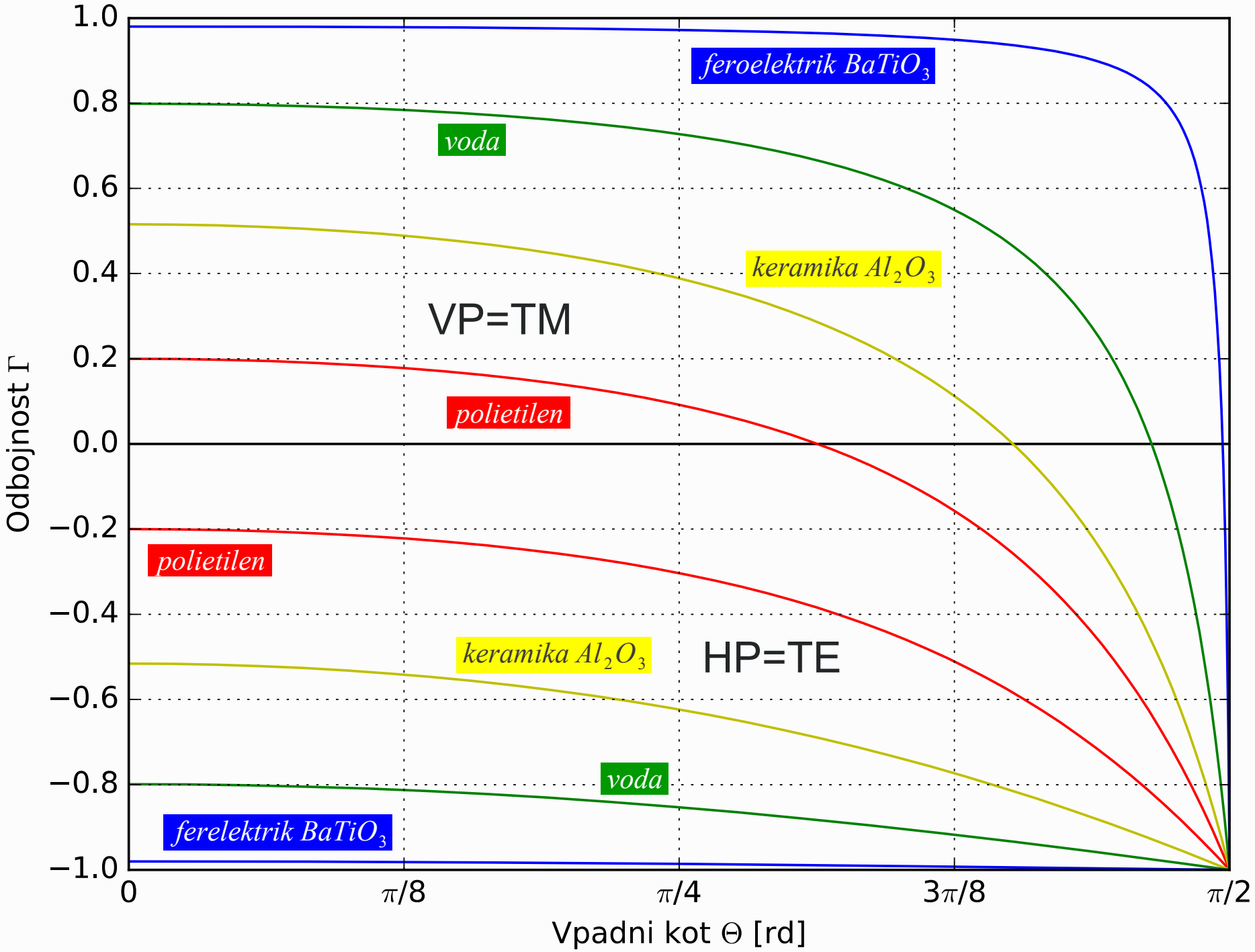
Lom $\cos\Theta_L=\sqrt{1-\left(\frac{\sin\Theta_V}{n}\right)^2}$

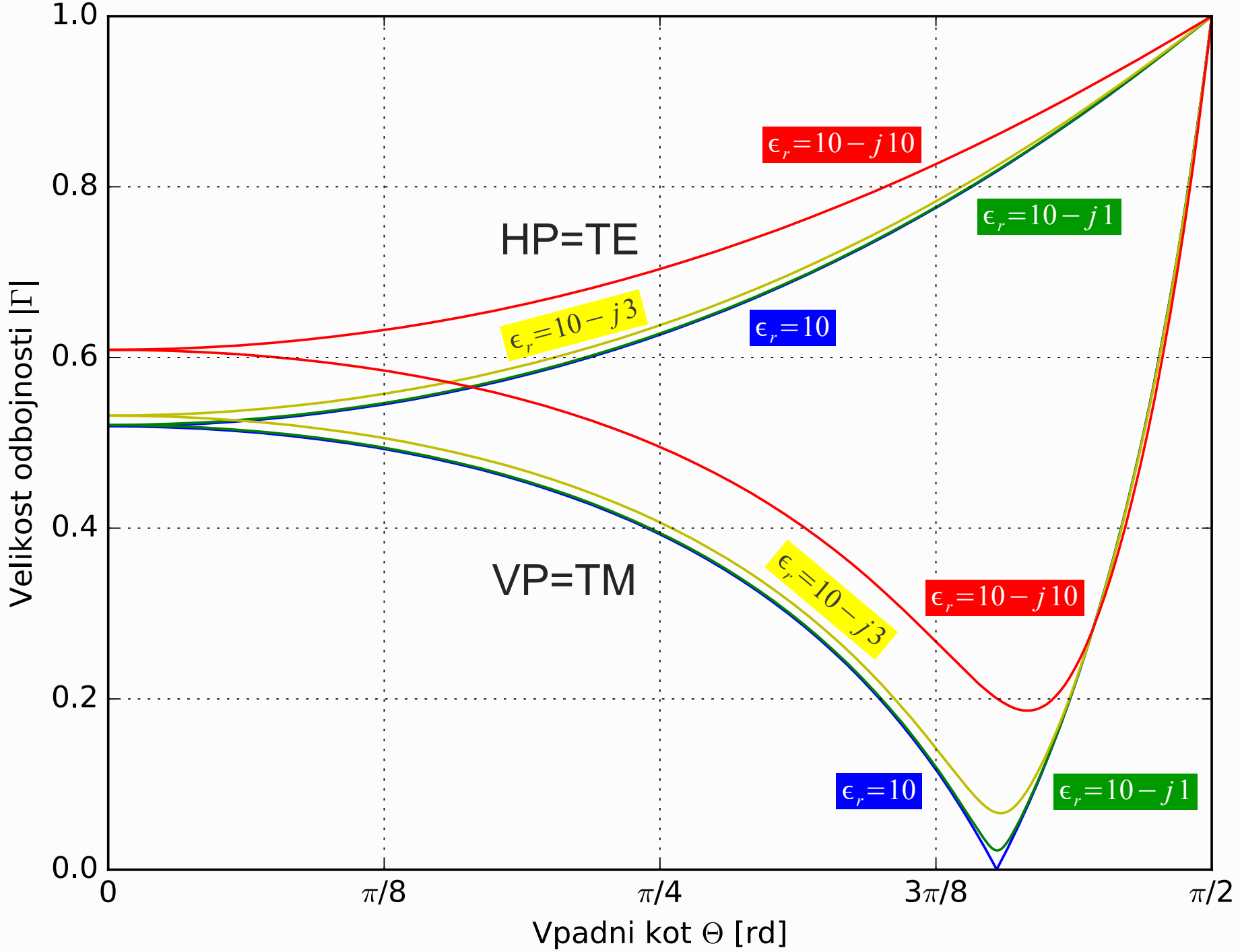
Dielektrik $\mu_r=1 \quad n=\sqrt{\epsilon_r}$

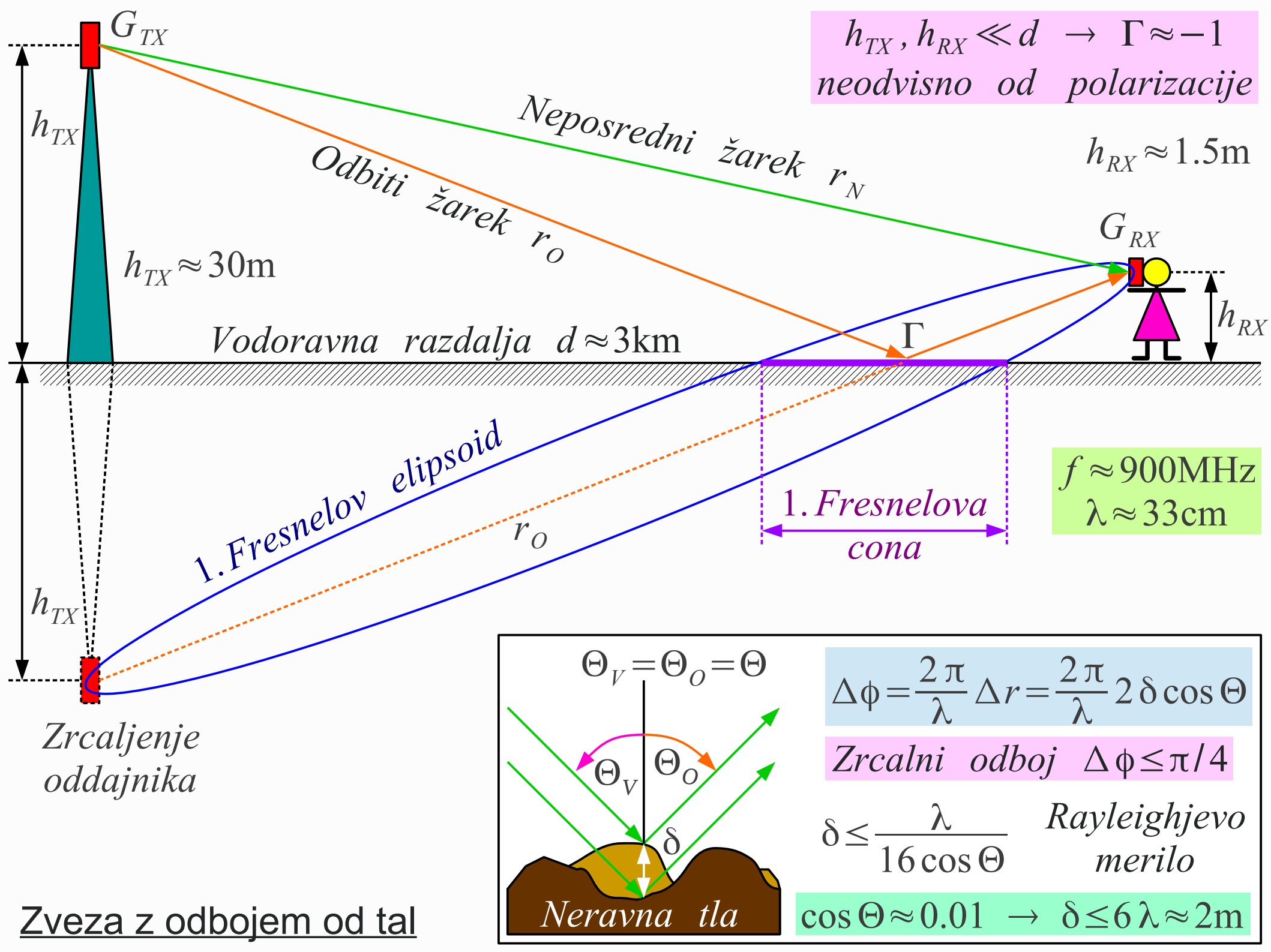
$\Theta=\Theta_V$

$$\Gamma_{VP}=\frac{\epsilon_r\cos\Theta-\sqrt{\epsilon_r-\sin^2\Theta}}{\epsilon_r\cos\Theta+\sqrt{\epsilon_r-\sin^2\Theta}}$$

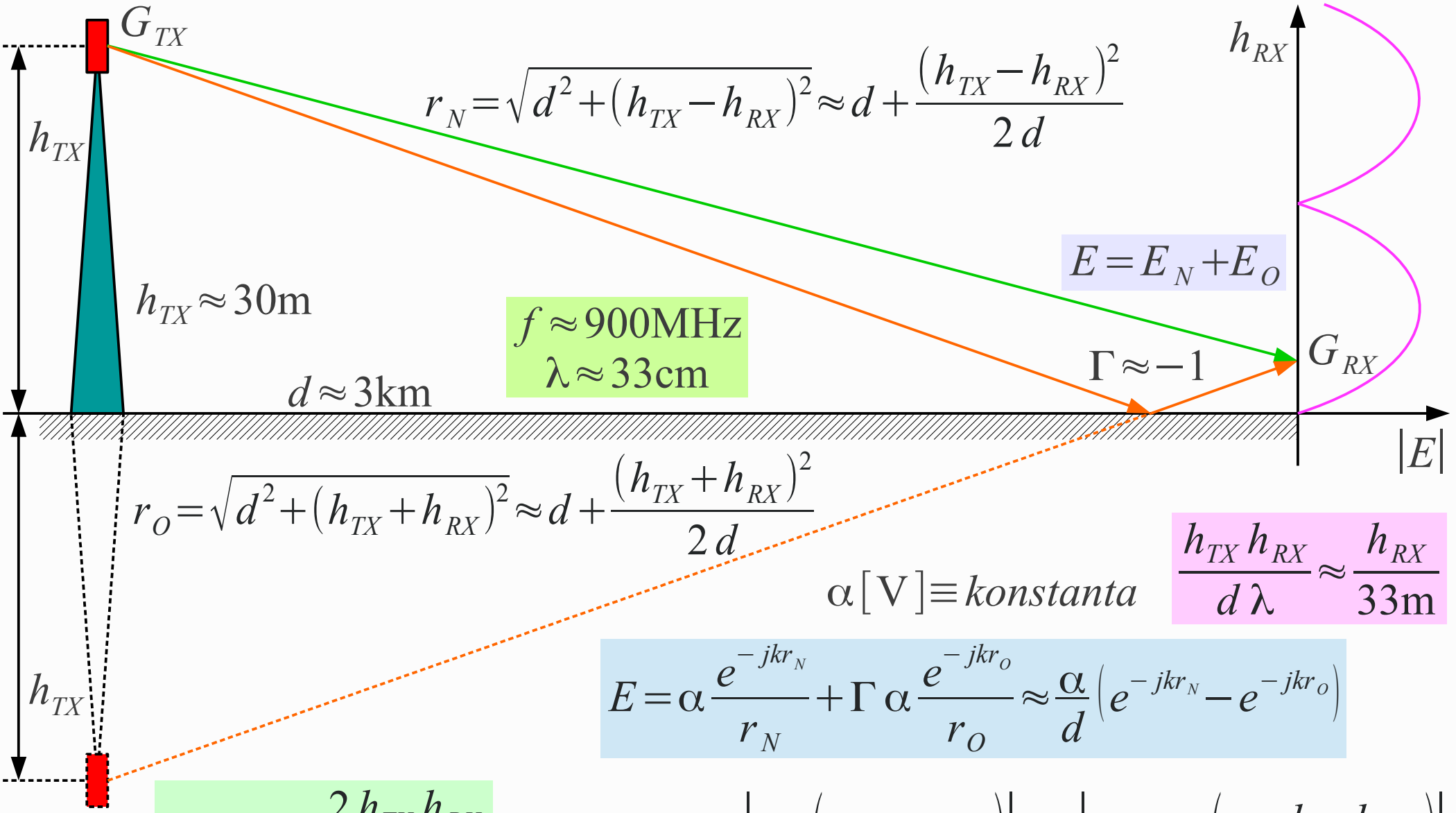
<u>Odboj pokončne polarizacije (VP ali TM)</u>


Dielektrik ϵ_r=2.25($polietilen$),9.8(Al_2O_3),80($voda$),10000($BaTiO_3$)
feroelektrik $BaTiO_3$
voda
keramika Al_2O_3
VP=TM
polietilen
polietilen
keramika Al_2O_3
HP=TE
voda
ferelektrik $BaTiO_3$
Odbojnost Γ
Vpadni kot Θ [rd]
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
0
π/8
π/4
3π/8
π/2


Dielektrik z izgubami ϵ_r=10,10-j1,10-j3,10-j10
1.0
0.8
0.6
0.4
0.2
0.0
Velikost odbojnosti |Γ|
HP=TE
VP=TM
$\epsilon_r = 10 - j\,10$
$\epsilon_r = 10 - j\,1$
$\epsilon_r = 10 - j\,3$
$\epsilon_r = 10$
$\epsilon_r = 10 - j\,10$
$\epsilon_r = 10 - j\,3$
$\epsilon_r = 10$
$\epsilon_r = 10 - j\,1$
0
π/8
π/4
3π/8
π/2
Vpadni kot Θ [rd]

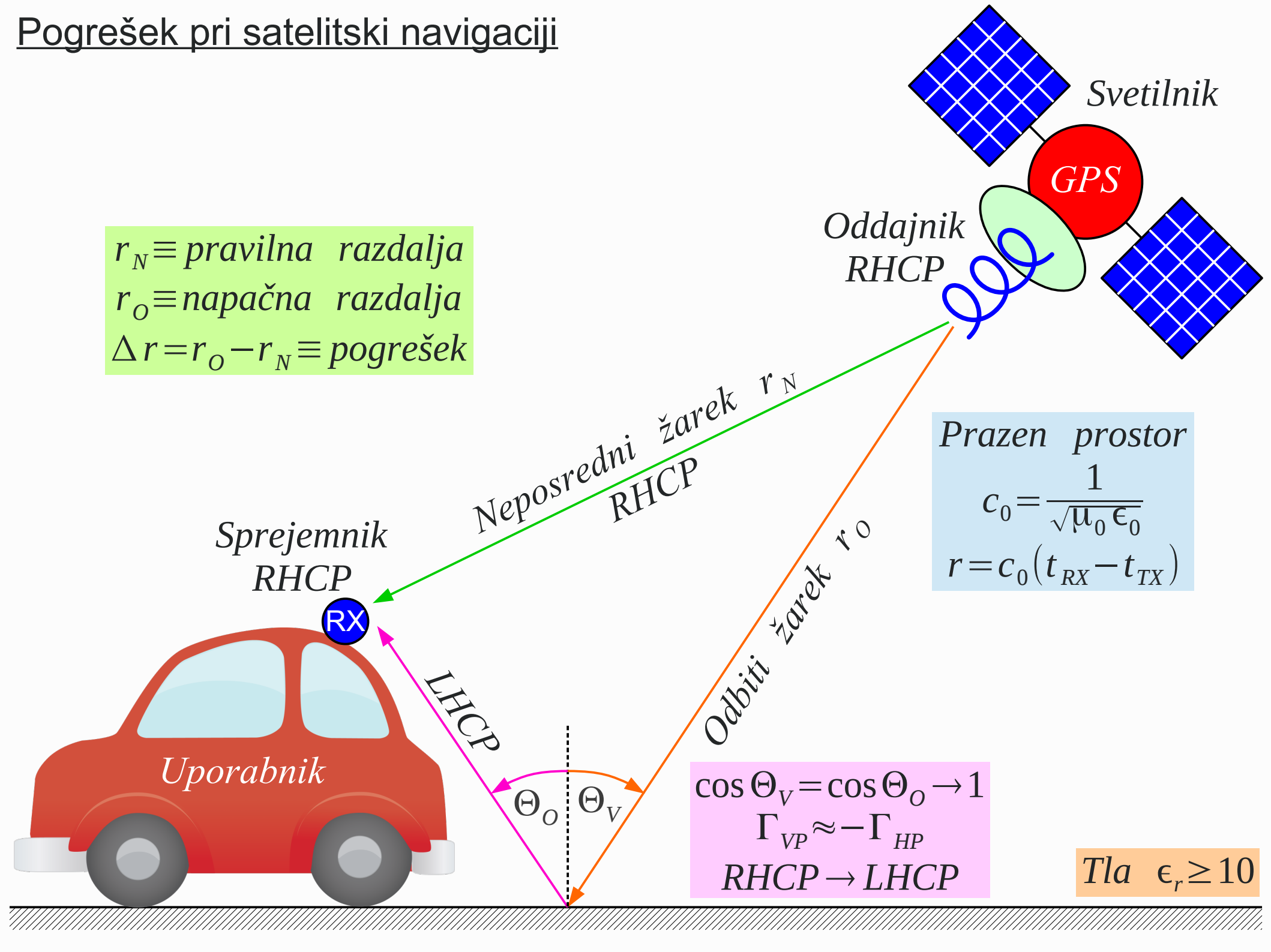


Zveza z odbojem od tal



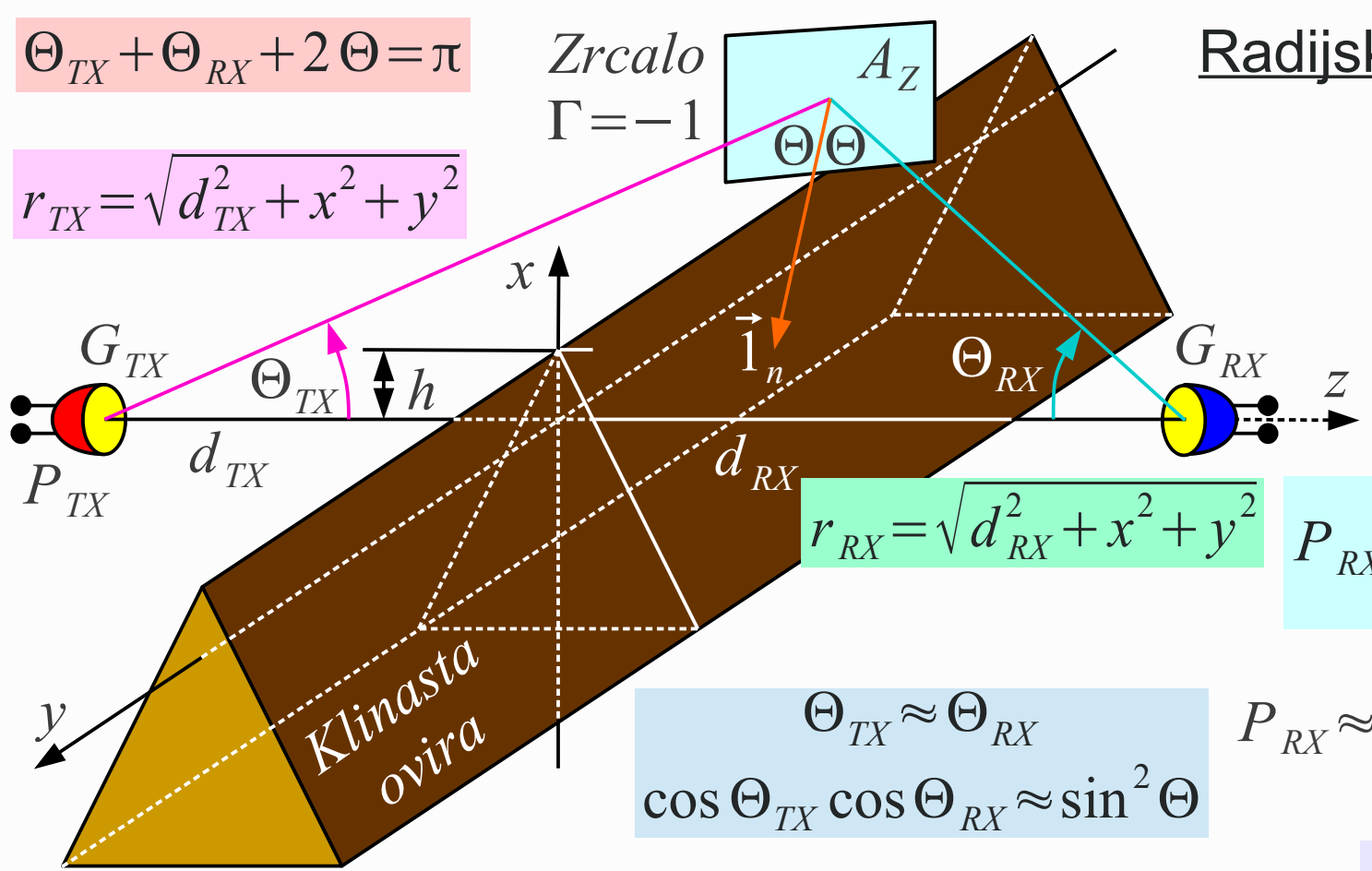
Interferenca odboja od tal

Pogrešek pri satelitski navigaciji



Radijska zveza preko zrcala

$$\Theta_{TX}+\Theta_{RX}+2\Theta=\pi$$



$$P_Z=\frac{P_{TX}G_{TX}A_Z\cos\Theta}{4\pi r_{TX}^2}$$

$$G_Z=\frac{4\pi}{\lambda^2}A_Z\cos\Theta$$

$$P_{RX}=P_Z G_Z G_{RX}\left(\frac{\lambda}{4\pi r_{RX}}\right)^2$$

$$\Theta_{TX}\approx\Theta_{RX}$$
$$\cos\Theta_{TX}\cos\Theta_{RX}\approx\sin^2\Theta$$

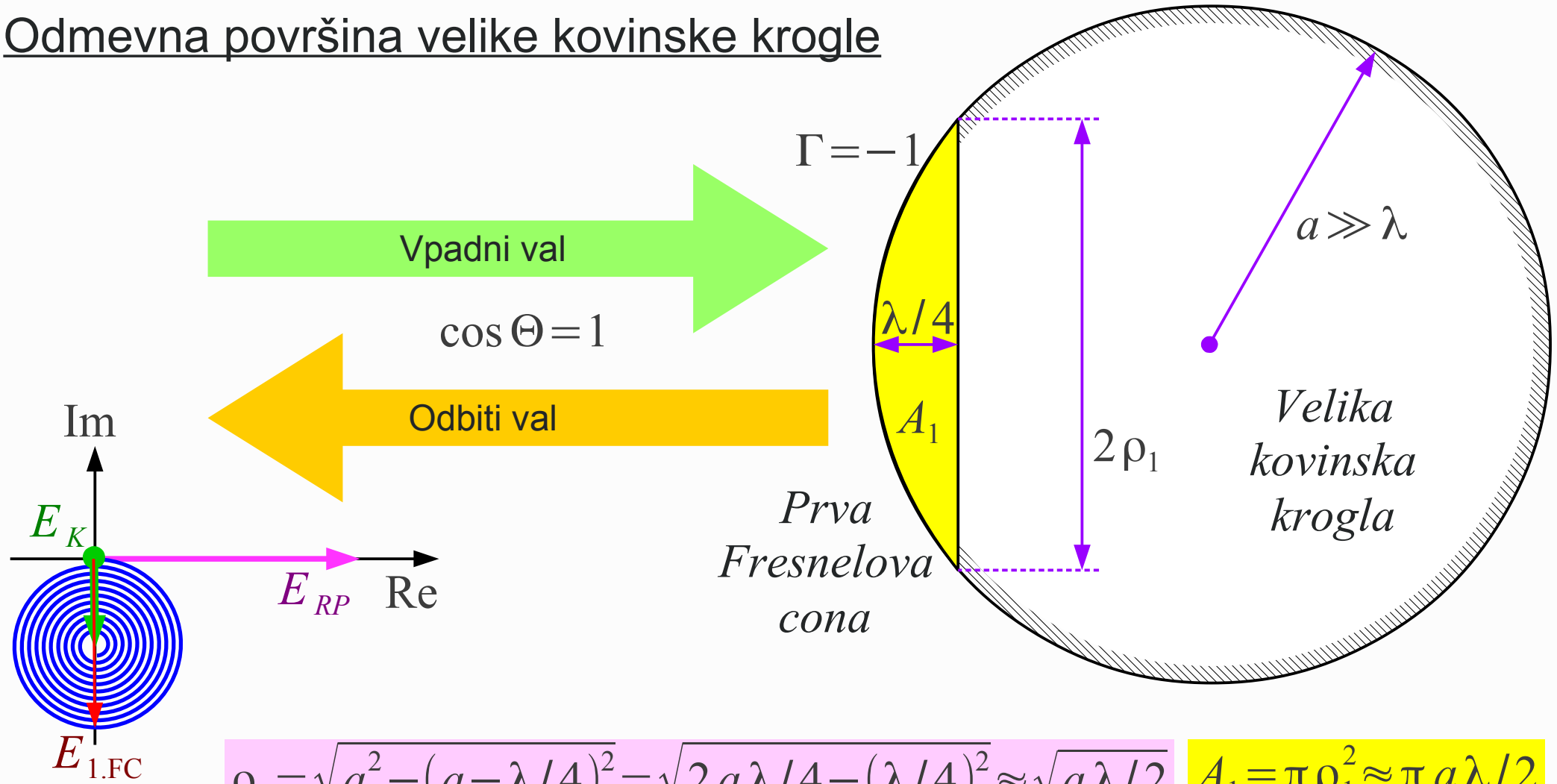
$$P_{RX}\approx\frac{P_{TX}G_{TX}G_{RX}}{(4\pi r_{TX}r_{RX})^2}A_Z^2\cos^2\Theta$$

$$\sigma=G_Z A_Z\cos\Theta=\frac{4\pi}{\lambda^2}A_Z^2\cos^2\Theta\equiv odmevna\quad površina$$

$$P_{RX}\approx\frac{P_{TX}G_{TX}G_{RX}\lambda^2}{(4\pi)^3 r_{TX}^2 r_{RX}^2}\sigma$$

Primerjava	Smer	Odmevna površina	Pogoji uporabe
Uklanjalnik	$\Theta_{TX}\neq\Theta_{RX}$	$\sigma=\frac{4\pi}{\lambda^2}A_U^2\cos\Theta_{TX}\cos\Theta_{RX}/\pi^2$	$x, y \ll d_{TX}, d_{RX}$
Zrcalo	$\Theta_V=\Theta_O=\Theta$	$\sigma=\frac{4\pi}{\lambda^2}A_Z^2\cos^2\Theta$	$x, y \approx d_{TX}, d_{RX}$

Odmevna površina velike kovinske krogle

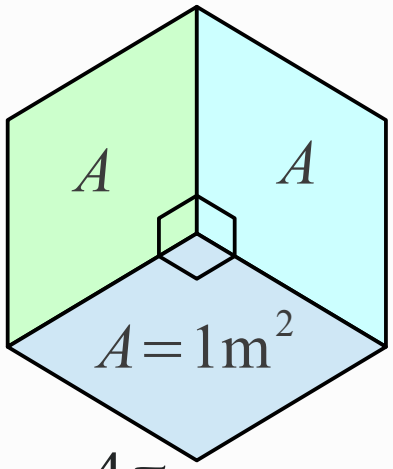


$$\rho_1 = \sqrt{a^2 - (a - \lambda/4)^2} = \sqrt{2a\lambda/4 - (\lambda/4)^2} \approx \sqrt{a\lambda/2} \qquad A_1 = \pi\rho_1^2 \approx \pi a\lambda/2$$

$$\textit{Ravna plošča } A_1 \rightarrow \sigma_{RP} = \frac{4\pi}{\lambda^2} A_1^2 \approx \frac{4\pi}{\lambda^2}(\pi a\lambda/2)^2 = \pi^3 a^2$$

$$\textit{Prva Fresnelova cona } A_1 \rightarrow E_{1.FC} = -j\left(\frac{2}{\pi}\right) E_{RP} \rightarrow \sigma_{1.FC} = \left(\frac{2}{\pi}\right)^2 \sigma_{RP} \approx 4\pi a^2$$

$$\textit{Velika kovinska krogla} \rightarrow E_K = \frac{1}{2} E_{1.FC} \rightarrow \sigma_K = \frac{1}{4}\sigma_{1.FC} \approx \pi a^2$$



Trirobnik

$$\sigma \approx \frac{4\pi}{\lambda^2} A^2 \approx 1257\,\mathrm{m}^2$$

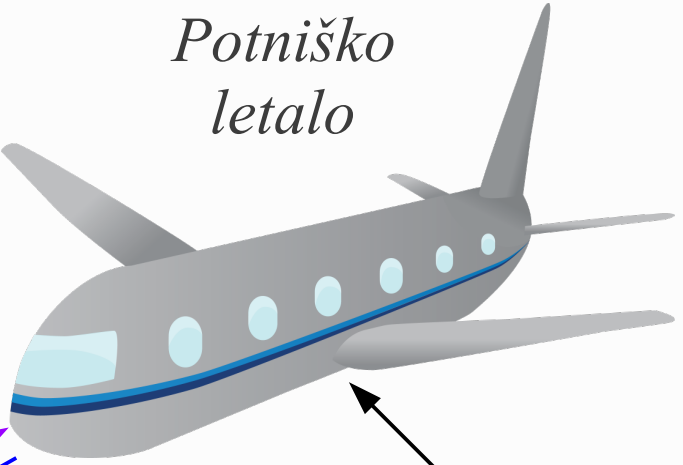
$\sigma \approx 0.1\,\mathrm{m}^2$

Vojaško letalo

$|\Gamma| \approx 0.1$

$\sigma \approx 0.01\,\mathrm{m}^2$

$\sigma \approx 30\,\mathrm{m}^2$



Potniško letalo

$\sigma \approx 3\,\mathrm{m}^2$

$\sigma \approx 30\,\mathrm{m}^2$

$f \approx 3\,\mathrm{GHz}$
$\lambda \approx 10\,\mathrm{cm}$

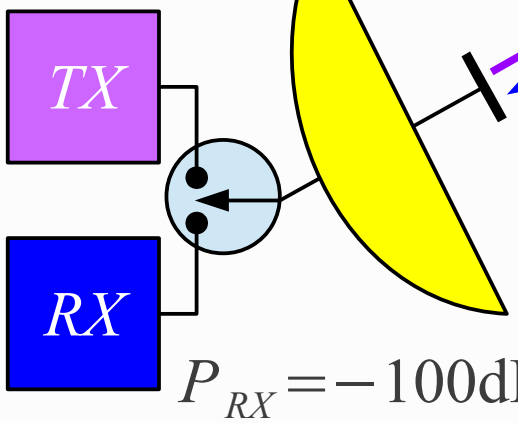
$P_{TX} = 100\,\mathrm{kW} = 10^5\,\mathrm{W}$
$(pulzno)$

t_{pulza}

$r = c_0 \Delta t / 2$

$$P_{RX} = \frac{P_{TX} G^2 \lambda^2}{(4\pi)^3 r^4} \sigma$$

$$r = \sqrt[4]{\frac{P_{TX} G^2 \lambda^2}{P_{RX} (4\pi)^3} \sigma}$$



$G = 40\,\mathrm{dBi} = 10^4$

$$A_{eff} = \frac{\lambda^2}{4\pi} G \approx 8\,\mathrm{m}^2$$

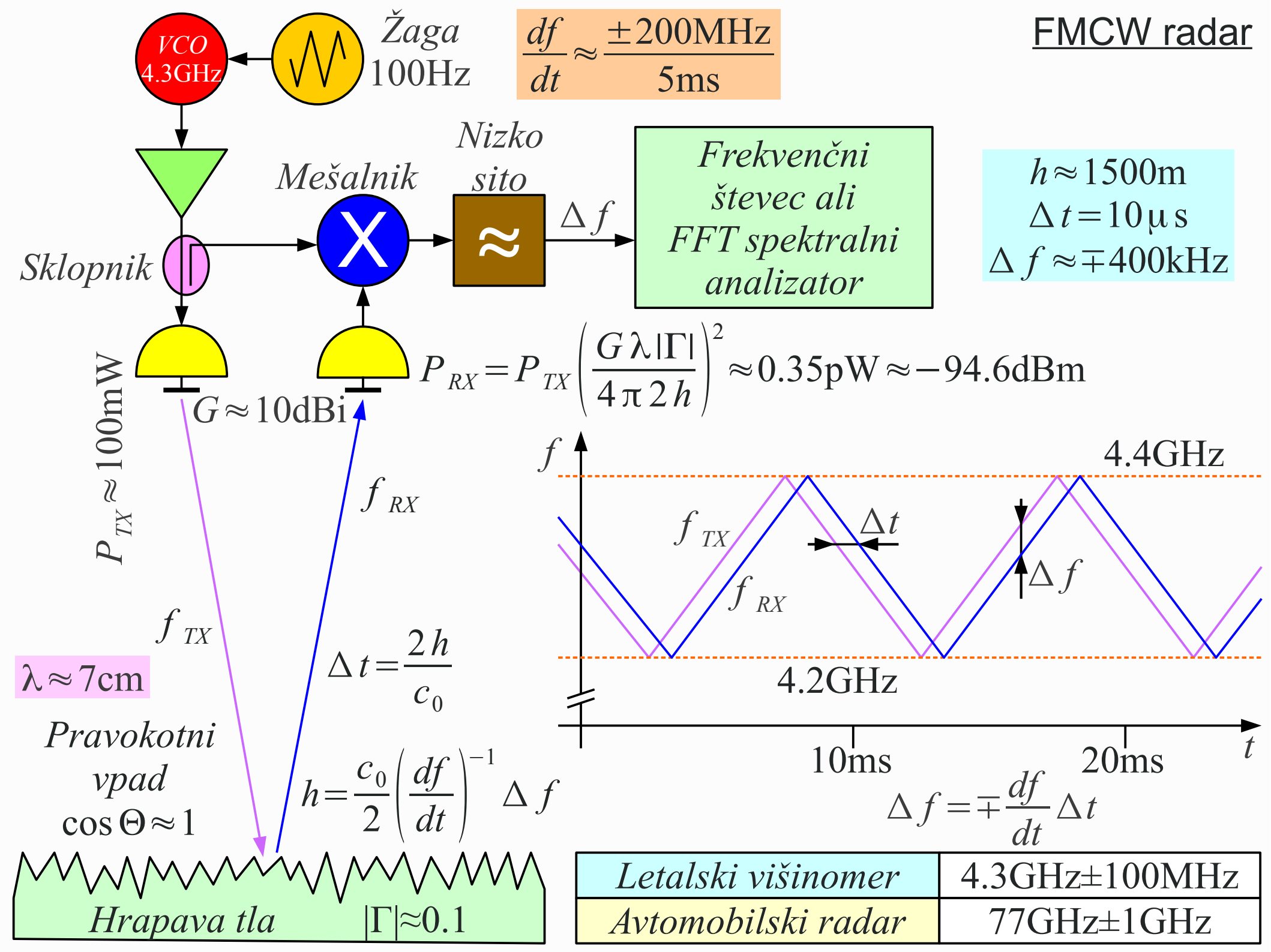
$P_{RX} = -100\,\mathrm{dBm} = 10^{-13}\,\mathrm{W}$

$t_{pulza} \approx 3\,\mu\mathrm{s} \rightarrow \Delta r \approx 450\,\mathrm{m}$
$T_{ponovi} \approx 4\,\mathrm{ms} \rightarrow r < 600\,\mathrm{km}$

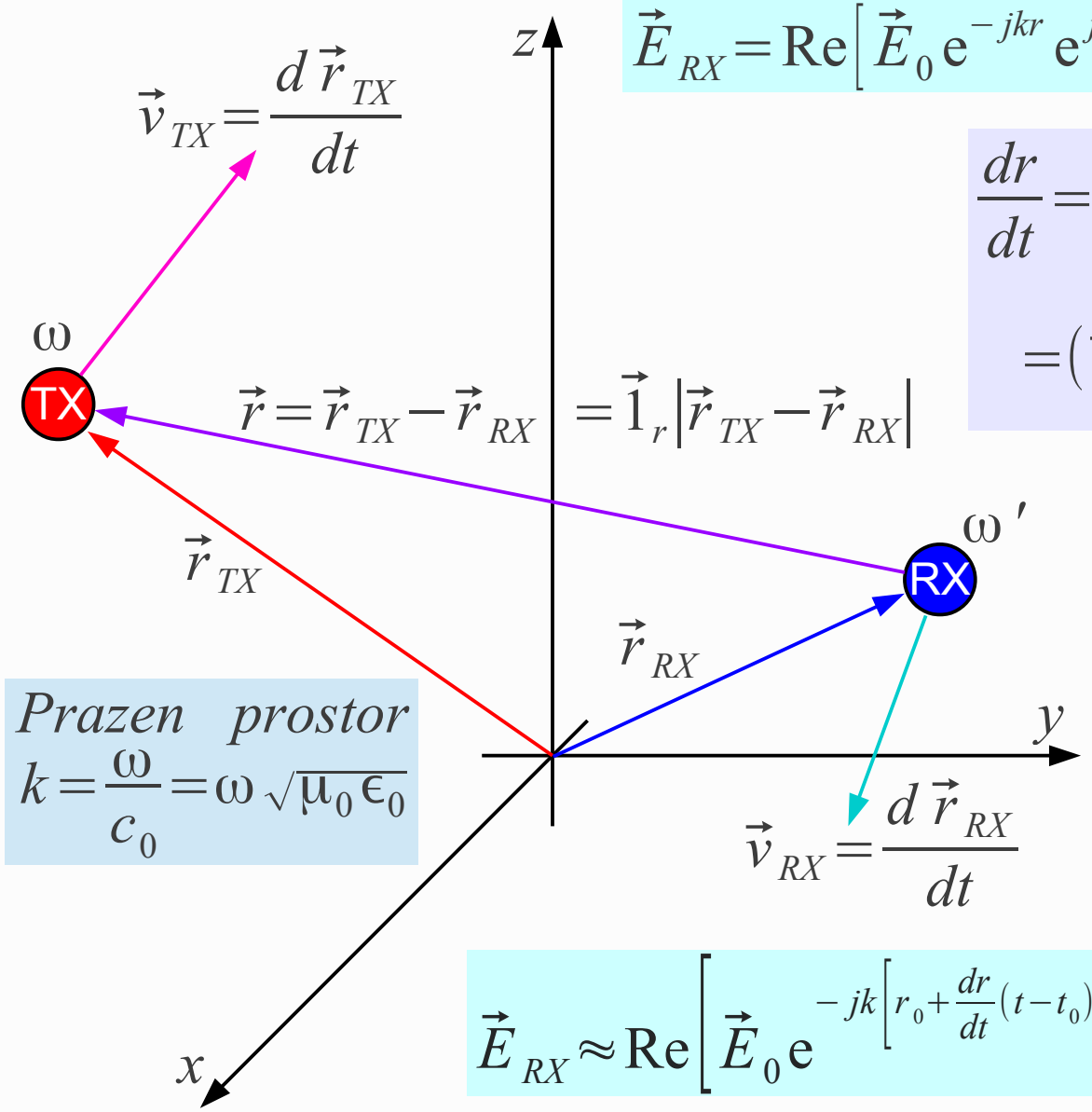
Cilj	Odmevna površina σ	Domet r
Trirobnik	$1257\,\mathrm{m}^2$	892km
Potniško letalo	$30\,\mathrm{m}^2$	351km
	$3\,\mathrm{m}^2$	197km
Vojaško letalo	$0.1\,\mathrm{m}^2$	84km
	$0.01\,\mathrm{m}^2$	47km

Domet letalskega radarja

FMCW radar



Letalski višinomer	4.3GHz±100MHz
Avtomobilski radar	77GHz±1GHz



$$\vec{E}_{RX}=\mathrm{Re}\left[\vec{E}_0\,\mathrm{e}^{-jkr}\,\mathrm{e}^{j\omega t}\right] \qquad \vec{E}_0\equiv konstanta \qquad r=\left|\vec{r}_{TX}-\vec{r}_{RX}\right|$$

$$\frac{dr}{dt}=\frac{d}{dt}\left|\vec{r}_{TX}-\vec{r}_{RX}\right|=\frac{d}{dt}\left[\vec{1}_r\cdot\left(\vec{r}_{TX}-\vec{r}_{RX}\right)\right]=$$

$$=\left(\vec{r}_{TX}-\vec{r}_{RX}\right)\cdot\frac{d\,\vec{1}_r}{dt}+\vec{1}_r\cdot\frac{d}{dt}\left(\vec{r}_{TX}-\vec{r}_{RX}\right)$$

$$\vec{1}_r\perp\frac{d\,\vec{1}_r}{dt}\;\rightarrow\;\left(\vec{r}_{TX}-\vec{r}_{RX}\right)\cdot\frac{d\,\vec{1}_r}{dt}=0$$

$$\frac{dr}{dt}=\vec{1}_r\cdot\left(\vec{v}_{TX}-\vec{v}_{RX}\right)=\vec{1}_r\cdot\Delta\vec{v}=\Delta v_r$$

Prazen prostor

$$k=\frac{\omega}{c_0}=\omega\sqrt{\mu_0\epsilon_0}$$

$$r\approx r_0+\frac{dr}{dt}\left(t-t_0\right)+\ldots$$

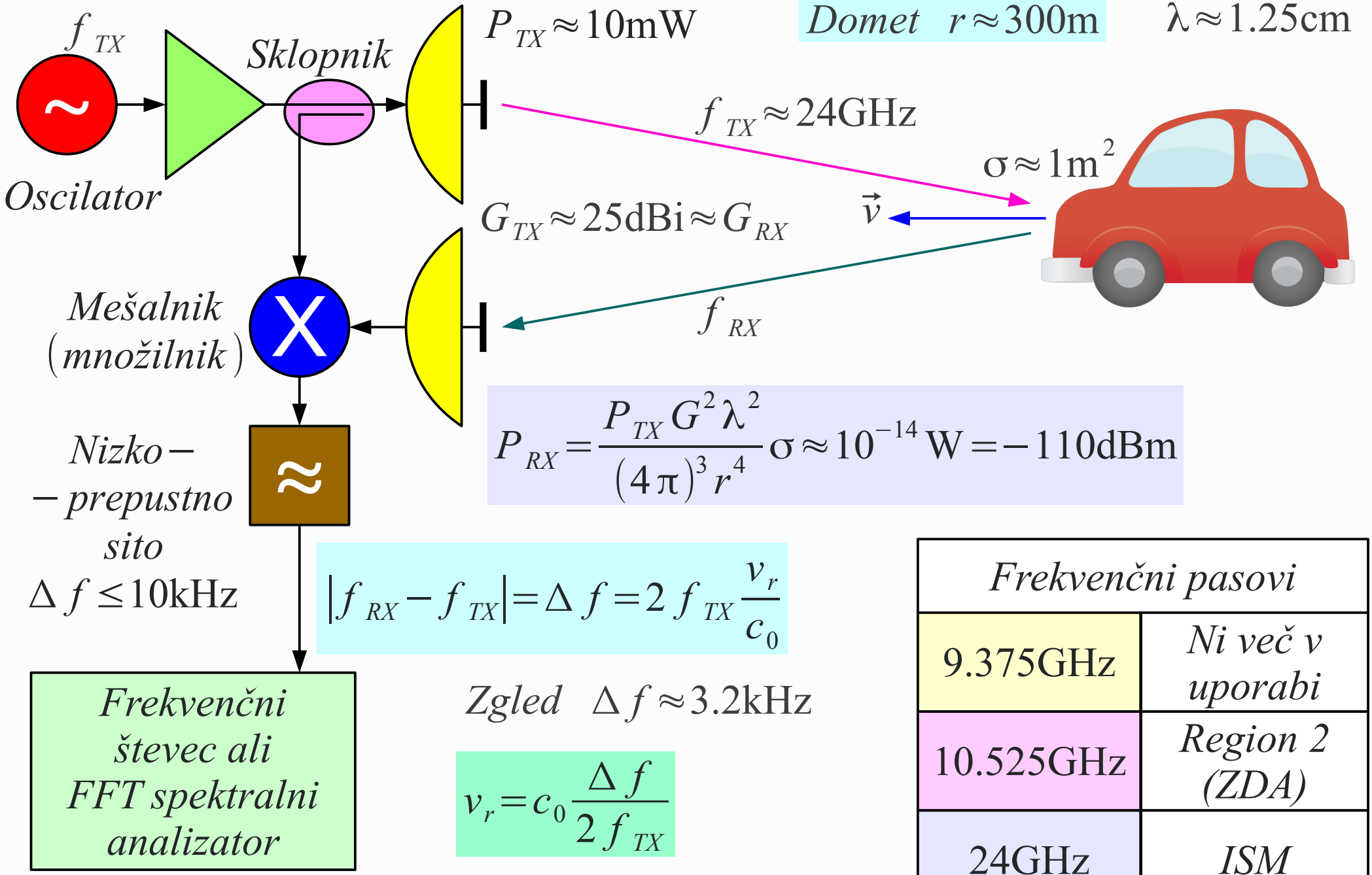
$$\vec{E}_{RX}\approx\mathrm{Re}\left[\vec{E}_0\,\mathrm{e}^{-jk\left[r_0+\frac{dr}{dt}\left(t-t_0\right)\right]}\mathrm{e}^{j\omega t}\right]=\mathrm{Re}\left[\vec{E}_0\,\mathrm{e}^{-jk\left(r_0-\frac{dr}{dt}t_0\right)}\mathrm{e}^{j\left(\omega-k\frac{dr}{dt}\right)t}\right]$$

Christian A. Doppler 1842

$$\omega'\approx\omega-k\frac{dr}{dt}=\omega-\frac{\omega}{c_0}\frac{dr}{dt}$$

$$\Delta\omega=\omega'-\omega\approx-\frac{\omega}{c_0}\frac{dr}{dt}=-\frac{\omega}{c_0}\frac{\left(\vec{r}_{TX}-\vec{r}_{RX}\right)\cdot\left(\vec{v}_{TX}-\vec{v}_{RX}\right)}{\left|\vec{r}_{TX}-\vec{r}_{RX}\right|}$$

Dopplerjev pomik



Frekvenčni pasovi	
9.375GHz	Ni več v uporabi
10.525GHz	Region 2 (ZDA)
24GHz	ISM
34GHz	Licenciran

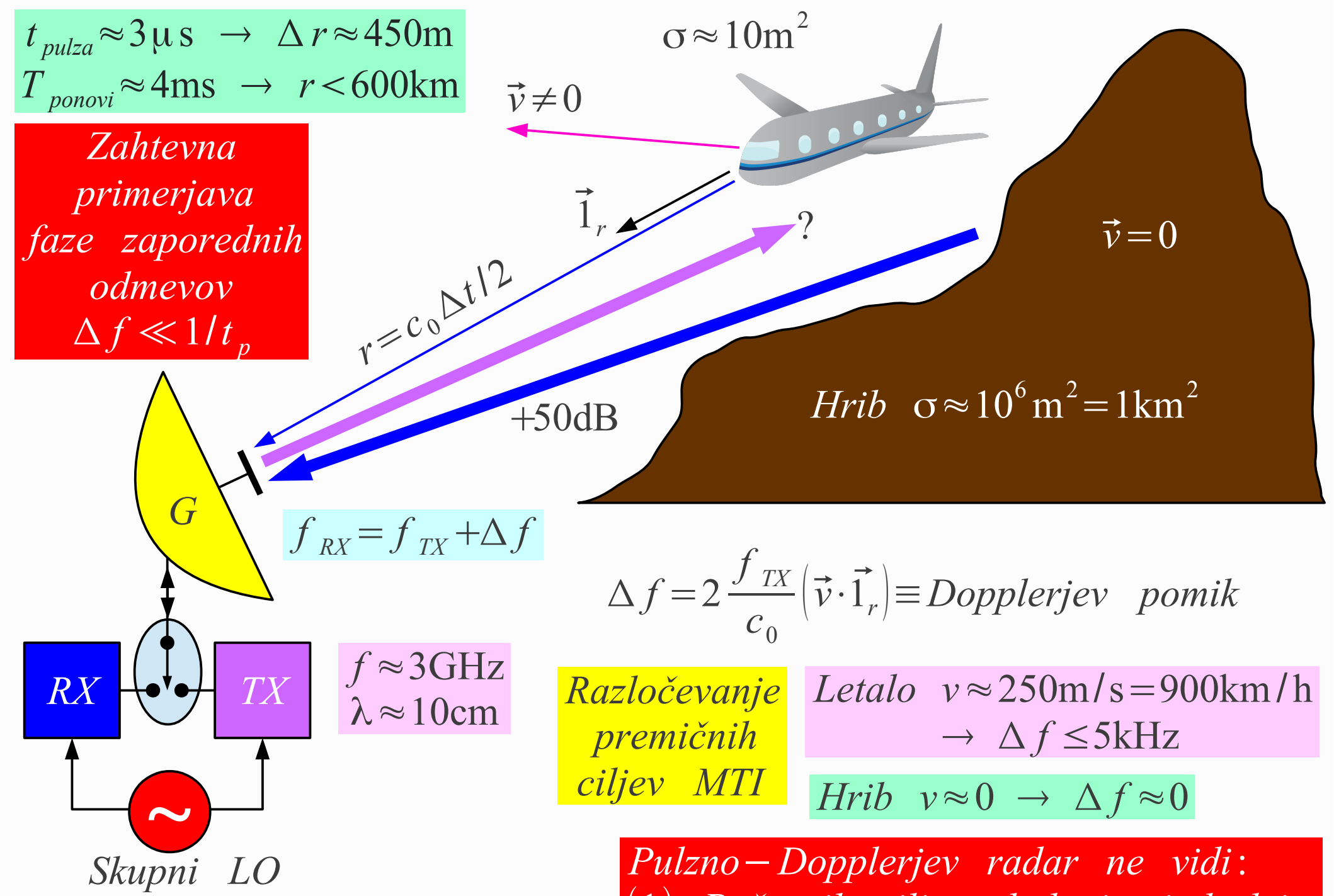
CW Dopplerjev radar

$t_{pulza} \approx 3\,\mu s \;\rightarrow\; \Delta r \approx 450\,m$

$T_{ponovi} \approx 4\,ms \;\rightarrow\; r < 600\,km$

Zahtevna primerjava faze zaporednih odmevov

$\Delta f \ll 1/t_p$



$f_{RX} = f_{TX} + \Delta f$

$$\Delta f = 2\frac{f_{TX}}{c_0}\left(\vec{v}\cdot\vec{1}_r\right) \equiv Dopplerjev\ \ pomik$$

$f \approx 3\,GHz$

$\lambda \approx 10\,cm$

Razločevanje premičnih ciljev MTI

Letalo $v \approx 250\,m/s = 900\,km/h \;\rightarrow\; \Delta f \le 5\,kHz$

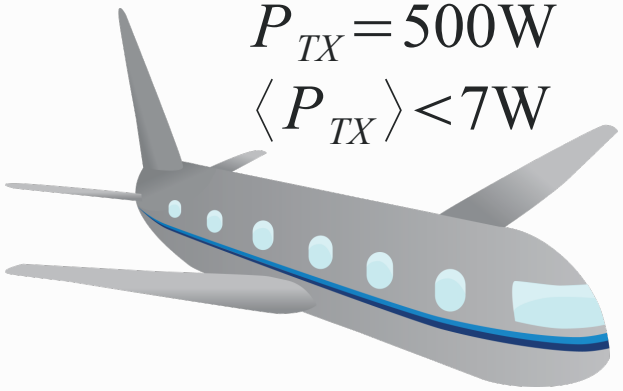
Hrib $v \approx 0 \;\rightarrow\; \Delta f \approx 0$

Pulzno – Dopplerjev radar ne vidi:

(1) *Počasnih ciljev: baloni, jadralci...*

(2) *Tangencialnih ciljev:* $\vec{v} \perp \vec{1}_r$

Pulzno-Dopplerjev radar

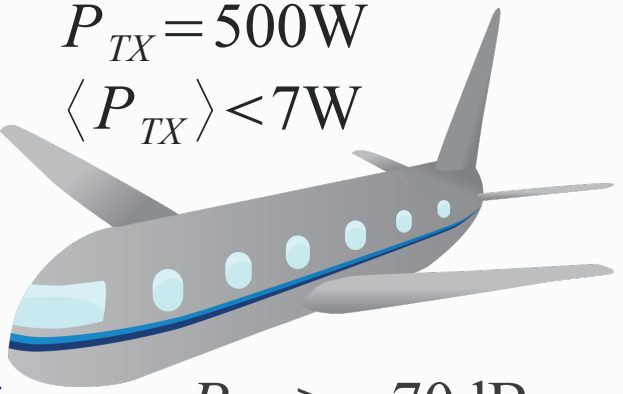


$P_{TX}=500\text{W}$
$\langle P_{TX}\rangle<7\text{W}$

TCAS

Vprašanje 1030MHz

Odgovor 1090MHz



$P_{TX}=500\text{W}$
$\langle P_{TX}\rangle<7\text{W}$

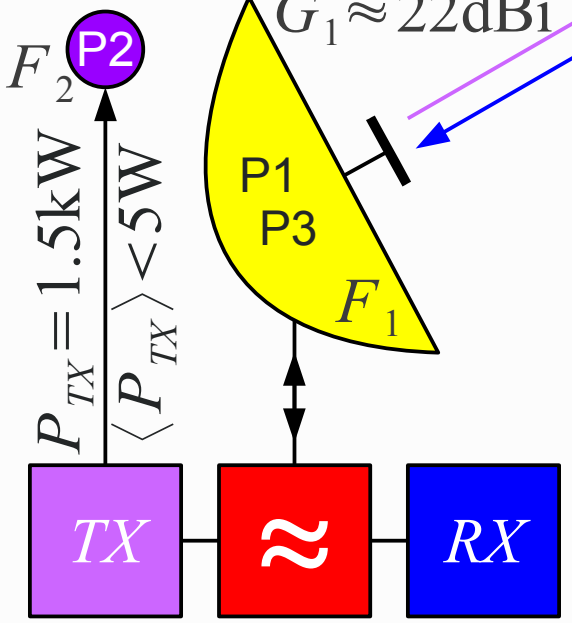
$P_{RX}\geq-70\text{dBm}$

Vprašanja 1030MHz:
Mode „A“ $t_3-t_1=8\mu\text{s}$
Mode „C“ $t_3-t_1=21\mu\text{s}$
Mode „S“ 56bit/112bit
4Mbps BPSK

Vprašanje 1030MHz

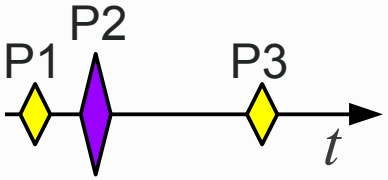
Odgovor 1090MHz

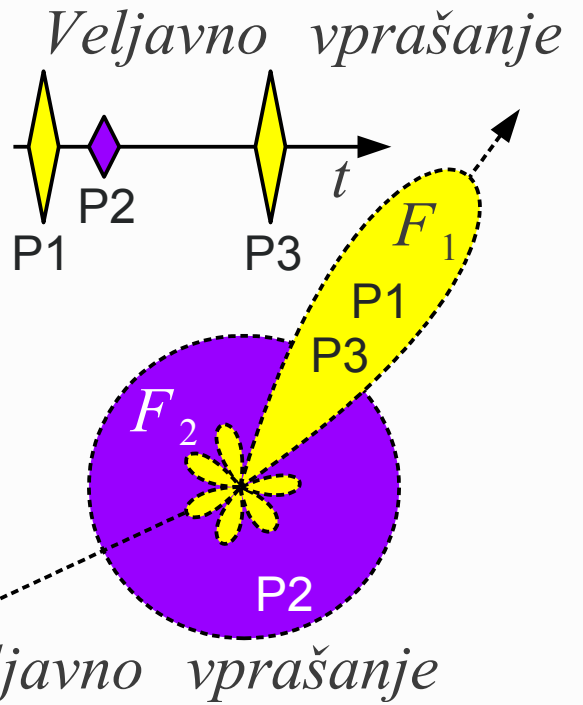
TCAS ≡ Traffic-alert Collision Avoidance System
TCAS-1: Traffic Advisory C/S
TCAS-2: Resolution Advisory S



Odgovori 1090MHz:
Mode „A“ koda letala 15bit
Mode „C“ višina letala 13bit
Mode „S“ 56bit/112bit
1Mbps Manchester/ASK

$t_2-t_1=2\mu\text{s}$





Sekundarni radar (IFF)