Кафедра електроніки, робототехніки і технологій моніторингу та інтернету речей
Факультет аеронавігації, електроніки та телекомунікацій (ФАЕТ)

ЕРМІТ

Електронні системи

Electronic Systems

Lecture #13

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Орієнтовний тематичний план лекцій

Основи теорії систем, сигнали і первинні перетворювачі електронних систем

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Електронні системи локації

1. Основні терміни, принцип дії, класифікація та застосування. 2
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7. Вимірювання кутових координат. 2
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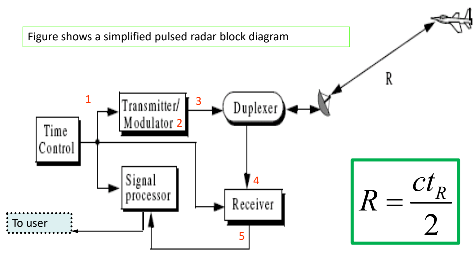
PULSED RADAR

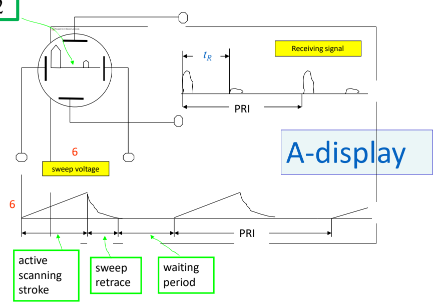
Figure shows a simplified pulsed radar block diagram



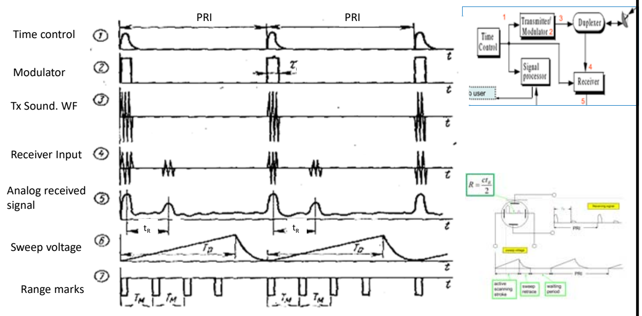
$$R = \frac{ct_R}{2}$$

$$R = \frac{ct_R}{2}$$

How to measure short time interval?



Waveforms at different points of radar diagram



Train of pulses

$R = \frac{ct_R}{2}$ $f_r = \frac{1}{PRI} = \frac{1}{T}$

In general, a pulsed radar transmits and receives a **train of pulses**.
The Inter Pulse Period (**IPP**) is **T**, and the pulse width is τ.
The **IPP** is often referred to as the Pulse Repetition Interval (**PRI**) or Pulse Repetition Period (**PRP**).
The inverse of the **PRI** is the **PRF**, which is denoted by f_r**=1/T**.

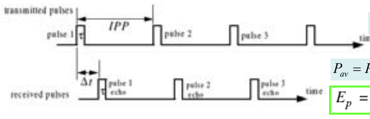
During each **PRI** the radar radiates energy only during shot time τ and listens for target returns for the rest of the **PRI**.
The radar transmitting duty cycle (factor) d_t is defined as the ratio $d_t=\tau/T$.

Inverse value is (**скважность**) **Q=T/τ** (**off-duty factor**).

The radar average transmitted power is $P_{av}=P_t d_t$, where P_t denotes the radar peak transmitted power.
The pulse energy is E_p.

$d_t = \tau / T$ Duty factor

$Q = T / \tau$ Off-duty factor



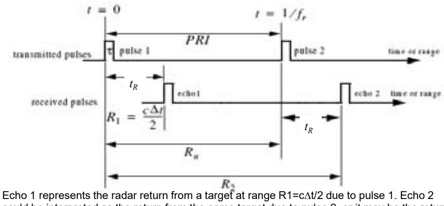
$P_{av} = P_t d_t = P_t \tau / T = P_t \tau f_r$

$E_p = P_t \tau = P_{av} T = P_{av} / f_r$

PULSED RADAR. Range Ambiguity

The range corresponding to the two-way time delay is known as the radar unambiguous range, R_u. Consider the case shown in Figure.

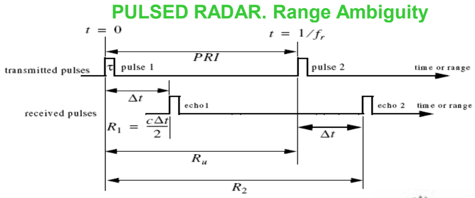
$t_R = \Delta t$



Echo 1 represents the radar return from a target at range R1=cΔt/2 due to pulse 1. Echo 2 could be interpreted as the return from the same target due to pulse 2, or it may be the return from a faraway target at range R2 due to pulse 1 again. In this case

$$R_2 = \frac{c\Delta t}{2} \quad or \quad R_2 = \frac{c(T + \Delta t)}{2}$$

PULSED RADAR. Range Ambiguity



$$R_2 = \frac{c\Delta t}{2} \quad or \quad R_2 = \frac{c(T + \Delta t)}{2}$$

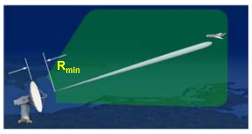
Clearly, range ambiguity is associated with echo 2. Therefore, once a pulse is transmitted the radar must wait a sufficient length of time so that returns from targets at maximum range R_{max} are back before the next pulse is emitted. It follows that the maximum unambiguous range must correspond to half of the PRI

$$T \geq \frac{2R_{max}}{C}$$

PULSED RADAR. Minimum range R_{min}

In case of sole antenna is used the value of Minimum Range of target detection is caused by the time duration, which is necessary to switch the antenna to receiver. Besides, the pulse duration also influences:

$$R_{min} = \frac{c(\tau_u + t_b)}{2}$$



τ_u — pulse length; t_b — time of inertia (deionization time in case of gas-discharge duplexer)

Radar Equation Description

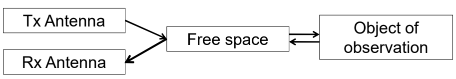
The radar equation gives the **received power** level, P_{Rx}, of a radar signal after it has reflected off a target at some distance, **R**, from the radar.
The equation shows the dependence of P_{Rx} on radar and target parameters such as transmit power, radar cross section, etc.
Finally it is used to calculate the maximum range of the radar R_{max} (energetic approach).

Радіолокаційне рівняння дає рівень потужності прийнятого сигналу P_{Rx} , відбитого від цілі на певній відстані, R, від радара.

Рівняння показує залежність P_{Rx} від параметрів радіолокатора і цілі, таких як потужність передавача, ефективна площа розсіяння цілі σ тощо.

Нарешті, це рівняння використовується для обчислення максимальної дальності дії радіолокатора R_{max} (енергетичний підхід).

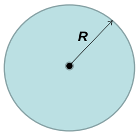
Radar Channel



Suppositions:
- Homogeneity of the Atmosphere;
- Absence of attenuation EM waves;
- Absence of the interferences;
- No influence of the Earth.

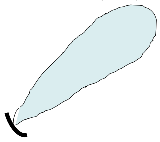
P_{Tx} - Tx power
G - Antenna gain
R - Range

Isotropic antenna (G=1)



$$\Pi_O = \frac{P_{Tx}}{4\pi R^2}$$

Directive antenna (G>1)



$$\Pi_O = \frac{P_{Tx} G}{4\pi R^2}$$

Reflective properties of an object

- Radar range in perfect channel depends on reflective properties of the object.
- It depends on size, shape, material, wavelength, direction of observation, etc.
- To estimate total influence of all factors, a special parameter is introduced – RCS of the object. **Ефективна площа розсіяння (ЕПР) об'єкту σ.**
- **Визначення ЕПР**

Reflecting properties of an object - RCS

- If RCS = σ , the object radiates power

$$P_{\text{Reflected}} = \Pi_O \sigma$$

- Then in receiving antenna at distance *R* from object, power density is created:

$$\Pi_{Rx} = \frac{P_{\text{Reflected}}}{4\pi R^2} = \frac{\Pi_O \sigma}{4\pi R^2}$$

- Substitute $\Pi_O = \frac{P_{Tx} G}{4\pi R^2}$

$$\Pi_{\text{Reflected}} = \frac{P_{Tx} G \sigma}{\left(4\pi R^2\right)^2}$$

$$P_{Rx} = \Pi_{\text{Reflected}} A_e$$

$$P_{Rx} = \frac{P_{Tx} G A_e \sigma}{(4\pi)^2 R^4}$$

From this, it is easy to define the range of operation of a radar system in free space

Maximum range R_{max}

- If P_{Rx}=$P_{threshold}$=S_{min}
- $P_{threshold}$ =S_{min}– threshold power – min power of the useful signal at the receiver input that provides required quality of system operation (detection probability, accuracy, etc.)

$$R_{\max} = \sqrt[4]{\frac{P_{Tx} G A_e \sigma}{(4\pi)^2 S_{\min}}}$$

In case single antenna (Tx and Rx)

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

$$R_{\max} = \sqrt[4]{\frac{P_{Tx} G^2 \lambda^2 \sigma}{(4\pi)^3 S_{\min}}}$$

$$R_{\max} = \sqrt[4]{\frac{P_{Tx} A_e^2 \sigma}{4\pi \lambda^2 S_{\min}}}$$

Decomposed Radar Equation

$$P_{Rx} = P_{Tx} G \cdot \frac{1}{4\pi R^2} \cdot \sigma_{Target} \cdot \frac{1}{4\pi R^2} \cdot \frac{\lambda^2 G}{4\pi}$$

Power from radar

Power density at target

Power reflected by target to the radar

Power density at radar

Power collected by radar antenna (i.e., power received)

Radar Equation

$$P_{Rx.} = \frac{P_{Tx} G^2 \lambda^2 \sigma}{(4\pi)^3 R^4}$$

A)Without losses
B)For concentrated targets

What is concentrated target?

Threshold power – Порогова потужність

- Radar equation serves for determination of range of operation in both basic modes: Detection and Measurement of parameters.
- Depending on the mode and features of the task different value of threshold power (sensitivity) is required.
- Радіолокаційне рівняння служить для визначення дальності роботи в обох основних режимах: Виявлення цілі та Вимірювання її параметрів.
- Залежно від режиму та особливостей завдання може бути необхідним потрібне різне значення порогової потужності (чутливості).

Influence of losses, conditions EMW propagation, etc.
Вплив втрат, особливостей поширення тощо

- Equation should be corrected according to real conditions

$$R_{max} = \sqrt[4]{\frac{P_{Tx} G \; A_e \sigma 10^{-0.2\alpha_{km-at} R_{max}}}{(4\pi)^2 \; P_{thresh} L}}$$

$$R_{max} = R_0 10^{-0,05\,\alpha_{km-at} R_{max}}$$

α_{km-at} [dB/km] – attenuation

Radar Equation without Losses

Restating P_{Rx} with ⍰ substituted for RCS:

$$P_{Rx.} = \frac{P_{Tx} G^2 \lambda^2 \sigma}{(4\pi)^3 R^4}$$

NO LOSSES WERE TAKEN INTO ACCOUNT !!!

There are losses that need to be considered also.
1. The loss due to multipath (ground / building reflections) can lessen your P_{Rx}.
2. Also, attenuation is given to the radiation by the atmosphere.
These losses are designated L_{MP} and L_A , respectively.

Influence of multi pass & atmospheric losses

These (dimensionless) losses lessen the effectiveness of P_{Rx}, thus they divide P_{Rx}:

$$P_{Rx.} = \frac{P_{Tx} G^2 \lambda^2 \sigma}{(4\pi)^3 R^4 L_{MP} L_A}$$

This is the theoretical signal power measured at the antenna terminals.

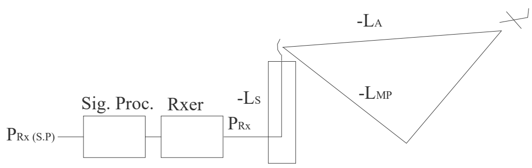
System Losses

3. If P_{Rx} is measured at the bottom of the tower (at the input of the receiver) then ***transmission line losses*** or system losses, L_S, need to be considered:

$$P_{Rx.} = \frac{P_{Tx} G^2 \lambda^2 \sigma}{(4\pi)^3 R^4 L_{MP} L_A L_S}$$

Losses

Losses (not considering space loss) and gains



In reality some more sources of losses exist, but we have considered the main losses.

Influence of interferences

Interfering power, P_I (not dimensionless) also needs to be considered. This lessens the effectiveness of your received power, thus it divides your P_{Rx}:

$$\frac{P_{Rx.}}{P_I} = \frac{P_{Tx} G^2 \lambda^2 \sigma}{(4\pi)^3 R^4 L_{MP} L_A L_S P_I}$$

This is also known as the Signal to Interference Ratio, or **S/I Ratio**

S I R

Thus:

$$\frac{S}{I} = \frac{P_{Rx.}}{P_I} = \frac{P_{Tx} G^2 \lambda^2 \sigma}{(4\pi)^3 R^4 L_{MP} L_A L_S P_I}$$

If we include in the definition of P_I any noise added by the receiver, then we can use that formula to give the power at the output of the Rxer:

$$\frac{S}{I} = \frac{P_{Rx.\,at\,S.P.\,input}}{P_I} = \frac{P_{Tx} G^2 \lambda^2 \sigma}{(4\pi)^3 R^4 L_{MP} L_A L_S P_I}$$

Process Gain

The signal processor will increase the S/I ratio, or give it gain. This gain (dimensionless) is known as process gain, G_P. It increases S/I, and, thus, it is multiplied by the right side:

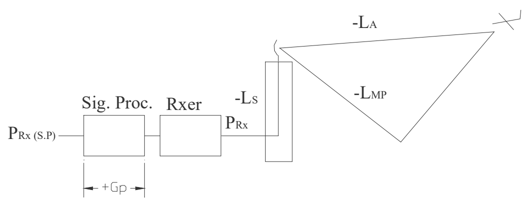
$$\frac{S}{I}_{At\,S.P\,Output} = \frac{P_{Tx} G^2 \lambda^2 \sigma \cdot G_P}{(4\pi)^3 R^4 L_{MP} L_A L_S P_I}$$

<u>This is the generic form of the radar equation.</u>

If gain is given to the S/N by the receiver, it will be captured in the process gain, G_P.

Losses and Gains

Losses (not considering space loss) and gains



Maximum Radar Range

For simplicity we use radar equation without losses:

$$P_{Rx} = \frac{P_{Tx} G^2 \lambda^2 \sigma}{(4\pi)^3 R^4}$$

P_{Rx} is the total power delivered to the radar signal processor.

Let $S_{min} = P_{Rx\,min}$ denote the minimum detectable signal power. It follows that the maximum radar range R_{max} is

$$R_{max} = \sqrt[4]{\frac{P_{Tx} G^2 \lambda^2 \sigma}{(4\pi)^3 S_{min}}}$$

This equation suggests that in order to double the radar maximum range, one must increase the peak transmitted power sixteen times; or equivalently, one must increase the effective aperture four times.

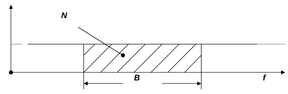
Noise

In practical situations the returned signals received by the radar will be corrupted with noise, which introduces unwanted voltages at all radar frequencies.

Noise is random in nature and can be described by its Power Spectral Density (**PSD**) function.

The noise power ***N*** is a function of the radar operating bandwidth ***B***.

$$N = Noise\ PSD \times B$$



The input noise power to a lossless antenna is $N_i = kT_e B$

k=1.38*10^{-23} [Joule/degree Kelvin] is Bolzman's constant;

T_e is the effective noise temperature in [degree Kelvin].

Receiver Sensitivity

It is always desirable that the minimum detectable signal (S_{min}) be greater than the noise power. The fidelity of a radar receiver is normally described by a figure of merit called the noise factor ***F***.

$$F = \frac{(SNR)_i}{(SNR)_o} = \frac{S_i/N_i}{S_o/N_o}$$

S_i is the input signal power, N_i is the input noise power, S_o and N_o are, respectively, the output signal and noise power.

Substituting and rearranging terms yield $S_i = kT_e BF(SNR)_o$

Thus, the minimum detectable signal power can be written as

$$S_{min} = kT_e BF(SNR)_{o_{min}} \qquad (SNR)_{o\,min} \equiv m_{discr}$$

$$R_{max} = \left(\frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 kT_e BF(SNR)_{o_{min}}}\right)^{1/4} \qquad (SNR)_o = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 kT_e BFR^4}$$

Radar Equation

Radar losses denoted as L reduce the overall SNR, and hence

$$L = L_A + L_{MP} + L_s + L_{others}$$

$$(SNR)_o = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 kT_e BFLR^4} \qquad R^4_{max} = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 kT_e FB(SNR)_{0\,min} L}$$

Although it may take on many different forms, this equation is what is widely known as the **Radar Equation**.

It is a common practice to perform calculations associated with the radar equation using decibel (**dB**) arithmetic

$$(X)_{dB} = 10 \log_{10}(X)$$

Radar Equation

$$R^4_{max} = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 kT_e FB(SNR)_{o\,min} L}$$

$P_N = kT_e FB$ *is power of noise*

$S_{min} = P_N (SNR)_{0\,min}$ *is sensitivity of receiver*

Reminder what is $(SNR)_{omin}$ – it is nothing but q_0

$$F = \frac{1}{2}\left[1 - \Phi(q_0)\right]$$

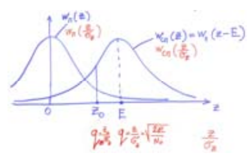
q_0 – *threshold* (relative threshold level)

q – *signal-to-noise ratio* $\quad q = \sqrt{\frac{2E}{N_0}}$

$$D = \frac{1}{2}\left[1 - \Phi(q_0 - q)\right]$$

$$q_0 = \frac{z_0}{\sigma_z} = \frac{\left(\frac{N_0}{2}\ln l_0 + \frac{E}{2}\right)}{\sqrt{\frac{N_0 E}{2}}} = \sqrt{\frac{N_0 E}{2}}\ln l_0 + \sqrt{\frac{N_0 E}{2}}$$

$$\sigma_z^2 = \frac{N_0 E}{2}$$



$$\Phi(\xi_0) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \exp\left(-\frac{\xi^2}{2}\right) d\xi$$ probability integral

Radar Equation

$$R_{\max}^4 = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 k T_e F B (SNR)_{0\min} L}$$

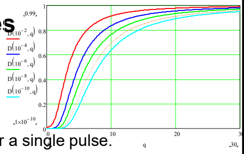
S_{min} - sensitivity

$P_N = kT_eFB$ *is power of noise*

$S_{\min} = P_N (SNR)_{0\min}$ *is sensitivity of receiver*

m_{discr}

Range version of detection curves

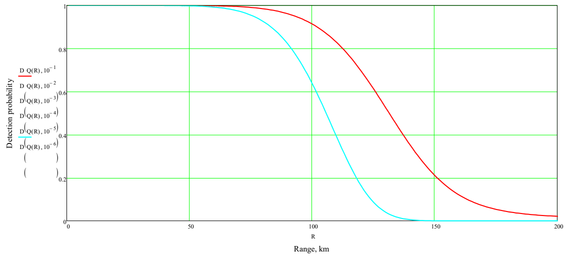


- *F* and *D* are related $D = F^{\left(1+\frac{q^2}{2}\right)^{-1}}$

where q is a parameter of detection, i.e. SNR for a single pulse.

- The farer the target the weaker the signal, i.e. $q = f(R)$
- For concentrated targets $E \propto R^{-4}$
- Expressing $q = f(R)$, one can come to range version of detection curves.
- From the curves one can clearly see the probabilistic nature of the notion R_{max}.

$q = kR^{-4}$



It is a common practice to perform calculations associated with the radar equation using decibel (**dB**) arithmetic

$$(X)_{dB} = 10\log_{10}(X)$$

Example: *A certain C-band radar with the following parameters:*

Peak power P_t **= 1.5 MW** *, operating frequency* f_o **= 5.6 GHz** *, antenna gain* **G=45 dB***, effective temperature* T_e **= 290 K***, pulse width* $\tau = 0.2\ \mu sec$*. The radar threshold is* $(SNR)_{min}$**=20dB***.* *Assume* noise factor **F=3 dB** *and target RCS* σ **= 0.1 m²**. ***Compute the maximum range***.

Solution: *The radar bandwidth is* $B = \frac{1}{\tau} = \frac{1}{0.2 \times 10^{-6}} = 5MHz$

The wavelength is $\lambda = \frac{c}{f_0} = \frac{3 \times 10^8}{5.6 \times 10^9} = 0.054m$

From ***Radar Equation***: $(R^4)_{dB} = (P_t + G^2 + \lambda^2 + \sigma - (4\pi)^3 - kT_eB - F - (SNR)_{o_{min}})_{dB}$

Before summing, the dB calculations are carried out for each of the individual parameters on the right-hand side. It follows:

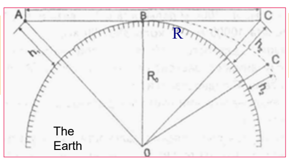
$$R^4 = 61.761 + 90 - 25.352 - 10 - 32.976 + 136.987 - 3 - 20 = 197.420dB$$

$$R^4 = 10^{\frac{197.420}{10}} = 55.208 \times 10^{18} m^4 \qquad R = \sqrt[4]{55.208 \times 10^{18}} = 86.199Km$$

Thus, the maximum detection range is $86.2Km$

Propagation within the line-of-sight range

Height of ground-based antenna



Height of aircraft (target)

$AB = \sqrt{2R_0h_1 + h_1}$

$BC = \sqrt{2R_0h_2 + h_2}$

$R_0 = 6371000m$

$h_1 << R_0 \quad h_2 << R_0$

$AB = \sqrt{2R_0h_1}$

$BC = \sqrt{2R_0h_2}$

$R = AB + BC = 3.57(h_1 + h_2)$

In case of $h_2 >> h_1 \Rightarrow R \approx 3.57h_2$ (the case air telecommunications)

Because of refraction $R_r = 4.12\sqrt{h_2}$

If h_2=1000 m, R≈120-130 km If h_2=10000 m, R≈350-400 km

- Thus, energetic detection range R_{max} determined with radar equation, is not reasonable to have more than the range of propagation within the line-of-sight R_r

$$R_{max} \le R_r$$