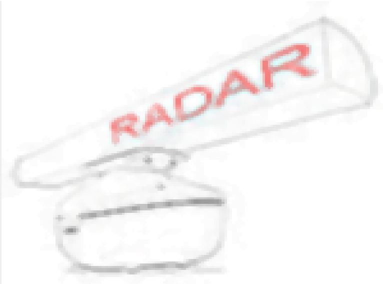
Radiolocation 1

Principles of maritime navigational radar

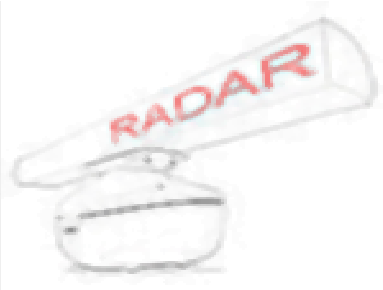


Introduction

RDF – Radio Direction Finding (UK)

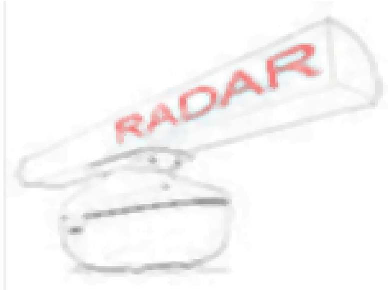
RADAR – Radio Detection and Ranging (USA)

- A device aiming at detecting an object (target) and determining a distance to it.
- A radio system that allows the determination of distance and direction of reflecting objects and of transmitting devices
(Res. MSC 192)



Introduction

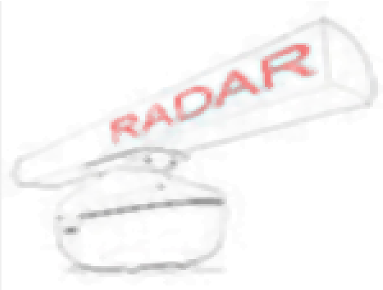
- Radar is an device which sends a modulated beams of radio waves (electromagnetic waves) by directional antennas (beam antennas) in order to locate objects in the space.
- Every object (target) reflects a fraction of radiation (echo) in the direction of the radar, which can be received, amplified, processed and presented to a radar operator.



Introduction

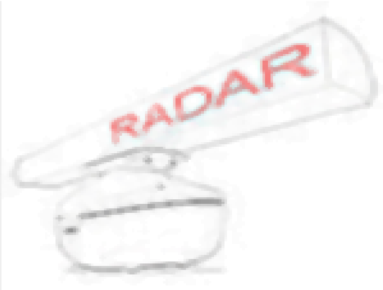
- Similarly a sonar, an echosounder and even an ordinary whistle uses an acoustic wave for detection and determination of a distance.

- In 1940 a cavity magnetron was invented which allowed to use microwaves (electromagnetic waves with length below 1 m) in radars



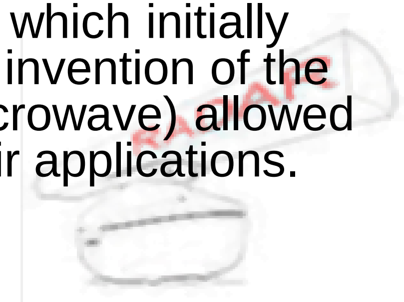
Introduction

- This invention allowed to transmit a pulses of radio energy in a shape of a focused beam and detect relatively small objects (like ships) in a distance of 10 - 15 Nm.



The history of radiolocation

- 1885 - H. Hertz - experimentally verified an electromagnetic field theory developed by J. Maxwell. Constructed a device, which transmitted electromagnetic pulses of a frequency about 450 MHz.
  - He proved that the light and electromagnetic waves have similar properties and differ in frequency. The experiment also proved that electromagnetic wave can be reflected by metal objects.
- Ab. 1900 - C. Hulsmeyer. – construct a device, conceptually similar to the modern monostatic pulse radars - developed the Hertz idea.
  In 1904 r. - the device had been patented as a navigational aid, but didn't find any practical application.
- Ab. 1921 – H. Taylor i L. Young - observed a electromagnetic signal fluctuation when an object appears between transmitter and receiver at located on the opposite side of a river (bistatic radar with continuous wave).
- The appearance of heavy strategic bombers has intensified work on improving the radar. The initial selection of bistatic radar technology did not give satisfactory results, therefore an attention to the Hulsmeyer invention was draw.
- Therefore the development of monostatic radar had been followed, which initially operated at much lower frequencies than at present. Only after the invention of the magnetron (microwave surce of high frequency and high power microwave) allowed the use of radar for a long distance detection, both in marine and air applications.



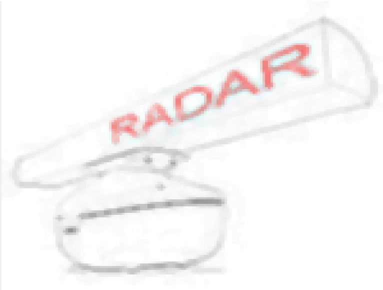
Historia radiolokacji

- After the II WW – a rapid development of radiolocation technology caused by invention of transistor and klystron (a microwave source generating continuous wave). The development of electronics caused that the Doppler phenomenon, for the identification of moving objects, began to be used in radars. New stable electronic generators have enabled the construction of mono-pulse radars;
- Pulse techniques allowed to increase the range and accuracy of radars. The next step was the radar with a synthetic aperture that allowed to make detailed maps of the area. Progress in the development of digital technologies, in turn, allowed to process the radiolocation signal and thus to obtain greater accuracy and effectiveness of object identification.
- Currently, the development of radiolocation continues. The construction of increasingly sophisticated integrated circuits has allowed the construction of radars for highly specialized applications, with decreasing sizes of devices.

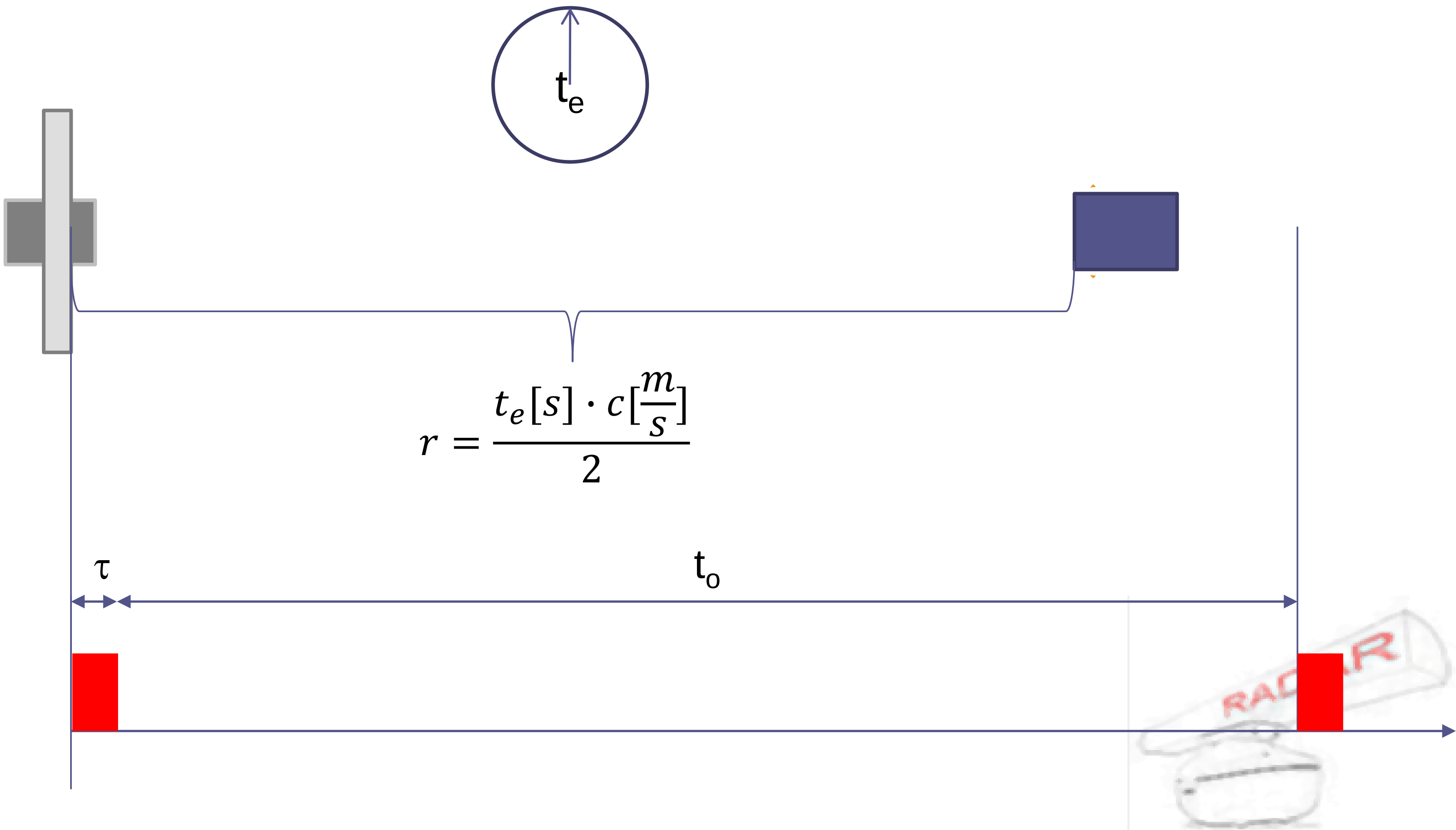
Basic task and cycle of radar work

- The basic task of RADAR is to measure the time between the moment of transmission and the moment of the echo reception;
- Based on the measured time, it is possible to determine the distance to the object.
- The radar duty cycle is the sum of the pulse transmission time and the waiting time - this is the time between consecutive transmissions of the pulse

$$t_c = \tau + t_o$$



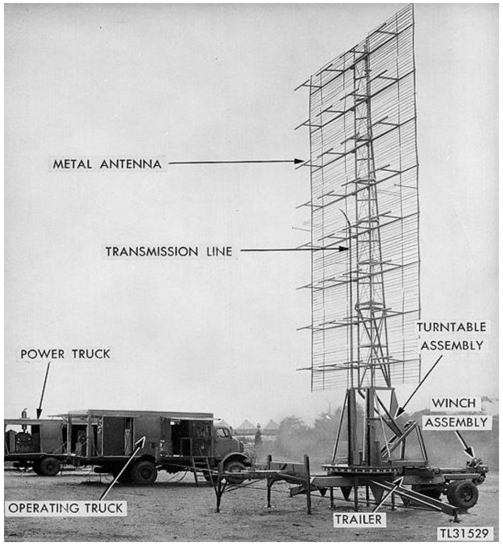
Basic task and cycle of radar work

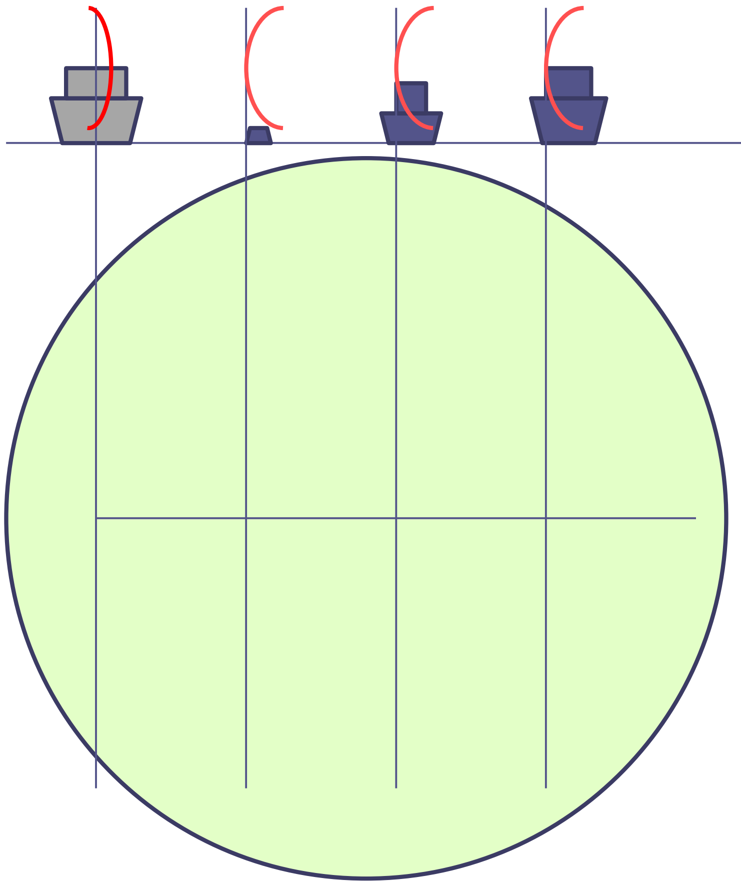


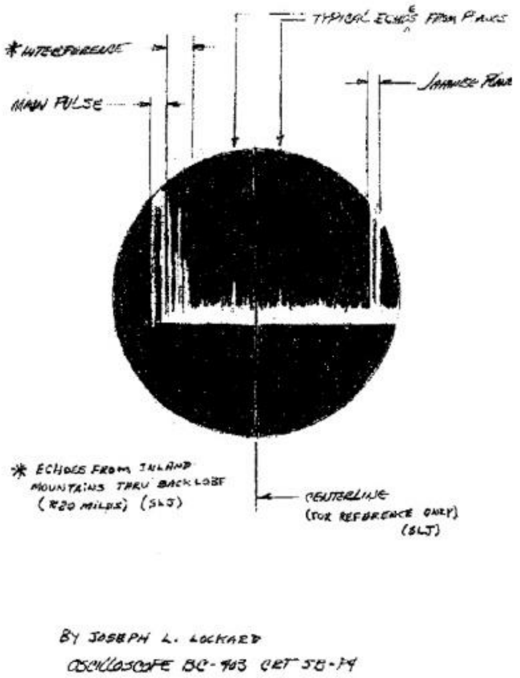
$$r = \frac{t_e[s] \cdot c[\frac{m}{s}]}{2}$$

A-scan display

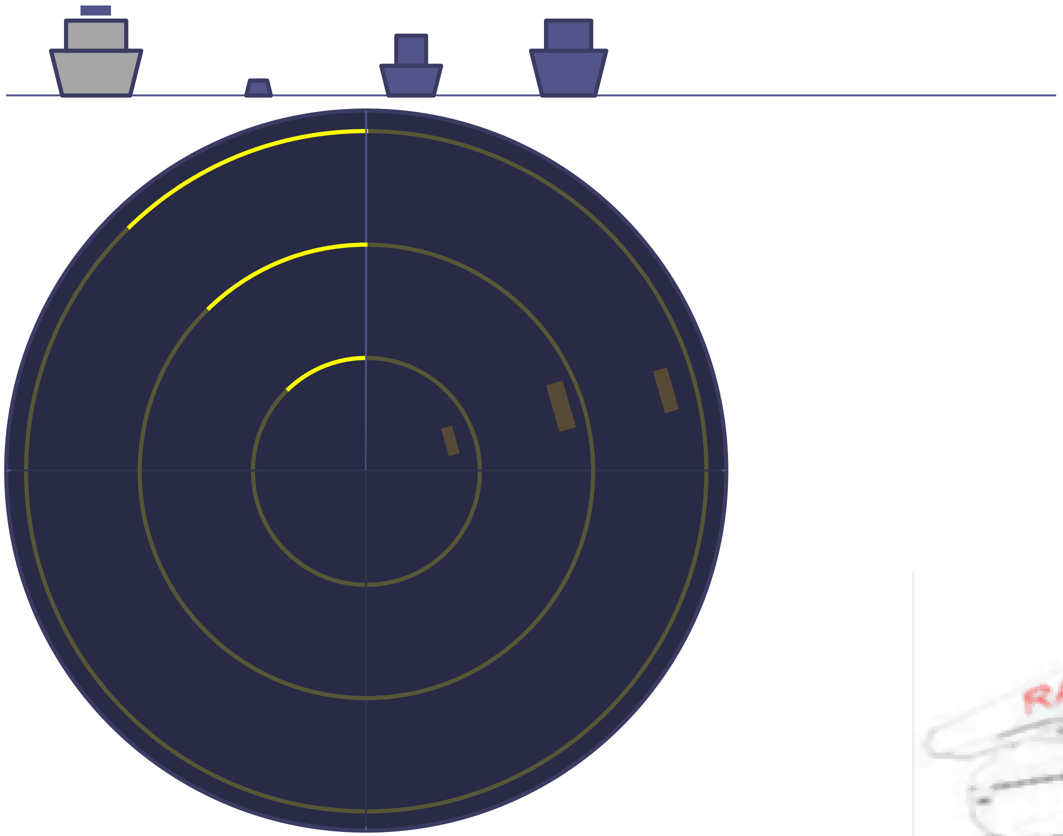
- Way of measuring distance in radars worked out in years 1940s

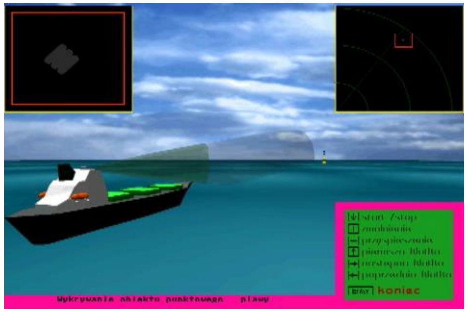


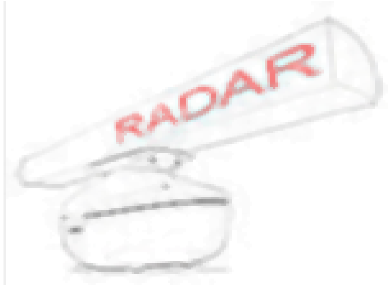




Plan Position Indicator (PPI)

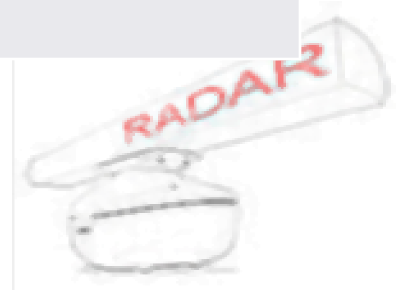






Podstawa czasu (the timebase)

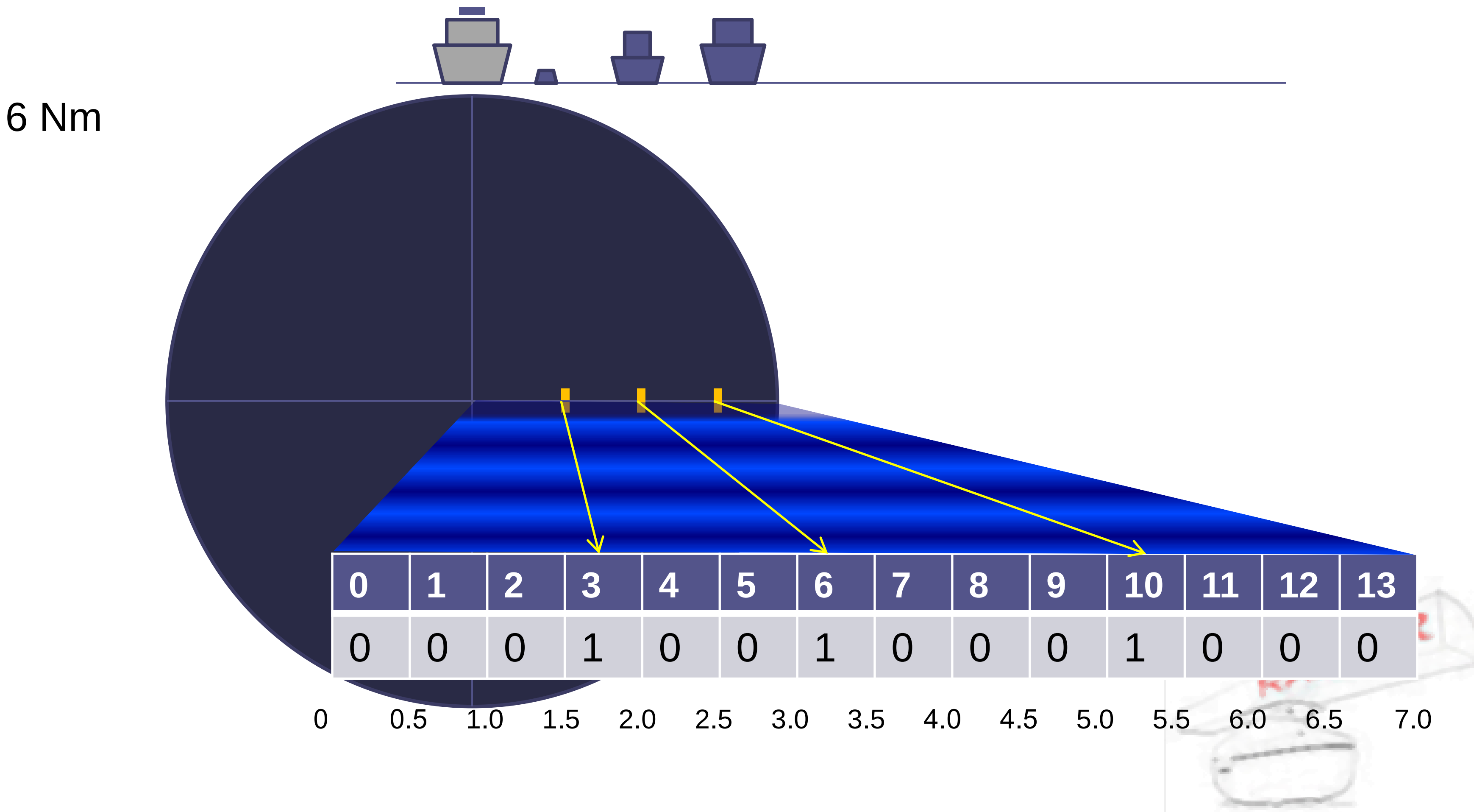
Zakres *Range scale [Nm]*	**Czas** *Timebase duration [µs]*	**Kręgi stałe** *Calibration [Nm]*	**Interwał** *Interval [µs]*	**Uwagi** Remarks
0.75	9.3	0.25	3.1	3 range rings
1.5	18.5	0.25	3.1	6 range rings
3	37	0.5	6.2	
6	74.1	1	12.4	
12	148.2	2	24.7	
24	296.3	4	49.4	
48	592.6	8	98.8	



Radial-scan, Raster-scan – synthetic display

- PPI (plan position indicator) – called the real-time displays
  - No data processing (distance, direction ,glow)
- The development of computer techniques and reduction of memory costs in years 1970s and1980s
- Technical revolution in the field of radar indicators
- The emergence of a new type of radar indicator - computer-controlled:
  - Synthetic display PPI: raster-scan, radial-scan

Synthetic display
Plan Position Indicator (PPI)



0	1	2	3	4	5	6	7	8	9	10	11	12	13
0	0	0	1	0	0	1	0	0	0	1	0	0	0

Synthetic display

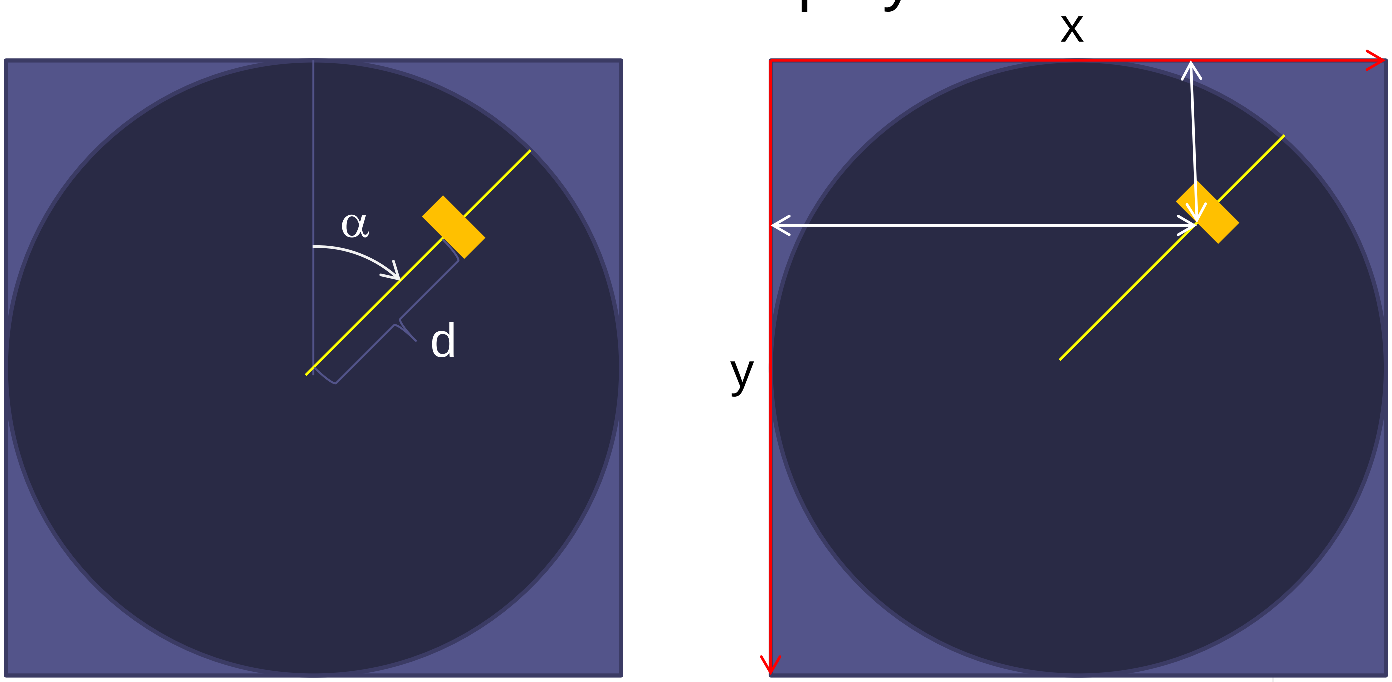
- The minimum number of memory cells for each work cycle is 1200;
- The returning echo is saved as '1' in the memory cell appropriate for the time interval;
- The writing time of memory cells depends on the range (time base);
- The reading time and the sweep time are constant and the same, usually corresponding to the range of 12 Nm (!).

Synthetic display

Zakres *Range scale [Nm]*	**Czas zapisu** *Write time[μs]*	**Czas odczytu** *Read-out [μs]*	**Czas odchylania** *Sweep time [μs]*
0.75	9.3	148	148
1.5	18.5	148	148
3	37	148	148
6	74.1	148	148
12	148.2	148	148
24	296.3	148	148
48	592.6	148	148

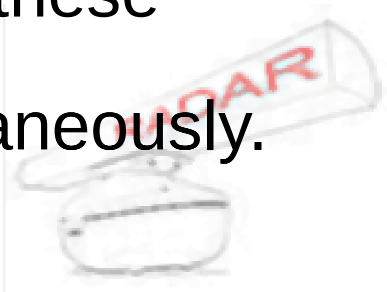
Synthetic display, raster-scan

- Conversion of polar coordinates to rectangular coordinates of CRT or LCD displays.



Basic principles of marine navigation radar

- Generation of radio waves in the form of short pulses;
- transmitting of these impulses into space in the form of a narrow beam performing continuous rotation in the horizontal plane;
- The reflection of these impulses by an object in the space;
- Receiving the reflected pulses (echoes) through the radar antenna;
- Amplifying, processing and then displaying these echoes in such a way that both bearing and distance are visible immediately and simultaneously.



Radio waves

By electromagnetic wave (radio wave) we understand the disturbance of the electromagnetic field, which propagates with the finite velocity (the speed of light).

At the beginning of the 19th century, the English physicist J.C. Maxwell created a theory of electromagnetic field that determines the essence of electromagnetic waves

These equations, from a practical point of view, can be interpreted as follows:

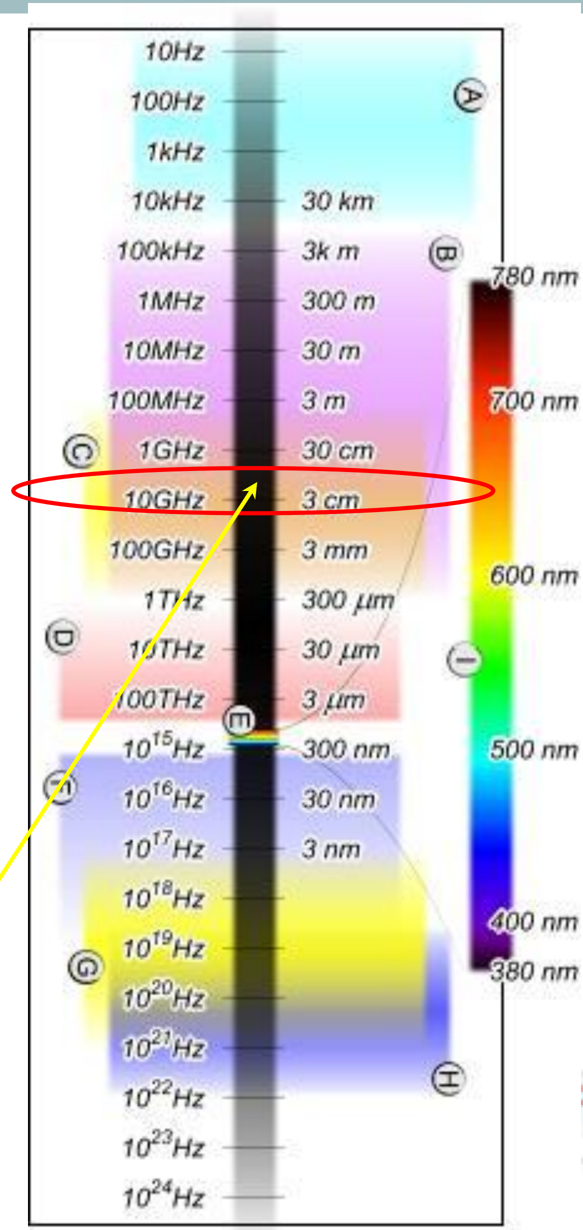
- The variable magnetic field is always accompanied by a variable electric field,
- The variable electric field is always accompanied by a variable magnetic field,
- Variable magnetic field creates closed loops of forces,
- The electromagnetic wave propagates in a vacuum with the speed of light, and in other mediums depending on their properties,
- The spatial distribution, strength and direction of the field in space is defined by the distribution of the electric charges of their source.

Radio waves

A – very long radio waves (ELF, SLF, ULF, VLF)
B – radio waves
C - microwaves
D - infrared
E – visible light
F – ultraviolet
G – X – ray
H – gamma ray

I – spectrum of visible light

Bands of radio waves used for marine radiolocation (X, S)

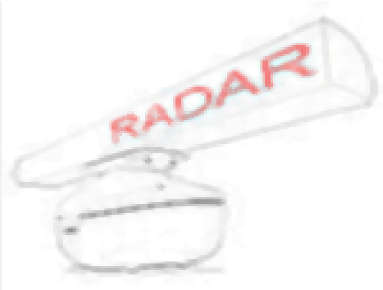


Types of radars

- area of use
  - maritime radar,
  - radar for aviation,
  - land radar,
- application
  - tracking of targets
  - meteorological
  - early warning etc.,
- operational principle
  - Continuous wave radar;
  - Pulse radar;
- radio waves frequencies
  - microwaves,
  - others.

Types of radar

- continuous wave radars CW are used in particular for Doppler shift measurements to accurately measure the velocity of fast-moving objects, as well as to guide ballistic missiles;
- Pulse radars PR can be additionally divided according to the repetition frequency (PRF - pulse repetition frequency).
  - In radars with a small PRF, where the Doppler shift is not measured, simpler electronic circuits are used,
  - Radars with higher PRF, in addition to measuring the distance and bearing to the object, allows a direct measurement of its speed, but it is necessary to use more advanced the measured systems.
- The selection of a radio waves frequency is a key element of the radiolocation system.



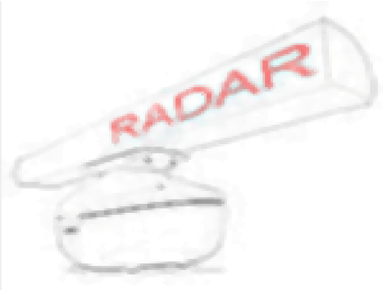
Frequencies used in radiolocation

Band name	Frequancy [GHz]	New letter designation
VHF	0,1 - 0,3	A
UHF	0,3 - 0,5	B
	0,5 – 1,0	C
L	1 - 2	D
S	2 - 3	E
	3 - 4	F
C	4 -6	G
	6 - 8	H
X	8 - 10	I
	10 - 12	J
Ku	12 - 18	J
K	18 - 26,5	J<20, K>20
Ka	26,5 - 40	K
millimeter waves	40 - 100	L<60, M>60

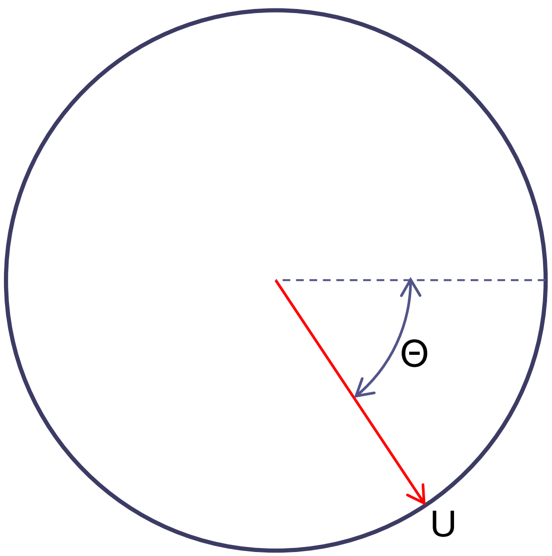
Radiation intensity

- The physical quantity which is defined as the radiation stream sent in a unit of solid angle; the unit of intensity is wat per steradian:

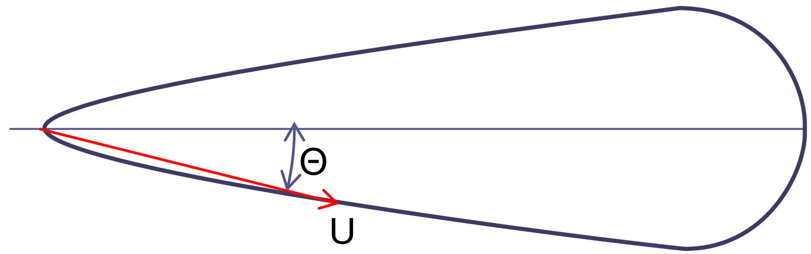
$$U = \frac{power}{4\pi}\left[\frac{w}{sr}\right]$$



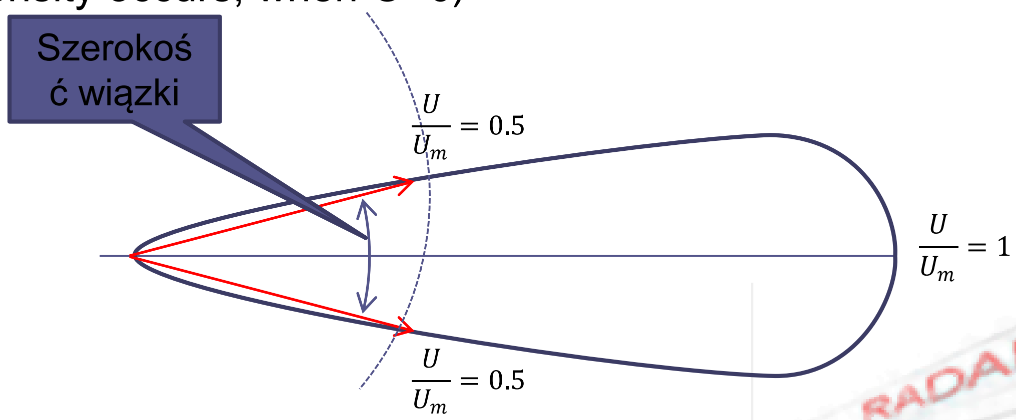
Rradiation pattern



Isotropic antenna: the intensity of radiation is independent to the angle Θ

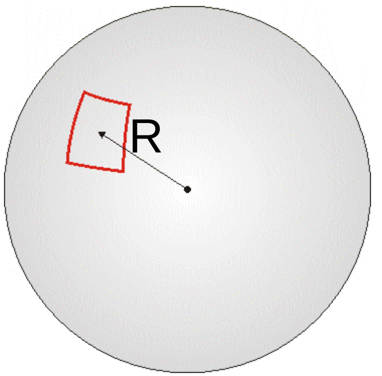


Directional antenna: the intensity of radiations U changes as a function of the angle Θ. maximum value of the intensity occurs, when Θ=0;



A normalized pattern for a directional source;

Power density

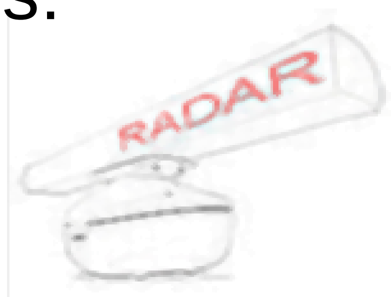


- For the radar with isotropic aerial the power density at a distance R is:

$$P_D = \frac{transmitted\ power}{sphere\ surface}\left[\frac{W}{m^2}\right]$$

- Therefore for an object in a distance R and transmitting power P_t the power density is:

$$\boxed{P_D = \frac{P_t}{4\pi R^2}}$$



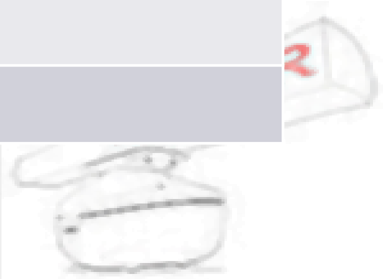
Aerial gain

- Marine radar systems use directional aerial with gain G_t and aperture A_e, which means that transmit the electromagnetic energy within specified angular limits of azimuth and elevation.

$$P_D = \frac{P_t G_t}{4\pi R^2}$$

$$G_t = K \frac{4\pi}{\Theta_e \Theta_a} \left[\frac{w}{sr}\right]$$

G_t	**Gain of transmitting antenna**
K	K≤1 – a factor that defines the physical radar aperture
Θ_e	vertical angle of beam
Θ_a	horizontal angle of beam



The energy reflected by an object

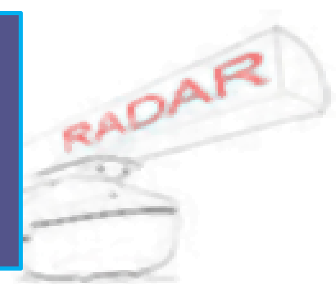
- By entering the factor ***σ,*** d which defines the ratio of the amount of energy captured by an object to the energy scattered by it, the power density close to antenna position can be expressed as follows:

$$P_s = \left(\frac{P_t G_t}{4\pi R^2}\right)\sigma\left(\frac{1}{4\pi R^2}\right) = \frac{P_t G_t \sigma}{\left(4\pi R^2\right)^2}$$

Power density [w/m^2] at the object

Energy [w] captured by the object

Isotropic scattering of the energy by the object [1/m^2]

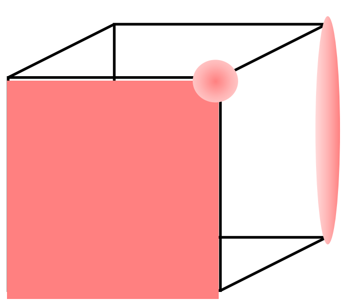


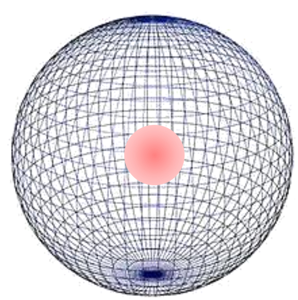
Radar cross section

- Factor **σ** - radar cross section (RCS) – is a surface area, which reflects in isotropic way the radiations (the energy) reaching the object and creating an echo which equals the echo reflected by the object.

$$\sigma = 4\pi R^2 \frac{P_D}{P_S} [m^2]$$

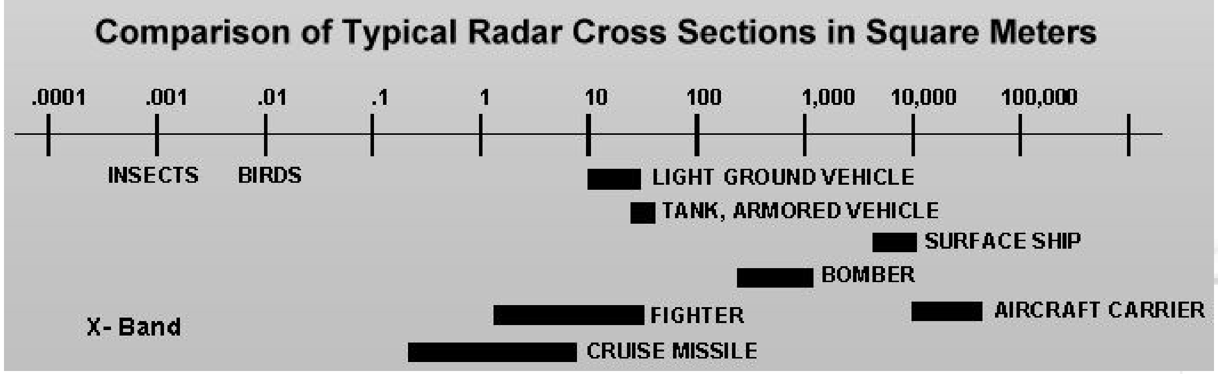
- The most typical isotropic surface is a sphere, for which the RCS is independent to a direction of radiation.

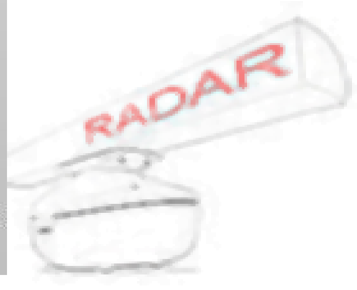




Radar cross section

- RCS depends on a shape, size aspect and material it is made from (reflecting properties);
- The real object does not scatter the Energy isotropically;
- RCS is an abstract term / theoretic surface of the object.





The power of reflected beam

- Taking the effective aperture of the antenna as A_{er}, the power of the reflected and captured beam by the antenna equals :

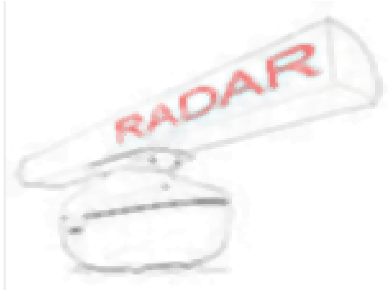
$$P_r = P_s A_{er} = \frac{P_t G_t \sigma A_{er}}{(4\pi)^2 R^4}$$

- Taking G_r as a gain of receiving antenna:

$$G_r = \frac{4\pi A_{er}}{\lambda^2}$$

- The power of received signal is:

$$P_r = \frac{P_t G_t G_r \sigma \lambda^2}{(4\pi)^3 R^4} [w]$$



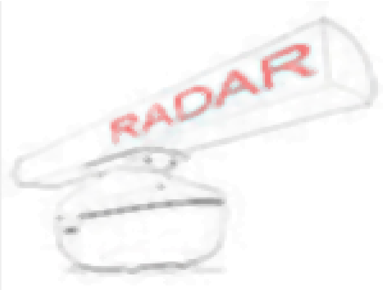
The power of received signal

- The gains of antenna during transmission and reception of a signal are the same for the monostatic radars: :

$$G_t = G_r = G$$

- Therefore:

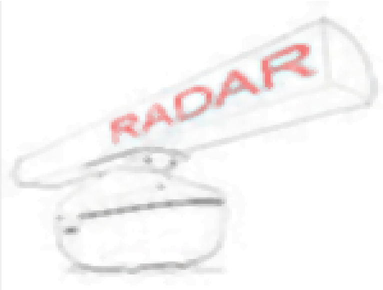
$$P_r = \frac{P_t G^2 \sigma \lambda^2}{(4\pi)^3 R^4} [w]$$



The power of received signal

- It is necessary to take into consideration losses into radar's circuits and surroundings L, and operational gain G_p:

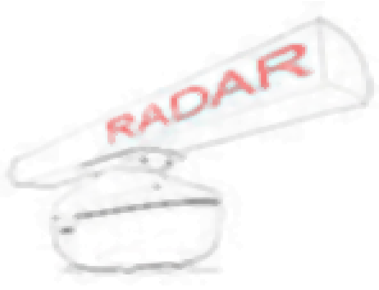
$$P_r = \frac{P_t G^2 \sigma \lambda^2 L G_p}{(4\pi)^3 R^4}$$



The radar equation

- The maximum detection range of radar R_{max}, when S_{min} stand for the minimum detectable power of returning signal, equals::

$$R_{max} = \sqrt[4]{\frac{P_t G^2 \sigma \lambda^2 L G_p}{(4\pi)^3 S_{min}}} \, [m]$$



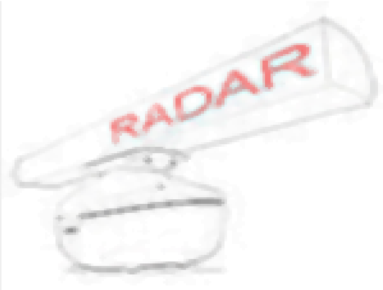
The maximum detectable range

- The maximum detection range in a free space is a maximum distance , from which a given radar can detect a specific object.
  The free space means no any limitations caused by curvature of the Earth and an absorption of the electromagnetic wave. Therefore:

$$R_{\max} = \sqrt[4]{\frac{P_i \cdot G_0 \cdot A_{sk} \cdot \sigma}{4 \cdot \pi^2 \cdot P_{\min}}}$$

where:

P_i	- power of transmitted signal,
G_0	- gain of the antenna,
A_{sk}	- antenna aperture,
σ	- radar cross section,
P_{min}	- the minimum detectable power of the signal.



The maximum detectable range

- After transformations for pulsed radar, we get:

$$R_{max} = f\left(\sqrt[4]{\underbrace{(P_i \cdot \tau)}_{\text{Transmitter}}\underbrace{(G_0 \cdot A_{sk})}_{\text{Antenna}}\underbrace{\left(\frac{\varsigma_r}{F}\right)}_{\text{Receiver}}\underbrace{\sigma}_{\text{Target}}} \right)$$

wheree:

τ - pulse time,

ζ_r- factor of tuning up of the radar,

σ – radar cross section,

F - receiver noise factor (sensitivity of the receiver).

The maximum range in the free space is proportional to the fourth root of the radar and object parameters, therefore 16-fold increasing of value, will result in a two-fold increase in range.

Definitions

- ***The power of radar pulse*** is the peak power of the pulse. For commercial vessels with an unlimited area of sailing, a power range of several to several dozen kW is used (Not applicable to non-magnetron radars).
- ***The pulse time*** is the period of time between moments, in which the pulse value exceeds 0.9 of its amplitude. As you can see from the equation, the pulse duration has the same effect on the radar range as the pulse power. In order to increase the maximum radar range, a longer duration of the probe pulse should be used.

Definitions

- ***Antenna gain*** is an energetic measure of directivity of the transmitting antenna. This parameter is defined as the quotient of the maximum power radiated by the directional antenna in the main direction of radiation to the maximum power of the non-directional antenna radiation in the same direction. Antenna gain depends on its design and dimensional relations to the length of the radiated wave.

- the antenna gain is directly proportional to the size of the antenna and vice versa to the square of the radiated wave length. Hence, 10 cm radar antennas have much worse directionality than 3 cm radar antennas.

Definitions

- ***The quality factor of the radar regulation*** depends on the precision of the adjustment process; it ranges from 0 to 1. The value 0 is assumed when a cardinal error is committed, e.g.: in the adjustment process the gain regulation was forgotten, leaving the knob in the left extreme position.
  Value 1 assumes when the optimal adjustment makes full use of the radar detection capability.

Definitions

- ***The receiver's noise ratio*** is a parameter defining the number of times a given receiver is deteriorating the signal-to-noise ratio at the output compared to a receiver that does not cause noise. This parameter is closely related to the minimum signal power that causes the echo to be displayed on the radar screen. The minimum signal power determines the sensitivity of the receiver, which is limited by its own noise. Own noise is called interference occurring in the radar due to the movement of electrons. At high gain, they are displayed and make it impossible to detect weak echoes. In order for the echo to be visible, the receiving signal must be more powerful than the own noise.
- The noise coefficient is given in decibels and amounts to a dozen dB in older radars up to several dB in newer radars.

The end