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

Електронні системи

Electronic Systems

Lecture #12

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Орієнтовний тематичний план лекцій

Основи теорії систем, сигнали і первинні перетворювачі електронних систем

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Електронні системи локації

Відбиваючі властивості об'єктів

Secondary radiation and radar cross section (RCS)

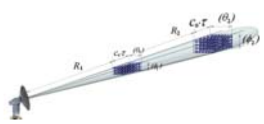
Radar Cross Section

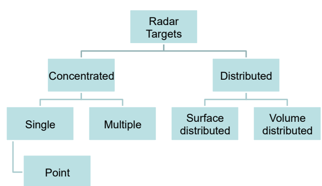
Ефективна площа розсіяння

- Function of
  - target size,
  - shape,
  - material,
  - Aspect angle
  - carrier frequency.
- Examples
  - Stealth planes
  - Stealth ships
  - Antennas for subs
- Limitations
  - Sensitive to the radar's frequency
  - Very sensitive to aspect angle

Target classification based on SR features

- Resolution volume (RV): $\Delta V = \Delta R \cdot R\theta \cdot R\varphi$.
- The intensity of the resultant EM field at the receive point at given point of time is formed by those reflecting elements (scatterers), which are located inside one RV.
- Returns, that are received from scatterers located in the neighboring volumes, do not concur (they do not come simultaneously).
- Hence the classification follows:

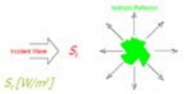




Radar Cross Section Definition

Radar Cross Section is a measure of power reflected back to the radar

$$\sigma = (4\pi)\frac{\text{power per unit solid angle scattered towards radar}}{\text{power density of the incident wave at the target}}$$



Radar Cross Section definition

The (fictional) area intercepting that amount of power which, when scattered *equally in all directions*, produces an echo at the radar equal to that from the target (IEEE).

In other words, RCS is the cross sectional area of an virtual object which isotropically reradiates all of its incident power at the same radiation intensity as the actual target reradiates towards the radar receiver.

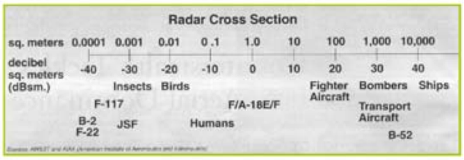
As a result, RCS of a target might be MUCH higher or smaller than the physical size of this target.

Radar Cross Section vs Physical Size

- RCS is *related* to size, wavelength and shape, but
- RCS is **not** a physical cross section but more an **effective area** of the incident wave energy interception which **intercept sufficient power** to create a given scattered field strength at the observation point assuming **isotropic radiation** of the scattered power.

E.g. a corner reflector is made to reflect most power back to the radar (narrow scattering diagram), therefore a corner reflector of 1 m^2 can have a radar cross section of 1000 m^2 (30 dBm^2) depending on the wavelength

Radar Cross Section
- Examples -



RCS Definition

1. Assume the power density of a wave incident on a concentrated target located at range ***R*** away from the radar is P_{Di}. The amount of reflected power from the target is

$$P_r = \sigma P_{Di}$$

→ σ denotes the target **RCS**

2. Define P_{Dr} as the power density of the scattered waves at the receiving antenna. It follows that

$$P_{Dr} = P_r/(4\pi R^2)$$

3. Equating Eqs. (1) and (2) yields

$$\sigma = 4\pi R^2\left(\frac{P_{Dr}}{P_{Di}}\right)$$

4. In order to ensure that the radar receiving antenna is in the far field (i.e., scattered waves received by the antenna are planar), Eq. (3) is modified

$$\sigma = 4\pi R^2 \lim_{R\to\infty}\left(\frac{P_{Dr}}{P_{Di}}\right)$$

The RCS defined by Eq. (4) is often referred to as either the monostatic RCS, the backscattered RCS, or simply RCS.

The RCS is measured from all waves scattered in the direction of the radar and has the same polarization as the receiving antenna. It represents a portion of the total scattered target RCS σ_t, where $\sigma_t > \sigma$. Assuming spherical coordinate system defined by (ρ, θ, φ), then ρ at range the target scattered cross section is a function of (θ, φ). Let the angles (θ_i, φ_i) define the direction of propagation of the incident waves. Also, let the angles (θ_r, φ_r) define the direction of propagation of the scattered waves. The special case, when $\theta_i = \theta_r$ and $\varphi_i = \varphi_r$, defines the monostatic RCS. The RCS measured by the radar at angles $\theta_i \neq \theta_r$ and $\varphi_i \neq \varphi_r$ and is called the bistatic RCS.

RCS Prediction Methods (1)

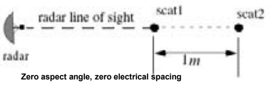
- Why RCS prediction is important?
- **1.** Most radar systems use RCS as a means of discrimination. Therefore, accurate prediction of target RCS is critical in order to design and develop robust discrimination algorithms.
- **2.** Measuring and identifying the scattering centers (sources) for a given target aid in developing RCS reduction techniques.
- **3.** RCS calculations require broad and extensive technical knowledge, thus many scientists find the subject challenging and intellectually motivating.

RCS Prediction Methods (2)

- Exact methods of RCS prediction are very complex. They require solving either differential or integral equations that describe the scattered waves from an object under the proper set of boundary conditions. Such boundary conditions are governed by Maxwell's equations. Even when exact solutions are achievable, they are often difficult to interpret.
- Approximate methods become the viable alternative. The majority of the approximate methods are valid in the optical region, and each has its own strengths and limitations.
- Most approximate methods can predict RCS within few dBs of the truth. In general, such a variation is quite acceptable by radar engineers and designers. Approximate methods are usually the main source for predicting RCS of complex and extended targets such as aircrafts, ships, and missiles.
- When experimental results are available, they can be used to validate and verify the approximations.
- Some of the most commonly used approximate methods are Geometrical Optics (GO), Physical Optics (PO), Geometrical Theory of Diffraction (GTD), Physical Theory of Diffraction (PTD), and Method of Equivalent Currents (MEC).

RCS Dependency on Aspect Angle (1)

- RCS fluctuates as a function of radar aspect angle.
- For the purpose of illustration, isotropic point scatterers are considered. An isotropic scatterer is one that scatters incident waves equally in all directions.

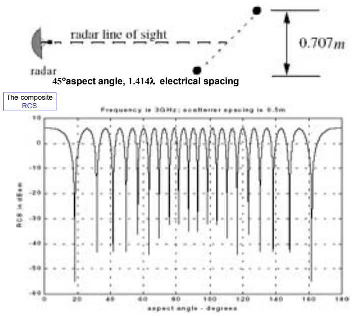


Two unity (1 m^2) isotropic scatterers are aligned and placed along the radar line of sight (zero aspect angle) at a far field range. The spacing between the two scatterers is 1 m. The radar aspect angle is then changed from zero to 180 degrees, and the composite RCS of the two scatterers measured by the radar is computed.

This composite RCS consists of the superposition of the two individual RCS. At zero aspect angle, the composite RCS is 2 m^2. Taking scatterer- 1 as a phase reference, when the aspect angle is varied, the composite RCS is modified by the phase that corresponds to the electrical spacing between the two scatterers. For example, at aspect angle 10°, the electrical spacing between the two scatterers is

$$elec\text{-}spacing = \frac{2 \times (1.0 \times \cos(10))}{\lambda}$$

RCS Dependency on Aspect Angle (2)



Knowledge of this constructive and destructive interference between the individual scatterers can be very critical when trying to extract RCS of complex or maneuvering targets. Reasons: 1) the aspect angle may be continuously changing; 2) complex target RCS can be made up from contributions of many individual scattering points distributed on the target surface (scattering centers).

RCS dependence on frequency

RCS depends on wavelength

WHY?

RCS dependence on frequency

RCS depends on wavelength

Because the scattered field spatial distribution depends on the electrical size of the object

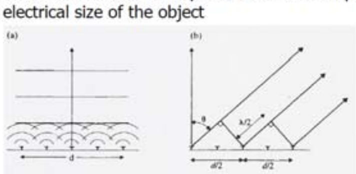


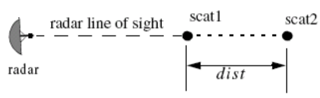
Figure 1.4 (a) Wavelets from small Huygens sources add coherently in front of the aperture. (b) At an angle $\sin\theta = \lambda/d$ they interfere destructively and the antenna gain falls to zero, thus giving an approximate characteristic beamwidth to the first nulls of $2\lambda/d$ and λ/d to the −3 dB (half-power) points.

RCS Dependency on Frequency (1)

Two scatterers

To demonstrate RCS dependency on frequency, consider the experiment

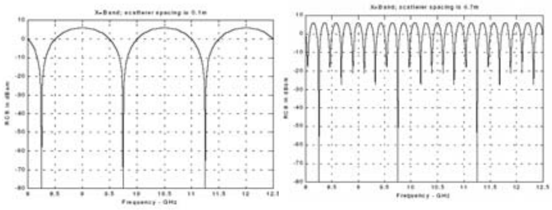
Two far field unity isotropic scatterers are aligned with radar line of sight. The composite RCS is measured by the radar as the frequency is varied from 8 GHz to 12.5 GHz (X-band).



RCS Dependency on Frequency (2)

Two scatterers

The composite RCS versus frequency for scatterer spacing of 0.1 and 0.7 meters:

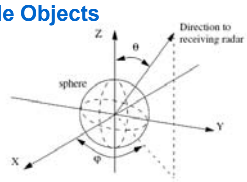


RCS fluctuation as a function of frequency is evident. Little frequency change can cause serious RCS fluctuation when the scatterer spacing is large. Alternatively, when scattering centers are relatively close, it requires more frequency variation to produce significant RCS fluctuation.

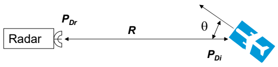
RCS Dependency on Polarization

RCS of Simple Objects

- Radar designers and RCS engineers consider the perfectly conducting sphere to be the simplest target to examine.
- Even in this case, the exact solution is very complex.
- Mostly we are considering approximation for the backscattered RCS measured by a far field radar in the direction (θ, φ), as is illustrated



Direction of antenna receiving backscattered waves.



$$\sigma = 4\pi R^2 \left(\frac{P_{Dr}}{P_{Di}} \right)$$

Sphere

- Due to symmetry, waves scattered from a perfectly conducting sphere are co-polarized (have the same polarization) with the incident waves.
- This means that the cross-polarized backscattered waves are practically zero.
- For example, if the incident waves were Left Circularly Polarized (LCP), then the backscattered waves will also be LCP.
- However, because of the opposite direction of propagation of the backscattered waves, they are considered to be Right Circularly Polarized (RCP) by the receiving antenna.
- Therefore, the PP backscattered waves from a sphere are LCP, while the OP backscattered waves are negligible.

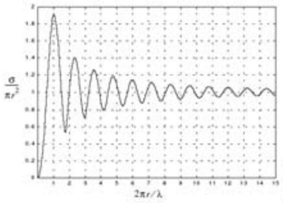
Three kinds of back scattering (1)

- **How does RSC depend on wavelength λ ?** The crucial role belongs to the ratio between λ and target size.
- When a target is very small comparatively to λ, it is very difficult to detect the target.For example, if weather radars use **L-band** frequency, rain drops become nearly invisible to the radar since they are much smaller than the wavelength.

Three kinds of back scattering (2)

- *RCS measurements in the frequency region*, *where the target extent is much less than the wavelength, are referred to as the* ***Rayleigh region***.
- Alternatively, the *frequency region where the target extent is much larger than the radar operating wavelength is referred to as the* ***optical region***.
- When *the target extent and the wavelength are comparable, the* ***resonance*** *and anti-resonance phenomena appear*, that is, echo can be ***very small or very big*** depending on little changes of ratio λ/***target size*** (***Mie*** or ***resonance region***).

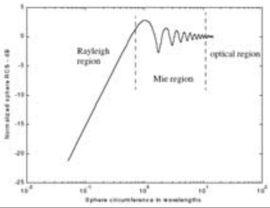
Plots of the normalized perfectly conducting sphere RCS as a function of its circumference in wavelength units are shown in figures



$\sigma \approx \pi^5 (2r)^6 / \lambda^4 \quad r << \lambda$ Raleigh

$\sigma = \pi r^2 \quad r >> \lambda$ Optics

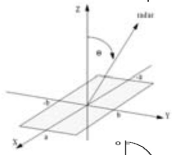
$\sigma = \pi r^2 \cdot f\left(\frac{r}{\lambda}\right) \quad r \approx \lambda$ Mie



The region between the optical and Rayleigh regions is oscillatory in nature and is called the Mie or resonance region.

Rectangular Flat Plate

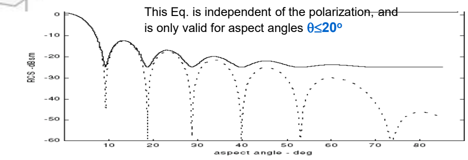
Consider a perfectly conducting rectangular thin flat plate in the x-y plane as shown in figure. The two sides of the plate are denoted by $2a$ and $2b$.



The backscattered RCS for a perfectly conducting thin rectangular plate for incident waves at any θ, φ can be approximated by

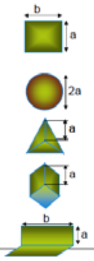
$$\sigma = \frac{4\pi a^2 b^2}{\lambda^2}\left(\frac{\sin(ak\sin\theta\cos\varphi)}{ak\sin\theta\cos\varphi}\,\frac{\sin(bk\sin\theta\sin\varphi)}{bk\sin\theta\sin\varphi}\right)^2 (\cos\theta)^2$$

This Eq. is independent of the polarization, and is only valid for aspect angles $\theta \leq 20^o$



Radar Cross Section of basic shapes at high frequencies

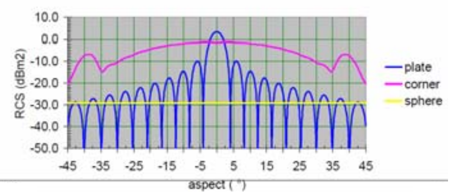
flat plate	$\frac{4\pi a^2 b^2}{\lambda^2}$	
sphere	πa^2	
triangular trihedral	$\frac{4\pi a^4}{3\lambda^2}$	
rectangular trihedral	$\frac{12\pi a^4}{\lambda^2}$	
dihedral	$\frac{8\pi a^2 b^2}{\lambda^2}$	



Radar cross section of basic shapes

frequency 35 GHz
polarisation HH

flat plate (6 x 6 cm)
trihedral corner (rib 6 cm)
sphere (diam. 5 cm)

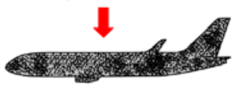


RCS fluctuation

The term fluctuation is applied to unsystematic (typically random) deviation of any physical quantity from its nominal value [1].RCS fluctuations are variations of target cross section with **time**.

Swerling I

(target that is made up of many independent scatterers)



The density of the probability of the RCS (σ):

$$P(\sigma) = \frac{1}{\sigma_{average}}\exp\left(\frac{-\sigma}{\sigma_{average}}\right)$$

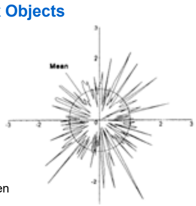
$\sigma_{average}$ - mean value of σ

[1] D. Barton, S. Leonov 'Radar technology encyclopedia', 1997

RCS of Complex Objects

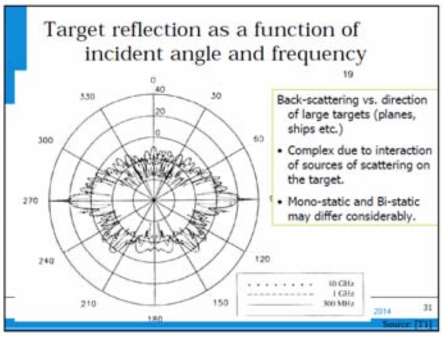
A complex target RCS is normally computed by coherently combining the RCS of the simple shapes that make that target.

The scattering centers can be modeled as isotropic point scatterers (N-point model) or as simple shape scatterers (N-shape model).



In any case, knowledge of the scattering centers' locations and strengths is critical in determining complex target RCS. This is true, because as seen in previous lecture relative spacing and aspect angles of the individual scattering centers drastically influence the overall target RCS.

Complex targets that can be modeled by ***many equal scattering centers*** are often called **Swerling 1 or 2** targets.
Alternatively, targets that have ***one dominant scattering center*** and many other smaller scattering centers are known as **Swerling 3 or 4** targets.



RCS Fluctuations and Statistical Models

In most practical radar systems there is relative motion between the radar and an observed target. Therefore, the **RCS** measured by the radar **fluctuates** over a period of time as a function of frequency and the **target aspect angle**.

RCS scintillation can vary slowly or rapidly depending on the target size, shape, dynamics, and its relative motion with respect to the radar.

Thus, due to the wide variety of **RCS** scintillation, sources changes in the radar cross section are modeled statistically as random processes.

The value of an **RCS** random process at any given time defines a random variable at that time. Many of the **RCS** scintillation models were developed and verified by experimental measurements.

RCS Fluctuations and Statistical Models

RCS Statistical Models - Scintillation Models

Consider the most commonly used **RCS** statistical models. The choice of a particular model depends heavily on the nature of the target under examination.

Chi-Square of Degree 2*m*

The Chi-sq. distribution applies to a wide range of targets; its *pdf* is given by

$$f(\sigma) = \frac{m}{\Gamma(m)\sigma_{av}}\left(\frac{m\sigma}{\sigma_{av}}\right)^{m-1} e^{-m\sigma/\sigma_{av}} \qquad \sigma \ge 0$$

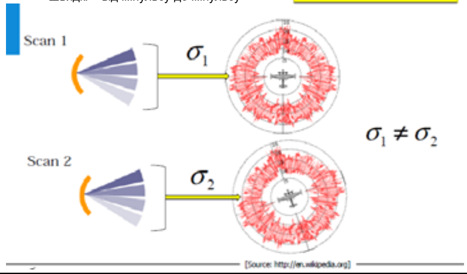
Γ(*m*) is the gamma function with argument ***m***, and σ_{av} is the average value.

As the degree gets larger the distribution corresponds to constrained RCS values (narrow range of values). The limit ***m***→∞ corresponds to a constant **RCS** target (steady-target case).

Швидкі і повільні флуктуації

Повільні – лише від скану до скану
Швидкі – від імпульсу до імпульсу

RCS constant from pulse to pulse, different from scan to scan

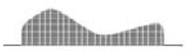


Swerling I and II (Chi-Square of Degree 2)

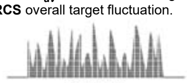
In **Swerling I**, the RCS samples measured by the radar are correlated throughout an entire scan, but are uncorrelated from scan to scan (slow fluctuation). In this case, the **pdf** is

$$f(\sigma) = \frac{1}{\sigma_{av}}\exp\left(-\frac{\sigma}{\sigma_{av}}\right) \qquad \sigma \ge 0$$

where σ_{av} denotes the average **RCS** overall target fluctuation.



Swerling I



Swerling II

Swerling II target fluctuation is more rapid than Swerling I, but the measurements are pulse to pulse uncorrelated. Swerling II RCS distribution is defined by the same equation.

Swerlings I and II apply to targets consisting of many independent fluctuating point scatterers of approximately equal physical dimensions.

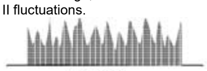
Swerling III and IV (Chi-Square of Degree 4)

Swerlings III and IV have the same **pdf**, and it is given by

$$f(\sigma) = \frac{4\sigma}{\sigma_{av}^2}\exp\left(-\frac{2\sigma}{\sigma_{av}}\right) \qquad \sigma \ge 0$$

The fluctuations in Swerling III are similar to Swerling I; while in Swerling IV they are similar to Swerling II fluctuations.

Swerling III

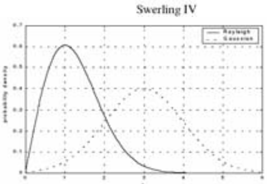


Swerling IV

Swerlings III and IV are more applicable to targets that can be represented by one dominant scatterer and many other small reflectors.

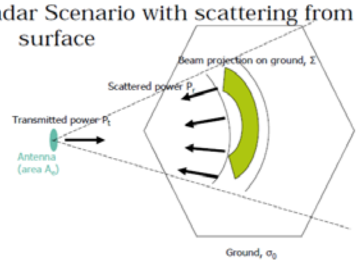
Swerling V

Swerling V corresponds to a steady RCS target case.



A typical plot of the pdfs for Swerling cases.

Radar Scenario with scattering from surface



Radar Cross Section for surfaces

The average radar backscatter coefficient σ_o (sigma-zero), is defined as:

$$\sigma_0 = \frac{\text{Summed RCS from illuminated area}}{\text{Illuminated area}}$$

- σ_o is dimensionless
- σ_o varies with frequency and type of background. For land at X-band typical value is -20 dB, for sea -30 dB. However other parameters (e.g. polarisation, incidence angle) influence the value

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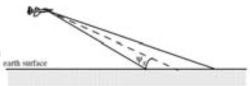
- White noise normally introduces the same amount of noise power across all radar range bins, while clutter power may vary within a single range bin.
- So, clutter returns are target-like echoes. Thus, the only way a radar can distinguish target returns from clutter echoes is based on the target RCS σ_t, and the anticipated clutter RCS σ_c (via clutter map).

Surface Distributed Targets / Clutter

RCS of SDT (clutter included) can be defined as the equivalent RCS attributed to reflections from a clutter area, A_c. The average clutter RCS is given by $\sigma_c = \sigma^0 A_c$.

where $\sigma^0 (m^2/m^2)$ is the **specific RCS**, or **specific scattering cross-section**, or **clutter scattering coefficient**. **σ^0** is a dimensionless quantity that is often expressed in dB.

SDT as area clutter manifests itself in airborne radars in the look-down mode. The grazing angle ψ_g is the angle from the surface of the earth to the main axis of the illuminating beam.



It is also a major concern for ground-based radars when searching for targets at low grazing angles.

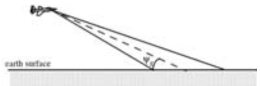
Surface Distributed Targets / Clutter

RCS of SDT (clutter included) can be defined as the equivalent RCS attributed to reflections from a clutter area, A_c. The average clutter RCS is given by

$$\sigma_c = \sigma^0 A_c$$

where $\sigma^0 (m^2/m^2)$ is the **specific RCS**, or **specific scattering cross-section**, or **clutter scattering coefficient**.
σ^0 is a dimensionless quantity that is often expressed in dB.

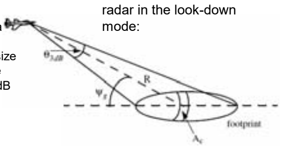
SDT as area clutter manifests itself in airborne radars in the look-down mode. The grazing angle ψ_g is the angle from the surface of the earth to the main axis of the illuminating beam.



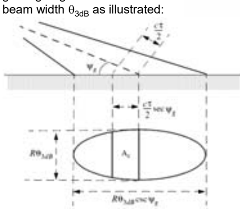
It is also a major concern for ground-based radars when searching for targets at low grazing angles.

Surface Distributed Targets (Area Clutter) – Continuation

1. Consider an airborne radar in the look-down mode:



2. The intersection of the antenna beam with ground defines an elliptically shaped footprint. The size of the footprint is a function of the grazing angle and the antenna 3dB beam width θ_{3dB} as illustrated:



3. The footprint is divided into many ground range bins each of size $(c\tau/2)\sec\psi_g$, where τ is the pulse width. The area A_C is:

$$A_c \approx R\theta_{3dB}\frac{c\tau}{2}\sec\psi_g$$

RCS: $\sigma_c = \sigma^0 A_c$

Volume Distributed Targets / Clutter

The volume clutter coefficient **η** is normally expressed in [1/m] (RCS per resolution volume).

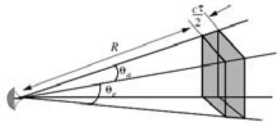
Defining **η** as RCS per unit resolution volume ***V_W***, it is computed as the sum of all individual scatterers RCS within the volume →

$$\eta = \frac{\sum_{i=1}^{N} \sigma_i}{V_W}$$

Definition of resolution volume:

$$V_W \approx \frac{\pi}{8}\theta_a\theta_e R^2 c\tau$$

$$\eta = \sum_i N_i \sigma_i(D_i, \lambda)$$



$$\eta = \int_0^\infty N(D)\,\sigma(D,\lambda)\,dD$$

$$\eta = \pi^5 \frac{|K|^2}{\lambda^4} \int_0^\infty N(D) D^6 dD = \pi^5 \frac{|K|^2}{\lambda^4} Z$$

$$\sigma = \eta V_W = \eta \frac{\pi}{8}\theta_a\theta_e R^2 c\tau$$

What you have learned today

- If scattered power only is of importance, the Radar Cross Section is used instead of the scattering matrix.
- The RCS of a target depends on its electrical size and orientation.
- RCS of an electrically large target fluctuates with its position (orientation) and is described with Swerling models.