ROHDE&SCHWARZ

Make ideas real

RADAR AND ELECTRONIC WARFARE

Illustrated collection of definitions and formulas

eGuide | Version 01.00

This eGuide is an illustrated collection of definitions and formulas on the subject of radar and electronic warfare.

Radar and electronic warfare | eGuide

Author: Dipl.-Ing. (FH) Christian Wolff

Christian B. W. Wolff studied radar engineering at the military college of the air force of the former GDR. He received the diploma for high-frequency technology from the Ministry of Education and Cultural Affairs of the Free State of Saxony. After that, he served for many years as the head of various Russian long-range radars. In unified Germany, he attended training on American long-range air defense and air traffic control radars. He worked as head of the engineering office in the German Air Force radar maintenance and repair group. He is retired now and still working as a freelancer.

Stay ahead of technological advancements in radar and electronic warfare with solutions that deliver precise analysis, clean signal sources and high-resolution measurements.

More information:
www.rohde-schwarz.com/radar

CONTENTS

Electronic warfare (EW) ... **4**
- Electronic warfare subareas ... 4
- Electronic warfare support activities ... 4
- Electronic attack activities ... 5
- Electronic protection measures ... 5
- ISM bands ... 7

Frequency bands ... **7**

Radar frequencies ... **8**

Antenna models ... **9**
- Field regions around an antenna ... 10
- Antenna pattern ... 11
- Antenna gain ... 12
- Antenna efficiency ... 12
- Antenna beamwidth (Θ) ... 13
- Beam solid angle (Ω) ... 14
- Antenna types ... 14
- Link budget ... 17
- Fresnel zone ... 18
- Earth bulge ... 18
- Fresnel zone distance (FZ) ... 19
- Free space path loss (FSPL) ... 19
- Antenna polarization loss ... 19
- Atmospheric attenuation ... 19
- Two ray loss model ... 21
- Knife edge diffraction ... 22
- Antenna beams for command guided missiles ... 23
- Noise factor (F_n) ... 26
- Noise figure (NF) ... 26
- Noise temperature (T_e) ... 26
- Signal-to-quantization-noise ratio (SQNR) ... 26
- Signal-to-noise and distortion ratio (SINAD) ... 27
- Signal-to-noise-plus-interference ratio (SNIR) ... 27

Effective number of bits (ENOB) 27
Chaff 28
Radar decoys 29
Electronic jamming and deception 30

Burn through range 30

Jamming-to-signal (J/S) ratio 30

Self-protection jamming 31

Remote jamming 31
J/S for support jamming 32
Burn through range for support jamming 32

Communications jamming 32
Radar blind range 33

Pulse radar 33
Radar unambiguous range 34
Chirp radar 34
Barker codes 35
Duty cycle 36
Unmodulated CW radar 37
Frequency modulated CW radar (FMCW) 37

CW radar 37
Frequency modulated interrupted continuous wave (FMiCW) radar 38
Probability of detection (P_D) 38
False alarm rate (FAR) 38
Dwell time (T_D) 38
Hits per scan 38
Radial speed 39
Jet engine modulation (JEM) 39
Doppler dilemma 39

Doppler frequency 39

Height estimation 40
Ducting 41

Refraction classification 41

Radar horizon 42
Point-like targets 43
Radar range resolution 43
Radar angular resolution 43
Volume targets 43

Radar resolution cell 43

One-way link equation 44

Two-way radar equation 44
Losses 45
Fluctuation loss (L_f) 45
Swerling cases 45

Radar equation for weather radar 46

Radar cross section (RCS) 47
Rayleigh, Mie and optical region 48
Retroreflectors 51
Absolute dB levels 52

Decibel (dB) 52

List of symbols 54

ELECTRONIC WARFARE (EW)

Electronic warfare (EW) is the art and science of denying an enemy the benefits of the electromagnetic spectrum while preserving them for friendly forces.

Electronic warfare subareas

Electronic warfare support (ES)
Detect, intercept, identify, locate and/or localize sources of intended and unintended radiated electromagnetic (EM) energy.

Signals intelligence (SIGINT), analyzing and identifying intercepted transmissions, includes frequency, bandwidth, modulation ("waveform") and polarization:
- Electronic intelligence (ELINT)
- Communications intelligence (COMINT)
- Foreign instrumentation signals intelligence (FISINT)

Electronic attack (EA)
Actions to interfere with enemy radar or communications (formerly known as electronic countermeasures, ECM):
- Passive jamming, expendables (decoys), chaff
- Active jamming (RF generators)
  - Barrier jamming
  - Deception jamming

Electronic protection (EP)
Features of radars or communications systems that reduce the effectiveness of enemy EW (formerly known as electronic counter-countermeasures, ECCM):
- Anti-passive
- Anti-active
- Electronic camouflage
- Low probability of intercept (LPI) measures for radars and communications
- "Stealth" technology

Electronic warfare support activities

Activities related to electronic warfare support include:
- **Electronic reconnaissance:** location, identification and evaluation of foreign electromagnetic radiation
- **Electronic intelligence:** technical and geolocation intelligence derived from foreign non-communications electromagnetic radiation emanating from sources other than nuclear detonations or radioactive sources
- **Electronics security:** protection resulting from all measures designed to deny unauthorized persons information of value that might be derived from the interception and study of non-communications electromagnetic radiation, e.g. radar

Electronic attack activities

Activities related to electronic attack are either offensive or defensive and include:

- **Countermeasures:** form of military science that, by the employment of devices and/or techniques, has as its objective the impairment of the operational effectiveness of enemy activity
- **Electromagnetic deception:** various electromagnetic deception techniques such as false target or duplicate target generation to confuse enemy intelligence, surveillance and reconnaissance systems
- **Electromagnetic intrusion:** intentional insertion of electromagnetic energy into transmission paths in any manner, with the objective of deceiving operators or of causing confusion
- **Electromagnetic jamming:** deliberate radiation, reradiation or reflection of electromagnetic energy for the purpose of preventing or reducing an enemy's effective use of the electromagnetic spectrum, and with the intent of degrading or neutralizing the enemy's combat capability
- **Electromagnetic pulse:** electromagnetic radiation from a strong electronic pulse (e.g. by directed energy weapons) that may couple with electrical or electronic systems to produce damaging current and voltage surges
- **Electronic probing:** intentional radiation designed to be introduced into the devices or systems of potential enemies for the purpose of learning the functions and operational capabilities of the devices or systems

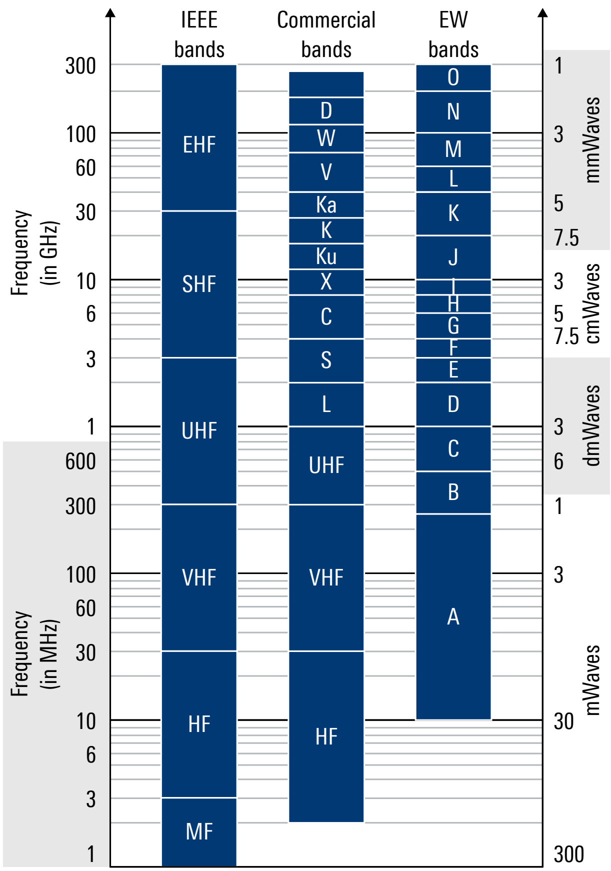
Electronic protection measures

- **Electromagnetic hardening:** action taken to protect personnel, facilities and/or equipment by blanking, filtering, attenuating, grounding, bonding and/or shielding against undesirable effects of electromagnetic energy, including:
  - **Anti-crosspol:** reduces cross polarized lobes
  - **Burn-through modes:** increase transmitter power or duty cycle to increase burn-through range
  - **Frequency agility:** requires jamming energy to be spread to cover transmission frequencies
  - **Home on jam mode:** makes self-protection jamming impractical, endangers stand-off jammers
  - **Monopulse radar:** counters multi-pulse angle deception
  - **PRF jitter:** requires longer cover pulses
  - **Pulse compression:** reduces J/S by the compression factor unless jammer has compression modulation
  - **Pulse doppler radar:** detects non-coherent jamming, detects chaff, requires coherent jamming
  - **Sidelobe blanking:** cancels pulse sidelobe jamming
  - **Sidelobe cancellation:** reduces CW sidelobe jamming
  - **Ultralow sidelobes:** reduces J/S and increases burn-through range in sidelobe jamming

- **Electronic masking:** controlled radiation of electromagnetic energy on friendly frequencies in order to protect the emissions of friendly communications and electronic systems against enemy electronic warfare support measures/signals intelligence without significantly degrading the operation of friendly systems
- **Emission control:** selective and controlled use of electromagnetic, acoustic or other emitters to optimize command and control capabilities while minimizing the following for operations security:
  - detection by enemy sensors
  - mutual interference among friendly systems
  - enemy interference with the ability to execute a military deception plan
- **Electromagnetic spectrum management:** planning, coordinating and managing joint use of the electromagnetic spectrum through operational, engineering and administrative procedures
- **Wartime reserve modes:** characteristics and operating procedures of sensors, communications, navigation aids, threat recognition, weapons and countermeasures systems that will contribute to military effectiveness if unknown to or misunderstood by opposing commanders before they are used, but could be exploited or neutralized if known in advance
- **Electromagnetic compatibility:** ability of systems, equipment and devices that use the electromagnetic spectrum to operate in their intended environments without causing or suffering unacceptable or unintentional degradation because of electromagnetic radiation or response

FREQUENCY BANDS

Fig. 1: Frequency bands from 1 MHz to 300 GHz



ISM bands

The ISM radio bands are portions of the radio spectrum reserved internationally for industrial, scientific and medical (ISM) purposes, excluding applications in telecommunications.

See table below and note the following type differentiation.

Type A: The use of these frequency bands for ISM applications shall be subject to special authorization by the administration concerned, in agreement with other administrations whose radiocommunications services might be affected. In applying this provision, administrations shall have due regard to the latest relevant ITU-R recommendations.

Type B: These frequency bands are also designated for ISM applications. Radiocommunications services operating within these bands must accept harmful interference which may be caused by these applications.

Frequency range	Bandwidth	Type	Remark	Availability
6.765 MHz to 6.795 MHz	30 kHz	A	subject to local acceptance	
13.553 MHz to 13.567 MHz	14 kHz	B		worldwide
26.957 MHz to 27.283 MHz	326 kHz	B	CB radio	worldwide
40.66 MHz to 40.7 MHz	40 kHz	B		worldwide
433.05 MHz to 434.79 MHz	1.74 MHz	A	remote control	Europe
902 MHz to 928 MHz	26 MHz	B		America
2.4 GHz to 2.5 GHz	100 MHz	B	Wi-Fi	worldwide
5.725 GHz to 5.875 GHz	150 MHz	B	Wi-Fi	worldwide
24.00 GHz to 24.25 GHz	250 MHz	B		worldwide
61.00 GHz to 61.5 GHz	500 MHz	A	subject to local acceptance	
122 GHz to 123 GHz	1 GHz	A	subject to local acceptance	
244 GHz to 246 GHz	2 GHz	A	subject to local acceptance	

RADAR FREQUENCIES

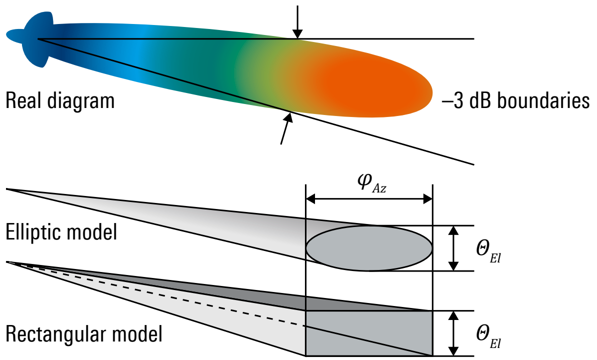
Frequency range	Application
3 MHz to 40 MHz	over-the-horizon radars
46 MHz to 68 MHz	wind profiler radars
150 MHz to 350 MHz	anti-stealth radars
420 MHz to 450 MHz	early warning radars
470 MHz to 494 MHz	wind profiler radars
850 MHz to 950 MHz	long range surveillance radars
1215 MHz to 1350 MHz	long range air defense and ATC radars
1270 MHz to 1295 MHz	wind profiler radars
2700 MHz to 2900 MHz	radar and navigation systems
2900 MHz to 3100 MHz	radar and navigation systems
3100 MHz to 3300 MHz	spaceborne radars
3100 MHz to 3410 MHz	airborne surveillance radars
4200 MHz to 4400 MHz	airborne radio altimeters
5250 MHz to 5725 MHz	tactical, VTS, weapon control, weather radars
5725 MHz to 5850 MHz	weather radars
8500 MHz to 10000 MHz	precision approach radars, air defence radars
8850 MHz to 9000 MHz	maritime navigation radars, shore-based radars
9200 MHz to 9300 MHz	maritime navigation radars, shore-based radars

Frequency range	Application
9300 MHz to 9500 MHz	airborne weather and military multifunction radars
9500 MHz to 9800 MHz	spaceborne radars
10.0 GHz to 10.5 GHz	civil and military radars
13.25 GHz to 14.0 GHz	military radars, ship berthing radars
15.4 GHz to 15.7 GHz	ground movement radars
15.7 GHz to 17.2 GHz	military radar applications
17.2 GHz to 17.7 GHz	missile control radars
24.0 GHz to 24.5 GHz	rain radar from satellites, didactical radars (ISM)
31.8 GHz to 33.4 GHz	airborne radars
33.4 GHz to 35.2 GHz	motion sensors, short range radars
35.2 GHz to 36.0 GHz	rain radar from satellites
59.0 GHz to 64.0 GHz	airborne radars
76.0 GHz to 77.5 GHz	road transport and traffic telematic radars
92.0 GHz to 95.0 GHz	short range radars
94.0 GHz to 94.1 GHz	cloud profiler radars
237.9 GHz to 238.0 GHz	spaceborne cloud radar

ANTENNA MODELS

To be able to make calculations for antennas, some simplifications or even models are customary for the calculations.

Fig. 2: Radiated energy of antenna patterns



$$G_{elliptic} = \frac{4\pi}{sin\varphi_{Az} sin\theta_{El}} \qquad G_{rectangular} = \frac{16}{sin\varphi_{Az}\, sin\theta_{El}}$$

- The radiated energy is completely concentrated in the mainlobe of the antenna pattern. There would be no sidelobes.
- All radiated energy is within the half-power beamwidth of the antenna. Outside of these –3 dB boundaries, there is no energy radiation.
- Within the –3 dB boundaries, the energy is uniformly distributed.

Applying these assumptions separately to the vertical and horizontal half-power beamwidths of the antenna results in a rectangular model (see Fig. 2, page 9). When these angles are combined to form a solid angle, the result is a model with an elliptical shape for the antenna pattern.

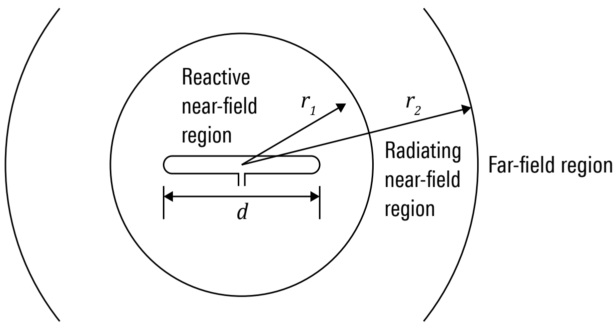
These models allow comparison of power densities on illuminated surfaces. Most often the simpler rectangular model is used.

The difference between both models corresponds to the difference between 16 and 4π and is equal to about 78%. The correction of these inaccuracies concerning the real antenna pattern is made using a so-called antenna efficiency factor k_a (see page 12) that is estimated for each antenna shape.

Field regions around an antenna

The boundaries between the individual regions depend on the wavelength λ and the size of the antenna. They exhibit a fluid progression and are not uniformly defined in the literature in terms of boundaries.

Fig. 3: Field regions



Reactive near-field region: The area in the immediate vicinity of the antenna. The electric and magnetic fields are not necessarily in phase with one other and the angular field distribution is highly dependent on the distance and direction from the antenna.

$$r_1 \approx 0.62\sqrt{\frac{d^3}{\lambda}}$$

d Maximum dimension of antenna
λ Wavelength

Radiating near-field (Fresnel) region: The electric and magnetic fields are in phase, but the angular field distribution is still dependent on the distance from the antenna.

For short antennas (i.e. $d << \lambda$): $r_2 \geq 2\lambda$

For large antennas: $r_2 \approx \frac{2d^2}{\lambda}$

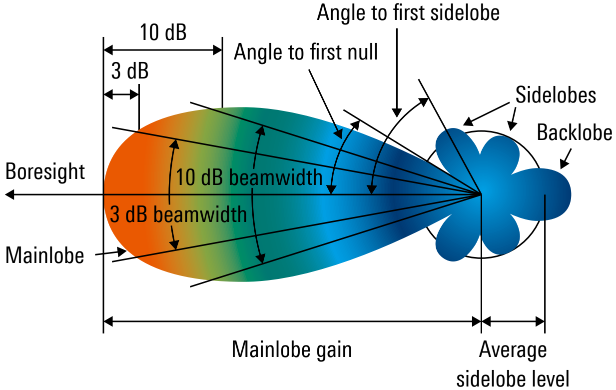
Far-field (Fraunhofer) region: The electric and magnetic fields are in phase, perpendicular to one other and perpendicular also to the direction of propagation. The angular field distribution is essentially independent of the distance from the antenna and can be approximated with spherical wavefronts.

Note: Directivity patterns and antenna gain are always expressed assuming far-field conditions.

Antenna pattern

Antenna pattern is a term for the angular dependence of the strength of the radio waves from the antenna source.

Fig. 4: Antenna gain in terms of direction



The **boresight** is the direction in which the antenna points. This is usually the direction of maximum gain when no electronic swiveling take place.

The **mainlobe** is the primary or maximum gain beam of the antenna. The mainlobe has both a vertical and a horizontal shape that can be the same (symmetrical) or different (asymmetrical). The power at this point is defined as 0 dB. All other values are relative to this point.

Antennas also have beams other than a mainlobe:

- The **backlobe** points in the opposite direction from the mainlobe.
- The **sidelobes** point in a different direction.
- **Grating lobes** is the term for very strong sidelobes in the antenna pattern. They may have approximately the size as the mainlobe. Grating lobes sometimes occur with phased array antennas depending on the steering direction (and also with ultrasound probes used in sonography).

Antenna gain

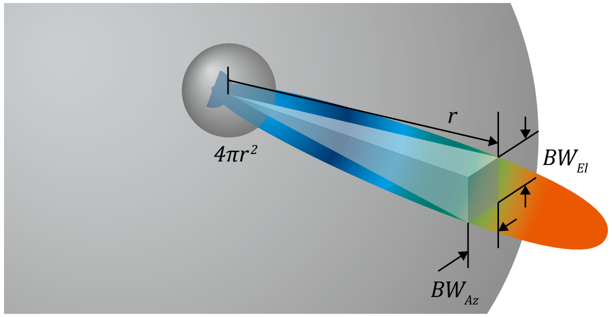
Comparison of the illuminated area with the area of an isotropic radiator (i.e. spherical surface). Rectangular model, angles in radians, for very small angles, $sin\varphi \approx \varphi$:

$$G = \frac{\text{Surface of sphere}}{\text{Surface of rectangle}} = \frac{4\pi \cdot r^2}{r^2 \cdot sin\,\varphi \cdot sin\,\theta} \approx \frac{4\pi}{\varphi \cdot \theta}$$

If beamwidth angles are in degrees:

$$G = \frac{4\pi}{\frac{\pi}{180} BW_{Az} \cdot \frac{\pi}{180} BW_{El}} = \frac{4 \cdot 180^2}{\pi \cdot BW_{Az} \cdot BW_{El}} \approx \frac{41253}{BW_{Az} \cdot BW_{El}}$$

Fig. 5: Antenna gain of rectangular model



Antenna efficiency

The theoretical models result in loss factors compared to the real antenna. This corresponds approximately to the percentage of total input or output power to or from an antenna that is transmitted or received within the –3 dB beamwidth (10 % frequency range dish can have an antenna efficiency factor $k_a \approx$ 55 %, 2 GHz to 18 GHz dish efficiency correlates with $k_a \approx$ 30 %).

Gain of non-symmetrical 55 % efficient parabolic dish.

Gain as factor:

$$G \approx \frac{23000}{BW_{Az} \cdot BW_{El}}$$

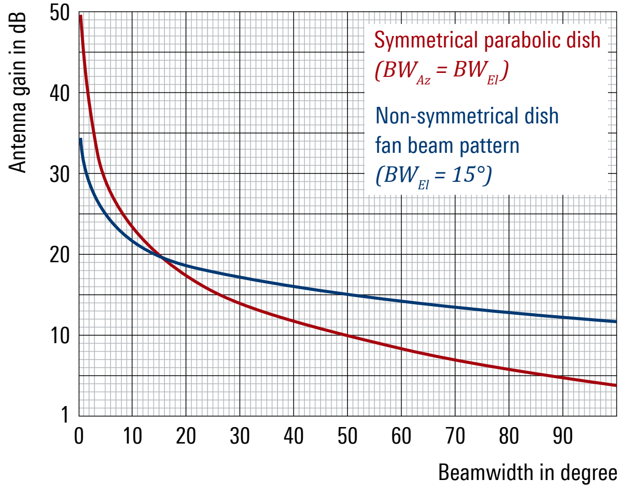
Gain in dB:

$$G \approx 43.6 - 10\log(BW_{Az} \cdot BW_{El})$$

This means that symmetrical parabolic dishes with a beamwidth of 1° have a gain of nearly 43.6 dBi.

Antenna efficiency	Adjustment to gain (versus 55 %)
60 %	+0.4 dB
50 %	–0.4 dB
45 %	–0.9 dB
40 %	–1.4 dB
35 %	–2.0 dB
30 %	–2.6 dB

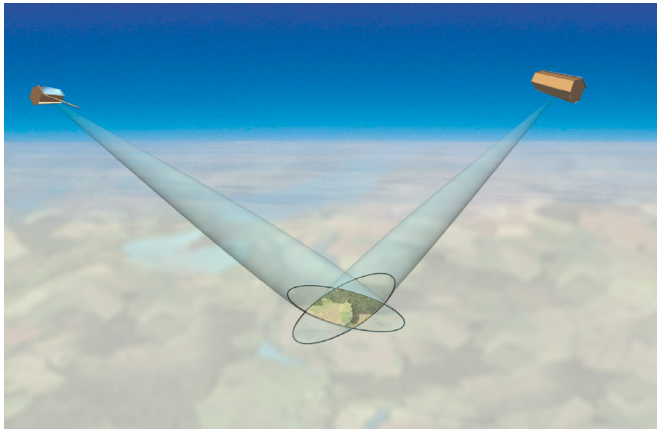
Fig. 6: Antenna gain versus beamwidth



Antenna beamwidth (Θ)

The beamwidth of the radar antenna is usually understood to mean the half-power beamwidth (–3 dB) for simplification, i.e. the boundaries of the antenna pattern where only half the transmit power is to be measured (see Fig. 2, page 9).

An additional term is **two way beamwidth**. This term means that radar can detect a target only if the antenna pattern of the transmitter and the receiver have common illumination areas.



The elliptical areas of illumination detect the same objects.

In the case of synthetic aperture radar, this also means that the elliptical areas of illumination detect the same objects. Therefore, the resolving power is smaller than for classical monostatic radar using real aperture: here at the boundaries of –1.5 dB because only about half of the ellipse of the footprint can be illuminated by all satellite positions.

Beam solid angle (Ω)

A solid angle is a two-dimensional angle measurement with the variable name Ω. The unit of measurement is the auxiliary unit Steradian (Sr). The beam solid angle Ω_A is defined as the solid angle through which all the power of the antenna would flow if its radiation intensity were constant (and equal to the maximum value) for all angles within Ω_A (see antenna models, page 9). It is a rather theoretical value but can be approximated for antennas with very large directivity and small sidelobes:

$$\Omega_A = \theta_{Az} \cdot \theta_{El}$$

θ_{Az} Horizontal half power beamwidth
θ_{El} Vertical half power beamwidth
(both in radians)

Antenna types

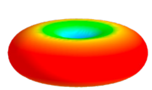
Illustration	Pattern	Typical specifications
Isotropic radiator		
		Beamwidth: 360° × 360° Gain: 0 dBi All other: individually defined like antenna under test
Halfwave dipole		
		Polarization: aligned with element orientation Beamwidth: 80° × 360° Gain: 1.76 dBi Bandwidth: 10% Frequency range: A to K

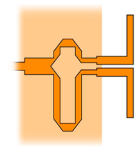
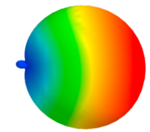
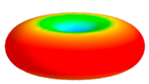
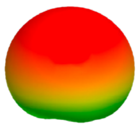
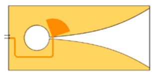
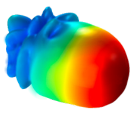
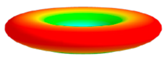
Illustration	Pattern	Typical specifications
PCB dipole with reflector		
		Polarization: aligned with element orientation Beamwidth: 70° × 90° Gain: 4.2 dBi Bandwidth: 10% Frequency range: D to K
Folded dipole		
		Polarization: aligned with element orientation Beamwidth: 70° × 90° Gain: 4.2 dBi Bandwidth: 10% Frequency range: D to K
Patch antenna		
		Polarization: linear and circular Beamwidth: 40° × 40° Gain: 2.97 dBi Bandwidth: 3% Frequency range: A to M
Tapered slot antenna		
		Polarization: aligned with element orientation Beamwidth: 50° to 70° Gain: 6 dBi to 12 dBi Bandwidth: 2 to 4 octaves Frequency range: A to K
¼ wave whip (monopole)		
		Polarization: aligned with element orientation Beamwidth: 45° × 360° Gain: 0 dB Bandwidth: 10% Frequency range: A to F

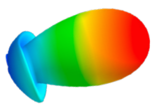
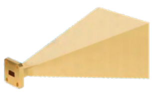
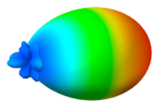
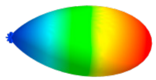
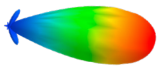
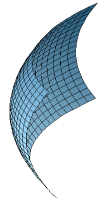
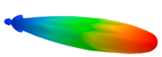
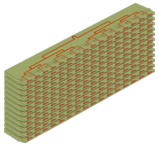
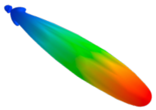
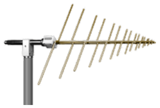
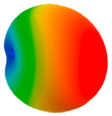
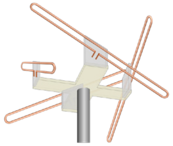
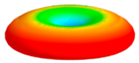
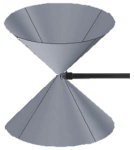
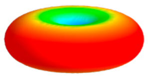
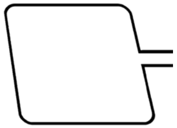
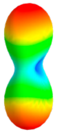
Illustration	Pattern	Typical specifications
Helix		
		Polarization: circular Beamwidth: 50° × 50° Gain: 10 dBi Bandwidth: 56 % Frequency range: A to F
Pyramidal horn		
		Polarization: linear Beamwidth: 40° × 50° Gain: 5 dBi to 15 dBi Bandwidth: 1 octave Frequency range: A to M
Conical horn		
		Polarization: linear or circular Beamwidth: 40° × 40° Gain: 5 dBi to 15 dBi Bandwidth: 1 octave Frequency range: A to M
Yagi		
		Polarization: aligned with element orientation Beamwidth: 10° to 90° Gain: 5 dBi to 17 dBi Bandwidth: 5 % Frequency range: A to F
Parabolic antenna		
		Polarization: depends on feed Beamwidth: 0.5° to 30° Gain: 10 dBi to 55 dBi Bandwidth: depends on feed Frequency range: A to K

Illustration	Pattern	Typical specifications
Phased array		
		Polarization: depends on elements Beamwidth: 0.5° to 30° Gain: depends on elements Bandwidth: 10 % Frequency range: A to K
Logarithmic-periodic dipole antenna		
		Polarization: linear Beamwidth: 80° × 60° Gain: 6 dBi to 8 dBi Bandwidth: 1½ octaves Frequency range: A to F
Lindenblad antenna		
		Polarization: circular Beamwidth: 80° × 360° Gain: 7.4 dB Bandwidth: 5 % Frequency range: A to F
Biconical		
		Polarization: aligned with element orientation Beamwidth: (40° to 100°) × 360° Gain: 0 dBi to 4 dBi Bandwidth: 25 % Frequency range: A to K
Rectangle loop		
		Polarization: horizontal Beamwidth: 80° × 360° Gain: 1.51 dBi Bandwidth: 10 % Frequency range: A to C

EFFECTIVE ISOTROPIC RADIATED POWER (EIRP)

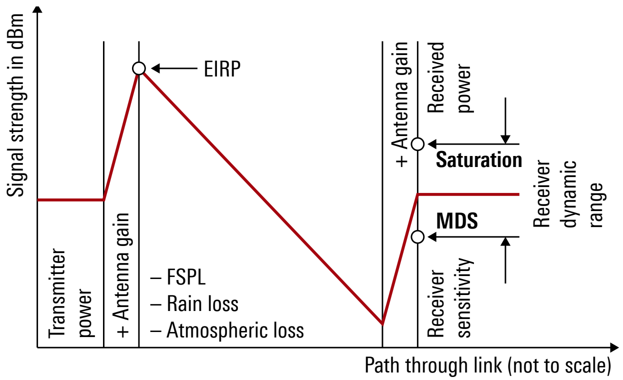
Effective isotropic radiated power is the hypothetical power that would have to be radiated by an isotropic antenna to give the same (equivalent) signal strength as the actual source antenna in the direction of the antenna's strongest beam.

$$EIRP = P_{TX} \cdot G_{TX}$$

$EIRP$	Effective isotropic radiated power in dBm
P_{TX}	Transmitted power in dBm
G_{TX}	Transmitter antenna gain in dBi

RADIO PROPAGATION

Fig. 7: Path through link from transmitter to receiver



Link budget

A link budget is an accounting of all power gains and losses between transmitter and receiver.

$$P_{RX} = EIRP - L_{TX} - L_{FSPL} - L_{atm} - L_M + G_{RX} - L_{RX}$$

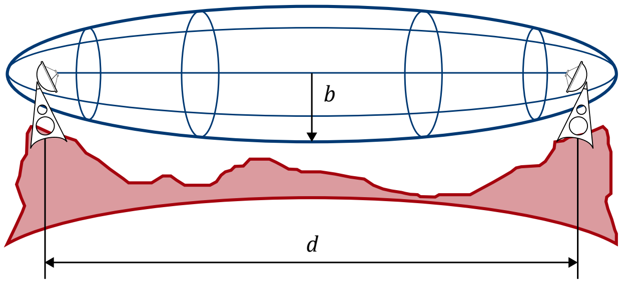
P_{RX}	Received power in dBm
$EIRP$	$P_{TX} \cdot G_{TX}$ = Effective isotropic radiated power in dBm
L_{TX}	Transmitter losses in dB (coax cable, connectors, ...)
L_{FSPL}	Free space path loss in dB
L_{atm}	Atmospheric loss in dB
L_M	Miscellaneous losses in dB (fading margin, body loss, polarization mismatch, other losses, ...)
G_{RX}	Receiver antenna gain in dBi
L_{RX}	Receiver losses in dB (coax cable, connectors, ...)

Signal and environment		Propagation model
High frequency and/or link path distant from ground and/or narrow antennas		Line of sight (FSPL)
Signal near ground or water and frequency below microwave	Link distance less than Fresnel zone radius	Line of sight (FSPL)
	Link distance greater than Fresnel zone distance	Two-ray loss model
Signal path passes near ridgeline or hill		Line of sight plus knife-edge diffraction loss

Fresnel zone

The first Fresnel zone is an ellipsoidal shaped region in space where the path difference is λ/2, centered around the line of the direct transmission path. In this region, the energy transfer between transmitter and receiver takes place. This zone must be kept largely free from obstructions to avoid interfering with the radio reception.

Fig. 8: Fresnel zone as an ellipsoidal shaped region



$$b = 0.5\sqrt{\lambda d} = 0.5\sqrt{\frac{c_0 d}{f}}$$

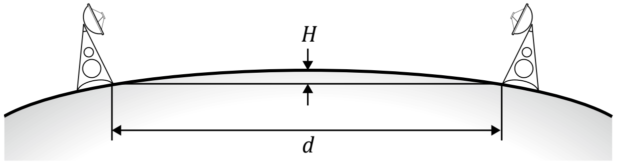
b	Maximum radius
d	Link distance
λ	Wavelength
c_0	Speed of light

An obstacle in the first Fresnel zone causes additional loss of approximately 6 dB despite a clear visual line of sight. Covering 40% of the first Fresnel zone can completely block the radio link.

Earth bulge

For transmission links, the earth bulge is the height at which an obstacle extends higher into the path due to the curvature of the earth.

Fig. 9: Relation of earth bulge and link distance



$$H = \frac{d^2}{66}$$

H	Earth bulge in m
d	Link distance in km

Fresnel zone distance (FZ)

The Fresnel zone distance is the distance from the transmitter at which the phase cancellation becomes dominant over the spreading loss.

$$FZ = \frac{4\pi h_{TX} h_{RX}}{\lambda}$$

h_{TX} Height of transmitter antenna
h_{RX} Height of receiver antenna

If the link distance is shorter than FZ, use the free space path loss (FSPL) and otherwise the two ray loss.

Free space path loss (FSPL)

FSPL is the loss between two isotropic radiators in free space, expressed as a power ratio between the transmitted power P_{TX} and the received power P_{RX}. It increases with the square of distance between the antennas because the radio waves spread out by the inverse square law and decreases with the square of the wavelength λ of the radio waves.

$$FSPL = \frac{P_{TX}}{P_{RX}} = \left(\frac{4\pi R}{\lambda}\right)^2$$

P_{TX} Transmitted power
P_{RX} Received power
R Range
λ Wavelength

Antenna polarization loss

The polarization of an antenna refers to the direction of the electric fields radiated by the antenna.

Practical values of polarization mismatch loss

Polarization		Point-like target	Volume target
Transmit	Receive		
H	H	0 dB	0 dB
H	V	–10 dB	–15 dB
V	V	0 dB	0 dB
V	H	–10 dB	–15 dB
RCP	RCP	–3 dB	–20 dB
RCP	LCP	0 dB	0 dB
LCP	LCP	–3 dB	–20 dB
H or V	RCP or LCP	–3 dB	–3 dB
PCP or LCP	V or H	–3 dB	–3 dB

Atmospheric attenuation

The atmospheric attenuation is the reduction with distance from the source of the intensity of an electromagnetic signal propagating through the atmosphere caused by interaction of the signal with gaseous constituents of the atmosphere (molecular dispersion), hydrometeors or aerosols (rain or fog).

See Fig. 10: Atmospheric and rain attenuation, page 20.

Note: Atmospheric loss and rain loss are commonly ignored below 10 GHz.

Fig. 10: Atmospheric and rain attenuation

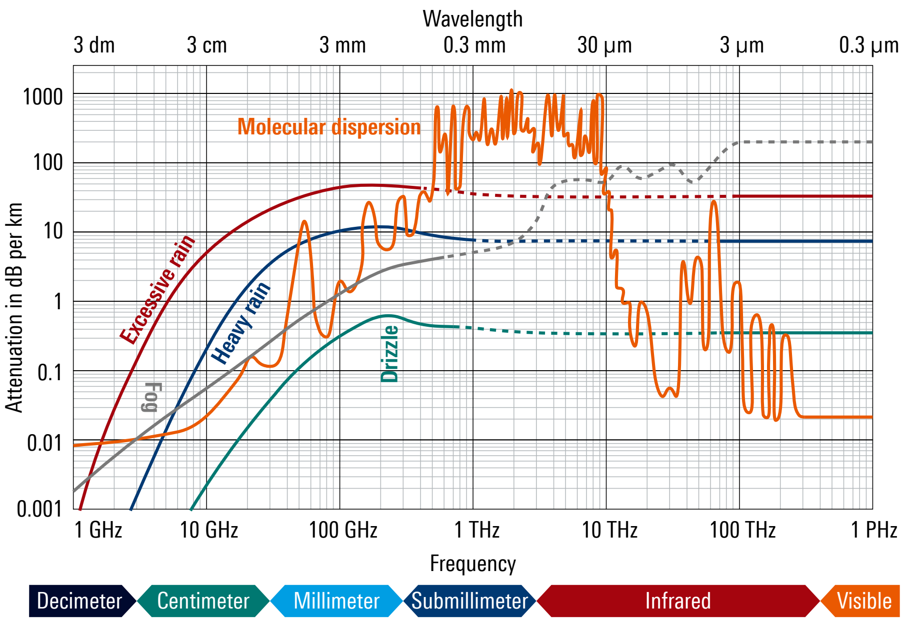
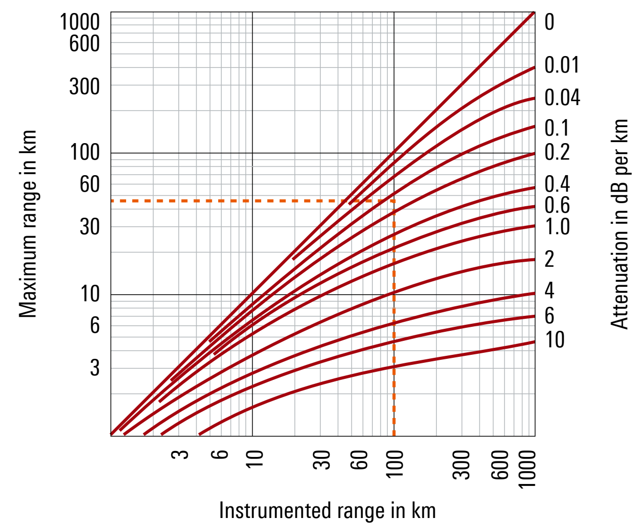


Fig. 11: Influence of atmospheric attenuation on the maximum range of a radar



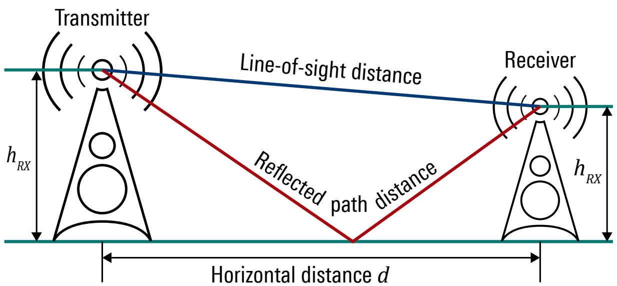
Example: Radar using 10 GHz in heavy rain has attenuation of 0.12 dB per km (see Fig. 10: Atmospheric and rain attenuation, page 20 for the attenuation per km). In addition, there is slight attenuation due to molecular dispersion of 0.02 dB per km. Added up, this equals 0.14 dB per km.

Here, the radar's original energetic maximum range of 100 km is reduced to less than 45 km.

Two ray loss model

The two ray model considers two components of the received signal at the receiving end. One of them is the line of sight (LOS) component, which is the same as the transmitted signal propagating in free space. The other component is reflected from the ground.

Fig. 12: LOS and reflected path distances



The distances traveled by the LOS ray and the reflected ray are given by:

$$d_{LOS} = \sqrt{d^2 + (h_{TX} - h_{RX})^2}$$
$$d_{ref} = \sqrt{d^2 + (h_{TX} + h_{RX})^2}$$

The phase difference is given by:

$$\varphi = \frac{2\pi\left(d_{ref} - d_{LOS}\right)}{\lambda}$$

Depending on the phase difference (φ) between the direct and reflected rays, the received signal may suffer constructive or destructive interference.

$$P_{RX} \approx P_{TX} \frac{G_{TX} h_{TX}^2 G_{RX} h_{RX}^2}{d^4}$$

In decibels (dB):

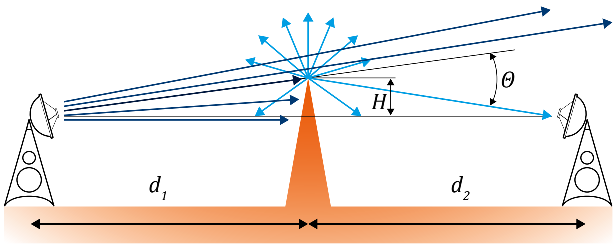
$$P_{TX} = P_{TX} + G_{TX} + G_{RX} + 20\,log(\,h_{TX}) + 20\,log(\,h_{RX}) - 40\,log(\,d)$$

This model is also known as the **two ray interference model**.

Knife edge diffraction

The knife edge diffraction loss is a loss in addition to the propagation model losses (two ray or FSPL). The line of sight path can pass above or below the top of the knife edge. If it is not too far above, knife edge diffraction loss will still occur.

Fig. 13: Knife edge diffraction



ν Fresnel-Kirchhoff diffraction parameter
H Height of knife edge relative to line of sight path if there were no knife edge
d_1 Distance to knife edge
d_2 Distance past knife edge
λ Wavelength

For estimation of the knife edge loss, we need an auxiliary variable, the **Fresnel-Kirchhoff diffraction parameter**:

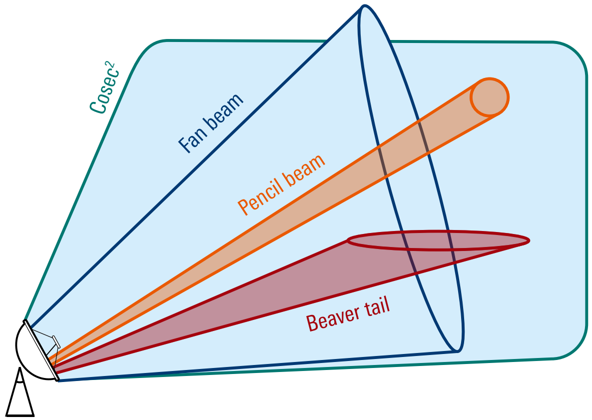
$$\nu = H\sqrt{\frac{2}{\lambda}\left(\frac{1}{d_1}+\frac{1}{d_2}\right)} = \theta\sqrt{\frac{2}{\lambda\left(\frac{1}{d_1}+\frac{1}{d_2}\right)}} \approx \sqrt{\frac{2H\theta}{\lambda}}$$

The knife edge loss (L_{KED}) can be closely approximated by:

$$\begin{array}{ll} \nu < 0 & L_{KED} = 0 \\ 0 < \nu < 2.4 & L_{KED} = 1.27\nu^2 + 9\nu + 6 \\ \nu > 2.4 & L_{KED} = 13 + 20\log\nu \end{array}$$

RADAR ANTENNA PATTERNS

Fig. 14: Radar antenna patterns at a glance



Pencil beam: a very narrow beam in both azimuth and elevation (thin like a pencil); used in 3D radars, such as instrumentation radar, weather radar and air defense radar

Fan beam: a very narrow beam in azimuth (nearly 1° to 2°) but wide in elevation (up to 30°); used in 2D radars, such as air-surveillance, naval navigation or terminal area radar

Beaver tail pattern: having a wider beamwidth in azimuth (about 5° to 10°) than in elevation (less than 1°); used in older height finders and in the glide-path part of precision approach radar

Cosecant-squared (Cosec² or CSC²) pattern: specially designed for 2D air-surveillance radar sets. The received power shall be independent of the radar range for a target with constant height (inverse Cosec² means the opposite, used in coastal radar)

Omnidirectional pattern: as much as possible without directivity; used for aeronautical radio, but also for radar as an auxiliary antenna for sidelobe suppression

Antenna beams for command guided missiles

Track beam: a thin pencil beam to track the target

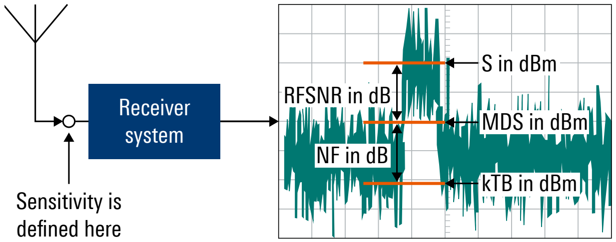
Guidance beam: slightly wider beam to transmit the commands to the surface-to-air missile

Capture beam: a short-range, very wide beam to find (to capture) a missile that was just launched

RECEIVER SENSITIVITY (S)

Sensitivity is a specific value of the minimum signal level from the antenna at which the receiver can provide an adequate output signal-to-noise ratio (SNR). The minimum discernable signal (MDS) is the signal level for 0 dB radio frequency signal-to-noise ratio (RFSNR). The MDS is generally expressed in dBm.

Fig. 15: Definition of receiver sensitivity



$S = kTB + NF + RFSNR$ (in dBm)

$kTB = -114 + 10\,log\left(\frac{BW}{1\ \text{MHz}}\right)$ (in dBm)

RECEIVER DYNAMIC RANGE (DR)

The dynamic range of a receiver in dB can be defined as the maximum possible signal level that can be received without changing the waveform (distortion due to saturation), minus the minimum discernable signal, both in dBm.

$DR \doteq P_{in,\,saturation} - MDS$ [1)]

1) $\doteq$ is the symbol for the approach of the limit value.

NOISE TYPES

In electronics, noise is an unwanted disturbance in an electrical signal:

- **Thermal noise:** generated by the random thermal motion of electrons inside an electrical conductor
- **White noise:** noise with equal power in any frequency band of a given bandwidth
- **Pink noise or flicker noise or 1/f noise:** noise with a frequency spectrum that falls off steadily into the higher frequencies
- **Brownian noise or red noise:** kind of noise produced by Brownian motion; its power density decreases by 6.02 dB per octave with increasing frequency over a frequency range (frequency density proportional to $1/f^2$)
- **Blue noise or azure noise:** power density increases by 3.01 dB per octave with rising frequency over a finite frequency range
- **Shot noise:** results from unavoidable random statistical fluctuations of the electric current
- **Dark noise:** shot noise level beyond the sensitivity of a spectrometer or light sensor
- **Burst noise (or "popcorn noise"):** consists of sudden step-like transitions between two or more discrete voltage or current levels at random and unpredictable times
- **Transit-time noise:** If the time taken by the electrons to travel from emitter to collector in a transistor becomes comparable to the period of the signal being amplified (i.e. at frequencies above VHF and beyond), the transit-time effect occurs and the noise input impedance of the transistor decreases.
- **Phase noise:** the frequency-domain representation of random fluctuations in the phase of a waveform, corresponding to time-domain deviations from perfect periodicity (jitter)

Noise factor (F_n)

Noise factor (F_n) is a measure of the way in which a system component degrades the signal-to-noise ratio (SNR).

$$F_n = \frac{\mathrm{SNR_{out}}}{\mathrm{SNR_{in}}}$$

Noise figure (NF)

Noise figure (NF) is the noise factor converted to dB.

$$NF = 10\,log(F_n)$$

Noise temperature (T_e)

The equivalent noise temperature (T_e) is the temperature of a hypothetical resistor at the input of an ideal noise-free device that would generate the same output noise power per unit bandwidth as that at the noise source at a specified frequency.

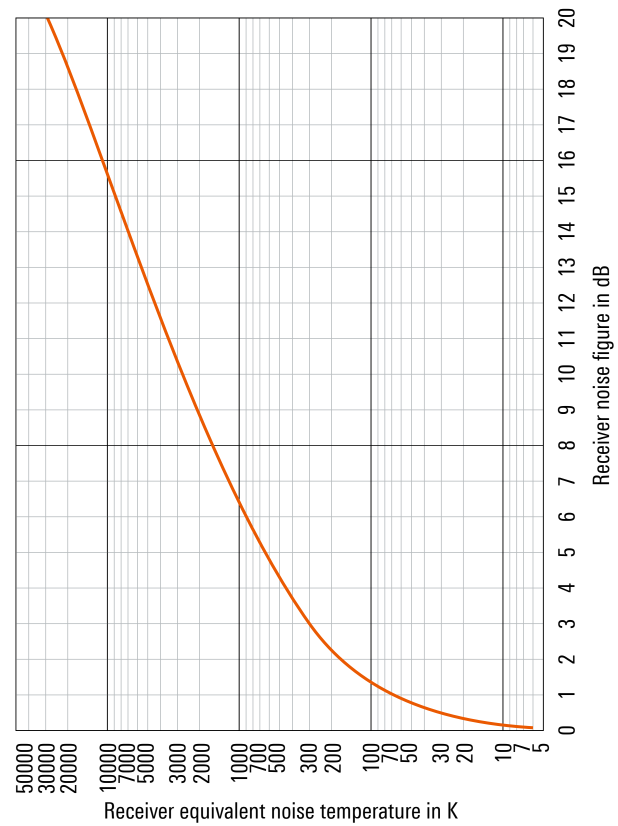
$$T_e = 290 - (F_n - 1) \qquad T_e = 290 \cdot \left[10^{\left(\frac{NF}{10}\right)} - 1\right]$$

For example, a receiver with a noise figure of 0.7 dB has the same internal noise as an ideal receiver with a matched input resistance at 51 K. Noise temperature is proportional to noise power, and the total noise temperature of two or more noise sources combined is the sum of the noise temperature of all of the sources.

Signal-to-quantization-noise ratio (SQNR)

SQNR is a measure of the quality of quantization or digital conversion of an analog signal. It is defined as the normalized power of the signal divided by the normalized power of the quantization noise. The SQNR in dB is approximately equal to six times the number of bits of the analog-to-digital converter (ADC). For example, the maximum SQNR for 16 bit is about 96 dB.

Fig. 16: Receiver noise temperature versus noise figure



Signal-to-noise and distortion ratio (SINAD)

Signal-to-noise and distortion ratio (SINAD) is a measure of the quality of a signal. SINAD is widely used as a parameter for measuring radio sensitivity.

$$\mathrm{SINAD} = 10\,log_{10}\left(\frac{P_S + P_N + P_D}{P_N + P_D}\right)$$

SINAD	Signal-to-noise and distortion ratio
P_S	Power of signal
P_N	Power of noise
P_D	Power of distortion

Signal-to-noise-plus-interference ratio (SNIR)

SNIR (or signal-to-interference-plus-noise ratio (SINR)) is defined as the power of a signal of interest divided by the sum of the interference power and the power of background noise.

$$\mathrm{SNIR} = \frac{P_S}{P_N + P_I}$$

P_S	Power of signal
P_N	Power of noise
P_I	Power of interference

The value range of the SINR is between –12 dB and +40 dB. Good connections exhibit values from about +10 dB upwards. An SINR between 0 dB and 9 dB is still quite usable. With measured values below 0 dB, however, noise and/or interference predominate. If the interference power is zero, this is equivalent to the signal-to-noise ratio (SNR).

Effective number of bits (ENOB)

The ENOB is a measure of the dynamic range of an analog-to-digital converter (ADC), digital-to-analog converter (DAC) or associated circuitry. It describes the effective resolution of the system in bit.

$$\mathrm{ENOB} = \frac{\mathrm{SINAD} - 1.76}{6.02}$$

SINAD	Signal-to-noise and distortion ratio in dB
1.76 =	10log(1.5), quantization error in an ideal ADC
6.02 =	20log(2), converts decibel (a decimal log_{10} power value) to bit (a binary log_2 voltage value)

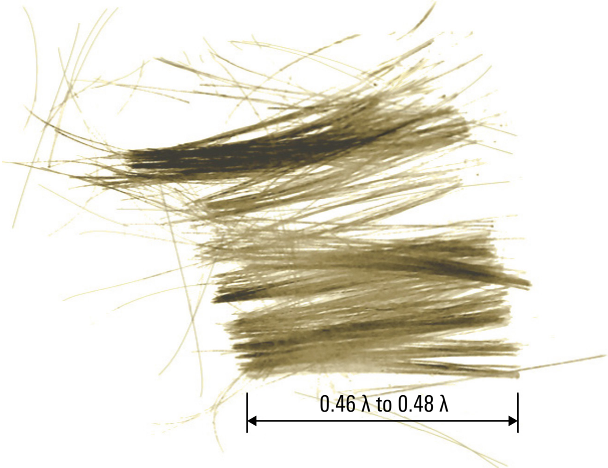
JAMMING

Mechanical jamming using chaff, corner reflectors and decoys.

Chaff

Chaff is a radar attack in which aircraft or other targets spread a cloud of small, thin pieces of aluminum, metallized fiberglass or plastic that either appears on the radar screen as a cluster of primary targets or swamps the screen with multiple returns.

Fig. 17: Chaff



Radar cross section (RCS) of chaff

Ribbon-shaped pieces of electrically conductive material deployed by aircraft to conceal other aircraft. Formerly thin staniol strips, now thin aluminum-vaporized glass fibers, generate strong clutter over large areas, moving with wind speed.

- Chaff fall rate ≤ 0.5 m/s
- Chaff cloud is effective 0.5 s after the start of its container; it remains in the air for up to 30 min.

RCS of single dipole is:

- Maximum: $\sigma_1 = 0.86 \cdot \lambda^2$ (tangentially oriented, same polarization)
- Average: $\sigma_1 = 0.155 \cdot \lambda^2$ (over randomly oriented dipoles)

RCS of the pulse volume V, page 43 including N dipoles of chaff:

- $0.925 \cdot N \cdot \sigma_1$ with λ spacing
- $0.981 \cdot N \cdot \sigma_1$ with 2λ spacing
- $N \cdot \sigma_1$ with wide spacing

The number of dipoles can be calculated by pulse volume divided by spacing to the power of three, e.g. by 2λ spacing: $N = V / (2\lambda)^3$.

Radar decoys

The purpose of any decoy is to make a sensor believe that it is seeing something real and then focus its action against the decoy.

Passive corner reflector decoys

(see retroreflectors, page 51)

Active decoys

Active decoys receive the radar's transmitted signal, amplify it, and retransmit it in real time. They thus generate a much higher RCS. Active decoys may use van Atta arrays, page 51.

$$\sigma = 39 + G_{amplifier} - 20\log(f)$$

σ	(Simulated) radar cross section
$G_{amplifier}$	Gain of amplifiers
f	Frequency in MHz

Fig. 18: Active decoys

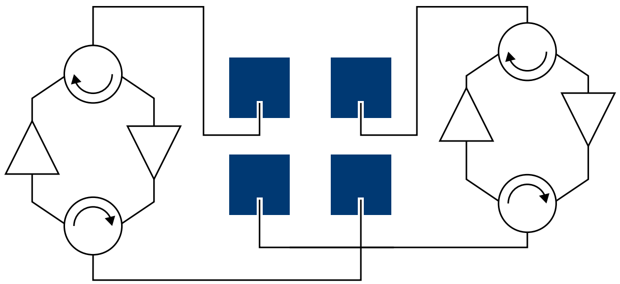
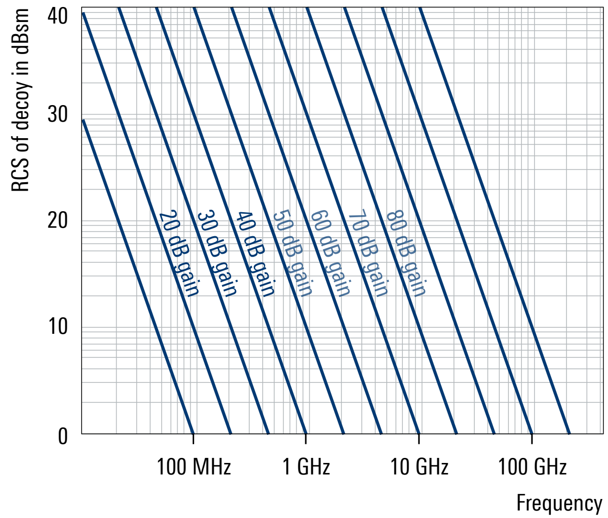


Fig. 19: RCS of decoys



Note: The amplifier gain cannot be very high because of the danger of feedback and self-oscillations.

Electronic jamming and deception

- **Noise jamming:** a continuous random signal radiated with the objective of concealing the aircraft echo from the enemy radar
- **Spot jamming:** narrow frequency band jamming concentrated against a specific radar at a particular frequency
- **Swept jamming:** narrowband jamming that is swept through the desired frequency band in order to maximize power output
- **Barrage jamming:** faster frequency shift such that the entire frequency band is jammed quasi-simultaneously
- **Base jamming:** a type of barrage jamming in which one radar is jammed effectively at its source at all frequencies; all other radars continue working normally
- **Pulse jamming:** noise jamming synchronous to antenna rotation of a search radar, making it harder to discover the jammer direction
- **Cover pulse jammer:** transmits noise if radar signal is received only; any aircraft flying behind the jammer is covered
- **Blip enhancement:** simulates a larger than real target
- **Repeater jamming:** receives the radar's waveform, records it and retransmits it after a delay
- **Deceptive jamming or range gate pull-off (RGPO):** like repeater jammer but with increasing delay from pulse to pulse (against tracking radar)
- **Velocity deception or velocity gate pull-off (VGPO):** This involves repeating a frequency-shifted replica of the received radar signal; the frequency of the false return is slowly altered to interfere with the true Doppler shift.
- **Jammer illuminated chaff (JAFF) or chaff illumination (CHILL):** An aircraft dispenses chaff and simultaneously illuminates it with the jamming signal.
- **Cross-eye jamming (CEJ):** This aims to create worst-case angular errors in monopulse radars through displacement of the tracking radar aiming point towards the direction of the stronger jamming signal.

JAMMING-TO-SIGNAL (J/S) RATIO

J/S or J-to-S is the ratio of the power received (J) from the jamming signal transmitted from the target to the power received (S) from the radar backscatter from the target.

BURN THROUGH RANGE

The radar to target range where the target echo signal (S) can first be detected through the electronic attack (J).

SELF-PROTECTION JAMMING

Also known as mainlobe jamming (radar echo source and jammer are collocated).

$$\frac{J}{S} = \frac{4\pi \cdot R^2 \cdot ERP_{Jam}}{\sigma \cdot ERP_{Radar}}$$

Burn through range:

$$R_{BT} = \sqrt{\frac{\sigma \cdot ERP_{Radar}}{4\pi \cdot ERP_{Jam}}}$$

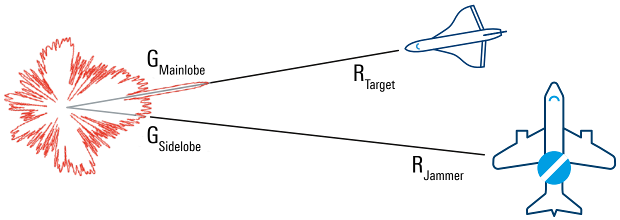
REMOTE JAMMING

Radar echo source and jammer have different locations:

- **Escort jamming:** jammer in another aircraft in slightly different angle and/or range. If the escort platform is sufficiently close to the target (within the beamwidth of the radar), the J/S calculations are the same as for self-protection jamming.
- **Support jamming or sidelobe jamming:** jammer in a platform used to protect other platforms or fulfill other mission requirements
- **Stand-in jamming:** distance of supporting jammer to the radar is smaller than distance of the aircraft to be protected to the victim radar
- **Stand-off jamming:** distance to the radar is larger than distance of the aircraft to be protected to the victim radar

J/S for support jamming

Fig. 20: Support jamming



$$\frac{J}{S} = \frac{4\pi}{\sigma} \cdot \frac{EIRP_J}{EIRP_S} \cdot \frac{G_S R_T^4}{G_M R_J^2}$$

In decibel (dB):

$$\frac{J}{S} = EIRP_J - EIRP_S + 71 - G_S - G_M + 40\log R_T - 20\log R_J - 10\log \sigma$$

Burn through range for support jamming

$$R_{BT} = \sqrt[4]{\frac{R_J^2 \cdot \sigma \cdot EIRP_S \cdot G_M}{4\pi \cdot EIRP_J \cdot G_S}}$$

COMMUNICATIONS JAMMING

$$\frac{J}{S} = \frac{ERP_J G_S R_T^2}{ERP_S G_M R_J^2}$$

ERP_J	Effective isotropic radiated power of jammer
ERP_T	Effective isotropic radiated power of target's radio
G_M	Gain of mainlobe
G_S	Average gain of sidelobe
R_T	Distance to target
R_J	Distance to jammer

All values in arbitrary but equal units except decibel.

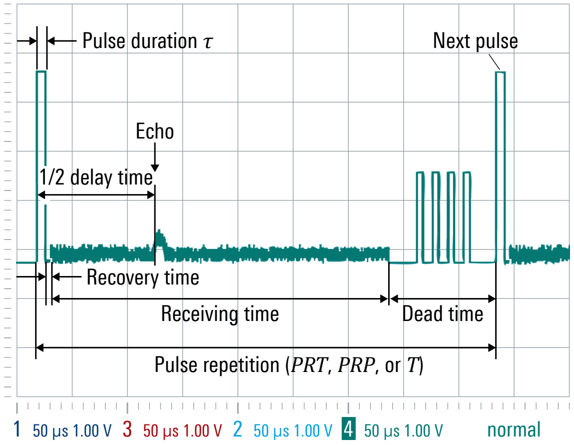
PULSE RADAR

The most common type of radar signal consists of a repetitive train of short-duration pulses.

$$PRF = \frac{1}{PRT}$$

PRF Pulse repetition frequency
PRT Pulse repetition time:
- Pulse repetition period (PRP)
- Pulse repetition interval (PRI)
- Inter-pulse period (IPP)
- Pulse duration T

Fig. 21: Pulse repetition time



- **Delay time** t_d: run time of the echo signal, used to calculate the distance:

$$R = \frac{c_0 \cdot t_d}{2}$$

- **Receiving time:** $t_{RX} = T - t_{dead} - t_{recovery}$
- **Dead time:**
  - originally to avoid ambiguous false targets
  - now: time for test routines in built-in test equipment or time for reprogramming the phased array antenna
- **Recovery time:** a switching delay due to some types of duplexers

Radar blind range

Minimal measuring range depends on the mode of operation of some duplexers.

$$R_{min} = \frac{c_0(\tau + t_{recovery})}{2}$$

There is no blind range when different transmitting and receiving antennas, or ferrite circulators are used (except shared phase shifters are used for transmitting and receiving in phased array antennas).

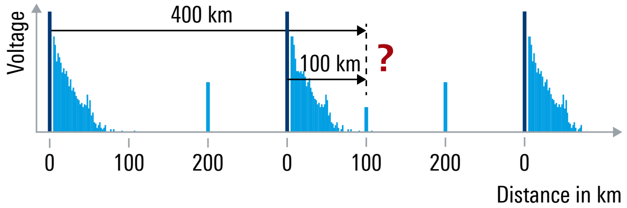
Radar unambiguous range

If the echo signal from a very long distance can only be received in the next pulse period, the calculation of the distance is ambiguous.

$$R_{unambiguous} \leq \frac{c_0(T-\tau)}{2}$$

$(T-\tau)$ means the radar must first receive the entire pulse before a target signal can be generated.

Fig. 22: Radar unambiguous range

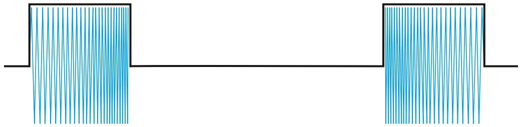


- **High PRF mode:** when PRF is chosen such that several pulses are transmitted during the time of signal round trip propagation towards a most distant target (e.g. used in satellite based radars)
- **Staggered PRF:** uses two or more PRT lengths to mark ambiguous targets; these then have no fixed position on the radar screen
- **Burst mode:** some transmitting pulses with short PRT followed by a very long dead time; used in short range coherent radars to reduce the probability of phase noise from the transmitter oscillator; moving target indication (MTI) can become more accurate

Chirp radar

Chirp radar is the general term for a pulse radar in which the transmitted pulse is intrapulse modulated. This can be a **frequency modulation on pulse (FMOP)** or a **phase modulation on pulse (PMOP)**. The transmitted pulses are longer, but have the same energy content as a short pulse with much higher pulse power (see duty cycle, page 36).

Fig. 23: Linear frequency modulation



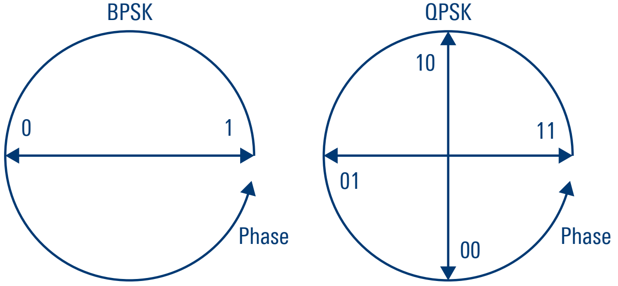
FMOP may be:

- linear frequency modulation (see Fig. 23):
  - up-chirp
  - down-chirp
- non-linear frequency modulation:
  - symmetric
  - nonsymmetric
  - exponential
  - hyperbolic
- stepped frequency modulation (increased from pulse to pulse in steps with constant frequency differences)

PMOP may be:

- bi-phase shift keying (BPSK)
- poly-phase modulation
  - quadrature phase shift keying (QPSK)
  - higher-order phase shift keying

Fig. 24: BPSK and QPSK



These long pulses are compressed into very short pulses in the receiver. The compression rate can be from two to several hundred.

For example, the pulse length may be 2 ms for strategic radars (AN/FPS-50). In the FPS-117, the pulse length is 800 µs for long range. To avoid an excessively large blind range, alternatively very short pulses with a short range may be transmitted that cover the blind range of the long pulse.

Chirp radars with complex waveforms are difficult to jam. The jammer's bandwidth must be very large and/or the waveform must be known to the jammer.

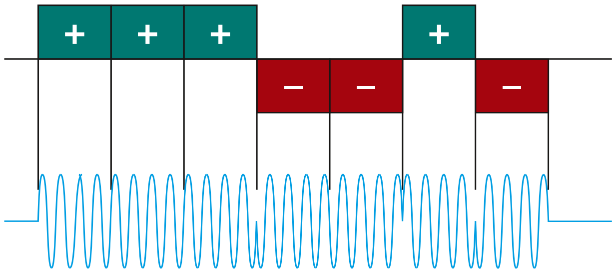
Barker codes

A Barker code is a BPSK that meets the condition of autocorrelation as perfectly as possible (size of sidelobes x_i are less than or equal to 1).

n	Code elements	Peak sidelobe level (PSL)
2	+− , ++	−6.0 dB
3	++−	−9.5 dB
4	++−+ , +++−	−12.0 dB
5	+++−+	−14.0 dB
7	+++−−+−	−16.9 dB
11	+++−−−+−−+−	−20.8 dB
13	+++++−−++−+−+	−22.3 dB

There are only seven known Barker codes but it is possible to use nested Barker codes, e.g. B5⊗B13 with a code length of n = 65.

Fig. 25: Bi-phase PMOP Barker code



Near-perfect code sequences
These are codes that do not meet the conditions of the Barker code but are close to it.

Peak sidelobe level (PSL)
The metric PSL compares the size of the highest time sidelobe to the size of the mainlobe.

$$PSL = 10\, log_{10}\, max\left(\frac{x_i^2}{x_0^2}\right)$$

x_0 Voltage level of mainlobe
x_i Voltage level of i-th time sidelobe

Integrated sidelobe level (ISL)
The metric ISL compares the total power contained within the sidelobes to the mainlobe.

$$ISL = 10\, log_{10} \sum_{i=0}^{i=n} \frac{x_i^2}{x_0^2}$$

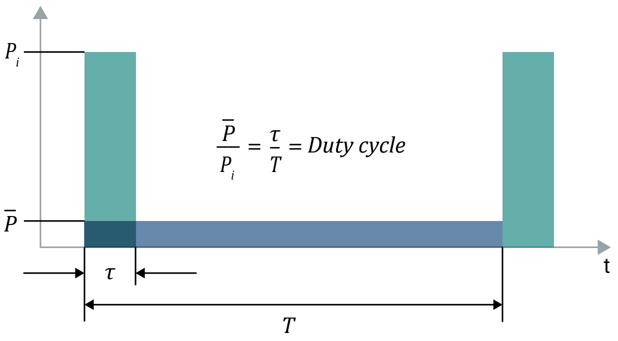
n Number of time sidelobes

Duty cycle

Duty cycle (or duty factor) is a measure of the fraction of time a radar is transmitting.

The average value is defined as that level where the pulse area above the average is equal to the (blue) area below the average between pulses.

Fig. 26: Duty cycle



CW RADAR

Continuous wave radar (CW radar) transmits a high-frequency signal continuously. The echo signal is received and processed permanently.

Unmodulated CW radar

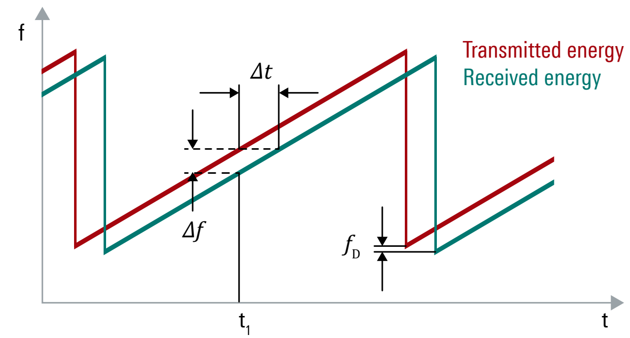
Unmodulated CW radar has no time reference other than the phase of the oscillation. It can only be used for measuring distances smaller than the wavelength. Everything above this is extremely ambiguous. Therefore, it can be used only as a Doppler radar or as a control of the constancy of a known distance.

Frequency modulated CW radar (FMCW)

Any defined change of the oscillation, i.e. modulation, enables a time (and therefore a distance) measurement. In sawtooth frequency modulation, however, the frequency difference Δf between the current emitted frequency and the reflected frequency as a measure of distance is superimposed on the Doppler frequency f_D as a measure of velocity [1)].

[1)] Therefore, a cheap naval radar using FMCW cannot work at an airfield. The expected Doppler frequencies would be much larger than the frequency differences due to the run time delay.

Fig. 27: FMCW principle



$$R = \frac{c_0|\Delta t|}{2} = \frac{c_0|\Delta f|}{2\left(\frac{d(f)}{d(t)}\right)}$$

R	Measured distance with FMCW
c_0	Speed of light
Δt	Run time difference
Δf	Frequency difference between actual oscillator and received echo signal

As in any radar, the range resolution depends on the bandwidth of the transmitted signal:

$$\Delta R \geq \frac{c_0}{2(f_{\text{high}} - f_{\text{low}})}$$

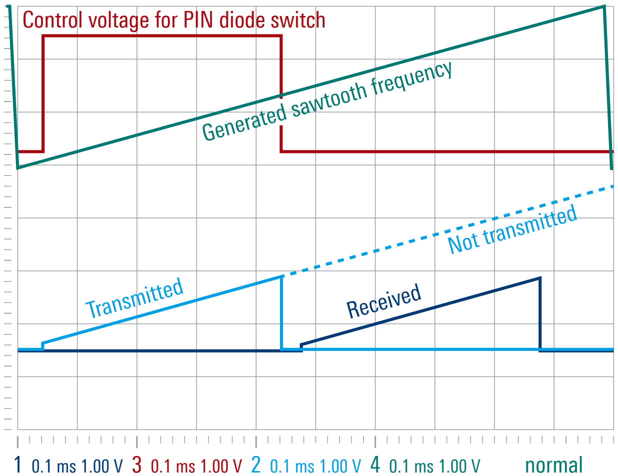
f_{high}	Upper frequency of the sawtooth
f_{low}	Lower frequency of the sawtooth

The range resolution in the 24 GHz ISM band, page 7 can only be 0.6 m at best.

Frequency modulated interrupted continuous wave (FMiCW) radar

FMiCW radar is defined as a pulse radar because the transmitter is switched off before the measurement is finished. However, internally the transmitter's source continues to operate and allows signal processing as with FMCW radar. The main advantage is that higher transmitted power and increased receiver sensitivity are possible. FMiCW technology is commonly used in traffic telematic radars.

Fig. 28: FMiCW radar



Probability of detection (P_D)

$$P_D = \frac{\text{Detected targets}}{\text{Sum of all possible targets}}$$

P_D is usually between 0.8 and 0.9 and is a compromise between P_D and the false alarm rate.

False alarm rate (FAR)

A false alarm is an erroneous radar target detection caused by noise or other interfering signals exceeding the detection threshold.

$$FAR = \frac{\text{False alarms per PRT}}{\text{Number of range cells}}$$

Constant false alarm rate (CFAR) uses a dynamic threshold depending on the noise or interfering signal level.

Dwell time (T_D)

Time that an antenna beam spends on a target.

$$T_D = \frac{\theta_{Az}}{6 \cdot n}$$

θ_{Az}	Beamwidth in azimuth
n	Turn speed n of antenna (in rotations per minute)
PRT	Pulse repetition time, page 33

Hits per scan

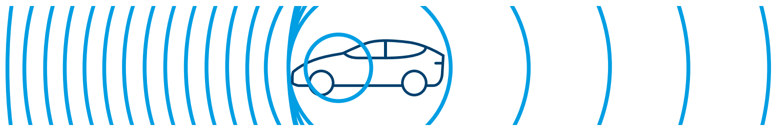
This term is used for a search radar with a rotating antenna and stands for the number of received echo pulses for a single target per antenna turn.

$$m = \frac{T_D}{PRT} = \frac{\theta_{Az}}{6 \cdot n \cdot PRT}$$

Hit numbers from 1 or 3 to 20 are necessary depending on the working principle of the radar system (bearing measurement with monopulse antenna or with sliding window).

DOPPLER FREQUENCY

Fig. 29: Doppler effect



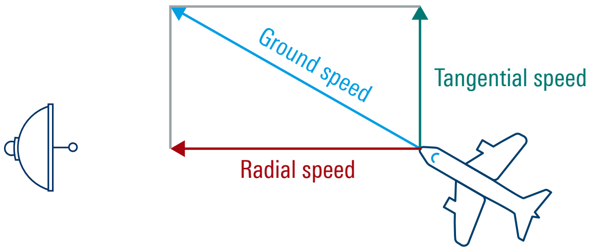
$$f_D = \frac{2v_r}{\lambda} = \frac{2v_r f_{tx}}{c_0}$$

f_D	Doppler frequency
f_{tx}	Transmitter frequency
λ	Wavelength of f_{tx}
c_0	Speed of light
v_r	Radial speed

Radial speed

The radial speed is the part of the speed that acts towards the radar or away from it.

Fig. 30: Different speeds



Jet engine modulation (JEM)

JEM is the Doppler frequency of the rotation of the compressor blades of the turbine. It occurs modulated at cavity return, page 45.

Doppler dilemma

- Maximum unambiguous range needs a PRF **as low as possible**
- Maximum unambiguous velocity needs a PRF **as high as possible**
- There is no single PRF that can maximize both at the same time

Nyquist sampling theorem: To measure a frequency f_d, it is necessary to sample at a frequency of at least $2 \cdot f_d$.

Maximum unambiguous Doppler velocity:

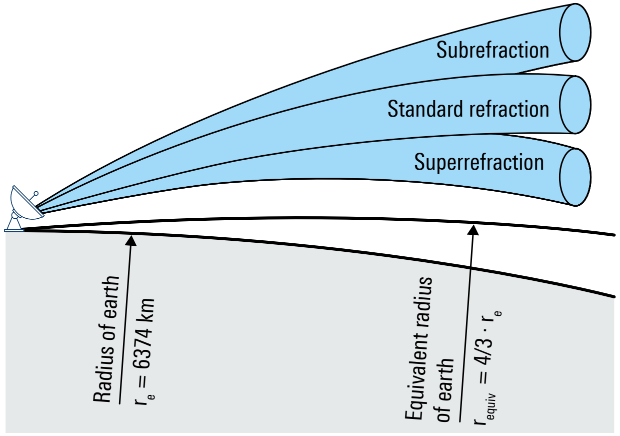
$$v_{max} = \frac{PRF \cdot \lambda}{4}$$

λ	Transmitter wavelength
PRF	Pulse repetition frequency, page 33

HEIGHT ESTIMATION

The radar beam does not propagate in a straight line in the earth's atmosphere. Under normal atmospheric conditions, it undergoes refraction in the atmosphere. This acts as a bend along the surface of the earth but not with the same radius. Therefore, an equivalent earth radius is used in the formulas, which is one third longer.

Fig. 31: Refractions

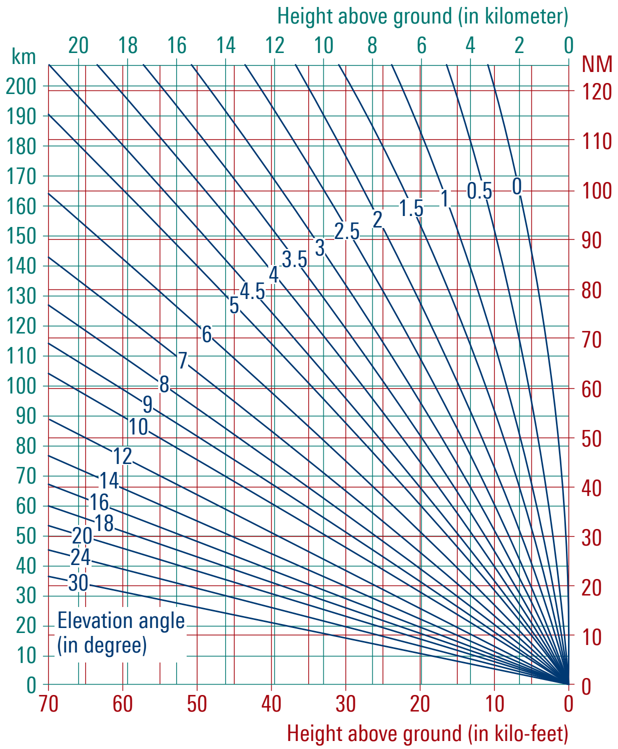


Since the actual strength of the refraction can only be determined inaccurately, the rounded value of $r_{equiv} \approx 8500$ km is sufficiently accurate.

$$H = R \cdot sin\, \varepsilon + \frac{R^2}{2r_{equiv}}$$

H	Approximate computed target altitude
r_{equiv}	Equivalent radius of earth ≈ 8500 km
R	Measured target range
ε	Elevation angle read at turntable of antenna

Fig. 32: Influence of refractions on range of radio horizon



NM: Nautical mile

REFRACTION CLASSIFICATION

Refraction is caused by the slightly different propagation speed of electromagnetic waves in air layers of different density. It depends on the refractivity gradient N (also known as the refractivity N).

$$N = 776\frac{\rho}{T} + 3.73 \cdot 10^6 \frac{e}{T^2}$$

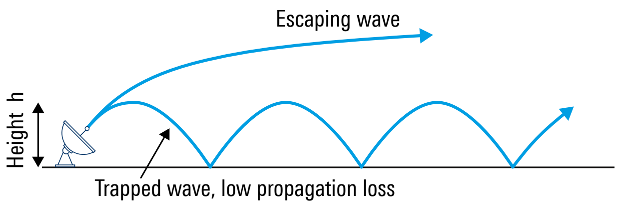
N	Refractivity gradient
ρ	Air pressure in kPa
T	Absolute temperature in Kelvin
e	Partial pressure of water vapor

Class	N/km	Effect
Standard refraction	−40	Standard atmosphere; waves bend towards earth, 4/3 earth model
Normal refraction	0 to −79	Normal variation of refractivity around the mean of the standard atmosphere
Sub-refraction	positive	Waves bend away from earth, distance to the radar horizon decreases
Super-refraction	−80 to −157	Waves bend towards earth more rapidly than in the normal atmosphere, distance to the radar horizon increases to ∞
Trapping or ducting	< −157	Radius of curvature smaller than earth radius; above a reflecting surface the waves are trapped in a duct

A **standard atmosphere** is a hypothetical vertical distribution of the atmospheric temperature, pressure and density which by international agreement is considered to be representative of the atmosphere for pressure-altimeter calibrations and other purposes.

Ducting

Fig. 33: Ducting



Ducts can trap radar waves. They are formed when there is a strong negative refractivity gradient in a thin layer of atmosphere:

- Elevated ducts can form higher up in the troposphere at boundaries of air layers of different density
- Surface based ducts are often caused by warm dry air flowing in over the sea from the land in a height up to 1000 m. Ducts form on land and over the sea with heights of not more than a few hundred meters.
- Evaporation duct, a low duct often present over the sea up to a height from 5 m to 15 m. Caused by high partial pressure of water vapor (exploited e.g. by the Italian coastal surveillance radar MM/TPS-755).

Ducting requires suppression of fixed targets at long distances.

RADAR HORIZON

Range to horizon:

$$R_{NM} = 1.23\sqrt{h_{Radar}}$$

R_{NM} Radar horizon in NM
h Height of antenna in ft

$$R_{km} = 4.12\sqrt{h_{Radar}}$$

R_{km} Radar horizon in km
h Height of antenna in m

Maximum range to an aim beyond the horizon:

$$R_{NM} = 1.23\left(\sqrt{h_{Radar}} + \sqrt{h_{aim}}\right)$$

h in ft

$$R_{km} = 4.12\left(\sqrt{h_{Radar}} + \sqrt{h_{aim}}\right)$$

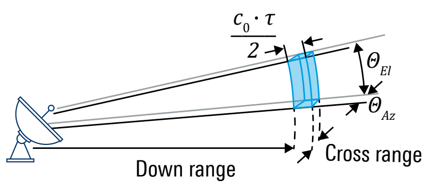
h in m

RADAR RESOLUTION CELL

Point-like targets

If two point-like targets are in one resolution cell, the classic pulse radar sees only one target.

Fig. 34: Point-like targets



Radar range resolution

For a simple keyed on/off pulse modulation:

$$S_r \geq \frac{c_0 \cdot \tau}{2}$$

τ Pulse duration of transmitted pulse
S_r Radial spacing

For a radar using intra-pulse modulation, the range resolution depends on the pulse duration of the compressed pulse. The pulse compression ratio (PCR) depends on the transmitted bandwidth BW_{tx}, i.e. the range resolution depends on the bandwidth.

$$S_r \geq \frac{c_0}{2 \cdot BW_{tx}} = \frac{c_0 \cdot \tau}{2 \cdot PCR}$$

Radar angular resolution

Radar angular resolution is the minimum distance between two equally large targets at the same down range that the radar is able to distinguish and separate from one other. It is easier to separate two targets when the spacing is larger than the half-power beamwidth of the antenna [2]. Sophisticated radars can nevertheless distinguish between two targets within the beamwidth when known radar signatures differ (e.g. at Doppler frequencies).

$$S_A \geq 2R \cdot sin\frac{\Theta}{2}$$

Volume targets

If the resolution cell is filled with a cloud of chaff or with rain drops, it is known as a volume target. The size of the volume V is:

$$V = \frac{\pi \theta_{Az} \theta_{El} R^2 c_0 \tau}{8}$$

θ_{Az} Horizontal beamwidth
θ_{El} Vertical beamwidth of antenna pattern (both in radians)
R Range to radar
c_0 Speed of light
τ Transmitter pulse width (or compressed pulse width)

Since the pulse volume increases with the square of the distance, the radar cross section, page 47 of the volume also increases and contains more reflective particles. Therefore, the radar equation for weather radar has only a square root instead of a fourth root as for point-like targets.

[2] Refer to the simplifications for antenna calculations, page 8.

ONE-WAY LINK EQUATION

The one-way link equation (transmitter to receiver) is commonly used in radar warning receivers, secondary radars and communications.

$$P_{rx} = \frac{EIRP_{TX} \cdot G_{RX} \lambda^2}{(4\pi R)^2}$$

Note: keep R and λ in same units

TWO-WAY RADAR EQUATION

$$R_{max} = \sqrt[4]{\frac{P_{TX} \tau G^2 \lambda^2 \sigma}{(4\pi)^3 kT \cdot L_{tot}}}$$

P_{TX}	Transmitter pulse power	stands for energy
τ	Transmitted pulse length	
G	Antenna gain	
λ	Carrier frequency's wavelength	
σ	Radar cross section	
k	Boltzmann constant = $1.3807 \cdot 10^{-23}$ Ws K^{-1}	stands for receiver noise
T	Absolute temperature in Kelvin	
L_{tot}	Sum of internal and external losses	

Losses

Loss components	Symbol	Loss
Atmospheric/rain loss	L_a	1.2 dB
Beamshape loss	L_{ant}	1.3 dB
Beamwidth factor	L_B	1.2 dB
Filter matching loss	L_n	0.8 dB
Fluctuation loss (for P_d = 0.9)	L_f	8.4 dB
Integration loss	L_i	3.2 dB
Miscellaneous signal-processing loss	L_x	3.0 dB
Receive line loss	L_r	1.0 dB
Transmit line loss	L_t	1.0 dB
Total system loss	L_{tot}	**21.1 dB**

The sum of losses in the table represents a very stringent value. Well designed radars typically have a more reasonable total loss from 13 dB to 15 dB.

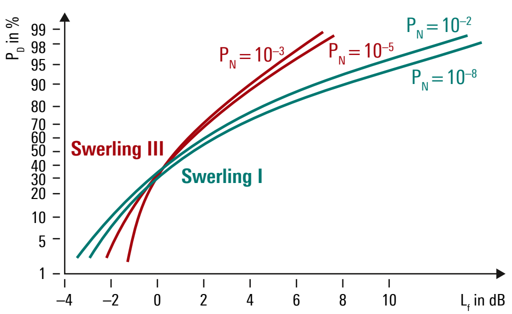
Fluctuation loss (L_f)

This relatively high loss is a result of variations in the values of the radar cross section, page 47.

Swerling cases

Stochastic models describe the fluctuation loss.

Fig. 35: Swerling targets



Swerling I and II apply to a target that is made up of many independent scatterers of roughly equal basic echo sources like airplanes.

Swerling I target: describes targets with relatively constant RCS during the dwell time (page 38) but varying independently from scan to scan (i.e. rotating surveillance radar), according to a chi-square probability density function with two degrees of freedom.

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

Swerling II target: similar to swerling I but varying independently from pulse to pulse (i.e. tracking radar).

Swerling III and IV approximate an object with one large scattering surface having several other small scattering surfaces. This may be the case for ships.

Swerling III target: similar to swerling I but with four degrees of freedom

Swerling IV target: similar to swerling III but the RCS varies from pulse to pulse rather than from scan to scan

$$P(\sigma) = \frac{4\sigma}{\sigma_{ave}^2} \cdot exp\left(\frac{-2\sigma}{\sigma_{ave}}\right)$$

Swerling 0 or **swerling V target:** reference without fluctuation

$P(\sigma)$ Probability distribution function
σ_{ave} Arithmetic mean of all values of RCS of reflecting object
P_N Probability of false alarms
P_D Probability of detection

RADAR EQUATION FOR WEATHER RADAR

Differences compared to surveillance radar:

- Weather radar measures and not only detects
- Volume targets, not point targets
- Scattering at raindrops is based on Rayleigh scattering

RCS of a single raindrop:

$$\sigma_i = \frac{\pi^5}{\lambda^4}|K|^2 D_i^6 \quad \text{with:} \quad |K|^2 = \left|\frac{\varepsilon - 1}{\varepsilon + 1}\right|^2$$

ε	Probability distribution function
K	Complex refractive index
$\|K\|^2$	≈ 0.93 for water and 0.21 for ice
D	Diameter of hydrometeor

The refraction term K in the equation depends on temperature, wavelength and the composition of the sphere.

$$\overline{P_{RX}} = P_{TX}\frac{G^2\theta^2\tau\pi^3|K|^2 L}{1024(ln\,2)\lambda^2} \cdot \frac{Z}{R^2}$$

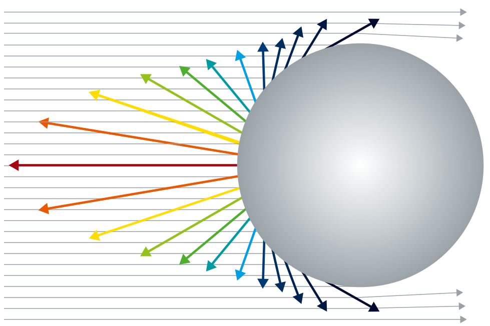
P_{RX}	Average received power
P_{TX}	Transmitted pulse power
G	Antenna gain of radar
θ	Angular beamwidth of a symmetrical parabolic dish
τ	Pulse width
λ	Wavelength
R	Distance rain to radar
Z	Reflectivity factor of precipitate
L	Loss factor of radar
$ln\,2$	Small correction for Gaussian beam pattern

The proportionality between power and distance is now only quadratic because the pulse volume and thus the number of reflecting hydrometeors increases as a function of distance.

RADAR CROSS SECTION (RCS)

The RCS is specified as a multiple of a perfectly conducting sphere with a diameter of 1.128 m. This sphere has a visible surface of 1 m² but with a small effective area for backscattering only. Better reflecting surfaces can therefore have much larger RCS than their geometric dimensions.

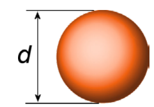
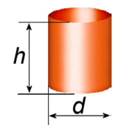
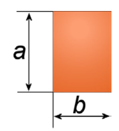
Fig. 36: Radar cross section



$$\sigma = \lim_{R\to\infty} 4\pi R^2 \frac{|E_S|^2}{|E_0|^2}$$

E_0 Electric field strength of incident wave impinging on target
E_s Electric field strength of scattered wave at radar (in range R)

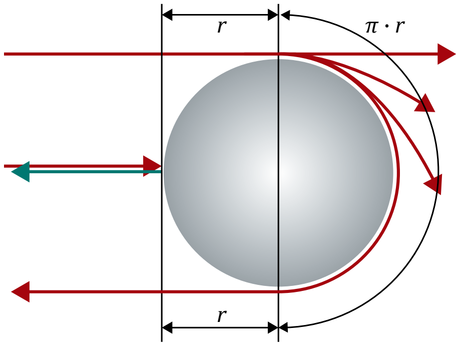
RCS for simple targets

Type of target	Dimensions for RCS ≈ 1 m²		
	L band	S band	X band
Sphere			
 $\sigma = \frac{\pi d^2}{4}$	d = 1.128 m, RCS is independent of frequency if $d \ll \lambda$		
Cylinder			
 $\sigma = \frac{\pi d h^2}{\lambda}$	h = 52 cm d = 26 cm	h = 40 cm d = 20 cm	h = 26 cm d = 13 cm
Rectangular plate			
 $\sigma = \frac{4\pi a^2 b^2}{\lambda^2}$	a = 26 cm b = 26 cm	a = 17 cm b = 17 cm	a = 10 cm b = 10 cm

Rayleigh, Mie and optical region

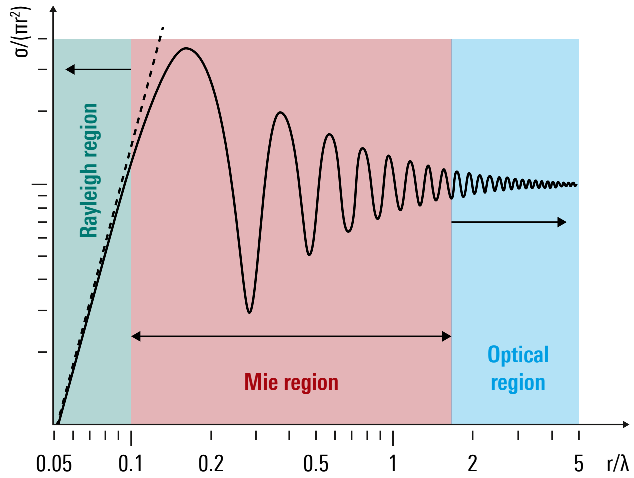
In the area of **Rayleigh scattering**, the size of the spherical reflection area is much smaller than the wavelength (applied mostly for weather radars).

Fig. 37: Creeping wave



$$\sigma = \pi r^2 \cdot 7.11 \left(\frac{2\pi r}{\lambda}\right)^4$$

Fig. 38: Rayleigh, Mie and optical region



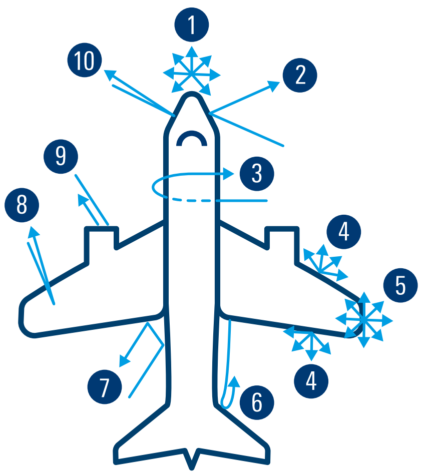
In the **Mie** or **resonance region**, the creeping wave interferes with the directly backscattered wave. The RCS may be up to four times higher (positive resonance) or a quarter (negative resonance) of the RCS calculated according to the optical rules.

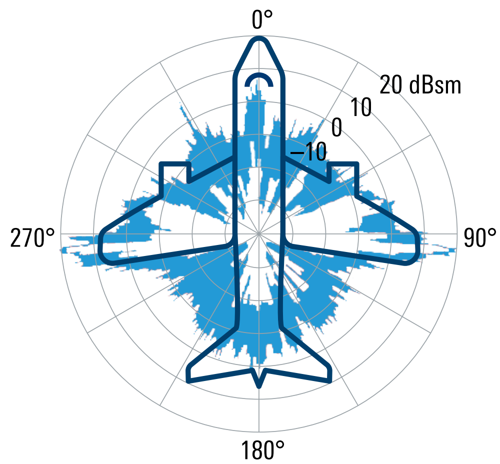
In the **optical region**, the RCS is like the calculation in the table for simple targets (mostly for radars with frequency higher than 1 GHz).

$$\sigma = \pi r^2$$

RCS for complex targets

Fig. 39: Basic echo sources on a typical airborne target
(according to E. F. Knott[3]):





1. Tip diffraction
2. Specular surface return
3. Creeping wave return
4. Edge diffraction
5. Corner diffraction
6. Travelling wave echo
7. Interaction echo
8. Gap or seam echo
9. Cavity return
10. Curvature discontinuity return

All of these basic echo sources overlap with varying degrees of phase shift which partly increase or partly cancel each other. In sum, they form a complex reflection pattern depending on the aspect angle.

The RCS can therefore fluctuate by more than 30 dB, which is noticeable as a fluctuation loss, page 45 in radar signal processing.

[3] E. F. Knott, "Radar observables," in Tactical Missile Aerodynamics: General Topics, Vol. 141, M. J. Hemsch, ed., Washington, DC: American Institute of Aeronautics and Astronautics, 1992, Chap. 4.

Examples of RCS (in X band)

Target	RCS in m²	RCS in dBsm
Insect (honeybee)	0.000032 to 0.0001	–45 to –40
Artillery shell	0.0001 to 0.0003	–40 to –35
F-22 Raptor	0.0001 to 0.0005	–40 to –33
F-117A Nighthawk	0.001 to 0.01	–30 to –20
F-35 Lightning II	0.0015 to 0.005	–28 to –23
Bird (sparrow)	0.017 to 0.018	–17.7 to –17.4
Bird (pigeon)	0.008 to 0.0145	–21 to –18.4
Nano-UAV	< 0.01	< –20
AA missile (frontal)	0.01	–20
Surface swimming diver	0.01	–20
Hellfire missile	0.01 to 0.032	–20 to –15
Large bird (eagle)	0.012 to 0.02	–19.4 to –17
Commercial quadcopter	0.032	–15
Anti-ship missiles	0.1	–10
B-2 Spirit	0.1	–10
Dog	0.1 to 0.3	–10 to –5.2
Re-entry body of ICBM	0.2 to 0.6	–7 to –1.9
Crawling man	0.3 to 0.4	–5.2 to –4.0
Tomahawk (cruise missile)	0.5	–3
Walking man	0.5 to 1.3	–3 to 0.8
Saab JAS-39 Gripen	0.5 to 1.5	–3 to 1.8
Eurofighter Typhoon	0.5 to 2.0	–3 to 3
F-18 E/F Super Hornet	0.5 to 2.0	–3 to 3
Dassault Rafale	0.5 to 2.0	–3 to 3
B-1B Lancer	0.75 to 1	–1.25 to 0
Mirage 2000	1 to 2	0 to 3
F-18 C/D Hornet	1 to 3	0 to 4.8
Bicyclist	2 to 20	3 to 13

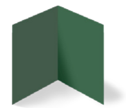
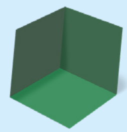
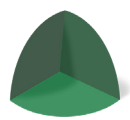
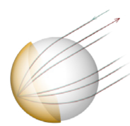
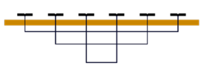
Target	RCS in m²	RCS in dBsm
Helicopter	3 to 5	4.8 to 7
MiG-29 Fulcrum	3 to 5	4.8 to 7
Inshore fishing vessel	3 to 10	4.8 to 10
F-16 A	5	7
Zumwalt-class destroyer	5 to 10	7 to 10
Light tank	6 to 9	7.8 to 9.5
F-4 Phantom	6 to 10	7.8 to 10
Compact vehicle (VW Golf V)	10 to 100	10 to 20
Su-27 Flanker	10 to 15	10 to 11.8
F-15 Eagle	10 to 25	10 to 14
Cabin cruiser	10 to 50	10 to 17
Heavy tank (T-72)	12 to 19	10.6 to 12.8
Small coaster	20 to 800	13 to 29
C-130 Hercules	80	19
Cargo aircraft	80 to 100	19 to 20
Larger vehicle (pickup)	100 to 150	20 to 23
Large cargo truck	200 to 300	23 to 25
Coasting trading vessel	300 to 4000	25 to 36
Cargo liner	4000 to 16000	36 to 42
Arleigh Burke-class destroyer	5000 to 50000	37 to 47
Medium tanker	5000 to 80000	37 to 49
Container ship	10000 to 80000	40 to 49

RCS approximation of a naval ship:

$$\sigma \approx 52\sqrt{fD^3}$$

f Radar carrier frequency in GHz
D Full-load displacement of vessel in kilotons

Retroreflectors

RCS	Beamwidth (X band)	View
Dihedral corner reflector		
$\sigma = \dfrac{8\pi \cdot w^2 h^2}{\lambda^2}$	36°	
Trihedral corner reflector		
$\sigma = \dfrac{4\pi \cdot a^4}{3 \cdot \lambda^2}$	40°	
$\sigma = \dfrac{12\pi \cdot a^4}{3 \cdot \lambda^2}$	52°	
$\sigma = \dfrac{15.6\pi \cdot a^4}{3 \cdot \lambda^2}$	48°	
Luneburg lens reflector		
$\sigma = \dfrac{4\pi^3 r^4}{\lambda^2} = \dfrac{\pi^3 d^4}{4\lambda^2}$	100°	
Van Atta array		
$\sigma \approx \dfrac{\pi n^2 \lambda^2}{4}$ n number of dipoles	110°	

Passive retrodirective arrays, like the van Atta array, use equal length connecting cables to redirect the signal. Active retrodirective arrays use mixers to create the phase conjugation necessary to redirect the signal.

It makes more sense to enlarge one corner reflector than to use several small corner reflectors. Due to the interference caused by the phase differences, the result would be similarly frayed as with an airplane (see Fig. 39: Basic echo sources on a typical airborne target, page 49).

DECIBEL (dB)

The auxiliary unit **Bel** expresses the logarithmic ratio L between the input and output of any given component, circuit or system and may be expressed in terms of voltage, current or power:

$$L\ (in\ dB) = 10 \log \frac{P_{out}}{P_{in}} \qquad \frac{P_{out}}{P_{in}} = 10^{\left(\frac{L\ (in\ dB)}{10}\right)}$$

If field quantities (voltages or currents) are used instead of power quantities, then:

$$L\ (in\ dB) = 10 \log \left(\frac{E_{out}}{E_{in}}\right)^2 = 20 \log \frac{E_{out}}{E_{in}}$$

Instead of multiplying gain or loss factors as ratios, we can add them as positive or negative dB values.

dB	Power ratio	Voltage or current ratio	dB	Power ratio	Voltage or current ratio
0.0	1.00	1.00	**10**	**10.0**	3.16
0.5	1.12	1.06	15	31.6	5.62
1.0	1.26	1.12	20	100	10
1.5	1.41	1.19	25	316	17.78
2.0	1.58	1.26	**30**	**1000**	31.6
3.0	**2.00**	1.41	40	104	100
4.0	2.51	1.58	50	105	316
5.0	3.16	1.78	60	106	1000
6.0	3.98	2.00	70	107	3162
7.0	5.01	2.24	80	108	10 000
8.0	**6.31**	2.51	90	109	31 620
9.0	7.94	2.82	100	1010	105

Example:
18 dB = **10** dB + **8** dB = **10.0** × **6.31** = 63.1
500 W = (**1000** W) / **2** = **30** dBW – **3** dB = 27 dBW

Absolute dB levels

(instead of an input signal an absolute reference value is used)

Power
dBm: power relative to 1 mW
dBW: power relative to 1 W (usually at 50 Ω)

Voltage
dBV: voltage relative to 1 V, regardless of impedance
dBmV: voltage relative to 1 mV
dBµV: voltage relative to 1 µV

Antenna gain
dBi: gain compared with isotropic antenna
dBd: gain compared with halfwave dipole

Radar cross section
dBsm: radar cross section relative to 1 m^2

WAVELENGTH AND SPEED OF LIGHT

The frequency of an oscillation is independent of the propagation speed, but the wavelength is dependent on the propagation speed. In a vacuum, the speed of light is c_0 = 299 792 458 m/s. With sufficient accuracy, $c_0 = 3 \times 10^8$ m/s may be used. The speed of propagation depends on the density of the medium. Therefore, the speed of light in the lower atmosphere is lower than in a vacuum, causing refraction. Conversion from frequency to wavelength is handled as follows:

$$\lambda = \frac{c_{0\ (\text{in m/s})}}{f_{\ (\text{in Hz})}} \approx \frac{300}{f_{\ (\text{in MHz})}} = \frac{0.3}{f_{\ (\text{in GHz})}}$$

This calculation is easy with a pocket calculator: 300 divided by frequency in megahertz gives wavelength in meter.

LIST OF SYMBOLS

Symbol	Description
c_0	Speed of light ($3 \cdot 10^8$ m/s)
d	Link distance
E_0	Electric field strength of incident wave
E_s	Electric field strength of scattered wave
f	Frequency
f_{tx}	Transmitter frequency
f_D	Doppler frequency
FZ	Fresnel zone distance
G_{TX}	Transmitting antenna gain
G_{RX}	Receiving antenna gain
G_M	Antenna main beam gain
G_S	Antenna sidelobe gain
h_{TX}	Height of transmit antenna
h_{RX}	Height of receiving antenna
k	Boltzmann constant
L	Losses in radar equation
L_{FSPL}	Free space path loss (FSPL)
L_{KED}	Knife edge loss
P_{TX}	Transmitted power
P_{RX}	Received power
$P(\sigma)$	Probability distribution function
P_D	Probability of detection

Symbol	Description
P_N	Probability of false alarms
R	Radar range
R_{BT}	Burn through range
R_E	Effective range
R_J	Range to jammer
R_T	Range to target
S	Sensitivity
S_r	Radial spacing
S_A	Azimuthal spacing
t_d	Delay time of echoes
T_S	System temperature
x_0	Voltage size of mainlobe
x_i	Voltage size of time sidelobe
λ	Wavelength
ρ	Air pressure
σ	Radar cross section (RCS)
σ_{ave}	Arithmetic mean of all values of RCS of reflecting object
T	Pulse repetition time
τ	Pulse width
θ	Beamwidth (in radians)
Θ	Beamwidth (in degrees)
Ω_A	Solid angle (in steradians)

About Rohde & Schwarz
The Rohde & Schwarz technology group is among the trailblazers when it comes to paving the way for a safer and connected world with its leading solutions in test & measurement, technology systems and networks & cybersecurity. Founded more than 85 years ago, the group is a reliable partner for industry and government customers around the globe. The independent company is headquartered in Munich, Germany and has an extensive sales and service network with locations in more than 70 countries.

www.rohde-schwarz.com

Rohde & Schwarz customer support
www.rohde-schwarz.com/support

3683477892

3683.4778.92 01.00 PDP/PDW 1 en

PD 3683.4778.92 | Version 01.00 | April 2022 (jr)

eGuide | Radar and electronic warfare