RadarLab Wiki

Frequency Modulated CW Radar

Abstract

The aim of this work is to present the main aspects of FMCW radars. After mentioning the main characteristic of this kind of radar, that is the ability to detect target range, focus is given on the description of the relationship among signal bandwidth radar resolution and maximum unambiguous range. Monostatic and bistatic configurations are presented in order to provide a comparison among their limitations. Moreover, a series of modulation techniques are reported giving particular attention to linear-triangular modulation that, till now, is the most used approach applied in several modern applications. Applications mostly concern short-range scenarios, as examples Altimeters radars, Advanced Driver Assistance Systems and Through The Wall Detection technologies are described in details. As a conclusion a list of the main advantages and disadvantages of a FMCW radar is given, providing a table with the most relevant differences between frequency modulated continuous wave radars and pulsed radars.

1 Introduction

Frequency Modulated-Continuous Wave radars are radars where the electromagnetic signals are continuously transmitted in time and the operating frequency can vary during measurements.
As continuous wave radars, they have relatively low peak power, reduced instantaneous bandwidth in transmission, no ambiguity in the Doppler velocity measurement and LPI characteristics (Low Probability of Intercept: the ability to avoid detection by detectors designed for pulses while ensuring conventional waveforms detection). On the other end, being FM radars, they are also able to determine target range by measuring the differences in frequency between transmitted and the received signal. This is not possible in simple CW radars (without frequency modulation) due to lack of a timing mark.
There are several modulation techniques used depending on the different purposes and applications.

2 Principles of FMCW radars

2.1 Target Distance and Range Resolution

Refereces.[1][2][3]
As an example, a "sawtooth modulation" technique is taken into account, like it is shown in figure 1.

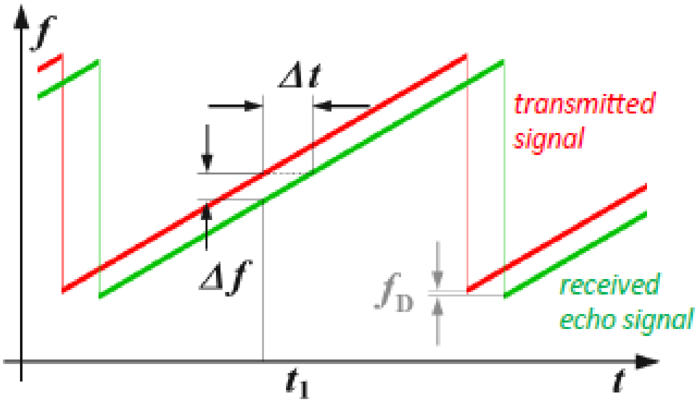


Figure 1: Principles of FMCW system, sawtooth modulation[2]

In order to obtain the target range computation, the frequency of the transmitted signal must vary over time, decreasing or increasing periodically. At the receiver the differences between transmitted and received signal's frequency are compared. The target distance (R) is obtained, knowing the slope, using the following equation:

$$R = \frac{(c_0|\Delta(t)|)}{2} = \frac{c_0|\Delta(f)|}{2\frac{\delta f}{\delta t}}[m] \tag{1}$$

Where

- c_0 is the speed of the light
- $\Delta(t)$ and $\Delta(f)$ are the time and frequency differences respectively
- $\frac{\delta f}{\delta t}$ is the frequency shift per unit of time

If the target is not moving, then the radar range is obtained by a simple frequency comparison. If the target is moving the echo signal will have a Doppler frequency that has the effect of “moving down (or up)” the graph of the received signal (the right green line in figure 1).
The **maximum unambiguous range** is related to the time needed to overlap the received signal with the delayed echo. In general, the maximum temporal delay is assumed to be:

$$t_d = 0.1t_m \tag{2}$$

So, the maximum unambiguous range is:

$$R_{max} = \frac{0.1c_0tm}{2} = \frac{0.1c}{4f_m} \tag{3}$$

Where t_m and f_m are the modulaton period and the modulation frequency respectivelly.
In FMCW the **range resolution** of the radar,that is the ability of the radar system to distinguish between two or more different targets, is determined by the transmitted modulated signal bandwidth: the higher the modulation bandwidth the better the range resolution. The Fast Fourier Transformation technique limits the maximum range resolution achievable. In the sawtooth modulation the smallest measurable frequency difference is the reciprocal of the sawtooth pulse duration limited by the FFT capabilities. Putting this Δf_{min} value inside the equation 1 the range resolution capability of the FMCW radar can be computed as follow:

$$\Delta R = \frac{c_0\frac{\delta f}{\delta t}}{2(f_1 - f_0)\frac{\delta f}{\delta t}} = \frac{c_0}{2(f_1 - f_0)} \tag{4}$$

Where $f_1 - f_0$ is the frequency sweep in the FMCW signal. Moreover, the energy of the transmitted signal is distributed over the modulation bandwidth that is wider with respect to the one needed to transport the information, for this reason the FMCW is a LPI technique. A potential jammer, in fact, is forced to use a wider bandwidth reducing his sensitivity and so reducing his capability to intercept FMCW signal parameters.

2.1.1 Relationship among signal bandwidth radar resolution and maximum unambiguous range

In order to understand in more details the relationship among the signal bandwidth, radar resolution and maximum unambiguous range, a chirp signal is considered as shown in figure 2:

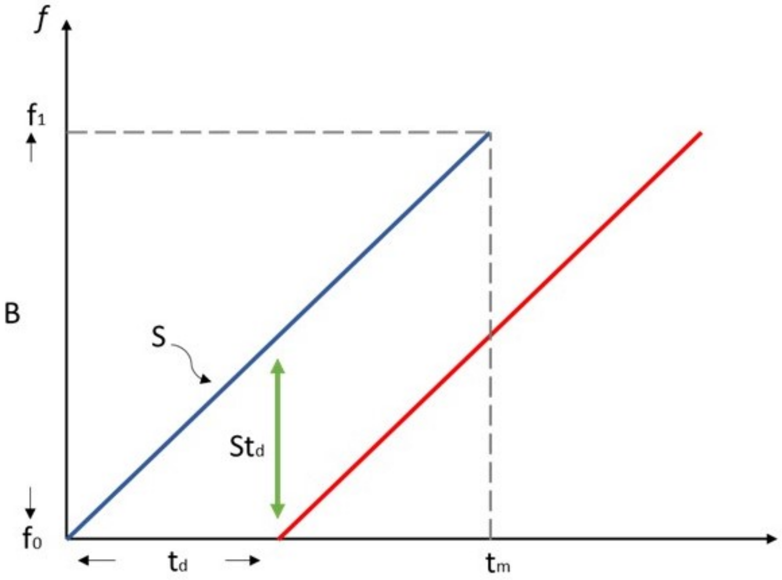


Figure 2: Instantaneous frequency of chirp signal

Where:

- S is the slope of the chirp
- t_m is the duration of the chirp
- B is the **bandwidth** of the chirp that is $f_1 - f_0 = B$.

In FMCW radars the transmitted and received signals are mixed together. The output of the mixer is a demodulated, compressed waveform with frequency f_b called *beat* frequency that is the difference of the instantaneous frequency of the transmitted signal and received echo.
It is assumed a single fixed target whose echo arrives with a delay equal to t_d that is a fraction of t_m (see equation 2). Recalling equation 1 to obtain t_d, the beat frequency produced after the mixer is given by:

$$f_b = St_d = S\frac{2R}{c_0} \tag{5}$$

It is not related to the radar resolution (the frequency difference doesn't depend from the distance among two close targets) but it is proportional to the target distance. The maximum bandwidth of the beat signal depends on the maximum distance (R_{max}) desired.
It is important to stress the fact that the maximum unambiguous distance is also limited by the ADC sampling rate. In order to digitalize the beat frequency, the ADC must support a sampling rate that is bigger or at least equal to the maximum value of f_b. So, **the larger the bandwidth of the beat signal produced by the mixer, the faster the chirp, the better the maximum distance achievable** and vice versa.

On the other hand, for what concerns the radar resolution, multiple targets are assumed. In figure 3 multiple reflected echo signals are showed, each of them results in a beat frequency proportional to the their own distance($f_b = S\frac{2R}{c_0}$).

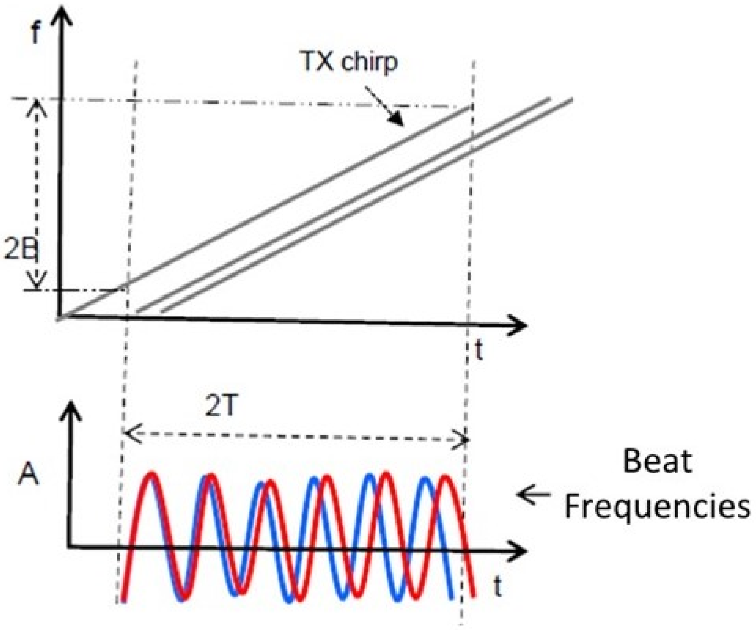


Figure 3: Range resolution and beat signal bandwidth[3]

The ability to resolve two close objects is strictly related to the observation period: in general, having an observation period of T, it is possible to separate frequency components that are divided by more than $1/T[Hz]$. So, the longer the observation period, the better the radar resolution.
The observation period, in this case, is the duration of the chirp t_m and so the smallest measurable frequency difference among two beat tones is greater than $1/t_m$. It is now possible to show that the radar resolution depends only on the bandwidth B:

$$\frac{S2\Delta R}{c_0} > \frac{1}{t_m} \Rightarrow \Delta R > \frac{c_0}{2B} \tag{6}$$

Having $B = t_m S$
So, **the larger the chirp bandwidth, the better the range resolution**.

2.2 Block Diagram and Isolation between Transmitter and Receiver

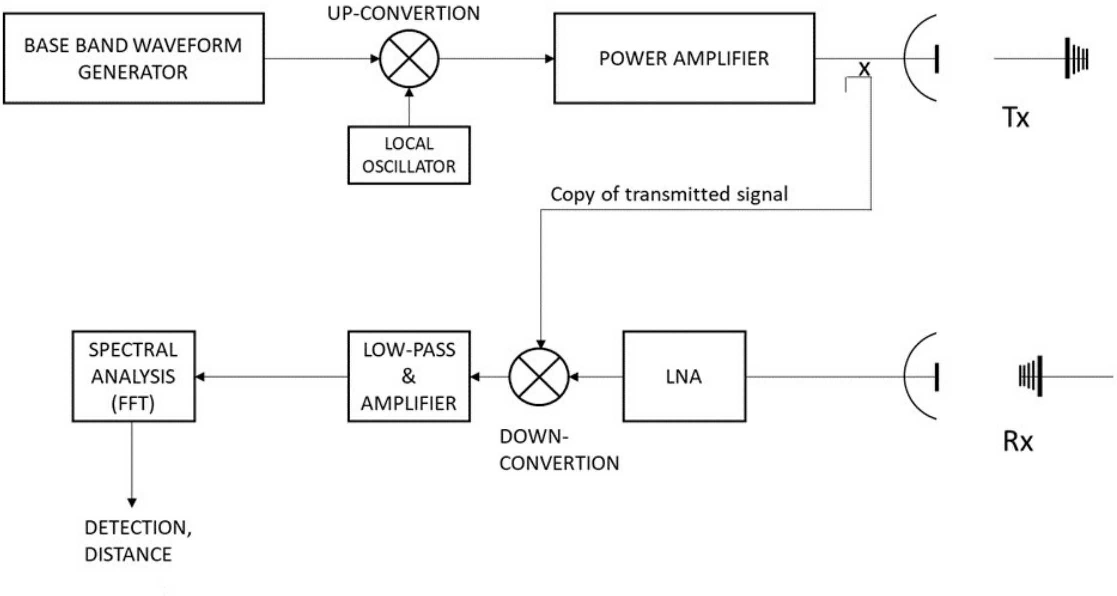


Figure 4: Block diagram for a generic bistatic CWFM radar[4].

The generic structure of a FMCW radar (homodyne type) is represented in figure 4. The set of low pass filter and mixer in reception realizes the correlation with the transmitted waveform (matched filter).
Processors based on FFT techniques are used to compute frequencies in a digital way in order to obtain the target distance.
One problematic related to FMCW radars is the coupling between the transmitted signal and the receiving chain. Transmission and reception take place simultaneously so, good isolation among transmitter and receiver is needed in order to avoid the presence of noise at the input of the receiver due to the transmitted signal. The transmission chain, in fact, can produce noise in bandwidth that could be wider with respect to every Doppler frequency. The main effect of this noise is a random phase modulation of the signal that leads to a partial loss of the useful received signal. To avoid this problem low-noise phase oscillators are used.
Isolation is also important to prevent "leakage" effects on the reference signal that are introduced in the mixer. Leakage is due to capacitive effects of the substrate on which local oscillator, LNA and mixer are set. Useful signal overlaps with the parts of local oscillator's signal that arrive as input of the LNA and the mixer.
Moreover, in the **bistatic case** (figure 4) the electromagnetic coupling between the two antennas must be reduced as much as possible by means of absorbers or coaxial metal shields.
In the **monostatic case**, the frequency of the received signal is modified by reflected waves that enter the waveguide. This is due to the mismatch between the single antenna and the free space. The block diagram for an FMCW radar with single antenna is shown in figure 5.

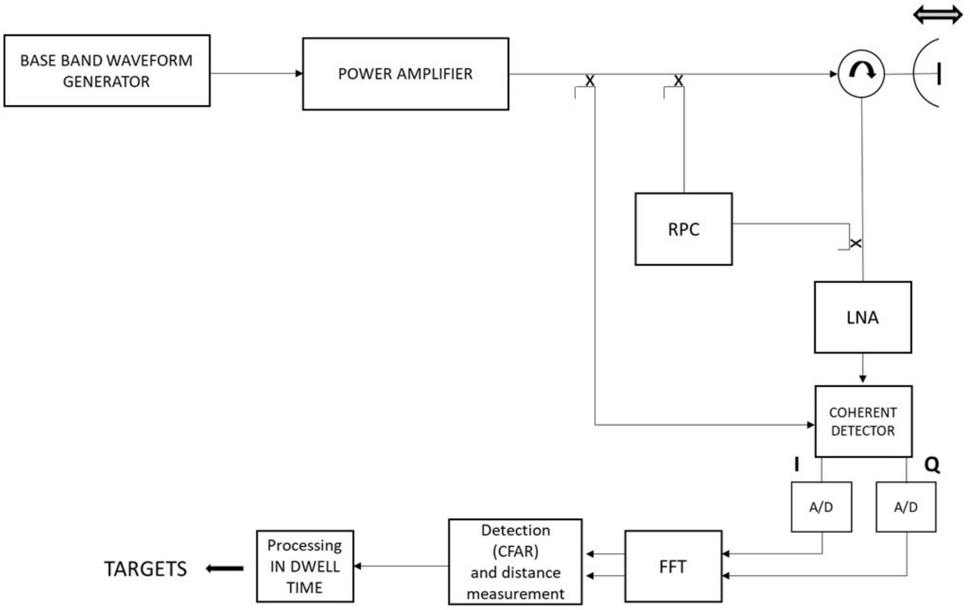


Figure 5: Block diagram for a monostatic CWFM radar[4].

The Circulator allows the signal to flow in only one direction, but the isolation of this device is limited. In the worst case the sum of the signal coming from the non-perfect isolation of the circulator and the one due to the antenna mismatch, can even saturate the receiver. To avoid the problems previously mentioned, an RPC (Reflected Power Canceller) is added. It is able to delete unwanted frequency components (due to coupling in reception and antenna mismatch) generating a replica of the transmitted signal with equal phase but disruptive interference.

3 Modulation Techniques

3.1 Linear Modulation

References[1][4].
In figure 6 the case in which frequency varies linearly with respect to time is shown. The solid line represents the transmitted signal, the dashed line represents the echo signal.
In the case of fixed target (no Doppler effects) located at distance R, the echo signal, generated by the target, will return after a time equal to $t_d = \frac{2R}{c}$.

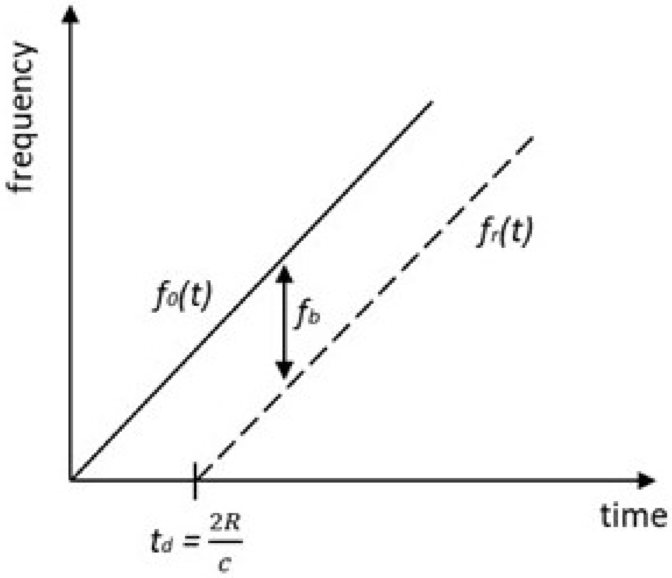


Figure 6: Linear frequency modulation[1].

The target distance can be computed using equation 1 where $\Delta(f)$ is obtained by putting the transmitted and the received signal as input of a mixer. If the received signal is a copy of the transmitted one, the frequency shift will be constant: $f_b = f_0 - f_r$.
Referring to equation 1 the following expression is obtained[1]:

$$f_b = \frac{(2R)\delta f_0(t)}{(c_0)\delta t} \tag{7}$$

3.1.1 Triangular Modulation

This is the most used frequency modulation technique.
In real applications $f_0(t)$ cannot have an infinite linear variation so, modulation techniques with finite range frequency variation are needed. A triangular-shaped frequency changing is shown in figure 7. The dashed line represents the instantaneous frequency of the echo of a fixed target at distance $R = \frac{c_0 t_d}{2}$ from the radar. The solid line represents the transmitted signal. The **bandwidth** is ΔF and the **modulation period** is t_m.

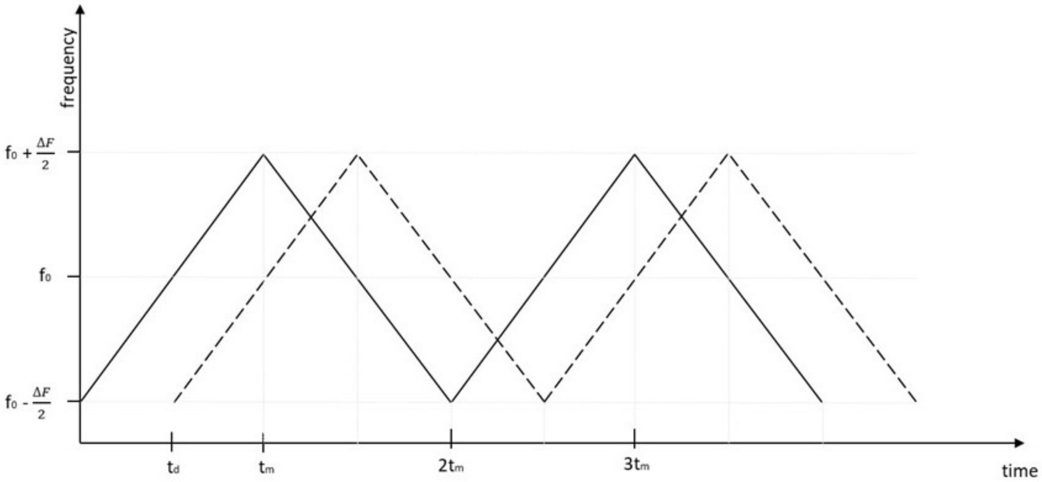


Figure 7: Triangular Frequency Modulation of a CWFM radar (istantaneous frequency vs. time) [1].

Fixed Target

Without Doppler frequency, homodyne receiver.
Transmitted signal frequencies are:

$$f_1(t) = f_0 - \frac{\Delta F}{2} + \frac{\Delta F}{t_m} t \tag{8}$$

for $0 < t < t_m$

$$f_2(t) = f_0 - \frac{\Delta F}{2} - \frac{\Delta F}{t_m}(t - 2t_m) \tag{9}$$

for $t_m < t < 2t_m$

Receieved signal frequencies are translated in time of a delay t_d.
The beat frequencies are obtained as the difference between the two signals:

$$f_{b1} = \frac{\Delta F}{t_m} t_d = \frac{2R\Delta F}{c_0 t_m} \tag{10}$$

$$f_{b2} = -\frac{\Delta F}{t_m} t_d = -f_{b1} \tag{11}$$

The echo signal is mixed with the transmitted waveform and down-converted to produce a tone at frequency f_b that is linearly proportional to the target distance (R).The behaviour of the instantaneous frequency after the correlation is shown in figure 8.

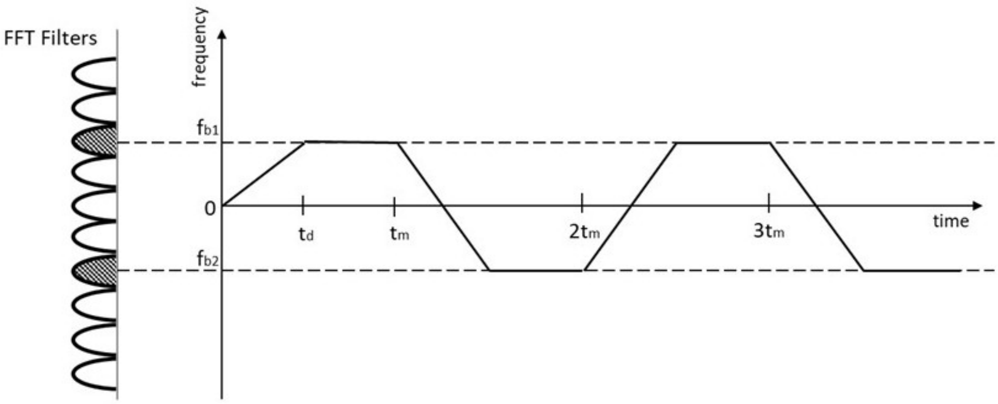


Figure 8: Instantaneous Frequency after Correlation (fixed target) [1].

The FFT filter correspondent to frequency f_b has an higher output with respect to the others. The number of filters is equal to:

$$N_F = \frac{\Delta F}{\frac{1}{t_m}} = \Delta F t_m \tag{12}$$

Where the frequency resolution is the inverse of the observation time(ΔF is in the order of tents of MHz, t_m is in the order of milliseconds). The range resolution (ΔR) has the same formulation of pulse compression radars. The values of ΔF and t_m are selected according to the expected ΔR.

$$\Delta R = \frac{c_o}{2\Delta F} \tag{13}$$

For example, if the FMCW technique is applied to X-band navigation radars (Pilot-Scout radar[5]) the modulation period and the bandwidth will be:
$t_m = 1ms$ and $1.7 < \Delta F < 55$ [MHz]
And so the range resolution and the N_F values will be in the range of:
$2.75 < \Delta R < 90$ [m] and $1700 < N_F < 55000$

Note that, as mentioned before, in the case of FMCW radars the energy of the signal is distributed over the all period t_m with peak power much lower with respect to pulse radars under the same conditions.
In figure 9 is shown a comparison among the peak power of

1. FMCW radar
2. pulse compression radar
3. pulse radar

Assuming frequency repetition of the waveform equal to 1 kHz for all the cases.

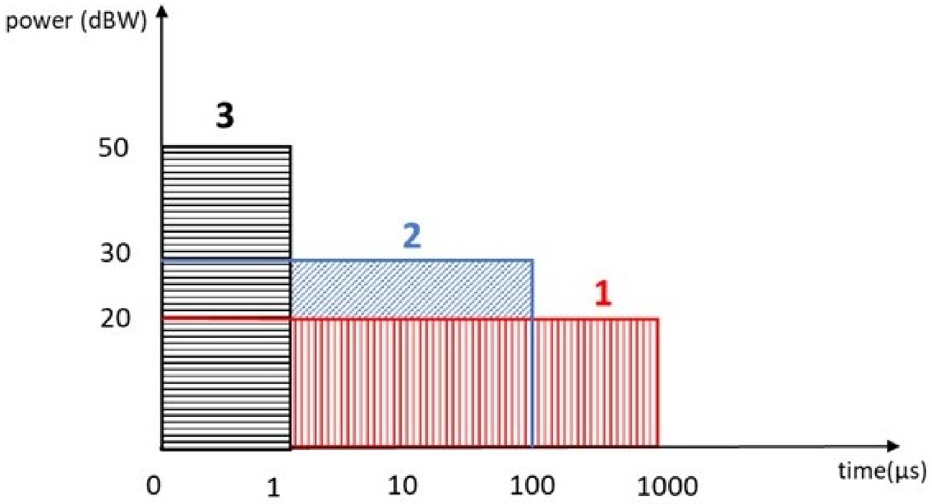


Figure 9: Radar Comparison [1].

Moving Target

When the target moves with a radial velocity, the Doppler frequency is obtained exploiting the sum and the difference between the two beat frequencies of the received signal (achieved by the FFT).
In figure 10 the solid line represents the transmitted signal and the dashed line represents the echo signal received.

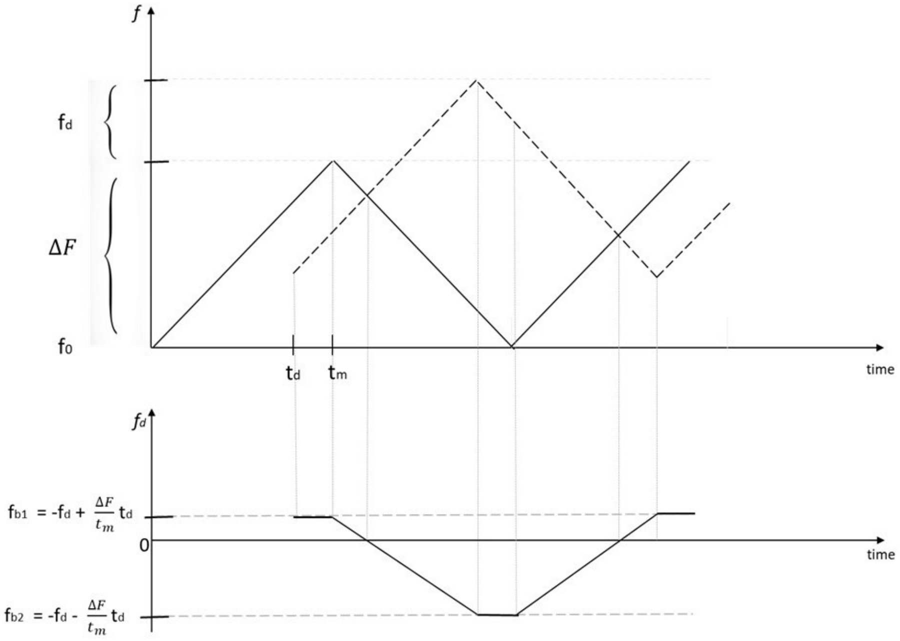


Figure 10: Triangular Modulation (moving target) [1].

The instantaneous frequency of the transmitted signal varies as the previous case (equations 8 and 9 noting that in figure 10 the line starts from zero). The Doppler frequency (f_d) shifts the echo signal in height (dashed line) so the frequency of the received signal is:

$$f_{r1}(t) = f_0 + f_d + \frac{\Delta F}{t_m}(t - t_d) \tag{14}$$

for $t_d < t < t_d + t_m$

$$f_{r2}(t) = f_0 + f_d - \frac{\Delta F}{t_m}(t - t_d - 2t_m) \tag{15}$$

for $t_d + t_m < t < t_d + 2t_m$
The beat frequencies are respectively:

$$f_{b1} = f_1(t) - f_{r1}(t) = -f_d + \frac{\Delta F}{t_m} t_d \tag{16}$$

$$f_{b2} = f_2(t) - f_{r2}(t) = -f_d - \frac{\Delta F}{t_m} t_d \tag{17}$$

The Doppler frequency (f_d) and the range ($R = \frac{c_o t_d}{2}$) are computed from equations 16 and 17:

$$t_d = \frac{f_{b1} - f_{b2}}{2\Delta F} t_m \tag{18}$$

$$f_d = -\frac{f_{b1} + f_{b2}}{2} \tag{19}$$

If there is more then one target inside the antenna beam, this procedure will become complex: there will be more than one beat frequency that will depend on the target velocity and its distance with respect to the radar. If the wrong Doppler frequency is assigned, ghost targets will appear.
If the number of periods t_m in the dwell time is big enough, it is possible to apply a coherent integration in azimuth with the use of 2-D FFT.

3.1.2 Sawtooth Modulation

References[2].

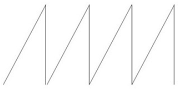


Figure 11: Sawtooth Wave

This is a kind of linear modulation technique. The main difference with respect to the triangular modulation is that in this case it is not possible to measure the Doppler frequency. In fact it appears in the form an added noise in the received signal producing errors in distance measurements. This kind of technique is used when the Doppler effect is negligible so that errors in measurement are very small like in the case of some maritime navigation radars.
In the worst case measurement errors can be greater than the distance to be measured making the target appear at a negative distance.

3.2 Coded Modulation

References[6].
In this kind of modulation, a code controls the phase of the transmitted waveform and then the received waveform is compared with a suitable delayed version of that code.
The **code** used is a sequence of length $2^n - 1$ made by plus and minus **1s**. It has the property that by multiplying it by itself and then by summing it by 0 delay, the value obtained is $2^n - 1$. Moreover, shifting it by **modulo k** (with $0 < k < 2^n - 1$) the sum of the products does not exceed the value -1. This code is generated with shift registers in small radars. Figure 12 shows the correlation function, as a function of delay, of a 31bit shift register code.

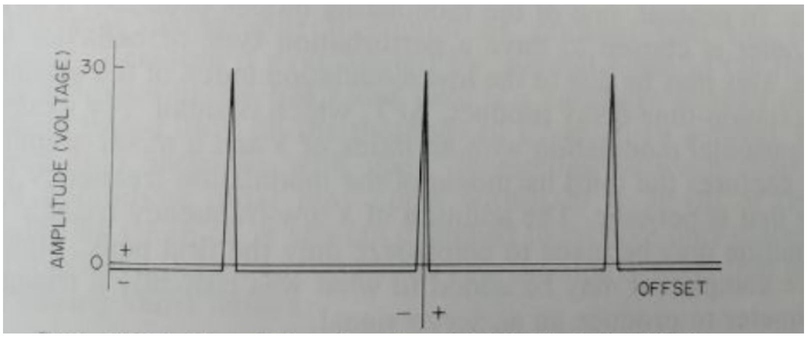


Figure 12: Correlation function 31 bit code[6] .

The main characteristic of this technique is that the product between the code and either the unmodulated or the modulated signal, generates a video signal with a bandwidth limited by the width of a single bit code. Ambiguity may happen when the code duration is comparable with the duration of one cycle of the highest Doppler frequency produced by the target.

3.3 Square-wave Modulation

References[2].
Frequency Shift Keying (FSK)

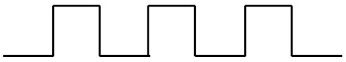


Figure 13: Rectangular Wave

In this modulation technique the frequency at which radar operates, varies according to a rectangular control voltage. The output of an FSK modulated wave is shown in figure 14 where the frequency f_1 corresponds to the high value of the rectangular pulse, and the second frequency f_2 corresponds to the interpulse period. In these periods of time (that are in the order of milliseconds) the radar works as a non-modulated CW radar. For each frequency is performed the measure of the phase difference between the echo signal and the transmitted one. The distance measurement is achieved by comparing the phase difference ($\Delta\varphi$) among the two echo signals associated to the two frequencies. More precisely, what is measured is the voltage difference, the values are digitally stored because of the non simultaneity between the two echo signals frequencies. This kind of modulation is not able to separate echo signals from different targets because only one phase angle can be measured at a time. Moreover the range of unambiguous measurements of the distance is very small, this is because of the periodicity of the sine wave: the phase difference between the two echo signals is smaller than the half-wavelength.

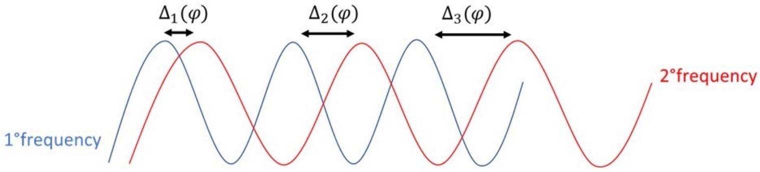


Figure 14: Phase difference between f_1 and f_2

FSK modulation is used for close range very precise distance measurements.

3.4 Sinusoidal Modulation

References[2][7][8][6].
This modulation technique has been used in the past because it is relatively simple to produce. It is useful to achieve range and velocity measurements in the case of targets with moving parts and it is easier to obtain with respect to linear modulation.

Single Sinusoid

In sinusoidal frequency modulation the difference frequency between transmitted and received signal is expanded in a trigonometric series whose terms are the harmonics at frequency f_m (modulating frequency). Distance value is obtained by comparing the spectrum of the transmitted and the echo signal. The amount of spectrum spread produced by propagation delay is proportional to the range. The transmitted waveform formula for an FM waveform is[6]:

$$\mu_s = U_s sin(\Omega_0 t + \frac{\Delta\Omega}{\omega_m} sin\omega_m t) \tag{20}$$

Where:

- ω_m is the modulation frequency
- Ω_0 is the carrier frequency
- $\frac{\Delta\Omega}{\omega_m}$ is the **modulation index**

The received echo signal is delayed in time by a quantity $t_d = T_0 + \frac{2vt}{c_0}$ (where v is the velocity of the target) its formulation is[6]:

$$\mu_e = U_e[sin[\Omega_0(t - t_d) + \frac{\Delta\Omega}{\omega_m} sin\omega_m(t - t_d)] + \Phi] \tag{21}$$

Where Φ is a phase angle produced in reflection. A good measurement of t_d implies a good measurement of the range.
Phase detectors are used in order to extract the value of the distance from the instantaneous frequency. The received signal is down-converted by the detection process using the transmitted signal. After some trigonometric computations the difference among transmitted and received signal can be written as[6]:

$$\mu_i = U_i cos[\Omega_0 t_d - \Phi + D cos\omega_m(t - \frac{t_d}{2})] \tag{22}$$

Where $D = \frac{2\Delta\Omega}{\omega_m} sin\frac{\omega_m t_d}{2}$ is a multiplicative function of the modulation index and a periodic function of the product between the time-delay of the echo and the modulation index.
The explicit formulation is obtained by expanding μ_i in a Fourier series and by neglecting the phase Φ[6]:

$$\begin{aligned} \mu_i = U_i(J_0(D)cos\Omega_0 t_d + \sum_{n_{odd}}^{\infty} -1^{(n+1)/2} J_n(D)[sin[n\omega_m(t - \frac{t_d}{2}) + \Omega_0 t_d] \\ - sin[n\omega_m(t - \frac{t_d}{2}) - \Omega_0 t_d]] + \sum_{n_{even}}^{\infty} -1^{(n/2)} J_n(D)[cos[n\omega_m(t - \frac{t_d}{2}) + \Omega_0 t_d] \\ - cos[n\omega_m(t - \frac{t_d}{2}) - \Omega_0 t_d]]) \end{aligned} \tag{23}$$

Where $J_n(D)$ is the Bessel function of order n.

The following figure shows the spectrum of the signal μ_i.Solid lines are for $D = 2.3$ and $Doppler = 10^6 Hz$, dashed lines are for $D = 4$ and $Doppler = 2x10^6 Hz$ and $\omega_m / 2\pi = 10^6 Hz$:

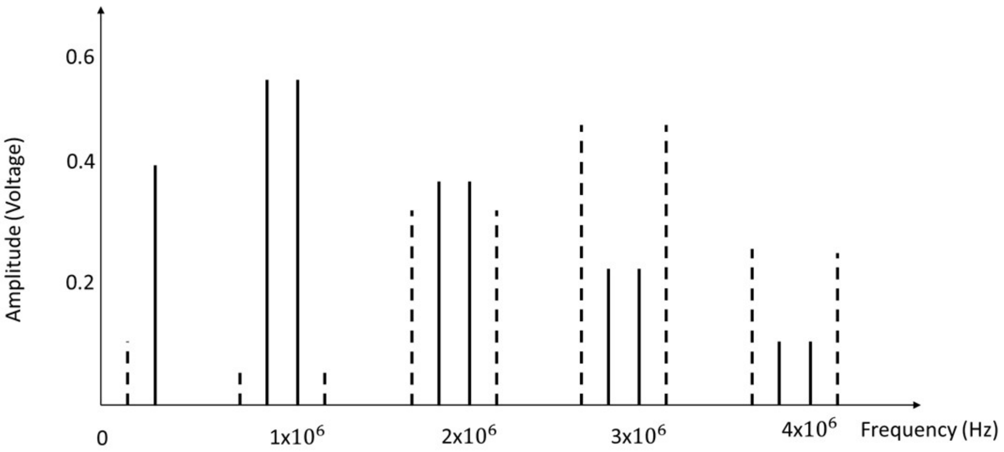


Figure 15: Spectrum of the signal μ_i [6]

The spectrum is composed of spectral lines that are pairs of sidebands around ω_m and its harmonics. The sidebands are equidistant from the frequency of the harmonic and the distance is the same for all the lines related to a given harmonic. The amplitude of these lines is proportional to $J_n(D)$.The relationship among modulation harmonics and Doppler sidebands is not so easy if the Doppler frequency exceeds the value $\omega_m/2\pi$.
The figure shows that there is a symmetry in the spectral components at the values $\frac{\omega_m t_d}{2} = n\pi$: the echo delay is equal to an integral number of periods of ω_m.

4 Some Applications

4.1 Altimeters Radars

References[1]

A radar altimeter has the aim to provide a measure of the vertical distance of an object with respect to a reference level (zero-level). It measures precisely the echo delay of the underlying surface in order to determine the altitude of an object. Its observation point is always vertical (nadir-looking) and it is part of the “*non-imaging*” radars family since it provides monodimentional distance values.
Frequency-modulated radars with a bandwidth of 200MHz are used in short-range radar altimeter systems. The frequency range is from **4.2 to 4.4 GHz** thus guaranteeing several radar altimeter's requirements such as: small antennas not so directive, low power, negligible scattering and attenuation.

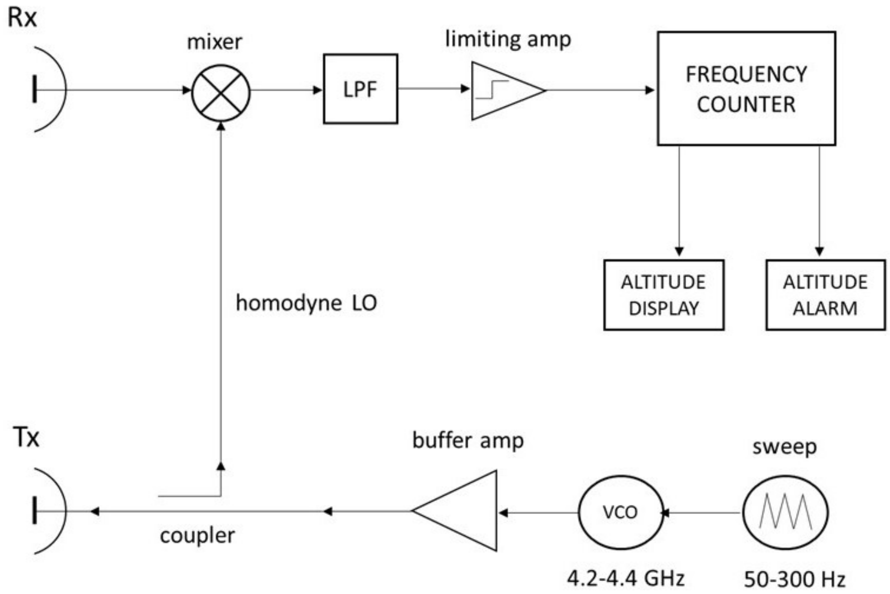


Figure 16: Block diagram FM radio-altimeter [1].

The general block diagram of a frequency-modulated radio-altimeter is shown in figure 16. The transmitter emits a CWFM wave with a triangular or sawtooth modulation.The modulation bandwidth varies between **50 and 300 Hz**: the lower bound is given by the doppler resolution capability and the upper bound is given by the thermal noise at receiver.
A radio-altimeter works correctly up to **1200m** and it is able to adjust its sensitivity at low altitudes where its accuracy is in the order of **30 cm**. Transmitted power ranges from **10 mW (+ 10 dBm) to 500 mW (+27 dBm)**. For the same power it is possible to achieve different radio-altimeter range depending on the reflectivity of the surface: smooth surfaces, like the see, provide bigger range with respect to rough surfaces like woods. As shown in figure 16 the receiver is homodyne type, signal is generated by solid-state devices, a mixer is used to obtain the beat frequency. The **frequency counter** deals with the altitude alarms and the display. The latter is achieved by measuring the frequency difference between the modulated signal and the signal reflected back by the surface. This difference is proportional to the distance of the target with respect to the surface.

Errors in altitude measurement

Radio-altimeters are typically located on aircrafts with fuselages made by conductor materials to easily obtain the isolation between transmitter and receiver and consequently to limit errors due to *leakage*.
Errors in altitude measurement may occur in case of ***multipath***: in case of strong signals there can be two reflections, one due to the surface and the other one due to the aircraft fuselage with the consequence of doubling the value of the altitude estimation. The lower the altitude, the more significant the error becomes.
Other errors in measurements are related to ***mushing***(figure 17): it appears when transmitter and receiver are too far. In the figure the altitude to be determined is h and the aircraft is approaching the ground. Direct and reflected rays form a triangle whose vertex is the incident point on the surface. The measured distance (the path of the wave from the transmitter to the receiver) is higher than the real vertical one.

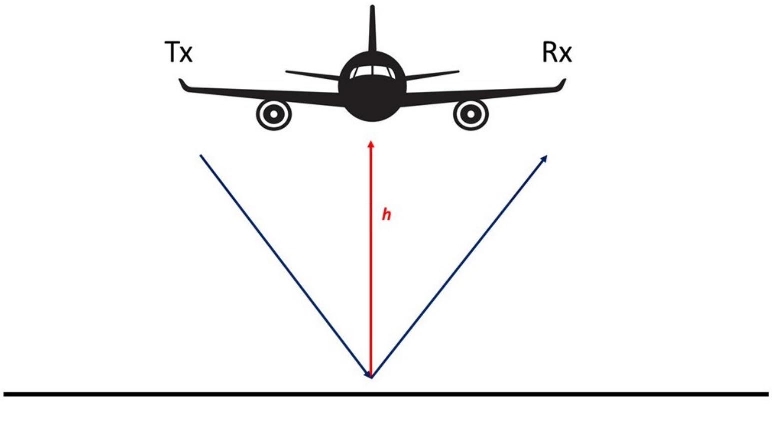


Figure 17: Mushing [1].

CWFM radio-altimeter are cheaper, smaller and less heavy with respect to pulsed altimeter radars.

4.2 Advanced Driver Assistance Systems (ADAS)

References[9][10][11] .

These systems can be considerd as the step before the self-driving cars.
FMCW radar provides the possibility to measure the target's relative distance and speed simultaneously. FMCW radars are mainly used in automotive applications like automatic emergency braking system (AEBS) and adaptive cruise control (ACC) exploiting ranges between 80 and 200 m and operating in the 77 GHz frequency band. Moreover the antennas used in these applications can be small. Figure 18 shows how FMCW radars are used to detect different objects:

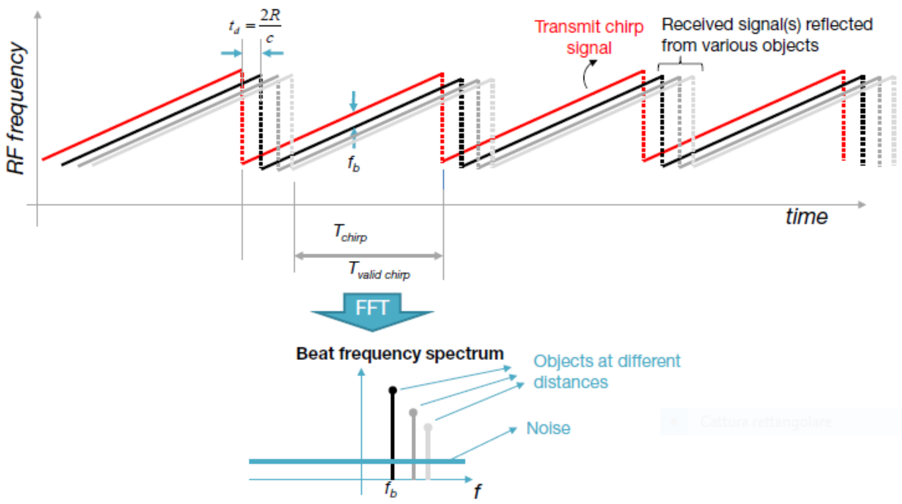


Figure 18: CWFM radar and objects distances [11]

Simplifying, the received signal is formed by different copies of the transmitted one and each copy corresponds to a different object. Each object is a tone with a beat-frequency that is proportional to the object distance from the radar. The radar identifies different objects and their distance (so different tones) performing a fast Fourier transform (FFT) of the beat-frequency signal. Note that a 2-D FTT transform is needed if there are multiple moving objects in order to estimate the Doppler component of the beat-frequency and so the relative velocity of targets.
The ACC system developed by **Robert Bosch**[10] can be considered as an example. The frequency modulation of this ACC system is liner and based on three ramps and four transmitting antennas as shown in figures 19and 20.

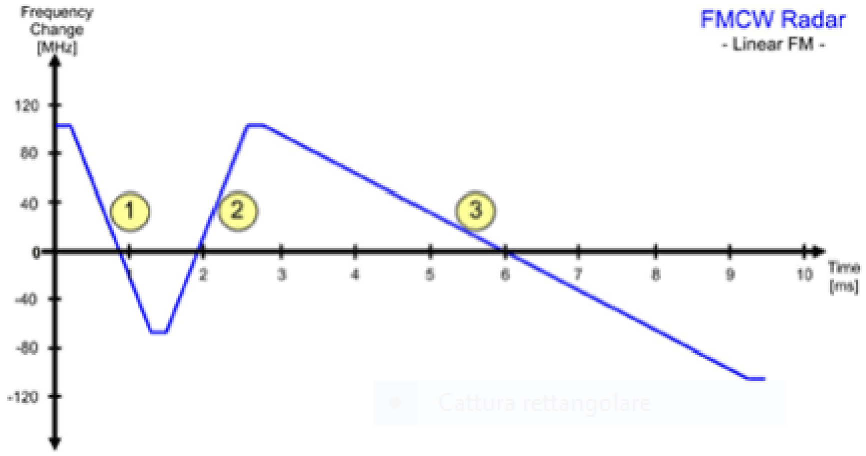
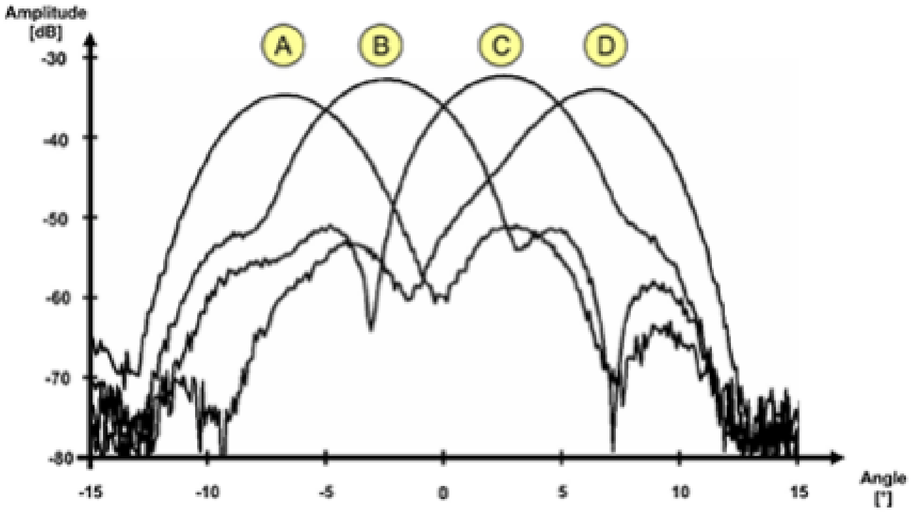
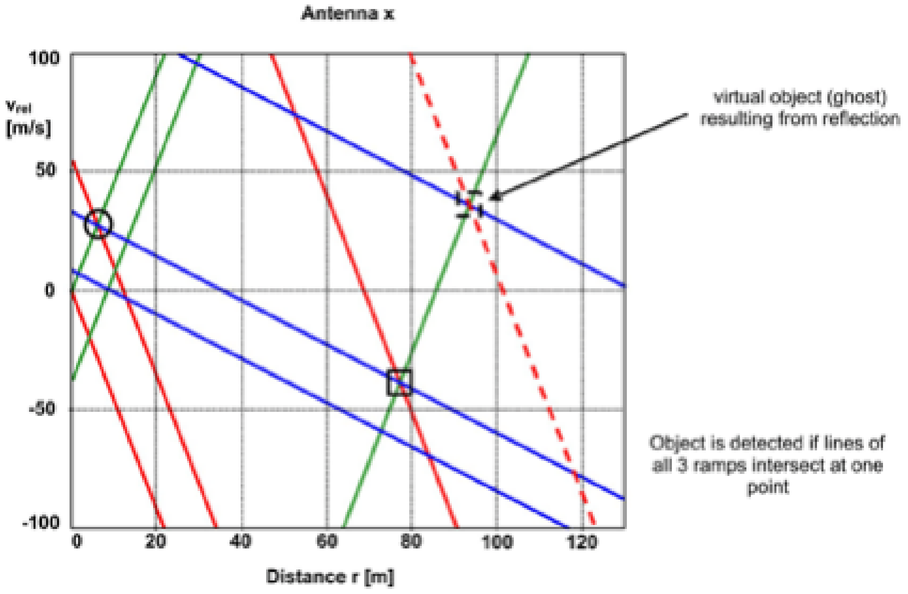


Figure 19: ACC system: three linear frequency ramp [10]



ACC system: simultaneous signals of 4 transmitting antennas
Figure 20: ACC system: simultaneous signals of 4 transmitting antennas [10]

The location of potential objects is computed by combining the received signal of each antenna with the current transmitted signal. The spectrum of 12 intermediate frequencies is obtained by means of fast FFT. Assuming a fixed threshold, all the frequencies below this threshold are considered as noise and not used for further computations. The remaining frequencies in the intermediate frequency spectrum, represent an object and each of these frequencies is reported as a line in a speed/distance diagram. An object is actually detected only if lines of all the three ramps intersect each other at a point on the diagram (figure 21)



virtual object (ghost) resulting from reflection

Object is detected if lines of all 3 ramps intersect at one point

Figure 21: Object detection in speed/distance diagram [10]

The angle between the object and the longitudinal axis of the host vehicle can be also measured if multiple receiving antennas are used. Note that a crucial issue that can compromise the future development of ADAS radars is related to the interferences among the huge number of vehicles that in future will be provided with these kinds of radars.

4.3 Through-The-Wall Detection of Human Beings

References[12][13][14]
Through-the-wall (TTW) radar technology exploits the possibility to detect the presence of human beings behind obscuring structures. These systems have a lot of applications in security and safety services ranging from domestic protection to public domain emergencies but, till now, the high cost of the development of these technologies have limited their worldwide deployment. TTW systems are typically based on ultra-wideband frequency modulated continuous wave radars. CWFM radars, in fact, are a cost-effective solution providing better power budget with respect to pulsed radars.

The first thing the radar has to deal with is the differences among several kinds of walls. In general, the dielectric characteristics of wall's materials are responsible of the manner in which waves propagate. In the literature of TTW systems, several wall models have been proposed: in [13] wall's measurement have been carried out by computing the wall transfer function in order to evaluate the behaviour of the frequency dependence of the wall attenuation for different kinds of materials and geometrics. Figure 22 shows the a wall model taken from [13] where the frequency bandwidth is between 1 to 5 GHz and the wall is made of brick blocks, rock-wool, air and plasterboard.

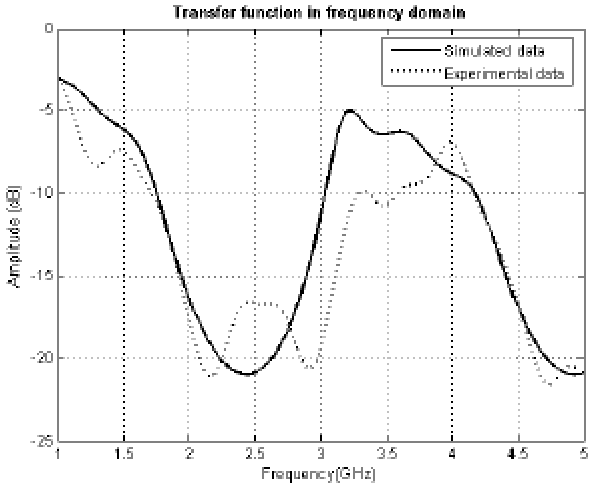


Figure 22: Wall model [13].

Assuming a given database of several human radar cross section (RCS) values (σ), it is possible to write the radar equation for a TTW system[13]:

$$\frac{P_r}{P_t} = \frac{T_{wall}^2 G_t G_r \lambda^2 \sigma}{(4\pi)^3 R^4} \tag{24}$$

Where:

- R is the distance between the radar and the target (human)
- T_{wall} is the one-path power coefficient of the TTW transmission
- P_t and P_r are the power transmitted and received by the radar
- G_t and G_r are the antenna gain in transmission and reception

The signal to noise ratio (SNR) is given by[13]:

$$\frac{S}{N} = \frac{P_t \eta \tau T_{wall}^2 G_t G_r \lambda^2 \sigma}{(4\pi)^3 R^4 K_B T_S L_S} \tag{25}$$

Where:

- τ is the integration time
- T_s is the system temperature $[K]$
- K_B is the Boltzman constant
- L_S are the system losses
- η is the duty cycle

It is important to correctly design the average transmitted power in order to detect human targets: the receiver should not be saturated by reflections coming from the wall. The reflections due to the wall, in fact, can be higher then the reflected echo emitted by human targets behind the wall so, the detection range is generally fixed by the ratio among the minimum received signal power for a target and the maximum signal captured in reception. After computing the ratio between the emitted power (P_t) and the power reflected back by the wall, it is possible to achieve the ratio between the wall reflections and the reflections of the target. The duty cycle η in 25, can be considered close to 1.
Figure 23 shows the results reported in [13] analysis:

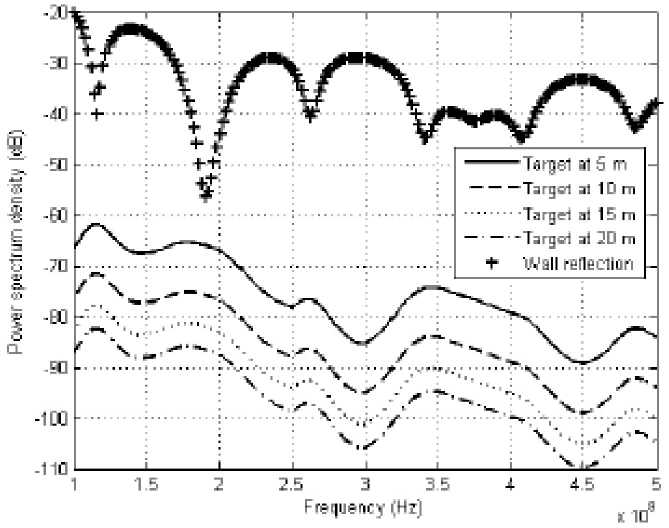


Figure 23: TTW: Dynamic Range [13]

As stated in [14] UWB FMCW radars give the best SNR providing the possibility to adjust the frequency sweeping time to optimize the received electromagnetic energy compatible with the target stationary time. In the radar, a fast frequency swept is provided by a YIG (Yttrium Iron Garnet) oscillator. In [13] it is assumed a sweeping velocity of $500\mu s/GHz$, frequency bandwidth of $2GHz$ and sweeping time of $1ms$). The block diagram of the UWB FMCW radar used in [13] is shown in figure 24:

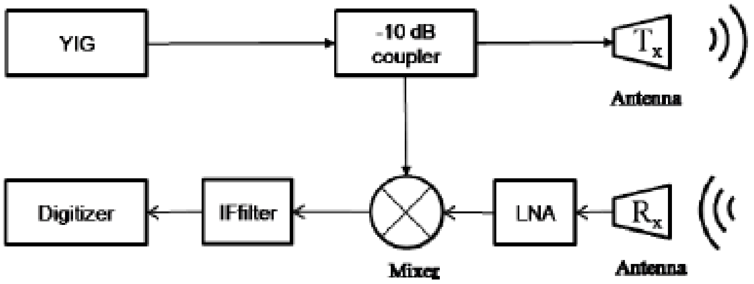


Figure 24: TTW: block diagram of UWB FMCW radar [13]

This radar is able to track humans moving behind the wall.
Knowing the location of the wall it is possible to filter out the unwanted reflections, FI filters are also useful to remove the coupling effects between transmitter and receiver, moreover, fixed echoes are deleted by MTI filtering.
Figure 25 shows the achieved 2D representation of a moving person that at time $t=0$ is near to the wall and at time $t=2s$ is at a distance of $2meters$.

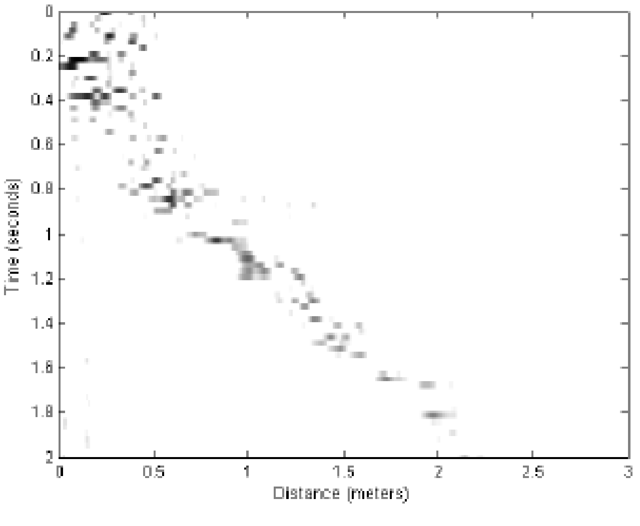


Figure 25: TTW 2D representation: track humans moving behind the wall [13]

So UWB FMCW radars are able to accomplish correctly the TTW systems requirements in terms of mitigation of unwanted wall transmission and range resolution.

5 Advantages and Disadvantages of FMCW radars

References[15][16].
FMCW radars have the following advantages:

- **Ability to detect target distance**: varying in time the transmitted frequency and measuring the received frequency. The range resolution can be high especially in the case of non-moving targets, for moving targets the radars are still able to achieve distance measurements, but they are less accurate and require more power consumption.
- **Higher bandwidth with respect to non-modulated CW radars**: FMCW modulation can be considered as an LPI technique. The larger the bandwidth of the signal produced by the mixer,the better the maximum distance achievable.
- **Low peak power**: this characteristic allows FMCW radars to be compatible with solid state transmitters that are able to supply only low power for transmission. This low-peak emitted power obviously implies lower power consumption and so lower costs. Moreover this allows more flexibility in all the applications where people are close to the antennas.

On the other hand, the drawbacks are:

- **Lower long-range performances with respect to pulsed radars**: the use of low-peak power in transmission implies that the received signal is more affected by attenuations. So FMCW radars have better target detection on short ranges and worst target detection at longer ranges with respect to pulsed radars.
- **More expansive with respect to pulsed radars**: this is due to the higher maturity of pulsed radars technologies in the marketplace.
- **Licence restrictions**: the range resolution can be reduced by limitations over the allowed frequencies
- **Interferences from other nearby radio systems**: this is due to the low peak power and the large range of frequencies used. For this reason FMCW radars are not so used in military applications (they can be more easily jammed with respect to pulsed radars)

In order to do a general comparison the following table summarizes the main differences between pulsed radars and FMCW ones[15].

Table 1: Differences between pulsed and FMCW radars.

Characteristics	**FMCW**	**PULSED**
Short-rage detection	BETTER	WORSE
Long-range detection	WORSE	BETTER
Target resolution in range	BETTER	WORSE
Requires stand-by period	NO	YES
Interferences from other radars	DIFFICULT TO SOLVE	EASY TO SOLVE
Future development	YOUNG TECHNOLOGY	MATURE TECHNOLOGY

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