CONTINUOUS WAVE RADARS–MONOSTATIC, MULTISTATIC AND NETWORK

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Abstract Radar technology was designed to increase public safety on sea and in the air. Today radars are used in many fields of application, such as air-defense, air-traffic-control, zone protection (in military bases, airports, industry), people search and others. Classic pulse radars are often being replaced by continuous wave radars. Unique features of continuous wave radars, such as the lack of ambiguity, very low transmitted power and good electromagnetic compatibility with other radio-devices, enhance this trend. This chapter presents the theoretical background of continuous wave radar signal processing (for FMCW and noise radars), highlights the most important features of this type of radar and shows their abilities in the field of security.

Keywords: continuous wave radar; linear frequency modulation; noise radar; noise; modulation; correlation function; ambiguity function; synthetic aperture; radar; target identification.

1. Introduction

Today security technology migrates from strictly military areas to many different civil applications. On one hand this migration is caused by the high risk of terrorist threats, on the other one observes the growing interest of society in protecting personal life regardless of the costs of rescue operations. Many sophisticated technologies are in everyday use to protect people in airports, shopping centers, schools and other public places. Strong efforts have been made to locate people in buildings and ruins during rescue and peacekeeping missions. One of the most important security problems is to remotely detect and localize objects of interest (often referred to as targets) and to distinguish between the target and its environment. Another issue is to extract as much useful information about the object as possible and to classify it properly.

The process of detection can be performed by using different sensing technologies and different sensors.

One very common and mature technology is based on optical sensing, which is used in many military and civilian areas such us "city surveillance". Optical cameras convert the electromagnetic object signature into an image of the target, which can be further processed and stored by the computer. However, this technology faces many limitations. Working in the visual light region it is necessary to illuminate the target either by natural light sources (sunlight, moonlight) or artificial illuminators (street lights, reflectors etc). Some interesting results can be achieved by using other parts of the electromagnetic spectrum. Deep infrared cameras can provide images in a completely dark environment, but they require a temperature difference between the target and its surroundings. Their detection range is usually very limited and detection is impossible or very difficult in bad weather conditions or behind fire, smoke and obstacles.

For a long time radio frequency emission has been used for target detection and tracking. Classical radar senses the object by emitting short, powerful electromagnetic pulses towards the target and listening to the return echo. The distance to the target is calculated from the delay of the echo signal. It is also possible to estimate the direction of the target, its velocity and, using more sophisticated synthetic aperture radar (SAR)/Inverse SAR (ISAR) technology, the target size and shape. Having all this information, it is possible to recognize and track different objects. This radar technology is independent of weather and day/night conditions, and may be used to detect targets hidden by obstacles, walls or even buried in the ground. However, pulse radar technology has many disadvantages. To achieve large detection range, high power transmitters are required. Due to the pulse nature of such radars, there are many ambiguity problems. Pulse radars can be easily detected by very simple electronic support measurement devices, which is a big disadvantage for covert security missions.

A present trend in radar technology is to decrease the emitting peak power. Instead of emitting a train of high power pulses, it is possible to emit a low-power continuous signal with appropriate modulation. Advanced signal processing of the received signal allows radars to detect target echoes far below the surrounding noise level and to extract all required target parameters. It is also possible to produce high-resolution target pictures. In some applications it is even not necessary to emit an illuminating signal, but to exploit existing radio, TV or other emissions.

A single sensor usually has limited range and accuracy — especially in the cross-range direction. The use of bistatic ideas, where the transmitter and receiver are separated in space, leads to a new technology with increased sensitivity and accuracy in selected regions. Increasing the number of sensors (multistatics) yields much bigger surveillance volume, much higher probability of detection and proper target classification. This technology is also much more robust to target shadowing, multipath signal fading and jamming. To fully use the information produced by the set of sensors, it is necessary to exchange information between sensors and generalize this information. This leads to the net-centric sensor concept.

Radar devices were primary designed to increase public safety and now are used in many security applications. The most obvious application fields are air traffic control (ATC) and air defense. Battlefield short or middle-range radar can now detect, track and identify slow moving targets such as tanks, cars, pedestrians and animals. Using micro-Doppler analysis, it is possible to identify vehicles, and using vibration analysis, to even distinguish between two cars of the some brand. Heartbeat analysis is used for people identification and, together with breathing analysis, can even provide information on the emotional state of each person. Walk analysis based on Doppler processing and walk modeling are being used for person tracking even in crowded areas. Ground-penetrating and wall-penetrating radars are used to search for people in rescue operations, when it is necessary to search big areas of ruins or avalanches. One of the most important security issues is to distinguish between people and animals, in order to save human life first. A big area of security is connected with trespass control as well. It is very important for border protection, airport and military base protection and elsewhere.

2. Radar fundamentals

The concept of radar was discovered in the beginning of the 20th century. The "father" of radar was Christian Huelsmeyer, who applied for a patent for his "telemobiloscope" on 30 April 1904. He was motivated in his work by a ship accident and his intention was to construct a device to boost the level of safety. His device worked reasonably well, detecting ships at ranges up to 3 km in all weather conditions, but he had no success in selling telemobiloscopes and that early radar concept faded from memory. The reinvention of radar was done almost simultaneously in many countries in the 1920's and 30's. In Great Britain, work on radar technology was carried out by the physicist Sir Edward Victor Appleton, who used radio echoes to determine the height of the ionosphere in 1924. The first demonstration of aircraft detection was done by Watson-Watt and Wilkins, who had used radio-wave transmissions from the powerful BBC short-wave station at Daventry and measured the power reflected from a Heyford bomber. Detection was achieved at at distance of up to 8 miles. As a matter of fact, this was the first demonstration of a bistatic, continuous wave passive radar. The first British radar patent was issued in April 1935. In the United States radar research was carried out in the early 1920's by Dr. A. Hoyt Taylor at the Naval Research Laboratory in Washington, D.C. Radar research was also carried out in France and in 1934 the French liner "Normandie" was equipped with a "radio obstacle detector". Work on radar technology was also carried out in many other countries, but usually such research was classified.

Early radars were non-coherent pulse radars. To obtain long range detecting capability, the radar emits short pulses with very high peak power — up to several megawatts. The detection range limitation usually comes from the inadequacy of the maximum peak power. Available microwave valves and waveguides limit this parameter. To decrease the required peak power pulse compression techniques have been worked out. The first radars were used for air defense to indicate moving targets. All ground echoes were unwanted, and to distinguish between ground clutter and moving targets Doppler processing was introduced. Long distance pulse radar suffered from range or Doppler ambiguity. It is not possible to measure instantaneously both range to the target and target radial velocity, without the ambiguity given by the sampling theorem. The pulse radar concept was relatively simple and pulse radars could be designed using only analogue components. The problem with signal storage, required for Doppler processing, was solved by using acoustic delay lines (e.g. mercury tubes) or memo-scope bulbs.

Rapid progress in digital signal processing (DSP) hardware and algorithms enabled designers to exploit more complicated ideas. One such idea was to use continuous wave (CW) instead of high power short pulses. The idea was not new — the first Daventry experiment was based on CW radio emission, but practical implementation of CW radars was impossible without digital technology. The first practical continuous wave radars were constructed as Doppler-only radars. The well known police radar belongs to that group. Further development in CW radars lead to linear frequency modulated CW radars (LMCW), in which both target range and range velocity can be measured. But again, due to the periodicity in modulation, the ambiguity problem was still there.

CW radars have a very big advantage — very low peak power. As the transmitted power can be below 1 W (many of them work with 1 mW power), they belong to the low probability of intercept (LPI) class of radars, which can detect targets while they remain undetected.

The search for ambiguity-free waveforms has lead to the concept of random-waveform radars, often referred to as noise or pseudo-noise radars. In this kind of radar, the target is illuminated by continuous noise-like radiation. The reflected power is collected by the radar receive antenna, and detection is based on match filtering of the received signals. The single filter is matched to the particular value of range and range velocity. Because the target's distance and speed are unknown, it is necessary to apply a set of filters matched to all possible range-velocity pairs. The computational power required by the noise radars is much higher than for other radar types, so to date noise radars have not been used very much. There are also other drawbacks of noise radars. Due to the fact that the noise radar has to emit and receive signals simultaneously, good separation between transmitting and receiving antennas is required. Furthermore, this radar simultaneously receives strong echoes originating from close targets, buildings and ground, and weak echoes from distant targets. Thus, a large receiver dynamic range is needed.

The noise-radar concept may be used for moving target detection and also for many other applications. There are several works showing possible implementation of noise technology for imaging radar working in SAR or ISAR mode, passive detection and identification of targets and space radiometric applications. Noise radars will also be used in the future in other fields, including air traffic control, pollution control, and especially security applications.

2.1 Radar range equation

Classical pulse radar emits high power (P_T) short electromagnetic pulses using a directional transmitting antenna of gain G_T. The power density at the target at distance R from the transmitter is equal to [44]

$$p(R) = \frac{P_T G_T}{4\pi R^2}. \tag{1}$$

The total power illuminating the target of effective cross-section S_o is equal to

$$P_S = \frac{P_T G_T}{4\pi R^2} S_o. \tag{2}$$

Assuming that the target reflects all illumination power omni-directionally, the power received by the receiving radar antenna with effective surface S_R is equal to

$$P_R = \frac{P_T G_T}{16\pi^2 R^4 L} S_o S_R, \tag{3}$$

where L stands for all losses in the radar system, including transmission, propagation and receiving losses. Substituting the antenna gain for the antenna effective surface in (3) one obtains the classical radar equation in the form

$$P_R = \frac{P_T G_T G_R \lambda^2}{(4\pi)^3 R^4 L} S_o. \tag{4}$$

The receiver's equivalent noise can be expressed as

$$P_N = kT_R B, \tag{5}$$

where T_R is the effective system noise temperature (dependent on the receiver's temperature, receiver's noise figure, antenna and outer space noise), B is the receiver's bandwidth (assuming that at the receiver's end match filtering is used) and k is the Boltzmann's constant (1.380 6505 x 10^{-23} $[JK^{-1}]$). Using the Neyman-Pearson detector it is possible to assume that there is a target echo in the signal when the echo power is higher than the noise power multiplied by the detectability factor D_o, usually having a value of 12–16 dB, depending on the assumed probability of false alarm. The radar range equation can be written in the form

$$\frac{P_T G_T G_R \lambda^2}{(4\pi)^3 R^4 L} S_o > kT_R B D_o, \tag{6}$$

and the maximum detection range is equal to

$$R_{max} = \sqrt[4]{\frac{P_T G_T G_R \lambda^2}{(4\pi)^3 L k T_R B D_o} S_o}. \tag{7}$$

For pulse radar, the receiver's bandwidth B is inversely proportional to the pulse width t_p. Substituting the receiver's bandwidth by pulse time in (7), one obtains the equation

$$R_{max} = \sqrt[4]{\frac{E_T G_T G_R \lambda^2}{(4\pi)^3 L k T_R D_o} S_o}. \tag{8}$$

The detection range depends on transmitted pulse energy E_T, transmitter and receiver antenna gains and wavelength, and does not depend on the pulse length or receiver's bandwidth. Thus, Equation 8 is very general and can be used to predict the detection range for all kinds of radars, including continuous wave ones. For continuous emissions the energy E_T is equal to the product of the transmitter power and the time of target illumination or coherent signal integration.

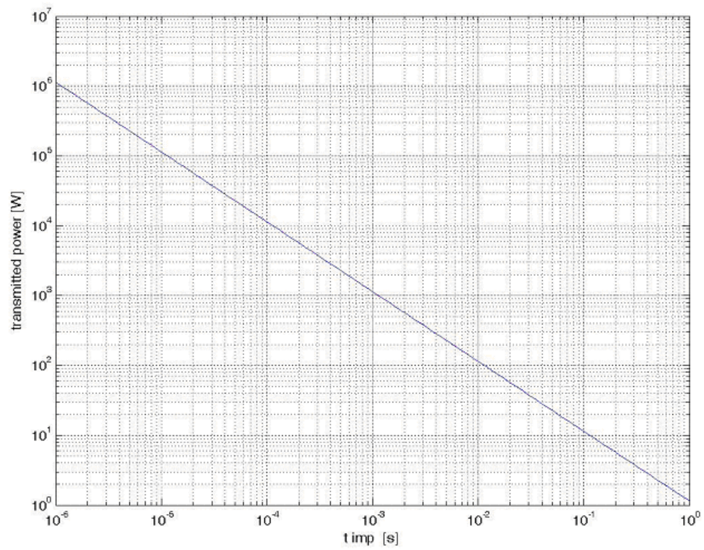

Figure 1. Transmitted power versus transmitted pulse length for X-band radar (30 dB antenna gain) — detection of 1dBsm (1 square meter) target at distance 50 km.

An example of required radar peak power for different pulse/illumination times, for X band radar equipped with a 30 dB antenna, is presented in Figure 1. For X band radar, emitting a 1 μs pulse, the peak power must be at the level of 1 MW. A continuous wave radar having 1 s integration time requires only 1 W emission.

A large group of radars are surveillance radars which have to search a certain surveillance solid angle α_s in time t_s. Let us assume that a radar is equipped with a transmitter having mean transmitted power P_{tm}. The ideal transmission antenna with gain G_T emits electromagnetic radiation in the solid angle $\alpha_T = 4\pi/G_T$. To scan the whole surveillance space it is necessary to scan $n_s = \alpha_s/\alpha_T = \alpha_s G_T/4\pi$ directions, so the time of a single direction illumination (time on target) is equal to $t_t = \frac{t_s}{n_s} = \frac{4\pi t_s}{\alpha_s G_T}$, and the total energy associated with the single scan direction is equal to $E_t = t_t P_{Ts} = \frac{4\pi t_s P_{Ts}}{\alpha_s G_T}$. The detection range of surveillance radar can be calculated using the formula:

$$R_{max} = \sqrt[4]{\frac{P_{Ts} t_s G_R \lambda^2 S_o}{(4\pi)^2 \alpha_s L k T_R D_o}} = \sqrt[4]{\frac{P_{Ts} t_s S_R S_o}{4\pi \alpha_s L k T_R D_o}}. \qquad (9)$$

It is easy to observe that the detection range depends on the receiving antenna gain, mean transmitter power, scanning angle and scanning time. The gain of the transmitting antenna does not contribute to the detection range, but influences the time-on-target.

In many radar systems a single antenna is used both for transmitting and receiving signals, and thus $G_T = G_R$. To extend effective radar range it is possible to use a set of highly directional, high gain antennas instead of a single receiving antenna. This leads directly to the concept of multi-beam or stack-beam antenna, very popular in 3-D surveillance radar. The multi-beam radar idea can be further extended. It is possible to develop a system with an omni-directional transmitter and a circular multi-beam receiving antenna set.

2.2 Radar range measurement and range resolution

The range to the target is determined in radar by measuring the time in which a radar pulse is propagated from the radar to the target and back to the radar. The time delay between the transmitted and received signal is equal to $\tau = 2R/c$, where R is the radar-target distance and c is the velocity of light, equal to 299,792,458 $[ms^{-1}]$. The radar-target distance can be easily calculated knowing the received signal delay by the formula

$$R = \frac{\tau c}{2}. \tag{10}$$

The time delay between two signals can be estimated using different methods; among them the most popular is finding the maximum of the cross-correlation function

$$r(\tau) = \int x_R(t) x_T^*(t - \tau) dt \tag{11}$$

between transmitted signal x_T and received signals x_R (* denotes complex conjugation of the signal). Using pulse radar, two objects can be separated if their distance is greater than the distance corresponding to pulse width $\Delta R = t_T c/2$. The theoretical spectrum of a boxcar shaped pulse signal is described by the sinc function. The width of the main lobe of the spectrum is equal to $B = 1/t_T$. For other types of transmitted waveforms, such as pulses with phase or frequency modulation or continuous waves with frequency or noise modulation, the range resolution depends on the width of the main lobe of the transmitted signal autocorrelation function. The typical range resolution for pulse-coded and continuous waveforms is equal to

$$r(\tau) = \frac{c}{2B}. \tag{12}$$

2.3 Radar range velocity measurement and range velocity resolution

The radar return signal is a delayed copy of the transmitted one only when the signal is reflected from a stationary (not moving) target. In most practical cases, the radar should detect moving targets. The reflection from moving targets modifies the return signal, which can now be written in the form

$$x_R^{HF}(t) = A(r(t))x_T^{HF}(t - \frac{2r(t)}{c}), \tag{13}$$

where x_T^{HF} is the transmitted (high frequency) signal, x_R^{HF} is the received signal, $r(t)$ is the distance between the radar and the target and A is the amplitude factor, which can be calculated using Equation (4). Most radars emit narrow band signals, which can be described by the formula

$$x_T^{HF}(t) = x_T(t)e^{j(2\pi Ft+\phi)}, \tag{14}$$

where $x(t)$ is the transmitted signal complex envelope, F is the carrier frequency and ϕ is the starting phase. For a constant velocity target ($r(t) = r_o + v_o t$) the narrowband received signal can be written in the form

$$x_R^{HF}(t) = A(r(t))x_T(t - \frac{2r(t)}{c})e^{j2\pi(F-2v_oF/c)t+j\phi_R}, \tag{15}$$

where $\phi_r = \phi - 4\pi r_o F/c$ is the received signal starting phase, and $4v_oF/c = 2v_o/\lambda$ is a Doppler frequency shift. For short pulse radars the Doppler shift is usually much smaller than the reciprocal of the time duration of the transmitted pulse ($4v_oF/c << 1/t_T$), and that Doppler shift has a very limited effect on a single pulse — it changes only the phase of the received pulse. Doppler frequency, and thus target radial velocity, can be estimated using a train of pulses and analyzing the phase difference between consecutive pulses. For long pulses, or for continuous waveforms, target movement introduces a Doppler shift of the carrier frequency, which can be measured by analyzing the received signal.

Velocity resolution is limited by the coherent signal processing time, which is smaller or equal to the time the target is illuminated by the radar (time-on target). Using classical filtering it is possible to separate two targets in velocity when the Doppler frequency difference is greater than the reciprocal of the coherent integration time. The velocity resolution is then equal to

$$\Delta v = \frac{2\lambda}{t_i} = \frac{2c}{t_i F}. \qquad (16)$$

For example, for a 10 cm wavelength and integration time 10 ms the velocity resolution is 20 m/s, while for 1 s integration the resolution is 0.2 m/s.

3. Linear Frequency Modulated Continuous Wave Radar

Frequency modulated continuous wave (FMCW) radar is most commonly used to measure range R and range (radial) velocity of a target [42, 43]. The most common structure of a homodyne FMCW radar is presented in Figure 2.

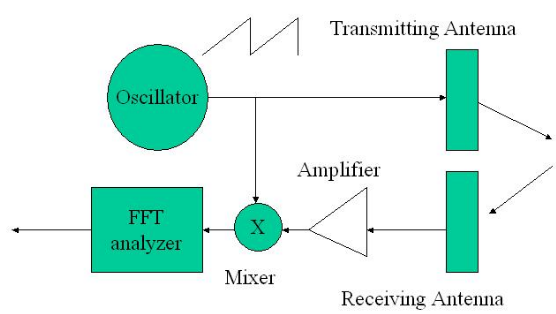

Figure 2. FMCW homodyne radar diagram

The microwave oscillator is frequency-modulated and serves simultaneously as transmitter and as the receiver's local oscillator. To estimate both the target range and velocity the triangle or sawtooth modulation is used. The echo signal is a delayed and Doppler shifted copy of the transmitted signal. After mixing the received signal with the transmitted one, the video (beat) signal is filtered and processed. Let us assume that the signal transmitted by the FMCW radar in time interval $[0, T_s]$, having linear frequency modulation, is in the form

$$s(t) = e^{j\phi(t)}. \tag{17}$$

The signal phase can be described by the second order time polynomial

$$\phi(t) = a_o + a_1 t + a_2 t^2. \tag{18}$$

The instantaneous frequency $f(t) = \frac{d\phi(t)}{dt}\frac{1}{2\pi}$ of the signal (17) is equal to

$$f(t) = \frac{a_1 + a_2 t}{2\pi}, \tag{19}$$

where $a_1/2\pi$ is the starting (carrier) frequency f_o, and $2a_2/2\pi$ is the slope of the frequency modulation. The signal bandwidth is equal to $2a_2T_s/2\pi$. After mixing the signal $s(t)$ with the return echo originating from a stationary target at distance R (which is equivalent to time delay $\tau = 2R/c$) one obtains

$$y(t) = s(t)s^*(t-\tau) = Y_o e^{j(b_0 + b_1 t)}, \tag{20}$$

where Y_o depends on the return signal amplitude and

$$b_0 = a_1\tau - a_2\tau^2, \tag{21}$$

$$b_1 = 2a_2\tau^1. \tag{22}$$

It is easy to notice that the video signal is the harmonic one, with frequency proportional to target range. To detect targets at different ranges, the Fast Fourier Transform (FFT) is often used [39, 13]. For moving targets, the range and time delay are continuously changing with time. This changes the starting phase of the video signal for each saw-tooth and shifts the video frequency. The video frequency shift, caused by the target movement, is equivalent to a change of the measured target range. The moving target range and velocity can thus be calculated using the 2-dimensional FFT. The dimension connected with "fast time" (time within each saw-tooth) gives a pseudo-range, while dimension connected with "slow time" (sawtooth count) gives information on the target velocity. The true range to the target is calculated by correcting the pseudo-range using velocity information.

LFMCW radar has many limitations [45, 41]. Minimum sawtooth length is limited by the maximum target distance. Usually the sawtooth length is 3-9 times longer than the maximum signal delay. This leads to a relatively low frequency of sawtooth modulation, which consequently limits the maximum unambiguous Doppler frequency (range velocity). It is possible to measure target velocity far beyond this ambiguity limitation, but this requires sawtooth modulation frequency diversity and use of the Chinese Reminder Theorem.

Classical FMCW radar can also be used for target acceleration estimation [45]. Constant target acceleration introduces a second order time polynomial to the starting phase of each sawtooth video signal. Using the Generalized Chip Transform (GCT) or Polynomial Phase Transform (PPT) it is possible to estimate not only range to target and target range velocity, but also target range acceleration.

4. Noise Radar

The name “noise radar” refers to a group of radars using random or pseudo-random waveforms for target illumination. In many papers this type of radar is referred to as a random signal radar (RSR) [5]. It can be used in a wide range of applications. It is possible to construct surveillance, tracking, collision warning, sub-surface and other radars using noise waveforms. Noise radars have several advantages over classical pulse, pulse-Doppler and FMCW radars. Noise waveforms guarantee the absence of range or Doppler ambiguity, low peak power and very good electromagnetic compatibility with other devices sharing the same frequency band. Due to the low peak power, noise radars also have very good electronic counter-countermeasures capability and very low probability of interception. This type of radar also has several disadvantages. Signal processing in noise radar is much more difficult and requires much higher computational-power than in traditional radar. Noise radars suffer from the near-far object problem. The received power changes with the reciprocal of the fourth power of the range, so for long-range radar very high effective dynamic range (usually much higher than 100 dB) is required. For smaller effective dynamic range the masking effect will be clearly visible; strong and close objects will mask weak and distant ones [38].

The first paper on noise radar was published in 1959 by B.M. Horton [1], who presented the concept of a range measuring radar. Further papers on that subject were published in the 1960s and 1970s [2, 15, 21]. At this time, the concept of noise radar had not attracted radar engineers, due to the fact that correlation signal processing was very difficult to implement using analog circuits. In the last decade, the noise radar concept has been “rediscovered” [4, 6, 18]. High-speed Digital Signal

Processors (DSP) and Programmable Logic Devices (PLD), equipped with hardware multipliers, make it possible to calculate transmitted and received signal cross-ambiguity functions in real time [12, 23] and to exploit Low Probability of Intercept (LPI) properties of noise radars fully. At present, the noise waveform concept is applied in many different types of radars. Many papers have been published on short-range surveillance radar, on imaging radar working in both SAR [9, 16, 17, 19, 20, 30, 31] and ISAR mode [10, 14], ground penetrating radars [3, 7] and others [22]. Noise radar may be used with a mechanically or electronically scanning antenna as well as with a multi-beam antenna. To avoid strong cross talk between transmitter and receiver, separate transmitting and receiving antennas are usually used. A noise signal is transmitted continuously, and the received signal, which is a delayed and Doppler-shifted copy of the transmitted signal, is divided into blocks and processed in a correlation processor. The ranges and radial velocities of the targets are evaluated directly by the correlation processor while the targets' azimuths are estimated using sigma-delta antenna angle estimation, beam power ratio or other techniques.

The detection process in noise radar is based on a correlation process [11]. The correlation-based radar diagram is presented in Figure 3.

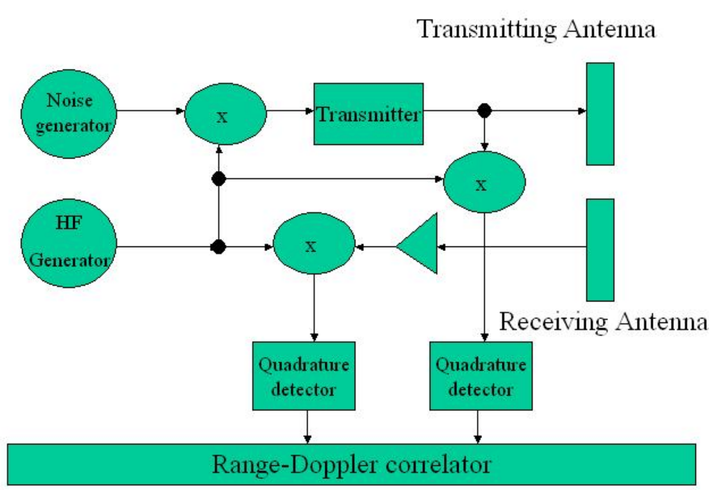

Figure 3. The structure of correlation-based noise radar

At the receiver the cross-correlation function between the transmitted and the received signal is calculated by

$$y_r(\tau) = \int\limits_{t=0}^{t_i} x_T(t)x_T(t-\tau)dt, \tag{23}$$

where x_T is the transmitted signal complex envelope, x_R - received signal complex envelope, and t_i - integration time. While radar is a device that should estimate range to target, Equation (23) can be rewritten in the form

$$y_r(r) = \int\limits_{t=0}^{t_i} x_T(t)x_T(t-\frac{2r}{c})dt. \tag{24}$$

A correlation receiver enhances the signal-to-noise ratio (S/N) by the factor t_iB, where B is the bandwidth of the transmitted noise signal. In Fig. 4, the output of a correlator with a t_iB factor of 100 is presented. To detect the useful signal in most radar systems the constant false alarm Rayleigh detector is being used. This detector compares the signal with the threshold. The hypothesis H_0 (there is only thermal noise and no useful signal) is assumed when the signal is below the threshold, and hypothesis H_1 (there is thermal noise plus target echo in the received signal) is assumed when the signal exceeds the threshold. It can be easily found that for a 10^{-6} probability of false alarm, the threshold level D_o should be at least 12 dB over the correlator output noise rms voltage.

This simple correlation processing can be used only for a short integration time radar. For longer correlation times Equation (24) can only be used for motionless targets. To detect moving targets, the Doppler frequency shift must be incorporated into the detection process. Assuming that the transmitted signal can be treated as a narrow-band one, then the received signal, reflected from the moving target, is a delayed and Doppler shifted copy of the transmitted signal. The complex envelope of the received signal can be expressed by the formula

$$x_R(\tau) = Ax_T(t-\frac{2r}{c})e^{j2\pi(-\frac{2vF}{c})t+j\phi}. \tag{25}$$

The optimal (in the mean-square sense) detector is based on the matched filter concept. The output of the filter matched to the signal echo described by Equation (23) can be calculated as an integral in the form

$$y = \int\limits_{t=0}^{t_i} x_R x_T^*(t-\frac{2r}{c})e^{-j2\pi(-\frac{2vF}{c})t}. \tag{26}$$

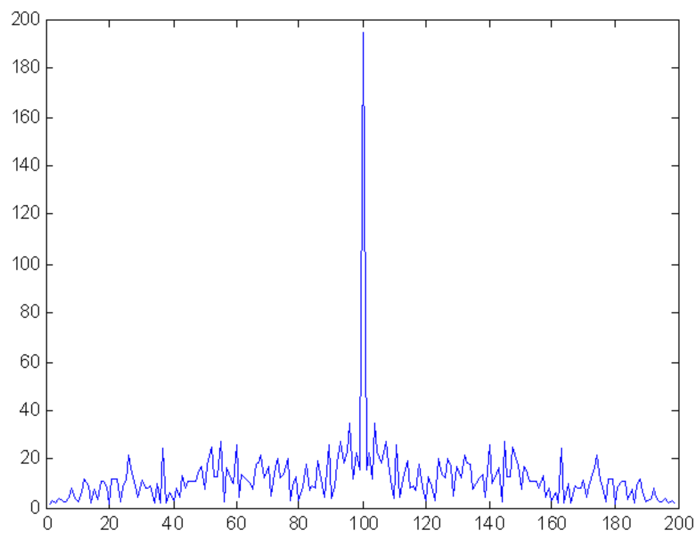

Figure 4. Example of noise correlation function for $Bt_i = 100$

The single matched filter can be used only when the target's position and velocity are known. To detect a target at an unknown position, it is necessary to utilize a bank of filters matched to all possible target ranges and velocities. This approach leads directly to the range-Doppler correlation function, described by the formula

$$y(r, v) = \int_{t=0}^{t_i} x_R x_T^*(t - \frac{2r}{c}) e^{-j2\pi(-\frac{2vF}{c})t}. \tag{27}$$

The above equation is very similar to the cross-ambiguity function, but here the time-delay is introduced only in the transmitted signal. This form of the transform is more convenient for digital implementation and will be referred to below as a range-Doppler correlation function.

Equation (27) can be treated as a set of correlation functions of the received signal and the Doppler shifted transmitted signal, or as a set of Fourier transforms of products of the received signal and the complex conjugate of the time shifted transmitted signal. An example plot of the absolute value of the range-Doppler correlation function for a single target at distance 10 km and radial velocity 100 m/s, calculated directly from Equation (27), is presented in Figure 5. It is easy to see the presence of very high side lobes along the frequency dimension, caused by the boxcar window introduced by integration limits. To decrease side lobe levels, more elaborate time windows (Hamming, Blackman and others) can be used. The windowing can be applied either at the transmission side (by changing the transmitted signal amplitude) or during signal processing. The second approach leads to the concept of unmatched filtering, described by the formula

$$y(r,v) = \int_{t=0}^{t_i} w(t) x_R x_T^*(t - \frac{2r}{c}) e^{-j2\pi(-\frac{2vF}{c})t}, \tag{28}$$

where $w(t)$ is a time windowing function [13]. The result of applying the Hamming window to range-Doppler correlation processing is presented in Figure 5. The first side-lobe level is decreased from -13 dB to -60 dB.

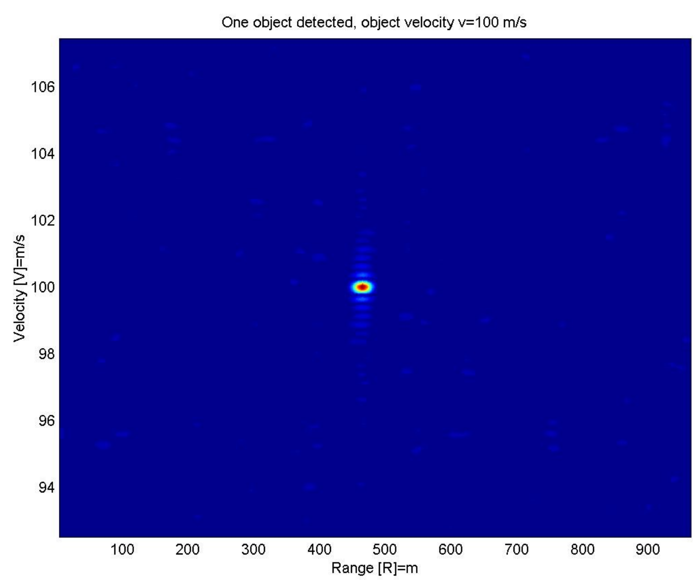

Figure 5. Range-Doppler correlation function, boxcar window, integration time t_i=0.05 s

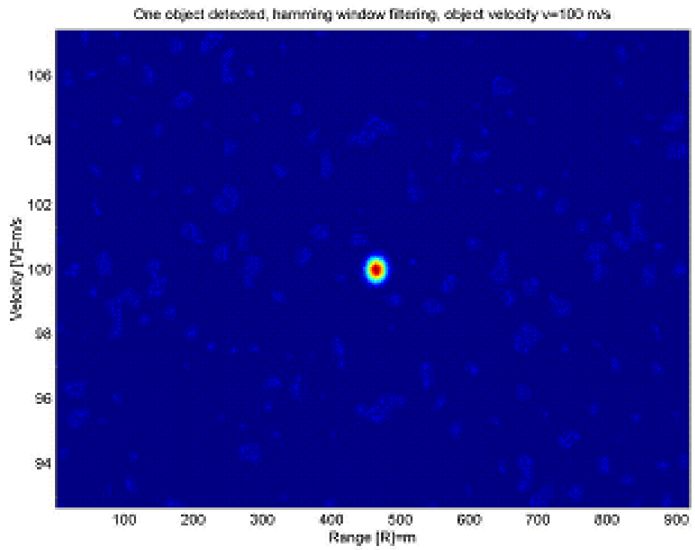

Figure 6. Range-Doppler correlation function, Hamming window, integration time $t_i = 0.05s$

5. Noise radar range equation

Noise radar, equipped with a transmitting antenna with gain G_T and a receiving antenna with gain G_R, transmitting microwave power P_T, receives a reflected noise signal from a target having a cross section S_o at distance R. The received power is equal to

$$P_R = \frac{P_T G_T G_R S_o \lambda^2}{(4\pi)^3 R^4 L}. \tag{29}$$

To detect the reflected signal in the presence of thermal white noise, the correlation process (matched filtering) is used according to the fundamentals given above. The received signal will be detected when its power is higher than the thermal noise power P_N multiplied by detectability factor D, e.g.

$$P_R \geq P_N D = kT_R BD. \tag{30}$$

The correlation receiver's property described above shows that the detectability factor is equal to

$$D = \frac{D_o}{t_i B}. \tag{31}$$

For medium integration time the time-bandwidth product is limited by the range migration effect [40]:

$$t_i B \leq \frac{c}{2V_{max}}. \tag{32}$$

Assuming that the maximum target velocity is equal to 3M (1000m/s), the maximum value of the time-bandwidth product is limited to 150,000. The maximum processing gain is then equal to 51.7 dB. The use of a windowing function will decrease this value by a few dB. The maximum detection range for the noise radar is given by the formula

$$R_{max} = \sqrt[4]{\frac{P_T G_T G_R S_o \lambda^2 t_t}{(4\pi)^3 L D_o k T}}. \tag{33}$$

To increase the detection range one can increase the transmitted power, antenna gain or integration time.

To achieve a longer correlation time it is necessary to incorporate range and Doppler cell migration effects into the detection process. Let us first consider the range cell migration problem. Assuming constant target radial velocity v_o, the range to target can be expressed as $r = r_o + v_o t$. In Equation (27) the target's velocity influence is limited only to the Doppler effect. For a longer integration time it is necessary to take into consideration the fact that the time delay of the signal changes considerably during the integration time. Incorporating time delay changes the detection process; one can obtain a modified correlation expression in the form

$$y(r,v) = \int\limits_{t=0}^{t_i} w(t) x_R x_T^*(t - 2\frac{r+vt}{c}) e^{-j2\pi(-\frac{2vF}{c})t}. \tag{34}$$

The computational complexity required to compute the range-Doppler correlation plane is now much higher than the computational cost of calculating results using equation (27), where it is necessary to time-scale the transmitted function. Time scaling may be performed in the time domain by resampling the transmitted signal or by using a chirp transform. For very long integration times it is hard to justify an assumption of a target's constant range velocity motion. The target's range velocity changes (range acceleration) can cause both velocity cell migration and additional range cell migration. Proper target detection can be achieved only when the target's velocity remains in the velocity resolution cell, which leads to the constraint

$$t_i < \sqrt{\frac{2\lambda}{a_{max}}}, \tag{35}$$

where a_{max} is the target's maximum range acceleration. For example, for a 10 cm wavelength and target acceleration of 1g (9.81 m/s), the coherent integration time is limited to 0.14 s, while for 10 g it is limitated to 0.045 s. Acceleration may also cause additional range migrations, if the integration time exceeds the limit

$$t_i < \sqrt{\frac{2\Delta r}{a_{max}}} = \sqrt{\frac{c}{Ba_{max}}}. \tag{36}$$

To extend the integration time further, it is necessary to introduce acceleration into the target's motion model. The range to the target should now be expressed as $r = r_o + v_o t + a_o t^2/2$. The matched filter concept now leads to the three-dimensional range-Doppler-velocity correlation function in the form

$$y(r, v, a) = \int\limits_{t=0}^{t_i} w(t) x_R x_T^*(t - \frac{2r + 2vt + at^2}{c}) e^{-j2\pi(-\frac{(2vt+at^2)F}{c})}. \tag{37}$$

Long integration time is important in multibeam radar. The transmitting antenna in this type of radar is either sector or omni-directional, and the transmitting gain is at the level of a few dB. The receiver antenna should be designed as a multi-beam antenna. Signals from each beam are passed to a multi-channel receiver where a correlation process according to Equation (37) is performed.

6. Bi-static and multi-static continuous wave radars

Monostatic radar is a radar which has the transmitter and receiver in one place. This idea has many advantages. For example it is easy to use a single clock source for both the transmitter and receiver and thus it is relatively easy to make a fully coherent device. There is no need to transmit the reference signal to the remote site; the entire processing can be done locally. The radar can send data to the command

and control center at the track level, which requires very low transmission throughput (1-20 kb/s), or on the plot level (10-100 kb/s). For continuous wave radar, the mono-static configuration also has several disadvantages. For example, very good separation (usually better than 60 dB) between transmitter and receiver antennas is required. Echo power changes as the reciprocal of the fourth power of the range. If the ratio between the maximum and the minimum targets' distance is at the level of 1000 (e.g. maximum distance 100 km, minimum distance 100 m), then the required dynamic range exceeds 120 dB. Additionally, there exist stealth targets, which reflect energy in different directions than the direction towards the radar. It is very difficult or even impossible to detect such targets using mono-static radars. The accuracy of the target's position estimation in monostatic radar is limited. The range to the target is calculated usually with good accuracy (estimation error 1-30 m), but cross-range accuracy is usually very poor (error of a few kilometers at 100 km distance).

Using the bi-static concept can reduce all of the above mentioned problems. The spatial separation of the transmitter and receiver antennas leads to significant attenuation of the direct path signal. In addition, the near-far target problem is reduced, while the target signal can be expressed by the formula

$$P_R = \frac{P_T G_T G_R S_o \lambda^2}{(4\pi)^3 R_1^2 R_2^2 L}, \tag{38}$$

where R_1 is the transmitter-target distance and R_2 is the target-receiver distance. The required dynamic range for the maximum and minimum targets' distance ratio equal to 1000 (e.g. the maximum target's distance from receiver 100 km, the minimum distance 100 m, the transmitter-receiver distance 10 km) is now reduced to 80 db (40 dB smaller than for the mono-static case). The maximum target detection range is described by the formula

$$R_{1max} R_{2max} = \sqrt{\frac{P_T G_T G_R S_o \lambda^2 t_t}{(4\pi)^3 L D_o k T}}. \tag{39}$$

The bi-static theoretical coverage diagram forms the so-called Cassini curve, presented in Figure 7. In practice it is not possible to detect targets in the direction of the transmitter line-of-sight, and practical bi-static radar coverage is presented in Figure 8.

With the receiving antenna in a different place than the transmitting one it is possible to increase the effective radar cross-section of stealth targets. Increasing the number of receiving antennas and forming a multi-static constellation, it is possible to decrease the detection

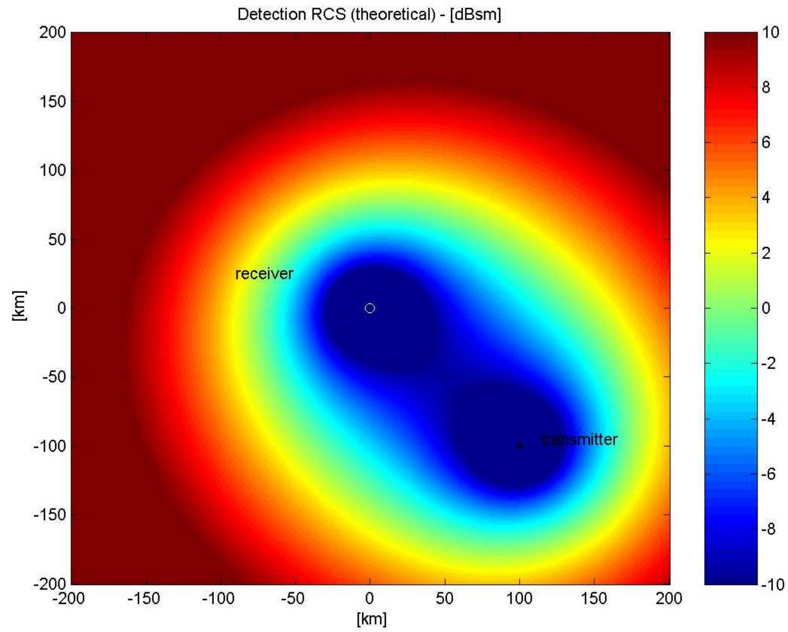

Figure 7. Bistatic theoretical coverage diagram, detected RCS [dBsm]

losses caused by signal fading, multi-path effects and target scattering directivity. It is also possible to locate and track targets very accurately using the multi-static concept. Expected errors in almost all surveillance spaces are at the level of 1–20 m. Using an adequate number of sensors (4 or more), it is possible to estimate the target's height, even in the case when the sensors do not have 3D measurement capabilities.

To use a multi-static configuration, it is necessary to have the reference signal at each receiving site. The reference signal can be received by the special reference channel or can be sent from the transmitter using high throughput (10-100 Mb/s) digital links.

Multi-static radar is usually combined with the net-centric approach to data exchange. All sensor sites have to be connected by high-throughput, self-configuring data links. The data links should also provide a very stable clock to make all processing coherent, and very accurate time data to synchronize all events in the distributed system.

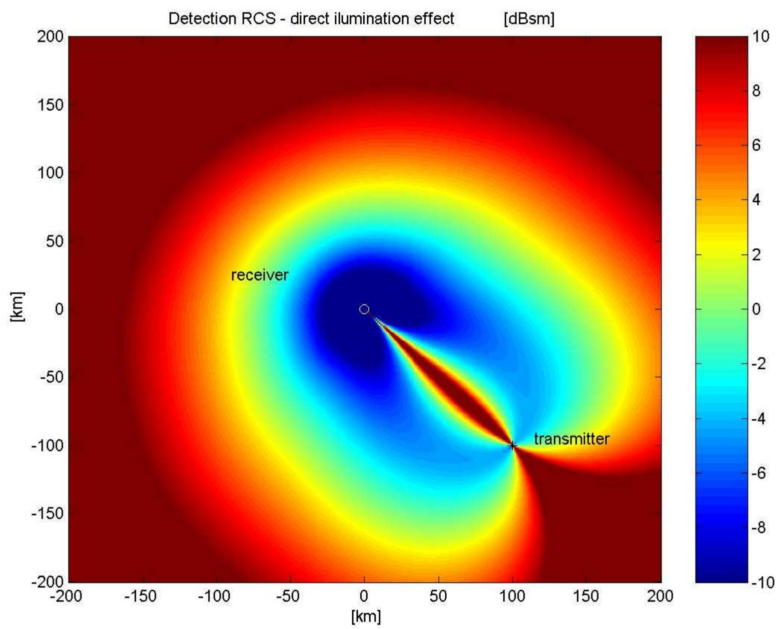

Figure 8. Bistatic coverage diagram — direct illumination attenuation effect, detected RCS [dBsm]

7. Target identification in continuous wave radars

Identification of the target is the final stage of radar signal processing. Parameters of the identified target can be displayed on the sensor screen or can be sent to a remote command center. There is no one superior identification procedure, so identification processes are designed using different approaches. Almost all of them are based on Doppler processing of the received radar signal.

One widely-used identification method is based on the SAR concept. The radar is mounted on a moving platform. Platform motion is perpendicular to the line-of-sight of the fixed radar antenna, and the antenna beam is scanning the target during platform motion. The distance from the radar to the selected scatterer is almost a hyperbolic function of time. The Doppler frequency of the target's signal is then a linear function of time, and as a result, each echo signal has a chirp form. Applying match filtering, it is possible to obtain a high-resolution image of the target. The classical angular resolution of the radar is equal to the product of the target's range and the antenna beam width. For a distance of 10 km and antenna beam width 50 [mrad] the angular resolution is equal to 500 m. Using SAR technology, it is possible to improve resolution to $D/2$, where D is the antenna length. Using a low-gain, small size antenna it is possible to obtain a sub-meter cross-range resolution and a very detailed image of the target. A SAR image example is presented in Figure 9. The raw radar image used for the SAR processing is presented in Figure 10.

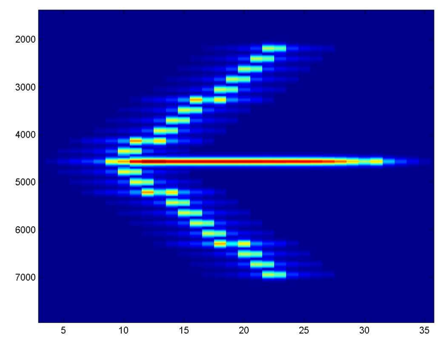

Figure 9. SAR image of arrow shaped object

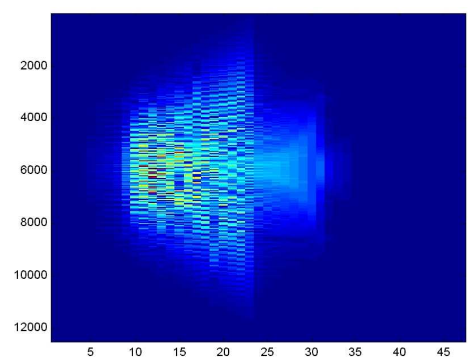

Figure 10. Raw radar data of arrow shaped object

In this example, the SAR compression factor was 1000. It is possible to achieve even higher compression ratios and a better cross-range resolution by using spotlight-SAR. In this mode the radar antenna tracks the target and observation time (time-on-target) is significantly enlarged. SAR is often used for air-borne and space-borne remote sensing. It is also used for ground penetrating radar and for imaging hidden targets.

An interesting modification of the above is ISAR (Inverse Synthetic Aperture Radar). The ISAR scenario is opposite to the SAR scenario. The radar is now placed in a fixed position and the target changes its position in time. The Doppler history of each scatterer on the target's surface is different, and the target image is reconstructed using a bank of digital filters matched to the signal originating from each target's scatterer. This technology is used for ship, airplane and space satellite imaging. Very often the radar, placed on a moving platform, is observing a moving target. For such a scenario it is possible to combine both of the above technologies.

Doppler processing is also used for vehicle and people identification. The identification can be achieved using micro-Doppler analysis. Micro-Doppler vibration analyses are based on detecting Doppler frequency modulations caused by vibration of the vehicle body resulting from engine or gearbox frequencies. Analyzing the Doppler signal originating from the vehicle it is possible to detect all characteristic frequencies, and even to make a mechanical diagnosis of the state of the engine and shafts.

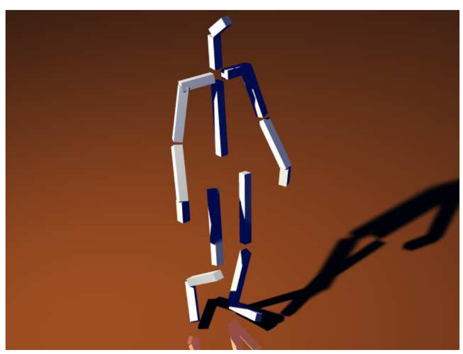

Figure 11. Wire model of human body used for walk Doppler signature analysis

Micro-Doppler analyses can also be used for people identification. In that case, it is possible to detect Doppler frequency modulation caused by heartbeats, breathing and body motion (walk, run, head turns etc.).

For people identification, it is also possible to combine micro-Doppler analyses with ISAR processing. During walk and run, there is a very characteristic movement of legs and hands. Making even a very simple "wire-model" of the human body (see Figure 11), it is possible to predict a human Doppler signature. The modeled signature of human walk is presented in Figure 12. The signature obtained using a real-life signal, registered in X-band radar, is presented in Figure 13. By

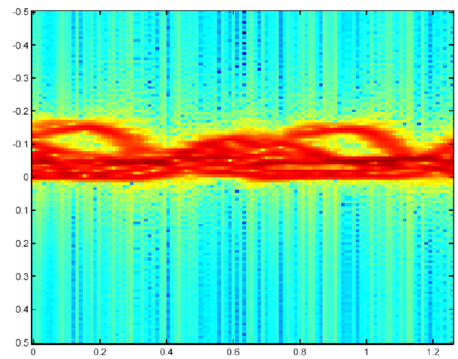

Figure 12. Simulated Doppler signature of human walk - x-axis: time, y-axis: Doppler frequency

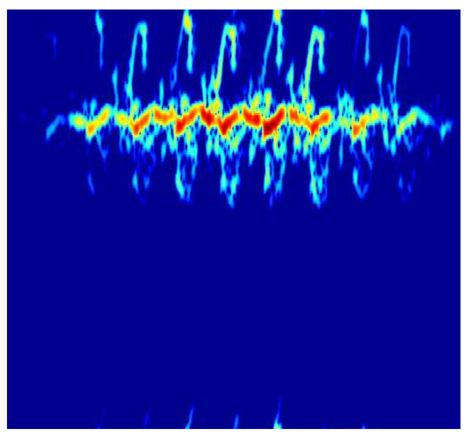

Figure 13. Registered Doppler signature of human walk - x-axis: time, y-axis: Doppler frequency

comparing the predicted signature with the recorded one it is possible to recognize individual behavior, and combining it with heartbeat, walk and breathing analysis it is possible to identify people and even estimate their emotional state.

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