Through Wall Detection and Recognition of Human Beings using Noise Radar Sensors

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SUMMARY

Elaboration of a new approach to solving of a contradictory and challenging problem of through wall detection radar design is the main goal of the paper. Two types of radars have been investigated: (1) CW radar that uses pseudo-random sequence (PRS) of the maximal length (m-sequence), hereinafter referred to as ***PRS-radar*** *and (2) CW radar with use of the noise waveform at corresponding carrier frequency referred to as* ***Noise Radar****. Besides, notional design of* ***Software Noise Radar*** *for these applications is briefly considered.*

1. INTRODUCTION

In spite of numerous R&D focused on surface penetrating radar design, e.g. [1-13], nevertheless there is no radar which enables reliable detecting of live human beings when performing search and rescue operations under conditions of extraordinary situations caused by man-made or natural catastrophes. Detection and identification of terrorists, criminals, etc. is an important problem as well. In particular, the problem gets more complicated in case of non-authorized penetrating into premises and intentional creating conditions which complicate their detection by available means, such as specially trained dogs or very sensitive sound receivers. The presence of extraneous smells is the limiting factor for the first case, while in the second case it is rather difficult to provide silence for rather long period during salvage operations.

The efforts have been spent [9-13] for design of Doppler radar systems intended for detection of various moving objects, including live human beings. The systems created have confirmed applicability of Doppler Effect based methods for detection of live human beings, however, they are not able working effectively under realistic conditions, for example, when attenuation of sounding signals is so large that the signal reflected from the wall exceeds significantly (by factor of many orders) the signal scattered by a target behind the wall. Besides, the need of weak signal detection under presence of strong signal reflected by the wall and other objects brings also considerable difficulties. For the above and some other reasons the known systems are useless for solving the problem of Through Wall Detection and Recognition.

2. PROBLEM POSING

In the radar suggested we also use the Doppler phenomenon, but for so small displacements of the object to be detected that it causes just an amplitude modulation of the optimal receiver output which is essentially a convolution of a broadband sounding signal (the reference) with radar returns, the phase of which is slightly modulated by a target performing slow and small enough periodic or non-periodic

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motions. Such motions can be associated with either human being body displacements or his breathing or even his heart beats. Though the body motion is the main factor in the through wall detection of persons, however the suggested radar potential will be sufficient for detection of even a nonmoving person because of his breathing or even his heart beats. When breathing, the periodic motion of the person's thorax takes place with magnitude of 2-7 mm, while his heart beats may cause periodic motion of the body parts with the magnitude not exceeding 0.2-1mm. Usual clothes of a person (if it is dry) is transparent for electromagnetic waves in the chosen frequency range, while the human body surface (largely consisting of water) is a rather good reflector. Actually separation between Doppler frequencies of breathing and heart beats is required for evaluation of his psychophysical status, while the Doppler signal caused by breathing is sufficient for detection of non-moving person because it significantly exceeds the Doppler signal produced by heart beats. Possible application of the Doppler radar suggested is schematically shown in Fig.1.

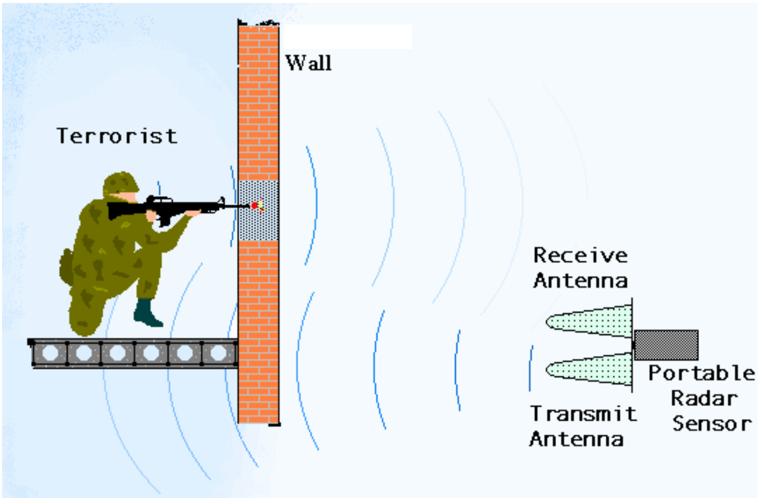

Fig.1. Possible application of the Doppler radar suggested (schematically).

It is known that the range sensitivity of the method attains 10^{-9} m in microwave [14]. Capability of a heart beats detection of a person located behind a break wall having thickness of 10 cm has been experimentally proven in [9]. Despite of an apparent simplicity of the radar, its design is a rather difficult technological problem since the hardware of the radar should meet the whole set of tuff requirements stipulated by the complicated radar conditions:

- Strong reflections of sounding signal by walls which can overload/saturate the radar receiver;
- Strong absorption of electromagnetic energy by walls which cause low levels of radar return;
- Strong interference signals due to multiple reflections of sounding signal from the operator, other rescuers, and other objects;
- Strong interfering signals due to radiation of the radar transmitter.

Operational frequency of the radar is dictated by two contradictory conditions. On the one hand, the shorter the wavelength, the higher sensitivity of the method to the phase modulation and the smaller dimensions of receive and transmit antennas. On the other hand, an increase in a central wavelength of the probing signal is desirable for enhancing the penetrating capability of electromagnetic waves through walls. However, desirable increase of the wavelength is limited, in turn, by two factors: the first one is tied with shielding sounding signals by metallic meshes in concrete walls, while the second one decreases the

RCS of the target when the wavelength exceeds the sizes of the target. The estimation carried out have shown that for conducting of rescue activities in ruins, typical concrete buildings and facilities the most optimal is the frequency range 800 – 2000 MHz.

However, the optimal frequency range chosen according to the above criteria does not allow creating of small-sized portable antennas with high enough directivity. In this range it is possible to count for a width of the antenna pattern of 20° – 30° having side-lobe level about -20dB in both elevation and azimuth planes. It is clear that it is not possible to localize a target using only directivity properties of the antennas. It is necessary also to provide a sufficient range resolution. High range resolution capability of the radar becomes especially important in case when ground around the area of rescue activities is covered with tall grass or bushes, etc. In this case, the radar returns may contain fluctuating components because of their motion due to wind. The Doppler spectrum of these fluctuations contains low frequencies and may have the same frequency range as the Doppler spectrum of the target. This will essentially increase the false alarm probability. Besides, the Doppler spectrum of the signal reflected by the operator, etc. also can fall into the same frequency range with a Doppler spectrum of the required target and exceeds significantly (by many orders) the signal scattered by the target. It is very important to provide a high range resolution for filtering out these signals. This is very important because the signals scattered by persons located in the neighborhood of the radar are by factor of many orders higher, as a rule, of the signals scattered by the target.

As it seen from the above, the impulse volume of the radar should be close to the geometrical volume of a target to be detected, while the side lobes of both the antenna patterns (AP) and ambiguity function (AF) of the sounding signal should be close to zero. In reality, it will not be possible to provide a very low level of AP sidelobes in portable transmit/receive antennas having acceptable sizes, while obtaining extremely small AF sidelobes that will provide the value of a received signal at the level of the receiver inherent noise is a solvable problem. This means that rescue activities are also may be arranged in the way that interferences may be outside the resolution cell of the radar and will not degrade its performance.

The radar should not just detect the presence or lack of a target, but also to point its coordinates as much precisely as possible, and also define the type of the target using its Doppler portrait. High angular resolution required for target position finding is ensured with application of triangulation method provided a high range resolution and a possibility of having two or more measurements. For the radar under consideration the required range resolution should be about of 0.5 – 1.5 m (the sizes of the target). The maximal working range of the radars under consideration, as a rule, is limited to several tens of meters. For applications of the radar inside small premises the minimal working distance should be no more than 1 – 2 m.

The listed above requirements to the radar determine in main the type and structure of the probing signal to be used. Unfortunately, application of pulsed waveform that provides perfectly zero AF range sidelobes is technically impossible in our case because of impossibility to provide simultaneously a very short radar blind zone and a sufficient energy potential. Therefore it is necessary to use a CW wideband probing signal with a large enough base. Among wide class of such signals, the greatest attention deserves random noise and pseudo-noise waveforms in view of sufficient simplicity of their generation and processing. Besides in a number of applications the covert operation of the radar under consideration is required that also is provided by noise waveform application [14-15].

In the paper, we shall consider two types of radars: (1) CW radar that uses pseudo-random sequence (PRS) of the maximal length (m-sequence), hereinafter referred to as **PRS-radar** and (2) CW radar with use of the noise waveform at corresponding carrier frequency referred to as Noise Radar. Besides, notional design of Software Noise Radar for these applications is briefly considered. In all cases correlation processing of the radar returns is used.

3. THE PRS-RADAR

The block diagram of the PRS-radar is presented in Fig.2. It operates as follows. A single frequency signal generated in the oscillator 6 with high frequency stability is fed into the phase manipulator (±π) 2. The phase manipulator 2 executes phase modulation of the signal according to pseudo-random *m*-sequence generated by the oscillator 1. As a result we get a phase-shift keying signal. After its amplification in the amplifier 3, the phase-shift keying signal is radiated by the transmit antenna 4. Unfortunately, because of not perfect rejection of the baseband signals there are three different signals at the phase modulator output, two of which cannot be filtered out from each other: (1) useful sounding signal; (2) spurious baseband PRS signals and (3) spurious monochromatic carrier signal. From the listed above signals the second one is considerably attenuated by a balanced modulator and its power spectrum density (PSD) is much below of probing signal PSD. It is practically completely suppressed in the circuit formed by filter of the modulator, the bandpass power amplifier 3 and frequency characteristic of the transmit antenna. In spite of the signal (3) is suppressed in the balance modulator by 20 – 30 dB (which is a typical suppression factor for realistic broadband modulators), nevertheless it makes the most negative influence onto the radar work and performance. The point is that the signal frequency falls into the frequency bandwidth of the sounding signal (1) and, therefore, also gets amplified in the power amplifier 3 and is radiated by the transmit antenna 4. This mans the sounding signal comprised of two signals: the phase-shift keying signal and single (the carrier) frequency one. The latter has no properties of range selection and, consequently, does not allow obtaining of AF side-lobes level less than – 20 – 30 dB after signal compression. The signal reflected by a target (a person) located behind a concrete wall of width ~ 30 cm apart of 10 m from the radar can be 90 dB lower of a signal reflected by the operator. Therefore, for recovery of usefull signal at the presence of signals from the operator, the range AF side-lobe level should be no more -110 dB. To suppress influence of monochromatic component of the sounding signal in the reference channel of the quadrature receiver the additional modulation has been used using signal generated by 8 which has meander form with phase $2n\tau_p$ where τ_p – duration of elementary pulse PRS, n – integer ≥ 1. The reference signal in the quadrature correlation receiver is formed as follows. The signal from the high-stable quartz resonator 6 is fed into the clock frequency generator 5, which starts the generator of delayed PRS 11. The delay equals round-trip propagation time of the sounding signal to the target (it is prescribed by the operator using PC). Delayed reference PRS is cross-multiplied with the signal of the oscillator 8 in the multiplier, representing the "&" circuit. This multiplied signal is fed into the phase manipulators 10 and 12, while their second inputs are fed by is fed by quadrature components of the carrier oscillator 6. Signals from phase manipulators 10 and 12 are fed into the mixers 15 and 16 in the quadrature correlation receivers.

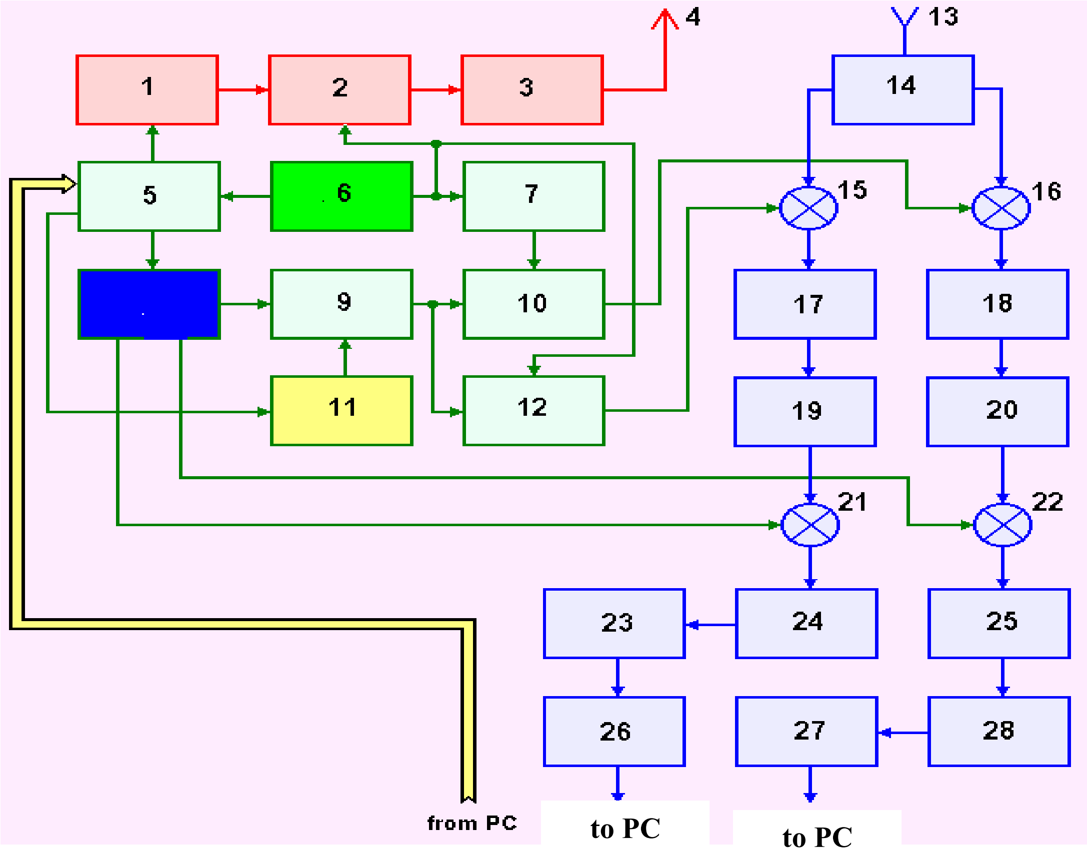

Fig.2. Block-diagram of the PRS-radar
1 – PRS-oscillator, 2, 10, 12 – phase manipulator, 3 – power amplifier, 4 – transmit antenna, 5 – clock frequency oscillator, 6 – quartz stabilized oscillator of carrier frequency, 7 – single frequency phase shifter (π/2), 8 – quadrature oscillator of additional modulation, 9 – digital multiplier, 11 – oscillator of reference PRS, 13 – receive antenna, 14 – LNA, 15 and 21- in-phase mixers, 16 and 22 quadrature mixers, 17 and 18 – IF filters, 19 and 20 – IF amplifier, 23 and 28 – Doppler amplifiers, 24 and 25 – Doppler filter, 26 and 27 – analog-to-digital converters (ADC).

The input signal from the receive antenna 13 and low-noise amplifier of power 14, represents itself an additive mixture of the following signals: 1 – a leakage signal from the transmitting antenna; 2 – a signal from the operator, the maintaining radar; 3 – a clutter signal and signal reflected by the wall; 4 – a signal reflected by a target, which the most weak one. The overall number of signals coming to the receiver input is at least 8. It is easy to see, that due to correlation processing all signals reflected by objects placed outside the correlation volume will be suppressed by factor of $\Delta f_s / \Delta F_{if}$, where Δf_s is effective bandwidth of the sounding signal, ΔF_{if} is effective bandwidth of the filters 17, 18. Therefore the letter should be as smaller as possible.

The dynamical range of the signals at the receiver input is to be very large(~100 dB).

To enlarge dynamical range of conventional receiver the second signal converter has been implemented using mixers 21 and 22, while the amplification rate of amplifiers 14, 19, 20 is made rather small, just to compensate the first down converting losses, and preserving SNR at the IF amplifier output within the whole dynamic range of the received signals. The quadrature signals from IF amplifiers are fed into the mixers 21 and 22, while the signals of additional modulation generator 8 is fed as the reference signals. This allows to suppress all parasitic signals providing high dynamical range of the radar. The signals with no Doppler shift (an echo from wall, parasitic leakage and coupling of antennas), will be outside the Doppler filters bandwidths 24 and 25. We have two signals having Doppler shifts: signal reflected by target and that scattered by the radar operator. It is important that the signal from the target will pass all circuits without losses, while the signal from the operator will be suppressed by $\Delta f_s / \Delta F_{if}$ time after compression. The dynamical range of the output signals of Doppler filters is essentially decreased, because of suppression of spurious components. After that the main amplification of the received signals is performed in the receiver. Narrowband Doppler signals are sampled and sent into PC for further computer processing: filtering, target detection and identification.

For PRS, the AF range side-lobe equals $1/N$, where $N = 2^k - 1$ is quantity of elementary impulses in PRS, k is an integer number. However, this is valid only for zero Doppler frequency $\Omega = 0$, while for $\Omega > 0$ he AF range side-lobe will increase essentially. For instance, in Fig. 3a the range sidelobe level γ for PRS as function of the Doppler frequency period to PRS period ratio is shown for k = 11. In the same figure the striped line shows range sidelobe level at the absence of Doppler shift. The more N, the higher influence of Doppler frequency shift on to the range sidelobe level. Fig.3b shows Doppler frequency period to PRS period ratio as function of PRS length (parameter k) for which the sidelobe level doubling is achieved.

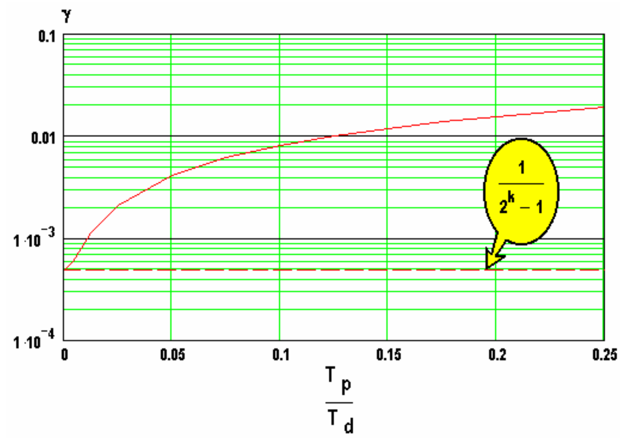

Fig. 3a. Sidelobe level γ for PRS as function of the Doppler frequency period to PRS period ratio :
Td / Tp ***k**** **= 11; Number of bits in PRS: *N*=2*k*-1**

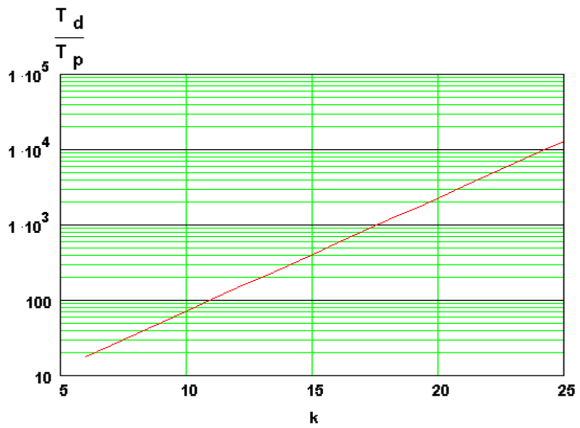

Fig. 3b. Doppler frequency period to PRS period ratio as function of PRS length (parameter *k*) for which the sidelobe level doubling is achieved

It is seen from the above figure, that for the selected duration of the elementary impulse required for providing of the range resolution, we cannot take PRS with an arbitrary number N of elementary impulses aiming decrease in range side-lobes just because of increase in its sensitivity to Doppler frequency shift which results in the growth of range side-lobes.

After final processing of the received signals it is possible to achieve rather good ratio of signals from the target and from the operator. For instance, for the radar having 1W transmit power, 150MHz frequency bandwidth (1m range resolution) of sounding signal, and $N = 65535$ of PRS length, RF losses in wall 50dB and a AP side-lobe level −13dB, the signal from the target located behind the wall at the 10 m distance from the radar exceeds the signal from the operator by 26dB, that it is quite enough for reliable detection of the target.

5. SOFTWARE NOISE RADAR

Fig.4 shows block-diagram of Software Noise Radar which uses truly noise signal as a sounding one. The latter is generated by noise generator 1 which has its central frequency as a carrier one. The frequency bandwidth of noise signal has the same value as in case of PRS-Radar.

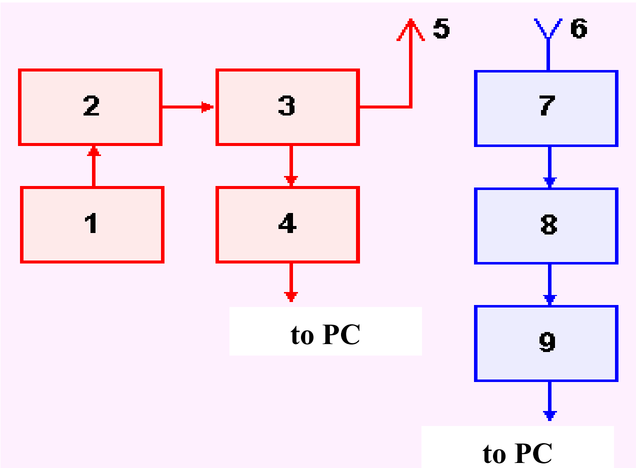

Fig.4. Block diagram noise radar
1 – noise waveform generator; 2 – power amplifier; 3 – directional coupler; 4, 9 – analog-to-digital converters; 5 – transmit antenna; 6 – receive antenna; 7 – RF filter; 8 – low-noise amplifier

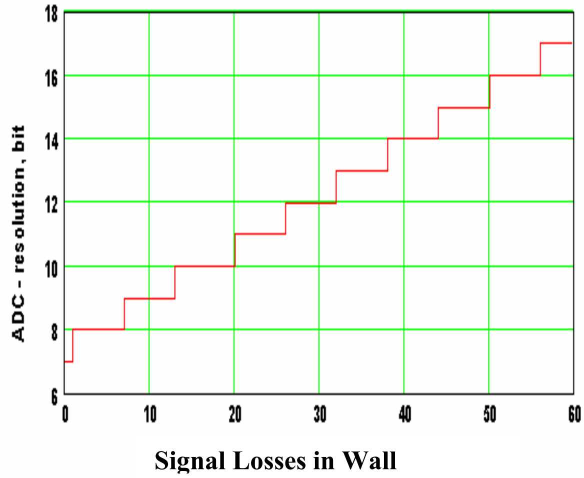

Fig. 5. Number of ADC bits required as a function of signal losses in wall.

The important feature of this radar is that the generator 1 produces sounding waveform with a required bandwidth which supposes no need in such unit as modulator, and therefore, all the problems related to its characteristics influence on to the radar performance are solved in this way. The noise signal gets amplified in the power amplifier 2 up to the required level and is fed into the transmit antenna 5.

As it is known, the delayed copy of sounding signal is necessary when performing correlation reception of noise radar returns. Because in our case the frequency spectrum of sounding signal can be centered in vicinity of 800±(50÷75) MHz, the usage of a fast analog-to-digital converter became feasible. Now days 8-bit ADC with clock frequency up to 2GHz are commercially available at this frequency range. The signal from ADC 4 is fed directly into PC where digital processing enables required delaying of sounding signal to generate the reference.

Block-diagram of the Software noise radar is very simple. In particular, there is no need in quadrature channel since quadrature processing is performed in PC. However, one faced some limitations when designing such radar. For instance, the signal from receive antenna 6, should go directly to the ADC input 9 just after RF-filter 7 and LNA 8 in the whole dynamical range and frequency bandwidth of the sounding signal. For this purpose the LNA 8 should amplify this signal up to the level r (typically: ± 5 V) required for normal operation of the ADC . Besides The number of ADC bits should be high enough to sample the received signal without distortions in the whole dynamical range. For 10mW transmitted power the amplifier gain should be about 55dB that is affordable today, while required number of ADC bits is a challenge for available hardware. In our case the dynamical range of radar returns is mainly dependent on signal absorption in the wall. Fig.5 shows number of ADC bits required as a function of signal losses in the wall in case of 10m distance between radar and the wall. As it is seen from Fig.5 in order to detect a target using Software Noise Radar one has to apply 16-bit ADC with clock rate ~ 500MHz, which should be available in the future. Nevertheless, fast 8-bit ADCs available today (for example, Analog Input Card for PCI Bus "CompuScope 82G" from GaGe corporations) enable design of Software Radar capable of detecting live persons behind brick walls having thickness of $1/4$ brick from distance ~ 10m. A low averaged power of RF radiation with very low power spectral density ($7 \cdot 10^{-11}$ W/Hz) of the sounding signal allow to use this radar with no ill effect on people and no electromagnetic interferences for other RF devices that may be used at the same time in the same area.

Fig. 6-8 shows the output signals obtained via computer simulation of the radar under consideration. Fig.6a shows the signal of heart beat of a non-moving person who is delaying his breathing, while Fig.6b shows its frequency spectrum of this signal. The average signal-to-noise ratio is about 10 dB. As it is seen from the figures, detection of a live person is possible even due to detection of his heart beat. Fig. 7 shows the signal from both breathing and heart beats of non-moving person, while Fig.7b shows Doppler spectra of these signals. It is seen, that the related spectra are easily distinguishable. With other things being equal – the signal due to breathing exceeds considerably signal due to hear beats. Received signal from a randomly moving person with maximal amplitude of the motion ~ 1/6 wavelength of center frequency and its Doppler spectrum are presented in Fig.8a and Fig.8b respectively. This signal is dominant above remaining, and on his background signals from breathing and palpitation practically are completely masked.

Obviously, that on the basis of the character of signals and their spectrums one may forecast emotional and physical status of the person located behind an obstruction. For example, when person does not move, but is strongly agitated he will speed up his breathing and heart beats. Motion of the person with big amplitude – will tell us that he has enough room to do that. His lasting motions can tell about his quite good physical status and a that he is doing some operations, etc

Signals of the radar after processing	Spectrums from these signals

PRS-radar

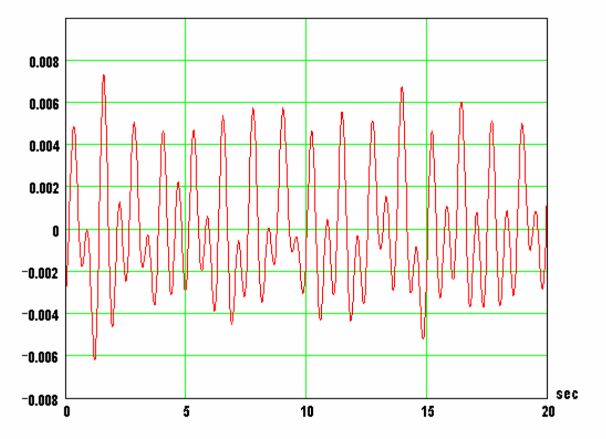

Fig. 6a. Signal scattered by non-moving and non-breathing person. SNR = 10 dB

PRS-radar

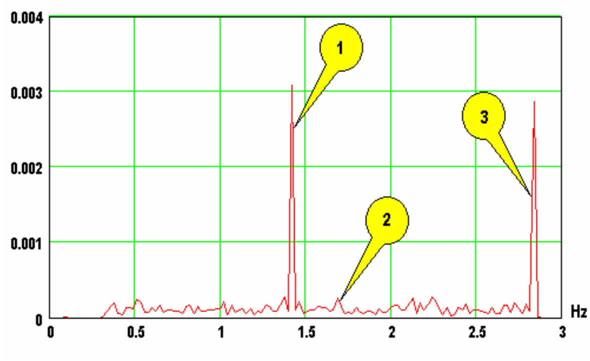

Fig. 6b. Doppler Frequency Spectrum of signal scattered by non-moving and non-breathing person: (1)- first harmonic of the signal; (2)- second harmonic of a signal; (3) -receiver noise floor

PRS-Radar

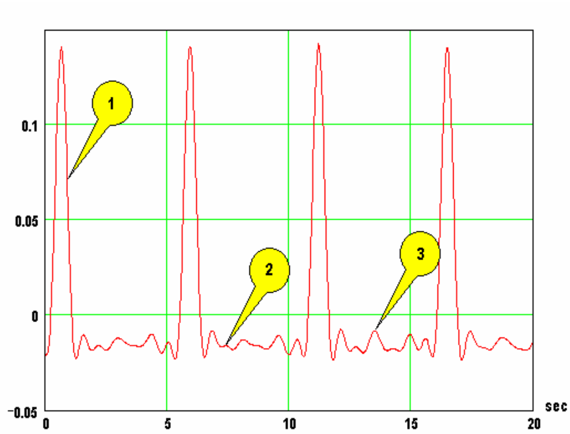

Fig. 7a. Signal scattered by: (1) - non-moving, but breathing person; (2) - heart beat of a person; (3) - receiver noise

PRS-Radar

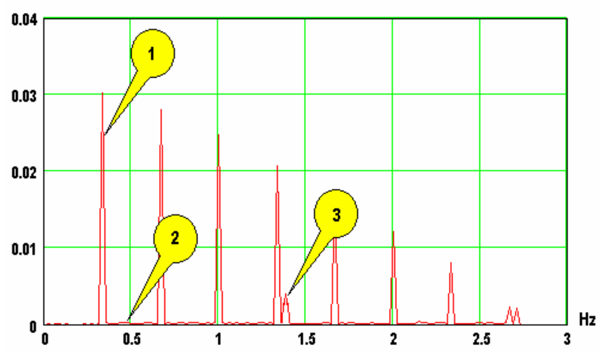

Fig. 7b. Doppler Frequency Spectrum of signal scattered by: (1) - non-moving, but breathing person; (2) - heart beat of a person. (3) - receiver noise

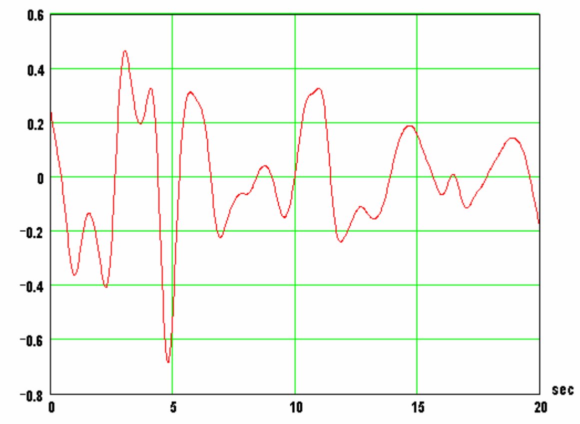

Fig. 8a. Signal scattered by random motion of the person with amplitude about 1/6 of the wavelengths s

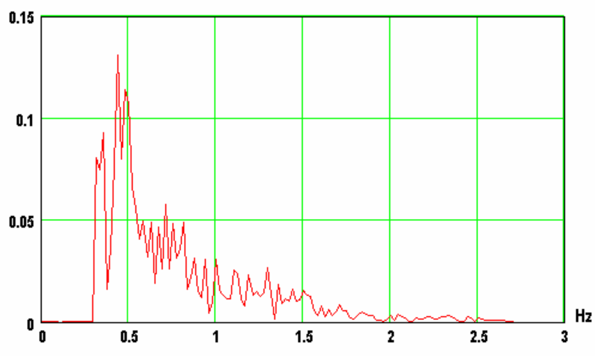

Fig. 8a. Signal scattered by random motion of the person with amplitude about 1/6 of the wavelength

CONCLUSIONS

Radar for Through Wall Detection and Recognition of Human Beings is to be designed on the basis of broadband RF signals with large base. Random Noise and Pseudo Noise waveforms are the most appropriate signals for that radar. Random Noise waveform is more appropriate one when covert operations or/and electromagnetic compatibility with other radar sensors are required. The first waveform is the most applicable one when the highest radar potential is needed, while the second waveform is the best one for those applications where rather low averaged power of RF radiation (having very low power spectral density) is required. For instance, when one has to provide no ill effect on people and no electromagnetic interferences for other RF devices that may be in use at the same time in the same area.. Possibility of detection of a live person behind a thick enough wall is shown when probing signal attenuation rate does not exceed ~ (50-60)dB that corresponds to (25-30)cm of a concrete wall or (40-50)cm of a brick wall. Using temporal and spectral characteristics of the detected signals one can estimate psychophysical status of the person and his activity.

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