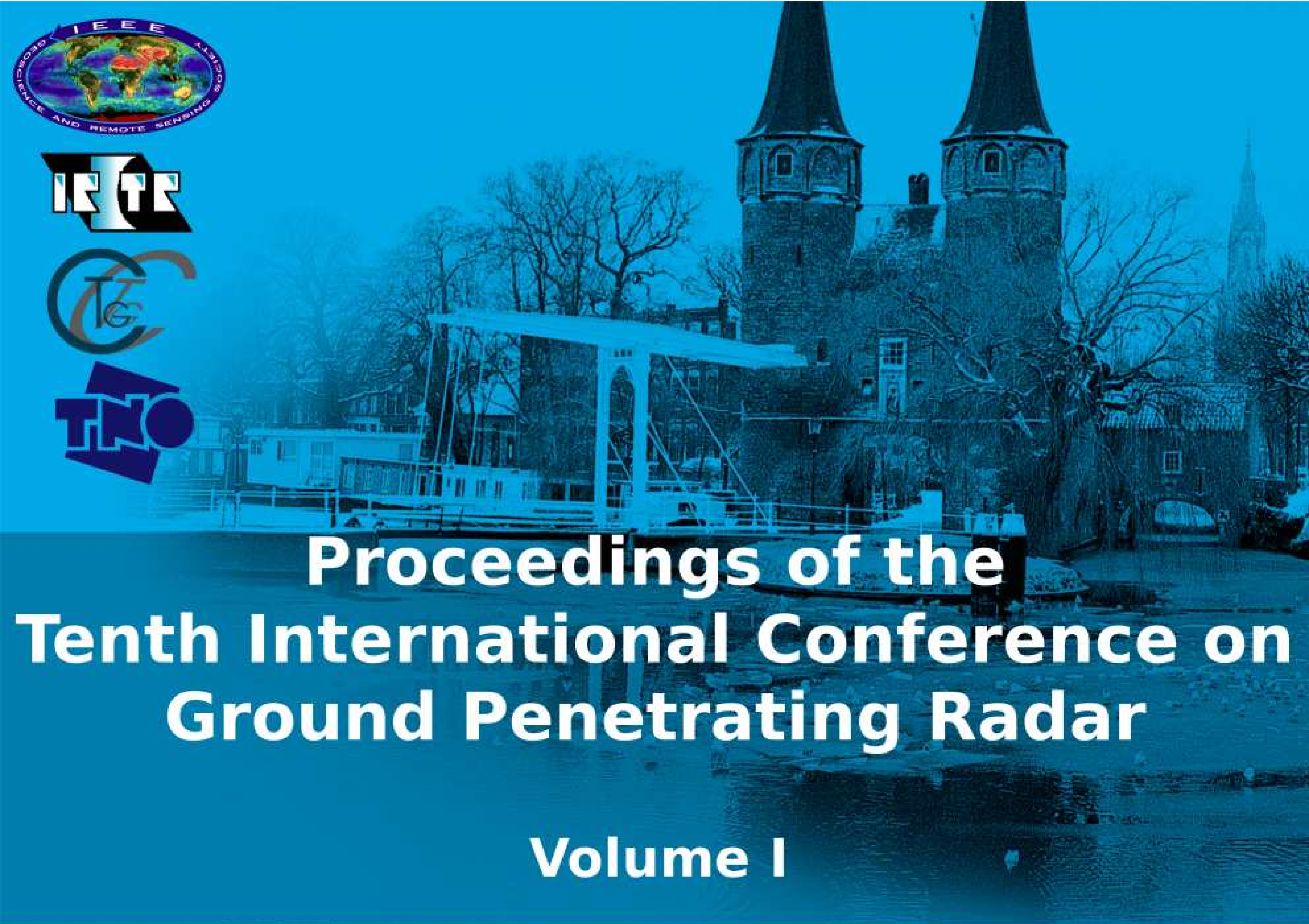

Proceedings of the Tenth International Conference on Ground Penetrating Radar

Volume I

June 21-24, 2004, Delft, The Netherlands

**Edited by: Evert Slob
Alex Yarovoy
and Jan Rhebergen**

Hosted by: TU Delft

Delft University of Technology

Through Wall Sensing of Human Breathing and Heart Beating by Monochromatic Radar

A.S. Bugaev
Institute of Radioengineering and Electronics
Russian Academy of Sciences
Moscow, Russia

V.V. Chapursky, S.I. Ivashov, V.V. Razevig,
A.P. Sheyko, I.A. Vasilyev
Remote Sensing Laboratory of RI AMM
Bauman Moscow State Technical University
Moscow, Russia, rslab@rslab.ru

Abstract—**A radar for detecting and testing health condition of an individual, who is separated from the radar by a non-metal wall or in poor visibility, could be useful in many critical services such as medicine, rescue service, law and antiterrorists enforcements In this paper, we describe the theoretical approach and experiments utilizing a continuous-wave subsurface radar. New theoretical results, experimental records and their frequency spectrums for heartbeat, respiration and articulation of a man are presented.**

I. Introduction

At the present time, many industries are taking a keen interest in the use of the method and equipment of the surface-penetrating radars [1] for detection and diagnostics of the individuals, who are buried under the rubble or hidden behind the building walls. Radars that operate with continuous unmodulated microwave sounding signals could offer the simplest realization of this method. In that case by rejecting the penetrating signal of a transmitter and the signals reflected from motionless objects, it is possible to achieve a high sensitivity at detection of objects, borders of which are subjected to mechanical fluctuations. The sensitivity of the microwave sounding with unmodulated signal could achieve 10^{-9}m [2]. Let's name the method as *vibro-electromagnetic sounding*. Even though the objects subjected to mechanical fluctuations could have a various nature, the current research is limited to detecting and testing of a human being.

The presence of the biometric information in the reflected microwave signals is related to the periodical reductions of a heart, blood vessels, lungs and other human internal organs and fluctuations of the skin in the process of breathing and heart beating. These processes are cyclical and the frequency of their recurrence is in the range of 0.8 – 2.5 Hz for heart beating and 0.2 – 0.5 Hz for breathing. A reflected microwave signal containing *biometric information* we call as *biometric radar signal*. The useful component of biometric information or in other words, *physiological signatures*, is preserved in the parameters of modulation of the radar biometric signal in time domain or in their spectrums in frequency domain. As a result of cyclical recurrence of the breathing and heart beating there are corresponding spectral components in the spectrum of a signal. The parameters of these components depend on the frequencies and intensities of the breathing and heart beating. The theoretical estimation of the spectrum of a reflected signal on the output of the receiver device of the microwave radar sensor has a special interest for many applied studies.

Support for this work was provided by the International Science and Technology Center and the Russian Foundation for Basic Research.

The main interest of these preliminary studies and experiments is remote measurement of the breathing and heart beating frequencies of a person through a non-metal wall by utilizing simple continuous-wave radar. The realization of this research is possible by creating an enough sensitive gauge and applying rejection algorithm of penetrating and background signals that could mask a useful signal. The main applications of the vibro-electromagnetic sounding could be:

- Detection of alive people who are buried under the rubles of buildings as a result of natural disasters, technical calamities or accidents [3]
- Detection of the people and parameters of their movements inside the building in process of law enforcement and antiterrorist operations [4]
- Remote testing of psychological conditions of the persons during the latent or open security checks, for example at the airports (remote lie detector) [5]
- Touchless measurement of the parameters of the heart beating and breathing of patients, when a contact sensor for some reasons cannot be used [6, 7]

The further research should reveal if this method could be applied for articulation recognition through wall without utilization of acoustic device.

II. Theoretical Model of Biometric Radar Signal

The simplest microwave gauge, capable to indicate the biological signatures is radar with the unmodulated probing signal of a kind:

$$\dot{u}_0(t) = U_0\, \mathbf{e}^{j\omega_0 t}, \tag{1}$$

Dominant reflections take place from the border "air - skin". The area of reflection and fluctuations of the skin of a person's body is located within the limits of one Fresnel zone, which is taking place on the average distance r_0. The current distance up to the skin border can be written down as

$$r(t) = r_0 + \Delta r(t), \tag{2}$$

where $\Delta r(t)$ characterizes fluctuations of a skin. With the account of (2) the useful signal accepted by the radar will receive decreasing factor q and phase shift $\varphi(t) = -2kr(t)$:

$$\dot{u}_c(t) = qU_0\, \mathbf{e}^{j\omega_0 t - j\varphi_0 - j2k\Delta r(t)}, \tag{3}$$

where $k = 2\pi/\lambda$ is wave number, λ is radiation wavelength and $\varphi_0 = 2kr_0$.

Usually at the input of the receiver along with useful signal, so-called penetrating signal of the transmitter operates:

$$\dot{u}_{inp}(t) = q_p U_0\, e^{j\omega_0 t - j\varphi_p} + qU_0\, e^{j\omega_0 t - j\varphi_0 - j2k\Delta r(t)}, \quad (4)$$

where q_p and φ_p are decreasing factor and phase of the penetrating signal. Further without reducing generality, it is possible to accept its zero phase φ_p =0.

Let's present fluctuations of the skin due to breathing and heart beating by biharmonic function:

$$\Delta r(t) = \Delta_1 \sin(\omega_1 t) + \Delta_2 \sin(\omega_2 t + \varphi_2), \quad (5)$$

where $\omega_1 = 2\pi f_1$, $\omega_2 = 2\pi f_2$ and f_1, f_2, Δ_1, Δ_2 - frequencies and amplitudes of breathing and heart beating, φ_2 is a constant phase.

In the microwave radar gauge, it is possible to apply the one of two types of receivers. There may be coherent receiver with two quadrature phase detectors, or amplitude receiver. These two types of receivers we should analyze in details.

Coherent quadrature receiver. Such receiver allocates on its output two quadrature components of the signal (4), which can be represented as the following complex amplitude:

$$\dot{U}_{outp}(t) = q_p U_0\left(1 + \alpha\, e^{-j\varphi_0 - j2k\Delta r(t)}\right), \quad (6)$$

where $\alpha = q/q_p$.

Usually, the constant components of a penetrating signal on the receiver outputs are excluded one or another way. Then, taking into consideration (5) the useful signal is characterized by the following complex amplitude normalized to value $q_p U_0$:

$$\dot{U}_s(t) = \exp\{-j\varphi_0 - j2k(\Delta_1 \sin(\omega_1 t) + \Delta_2 \sin(\omega_2 t + \varphi_2))\}. \quad (7)$$

The Fourier signal spectrum for infinite time interval follows from series expansion of (7), which includes Bessel functions:

$$\dot{U}_s(t) = e^{-j\varphi_0} \sum_{m_1, m_2 = -\infty}^{\infty} J_{m_1}(2k\Delta_1) J_{m_2}(2k\Delta_2) \times$$
$$\times\, e^{-jm_2\varphi_2} e^{-j(m_1\omega_1 + m_2\omega_2)t}. \quad (8)$$

Thus, a spectrum of the signal (7) contains a constant component at $m_1 = m_2 = 0$, the basic harmonics with frequencies of breathing and heart beating ω_1 and ω_2, and also combinational harmonics with frequencies $m_1\omega_1 + m_2\omega_2$.

In practice, at the signal spectrum estimation on the given time interval $(-T/2, T/2)$ the subtraction of time average value from realization preliminary should be done. Then multiplication of centered realizations on suitable window function is performed. It achieves necessary reduction of a spectrum side lobes level in interests of revealing of "weak" harmonics on a background of "strong" ones. Generalized Hamming window in time domain looks like [8]:

$$w_H(t) = \begin{cases} a + (1-a)\cos\left(\dfrac{2\pi t}{T}\right), & |t| \le \dfrac{T}{2}, \\ 0, & other \quad t. \end{cases} \quad (9)$$

Thus, Fourier spectrum of the process (7) on a finite time interval is calculated as follows:

$$\dot{G}_0(\omega) = \frac{1}{2\pi} e^{-j\varphi_0} \int_{-T/2}^{T/2} \left[\dot{U}_s(t) - \frac{1}{T}\int_{-T/2}^{T/2} \dot{U}_s(\tau)d\tau\right] w_H(t) e^{-j\omega t}\, dt \quad (10)$$

Finally spectrum with the account of (8) looks like:

$$\dot{G}_0(\omega) = e^{-j\varphi_0}\left\{\dot{G}(\omega) - \bar{\dot{U}}_{s0} W_H(\omega)\right\}, \quad (11)$$

where

$$\dot{G}(\omega) = \sum_{m_1, m_2 = -\infty}^{\infty} J_{m_1}(2k\Delta_1) J_{m_2}(2k\Delta_2) e^{-jm_2\varphi_2} W_H(m_1\omega_1 + m_2\omega_2 + \omega), \quad (12)$$

$$\bar{\dot{U}}_{s0} = \sum_{m_1, m_2 = -\infty}^{\infty} J_{m_1}(2k\Delta_1) J_{m_2}(2k\Delta_2) e^{-jm_2\varphi_2} \mathrm{sinc}((m_1\omega_1 + m_2\omega_2)T/2\pi) \quad (13)$$

$W_H(\omega)$ is Fourier transform of (9):

$$W_H(\omega) = T\left\{a\,\mathrm{sinc}\left(\frac{\omega T}{2\pi}\right) + \frac{1-a}{2}\left[\mathrm{sinc}\left(\frac{\omega T}{2\pi} - 1\right) + \mathrm{sinc}\left(\frac{\omega T}{2\pi} + 1\right)\right]\right\} \quad (14)$$

and $\mathrm{sinc}(x) = \sin(\pi x)/\pi x$.

It follows from (11), that at coherent quadrature reception the module of spectrum does not depend on φ_0 and hence on average range r_0 up to the object.

The calculation example of the module of spectrum (11) (at a = 0.54) is submitted in fig. 1 at the following parameters: the frequencies and amplitudes of skin vibrations due to breathing and heart beating are $F_b = \omega_1/2\pi = 0.23$Hz, $F_h = \omega_2/2\pi = 1.1$Hz, $\varphi_h = \varphi_2 = 60^\circ$; $\Delta_b = \Delta_1 = 1$cm; $\Delta_h = \Delta_2 = 0.1$mm; the operational frequency of the microwave radar is 2.0 GHz. Resolution of the spectral analysis is equal 0.01 Hz according to chosen time interval of 100s. In this diagram, in addition to the basic spectral lines combinational spectral lines are visible. It quite corresponds to the form of a spectrum of biharmonic phase modulation of a signal at reflection from the air-skin border, which vibrates in a step to breathing and heart beating. Calculations have shown also, that amplitude spectrum at coherent quadrature reception does not depend neither on average distance up to object,

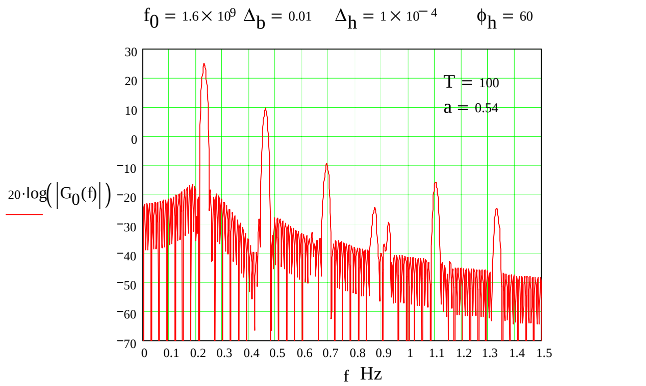

Figure 1. The module of signal spectrum for coherent quadrature receiver at F_b = 0.23Hz and F_h = 1.1Hz.

nor practically on a phase difference $\varphi_h = \varphi_2$ of breathing and heart beating.

Amplitude receiver. The analysis of such simpler variant of signal processing in the microwave radar is caused by presence of amplitude detection in known microwaves gauges such as RASCAN [3]. Let's assume that characteristic of the detector is approximated by square-law dependence and the penetrating signal of the transmitter is presented. Then the voltage at output of the detector with the account of (4) can be submitted as:

$$u_d(t) = \left|\dot{u}_{inp}(t)\right|^2 = q_p^2 U_0^2 \left|1 + \alpha \dot{U}_s(t)\right|^2, \qquad (15)$$

where $\alpha = q/q_p$ and $\dot{U}_s(t)$ is defined by (7) or (8).

We determine Fourier spectrum of normalized process $u_{d0}(t) = u_d(t)/(q_0^2 U_0^2)$ by analogy with (10):

$$\dot{G}_{d0}(\omega) = \frac{1}{2\pi} \int_{-T/2}^{T/2} \left[u_{d0}(t) - \frac{1}{T} \int_{-T/2}^{T/2} u_{d0}(\tau) d\tau \right] w_H(t) \mathrm{e}^{-j\omega t} dt. \qquad (16)$$

Final expression for a spectrum in view of the formerly entered designation (11) for $\dot{G}_0(\omega)$ looks compactly:

$$\dot{G}_{d0}(\omega) = \alpha \left\{ \dot{G}_0(\omega) + \dot{G}_0^*(-\omega) \right\}, \qquad (17)$$

It follows from (17) and (11) that there exist the dependence of spectrum module $\left|\dot{G}_{d0}(\omega)\right|$ on output of the amplitude receiver from "range" phase φ_0 and average range r_0 up to the object. This special feature of amplitude processing can complicate measurement of physiological signatures in comparison with coherent quadrature processing, at which the given phenomenon is excluded. For illustration of the marked phenomenon, modules of spectrum (17) submitted in Fig. 2 and 3 at "range" phase $\psi_0 = \varphi_0 \cdot 180^\circ/\pi$ equals to 0°, 90°, and $\alpha = 1$.

It follows from Fig. 2 that at range phase $\psi_0 = 0^\circ$ useful components with frequencies 0.23Hz and 1.1Hz vanish from a useful signal spectrum, at which there are only some combinational components. At range phase $\psi_0 = 90°$ (Fig. 3) there are useful components of a spectrum and those combinational components, which were absent at $\psi_0 = 0°$.

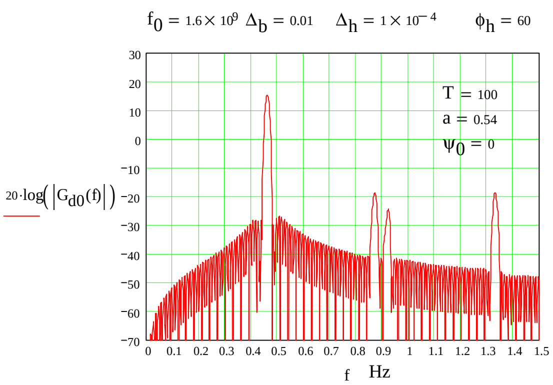

Figure 2. The module of signal spectrum for amplitude receiver at $F_b = 0.23$Hz, $F_h = 1.1$Hz and "range" phase $\psi_0 = 0^{\text{O}}$.

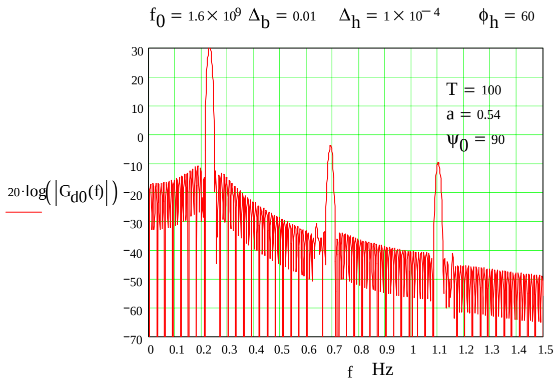

Figure 3. The module of signal spectrum for amplitude receiver at $F_b = 0.23$Hz, $F_h = 1.1$Hz and "range" phase $\psi_0 = 90^{\text{O}}$.

At intermediate values of "range" phases, both useful and combinational components of a spectrum are presented. In the case $\psi_0 = 60^\circ$, the spectrum almost coincides with the signal spectrum on the output of coherent quadrature receiver, submitted in Fig. 1.

III. The Description of Experiments

During experiments, we applied the method of subsurface sounding by monochromatic signal of RASCAN-type radar [3]. Modified RASCAN radar with the following parameters was used:

Operational frequency	1.6 GHz (λ=19cm)
Gain factor	40 dB
Frequency range of recorded signals	0.03 – 3.0 Hz
Dynamic range	60 dB
Sampling frequency	20 Hz
Antenna's dimensions:	
diameter	120 mm
length	200 mm

The sketch of the experiment is shown in Fig. 4. The thickness of a wall, behind which there was an examinee, equals 10 cm. The examinee was settled down at distance about 1 m from the wall. The radar's antenna was fastened directly at the wall surface. To decrease interference from a back hemisphere, the antenna and the part of the wall was veiled by antiradar coating with dimensions of 2×2 m.

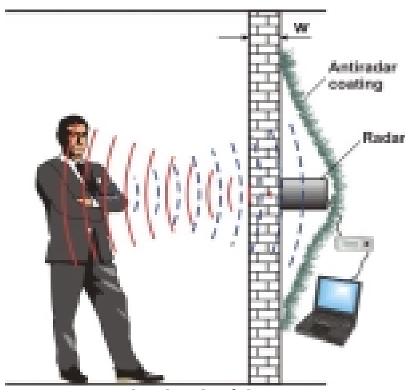

Figure 4. The sketch of the experiment.

Figure 5. Pulse record of the examinee and its signal spectrum (below). Breath delay equals to approximately 30 s.

Figure 6. Pulse record of the examinee and its signal spectrum.. Breath delay equals to about one minute.

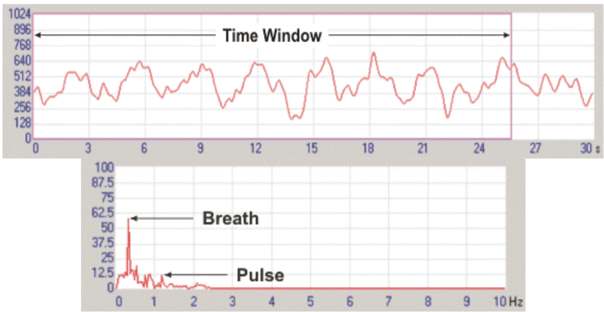

Figure 7. Breath and pulse record of the examinee and their signal spectrum without breath delay.

The radar signals after amplitude detection through an interface module were recorded in the computer memory.

In Fig. 5 and 6, signal spectrum and pulse records of the examinee, which detained his breathing, are presented. In Fig. 5, breath delay is approximately 30 s. And in Fig. 6, the delay is about one minute. It is clear that with increase of breath delay time the amplitude and rate of examinee pulse are also increased as a result of oxygen starvation.

The results of simultaneous recording of pulse and breath rate are presented in Fig. 7. Amplitude of breathing oscillations considerably surpasses heart beating vibrations, so combinational components are clearly visible.

A record and spectrum of breathing, heart beating and speech articulation of the examinee pronouncing consistently words: one, two, three... one, two, three...(in Russian) are presented in Fig. 8. Taking into account that the bandwidth of input filter is limited only 3 Hz, we have no proof at this time to assert that the data of similar measurements could be used for speech recognition yet.

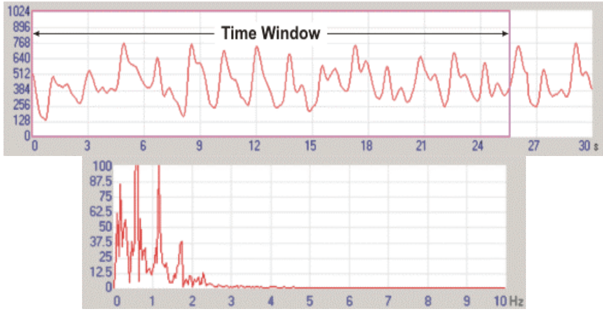

Figure 8. Articulation record of the examinee pronouncing words: one, two, three,… and its signal spectrum (below).

The results obtained in the experiments in many respects are similar to the signals registered by time-domain impulse radars in free space [6, 7]. However, the use of monochromatic wave radars simplifies the experimental installation and subsequent data processing.

IV. Conclusion

Theoretical model of monochromatic signal reflections from human integuments that vibrate synchronously with breathing and heart beating is offered. Calculations testify to presence of the basic and combinational components in reflected signal spectrum. Frequencies and amplitudes of periodic skin vibrations at breathing and heart beating define frequencies and intensities of these components. Combinational character of a spectrum proves to be true experimentally. For exception of vanishing of the basic frequencies in a received signal spectrum one should use the principles of quadrature coherent signal processing. The experiments on radar sounding of heart beating and breathing of the man through a wall separating two adjacent rooms allow to consider technically feasible the task of remote diagnostics of the man parameters utilizing the continuous-wave subsurface radars of RASCAN type.

References

[1] D.J. Daniels, Surface-penetrating radar, Piscataway, NJ: IEEE Press, 1996.

[2] W.R. Scott, C. Schroeder, J.S. Martin, “An acousto-electromagnetic sensor for locating land mines,” Part of the SPIE Conference on Detection and Remediation Technologies for Mines and Minelike Targets III. Orlando, Florida, SPIE vol. 3392, 0277-786X, 98, pp. 176-186, April 1998.

[3] A.S. Bugaev, I.A. Vasilyev, S.I. Ivashov, V.V. Razevig, A.P. Sheyko, “Detection and Remote Diagnostics by Radar of Humans behind Obstacles,” Radiotechnika, No. 7, pp. 42-47, 2003, (On Russian).

[4] M.A. Barnes, S. Nag, T. Payment, “Covert situational awareness with handheld ultra-wideband short pulse radar,” SPIE Conference on Radar Sensor Technology VI, Orlando, Fla. 19 April 2001, Proc. SPIE vol. 4374, pp. 66-77, 2001.

[5] Greneker E.F. Radar Sensing of Heartbeat and Respiration at a Distance with Security Applications. Proceedings of SPIE, Radar Sensor Technology II, Volume 3066, Orlando, Florida, April 1997, pp. 22-27.

[6] E.M. Staderini, “UWB Radars in Medicine,” IEEE Aerospace and Electronic Systems Magazine, pp. 13-18, January 2002.

[7] I. J. Immoreev, S.V. Samkov, “Ultra Wideband (UWB) Radar for the Remote Measuring of Main Parameters of Patient's Vital Activity,” Radio Physics and Radio Astronomy (Ukraine), vol. 7, No. 4, pp. 404-407, 2002.

[8] L. R. Rabiner, B. Gould. Theory and application of digital signal processing. Prentice – Hall, Inc. 1975.