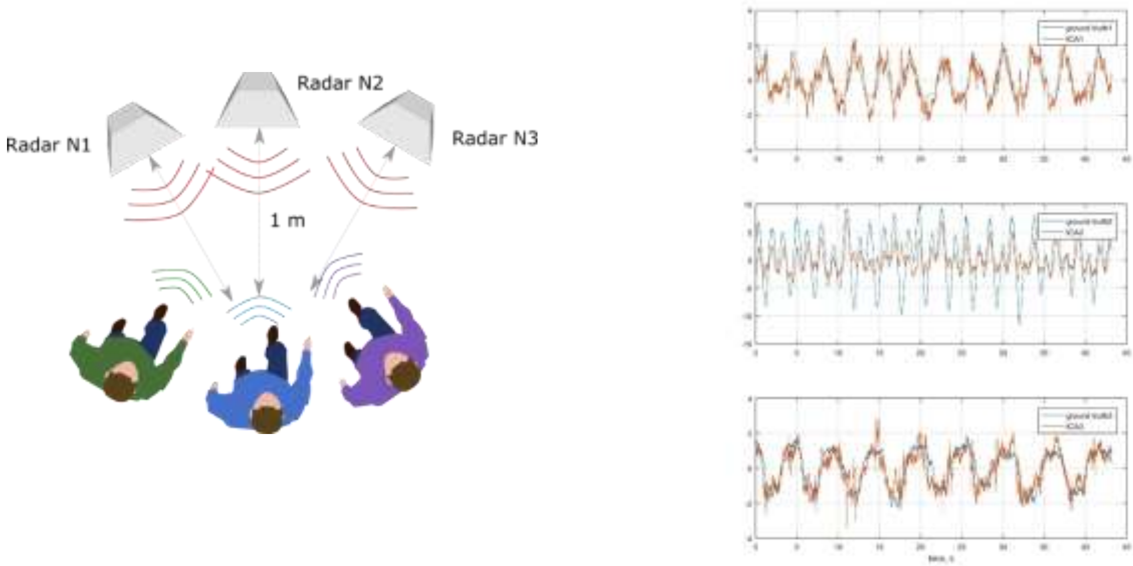
Разработка новых бесконтактных многоканальных методов для выявления потенциально опасных лиц в местах массового скопления людей

В рамках выполнения проекта были решены следующие основные задачи:

Проанализированы ситуации одновременного наблюдения двух и трех человек, расположенных в непосредственной близости друг от друга (рис.1 а), и на результатах математического и физического моделирования (рис.1 б) продемонстрирована возможность разделения паттернов одновременно наблюдаемых людей при помощи метода независимых компонент.



а б

Рисунок 1 – Схема проведения эксперимента

Разработана методология проведения экспериментов в случае одновременной регистрации биорадиолокационного и видеосигнала с целью оценки поведения и двигательной активности людей и соответствующий экспериментальный макет многоканального комплекса оценки психоэмоционального состояния человека с целью выявления потенциально опасных лиц, объединяющий в своем составе стандартную видеокамеру и радиолокационные датчики. В качестве стандартной видеокамеры в настоящей работе была использована система Intel RealSense D435, содержащая две стереокамеры, RGB-сенсор и активный инфракрасный проектор.

С привлечением добровольцев осуществлен сбор базы экспериментальных данных, соответствующих различным типам повседневной двигательной активности человека, которая в дальнейшем была использована для разработки алгоритмов распознавания различных типов двигательной активности человека по совокупности данных, регистрируемых многоканальным комплексом. Схема проведения эксперимента приведено на рис. 2 а и фотография эксперимента.

С использованием методов машинного обучения разработан специализированный алгоритм распознавания различных типов двигательной активности человека по совокупности биорадиолокационных и видео- данных. Точность разработанного алгоритма для классификации спокойное/агрессивное поведение на экспериментальной выборке составила 98 %.

Проведено теоретико-экспериментальное исследование целесообразности использования системы из нескольких биорадиолокаторов для повышения качества регистрации паттернов дыхания и двигательной активности. Доказано, что использование системы, состоящей из нескольких биорадилокаторов, предпочтительней использования одиночного биорадиолокатора для случаев, когда положение испытуемого в ходе проведения эксперимента может изменяться. В этом случае использование системы из двух радиолокаторов характеризуется приростом точности более 10 %, что обусловлено нивелированием влияния неоптимальности расположения испытуемого по отношению к радиолокатору.

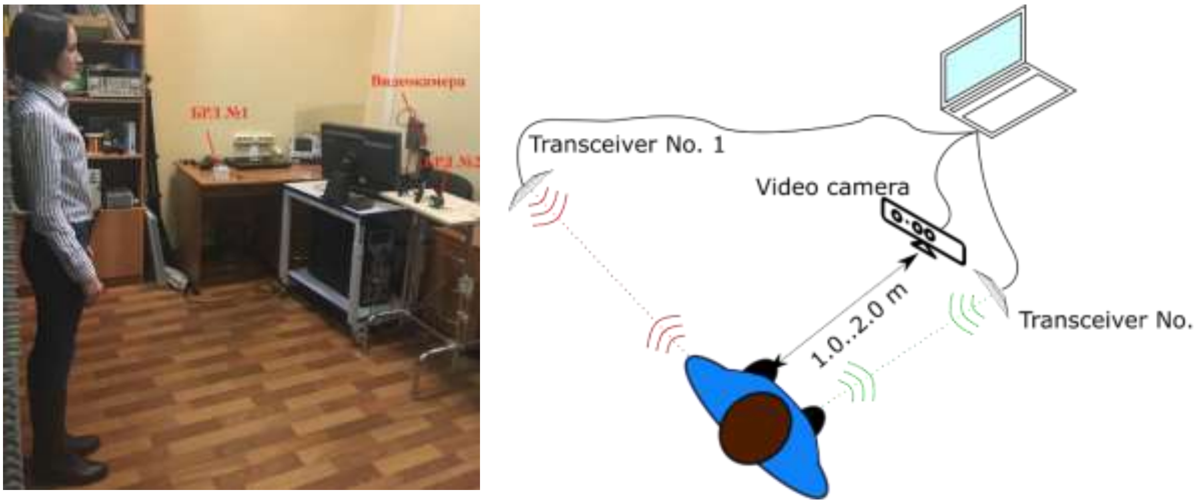


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Рисунок 2 –Проведение эксперимента с использованием многоканального комплекса

Разработана методология обеспечения оптимальной ориентации биорадиолокационного канала в направлении испытуемого в течение эксперимента по данным видеоканала, входящего в состав многоканального комплекса, на базе которой спроектирована биотехническая система и соответствующая методика оценки психофизиологических параметров человека при помощи разработанного многоканального комплекса (рис.3). Новизна методики заключается в том, что она, в отличие от описанных на настоящее время в научных работах методик, подходящих исключительно для единичной оценки психоэмоционального состояния человека, также может быть использована для длительного мониторинга. Это актуально для контроля состояния операторов сложных машинных комплексов, диспетчеров аэропортов, и других областей.

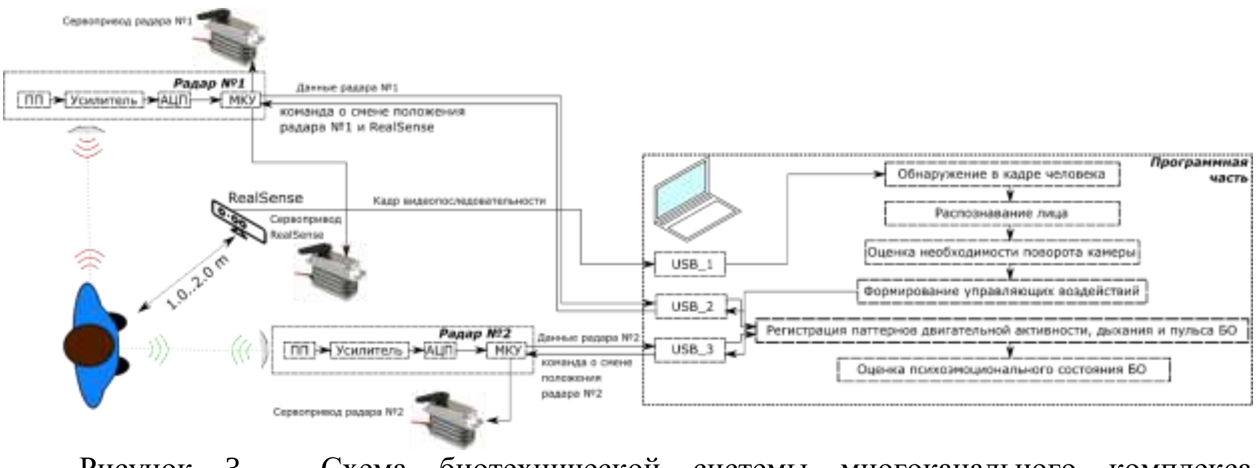

Рисунок 3 – Схема биотехнической системы многоканального комплекса дистанционной оценки психоэмоционального состояния человека

Sensing of Human Breathing and Heart Beating at Different Orientation Angles by CW Doppler Radar

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***Abstract*— Bioradiolocation is an experimentally confirmed method for frequency and amplitude detection of human breathing and heart beating. The aim of this paper is to present the results of the research on dependency of bioradar signal quality on the orientation angle of an examined person. Furthermore, the impact of a distance between radar and an examined person on bioradar signal is discussed. In addition, the subject on necessity of using radar with higher operating frequency to detect breathing patterns and heart rate is touched upon. The results of this research might be useful for the development of monitoring systems for sleep disorders diagnostics and for a remote assessment of mental and emotional human state.**

Keywords—bioradiolocation, signal processing, Fourier analysis, arctangent demodulation, independent component analysis, principal component analysis

I. Introduction

At the present time plenty of various methods for heartbeat and breathing detection exist. However, almost all of these methods require a contact with a human body by means of electrodes or electrode systems. That may limit movements of a patient, cause discomfort and even influence on the examination results.

In the work [1] there was an experimental proof that frequency and amplitude of body surface deflection due to breathing and heart beating movements can be detected using continuous-wave (CW) bioradars. Bioradiolocation is a method for remote detection and diagnostics of biological objects by means of radar, even behind optically opaque obstacles. This method is based on a modulation of a radar signal reflected from the body surface. The modulation occurs because of contraction of visceral organs, movements of limbs, and movements of the body surface due to breathing and heart beating [2].

In some applications, the accuracy of determination of breathing and heart beating frequencies is essential to ensure the validity of examination results. Therefore, in this paper we are going to consider the requirements for bioradar's probing frequency used for heartbeat detection, various mathematical methods for decomposition of bioradar's signal into breathing and heart beating signals, and the dependency of accuracy of breathing and heart rates detection on angle and distance between a bioradar and an examined person.

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II. Required Probing Frequency of a Bioradar for Accurate Heartbeat Detection

Table 1 presents the amplitudes of the body surface displacement due to breathing and heart beating for a human [1, 3].

TABLE I. Parameters of Body Movements

Movement	Frequency, Hz	Amplitude, mm
Breathing	0.1…0.5	5…15
Heartbeat	0.6…3	0.46…0.68

It is well known that radars with short wavelengths (high probing frequencies) are more sensitive to small displacements [4]. According to the table 1, the smallest detectable body movement caused by heart beating is 0.46 mm. Since the experiments described below were carried out at the Remote Sensing Laboratory at Bauman Moscow State Technical University (BMSTU) using radars BioRASCAN-4 [5, 6] and BioRASCAN-24 [7, 8], which have a phase error equal to 5°, it was found based on (1) that the minimal required probing frequency for accurate heartbeat detection is around 9 GHz.

$$f = c / \lambda = (\varphi * c) / (2\pi * d) \qquad (1)$$

where f – probing frequency required for accurate heartbeat detection, c – speed of light, λ – required wavelength, φ – phase error of a radar, d – the smallest detectable body movement caused by heart beating.

Fig. 1 presents a curve that indicates the dependency of radar's sensitivity on its probing frequency.

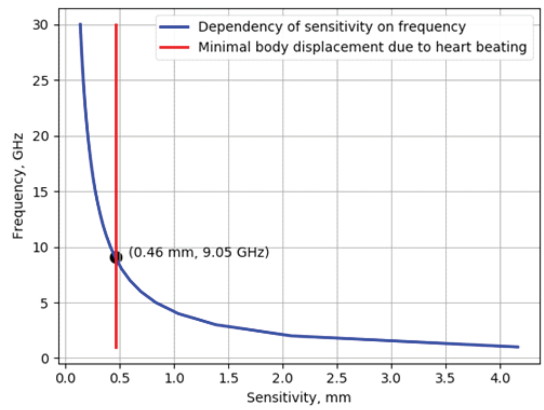

Fig. 1. Dependency of radar's sensitivity on probing frequency. Point with coordinates (0.46 mm, 9.05 GHz) indicates the minimal probing frequency for accurate heartbeat detection.

III. Experimental Part

The following bioradars were used for the experiments: BioRASCAN-4 and BioRASCAN-24 both designed at Remote Sensing Laboratory at BMSTU. Main characteristics of the bioradars are presented in the table 2. The maximum power density radiated by each of the radars is less than 3 µW/cm2. Such value satisfies the Russia safety standard for microwave emission, which is 25 µW/cm2 in the frequency range of 3–300 GHz (for 24 hours exposure) [9].

TABLE II. Technical characteristics of Doppler CW radars: BioRASCAN-4 and BioRASCAN-24

Parameters	BioRASCAN-4	BioRASCAN-24
Number of frequencies	8	1
Probing frequency, GHz	3.6-4.0	24.0-24.4
Wavelength, cm	8	1.25
Sensitivity, mm	1	0.17
Radiated power density, µW/cm2	1.36	<3
Sampling frequency, Hz	50	250

Two healthy volunteers participated in the experiments. Each of them gave the informed consent prior to the participation.

During the first experiment, a volunteer was sitting on a chair at first at the distance of 50 cm to the radars and then at the distance of 1 m. A volunteer has to lean on a back of a chair to provide a stable position. This requirement is important to reduce number of possible artifacts, which are caused by body's displacements during the experiment. A volunteer was breathing normally during 3 minutes. Both radars were directed to the volunteer`s thorax in such way that the incidence angle of the electromagnetic wave to the thorax surface is close to 90° to obtain the maximal level of the useful signal. After the experiment, a volunteer took a break for at least two minutes.

A scheme of the second experiment is presented in the Fig. 2.

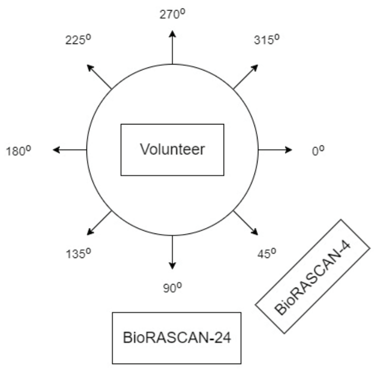

Fig. 2. Scheme of the second experiment.

During the second experiment, a volunteer was sitting on a chair in the same way as in the first experiment at the distance of 50 cm from bioradars. At first, a volunteer was sitting on a chair in the direction of 0° position as depicted in the Fig. 2. Each minute a volunteer was asked to change his or her position on the chair by 45°, thus the recording time was approximately 8 minutes. After the experiment, a volunteer took a break for at least two minutes.

In both experiments, number of breathing cycles was set using electronic metronome. Heart rate was obtained based on the electrocardiogram (ECG) recorded by Alive Bluetooth Heart and Activity Monitor [10].

IV. Signal Processing

Processing of the recorded signals was done in Python environment. Signals from both bioradars and Alive Monitor were synchronized by a movement artifact at the beginning of each record and at the moments, when a volunteer changed his or her position, as presented in the Fig. 3.

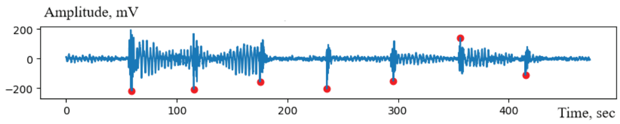

Fig. 3. A signal recorded by BioRASCAN-24. Movement artifacts are indicated with red dots. Artifacts at the beginning and at the end of the record were cut beforehand.

Movement artifacts were recognized in raw signals automatically by detection of maximum or minimum amplitude value in the certain time periods. Afterwards a raw signal was divided into eight signals related to each orientation angle and each signal was processed separately.

For decomposition of the bioradar's signals into breathing and heart beating signals four mathematical methods were used: Fourier analysis, arctangent demodulation, independent component analysis (ICA) and principal component analysis (PCA).

Breathing and heart rates were derived using scipy.signal.find_peaks package with limitations that:

1) The smallest possible frequencies of human breathing and heart beating are 0.1 Hz and 0.6 Hz respectively.

2) The highest possible frequencies of human breathing and heart beating are 0.5 Hz and 3 Hz respectively.

An example of the peak detection algorithm result is presented in the Fig. 4.

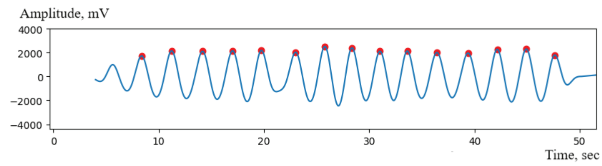

Fig. 4. Peaks detection on the breathing signal derived by Fourier analysis from BioRASCAN-4 signal. Peaks are marked with red dots. First peak is not marked due to algorithm features, however it is considered in this and further algorithms.

A. Signal decomposition using Fourier analysis

To find a frequency of respiratory movements, it was necessary to obtain a spectrum of the bioradar's signal using the scipy.fftpack.fft function — discrete fast Fourier transformation (FFT). After that, the bioradar's signal was filtered by a Butterworth band-pass filter (BPF) of the second order with a window (2).

$$fbreath - 0.1\ Hz\ ...\ 0.6\ Hz \qquad (2)$$

where fbreath – breathing frequency derived from the spectrum, 0.6 Hz accords to the minimum heart rate. As a result, the bioradar's signal was converted into a breathing signal.

Afterwards, the breathing signal was subtracted from the initial bioradar's signal to obtain the signal of heart beating, which was filtered by a Butterworth BPF of the second order with a window of 0.6…3 Hz.

Breathing and heart rates were obtained using the scipy.signal.find_peaks package as described above. Signal decomposition algorithm using Fourier analysis is presented in the Fig. 5.

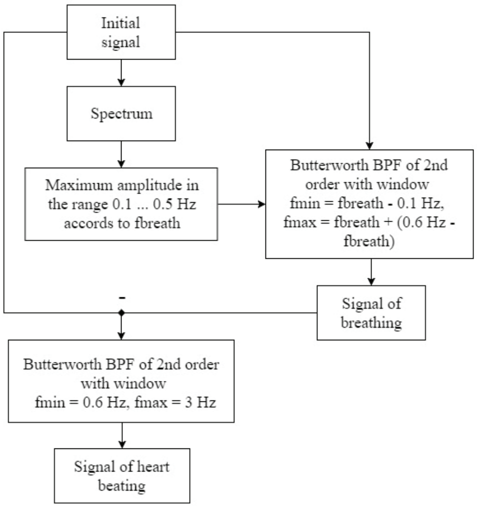

Fig. 5. Algorithm of bioradar's signal decomposition using Fourier analysis. fbreath – breathing frequency, fmin – minimum frequency, fmax – maximum frequency.

B. *Signal decomposition using arctangent demodulation*

This algorithm is based on obtaining of phase modulation, which is determined by different movements of a human body. Phase can be calculated according to (3).

$$\varphi = \arctan(Q(t) / I(t)) \tag{3}$$

where φ - phase, Q(t) – quadrature component, I(t) – in-phase component.

To implement the arctangent demodulation in Python environment, math.atan2 function was used. Algorithm of signal decomposition using arctangent demodulation is presented in the Fig. 6.

C. *Signal decomposition using ICA and PCA methods*

To implement the ICA method in Python environment, the FastICA algorithm from the sklearn.decomposition library was used. The disadvantage of the algorithm is that FastICA does not always work accurately, because a mixing matrix and a matrix of independent components are initially filled in with random numbers, and this leads to a different speed and accuracy during each run of the algorithm [11]. Mathematical modelling, which confirms that ICA method is appropriate for separating vital signs patterns in bioradar signals, is discussed in the works [12, 13]. For implementation of PCA method, the PCA algorithm from the sklearn.decomposition library was used.

Algorithm of signal decomposition using ICA and PCA methods is presented in the Fig. 6.

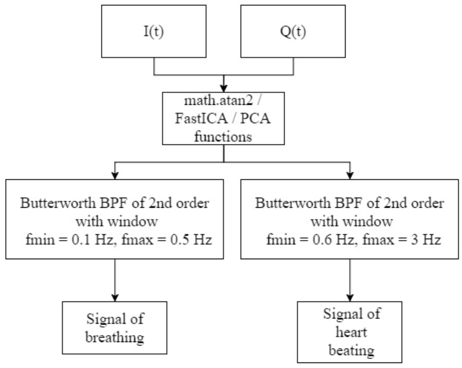

Fig. 6. Algorithm of bioradar's signal decomposition using arctangent demodulation method, ICA and PCA python functions. Q(t) – quadrature component, I(t) – in-phase component, fmin – minimum frequency, fmax – maximum frequency.

V. Results

The results of the first experiment are presented in the table 3 and table 4. We can see that for BioRASCAN-4 the relative error for breathing signal is less dependent on the distance between a bioradar and an examined person in comparison with BioRASCAN-24. Arctangent demodulation shows the best processing result for the distance of 0.5 m. For the distance of 1 m Fourier analysis, ICA and PCA lead to approximately same results. BioRASCAN-24 shows better result in heart rate estimation than BioRASCAN-4, which can be explained with higher probing frequency (higher sensitivity). Again, for the distance of 0.5 m arctangent demodulation shows the best processing result for both bioradars. For the distance of 1 m Fourier analysis is better to use for BioRASCAN-4; Fourier analysis, ICA and PCA methods show approximately the same results for BioRASCAN-24.

The results of the second experiment are presented in the tables 5 and 6, where "Fourier" means Fourier analysis, and "Atan" means arctangent demodulation. Angles with worst results of signal processing for breathing were 270° for BioRASCAN-4 and 315° for BioRASCAN-24, for heart beating the worst angle was 315°. Considering the remaining angles, BioRASCAN-4 shows good results at the angle of 45° and BioRASCAN-24 – at the angles of 45° and 90°. Such results can be explained by the fact that body displacement amplitudes due to breathing and heart beating from the back of the human body is less than ones from the front [3].

TABLE III. PROCESSING OF THE BREATHING SIGNALS: RELATIVE ERROR (%) BETWEEN DERIVED AND REAL VALUES AT THE DISTANCES OF 0.5M AND 1M BETWEEN A BIORADAR AND AN EXAMINED PERSON

Bioradar	**Methods**			
	Fourier analysis	***Arctangent demodulation***	***ICA***	***PCA***
	Distance: 0.5 m			
BioRASCAN-4	4	2.8	2.8	5.4
BioRASCAN-24	1.4	0	2.8	2.8
	Distance: 1 m			
BioRASCAN-4	0	7.9	0	2.5
BioRASCAN-24	3.8	2.5	5	2.5

TABLE IV. PROCESSING OF THE HEART BEATING SIGNALS: RELATIVE ERROR (%) BETWEEN DERIVED AND REAL VALUES AT THE DISTANCES OF 0.5M AND 1M BETWEEN A BIORADAR AND AN EXAMINED PERSON

Bioradar	Methods			
	Fourier analysis	***Arctangent demodulation***	***ICA***	***PCA***
	Distance: 0.5 m			
BioRASCAN-4	17.5	9.5	21.5	22
BioRASCAN-24	13.5	9.5	13.5	12.5
	Distance: 1 m			
BioRASCAN-4	17	11.3	32.7	29.7
BioRASCAN-24	6.8	11.3	8.7	7.6

TABLE V. PROCESSING OF THE BREATHING SIGNALS: RELATIVE ERROR (%) BETWEEN DERIVED AND REAL VALUES AT THE DIFFERENT ORIENTATION ANGLES

Methods	Orientation angle							
	0	***45***	***90***	***135***	***180***	***225***	***270***	***315***
	BioRASCAN-4							
Fourier	4	1.4	20	39.8	29	11	42.8	18
Atan	5.5	2.9	26	25	23.5	0	40.7	35
ICA	5.5	2.9	5.7	8	11	8.5	13	10
PCA	8.5	22	5.5	19	23	11	13.5	17
	BioRASCAN-24							
Fourier	4.4	4	6.9	9	4	4	4	15
Atan	2.7	5.7	5.5	8	3	2.6	2.6	27
ICA	0	12	16	10	15	5	2	7
PCA	0	24	8.5	19	23.5	8	11	9

TABLE VI. PROCESSING OF THE HEART BEATING SIGNALS: RELATIVE ERROR (%) BETWEEN DERIVED AND REAL VALUES AT THE DIFFERENT ORIENTATION ANGLES

Methods	Orientation angle							
	0	***45***	***90***	***135***	***180***	***225***	***270***	***315***
	BioRASCAN-4							
Fourier	14	10	12	13	15	17	9	27
Atan	15	14	14	16.4	17	20	12.5	31
ICA	22	17	18	20.3	18	11.3	7	38
PCA	21	15	14	18	17.7	11.3	5	39
	BioRASCAN-24							
Fourier	20	16	16	21	19	20	15	38
Atan	13	9	9	13	14	16	8	27
ICA	17	16	24	15	29	6.5	5	30
PCA	27	16	26	16	34	8	10	31

VI. CONCLUSION

In accordance with the obtained data, we can make a conclusion that the accuracy of heartbeat detection depends on the probing frequency: using a bioradar with 24 GHz probing frequency instead of a bioradar with 4 GHz probing frequency, we obtained results, which are 2 times more accurate. The detection accuracy of breathing and heart rates at different distances from a bioradar totally depends on the signal processing algorithms, thus the influence of the distance on the signal quality can be eliminated using subsequent processing. On the contrary, orientation angle of a patient has a great influence on the result's quality. The error of breathing and heart rates detection may increase up to 10 times depending on the angle. Therefore, signal processing, when a person changes his or her position, can be quite challenging.

In further experiments, we are going to collect data from volunteers of different age and weight, try other methods for signal processing to increase the heartbeat and respiration rate accuracy. In addition, we are going to make a research on analysis of longer recordings, e.g. obtained during sleep or at working places, which would be helpful in development of monitoring systems for sleep disorders diagnostics and for a remote assessment of mental and emotional human state respectively.

REFERENCES

[1] A. S. Bugaev, I. A. Vasilyev, S. I. Ivashov, V. V. Razevig, and A. P. Sheyko, "Detection and remote diagnostics of human beings behind obstacles with the radar help," Radioengineering, vol. 7, pp. 42–47, 2003.

[2] L. Anishchenko, et.al., «Bioradiolocation as a Technique for Remote Monitoring of Vital Signs», in Advanced Ultrawideband Radar: Signals, Targets and Applications, 1st ed., J. D. Taylor, Ed. CRC Press, 2016, pp. 297-321.

[3] A. B. Tataraidze, "Development of the technology and hardware-software complex for investigation of human sleep structure", Bauman Moscow State Technical University, 2016.

[4] Y. Xiao, J. Lin, O. Boric-Lubecke, and V. Lubecke, "A Ka-Band Low Power Doppler Radar System for Remote Detection of Cardiopulmonary Motion," Proc. of 27th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), pp. 7151-7154, 2005.

[5] M. K. Dremina, I. L. Alborova, and L. N. Anishchenko, "Importance of the bioradar signal preprocessing in fall detection," 2017 Progress In Electromagnetics Research Symposium - Spring (PIERS), pp. 699-703, 2017.

[6] A. B. Tataraidze, L. N. Anishchenko, L. S. Korostovtseva, M. V. Bochkarev, and Y. V. Sviryaev, "Non-contact Respiratory Monitoring of Subjects with Sleep-Disordered Breathing," 2018 IEEE International Conference "Management, Transport and Information Security, Information Technologies" (IT&QM&IS), pp. 736-738, 2018.

[7] L. N. Anishchenko, "Challenges and Potential Solutions of Psychophysiological State Monitoring with Bioradar Technology", Diagnostics, vol. 8(4), no. 73, 2018.

[8] RFbeam Microwave GmbH, "K-LC5 High Sensitivity Dual Channel Transceiver". [Online]. Available: https://www.rfbeam.ch/product?id=9. [Accessed: 13-Mar-2019].

[9] Radiofrequency electromagnetic radiation (RF EMR) under occupational and living conditions, SanPin 2.2.4/2.1.8.055-96, 1996.

[10] Alive Technologies, "Alive Bluetooth Heart and Activity Monitor". [Online]. Available: https://www.alivetec.com/pages/alive-bluetooth-heart-activity-monitor. [Accessed: 26-Jan-2019].

[11] Tetraquark.ru, "FastICA - Independent component analysis". [Online]. Available: http://tetraquark.ru/archives/311. [Accessed: 28-Jan-2019].

[12] L. N. Anishchenko, "Independent component analysis in bioradar data processing," 2016 Progress in Electromagnetic Research Symposium (PIERS), pp. 2206-2210, 2016.

[13] L. N. Anishchenko, V. V. Razevig, and M. A. Chizh, "Blind separation of several biological objects respiration patterns by means of a step-frequency continuous-wave bioradar," Proc. of Int. Conf. IEEE COMCAS, 2017.