Radar for vital signs characterization: a comparison between two different frequency band systems

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***Abstract*—This paper deals with the exploitation of two bio-radar systems (4 GHz and 14 GHZ frequency) developed at Remote Sensing Laboratory of the Bauman Moscow State Technical University for vital signs characterization (breathing and heartbeat). In particular, an experiment has been performed with the two radar systems, in order to appraise the different performance, in terms of detection and accuracy, with respect to vital signs estimation. For this experiment, the data have been processed by means of a recently developed approach that allows us to perform the parameter estimation (and therefore the overall monitoring process) in an automatic way.**

Keywords-component; vital signs detection, inverse problems, radar system

I. INTRODUCTION

The detection of vital signs by radar measurements is of timely interest for its applicative implications in many areas, which range from security and military operations, to rescue in crisis events (under rubbles or beyond a fire) and for medical diagnostics and space medicine (monitoring of astronauts movements inside and outside of spacecraft, and remote monitoring of their health), sleep medicine and so on [1-8].

In this framework, the term “bioradiolocation” refers to a method for detection and diagnostics of biological targets, even located behind optically opaque obstacles, by means of radar surveys. The main task of bioradiolocation is remote or non-contact measurement of movement, breathing and pulse parameters of biological targets behind an obstruction or in open space at some distance. In fact, the sensing phenomenon is based on the modulation of the reflected radar signal that occurs due to the movement of the body surface and interior. In the human’s body, the cardiac muscle and lungs exhibit periodic fluctuations and the patient’s physical activity and medical status determines the values of these frequencies [2,6].

At Bauman Moscow State Technical University (BMSTU) bioradiolocation has been extensively tackled since 2002. At the beginning stage of the activity, a pulsed radar system working in a standard surface penetrating configuration has been used for bioradar applications. However, experiments have shown that bio-radiolocation requires specific apparatuses and algorithms [9]. For this motivation, in 2005 a new bioradar system was designed and implemented at the Remote Sensing Laboratory, BMSTU. Opposite to the previous system, this new one exploits a stepped frequency modulated signal in the range 3.6-4 GHz, which allows to carry out non-contact examinations. Then, in order to increase sensitivity of the bioradar method to detect and characterize micro-movements of the chest due to heartbeat, another higher frequency bioradar was designed and realized in 2008. This radar has been designed similarly to the other low frequency system, but operates in the frequency range from 13.8 to 14.2 GHz. Accordingly, antennas size is three times smaller as compared to the first bioradar system.

During last five years several types of bioradar experiments have been carried out at RSLAB.

1) Comparative experiments for bio-radiolocation and optical measurements of chest movements during breathing. A quick-shot camera and radar were applied simultaneously. These experiments have shown that data from quick-shot camera and bio-radar has the highest correlation for abdominal area movements [10].

2) Comparative experiments for contact and non-contact methods. During this type of experiments breathing and pulse parameters were simultaneously measured by contact methods (rheocardio-monitoring) and non-contact method (bio-radiolocation). 27 male and 25 female adult subjects participated in the experiments. For each subject, radar and rheocardio-monitor signals were recorded three times (duration of one record is 1 min). Finally, the values of breathing and pulse frequencies for contact and non-contact methods were compared and an agreement between the results of about 95% was achieved [11].

3) Sleeping monitoring. This experiment is included into the MARS-500 program, started in June 2010 at the Institute of Medical and Biological Problems, Moscow and concerned with

978-1-4799-0940-7/13/$31.00

the simulation of different aspects of an interplanetary manned flight. The main part is a series of experiments on long-term isolation of the crew, in conditions of the specially built ground-based experiment facility. Bioradar has been used for remote measurements of movement activity, breathing and heart rate parameters of the crew during sleeping. Such a monitoring is necessary since detecting any changes in these parameters may indicate sleep disorders (which are a common problem for long-term isolation and space flights) and henceforth address timely counter-actions [12].

4) Human adaptive capabilities estimation of physical and mental stress.

5) Estimation of the movement activity of laboratory animals. During these experiments the animal was placed into a box with dielectric walls. Transmitting and receiving antennas of the radar were pointed to the box. A corner reflector was used to reduce influence of the distance between the animal and the antennas block on power density of the received signal. Specific frequency spectrums for different animal conditions were obtained. The spectra greatly differ one from the other in both magnitude and shape, thus making it possible to distinguish between different types of animals' movements [13].

In this work, we will deal with the exploitation and analysis of the two different above mentioned frequency band bio-radar systems in an experiment with the same subject. The data have been processed in an automatic way by using an approach recently developed at CNR-IREA [14, 15] and the reported results show the possibility of monitoring vital signs at different time-scales.

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II. RADAR SYSTEMS AND DATA PROCESSING

This Section gives a brief description of the multi-frequency radar systems and of the exploited data processing approach.

The lower frequency bioradar system operates by emitting and collecting a field in the band from 3.6 GHz to 4 GHz. This entails a range resolution in free space, related to the adopted band, which is approximately equal to 0.5m. The radar has the technical characteristics reported in Table 1.

Number of frequencies	16
Sampling frequency	52.1 Hz
Operating frequency band	3.6 – 4.0 GHz
Recording signals band	0.01 - 5 Hz
Dynamic range of the recording signals	60 dB
Dimensions of antennas block	150x370x370mm

Table 1. Technical parameters of the low-frequency bioradar

The second radar has almost the same technical characteristics but for the adopted frequency range (13.8 to 14.2 GHz) and related antennas size, which allows to greatly enhance the system's portability.

The problem at hand is concerned with the detection of the vital signs (breathing and heartbeat) and the determination of their frequency for the case of human being in free space. It is worth to note that this simplified condition has been assumed in order to provide a more controlled comparison between the two systems. However, the overall approach can be applied in free space as well as for buried/hidden targets, as shown in [14, 15].

In this configuration, a simple, yet effective, electromagnetic model is provided by the scattering of a vibrating metallic (perfectly electric conducting) plate in free space. The metallic plate is located at a distance z_0 from the antenna system and its time-harmonic varying position is described as $z(t) = z_0 + A\sin(\varpi_D t)$, where A is the maximum displacement with respect to the rest position z_0 and ϖ_D is the unknown Doppler frequency to be estimated. To compute the field reflected by the vibrating plate, we exploit the hypothesis of quasi-stationarity, i.e., we "freeze" the plate at each time $\boldsymbol{t}$, when it occupies the position $\hat{z}$ **,** and compute the field as if it was stationary.
If we assume the electromagnetic field as a plane wave with propagation direction along the z-axis, the field collected by the antenna system is given as:

$$E_R = E_0 \exp(-2jk_0(z_0 + A\sin(\varpi_D t))) + E_{clut} \qquad (1)$$

where $k_0 = 2\pi/\lambda$ (being λ the wavelength in free space) and E_{clut} is due to the static clutter in absence of the plate, i.e., it accounts for the scattering from static objects.
Thus the problem at hand is stated as the estimation of the Doppler frequency ϖ_D starting from the knowledge of the reflected field in (1) measured over an observation time-interval [0, T].
The proposed reconstruction procedure is based on three different steps. The first one is concerned with removal/mitigation of the static clutter, i.e., the E_{clut} term in (1). The ideal clutter removal strategy would be based on the difference between the actually measured signal and the one when no vital signs are present (background signal). Since such a background measurement is usually not available, the necessity of alternative strategies arises. In this paper, the static clutter is simply removed as follows: first, we compute the mean value E_{mean} of the signal over the interval domain [0, T]; then we subtract E_{mean} to the measured one $E_R(t)$, so to achieve $\tilde{E}_R(t) = E_R(t) - E_{mean}$, which is the quantity processed in the subsequent steps.

Figure 1. Scheme of the experiment

The second processing step consists of a Fourier transform of the resulting signal $\widetilde{E}_R(t)$, so to compute the function $G(\omega_D)$ in the Doppler domain.

To analyse the spectral properties of this signal, we compute the Fourier transform, in the Doppler domain, of the model signal $\exp(-j2k_0 A\sin(\omega_D t))$ as:

$$E_{model}(\omega_D) = \int_o^T \exp(-2jk_0 A\sin(\overline{\omega}_D t))\exp(-j\omega_D t)dt = ..$$

$$\int_o^T \sum_{n=-\infty}^{\infty} J_{-n}(2k_0 A)\exp(jn\overline{\omega}_D t)\exp(-j\omega_D t)dt = .. \qquad (2)$$

$$= \sum_{n=-\infty}^{\infty} J_{-n}(2k_0 A)\sin c[(T/2)(\omega_D - n\overline{\omega}_D)]\times$$

$$\exp(-j(\omega_D - n\overline{\omega}_D)(T/2))$$

where we have exploited the well know Fourier-Bessel expansion of $\exp(-j2k_0 A\sin(\overline{\omega}_D t))$ and $J_n(\bullet)$ denotes the Bessel function of first kind and *n*-th order. As can be noted, the Fourier transform $E_{model}(\omega_D)$ is made up of a train of *sinc(.)* pulses each centred at $n\overline{\omega}_D$.

Finally, the unknown Doppler frequency $\overline{\omega}_D$ is determined as the quantity that maximizes the scalar product $Corr(\omega_D)$ between the modulus of the “measured” Fourier transform $|G(\omega_D)|^2$ and the modulus of the Fourier transform of the model signal $|E_{model}(\omega_D)|^2$.

It is worth noting that in the above outlined procedure the maximum displacement *A* (see eq.(2)) is still unknown. In principle, such a quantity could be determined together with the Doppler frequency to maximize the scalar product. In the cases at hand, in order to make the determination procedure fast and easily deployable in realistic cases, we assume a maximum displacement equal to *A*=0.5cm for the breathing and *A*=1mm for the heartbeat.

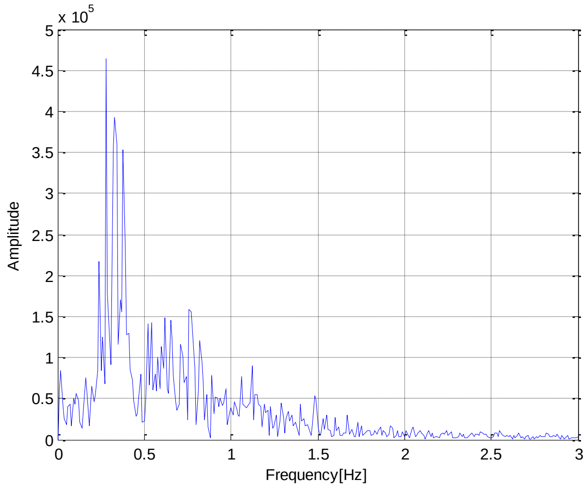

Figure 2. The amplitude of the Fourier Transform for the modulated bioradar signal at 13.8 GHz

III. EXPERIMENT AND RESULTS

The experiment has been concerned on a 21 years old healthy female subject. During the experimental procedure the examinee was calmly sitting in front of bioradar and the distance between bioradar antennas and the chest of the examinee was about 1 meter (Figure 1).

During the experiment, bio-radars were used in both multi-frequency and mono-frequency modes, and breathing and heart-beat frequencies have been measured remotely by bioradar at steady state. Duration of each radar measurement was approximately 3 min.

The processing has been carried out in an extensive way and, for the sake of brevity, here we report only the results and the comparison between the two radar systems working at the single frequencies of 3.6 GHz and 13.8 GHz, respectively. The results reports on the application of the reconstruction approach described in Section II to the radar signals recorded at 7500 time samples, spaced by (1/52.1=0.0192 sec), with an overall measurement time equal to about 144 sec.

First we consider the high frequency bioradar. The amplitude of the Fourier transform of the radar signal recorded at 13.8 GHz is reported in Figure 2, with respect to the overall measurement time of 144 sec. The examination of the Fourier transform allows us to point out two spectral areas: the one accounting for the breathing activity around 0.3 Hz and a peak at about 1.5 Hz that accounts for the heartbeat activity.

The application of the proposed inversion approach permits to estimate a breathing frequency of 0.28 Hz (about 17 breathing acts for minute) and a heartbeat frequency of 1.49 Hz (90 heartbeats/min). For the breathing activity also other main frequencies arise at 0.33 Hz and 0.38 Hz: this is an indicator of a breathing activity variation, which is physiologically normal, given the measurement duration. Moreover, this result is consistent with the one achieved when the monitoring is made on sub-intervals (see Figure 8). Figures 3 and 4 depict

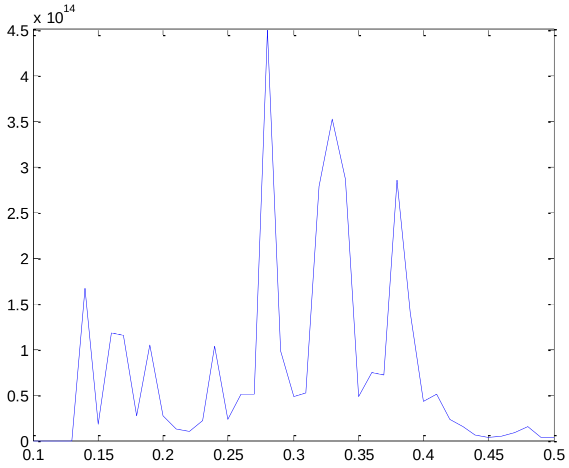

Figure 3. Behavior of $Corr(\omega_D)$ in the sub-range relevant for breathing activity estimation. The function peaks at about 0.28 Hz

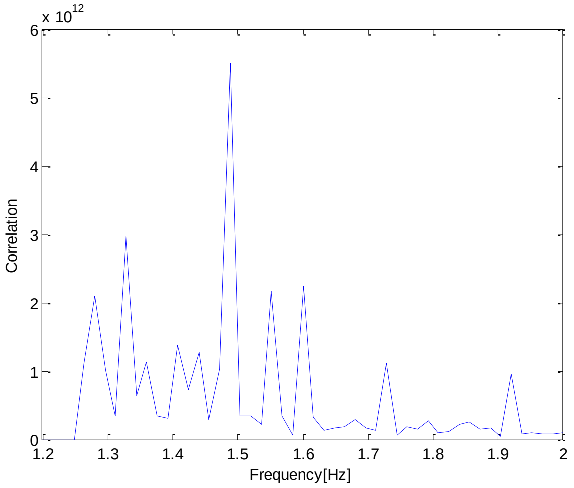

Figure 4. Behavior of $Corr(\omega_D)$ in the sub-range relevant for heartbeat activity estimation. The function peaks at about 1.5 Hz.

the function $Corr(\omega_D)$ for the determination of the breathing and heartbeat frequency, respectively.

Let us now observe the results for the 3.6 GHz bio-radar. A first interesting result is given by Figure 5, that depicts the amplitude of the Fourier Transform of the modulated bioradar signal. As can be noticed, in this case the heartbeat frequency cannot be detected.

The inversion approach is able to estimate a breathing frequency equal to 0.37 Hz (22 breathing acts for minute) (see figure 6). Whereas, according to the outcomes of Figure 5, the investigation of $Corr(\omega_D)$ does not permit us to fix the heart beat frequency with confidence (see Figure 7).

Finally, the same analysis has been carried out by dividing the overall 144 sec in 15 time intervals of 500 time samples for a single interval time of 9.6 sec.

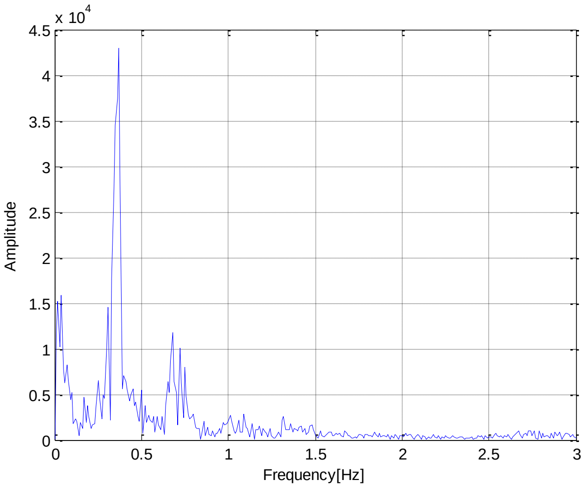

Figure 5. The amplitude of the Fourier Transform for the modulated radar signal at 3.6 GHz

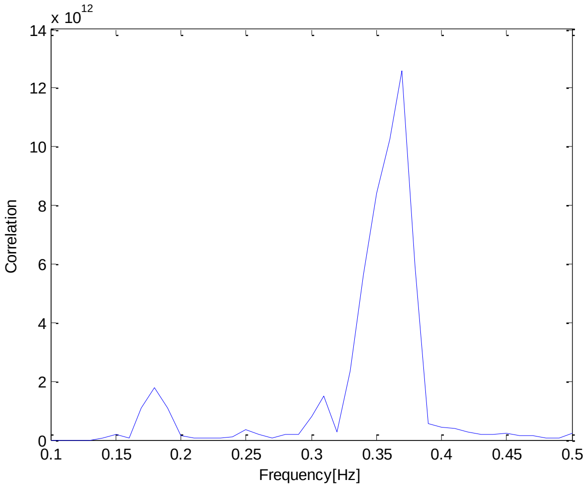

Figure 6. Behavior of $Corr(\omega_D)$ in the sub-range relevant for breathing activity estimation. The function peaks at about 0.37 Hz

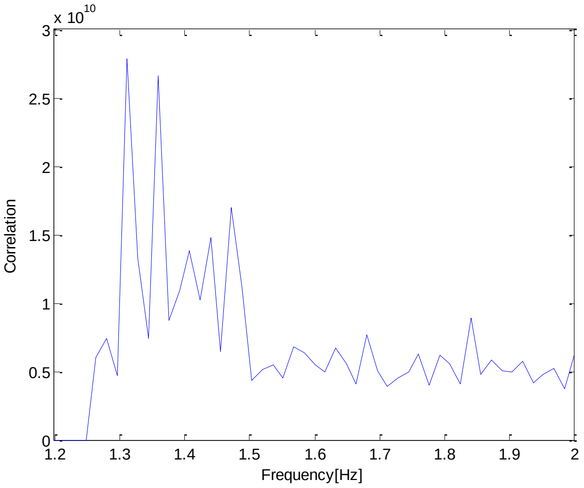

Figure 7. Behavior of $Corr(\omega_D)$ in the sub-range relevant for heartbeat activity estimation. In this case, it is not possible to estimate reliably the heartbeat frequency.

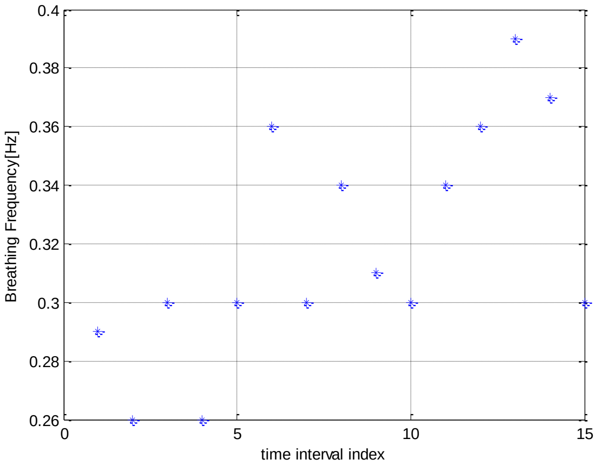

Figure 8. Breathing frequency for the 15 time intervals (13.8 GHz).

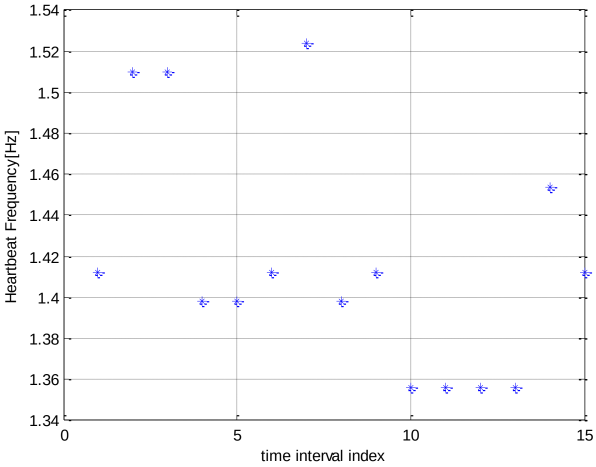

Figure 9. Heartbeat frequency for the 15 time intervals (13.8 GHz).

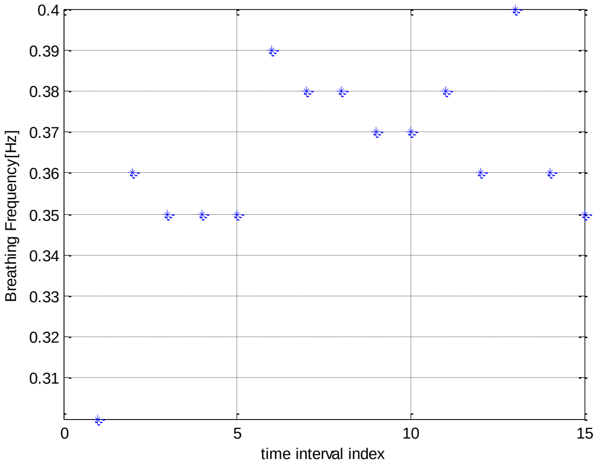

Figure 10. Breathing frequency for the 15 time intervals (3.6 GHz).

For the frequency 13.8 GHz, the time behavior of the breathing frequency is shown in Figure 8, whereas the heart-beat frequency is shown in Figure 9. Figure 8 shows how the monitoring of the breathing activity can be briefly subdivided in three subinterval, which are characterized by an increase of the breathing frequency. The behavior of the varying breathing activity justifies the arising of different peak-frequencies detected in Figs. 2 and 3.

The same analysis has been performed for the breathing activity monitored at 3.6 GHZ and the results are shown in fig.10.

IV. CONCLUSIONS

In this paper, we have discussed the exploitation of two different frequency bio-radar systems developed at RSLAB-BMSTU. The analysis of the data, carried out using an algorithm developed at CNR-IREA, has permitted to point out how the higher frequency radar system is able to detect and characterize heartbeat sign, differently from the lower frequency system.

The activity presented in this work is a part of a more general activity which is performed under the FP7 Marie Curie Action AMISS, regarding the improvement of passive and active microwave imaging technologies for different applications in subsurface prospecting, safety and security.

ACKNOWLEDGMENTS

This research has been performed in the framework of the “Active and Passive Microwaves for Security and Subsurface imaging (AMISS)” EU 7th Framework Marie Curie Actions IRSES project (PIRSES-GA-2010-269157).

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