Millimeter Wave Radar for Remote Measurement of Vital Signs

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***Abstract*— We present the development of a 228 GHz heterodyne radar system for the remote measurement of respiration and heart rates. The advantages of a millimeter wave system include a higher sensitivity to small displacements, transmission through the atmosphere and clothing and the ability to maintain a collimated beam over large distances. We present a set of respiration and heart rate measurements out to a range of 50 meters.**

I. Introduction

There is an every increasing need for additional technologies that can be applied to force protection and medical applications under a number of different circumstances. For force and facilities protection, it is very likely that a multitude of deployed sensor systems will be needed to accurately identify suspicious behavior from cooperative and non-cooperative individuals at a safe distance. Likewise, for any sort of natural disaster or large scale accident, remote triage systems will be needed to rapidly identify those individuals in need of immediate medical attention. Such systems simply measure the Doppler shifted reflected signal off of the torso to determine the displacement of the torso associated with cardiopulmonary activity. There are several significant advantages to using higher frequency millimeter wave systems for the remote detection of vital signs. The first is at higher frequencies, such as 228 GHz, the shorter wavelengths provide a greater sensitivity to monitor small displacements while avoiding nulls that can be associated with lower frequency systems [1]. While at higher frequencies there will be greater scattering and attenuation effects due to the atmosphere and clothing, Fig. 1 shows there are several atmospheric windows below 1 THz and can be utilized and there is at least 50% single-pass transmission through most garments at frequencies below 300 GHz [2]. The final advantage is associated with the ability to maintain a collimated beam over much greater distances for reasonable aperture sizes. For instance, the beam width from a 30 cm aperture operating at 228 GHz is just over 0.5 meters at a distance of 100 meters. Such a collimated beam improves the signal to noise of the system and greatly reduces clutter and other artifacts.

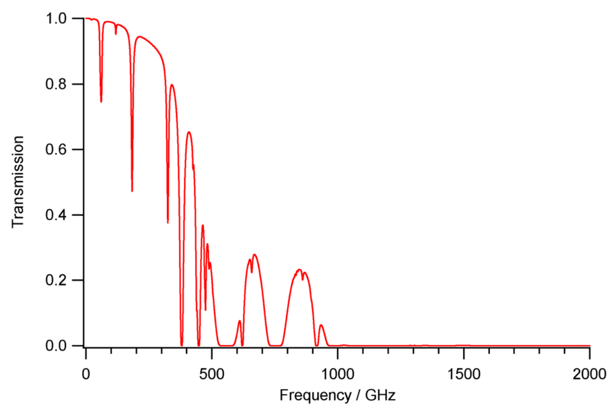

Figure 1. Transmission through the atmosphere over a distance of 100 meters at 50% relative humidity at 20oC. This was calculated with the atmospheric model code from Ref. [3].

II. System Design

The radar system designed for this work is based on a transmitter and heterodyne receiver that can monitor the phase of the returned signal [4]. While our earlier systems were designed to only monitor the Doppler shift in the frequency, we have found it more advantageous to use direction Doppler that is realized through the digitization of the in-phase (*I*) and quadrature (*Q*) signals recorded from the intermediate frequency (*IF*) of the heterodyne receiver. We can express the *IF* signal in terms of the *I* and *Q* channels by

$$I + iQ = \mathrm{R}e^{i\phi} \qquad (1)$$

where the changing phase, $\phi(t)$, can be used to monitor the displacement, $x(t)$, of an individual's torso via

$$\phi(t) = \frac{4\pi}{\lambda} x(t). \qquad (2)$$

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The 228 GHz radar system is shown in Fig. 2. It is based on a Virginia Diodes Inc. 228 GHz transmitter that has an output power of approximately 1 mW. The 230.4 GHz heterodyne receiver provides a 2.4 GHz *IF* and the mixer noise temperature is approximately 1150 K. The *IF* frequency is down converted to 100 MHz by mixing the signal with a 2.3 GHz local oscillator to provide an *IF* signal to a SRS 844 RF Lock-in amplifier. All the oscillators and the Lock-in are referenced to the same 100 MHz crystal oscillator. The Mylar beam splitter couples the optical paths of both the transmitter and receiver in a monostatic configuration to the 15 cm diameter optical mirror that has a 0.5 meter focal length that is mounted on a pan-tilt unit. The transmitter and receiver are typically placed 0.5 meters away from the mirror to collimate the beam to approximately a 15 cm diameter, but this distance can be adjusted to focus the beam. The *I* and *Q* channels are digitized by an National Instruments data acquisition board at a 1 kHz rate with the time constant on the Lock-in set to 1 msec. A Labview program was written to provide real-time monitoring of the signals and includes phase unwrapping algorithms to monitor the displacement. A retroreflector is used to diagnose the optical system and the beam. A photo of the system is shown in Fig. 3 and is on a cart to easily transport it to different locations for field experiments.

To provide a ground truth of the respiration and cardiac signatures and rates, we utilized the BioRadio 150 from Cleveland Medical Devices Inc. This is a wireless health monitor that can be used to record the respiration and cardiac signals using an electrocardiogram and a respiration belt that is based on a piezoelectric sensor. The specified range of the system is up to 30 meters and has satisfactorily functioned up to 50 meters. The data collection from the BioRadio was synchronized with the radar system using Labview.

Radar data is closely analyzed using programs written in Matlab using standard toolboxes. This includes various band pass filtering on the *I* and *Q* channels as well as analyzing the unwrapped phase. Time windowed Fourier Transforms were employed on both the BioRadio data and the radar data to measure both the respiration and heart rates.

III. Results

Several different experimental trials were performed using this 228 GHz radar system. In all cases, subjects sat on a chair

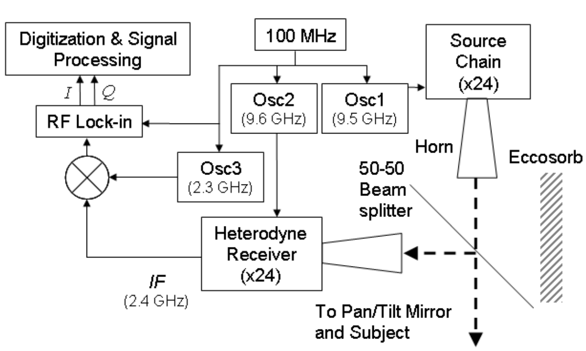

Figure 2. Schematic diagram of the 228 GHz radar system.

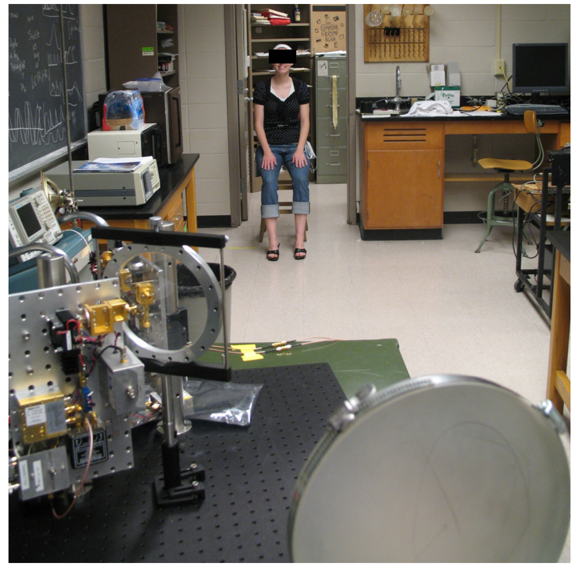

Figure 3. Photo of the radar system with a subject sitting approximately 8 meters away from the system.

at distances that ranged from 1 meter to 50 meters. Most trials lasted approximately 30 seconds to 2 minutes. Ranges up to 8 meters were performed in the lab while trials from 8-50 meters were performed in the hallway outside of the laboratory.

A. *Respiration Trials*

While normal respiration rates were recorded and measured, we also ran trials where the subject would breathe deeply or intentionally change their respiration rate. Fig. 4 shows the monitored torso displacement compared to the respiration belt for three trials: breathing deeply and variable breathing with subject distances of 10 m and breathing normally with a subject distance of 50 m. The comparisons between the BioRadio and radar data are made by scaling each signal to the same amplitude for direct comparison. Data was collected for 80 seconds in the first two trials and 60 seconds for the third. Each radar data set shows excellent agreement with the respiration belt. The top graph in Fig. 4 clearly shows the subject inhaling deeply just before 30 seconds and just after 60 seconds into the trial. The middle graph clearly shows the subject's increased respiration rate from approximately the 20 to 50 second time interval. The bottom graph shows a trial of a subject breathing normal measured at a distance of 50 m.

B. *Heartrate Trials*

Several trials were also done with subjects holding their breath to better examine the heartbeat signature. A trial spanning approximately 11 seconds is shown in Fig. 5. When the subject holds his or her breath, two distinct cardiac signatures are evident. One could be interpreted as a large scale feature that has a main Fourier frequency component of 1 Hz, that of the heart rate. A sharp feature has a main Fourier frequency component near 10 Hz also has the same periodicity associated with the heart rate. The sharp feature appears to be associated with the sharp QRS feature of the electrocardiogram and provides a very distinctive signature associated with the cardiac activity.

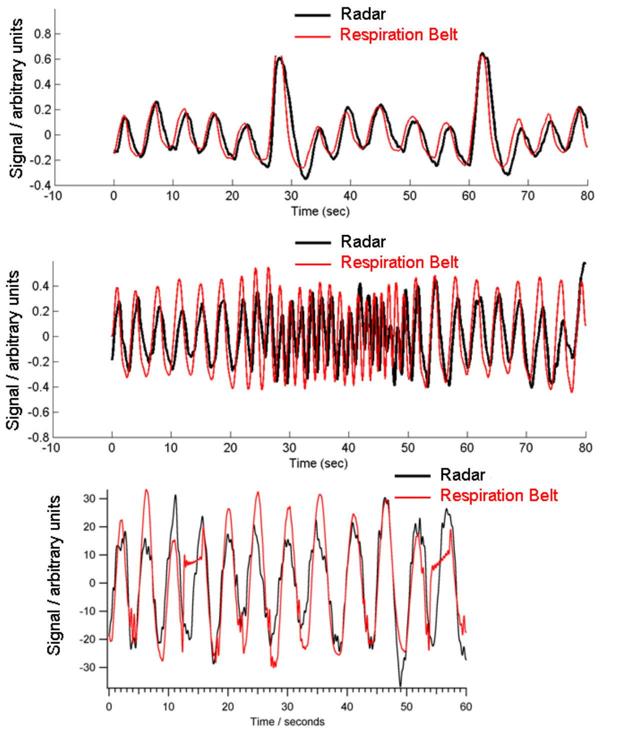

Figure 4. Three trials showing of the vital signs monitor. The top two graphs have the subject located 8 meters from the radar and represent deep breathing and variable breathing patterns, respectively. The bottom graph was taken with the subject located 50 m from the radar system. The respiration belt signal represents changes in the pressure of an air bladder in the belt and has been scaled to the same relative magnitude as the signal from the radar system that represents the displacement of the chest.

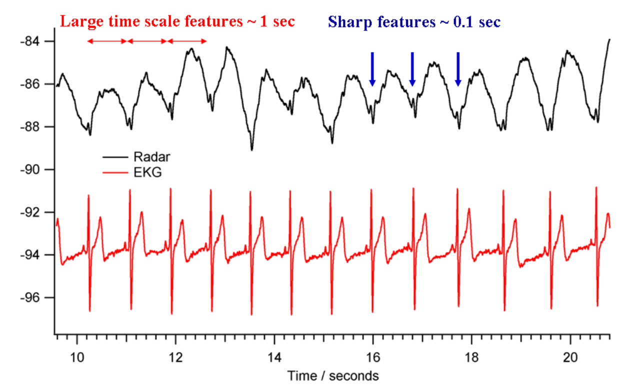

Figure 5. Radar and electrocariogram data of a subject that is holding his/her breath.

C. *Respiration Rate Measurements*

A Fourier Transform was applied to both the BioRadio respiration data and the radar data over 10-second windows in order to compare the measured respiration rate as a function of time. Fig. 6 shows the results by sliding the 10 second windows in 1 second time intervals applied to a 40 second trial when the individual was breathing normally and at a perceived steady rate. The peak frequency of the Fourier Transform of each window was recorded as the respiration rate. The radar and belt monitors are in very close agreement.

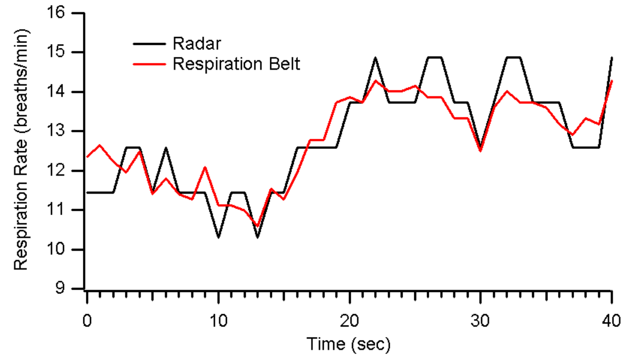

Figure 6. Fourier Transform analysis with a 10-second window measuring the respiration rate as a function of time for the respiration belt and radar system.

IV. CONCLUSIONS

In this paper we have demonstrated the ability of a 228 GHz radar system with a 15 cm aperture to accurately measure the cardiac and respiration signatures up to a distance of 50 meters. The agreement with ground truth instruments is quite good and by applying Fourier Transform techniques, both the respiration and heart rates can be determined. Current efforts are focused on the development of signal processing algorithms to separate the respiration and heart rate measurements simultaneously.

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