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Gait Variations in Human Micro-Doppler

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***Abstract*—Measurement of human gait variation is important for security applications such as the indication of unexpected loading due to concealed weapons. To observe humans safely, unobtrusively, and without privacy issues, radar provides one method to detect abnormal activity without using images. In this paper we focus on modeling the characteristics of human walking parameters in order to determine signature differences that are distinguishable and to determine the variability of normal walking to be compared to armed or loaded walking. We extract micro-Doppler from motion-captured human gait models and verify the models with radar measurements. We then vary the model to determine the extent of normal micro-Doppler variation in multiple dimensions of human gait. We also characterize the ability of radar to determine gender and suggest that alternative views to the frontal view may be more discriminative.**

***Keywords*—Radar, human, gait.**

I. Introduction

FOR observing humans, radar has advantages over other sensors. Radar signals can penetrate clothing, preventing disguise from being effective, while not compromising individual privacy. Using radar to determine unexpected loading, and thus to identify individuals trying to smuggle weapons or other items through a security checkpoint, is of interest for security applications. Understanding the variability of normal human motion as viewed by the radar can determine the capabilities and limitations of this type of device in determining loading accurately.

Detailed radar processing can reveal characteristics of the walking human. The different parts of the human body do not move with constant radial velocity; the small micro-Doppler signatures are time-varying and therefore analysis techniques can be used to obtain more characteristics [1], [2]. The modulations of the radar return from arms, legs, and even body sway are being studied [3]–[5]. We analyze these techniques and focus on modeling human body motion to simulate the variations.

The Doppler information measured by a radar arises from target motions. If we denote the target position by $P(T)$, where the coordinates x and y are functions of slowly varying time T and the origin is the radar:

$$P(T) = \begin{pmatrix} x(T) \\ y(T) \end{pmatrix} \tag{1}$$

then the instantaneous radial target speed is given by

$$v_r(T) = \frac{d}{dT}P(T) \cdot \frac{\vec{r}(T)}{|\vec{r}(T)|} \tag{2}$$

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where $\vec{r}(T)$ stands for the vector between the radar and the target. The resulting Doppler frequency shift F_d is then:

$$F_d(T) = \frac{2v_r(T)}{\lambda} = \frac{2F_tV_r(T)}{c} \tag{3}$$

where F_t is the frequency of the transmitted signal, λ is the wavelength, and c is the speed of light. The equation for computing the non-relativistic Doppler frequency shift of a simple point scatterer moving with speed v with respect to a stationary transmitter is:

$$F_d = F_t\frac{2v}{c}\cos\theta\cos\phi \tag{4}$$

where θ is the angle between the subject motion and the beam of the radar in the ground plane, and ϕ is the elevation angle between the subject and the radar beam. This assumes that the radar itself is stationary. For complex objects, such as walking humans, the velocity of each body part varies over time as the person walks. The radar cross-section of various body parts is also a function of aspect angle and frequency. The Doppler of a moving vehicle is similar to a point scatterer, but humans have a larger spread of velocities due to their bipedal motion.

A short-time FT (STFT) is one way to explore the slow-time dependent behaviour of the Doppler spectrum by doing a Fourier transform over a small window in time, then sliding the window [6]. This avoids the loss of time information that occurs when applying a Fourier transform. The continuous form of the STFT is:

$$STFT(x(t)) = X(\tau,\omega) = \int_{-\infty}^{\infty} x(t)w(t-\tau)e^{-jwt}dt \tag{5}$$

where $w(t)$ is the window function. Because human micro-Doppler varies slowly with time, we employ STFTs of the IQ radar data. The length of time used in the STFT is called the dwell time or coherent processing window, and this determines the resolution in Doppler frequency that can be measured. This can partially be overcome by super-resolving methods. The spectrogram is the square modulus of the STFT and is then:

$$Spectrogram(\tau,\omega) = 10\log_{10}|X(\tau,\omega)|^2 \tag{6}$$

Which is often used to display micro-Doppler data in decibels, as is done for the images in this paper. Much of the analysis in this paper makes use of spectrograms for the display of micro-Doppler phenomenology.

We perform simulations of the human gait and verify them with radar measurements. We break down the radar spectrogram into its components based upon simulated and measured human signatures. We model the variation to be expected when measuring human micro-Doppler signatures and compare them to the measured variations. We then analyze the capability of detecting gait variation due to loading as a security technology.

II. Simulation Method

Simulation of the human gait has been performed by many researchers, often with the goal of improving animated movies [7]–[13]. Here we are taking the extensive research on human gait and animation and using it to model the expected Doppler shifts measured over time by a radar system. We started with the measurements made in [14]. Twenty men and twenty women whose ages ranged from 20 to 38 years with an average age of 26 years had their motions captured on video and extracted, then their characteristics analyzed. The resulting motion information was extracted, and then animated. We took the animated gait and extracted the micro-Doppler velocities that would be created by differentiating the motions using a point-scatterer model for each separate part.

We neglected obscuration for these simulations because they were limited to frontal-view, and we used a metallic skin approximation to simplify the calculations. The simulated micro-Doppler motions for different body parts are shown in Figure 1. These are calculated from the actual motions of the model and are calculated at 17GHz. The resulting spectrogram and a comparison with measured radar data is shown in Figure 2. The scaling for the images was set at a 2m/s foot swing max in order to simplify the comparison of images to demonstrate the variability of the human gait as viewed by the radar. The stride rate is also held fixed to simplify comparisons. We also do not simulate noise in the models. Highly accurate mesh-modeled simulations of the human micro-Doppler signature have been done [15] but not with studies of the variability.

The effectiveness of the simulations is in the ability to depict both the variability of normal motion of both men and women without months of measurements. They also provide the ability to create a simulated database to test algorithms and approaches. There is not perfect agreement between simulated and actual measurements, as can be seen in Figure 2 and as is expected, but much of the qualitative pieces are in the simulations. The torso line, foot swing, and arm motions are all contained in the simulation. This compares well to other micro-Doppler simulations [16], [17].

We validated the entire motion as is shown in Figure 2, but also measured the parts of the human motion. We measured only the legs of a man walking toward the radar, and that data along with the simulated Doppler from the legs is shown in Figure 3 [18]. Note that the torso line is significantly diminished, as expected, and the arm motion is gone.

We varied the simulations based on extracted motion characteristics. These did not include the height or the roundness of the individual, but did include the gender, the sway, the hop, and the bounce in the individuals walk. These provide a guide to the true variability of human walking motion as viewed by the radar. Simulated spectrograms of the nominal range of expected variation are given in Figure 4, with each gait characteristic accentuated individually.

III. Measured Variability

Multiple measurements were done to try to characterize the micro-Doppler of human versus animal and vehicular motion. Details of the systems can be found in [19], [20] and details of the experiments and test plan can be found in [21]. Measurements of humans and animals were taken at the outdoor radar test range with realistic but low levels of clutter.

An algorithm was developed to track subjects and extract the micro-Doppler motions centered on them as they moved in time. The technique is specific to searching for single moving subjects in the beam of the radar. As range cells are scanned, the mean of the negative frequency Doppler cells is compared with the mean of the positive frequency Doppler cells. An exclusion zone around the clutter Doppler cells is created to prevent fluctuations in clutter from causing extraneous background signals. The standard deviation of the imbalances over all ranges is used to set a threshold. Range cells exceeding this threshold are flagged as having a possible target. If the imbalance is negative, negative Doppler frequencies dominate and an outbound target is indicated. A positive imbalance results when positive Doppler frequencies dominate, indicating an inbound target. A sub-image is extracted around flagged range gate. The sub-images are then sequenced in time. This provides a continuous motion capture centered on the subject. Once the range gates with the subject are isolated and stitched together in time, the spectrogram can be created.

IV. Variability Results

The gender has the least effect of any of the characteristics, but the height was not varied and this is one key to determining gender. One of the key variations is the phase of the knee motion relative to the foot motion. This is different in all four simulations. The arm motion as measured from the front is relatively consistent; however, this has been shown to be indicative of loading [6]. The torso shape also varies but this could be difficult to quantify. The velocity of the torso line is also variable in each of the simulations. There is also the variation of the plant foot and the phase of the foot to the torso.

Utilizing the knee measurement will often be difficult because the foot swing and arm are also creating overlapping signals in the same area. The knee measurements were clearer when the arms were blocked from the radar, as is shown in Figure 3, but highly accurate measurements may not be feasible without an extremely good system or without an imaging Doppler radar. Measuring the phase of the knees relative to the torso may still be possible. Characterizing the torso line has similar difficulties due to the crossing of the foot, arms, and knee signals, and the relative width does not seem to vary much either in simulation or in measurements. Measuring the plant foot is often obscured by clutter, and the variation of the phase of the foot to torso appears to be small but potentially measureable.

The simulations in this paper have used primarily front-view approaches. The difficulty in measuring micro-Doppler at different angles is known [22] and in particular the measurement of the foot is difficult at high azimuth, as is shown in Figure 5.

These simulations have shown that the difference in motion between a male and a female are not that large, and further that the normal variation of human motion can be large. This means that the determination of gender using front-view radar may be extremely challenging. However, using a correlation approach [23] we found could be accurate as much as 80% of the time on the measured data, indicating that the whole measured motion can be informative. The measurements did show a high degree of similarity between individuals, as is shown in Figure 6, with more subtle variations than those suggested by the models. A loaded individual did appear different, as is shown in Figure 7, than the typical individual variations, but the accuracy of that classification cannot be explored due to data constraints. However, considering the observable differences in the spectrogram and the effectiveness at individual identification, the determination of loaded individuals should be feasible.

V. Conclusions and Future Work

Simulation and measurement of the variability of human micro-Doppler motion has given us new insight into the possible measurements that can distinguish individual gait patterns and loaded versus unloaded individuals. We have incorporated motion-captured gait data into radar simulations and extrapolated the potential variability of the radar return from a human walking. We discuss the variability of several features that could be extractable, and discuss their viability. We determined that the correct classification using only a front-view radar may be challenging but also should be feasible.

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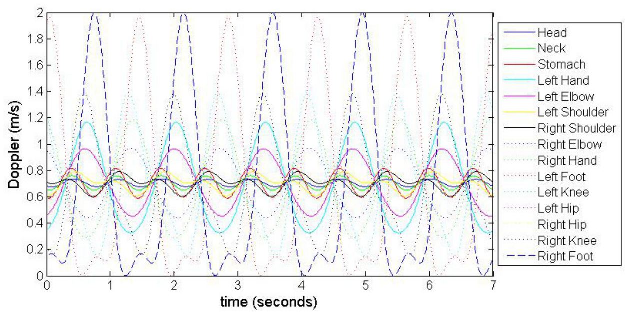


Fig. 1. Simulated Doppler motions for a man walking, with the Doppler of each part of the man displayed. This simulation is noiseless. Note that body-part interactions are eliminated from this plot, and this simulated motion in the radial direction to the radar.

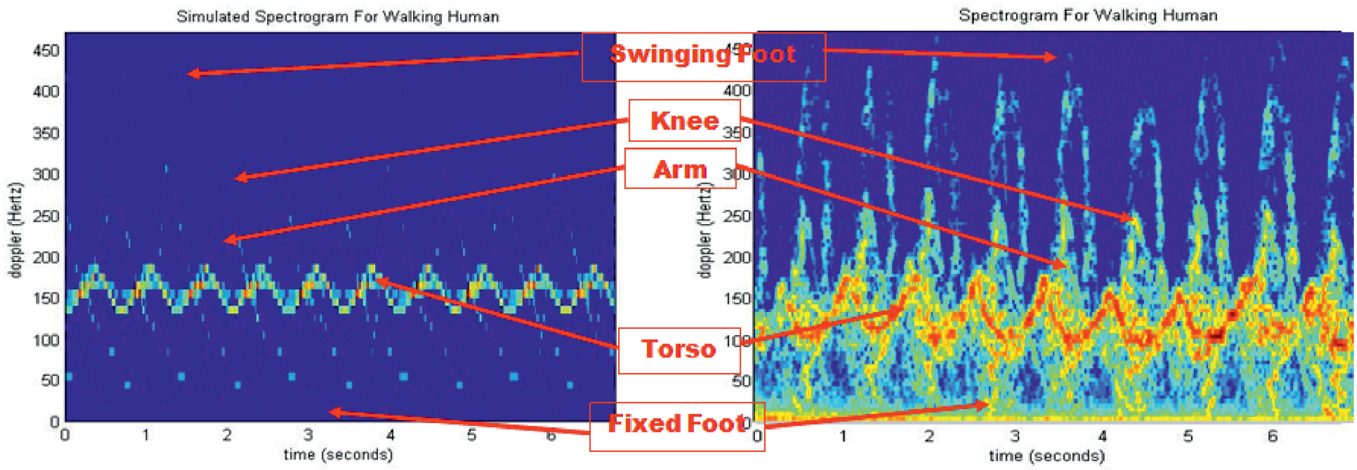


Fig. 2. Simulated spectrogram compared to a measured spectrogram of a man walking toward the radar. Different parts of the motion are qualitatively similar, though there are qualitative differences. The velocity and width of the torso line are different, and the radar cross section is not well matched. This simulation is noiseless.

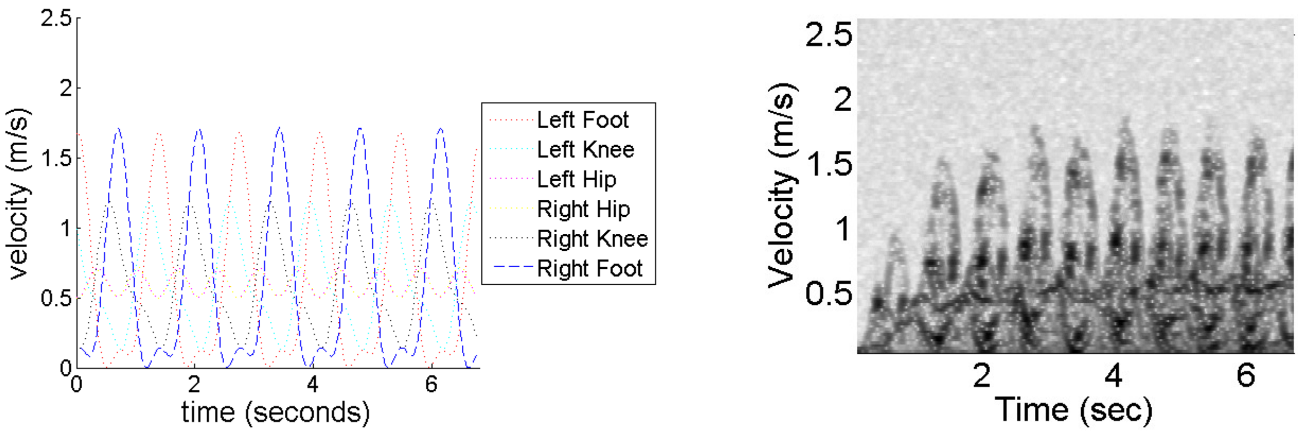
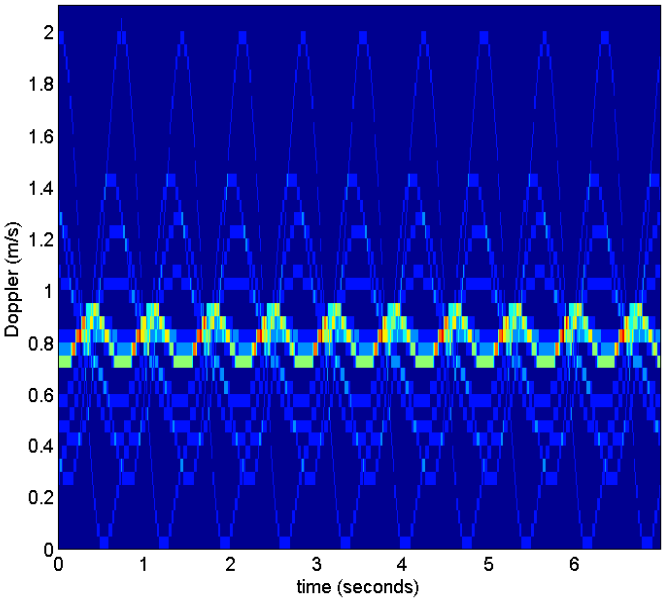
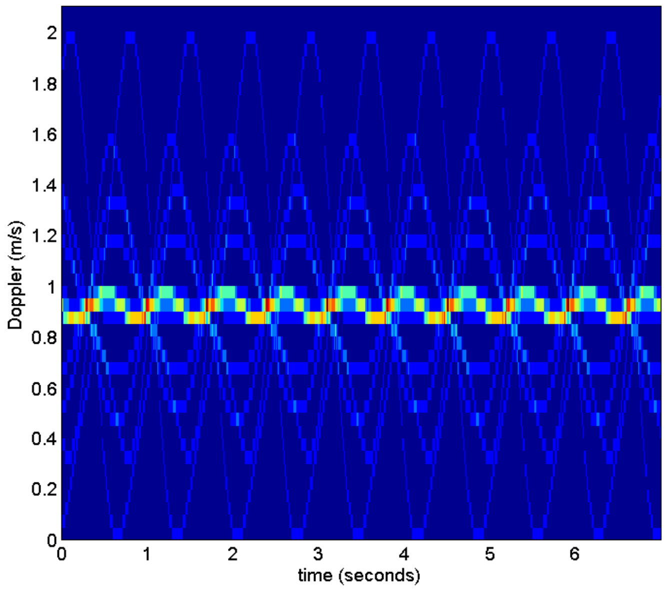


Fig. 3. The foot and knee motions as predicted by the model, and the measured spectrogram for a walking man's legs, measured with the same system as Figure 2.

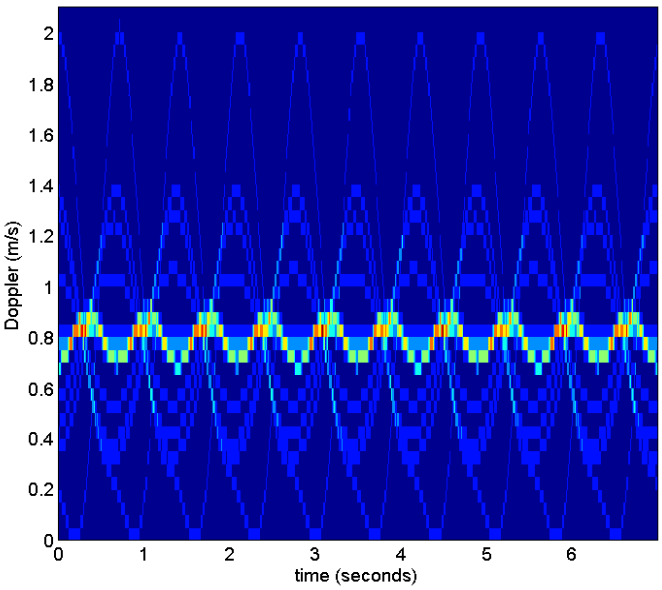
a)



b)



c)



d)

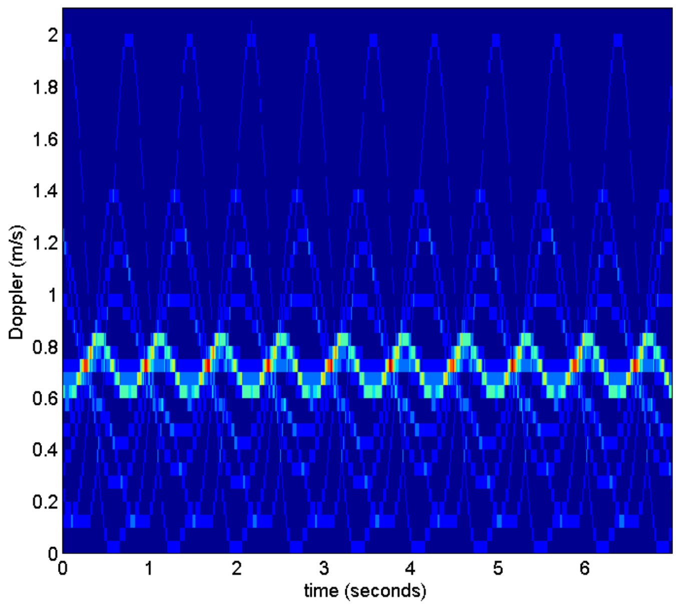


Fig. 4. Simulated spectrogram with the lack of sway is shown in (a), while the lack of hop is shown in (b). The lack of bounce is shown in (c), while the female gender is shown in (d). The gender has the least effect of any of the characteristics at this angle, but the height was not varied and this is one key to determining gender. These are all in comparison to the standard shown in Figure 2. One of the key differences is the phase of the knee motion relative to the foot motion. The arm motion as measured from the front is relatively consistent. The torso shape also varies as well as the relative height of the torso line to the foot swing. Note that the maximum and minimum foot velocities are standardized across the spectrograms.

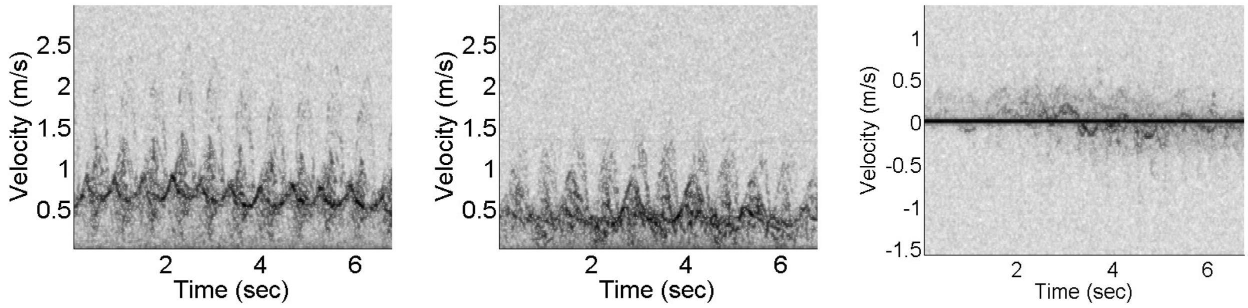


Fig. 5. Doppler signature of walking man with azimuth angles of 0, 45, and 90 degrees. Note the difficulty measuring the foot swing at 90 degrees.

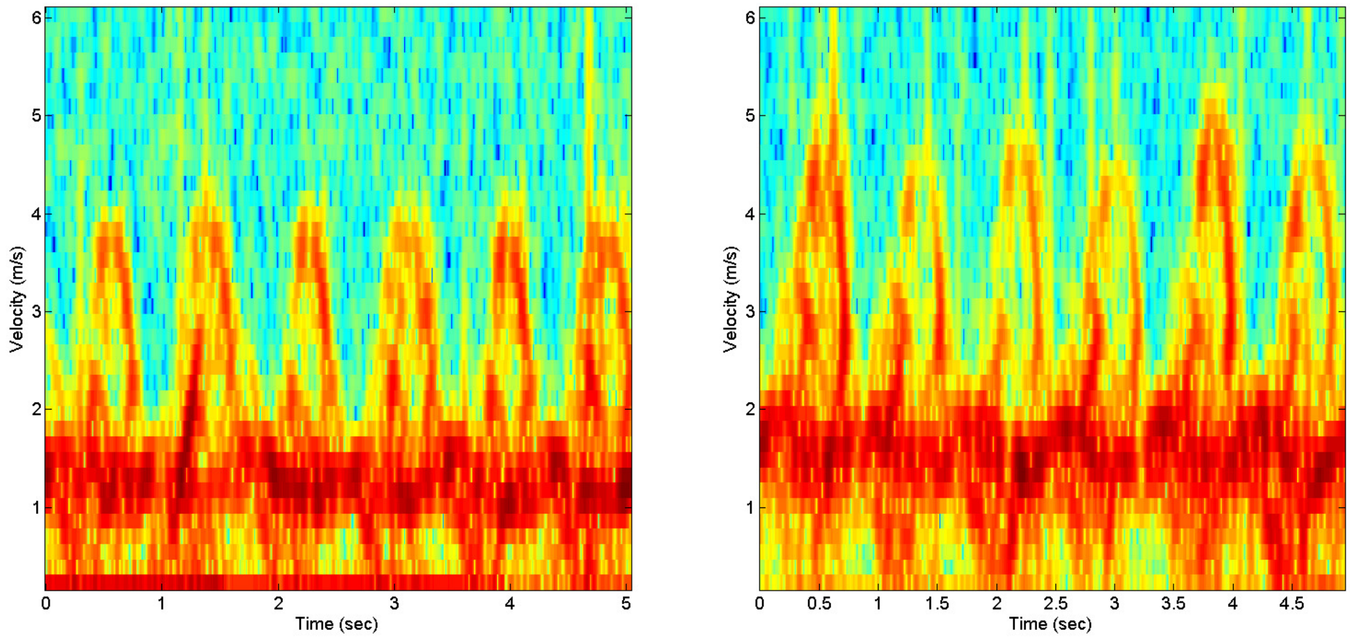


Fig. 6. Measured spectrograms of two different individuals walking toward the radar.

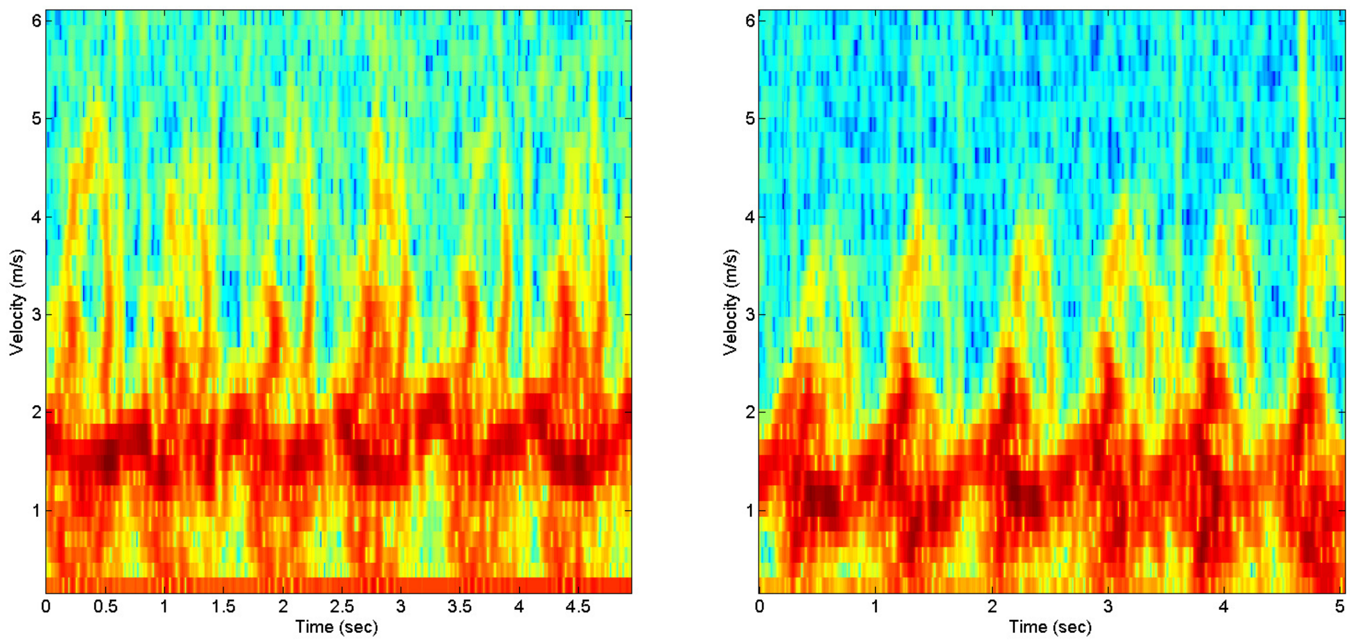


Fig. 7. Measured spectrograms of two different individuals walking toward the radar, one of which is inappropriately loaded.