Human Tracking Using Doppler Processing and Spatial Beamforming

Shobha Sundar Ram, Yang Li, Adrian Lin and Hao Ling
Department of Electrical and Computer Engineering
University of Texas at Austin
1 University Station
Austin, TX 78712, USA
5124711910, shobhasram@mail.utexas.edu

Abstract— **We present a continuous-wave Doppler radar with a multi-element receiver array for tracking humans. Joint Doppler processing and spatial beamforming are used to resolve multiple movers in the Doppler and direction of arrival (DOA) space. The improvement in the performance of the multi-element array compared to a previously developed two-element system is evaluated through Monte Carlo simulation. In an array of limited size, the sidelobes of the strong targets prevent the detection of weaker targets. To overcome this limitation, the monopulse, CLEAN and RELAX algorithms are investigated in conjunction with software beamforming. The improvement in the performance of the radar towards the detection of multiple targets is evaluated by simulation. Measurements are conducted using a 4-element receiver for different targets in line-of-sight and through-wall scenarios.**

Index Terms—**beamforming, direction of arrival, Doppler, CLEAN, RELAX**

I. Introduction

Detection and tracking of human targets through walls by radar has important applications in law enforcement, urban area operations and search-and-rescue missions. Developments that have been reported include wideband radar using impulsive [1-3], stepped frequency [4] or FMCW [5] waveforms to obtain high spatial resolution. Alternately, continuous wave radars of low power have been implemented to suppress stationary clutter [6]. A low-complexity CW radar of two elements was reported by us in [7-9]. It uses the phase difference of the scattered signal at the two elements to determine the direction of arrival (DOA) of the target. In addition, Doppler discrimination facilitates the tracking of multiple movers. However when the Doppler separation among the multiple targets is poor, the DOA error is found to increase significantly.

In this paper, we investigate the performance gain achievable by a multi-element array versus the two-element system. We implement Doppler processing in conjunction with spatial beamforming in software to resolve multiple targets in the Doppler and DOA space. Monte Carlo simulations are carried out to assess the performance gain of a multi-element system. To further overcome the broad beamwidth and high sidelobes in a limited size array, three different DOA estimation algorithms are implemented. They are the amplitude-comparison monopulse technique [10], the CLEAN algorithm [11], and the RELAX algorithm [12]. The performance of the different algorithms is studied by simulation and experimentally verified by using a 4-element receiver array. Measurements are conducted under line-of-sight and through-wall scenarios for audio loudspeakers and human targets.

This work is supported by DARPA, the Office of Naval Research, Texas Higher Education Coordinating Board under the Texas Advanced Technology Program and the National Science Foundation Major Research Instrumentation Program.

II. Radar Theory and Simulation

A. Joint Doppler Processing and Spatial Beamforming

Fig.1 shows the basic radar architecture under consideration. A CW signal is radiated from a transmitter and each target introduces a Doppler shift on the scattered signal. The radar receiver consists of a multi-element antenna array, with each element connected to a separate receiver channel where the signal is amplified, downconverted and digitized before it is fed to a computer for further signal processing. To carry out the Doppler processing and spatial beamforming, the time domain signal from each receiver, $y_n(t)$, is first fast Fourier transformed to generate the Doppler information and then phase shifted and summed to generate the DOA information. This is described by

$$Y\left(f_d,\theta\right)=\sum_{n=1}^{N}\left\{\int y_n\left(t\right)e^{-j2\pi f_d t}dt\right\}e^{-j(n-1)\frac{2\pi d}{\lambda_c}\sin\theta} \quad (1)$$

In the above equation, N is the number of array elements, f_d is the Doppler frequency, d is the spacing between two adjacent elements, λ_c is the RF wavelength and θ is the steered beam angle from the array boresight. Note that the order in which the Doppler processing and spatial beamforming are applied could be reversed without any change in the results.

1-4244-0284-0/07/$20.00 ©2007 IEEE

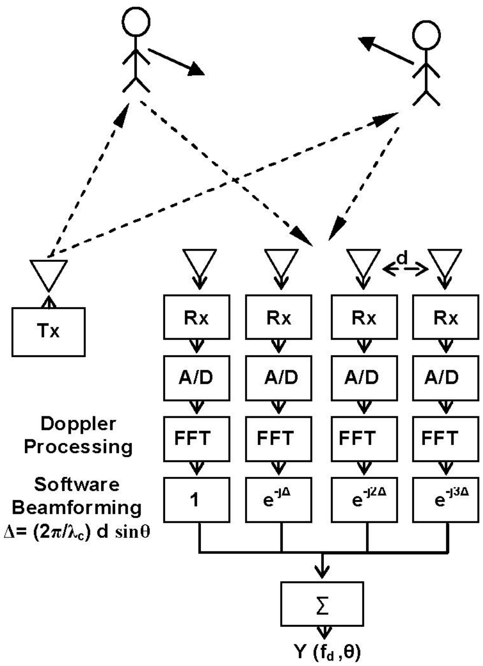
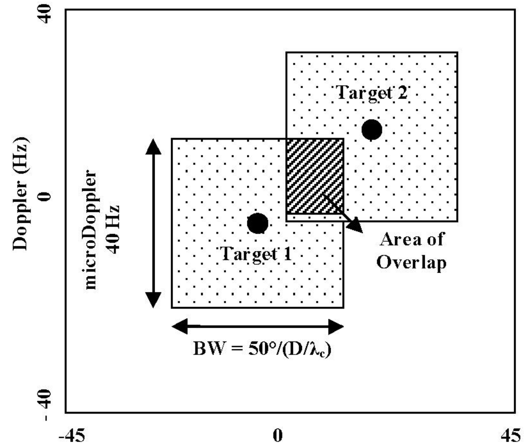


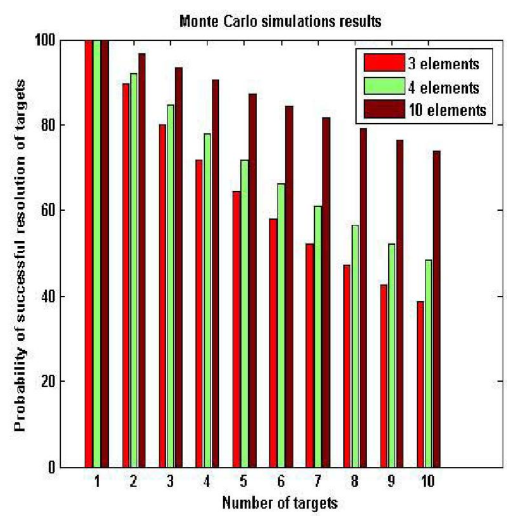
Fig 1. Radar architecture

B. Monte Carlo Simulation

Monte Carlo simulations are next performed to gauge the performance of the joint Doppler-beamforming algorithm towards the successful tracking of multiple targets. The following assumptions are made for the simulation. For each realization, a given number of targets are randomly placed inside a sectorial region of space bounded in range from 1 to 10m and DOA from -45° to +45°. Each target is randomly assigned a velocity of magnitude in the range of 0 to 2.5m/s and direction in the range of 0° to 360°. This yields Doppler values in the range of -40Hz to +40Hz for an RF wavelength of 12.5cm. We then assume that the ability of the radar to resolve a single target's returns is constrained in the DOA dimension by the beamwidth of the linear array, which for an antenna aperture of size D is $50°/(D/\lambda_c)$. In the Doppler dimension, the ambiguity is mainly caused by the microDoppler components from the arms and legs of the human movement [13]. A 40Hz Doppler spread is introduced to simulate the microDoppler spread for each target. With these two assumptions, each target is resolvable up to the rectangular ambiguity region in the DOA vs. Doppler space as shown in Fig. 2a. For multiple targets, the chance of overlap between the targets' ambiguity regions is increased. When the ambiguity regions of any two targets overlap by more than 50%, we consider that realization to be unresolvable by the radar. We perform this simulation for 500,000 realizations and tally the results. Fig. 2b shows the probability of successfully resolving multiple targets versus the number of targets. Each color represents a different assumed number of array elements, and therefore a different size antenna aperture. As expected, as the number of targets is increased, the probability of successfully resolving the targets drops. Using more array elements improves the performance, especially in the case of a large number of targets, since a narrower beamwidth improves the DOA resolution. This is done at the expense of increased system cost and complexity. We see that with 4 elements, there is a 78% probability of successfully resolving 4 targets.



(a)

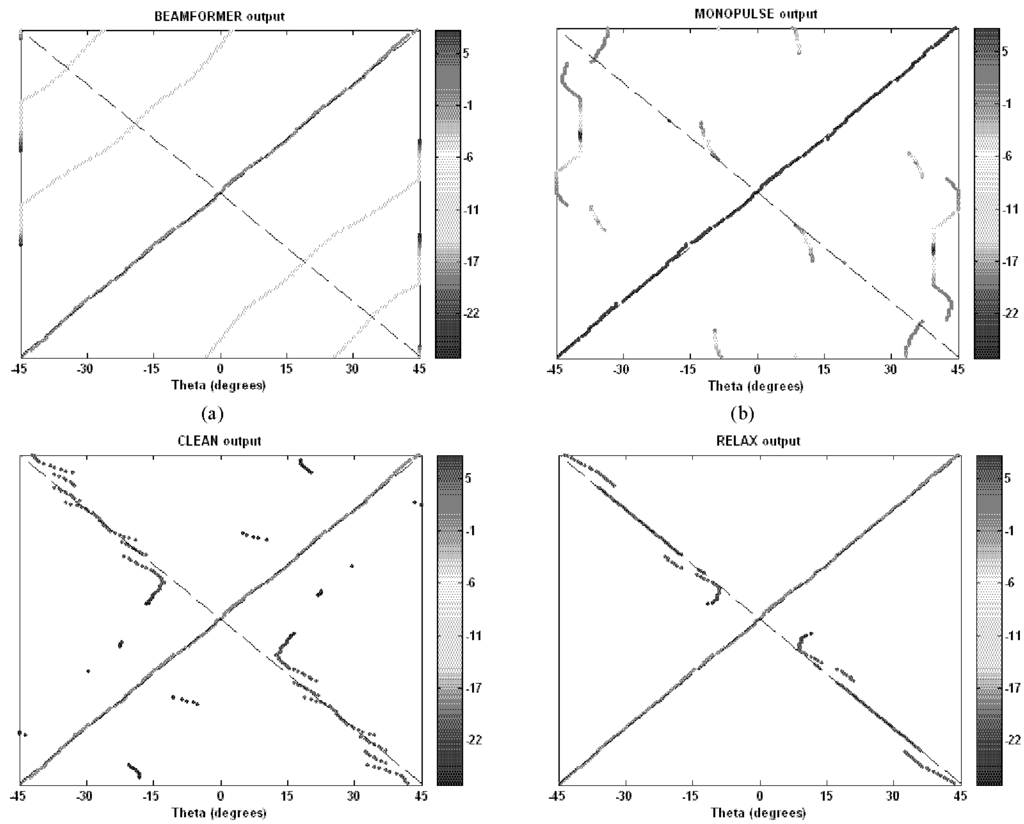


(b)

Figure 2: (a) Detection of targets in the Doppler versus DOA plot (b) Monte Carlo simulation results for probability of successfully resolving multiple targets with an antenna array

C. DOA Estimation

If multiple targets are not well resolved in the Doppler domain, their successful DOA determination becomes quite difficult using a small size array, especially when the target strengths are very different. This is understood from the following simulation performed in a two target scenario where the targets are of the same Doppler. Hence the detection of the two targets is entirely determined by spatial beamforming. The simulation is conducted for a four-element antenna array and the ratio of the strength of the two targets is set to 20dB. The angular position of the strong target is varied from -45°



(a) (b) (c) (d)

Fig.3. Simulation results when ratio of strength of targets is 20dB for (a) Spatial beamforming , (b) Monopulse, (c) CLEAN, and (d) RELAX techniques

to +45° while that of the weak target is varied from +45° to -45°as indicated by the dashed lines in Fig. 3a. For each pair of simulated angular positions of the targets, the main lobe and sidelobe patterns arising from the two targets are computed by spatial beamforming. The DOA of the targets are estimated to be at the peaks of the beamformer pattern and their strengths are represented by the colored intensity as indicated in Fig. 3a. It is observed that the DOA of the strong target is detected correctly at every possible DOA position of the targets. The weaker target however is not detected at all because it is buried beneath the sidelobes of the strong target. This result is unsatisfactory. In order to improve the tracking of weak targets in the presence of strong targets, we implement three different algorithms, namely, monopulse, CLEAN and RELAX, and evaluate their performance using the same simulation set up.

1) Monopulse: Monopulse processing is a standard technique to improve the angular resolution in target tracking. The amplitude comparison monopulse technique described in [10] is implemented here. In order to estimate the DOA of a single target, the strength of the scattered signal from the target is measured at two specific angular values or lobes using the beamforming equation (1). In order to try to handle multiple targets, the technique is modified by increasing the number of lobes to M ($Y_{1:M}$). Normalized difference values ($D_{1:M-1}$), of the signal strength are computed for each pair of adjacent lobes:

$$D_i = \frac{|Y_i| - |Y_{i+1}|}{\sum_{j=1}^{M} |Y_j|} \quad , \quad i = 1, \ldots, M-1 \qquad (2)$$

For each possible angular position of a target, a data set of difference values is computed theoretically and stored The measured data set is then compared with each of the multiple data sets obtained by theory. The DOA of the target is identified as that angular value which gives the closest fit between the measured and theoretical data sets. While it is possible to estimate the DOA of two targets of equal strength that are well resolved in the DOA space, the performance of the algorithm deteriorates for a higher dynamic range. This is seen when the technique is simulated in the two target scenario described earlier using M=5. The presence of the sidelobes prevents the detection of the weak targets as indicated in Fig. 3b

2) CLEAN: The CLEAN algorithm is a well-known technique to extract weaker features in the presence of strong features, given that the feature response function is known [11]. Here we apply the algorithm to extract the DOA of multiple targets. The DOA of the strongest target is first extracted by picking out the strongest response from the beamformer output:

$$| a_p |^2 = \max_{\theta_p} \left| \frac{1}{N} \sum_{n=1}^{N} y_n \, e^{-j(n-1)\frac{2\pi d}{\lambda_c} \sin\theta_p} \right|^2 \qquad (3)$$

Once the DOA of the strongest target is found, its presence is removed from the original array signal:

$$y_{n,residual} = y_n - a_p e^{j(n-1)\frac{2\pi d}{\lambda_c} \sin\theta_p} \qquad (4)$$

Since the strongest target is removed together with its sidelobe contribution, the weaker target becomes better revealed. The next strongest target and its DOA are then determined and removed from the residual signal. This procedure is continued in successive steps until the strength of the residual pattern converges or falls below the noise floor. This algorithm is simulated for the two target scenario described earlier and the results are presented in Fig. 3c. It is observed that the weak target is detected in the presence of a stronger target as long as their angular separation exceeds the beamwidth of the array. The algorithm clearly performs better than the ordinary beamforming and monopulse techniques towards detecting multiple targets. However there does appear to be false targets near the strong target due to the influence of the weaker target on the strong target.

3) RELAX: The RELAX algorithm is an enhanced version of CLEAN that relieves the error propagation tendencies in CLEAN [12]. It introduces a relaxation step that iteratively identifies target parameters (strength and DOA) until the energy of the residual pattern at each CLEAN step converges. Relaxation occurs in the CLEAN algorithm once the second target has been found. At that stage, the second target's contribution is extracted from the original signal. The goal is to more accurately extract the first and strongest target a second time, without the mutual interference effects of the second target. The re-extraction of the two targets repeats until convergence. Afterwards, the algorithm resumes in order to extract the next strongest target from the residual. The relaxation process is then initiated again to individually adjust the values of all known targets in the absence of the contribution of the others. While this inner relaxation loop makes the algorithm computationally more expensive than ordinary beamforming and CLEAN, it allows the accurate determination of the number of targets. The results obtained when this algorithm is implemented for the two target scenario described earlier are presented in Fig. 3d. It is observed that angular position and the strength of the two targets are detected with better precision. The number of erroneous detections or false targets is much smaller than the earlier cases. Additionally, successful detection is possible even when their angular separation is within the beamwidth of the antenna array. Thus RELAX enhances the performance of the CLEAN algorithm at the price of increased computation time.

III. Measurement Results

The radar prototype used to demonstrate the above concepts is shown in Fig. 4. It consists of a signal generator that transmits a 2.4GHz signal through a horn antenna. The receiver consists of a four-element microstrip array on an FR4 substrate of 1.6mm thickness. The inter-element spacing of the array is 0.56 λ_c. This allows the antenna array to scan from -45° to +45° without the occurrence of grating lobes. Each element is connected to an integrated quadrature receiver from which the signal is amplified, downconverted and fed to the A/D converter. The digitized output is fed to the computer for signal processing.

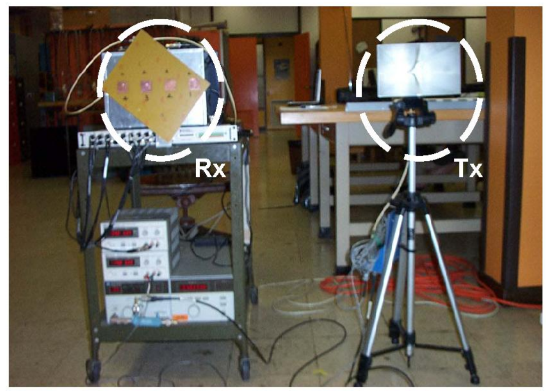


Fig. 4. RADAR set up

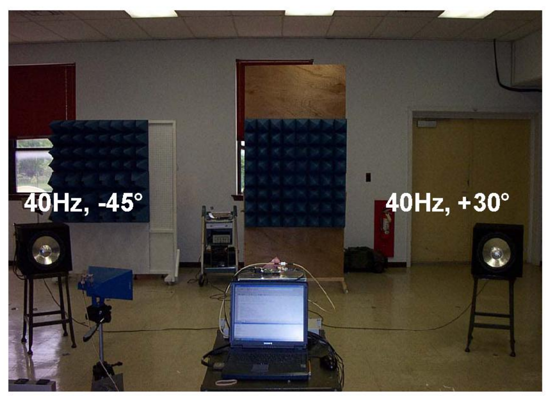


Fig. 5. Speaker test: speakers well resolved in DOA but identical Doppler

First we use audio loudspeakers as steady test targets. When a loudspeaker is driven by a single audio tone, the FM signal that is generated gives rise to a two-sided Doppler return. The two-element DDOA radar reported in [7-9] is not capable of resolving targets of identical Doppler. To demonstrate that the current radar is capable of resolving targets of identical Doppler along the DOA axis, the following measurement is made with two loudspeakers as shown in Fig. 5. Two loudspeakers are driven at the same frequency (40Hz) but are located at different DOA (30° and -45°). From the results presented in Fig. 6a, it can be seen that two targets of identical Doppler are resolved along the DOA axis using spatial beamforming. However, the high sidelobes appear as false targets. When the CLEAN algorithm is tried on the same measurement, it becomes apparent from Fig. 6b that the algorithm is able to correctly identify the DOA of the two targets despite the presence of high sidelobes. To display the CLEAN results, which are a set of discrete DOA estimates, a point spread response with high resolution and low sidelobes is convolved with the discrete estimates. The RELAX result, which is not shown here, further improves the CLEAN result slightly.

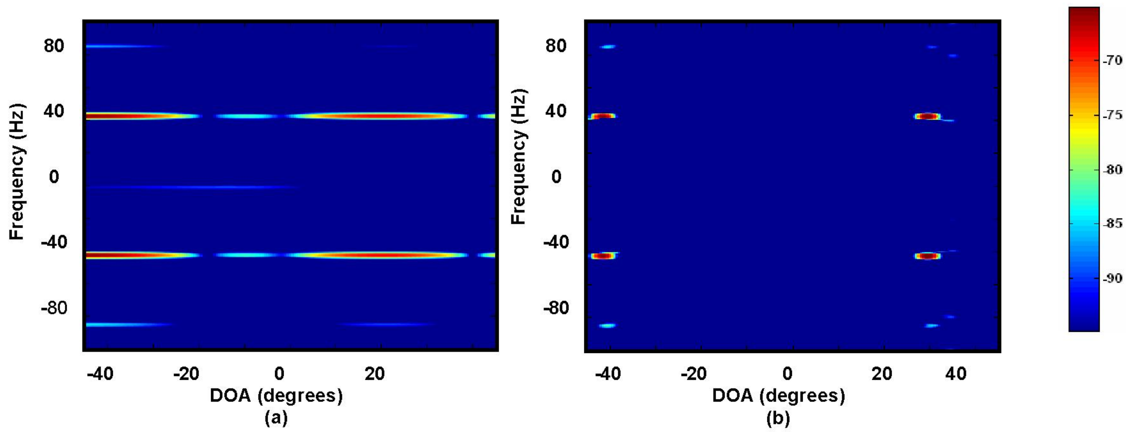


Fig. 6. Speaker test with: (a) Spatial beamforming and (b) CLEAN

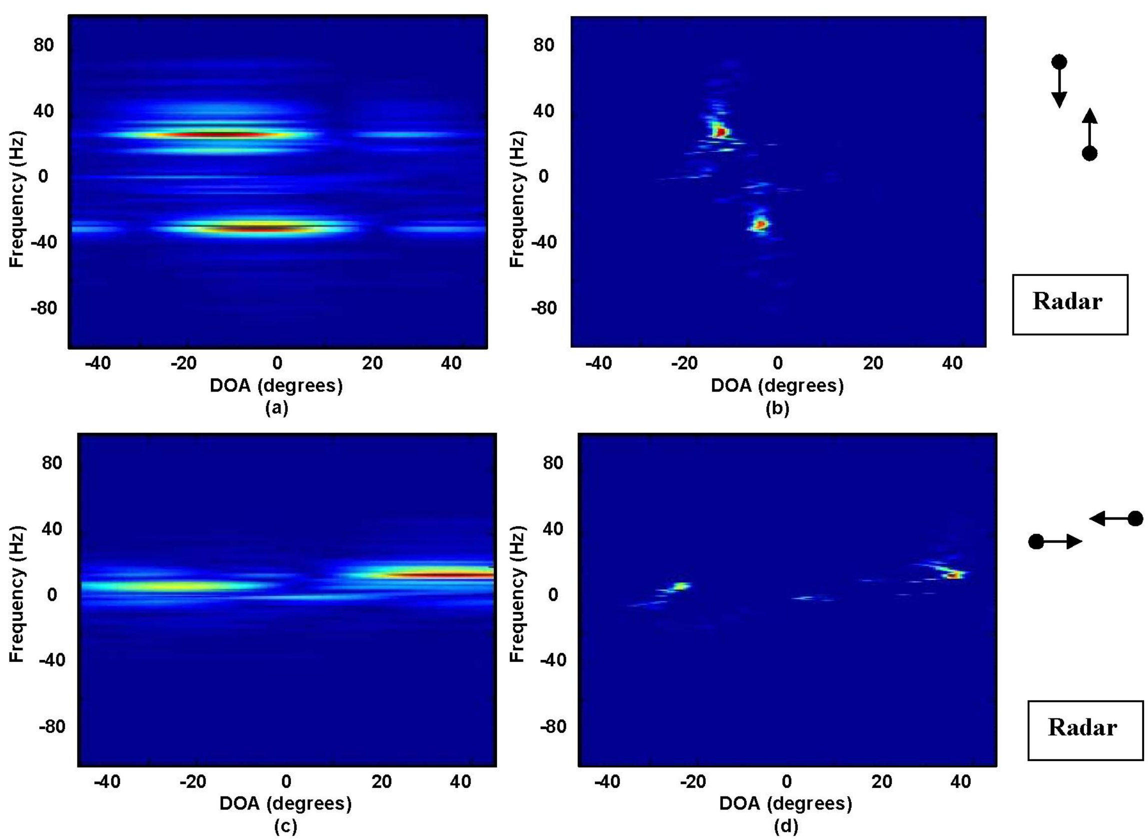


Fig. 7. Measurement results for human targets under line-of-sight.
Top figures illustrate two targets with high Doppler separation and low DOA separation: (a) Spatial beamforming. (b) CLEAN.
Bottom figures illustrate two targets with low Doppler separation and high DOA separation: (c) Spatial beamforming. (d) CLEAN.

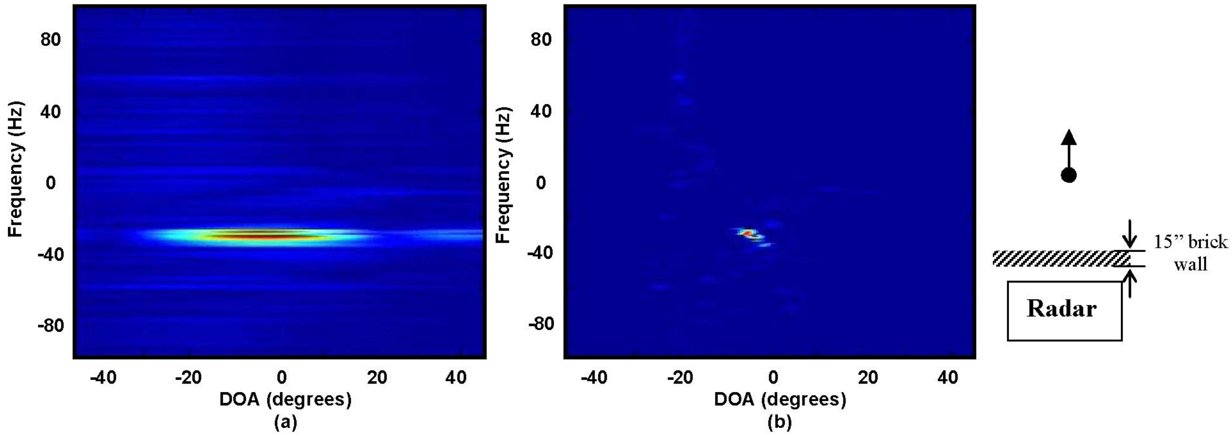


Fig 8: Measurement results for a human subject for through a 15” exterior brick wall . (a) Spatial beamforming. (b) CLEAN

Measurements are next conducted on two human subjects under an indoor line-of-sight environment. Human walking returns are characterized by microDoppler features, causing spreading along the Doppler dimension. Two cases are studied. In the first case, the first subject walks away from the radar (negative Doppler) while the second subject approaches the radar (positive Doppler) along two paths that lie very close to each other. Thus the Doppler separation between the two targets is high while the DOA separation is low as is apparent from the Doppler-DOA plot in Figs. 7a and 7b. In the second case, while one target approaches the radar from the right (positive Doppler), the second target approaches from the left (positive Doppler). Thus the Doppler separation is low while the DOA separation is high. This is seen in the Doppler-DOA plot in Fig. 7c and 7d. The two targets are clearly resolved in both scenarios. Again, the CLEAN algorithm (Figs. 7b and 7d) leads to improved DOA estimation and lower sidelobes as compared to the standard beamforming (Figs. 7a and 7c).

Measurements of human target are conducted for a through-wall paradigm on an exterior brick wall of 15” thickness. The results for a single human case are shown in Fig. 8. As we can see from the result, the target is successfully tracked in the through-wall scenario. The wall, however, introduces a significant attenuation on the signal and leads to a lower signal-to-noise ratio. Other types of walls are being investigated to assess additional wall phenomenology.

IV. Conclusion

Using the principles of Doppler processing and spatial beamforming, the performance of a radar for tracking multiple humans can be improved by using additional receiver elements. The resolution of the target along the DOA axis is limited by the beamwidth of the antenna array and the sidelobes give the appearance of false targets To overcome these limitations, three algorithms including monopulse, CLEAN and RELAX are investigated for use in conjunction with software beamforming. It was found that the CLEAN algorithm performed satisfactorily for multiple targets without excessive computational cost. These concepts are demonstrated by conducting measurements on different targets in line-of-sight and through wall scenarios.

References

[1] G.Franceschetti, J.Tatoian, D.Giri and G.Gibbs, “Timed arrays and their application to impulse SAR for "through-the-wall" imaging,” *IEEE Antennas Propagat. Soc. Int. Symp. Digest,* vol. 3, pp.3067-3070, June 2004.

[2] A.R.Hunt, “Image formation through walls using a distributed radar sensor network,” *SPIE Proc., Sensors, and Command, Control, Communications and Intelligence (C3I) Technologies*, vol. 5778, pp.169-174, May 2005.

[3] S.Nag, M.A.Barnes, T.Payment and G.Holladay, “Ultrawideband through-wall radar for detecting the motion of people in real time,” *SPIE Proc. Radar Sensor Technology and Data Visualization,* vol. 4744, pp.48-57, July 2002.

[4] F.Ahmad, G.J.Frazer, S.A.Kassam and M.G.Amin, “Design and implementation of near field wideband synthetic aperture beamformer,” *IEEE Transactions Aerospace and Electronic Systems,* vol. 40, pp.206-220, January 2004.

[5] D.G.Falconer, K.N.Steadman and D.G.Watters, “Through-the-wall differential radar,” *SPIE Proc. Command, Control, Communications, and Intelligence Systems for Law Enforcement*, vol. 2938, pp.147-151, February 1997.

[6] D.D.Ferris Jr.and N.C.Currie, “Microwave and millimeter-wave systems for wall penetration,” *SPIE Proc. Targets and Backgrounds: Characterization and Representation IV*, vol. 3375, pp.269-279, July 1998.

[7] A.Lin and H.Ling, “Human tracking using a two-element antenna array,” *SPIE Proc. Radar Sensor Technology and Data Visualization*, vol. 5788, pp.57-64, May 2005.

[8] A.Lin and H.Ling, “Through-wall measurements of a Doppler and direction-of-arrival (DDOA) radar for tracking indoor movers,” *IEEE Antennas Propagat. Soc. Int. Symp. Digest,* vol. 3B, pp.322-325, July 2005.

[9] A. Lin and H. Ling, “A Doppler and direction-of-arrival (DDOA) radar for multiple-mover sensing based on a two-element array,” to appear in *IEEE Trans. Aerospace Electronic Syst.*, July 2007.

[10] S.M.Sherman, *Monopulse Principles and Techniques*, Dedham MA, 1984.

[11] J.Tsao and B.D.Steinberg, “Reduction of sidelobe and speckle artifacts in microwave engineering: the CLEAN technique,” *IEEE Trans. Antennas Propagation*, vol. 36, pp 543-556, April 1988.

[12] J. Li and P.Stoica, “Efficient mixed-spectrum estimation with applications to target feature extraction,” *IEEE Trans. Signal Processing*, vol. 44, pp 281-295, February 1996.

[13] J.L.Geisheimer, E.F.Greneker and W.S.Marshall, “High-resolution Doppler model of the human gait,” *SPIE Proc. Radar Sensor Technology and Data Visualization*, vol. 4744, pp. 8-18, July 2002.