Robust Detection of Moving Human Target in Foliage-Penetration Environment Based on Hough Transform

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Abstract. *Attention has been focused on the robust moving human target detection in foliage-penetration environment, which presents a formidable task in a radar system because foliage is a rich scattering environment with complex multipath propagation and time-varying clutter. Generally, multiple-bounce returns and clutter are additionally superposed to direct-scatter echoes. They obscure true target echo and lead to poor visual quality time-range image, making target detection particular difficult. Consequently, an innovative approach is proposed to suppress clutter and mitigate multipath effects. In particular, a clutter suppression technique based on range alignment is firstly applied to suppress the time-varying clutter and the instable antenna coupling. Then entropy weighted coherent integration (EWCI) algorithm is adopted to mitigate the multipath effects. In consequence, the proposed method effectively reduces the clutter and ghosting artifacts considerably. Based on the high visual quality image, the target trajectory is detected robustly and the radial velocity is estimated accurately with the Hough transform (HT). Real data used in the experimental results are provided to verify the proposed method.*

Keywords

Bistatic LFMCW ground radar, foliage-penetration, human target detection, Hough transform, multipath mitigation, time-varying clutter suppression.

1. Introduction

Robust weak moving ground target detection in the presence of foliage clutter is always a challenging subject in the field of radar signal processing, which also has significant importance in military and civil fields. The foliage is a random medium with many discrete scatterers such as the randomly distributed leaves, branches and tree trunks. Radio waves propagating in the foliage naturally experience multiple scattering, reflection, refraction, diffraction, and absorption of radiation. These different propagation mechanisms, when combined, can result in dense multipath effects and clutter and severe fades in the received signal [1] - [3].

It is well known that the detectability of a target is directly related to the amount of radar energy reflected from the target. Traditionally, a range cell return is compared against a threshold and a detection decision is made. Once this is done, the information of that cell is discarded and other cells are considered independently. It is clearly wasteful to discard this data which still may contain target returns even if no detection is declared. For weak targets embedded in foliage environment with low signal-clutter-ratio (SCR) responses, this kind of approach will encounter difficulties.

Another approach that uses unthresholded data (e.g. a sequence of time-range images, gray-scale images) for simultaneous detection and tracking is referred to as track-before-detect (TBD) [4]. As one of the TBD methods, the Hough transform (HT) [5] is a feature detection method originally developed for the detection of straight lines in an image space corrupted by noise [6]. As the very pioneer, Carlson applied HT to detect target in search radar [7] - [9]. This method makes full use of the previous data information which may contain weak undetected targets. Owing to better use of old energy and spatially separated energy, the target detectability is improved. Consequently, HT has been widely applied to detect and track low SCR targets in environment of dense clutter [10] - [12].

Nevertheless, unlike indoor or urban environment, in foliage-penetration environment there are some effects that HT cannot face up to so efficiently. Among them, the aforementioned multipath effects and time-varying clutter must be considered and will be exclusively focused on in this work. In foliage-penetration environment the intended target is hidden or surrounded by many bushes, trunks, and branches, its signature consists of the directly reflected waveform as well as the secondary returned waveforms due to those scatters, which degrade echo quality severely [13]. Due to the weak cross-correlation of the cluttered data, conventional clutter suppression methods do not work well for the time-varying clutter. Even after clutter suppression, the residual clutter is so strong that the moving target trajectory in time-range image is submerged and can not be detected. Moreover, the multipath echoes have remarkably similar characteristic to that of a moving target. The trajectories appearing in the time-range image seem to be other moving targets. Thus the ghost targets will severely influence the target detection performance and increase the probability of false alarm.

In order to detect the moving human target embedded in foliage-penetration environment with dense clutter, an innovative detection procedure is proposed, which can be divided into three steps. First, within each coherent processing interval (CPI) range alignment based moving target indication (RA-MTI) is presented to suppress the antenna coupling and time-varying clutter caused by the movement of bushes. Second, entropy weighted coherent integration (EWCI) algorithm is utilized to reduce the multipath effects. Finally, HT is applied to project the detection results of the second step into Hough parameter space. The detecting result in the Hough parameter space then can be projected back to the data space for target tracking and parameter estimation.

The remaining part of the paper is organized as follows. Section 2 briefly describes a bistatic linear frequency modulation continuous wave (LFMCW) ground radar system used for foliage-penetration experiment. Our proposed approach including clutter suppression, multipath mitigation and HT is presented in detail in Section 3. The application of the approach to real data is addressed in Section 4. Finally, some conclusions are drawn in Sec. 5.

2. Radar System

The bistatic LFMCW ground radar has been developed by National University of Defense Technology. Its parameters for experimental data acquisition are detailed in Tab. 1. The operational frequency band of the radar is at ultra-high frequency (UHF) band, from 675 MHz to 825 MHz, which gives a down-range resolution of 1 m and also the possibility to penetrate the bushes to detect a concealed moving target. The antennas used in the radar system are panel antennas. Besides, the polarization of the antennas is horizontal, which outperforms other polarization modes after many trials in foliage-penetration measurements. On the other hand, CPI is selected to be 400 ms to ensure the moving human target remains in the same range cell.

Central operational frequency (f_c)	750 MHz
Transmitted bandwidth (B)	150 MHz
Pulse repetition frequency (PRF)	5000 Hz
Sampling rate (f_s)	8 MHz
CPI (T_{CPI})	400 ms
Transmitted power	29 dBmW
Range	45 m
Polarization	Horizontal

Tab. 1. Bistatic LFMCW ground radar parameters for experimental data.

During working, the bistatic LFMCW ground radar stays immobile and the transmit antenna is separated from the receive antenna with some distance to reduce the antenna coupling. The digitized radar data are organized in a two dimensional (2-D) matrix whose columns represent the received signal during each pulse period (fast time), so consecutive pulses are stored in successive columns (slow time). To obtain range profiles, fast Fourier transform (FFT) is performed along the fast time dimension. On the other hand, along the slow time dimension the radar observation time can be divided into multiple CPIs. By utilizing the temporal information inherent to a sequence of these range profiles, a time-range image containing the target motion information can be synthesized.

3. Moving Human Target Detection

3.1 RA-MTI

In comparison with the antenna coupling, bushes clutter and other strong ambient clutter, the echoes reflected by human body are fairly low. Additionally, the high signal attenuation of bushes and leaves further weakens the target echo energy. As a result, the SCR is too low to be applicable for detection. Therefore, it is essential for moving target indication to suppress clutter and improve the SCR by appropriate algorithms.

Generally, conventional time-domain methods, such as single-delay MTI canceller and background subtraction (BS), are essentially different recursive MTI filters with different tap-lengths [14]. These methods work well to suppress the stationary clutter which is stable in indoor or urban environment. However, foliage is time varying from time to time because of the movement of branches and leaves. Therefore, the propagation channel cannot be as stationary as that of indoor or urban environment. The echoes from the bushes and branches are no longer stable and time-invariant, and then range misalignment occurs from time to time, which is shown in Fig. 1. It is observed that the delays of the echoes are varied severely. At the same time, the antenna coupling hopefully should be in the same range bin, which can be seen as another kind of stationary clutter. Unfortunately, it is also not perfectly stable over time due to low system stability of the bistatic LFMCW ground radar.

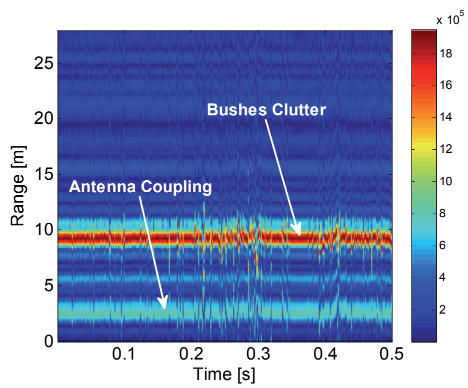
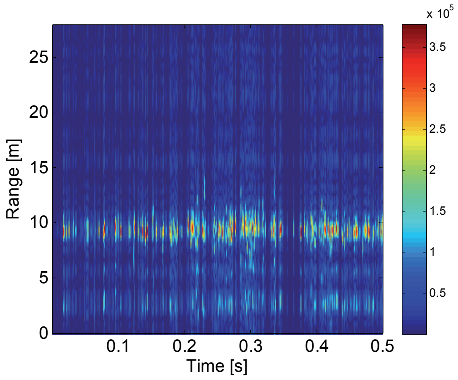
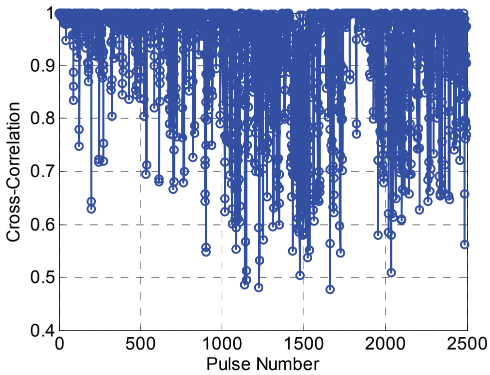


Fig. 1. Time-range image of raw echo data in foliage-penetration environment.

Among the time-domain methods, exponential average background subtraction (EABS) method [15] permits meaningful control over its clutter-reduction behavior and can achieve good results. Thus EABS is applied to suppress the clutter. Fig. 2 a) is the result after clutter removal with EABS, showing that there is still a lot of strong residual clutter, which will influence the detection performance. The reason is that because of scintillation of the reflectivities leading to misalignment, the cross-correlation between adjacent pulses is very weak, which is shown in Fig. 2 b). On the other hand, EABS operates upon the returns from the same range bin, which are of high cross-correlation. Consequently, conventional clutter suppression methods are inapplicable to this kind of clutter.



a)



b)

Fig. 2. Range misalignment. a) Result after clutter removal with EABS. b) Cross-correlation between adjacent pulses.

To improve the cross-correlation of the adjacent pulses, range misalignment should be corrected at first. Spatial domain realignment method [16] is a classic algorithm. Nevertheless, it is widely accepted that the spatial domain realignment algorithm is likely to fail in the presence of clutter and scintillation of reflectivities, and the misalignment error may accumulate across the coherent integration interval. Thus, for a more robust range alignment, average cross-correlation method is utilized in this paper.

Let $\mathbf{S}(r)$ denote the vector formed by the consecutive complex returns from adjacent range profiles in one CPI:

$$\mathbf{S}(r)=\left[s_{t-KT}(r),\cdots,s_{t-2T}(r),s_{t-T}(r),s_t(r)\right] \tag{1}$$

where T is the pulse repetition interval (PRI) and r is the range assumed within one PRI. K is the number of the adjacent range profiles and $KT<T_{CPI}$. The amplitudes of the returns are considered to be time-invariant owing to the tiny aspect angle change over very short period. Thus we have

$$e_{t-iT}(r+\Delta r_i)\approx e_t(r),\quad i=1,2,\cdots,K \tag{2}$$

where $e_t(r)$ is the amplitude of the range profile $s_t(r)$ following as

$$e_t(r)\cong\left|s_t(r)\right|. \tag{3}$$

Moreover, Δr_i denotes the amount of misalignment which we would like to estimate.

A cross-correlation function between two range profiles is defined as:

$$R_i(s)\cong\frac{\int e_t(r)e_{t-iT}(r+s)dr}{\left[\int e_t^2(r)dr\cdot\int e_{t-iT}^2(r)dr\right]^{1/2}}. \tag{4}$$

From the Schwartz inequality we can tell that $R_i(s)$ will be maximal at $s=\Delta r_i$ and then the amount of misalignment can be determined based on the peak location. It is observed from (4) that since the denominator is independent of $R_i(s)$, it can be dropped without affecting the peak location. Thus for digitized radar data, (4) is modified as:

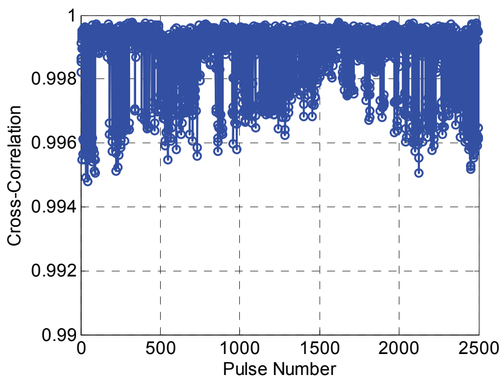
$$R_i(m)=\sum_n e_t(n)e_{t-iT}(n+m). \tag{5}$$

Consequently, for the current range profile $s_t(r)$, $s_{t-iT}(r)$ is selected to estimate the amount of the misalignment using (5). So we can obtain the estimation $\mathbf{\Delta\hat{r}}$

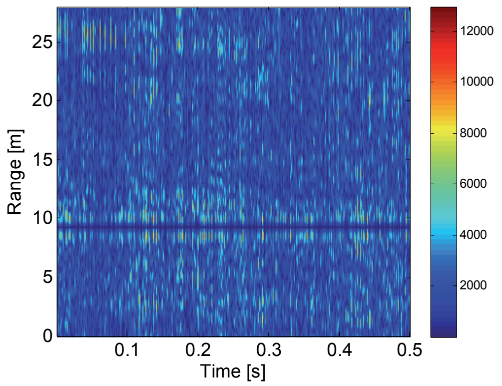
$$\mathbf{\Delta\hat{r}}=\left[\Delta\hat{r}_1,\Delta\hat{r}_2,\cdots,\Delta\hat{r}_K\right]. \tag{6}$$

At last, the amount of the misalignment should be

$$\Delta\hat{r}=\frac{1}{K}\sum_i\Delta\hat{r}_i. \tag{7}$$



a)



b)

Fig. 3. Range alignment. a) Cross-correlation between adjacent pulses. b) Result after clutter removal with RA-MTI.

After the range alignment, the cross-correlation between the adjacent pulses is much better, as presented in Fig. 3 a). EABS is then applied to this realigned time-range data. Fig. 3 b) is the result after clutter removal with RA-MTI. Compared with the result in Fig. 2 a), the residual clutter is suppressed greatly and the clutter power is about 19.9 dB lower.

3.2 EWCI

As mentioned above, except for the time-varying clutter, multipath propagation is the other key problem. RA-MTI is executed to only suppress the stationary clutter, but with plenty of multipath signal remaining. We refer to these as ghost trajectories since they obscure true target trajectory and lead to poor visual quality, making target detection particularly difficult.

After clutter suppression, the resulting signal will be made up of the direct echo and a number of multipath returns. For the sake of simplicity, assuming the transmitted signal is $s(t)$. Then the return corresponding to a specific range cell containing the target is given by:

$$r(t) = s(t-\tau_0) + \sum_{p=1}^{P} a_p s(t-\tau_p) \tag{8}$$

where τ_0 is the roundtrip delay between the radar and the target along the direct path. Moreover, a_p and τ_p are the propagation gain and roundtrip delay along the p-th path, respectively. P represents the total number of possible multipath components between the radar and the target. Note that the foliage environment with many random reflected components and without specifying the concrete geometry, the multipath effects are so complex that the nature of the multipath phenomenon should be considered to be random. Thus, the values of a_p, τ_p, and P are assumed to vary among different pulse echoes owing to the random multipath components.

Consequently, to reduce the multipath effects and to detect the target trajectory using HT robustly, the EWCI algorithm is put forward. Entropy is a kind of assessment index that can assess the stationary level for the same range bins along a sequence of pulses within one CPI. The entropy of the j-th range bin is defined by [17], [18] :

$$E_j = -\sum_i P_{i,j} \log P_{i,j} \quad i = 1,2,\cdots,I \quad j = 1,2,\cdots,J , \tag{9}$$

$$P_{i,j} = \frac{|x_{i,j}|}{\sum_i |x_{i,j}|} \tag{10}$$

where $|x_{i,j}|$ is the amplitude of the i-th pulse signal in the j-th range bin. I is the number of the pulses within each CPI and J is the number of the range bins in each pulse. It is stressed that the moving target should remain in the same range cell during the CPI period.

$E_j = \log I$ means that the amplitudes of the signals in the j-th range bin are relatively stationary and there may be a target in this range bin. Then the data information should be entirely accumulated. On the other hand, $E_j \to 0$ means the amplitudes of the signals in the j-th range bin are badly fluctuating and there may be the multipath clutter. The data information should be decreased after integration. Based on the entropy of every range bin, the coherent integration result within each CPI is defined by:

$$A_j = \sum_{i=1}^{I} \left(\frac{E_j}{\log I} \right)^{i-1} z_{i,j} \tag{11}$$

where $z_{i,j} = \mathrm{sort}(|x_{i,j}|, i)$ sorts $x_{i,j}$ in ascending order of amplitude along the pulses in sequence within each CPI. As (11) presented, it is important to take into account the weighting coefficients $(E_j / \log I)^{i-1}$ in the coherent integration. Using (11) the target data information will be entirely accumulated while the multipath data decreased. Thus the multipath effects will be mitigated remarkably.

3.3 HT

HT is a method for finding geometric objects such as lines, parametric curves, and shapes in images. However, because the human target was designed to travel the surveillance space with only a constant radial velocity in the foliage-penetration measurement, its trajectory in the time-range image appeared a straight line. Accordingly only the detection of a straight line is considered in this paper.

This line can be defined by the angle θ of its perpendicular to the origin and the distance ρ from the origin to the line along the perpendicular. HT then maps points in the time-range $(t-r)$ data space into curves in a Hough parameter $(\rho-\theta)$ space by:

$$\rho = r\cos\theta + t\sin\theta . \tag{12}$$

Based on HT, the points in the lines are all integrated in the Hough parameter space. At the same time, the value of the noise points and separated points is very small because of hardly integrated. Actually, HT enables one to do noncoherent integration from range cell to range cell. Consequently, the SCR is significantly improved and good for target detection.

After the detection of the target trajectory, the estimation of the radial velocity of the target can be evaluated as [19] :

$$\hat{v} = \frac{\delta R}{T_{CPI}} \tan \hat{\theta} \qquad (13)$$

where δR is the range resolution cell and $\hat{\theta}$ is the estimated value of the angle θ.

In conclusion, the main stages of the proposed approach are summarized in the flowchart of Fig. 4.

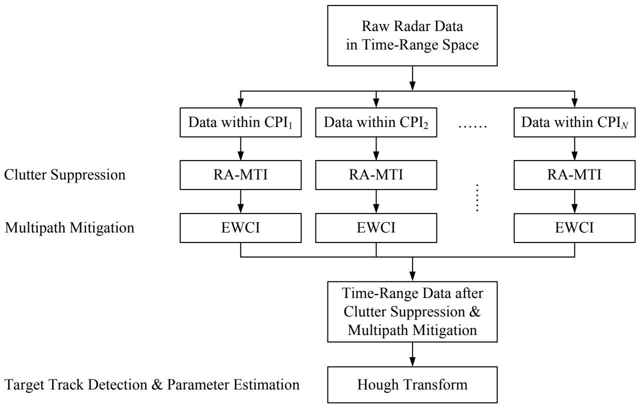


Fig. 4. Overview of the proposed approach.

4. Experimental Results

4.1 Measurement Setup

The foliage-penetration measurement effort began from April 2013 to May 2013. The measurements were taken in the foliage at National University of Defense Technology. The data used in this paper were measured on a sunny day with gentle breeze in May. The foliage is made up of both deciduous trees and bushes with a higher percentage of deciduous. The trees are spaced 4 m apart with trunk diameters in the range of 16-20 cm and up to 15 m tall. Besides, the thickness and height of the bushes are about 2.5 m and 3.5 m, respectively. Fig. 5 illustrates the foliage-penetration measurement environment.

For the measurement data acquisition, the bistatic LFMCW ground radar was placed inside the forest and in front of the bushes with the distance of 9.4 m. To reduce the antenna coupling, the transmit antenna was kept at 5.2 m distance away from the receive antenna.

The measurement was carried out by one camouflaged person behind the bushes walking straight with a constant radial velocity apart from the radar, which means that the line-of-sight (LOS) propagation path from the radar to the target is unavailable. The person was concealed and surrounded by the bushes and trunks in the forest, which are the main sources of clutter and multipath.

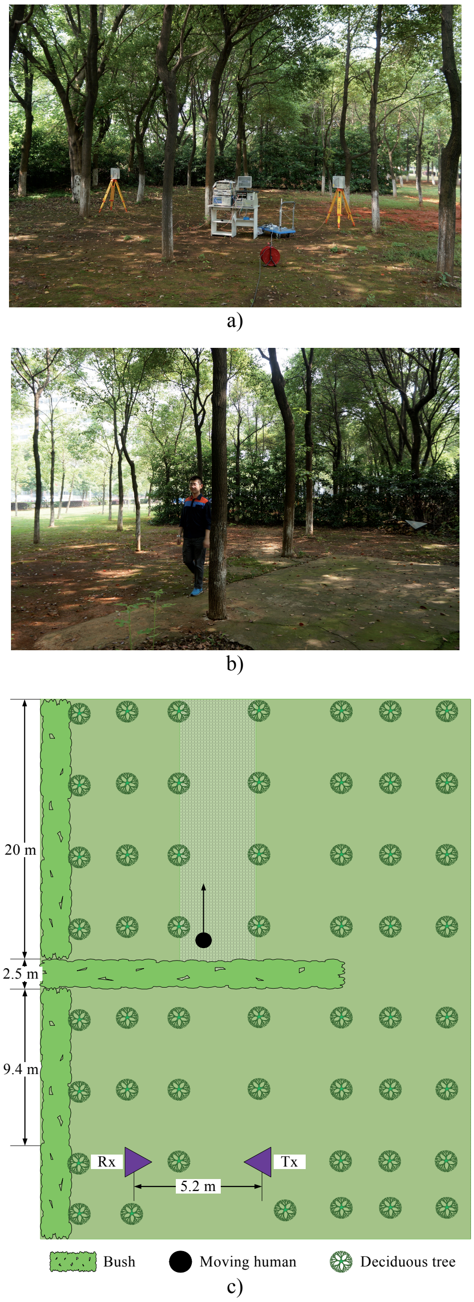


Fig. 5. Foliage-penetration environment of experimental data. a) Measurement environment. b) Moving human target detection measurement. c) Geometry of the foliage-penetration environment.

4.2 Results

The time-range image of the foliage-penetration environment is presented in Fig. 6 a). The resulting image is composed of the desired target track as well as several ghosting artifacts owing to multipath propagation. Particularly, the bushes clutter and the antenna coupling are so strong that the human signal and the multipath are masked and invisible. Clutter suppression result with RA-MTI is

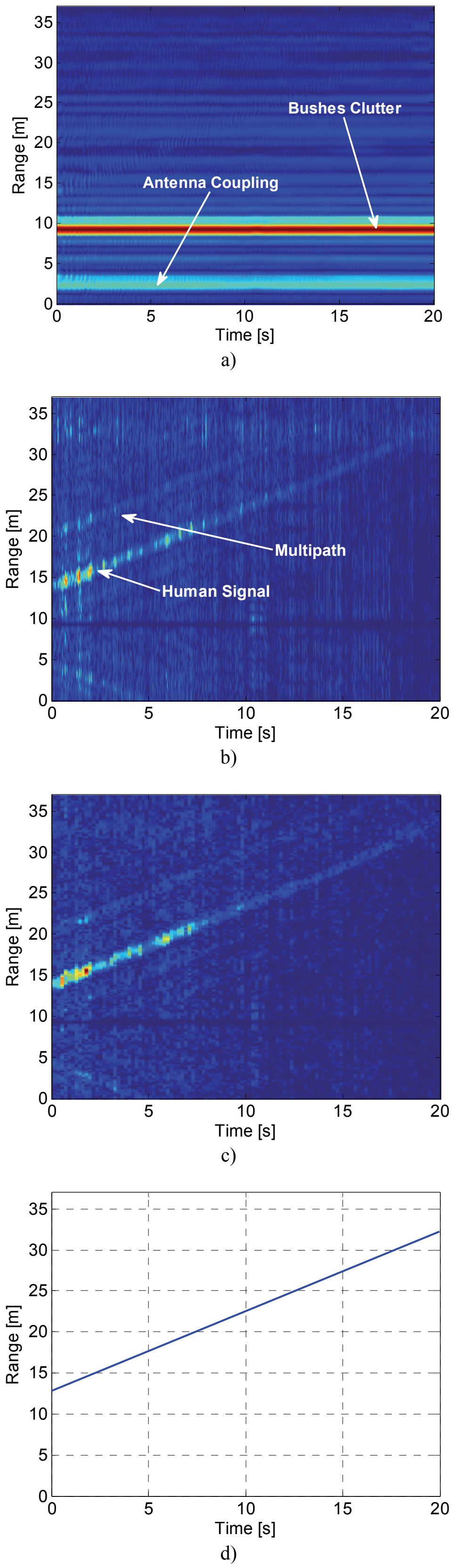


Fig. 6. Moving human target detection results in the foliage-penetration environment. a) Time-range image after range alignment. b) Clutter suppression result with RA-MTI. c) Multipath mitigation result with EWCI. d) Target track detection result with HT.

displayed in Fig. 6 b). As can be seen, the bushes clutter and the antenna coupling are greatly removed and the human target path is much clearer. As expected, however, there is also one strong dominant ghost path emerging because of the powerful multipath echoes, which seems to be another moving target. This kind of ghosting artifact will severely influence the target detection performance and increase the probability of false alarm. Fig. 6 c) depicts the result after EWCI. Compared with the result in Fig. 6 b), the energy of the multipath signal is reduced remarkably and the ghost path is almost invisible. On the other hand, it is interesting to see that with EWCI the residual clutter in the result of Fig. 6 b) is further suppressed efficiently. The reason is that the clutter caused by the leaves and the branches is not stationary and fluctuating over the CPI period, resulting in fairly low entropy.

As a result, after RA-MTI and EWCI the time-range image has better visual quality. The human target can be distinguished more easily. At last, based on HT, the target trajectory is detected robustly and accurately, as presented in Fig. 6 d). At the same time, the radial velocity of the human target is estimated to be 0.97 m/s.

5. Conclusion

Moving targets are usually detected using a frequency-domain approach, i.e., Doppler processing, as they exhibit a Doppler shift on the received echoes. It has been shown that higher working frequency is more sensitive to small motions than lower working frequency. However, in order to detect a moving target in foliage-penetration environment, the upper frequency of the radar system has to be limited because the energy attenuation through the bushes and leaves increases with higher frequency. On the other hand, the frequency-domain motion detection approach rarely works effectively due to the low working frequency, penetration loss, and small motions. Consequently the time-domain approach based on HT has been considered in this paper.

Unfortunately, unlike indoor or urban environment, in foliage-penetration motion detection application there are some effects that HT is not able to face up to so efficiently. Among them, the multipath effects and time-varying clutter must be highlighted, since they tend to severely influence the target detection performance. That is the reason why it is needed to develop new approaches aimed at suppressing and mitigating this undesired phenomenon. Based on this main motivation, an innovative method is proposed, which consists in three distinct parts.

The first part is focused on the suppression of the time-varying clutter and the instable antenna coupling. In order to do this, we presented a clutter suppression technique based on range alignment. Compared with the performance without range alignment, the clutter is suppressed greatly and the clutter power is about 19.9 dB lower.

Once the clutter is removed effectively, the moving target track as well as the multipath effects can be observed in the time-range image. Then the second part is addressed to mitigate the multipath effects. Based on the fact that the entropy of the target echoes is higher than that of the multipath echoes for the same range bins along a sequence of pulses within one CPI, the target data information should be entirely accumulated while the multipath data not. In consequence, with EWCI the energy of the multipath signal is reduced remarkably and the residual clutter is further suppressed efficiently.

The third part is HT. Based on the time-range image with high visual quality, the target trajectory is detected robustly and the radial velocity is estimated accurately.

In the end, the paper addresses the performance of the proposed algorithm by using real data acquired by the LFMCW radar system. In this context, the experimental results have been shown that the method is able to effectively resist the complex multipath propagation and clutter and to obtain robust and reliable moving human target detection performance.

Acknowledgements

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