Compensation of Wall Effect for Through Wall Tracking of Moving Targets

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Abstract. *Through wall tracking of moving targets is of interest for rescue, surveillance and security operations. A useful method applies an ultra-wideband radar approach for this purpose since electromagnetic waves in the lower GHz-range penetrate most common building materials, such as bricks, wood, dry walls, concrete and reinforced concrete. However in consequence of a wall effect, estimated target track can be considerably spatially shifted and distorted. In the paper, two different methods for compensation of this effect are described. Their effectiveness is evaluated at synthetic as well as real radar data. Obtained results prove that proposed novel approach reach the best outcomes.*

Keywords

Direct localization method, moving targets, through wall tracking, UWB radar, wall effect.

1. Introduction

There are a number of situations where the entering of a room or a building is considered hazardous and it is desired to inspect its interior from the outside through the walls. Examples include tracking of people in dangerous environments (for policemen, firemen), through rubble localization following an emergency (e.g. earthquake or explosion) and so on. In these cases, ultra wideband (UWB) radars which operate in a lower GHz-range base-band (up to 5 GHz) can provide significant help by detecting and localizing the people [1], [2].

In the case of target localization and tracking, target coordinates as the function of time are usually evaluated by using time of arrival (TOA) corresponding to target to be tracked as well as electromagnetic wave propagation velocity along the line transmitting antenna - target - receiving antenna [3], [4]. In many applications of target tracking, it can be assumed that the environment, through which the electromagnetic waves emitted by the radar are radiated, is homogenous (usually air). This is not true for through wall moving target localization because the wall is medium with different permittivity and permeability than that of the air [5]. Therefore, the electromagnetic wave propagation velocities in the air and wall are different. Besides the mentioned quantities, wall thickness has also strong influence on target location precision. This effect, which is sometimes referred to as wall effect, displaces targets outside their true positions, if the target localization is based on frequently used simplified assumption for through wall scenario that the electromagnetic wave propagation velocity is constant and equal to velocity of light. With regard to these facts, the precision of through wall target location can be improved if additional information such as permittivity, permeability and thickness of the wall (so-called wall parameters) are used for target position computation. This is done through the estimation of time difference, referred to as delay time, by which through wall TOA are corrected [6], [7].

In the literature, several methods for exact or approximative computation of the above mentioned delay times can be found, e.g. in [8], [9], [10]. However, most of them are connected with radar imaging techniques, when the target locations are not calculated analytically but targets are seen as radar blobs in gradually generated radar images [11]. For these techniques it is possible to compute exactly the delay time caused by the wall for the reason that for every pixel of the radar image (which corresponds to spatial position in scanned area) we can uniquely determine TOA as well as the distance which the signal propagates through the wall [12]. Inverse assignment, that is required for conventional localization algorithms, is not unique, i.e. a whole set of points belongs to known TOA and these points differ with regard to the delay time under consideration. As a result of this, effect of the wall can be compensated only by approximative methods in the case of direct localization technique.

In this paper two methods of that kind (so-called wall effect compensation methods) referred to as target trace correction of the 1st and 2nd kind are presented. The target trace correction of the 1st kind is based on a simplified assumption that the electromagnetic waves emitted and received by radar propagate always in the perpendicular direction with regard to wall plane. The target trace correction of the 2nd kind does not use this simplified assumption, i.e. for different positions of the target different delay time can be evaluated. The solution of this task is based on the novel approach of delay time estimation. Here, delay time is obtained as a time difference between TOA obtained by UWB radar signal processing and TOA corresponding to the same target position under assumption that no wall is located between the radar and the target. The effectiveness of the discussed methods of the wall compensation effect is evaluated using synthetic as well as real UWB radar signals.

2. Wall Effect and Its Consequences Demonstrated on Synthetic Data

In order to compare results of synthetic and real radar data, in both cases the same scenario is considered: a person is walking along the perimeter of a rectangular room with size 3.9 m ×2.6 m. The walls are concrete with thickness of 0.5 m, relative permittivity $\varepsilon_r = 5$ and relative permeability $\mu_r = 1$. UWB radar system includes one transmitting antenna Tx and two receiving antennas Rx_1 and Rx_2. Their configuration is depicted in the scanned area scheme in Fig. 1.

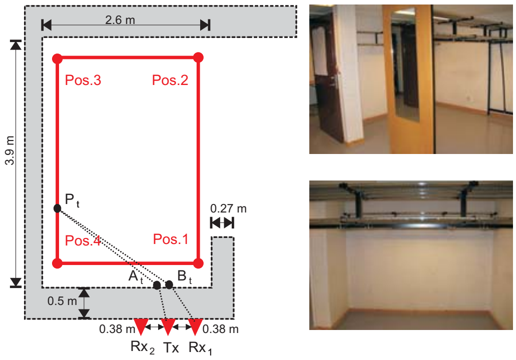

Fig. 1. A scheme and photos of scanned area for examined measurement scenario with illustration of distances required for $TOA_{TW,1}(P_t)$ computation.

Let us assume ideal conditions for simulations, i.e. a point target with uniform velocity and no additional sources of errors. Simulated TOA pertaining to rectangular trajectory were computed for scenario with and without a wall. TOA as a function of time form for both receivers continuous curves called target traces, are depicted in Fig. 2, where horizontal axis represents time observation t and vertical axis corresponds to TOA of signal transmitted by Tx, reflected by target at position P_t and received by antenna Rx_i, for $i = 1, 2$.

For scenario without wall, TOA are calculated as

$$\mathrm{TOA}_{noW,i}(P_t) = \frac{dist(Tx, P_t) + dist(P_t, Rx_i)}{c} \tag{1}$$

where $dist(X,Y)$ represents distance between points X,Y and c is the velocity of light. In case of through wall scenario, the computation is more complex:

$$\mathrm{TOA}_{TW,i}(P_t) = \frac{dist(Tx, A_t) + dist(B_t, Rx_i)}{v_w} + \\ + \frac{dist(A_t, P_t) + dist(P_t, B_t)}{c} \tag{2}$$

where A_t and B_t are refraction points at border line wall-air and v_w is velocity in the wall (Fig. 1). It depends on the relative permittivity and permeability of the wall and for the concrete wall under consideration yields

$$v_w = \frac{c}{\sqrt{\varepsilon_r \cdot \mu_r}} = \frac{3.10^8}{\sqrt{5 \cdot 1}} \doteq 1.34 \cdot 10^8 m/s\ . \tag{3}$$

The calculation of distances inside the wall, $d_w = dist(Tx, A_t) + dist(B_t, Rx_i)$, is a challenging task particularly in the case when there is some separation between the antennas and the wall and a three layer model (air-wall-air) has to be considered. Because the coordinates of refraction points are unknown and cannot be computed directly, some minimization method has to be used. The solution of this task for the two layer model is well known from an area of ground penetrating radar and is described e.g in [7]. However, the task for three layer problem is more complex. We have proposed its effective solution in [12].

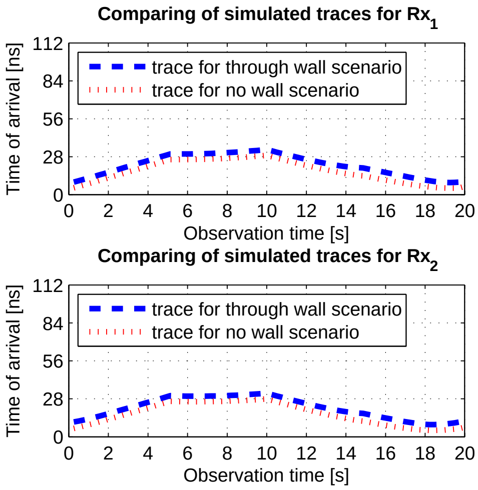

Fig. 2. Ideal simulated traces for through wall and no wall scenarios.

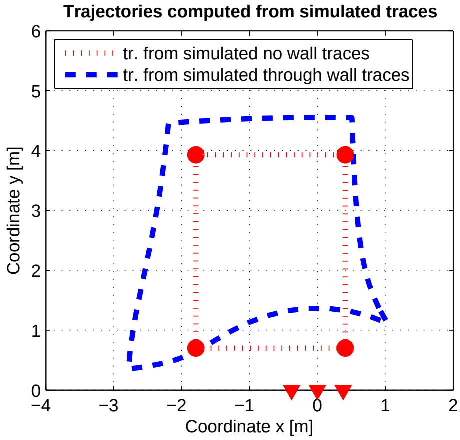

Fig. 3. Consequence of wall effect on the estimated trajectory.

As mentioned above, TOA are recomputed during the phase of target localization to distances by utilization of velocity of light. In such a way, the true rectangular trajectory can be achieved by combination of TOA$_{noW}$ from both receivers, but in case of through wall data, TOA$_{TW}$, the resulting trajectory is shifted and distorted (Fig. 3).

3. Wall Effect Compensation Methods

The first presented approach belongs to the most frequently used wall compesation methods and is described in [8], for instance. The second one introduces novel approach based on knowledge of the delay time for radar images.

3.1 Target Trace Correction of the 1st Kind

The easiest way to reduce the effect of the wall is to assume a simplified model in which the signal propagates through the wall always perpendicularly. The delay time through the wall compared to free space propagation is determined by

$$\tau_{delay} = \frac{d_w}{v_w} - \frac{d_w}{c} = \frac{\sqrt{\varepsilon_r} d_w}{c} - \frac{d_w}{c} = \frac{d_w}{c}\left(\sqrt{\varepsilon_r} - 1\right) . \qquad (4)$$

For the simplified model under consideration, the distance inside the wall d_w gets value $2 \cdot 0.5$ m, which corresponds to thickness of wall overflown in both directions. Target traces modified by $\tau_{delay} = \frac{2 \cdot 0.5}{3 \cdot 10^8}(\sqrt{5} - 1) \doteq 4.12$ ns are depicted in Fig. 4 as green dash-dot curves.

Distances $d_{i,t}$ between Tx, P_t and Rx_i for $i = 1,2$, which allow to estimate target location in the given observation time instant t, are computed now as

$$d_{i,t} = [TOA_{TW,i}(P_t) - \tau_{delay}] \cdot c \, . \qquad (5)$$

The resulting trajectory is shown in Fig. 5 with the same color and line type. As can be seen, the obtained location estimations much better correspond with the true trajectory, but still some distortion is visible there. The reason is that the delay time is not constant, but it changes depending on the target position relative to the antenna array.

3.2 Target Trace Correction of the 2nd Kind

The aforesaid defection can be solved by the following proposed method. It computes the delay time for every time instant of observation particularly. At first we need to determine the spatial grid in which the individual points will be examined, e.g. for the coordinate system used in the presented scenario the grid is from -4 m to 2 m in the x direction and from 0 m to 6 m in the y direction with step of 0.025 m in both directions.

For these points we know to calculate TOA$_{noW,i}$ and TOA$_{TW,i}$ according (1) and (2), respectively for receiving antennas Rx_i, $i = 1,2$. The next step rests in finding all points P from matrix of TOA$_{TW,i}$ for which TOA$_{TW,i}(P) =$ TOA$_{TW,i}(P_t)$, i.e. it is equal to a known value of through wall TOA for the given receiver i and time observation t. Since we work with bistatic radar (Tx and Rx_i are not identical), the set of searched points forms roughly an ellipse around Tx and the corresponding Rx_i. If on ellipse E_1 belonging to Rx_1 and on ellipse E_2 belonging to Rx_2 it is able to find the same points (i.e. "intersections" I_t), the delay time caused by the wall is given by

$$\tau_{delay}(i,t) = \underset{P \in I_t}{mean}[\mathrm{TOA}_{TW,i}(P) - \mathrm{TOA}_{noW,i}(P)] \, . \qquad (6)$$

The mean value of the difference is based on the consideration that with a small step of the spatial grid more points in the vicinity can have the same value of a given TOA. If it is not possible to find such points, the delay time is estimated as

$$\tau_{delay}(i,t) = \underset{P \in E_i}{mean}[TOA_{TW,i}(P) - TOA_{noW,i}(P)]. \qquad (7)$$

In such way not only the time value by which it is needed to decrease through wall TOA is obtained, but also primary estimation of searched target locations are available. These can advantageously be used e.g. as initialization values for more complex iterative localization algorithms [3].

For ideal synthetic radar data, the proposed method almost totally removes the effect of the wall, i.e. by localization the true rectangular trajectory is reached (black solid curves in Fig. 4 and Fig. 5).

4. Method Performance Evaluation on Real Radar Data

The real signals were acquired by M-sequence UWB radar system [13] with 4.5 GHz internal clock and measurement speed 13.44 impulse responses per second. The double-ridged horn antennas were used as the transmitter Tx and receivers Rx_1 and Rx_2, respectively. During measurement, all antennas were placed in 1.25 m elevation above the floor and there was no separation between the antennas and the wall (Fig. 1).

Target traces were obtained based on raw radar signal processing by methods of preprocessing, background subtraction, detection and trace estimation described in [14] and shown in Fig. 6. The aim of the preprocessing was to synchronize the first elementary impulse of M-sequence with the spatial position of the transmitting antenna and it was done by utilization of a cross-talk signal. An exponential averaging, that is ranked among popular and often used methods of background subtraction, has rejected the stationary and correlated clutter and in this way the signal to noise ratio has been improved. The solution of target detection task is based on statistical theory that allows to reach decision whether a signal scattered from the target is absent or present in the examined radar data. In the case of through wall target detection by UWB radar, a constant false alarm rate (CFAR) detector has been able to provide good and robust results. Within the phase of trace estimation, a substitution of the distributed target with a proper simple target has been realized. It has enabled to utilize direct method for target localization in the next phase of radar signal processing. The applied method of trace estimation was introduced in [14].

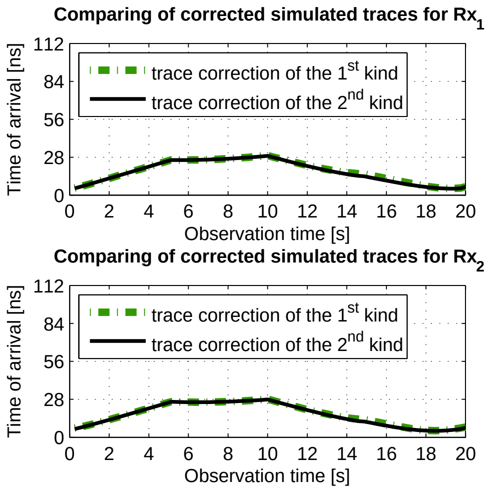

Fig. 4. Compensation of the wall effect by correction of traces.

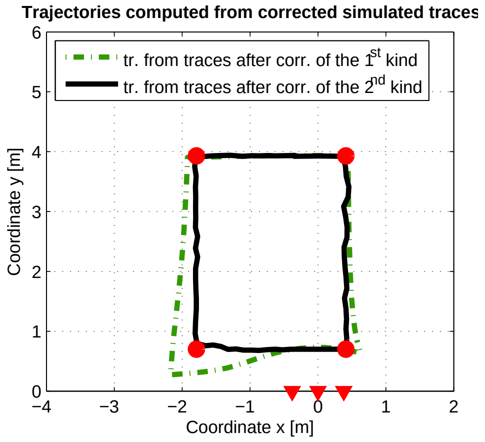

Fig. 5. Resulting trajectories after trace correction.

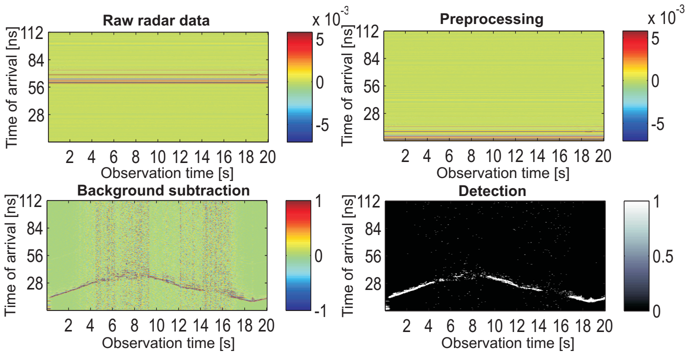

Fig. 6. Phases of radar signal processing performed at radar data from channel Rx_1.

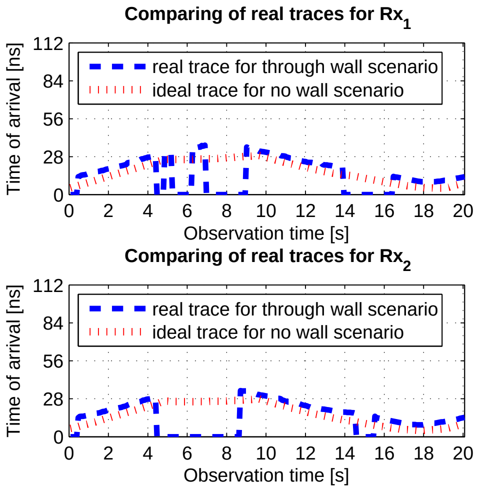

Fig. 7. Traces obtained from real through wall radar data.

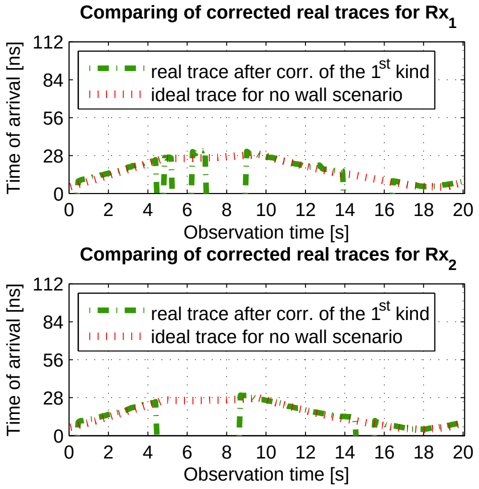

Fig. 8. Real through wall traces after correction of the 1^{st} kind.

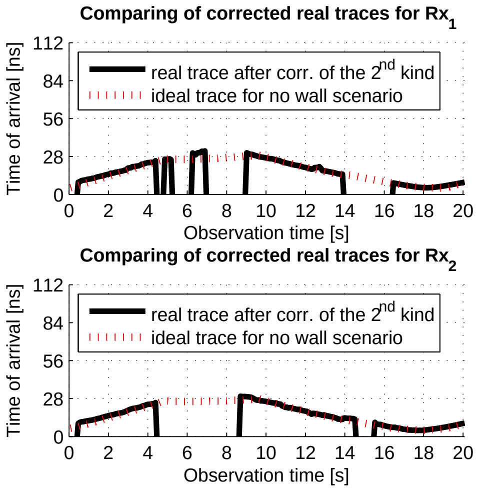

Fig. 9. Real through wall traces after correction of the 2^{nd} kind.

The resulting target traces are depicted in Fig. 7 by blue dashed curve, red dotted curve represents ideal trace for no wall scenario. As can be seen from this figure, through wall traces are now acquired not only with time delay caused by the wall, but also the problem of missing data is visible. This is a consequence of more noisy signals in the time instants when moving target was changing direction. The traces in Fig. 8 and Fig. 9 represent real target traces shifted by the delay time computed by two kinds of methods for wall effect compensation described in the previous section.

A comparison of average differences between ideal no wall traces and traces for through wall scenario, respectively, for their corrected versions, is made in Tab. 1 for synthetic radar data and in Tab. 2 for real radar data. In both data sets the realized corrections markedly decreased the average differences between traces. The proposed method for compensation of the wall effect (i.e. trace correction of the 2^{nd} kind) reached the best results in all examined cases.

Trace in noW Scenario compared with	Average diff. for Rx_1	Average diff. for Rx_2
trace in TW Scenario	4.57 ns	4.51 ns
trace after Corr.1	0.45 ns	0.39 ns
trace after Corr.2	0.02 ns	0.02 ns

Tab. 1. Average difference between traces for synthetic radar data.

Trace in noW Scenario compared with	Average diff. for Rx_1	Average diff. for Rx_2
trace in TW Scenario	5.30 ns	5.13 ns
trace after Corr.1	1.29 ns	1.18 ns
trace after Corr.2	0.97 ns	0.94 ns

Tab. 2. Average difference between traces for real radar data.

It is usual that trajectories obtained by processing of real radar data have zig-zag form and need additional smoothing by means of tracking algorithms. In the presented processing, we have used Kalman filter which enables also completion of missing data through the use of predictions [15]. The resulting track calculated from real uncorrected data is depicted in Fig. 10 by blue thick line, below the original trajectory is drawn with the same color and thinner dotted line. In a similar manner the trajectories and tracks from corrected real traces are shown in Fig. 11 and Fig. 12.

Comparison of average localization errors for synthetic as well as for real radar data is made in Tab. 3. Trace correction of the 1^{st} kind decreased the quantity under consideration by almost 75 % for synthetic data and by 60 % for real data in comparison with average localization error for uncorrected trajectory. Trace correction of the 2^{nd} kind removed average localization error almost totally in the case of synthetic data and for real data this error was decreased by almost 80 %.

5. Conclusion

In this paper, we have dealt with the problem of the wall effect presented at through wall tracking of moving target by

Trajectory from traces	Average loc. error for synth. data	Average loc. error for real data
for TW Scenario	0.73 m	1.04 m
after Corr.1	0.18 m	0.39 m
after Corr.2	0.02 m	0.16 m

Tab. 3. Average localization errors for synthetic and real radar

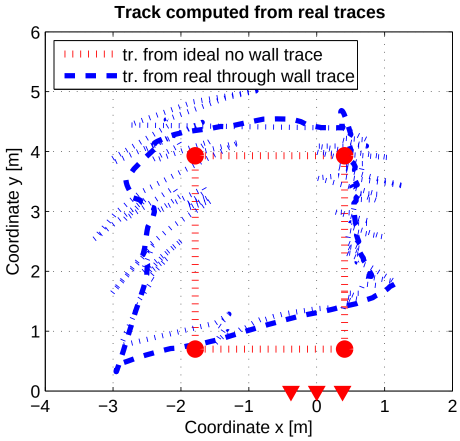

Fig. 10. Trajectory and track obtained from real through wall traces.

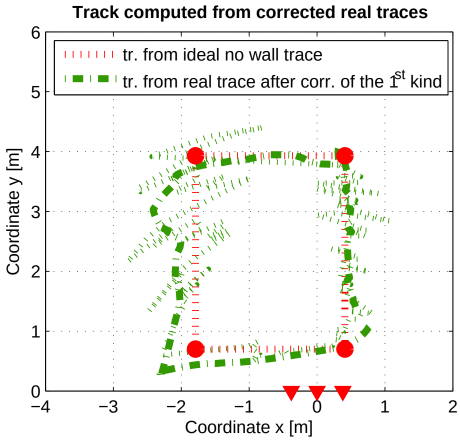

Fig. 11. Resultant trajectory and track after trace correction of the 1^{st} kind.

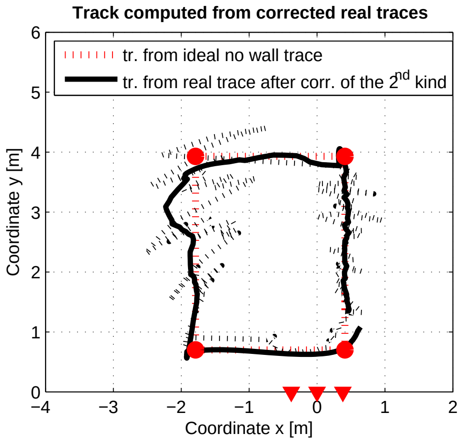

Fig. 12. Resultant trajectory and track after trace correction of the 2^{nd} kind

using M-sequence UWB radar. Firstly, by using synthetic radar signals for through wall scenario, the wall effect has been outlined. It has been shown that if the wall parameters are not taken into account, the target position can be determined with an error. It follows from the wall effect genesis, that the less ratio of the trajectory of transmitting antenna-target-receiving antenna to wall thickness multiplied by $\sqrt{\varepsilon_r}$, the greater localization error of target. Therefore e.g., if a target is located close behind the wall, a high localization error can be expected.

In order to improve the target position estimation, two methods of wall effect compensation referred to as target trace correction of the 1st and 2nd kind have been described in this paper. While the trace correction of the 1st kind belongs to well-known conventional wall effect compensation methods, the trace correction of the 2nd kind is a new method introduced in this paper. The performance of both methods has been analyzed by synthetic and real UWB radar signal processing for through wall scenario. The obtained results have shown that the trace correction of the 2nd kind can clearly overcome the trace correction of the 1st kind or target localization not taking into account any wall effect compensation method. This performance property of the trace correction of the 2nd kind can be reached at the cost of its higher computational complexity in comparison with other outlined approach.

As follows from the described wall effect compensation methods, the wall parameters (permittivity and permiability of wall material, wall thickness) should be known in advance. From our point of view, this is the most important limitation of the method application. However, this restriction can be overcome by using a suitable method of wall parameter estimation based on measurement by the same UWB radar, which is applied for target tracking. The development of a wall parameter estimation method of that kind is the subject of our actual research.

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