Efficient Method of TOA Estimation for Through Wall Imaging by UWB Radar

Michal Aftanas, Jana Rovňáková, Miloš Drutarovský, Dušan Kocur
Technical University of Košice, Dept. of Electronics and Multimedia Communications, 041 20 Košice, Slovak Republic
Email: {Michal.Aftanas, Jana.Rovnakova, Milos.Drutarovsky, Dusan.Kocur}@tuke.sk

Abstract—**Precise Time Of Arrival (TOA) estimation is a basic step of standard migration methods for object imaging from SAR measurements. In this paper, an effective computation method of the TOA for through wall model of object recognition is presented. The conventional method that uses constant velocity model produces errors in object shape and position estimations. Computation of the TOA (corresponding to true flight distance) for three layer model requires the complex minimization algorithm. Proposed method transforms three layer (air-wall-air) model to equivalent two layer (air-wall) model with lower computation complexity. It uses iterative solution of well defined minimization problem. Moreover, conveniently selected initial conditions of iteration process can further decrease computational complexity of the method. The proposed method provides more precise TOA estimation than conventional one and is less complex than three layer methods. Therefore, it is suitable for implementation on realtime hardware. The method performance is demonstrated by processing of real 2-dimensional SAR data acquired by through wall M-sequence UWB radar system.**

I. INTRODUCTION

Through the wall surveillance is a difficult but important problem because of its perspective wide utilization in such fields as through the wall imaging during security operations: e.g. to locate hostages or terrorists and weapons behind walls, people trapped in a building during fire, persons buried under fallen walls after earthquake, border controls for the detection of illegal immigrants, cigarettes in trucks, etc. The second wide area of utilization is detection, localization and tracking of the moving objects behind the wall. These technologies can save many lives during rescue operations because rescue work will be more safe and localization of the victims will be faster.

TOA is commonly reffered to the flight time of wave between transmit antenna, target, and receive antenna. To simplify the notation we will understand TOA as the flight time of wave between transmit or receive antenna and target. TOA correspond to the summation of distances between antenna and target divided by appropriate velocities in air and wall (2). The conventional method for computing TOA with constant velocity model, which does not consider different velocity in the wall and air, introduces an error in estimation of target shape and position. Therefore, in praxis more or less accurate methods based on ray theory and Snell's law are used in algorithms of TOA computation to compensate the presence of the wall [1]–[4]. It is well known that imprecise wall parameter estimation causes target position error [5]. The TOA for multilayer model cannot be computed directly, some numerical minimization method [6], has to be chosen. In general, the optimization techniques use TOA as an error function, and a vector of independent variables over which the error is minimized [7]. The number of variables is equal to the number of layers. This is a very time consuming process, but for small number of layers (especially for air-wall-air structure) a few improvements that rapidly reduce the computation complexity can be done.

II. PROPERTIES OF THE WAVES PENETRATING THROUGH THE WALL

Through the wall imaging requires wave penetrating through the specific building materials such as concrete blocks, clay bricks, drywall, asphalt shingles, fiberglass insulation etc. The transmitted signal is attenuated several times due to free space loss, scattering from air-wall interface, loss in the wall, and the scattering from objects. The propagation loss inside the wall is a function of the frequency [8]. Electromagnetic waves are able to penetrate through the concrete walls without massive attenuation up to approximately 3 - 4 GHz [9]. With regard to this fact, M-sequence UWB radar technology is very attractive for through wall object imaging.

When the wave arrives to the wall under a certain angle, the wave in the wall will continue its propagation but with changed direction. This holds in the case when the permittivity of the wall differs from the permittivity of the layer in front of the wall. Even more, when the wave is leaving the wall, it changes its direction once more. When the permittivity of the wall is greater than the permittivity of the air, the wave velocity in the wall will be lower than in the air. In the case when the relative permittivity of the air ε_{r_A} is equal to 1, the wave velocity in the air is equal to the velocity of the light c. The velocity in the wall is given by:

$$v_W = \frac{c}{\sqrt{\varepsilon_{r\_W}}} \qquad (1)$$

where ε_{r_W} is relative permittivity of the wall.

In the case when ϵ_{A1} of the air in front of wall and ϵ_{A2} of the air behind the wall are the same, $\epsilon_A = \epsilon_{A1} = \epsilon_{A2}$, the incidence angle of the incoming wave is the same as the angle of the outgoing wave which is leaving the wall, so the wave behind the wall has the same direction as that in front of the wall. This condition is fulfilled only for homogeneous wall or if the wall consists from an arbitrary numbers of homogeneous layers in parallel to the wall.

This paper is focused on computation of the true TOA between antenna and target, with a wall in between them. The losses in the wall are not considered.

III. TRUE TOA BETWEEN ANTENNA AND TARGET

To estimate the correct position of the objects behind the wall, the exact TOA between the antenna and the object has to be known. To compute this time, the model that is shown in Fig. 1 is used.

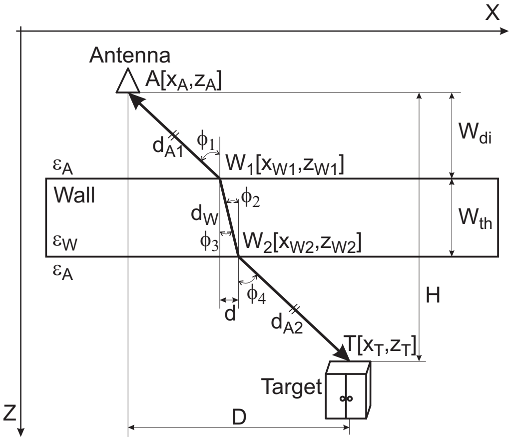

Fig. 1. True flight distance model in through the wall scenario.

There are several assumptions: the wall is homogeneous with constant permittivity and constant thickness; the relative permittivity of the air in front of the wall and behind it is the same and equals to one; the coordinations of the antenna $A[x_A, z_A]$ and the target $T[x_T, z_T]$, the permittivity of the air ϵ_A and wall ϵ_W, the thickness of the wall W_{th} and distance of the wall from antenna in Z direction W_{di} have to be known. Because the material inside the wall is homogeneous, the angles $\phi_1 = \phi_4$ and $\phi_2 = \phi_3$.

The true flight distance between antenna and target is not equal to straight distance between them $|AT|$. It has to be computed as summation of distances $d_{tot} = d_{A1} + d_W + d_{A2}$. Because the coordinates of W_1 and W_2 (Fig. 1) are unknown and cannot be computed directly, some minimization method has to be used. Optimization procedures are based on the principle of minimization of the travel time. For example the travel path must be such that the travel time between two arbitrary points is minimal [7]. Ryohei Tanaka in [10] introduced a method how to compute true TOA for 2 layers model (air-ground) used for ground penetrating model. Four roots are computed from derivation of the TOA equaled to zero. Then, the right one is chosen and the true TOA is computed. This works well for 2 layers model. For 3 layers model (air-wall-air) we introduce one simple trick which enables to simplify all the computations.

The distance between the antenna and the wall in Z direction does not play any role in the TOA (Fig. 2). When distance between antenna and wall changes from W_{di1} to W_{di2}, the true flight distance between antenna and target will not be changed.

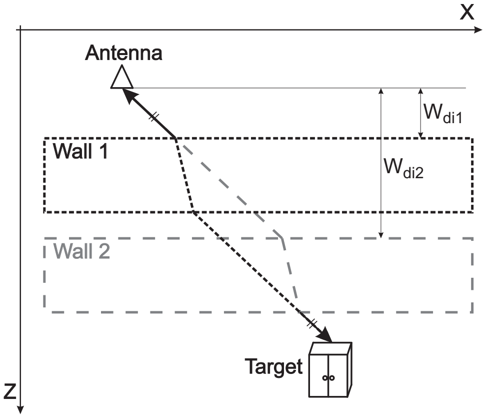

Fig. 2. Total flight distance does not depend on distance between antenna and wall.

The only one condition has to be fulfilled, the whole wall has to be between antenna and target. Now, all computations can be done with assumption that the rear side of the wall is at the target position and the 2 layer model (air - wall) can be used. With this simple trick we do not need to compute minimization process for 3 layers model, and it leads to much faster computation.

The true TOA can be computed like summation of both times, the time of flight in the air and the time of flight in the wall:

$$TOA(d) = \frac{d_A}{c} + \frac{d_W}{v_W} \tag{2}$$

where $d_A = d_{A1} + d_{A2}$. The distance d_{tot} is computed as:

$$\begin{gathered} d_{tot} = d_A + d_W \\ d_A = \sqrt{(H - W_{th})^2 + (D - d)^2},\ d_W = \sqrt{W_{th}^2 + d^2} \end{gathered} \tag{3}$$

After substituting d_A and d_W from (3) to the (2) only d will be unknown, D, H and W_{th} are known for all pixels of computed image. The minimization process is computed by derivation:

$$\frac{\boldsymbol{d}TOA(d)}{\boldsymbol{d}d} = 0 \tag{4}$$

After several simple mathematical operations the fourth order polynomial equation is obtained:

$$co_1 d^4 + co_2 d^3 + co_3 d^2 + co_4 d + co_5 = 0 \tag{5}$$

where

$$\begin{aligned} co_1 &= c^2 - v_W^2, & co_2 &= 2D\left(v_W^2 - c^2\right) \\ co_3 &= D^2\left(c^2 - v_W^2\right) + c^2\left(H - W_{th}\right)^2 - v_W^2 W_{th}^2 \\ co_4 &= 2 v_W^2 W_{th}^2 D, & co_5 &= -v_W^2 W_{th}^2 D^2 \end{aligned} \tag{6}$$

The analytical solution of (5) even with Ferraris or Galois method requires huge number of divisions and square root operations. Therefore, we have chosen Newton-Horner iteration method [11], [12] for root computation because of its low computational cost. Two of roots are complex conjugate, one is real but negative and the fourth, the sought one, is real and positive. A few simplifications can be used now. All four roots do not have to be computed. Because the required root can be estimated from initial value quite well, only this one root is computed. This root represents the examined value of d, therefore it is restricted to the interval $d \in < 0, D >$. In praxis the limitation of d can be much more narrower. There are many possibilities how to estimate the initial values of d very close to the right one, so only a few iterations have to be done to obtain correct d with sufficient precision, but this is out of scope of this paper.

The iteration algorithm requires only a few Multiply And Accumulate (MAC) operations and one division. The proposed algorithm for true TOA computation do not require sine or cosine computation and the whole algorithm can be implemented on realtime hardware with relatively small computational requirements. The conventional method computes the TOA as:

$$TOA = \sqrt{\left(x_T - x_A\right)^2 + \left(z_T - z_A\right)^2}/c \tag{7}$$

It requires 5 MAC and 1 square root operation. In proposed algorithm the co_i, d and TOA are computed from (6), (8) and (2), respectively. It requires 219 MAC operations, 2 square roots and 20 divisions for 20 iterations. The Newton-Horner iteration algorithm can be described as follows:

$$d_{n+1} = d_n - \frac{\sum\limits_{i=1}^{5} c_i d_n^{5-i}}{\sum\limits_{j=1}^{4} \left(\sum\limits_{k=1}^{j} c_k d_n^{j-k} \right) d_n^{4-j}}, \; \begin{array}{l} n = 1, 2, ..., I \\ d_1 = d_{initial} \end{array} \tag{8}$$

where I is number of iterations. After 20 iterations the result has higher accuracy than is required in praxis for standard applications, even after 10 iterations the results are sufficient. Computation of the TOA by the proposed method is much more time consuming process than by the conventional method, but it is still very fast process comparing to the three layer model with different permittivity in each layer. TOA can be expressed by the one unknown variable also for three layer model, but it is very complex relation and after derivation the very high order polynomial is obtained. Therefore, the simple numerical method for root computation is very time consuming and the critical points have to be investigated with the second order derivation.

With this proposed algorithm the TOA of targets behind and inside the wall can be computed. For targets in front of the wall, the conventional geometrical approach can be used. For targets inside the wall, only the thickness of the wall has to be changed and the same algorithm as for the targets behind the wall can be used. Therefore it is possible to use this approach for correct imaging of the targets behind the wall as well as for the wall itself.

This algorithm can be used for computation of TOA between transmitter and target as well as between target and receiver for both monostatic and bistatic cases. It is interesting that from d the true flight distance between antenna and target from (3) can be computed, although the coordinates of W_1 and W_2 stay unknown.

IV. SIMULATIONS AND EXPERIMENTAL RESULTS

The true TOA can be computed for static radar when the targets are moving (detection of moving people behind the wall) as well as for static objects and moving antennas (SAR imaging). We tested this algorithm on simulated and measured data. The simulation results are almost the same as the ideal ones, the error depends only on the number of iterations. The influence of the wall on imaging results is illustrated on two experiments. For testing of the proposed algorithm the 2-dimensional SAR measurements were chosen. The measurements were done with the M-sequence UWB radar system [13]–[15]. Bistatic model with the double-ridged horn antennas was used. For bistatic system the d_{tot} has to be computed twice, for transmitter-target flight distance and for target-receiver flight distance $d_{tot\_bist} = d_{tot\_TX2T} + d_{tot\_T2RX}$. Before SAR imaging was applied, several preprocessing steps were undertaken: time zero estimation, crosstalk removing, oversampling in time domain (TOA direction) and data deconvolution with impulse response of the whole system (including the antennas) [16]. In order to transform time domain into the depth domain, where the depth means the coordination from antenna to the target direction (Z direction), the simple SAR imaging in time domain was applied [16]. It is a migration with simple geometrical approach often also called back projection [17] or diffraction summation [18] and it does not take into account wave equation.

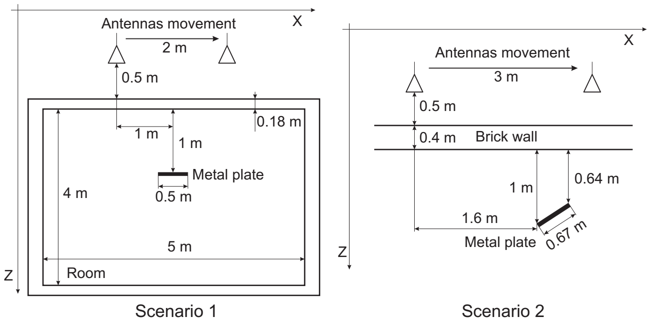

Fig. 3. SAR measurement, scenario 1 (left), scenario 2 (right).

A. Scenario 1

The measurement room was approximately 4 m × 5 m large, with the wall thickness about 0.2 m. The wall was made from brick with relative permittivity approximately $\epsilon_{r\_W} = 4$. Distance between the centers of antennas was 0.45 m vertically. The antenna system was moved in parallel to the wall along 2 m at distance 0.5 m from the wall. The object was placed 1 m behind the wall inside the room (Fig. 3, left). A metal plate of size 1 m × 0.5 m and thickness of a few millimeters was chosen as object behind the wall.

In Fig. 4 a) and Fig. 4 b), the migrated images with conventional and proposed method of TOA computation respectively are shown. The targets have marked distances d_{tot_bist}. The position of metal plate in Z direction in Fig. 4 a) is about 1.9 m what is approximately 0.2 m far from the correct position.

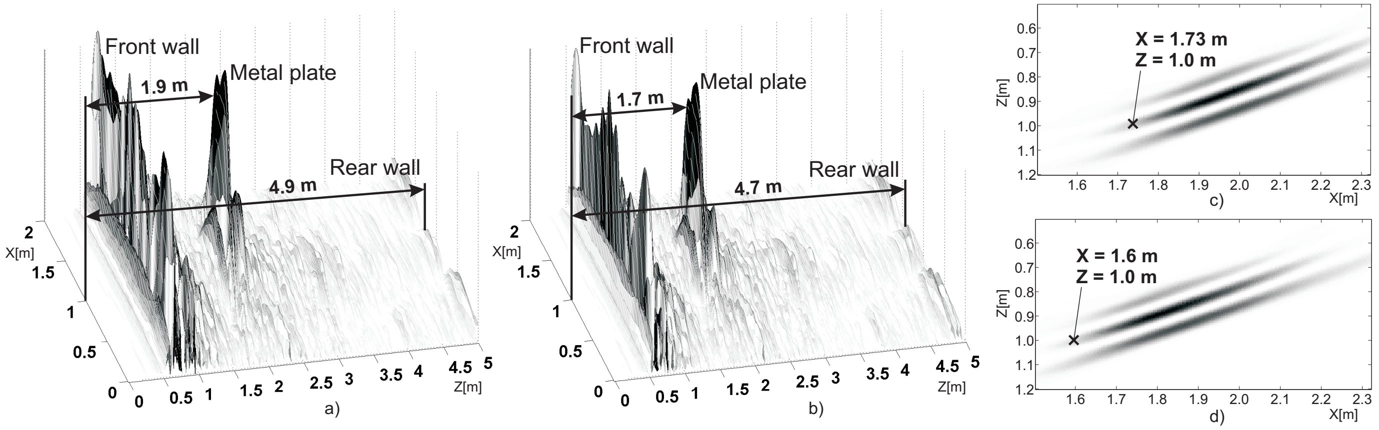

Fig. 4. Migrated images with 20 iteration steps for TOA computation. Scenario 1: a) without wall compensation, b) with proposed wall compensation. Scenario 2: c) with simple wall compensation, d) with proposed wall compensation.

In Fig. 4 b) it is about 1.7 m what is approximately the correct position. The front wall is in both images at the correct position, it starts approximately at 0.5 m in Z direction. The rear wall is at correct position only in Fig. 4 b), approximately at 4.7 m in Z direction, in Fig. 4 b) it starts at 4.9 m. Non compensation of the wall will cause that the objects will not be imaged at correct position and also the image will be unfocused [5].

B. Scenario 2

The wall compensation can by done also by much simpler way. The additional delay for a wave penetrating perpendicularly the wall can be computed and used for wall compensation [3]. This method works when the objects are in parallel with the wall. In order to show inaccuracy of such method we chose the second scenario. The metal plate of size 0.67 m × 0.75 m was placed aslant behind the 0.4 m thick brick wall with relative permittivity approximately $\epsilon_{r\_W} = 4$. It can be seen even if the waves penetrate aslant in the wall, proposed method provides correct coordinations of the left-bottom metal plate corner [X = 1.6 m, Z = 1 m], unlike simple method for compensation [X = 1.73 m, Z = 1 m].

V. CONCLUSION

In this paper we present an algorithm for computing the true TOA for through the wall scenarios using efficient method. The algorithm can be used for improved SAR based object imaging by using UWB radar. The algorithm significantly improves the position of objects and focused image quality over conventional migrations with constant velocity model, especially, when the wall thickness and relative permittivity is not neglectable.

ACKNOWLEDGMENT

This work was supported by the Slovak Research and Development Agency under the contract No. LPP-0287-06, European Commission under the contract COOP-CT-2006-032744 RADIOTECT and by the DAAD scholarship.

REFERENCES

[1] S. Gauthier, E. Hung, and W. Chamma, "Surveillance Through Concrete Walls," *Proceedings of SPIE 5403*, pp. 597–608, Dec. 2004.
[2] F. Ahmad and M. G. Amin, "High-Resolution Imaging using Capon Beamformers for Urban Sensing Applications," *Acoustics, Speech and Signal Processing, ICASSP, IEEE*, vol. 2, pp. 985–988, Apr. 2007.
[3] C. Lei and S. Ouyang, "Through-wall Surveillance using Ultra-wideband Short Pulse Radar: Numerical Simulation," *Industrial Electronics and Applications, 2007*, pp. 1551–1554, May 2007.
[4] F. Ahmad, M. G. Amin, and S. A. Kassam, "Synthetic aperture beamformer for imaging through a dielectric wall," *Aerospace and Electronic Systems, IEEE*, vol. 41, pp. 271–283, Jan. 2005.
[5] G. Wang and M. G. Amin, "Imaging Through Unknown Walls Using Different Standoff Distances," *Signal Processing, IEEE*, vol. 54, pp. 4015–4025, Oct. 2006.
[6] P. Pardalos and H. Romeijn, *Handbook of Global Optimization*, 2nd ed. Springer, June 2002.
[7] E. M. Johansson and J. E. Mast, "Three-dimensional ground-penetrating radar imaging using synthetic aperture time-domain focusing," *AMMWD, Proceedings of SPIE*, vol. 2275, pp. 205–214, Sep. 1994.
[8] B. Yang, A. Yarovoy, T. Savelyev, and L. Ligthart, "Estimated Path Loss for Through Wall Imaging," Internal Radiotect intermediate report on workpackage 2, IRCTRS01807, May 2007.
[9] A. Muqaibai, A. Safaai-Jazi, A. Bayram, A. Attiya, and S. Riad, "Ultra-wideband through-the-wall propagation," *IEE Proc. Microw. Antennas*, vol. 152, pp. 581–588, Dec. 2005.
[10] R. Tanaka, "Report on SAR imaging," Internal Report, Oct. 2003.
[11] D. Calvetti and L. Reichel, "On the evaluation of polynomial coefficients," *Numerical Algorithms*, vol. 33, pp. 153–161, Aug. 2003.
[12] A. Quarteroni, R. Sacco, and F. Saleri, *Rootfinding for Nonlinear Equations*. Springer New York, Aug. 2007, vol. 37.
[13] J. Sachs, P. Peyerl, P. Rauschenbach, F. Tkac, M. Kmec, and S. Crabbe, "Integrated Digital UWB-Radar," *Amerem*, pp. 507–514, Juny 2002.
[14] D. Daniels, "M-sequence radar," in *Ground Penetrating Radar*. London, United Kingdom: The Institution of Electrical Engineers, July 2004.
[15] M. Aftanas, J. Rovnakova, M. Riskova, D. Kocur, , and M. Drutarovsky, "An Analysis of 2D Target Positioning Accuracy for M-sequence UWB Radar System under Ideal Conditions," *Proceedings of 17th International Conference Radioelektronika, Brno*, pp. 189–194, Apr. 2007.
[16] M. Aftanas, "Through Wall Imaging Using M-sequence UWB Radar System," Thesis to the dissertation examination, Technical University of Kosice, Department of Electronics and Multimedia Communications, Slovak Republic, Feb. 2008.
[17] L. Ulander, H. Hellsten, and Stenstrom, "Synthetic aperture radar processing using fast factorized back-projection," *Aerospace and Electronic Systems*, vol. 39, pp. 760–776, July 2003.
[18] D. Miller, M. Oristaglio, and G. BeylkinG, "A new slant on seismic imaging," *Migration and integral geometry: Geophysics*, vol. 52, pp. 943–964, July 1987.