Signal Processing Steps for Objects Imaging Through the Wall with UWB Radar

Michal AFTANAS,

Dept. of Electronics and Multimedia Communications, FEI TU of Košice, Slovak Republic

Michal.Aftanas@tuke.sk

***Abstract*—UWB radar system facilitates us to estimate positions and shapes of the objects behind the wall. It has a great utilization especially for rescue and security applications. This paper briefly describes all signal processing steps that are required for Imaging of the objects scanned by ultra wideband radar device. It involves the description of the basic scanning method, data preprocessing and calibration, migration methods, wall parameters measurement techniques and compensation of the wall effect on wave that penetrate through the wall. The practical results from real measurements with M-sequence UWB radar device are shown.**

***Keywords*—UWB radar system, through the wall imaging, SAR scanning, signal processing.**

I. Introduction

Ultra WideBand (UWB) electromagnetic waves with frequency's approx. from 0.5 GHz to 3 GHz can penetrate through the non-metallic walls with relatively small attenuation. Such ability is very widely used for the whole field of rescue and security applications. These techniques are most useful when the entering to the room is very dangerous for a man. In such situations, any additional informations about what is currently inside the room and how the room looks like can be helpful for making the strategies before entering the room. Through the wall imaging with UWB radar can be used 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, to reconstruct the interior of a room full of smoke during fire, etc.

In this paper, we will refer to the M-sequence UWB radar device used for through the wall scanning, briefly describe whole preprocessing and main processing algorithms. The last part of paper present the practical measurements and results.

II. M-sequence UWB Radar System

For measurements presented in this paper the UWB Maximum Length Binary Sequence (M-sequence) radar system [1] [2] is used, because it has many advantages in comparison with classical pulse, or continuous wave radar. The main advantages of UWB radar system are e.g. improved range measurement accuracy and object identification (greater resolution), reduced radar effects due to passive interference (rain, mist, aerosols, metalized strips, ...), decreased detectability by hostile interceptor, availability of low cost transceivers, the UWB signal can be transmitted with no carrier, producing of transmitted signal requires less power, etc. [3].

The first idea to use a very well known M-sequence in UWB radar was proposed in 1996 by Jürgen Sachs and Peter Peyerl, US patent No. 6272441 [1]. The main advantages of using M-sequence are e.g. the use of periodic signals avoids bias errors, allows linear averaging for noise suppression, M-sequence has low crest factor what allows to use the limited dynamics of real systems and the signal acquisition may be carried out by undersampling. These signals of an extreme bandwidth may be sampled by using low cost, commercial Analog to Digital Converters (ADC) in combination with sampling gates.

The block diagram of M-sequence UWB radar system is shown in Fig. 1. The principle of the M-sequence UWB

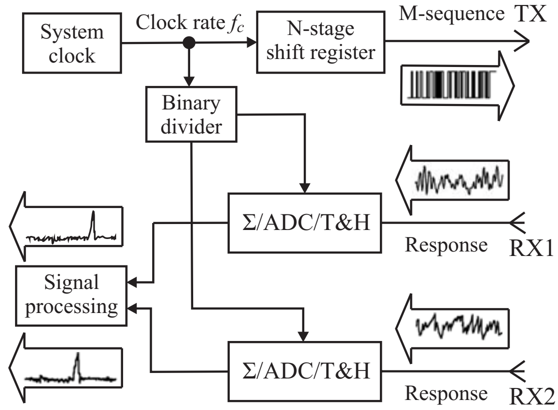

Fig. 1. Block diagram of M-sequence UWB radar system.

radar system can be simply explained as follows. N-stage shift register generates the M-sequence which is transmitted via transmitting antenna, electromagnetic wave is reflected from targets and received via receiving antennas. Received M-sequence is averaged and correlated with transmitted one. The time shift between them corresponds to the distance between transmitter, target and receiver. In principle, the output from M-sequence radar system is the same after the correlation as the output from classical pulse radar system. Therefore, the common preprocessing and imaging algorithms can be used.

III. Synthetic Aperture Radar Scanning

In order to obtain more information about the investigated object and to narrow antenna flaring angle beam, the Synthetic Aperture Radar (SAR) scanning is applied. The basic 2D SAR spatial model is shown on Fig. 2 a). Transmitted wave is reflected from target to all directions uniformly. Because antenna beam is wide signal reflected from target is received not only when antenna system is exactly over the target, but in all positions that allow to "see" the target. This will cause that pointed target will be represent in acquired B-scan as

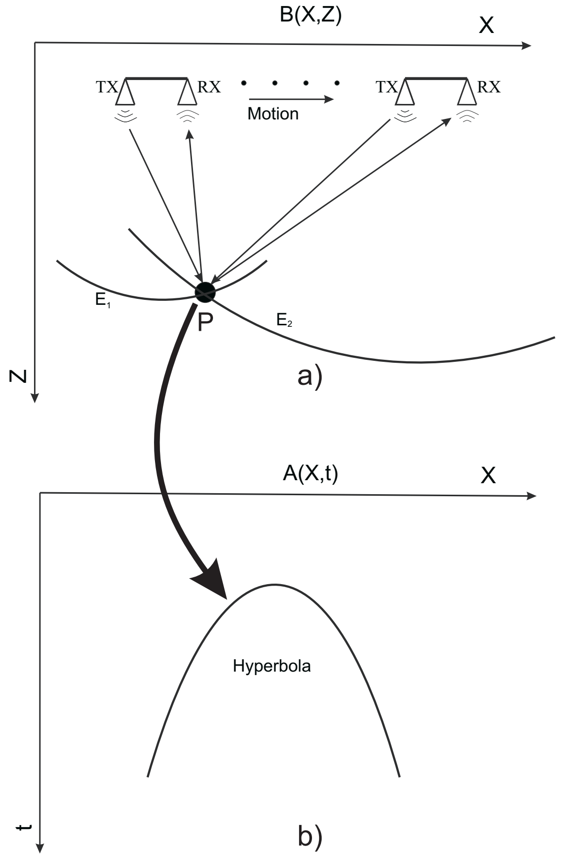

Fig. 2. a) 2D SAR spatial model b) B-scan of pointed target.

hyperbola, like it is show in Fig. 2 b). Time Of Arrival (TOA) is the time when wave is flying from transmitter to target and back to receiver.

IV. Calibration and Preprocessing

Before SAR imaging can be applied to the measured data, several preprocessing and calibration steps have to be undertaken such as: time zero estimation, crosstalk removing, deconvolution and oversampling. Such preprocessing is necessary for imaging of the objects behind the wall and greatly improve the resultant image. Time zero is the time instant in which the transmitted signal leaves the transmit antenna. This time instant has to be shifted at the beginning of the data set for all received impulse responses. Crosstalk is the signal which is transmitted directly from transmitting antenna to the receiving antenna. It does not contain any information about scanned object, but mostly represents the biggest part of received signal. Therefore has to be removed from all impulse responses. The whole system and mostly the antennas have their own impulse responses, which significantly affect the received signal. To reduce this influence, the received impulse responses are deconvolved with the impulse response of the whole radar system including the antennas. Such impulse response of the whole radar system can be measured in anechoic chamber room or in free space towards a big metal plate. The last preprocessing step is to oversample the received impulse responses in the time domain. This step does not improve hardware resolution of the radar system, but can help to find crosstalk and time zero more precisely and can softly improve the image after SAR imaging.

V. Through Wall Imaging Algorithm

As it is shown on Fig. 2, the SAR scanning will provide the measured data in $A(X,t)$ domain. In order to transform $A(X,t)$ domain back to the $B(X,Z)$ domain, some migration algorithm have to be used. The signal received in given time can be reflected from all points that lies on the locations where TOA is constant. The points that have the same TOA are on hyperbola H with focuses at transmitter and receiver positions. This method geometrically focus hyperbolas from $A(X,t)$ in to the one point in $B(X,Z)$.

There are several migration algorithms which can be used to image the objects behind the wall [4]. The simplest imaging method is 2-dimensional SAR migration in time domain [4]. It is a migration with simple geometrical approach often called a back projection [5] or diffraction summation [6] and it does not take into account wave equation. This method is simple to implement, easy to modify, but require big computation power. The similar approach is used in so called Kirchhoff Migration. It is based on solving scalar wave equation. Partial differential equations called separation of variables based on Green's theorem is used to solve this scalar wave equation. Kirchhoff migration theory provides a detailed prescription for computing the amplitude and phase along the wavefront, and in variable velocity, the shape of the wavefront. Kirchhoff theory shows that the summation along the hyperbola must be done with specific weights and, for variable velocity, then the hyperbola is replaced by a more general shape. Kirchhoff migration is mathematically complicated algorithm and is deeply described e.g. in [7], [8]. Wave equation based migration can be done also in frequency domain. Stolt showed that migration problem can be solved by Fourier transform [9]. This process is called f-k migration, or Stolt migration. This method is very fast with low computation complexity, but it is not a very scalable for additional improvements.

Because the antenna flaring angle is not the ideal, the waves that are transmitted or received aslant to the antennas have lower amplitudes. Such signals should be weighted by the antenna footprint function in order to avoid this effect.

VI. Compensation of the Wave Penetration Through the Wall

Scanning of the objects behind the wall requires penetrating the electromagnetic wave through the wall. Because the wall has another permittivity, permeability and conductivity as the air, the shape, the amplitude and the velocity of the wave inside the wall will change. The through the wall wave penetrating model is shown in Fig. 3. 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 [10]. Therefore, in praxis more or less accurate methods based on ray theory and Snells law are used in algorithms of TOA computation to compensate the presence of the wall [11], [12], [13], [14]. The precise and low complexity algorithm for TOA computation through the wall we described in [15]. This 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 wall parameters that are required for TOA estimation such as such wall permittivity and wall thickness are not known apriori and have to be measured. There are several

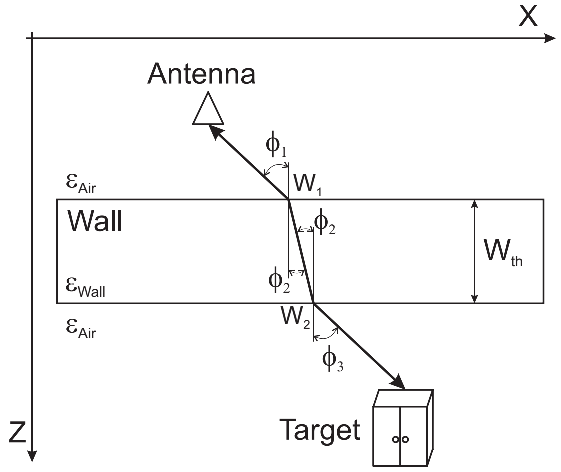

Fig. 3. The model of the wave penetrating through the wall.

methods how to measure them. They can be estimated most precisely when the wall is placed in between the antennas [16], [17]. However this is not practical especially in the case with terrorists or fire since it is meaningless for the intended applications to measure the wall from both sides. A further approach uses different standoff distances for wall parameter estimation in [10], [18]. SAR image de-smearing or auto-focusing can be also used [19], [20]. By representing the wall reflections in the Laplace domain, the pole positions can be used for wall parameter estimation using Prony's method [21]. A model based solution of an inverse problem was also proposed. It solves iteratively the wave equations using Green's function [22], [23]. The time domain reflectometry and the Fresnel equations can be also used [24], [25]

The wave penetrating through the wall is attenuated much more considerably in the wall than it is attenuated in the air. The attenuation inside the wall is mostly depended on the wall conductivity. The magnitude of the wave is reduced with distance even in air. Such attenuation is called spread losses. The spread losses for long distances such as few meters are not neglectable. Because most of the objects that are scanned including walls have flat surfaces, the spread losses can be expressed by reciprocal proportion of distance and wave amplitude. Compensation of the wave attenuation and losses should improve the magnitudes level of all scanned objects according to their reflection properties. However, the small magnitudes from far objects behind the wall are increased including the noise level.

VII. Measurements with Radar Device

For testing the whole string of signal processing steps described above, SAR measurements with 3 scenarios were produced. The measurements were done with M-sequence UWB radar device [1] with frequency range from DC to 2.25 GHz. Two receiver and one transmitter Horn antennas with frequency range approx. 0.5 GHz to 4 GHz were used. The measurement description with scanned results of scenario 1 is shown in Fig. 4 [26]. The aquarium filled with water was placed behind the 18 cm thick brick wall. It can be seen, that the position of the aquarium is shown at correct position, because the algorithm for precise TOA computation described above was used.

The measurement description with scanned results of scenario 1 is shown in Fig. 5 and Fig. 6 respectively [15]. The thin metal plate was placed behind the 18 cm and 40 cm thick brick walls. It can be seen, that the correct position of metal plate can be obtained only when the precise method of TOA computation is used Fig. 6 a), b). For the metal plate that is placed aslant to the wall a simple compensation algorithm described in [15] is not sufficient for obtaining the correct results Fig. 6 c), d). The precise method of TOA computation described above have to be used.

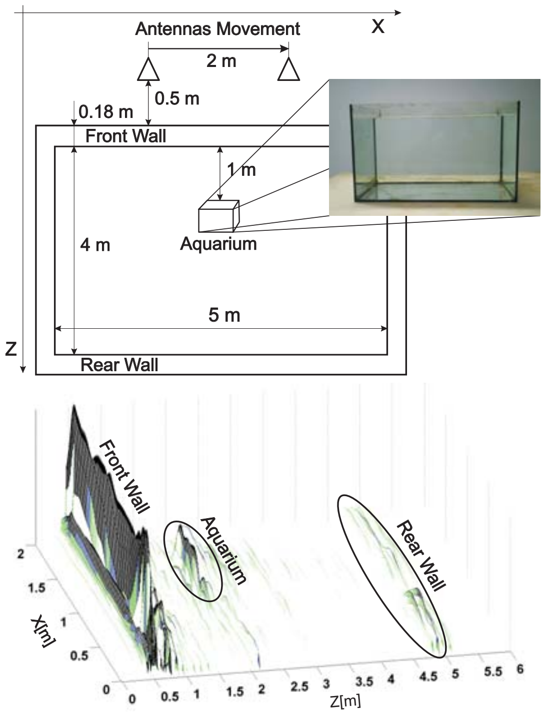

Fig. 4. SAR measurement, scenario 1 resulting in correct target positions after respecting wave propagation in the wall.

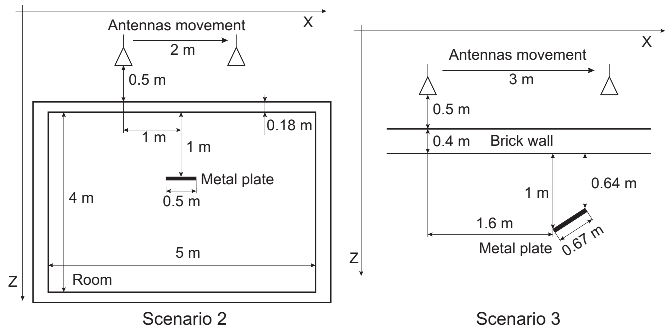

Fig. 5. SAR measurement, scenario 2 (left), scenario 3 (right).

VIII. Conclusion

In this paper the signal processing steps that are required for objects imaging through the wall with UWB radar were described. Theoretical approach of SAR scanning, data preprocessing, calibration, migration and compensation of wall effect were tested on real measurements with M-sequence UWB radar device. Three scenarios were measured and processed. From shown results can be seen, that the proposed algorithms and radar device are suitable for imaging of the objects behind the wall. The whole system can be used for rescue and security applications.

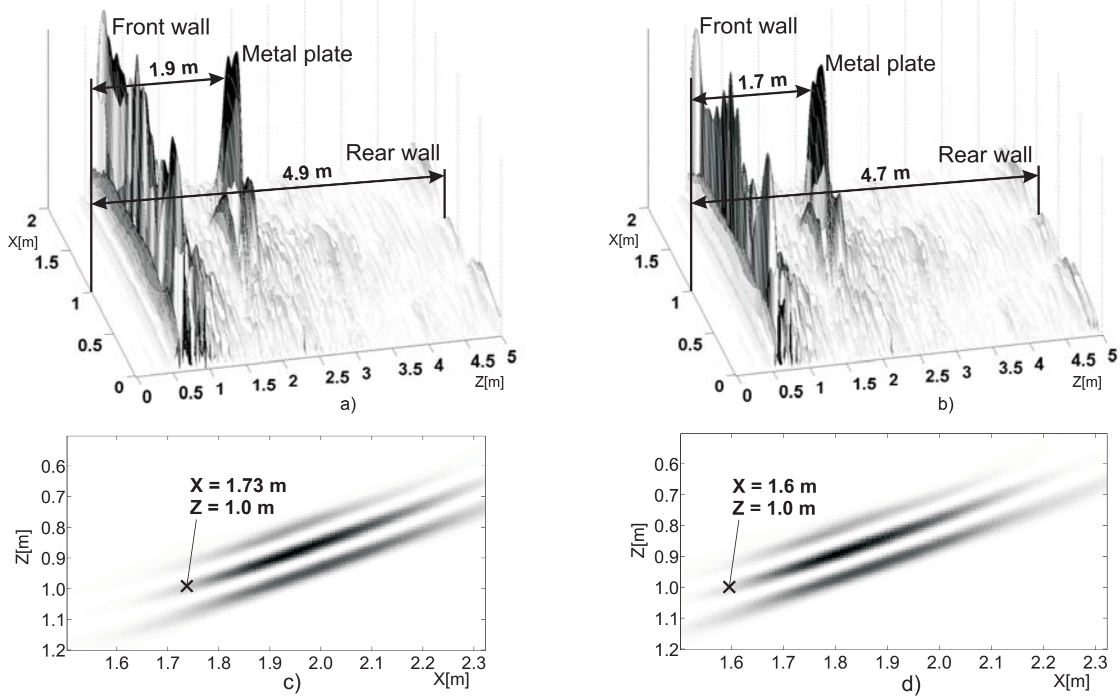

Fig. 6. Scenario 2: a) without wall compensation, b) with proposed wall compensation. Scenario 3: c) with simple wall compensation, d) with proposed wall compensation.

ACKNOWLEDGMENT

This work was supported by the European Commission through the 6th framework under the contract COOP-CT-2006-032744 RADIOTECT and the Slovak Research and Development Agency under the contract No. LPP-0287-06.

REFERENCES

[1] D. Daniels, “M-sequence radar,” in *Ground Penetrating Radar*. London, United Kingdom: The Institution of Electrical Engineers, 2004.

[2] J. Sachs, P. Peyerl, S. Wockel, M. Kmec, R. Herrmann, and R. Zetik, “Liquid and moisture sensing by ultra-wideband pseudo-noise sequence signals,” *Meas. Sci. Technol.*, pp. 1074–1087, Apr. 2007.

[3] I. Immoreev and Fedotov, “Ultra wideband radar systems: advantages and disadvantages,” *Ultra Wideband Systems and Technologies*, pp. 201–205, 2002.

[4] 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.

[5] L. Ulander, H. Hellsten, and G. Stenstrom, “Synthetic aperture radar processing using fast factorized back-projection,” *Aerospace and Electronic Systems*, vol. 39, pp. 760–776, July 2003.

[6] D. Miller, M. Oristaglio, and G. Beylkin, “A new slant on seismic imaging,” *Migration and integral geometry: Geophysics*, vol. 52, pp. 943–964, July 1987.

[7] G. F. Margrave, “Numerical methods of exploration seismology with algorithms in matlab,” Master’s thesis, Department of Geology and Geophysics, The University of Calgary, Jan. 2001.

[8] O. Yilmaz, *Seismic Data Processing, volume 2 of Investigations in Geophysics*. Tulsa: Society of Exploration Geophysicists, Oct. 1987.

[9] R. H. Stolt, “Migration by Fourier transform,” *Geophysics*, vol. 43, pp. 23–48, Feb. 1978.

[10] G. Wang and M. G. Amin, “Imaging Through Unknown Walls Using Different Standoff Distances,” *Signal Processing, IEEE*, vol. 54, pp. 4015–4025, Oct. 2006.

[11] S. Gauthier, E. Hung, and W. Chamma, “Surveillance Through Concrete Walls,” *Proceedings of SPIE 5403*, pp. 597–608, Dec. 2004.

[12] 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.

[13] 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.

[14] 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.

[15] M. Aftanas, J. Rovnakova, M. Drutarovsky, and D. Kocur, “Efficient Method of TOA Estimation for Through Wall Imaging by UWB Radar,” *IEEE International Conference on Ultra-Wideband (ICUWB2008)*, vol. 10, pp. 101–104, Sept. 2008.

[16] A. Muqaibel and A. Safaai-Jazi, “A new formulation for characterization of materials based on measured insertion transfer function,” *Microwave Theory and Techniques*, vol. 51, pp. 1946–1951, Aug. 2003.

[17] G. Cui, L. Kong, J. Yang, and X. Wang, “A New Wall Compensation Algorithm for Through-the-wall Radar Imaging,” *Synthetic Aperture Radar, 2007. APSAR 2007*, pp. 393–396, Nov. 2007.

[18] H. Wang, Z. Zhou, and L. Kong, “Wall Parameters Estimation for Moving Target Localization with Through-the-Wall Radar,” *Microwave and Millimeter Wave Technology, 2007*, pp. 1–4, Apr. 2007.

[19] F. Ahmad, M. G. Amin, and G. Mandapati, “Autofocusing of through-the-wall radar imagery under unknown wall characteristics,” *IEEE transactions on image processing*, vol. 16, pp. 1785–1795, July 2007.

[20] G. Mandapati and M. Amin, “Blurness and focusing-defocusing for Through the Wall Radar Imaging,” *Signal Processing and Information Technology, 2004*, pp. 246–249, Dec. 2004.

[21] A. T. S. Ho, W. H. Tham, and K. S. Low, “Improving classification accuracy in through-wall radar imaging using hybrid prony’s and singular value decomposition method,” *Geoscience and Remote Sensing Symposium, 2005*, vol. 6, pp. 4267–4270, July 2005.

[22] R. Linnehan, J. Schindler, D. Brady, R. Kozma, R. Deming, and L. Perlovsky, “Dynamic Logic Applied to SAR Data for Parameter Estimation Behind Walls,” *Radar Conference, 2007 IEEE*, pp. 850–855, Apr. 2007.

[23] C. L. Bastard, V. Baltazart, Y. Wang, and J. Saillard, “Thin-Pavement Thickness Estimation Using GPR With High-Resolution and Superresolution Methods,” *IEEE Transactions on Geoscience and Remote Sensing*, vol. 45, pp. 2511–2519, Aug. 2007.

[24] F. Sagnard and G. E. Zein, “In Situ Characterization of Building Materials for Propagation Modeling: Frequency and Time Responses,” *IEEE Transactions on Antennas and Propagation*, vol. 53, pp. 3166–3173, Oct. 2005.

[25] H. Khatri and C. Le, “Identification of Electromagnetic Parameters of a Wall and Determination of Radar Signal Level Behind a Wall,” *Proceedings of SPIE, the International Society for Optical Engineering*, vol. 6210, pp. 62 100Q.1–62 100Q.7, Apr. 2006.

[26] J. Sachs, M. Aftanas, S. Crabbe, M. Drutarovsky, R. Klukas, D. Kocur, T. Nguyen, P. Peyerl, J. Rovnakova, and E. Zaikov, “Detection and Tracking of Moving or Trapped People Hidden by Obstacles using Ultra-Wideband Pseudo-Noise Radar,” *5th European Radar Conference, EuRAD 2008*, pp. 408–411, Oct. 2008.