# Efficient and Fast Method of Wall Parameter Estimation by Using UWB Radar System

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***Abstract*—Precise SAR imaging of objects or detection of moving a person behind a wall with UWB radar or non-destructive testing of walls in civil engineering requires the knowledge of wall parameters like thickness and permittivity. Their use in the data processing produces more precise and realistic results. The measurement of the wall parameters is challenge in a real environment especially when there is access only from one side of the wall. In this paper, an effective and fast algorithm for wall parameters estimation that can be used in practice is presented. For that purpose the magnitudes and the time positions of reflections from inner and outer interfaces of the wall are extracted from the data. A new scanning method reduces drastically the clutter caused by objects in the measurement environment such as reflections from other walls, the ceiling, the floor and antenna crosstalk. The algorithm was tested on 13 different types of walls with different permittivity and thickness. A handheld M-sequence UWB radar with horn and circular antennas was used for data gathering. The proposed method is very robust and the error of the thickness estimation was less than 10% for most of walls. The whole measurement can be handled by one person. The wall parameter estimation runs in real time and is fully automated.**

***Index Terms*—Wall parameters estimation, Wall permittivity, Wall thickness, UWB radar.**

## I. Introduction

THROUGH wall sensing such as hostages or terrorists localization or weapon detection behind walls, the search for people trapped in a building due to fire or an earthquake, the detection of illegal immigrants, cigarettes in trucks as well as the detection, localization and tracking of the moving objects behind a wall becomes more and more important nowadays. The same is with non-destructive testing in civil engineering in order to investigate the state or quality of constructions.

Ultra-wideband radar imaging presents an interesting technology for that purpose. However, the imaging algorithms need the wall parameters such as thickness and permittivity in order to correct and to improve the obtained results. The more precise the wall parameters are known the better the complex algorithms for Synthetic Aperture Radar (SAR) imaging or detection of moving persons can be enhanced [1].

There are a few methods for estimation of the wall parameters. They can be estimated most precisely when the wall is placed in between the antennas [2]–[4]. 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 [5], [6]. Some small object, that has to be visible from at least two antenna positions, has to be situated behind the wall which is impractical as well. Moreover, the wall parameters will be estimated totally wrong if the position of this object is estimated even with small inaccuracy. This method was tested only on simulated data. SAR image de-smearing or auto-focusing were also used [7], [8]. However the blurring of SAR images is in practice very small and mostly lost in noise. Mainly the position of an object is changing significantly when the wall parameters are unknown. Also this method was tested only on simulated data. By representing the wall reflections in the Laplace domain, the pole positions can be used for wall parameter estimation using Prony's method [9]. However, even small noise will shift the pole positions significantly. Therefore, the approach is only useful for simulations. A model based solution of an inverse problem was also proposed. It solves iteratively the wave equations using Green's function [10], [11]. These methods are very complicated, require huge computation power as well as the time and most of them were only tested on simulated data.

In this paper a new method for estimation of thickness and permittivity of a wall is introduced. The main attention was paid to a practical estimation method that can be used in the real environment. The measurement is carried out from one side of the wall, thus there is no need to enter a dangerous space. The measurement process is very fast and easy to handle. A positioning system is not required. The processing of the proposed algorithm does not take more than 2 seconds on a normal laptop in MATLAB.

## II. Model of the Wave Propagation in the Wall

The main idea of the wall parameter estimation is to use time domain reflectometry. The Fresnel equations at the wall interfaces and plane wave propagation within the wall is applied. This idea was firstly introduced in [12]. However, the piece of wall have to be placed in Anechoic chamber room and measured with and without a metal plate behind it, what can not be done in dangerous environment. The idea with reflectometry was also used in [13]. However, only the theoretical approach was tested there on simulated data and an extensive iteration algorithm was used to estimate the wanted parameters. Furthermore, the whole wave propagation was assumed to be planar. This is not practical since it requires a large distance between the wall and the radar device.

Our approach permits spherical wave propagation. But within the wall we also simplify to planar waves in order to keep simple. The error made by that approximation is negligible since it only neglects the spreading losses in the wall. For our wall model, we suppose as in [13] a flat wall surface, a homogeneous wall structure, normal incidence of the sounding waves and frequency independent wall permittivity $\varepsilon_w$ and wall conductivity $\sigma_w$. Moreover, it can be assumed that the relative permeability of usual wall material will be $\mu_{rw} = 1$ and the wave attenuation will not be too strong at the applied radar frequencies.

Fig. 1 illustrates the wave propagation within a wall. Obviously, we have to deal with the reflections at both wall surfaces and the wave propagation within the wall. As demonstrated below, the two emphasized reflections will be used to determine the wall parameters and the transmitted wave should sound the targets behind the wall. Reflections of higher order are not of interest. Their amplitudes are negligible.

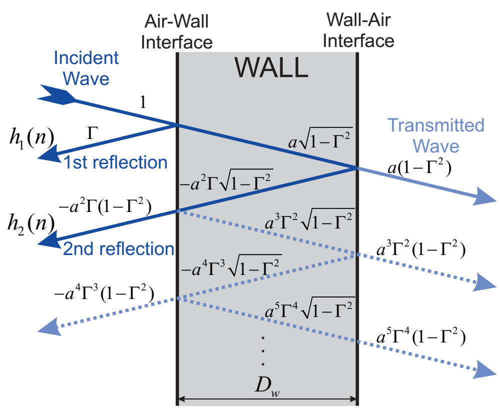


Fig. 1. Through the wall magnitude model - Reflectogram. Note, the aslant incidence of the wave is only plotted for better illustration of multiple reflections.

Fresnel's equations give the ratios between the incident wave and the scattered respectively transmitted electrical field at a flat boundary for normal incident waves:

$$\Gamma = \pm\frac{\sqrt{\varepsilon_a} - \sqrt{\varepsilon_w}}{\sqrt{\varepsilon_a} + \sqrt{\varepsilon_w}}, \quad T = \frac{2\sqrt[4]{\varepsilon_a\varepsilon_w}}{\sqrt{\varepsilon_a} + \sqrt{\varepsilon_w}} = \sqrt{1-\Gamma^2} \tag{1}$$

where $\Gamma$ is a reflection coefficient, $T$ is a transmission coefficient and $\varepsilon_a$ is the permittivity of the air or vacuum. The positive sign in $\Gamma$ holds for the propagation air to wall and the negative sign has to apply if the wave moves from wall to air.

The wave propagation within the wall is characterized by the propagation speed $v_w$ and the propagation loss $a$. Propagation factor result from the solution of the plane wave equation of the electromagnetic field, which is usually determined for the frequency domain:

$$\beta = \frac{2\pi f}{v_w} = \pm 2\pi f \sqrt{\frac{\varepsilon_w\mu_w}{2}\left(\sqrt{1+\left(\frac{\sigma_w}{2\pi f\varepsilon_w}\right)^2}+1\right)} \approx$$
$$\approx 2\pi f\sqrt{\varepsilon_w\mu_w} = \frac{2\pi f\sqrt{\varepsilon_{rw}}}{c} \tag{2}$$

where $\mu_w$ is the permeability of the wall, $\varepsilon_{rw}$ is the relative permittivity of the wall, $f$ is the frequency of the wave and $c$ is the wave velocity in vacuum.

Equation (2) also indicate approximations which follow from the fact that the conductivity of most common wall materials is sufficiently small. Otherwise, the wave could not penetrate through the wall and the whole approach of object detection behind the wall would fail.

From this set of simple equations, it is possible to estimate the wanted wall parameters. The first reflection will provide us the permittivity of the wall. From that the propagation speed can be calculated. Hence, the time delay of the inner wall reflection will give us the wall thickness. Thus, there is no iteration required as in [13] and the data may be taken directly from radar measurements which are usually given in the time domain.

## III. Reducing of Clutters with New Scanning Method

An M-sequence UWB radar device developed by TU Ilmenau and Meodat GmbH [14] was used for the measurements. The precise allocation of the second reflection from the wall is a big challenge in practice because of antenna ringing, lots of clutter and random noise. Additionally, antenna crosstalk and wall reflections are overlapped at close proximity to the wall (Fig. 2). In order to separate the wall reflections

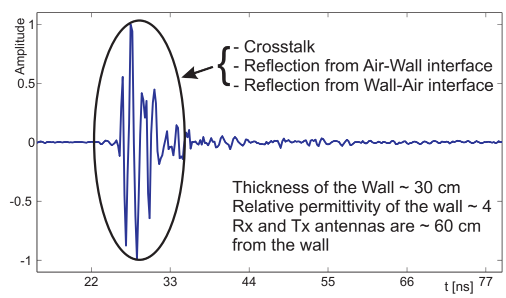


Fig. 2. Measurements of the reflections from the wall.

from unwanted components, we introduce a new method of scanning. The main idea behind this method is to move the antennas towards the wall (Fig. 3) and to average the data appropriately. During scanning, the positions of all clutter

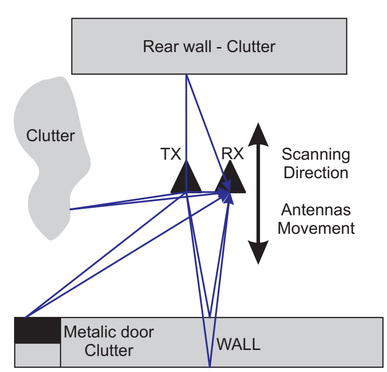


Fig. 3. Antennas movement with new scanning direction.

signals in the measured data are shifting with another velocity (sometimes even directions) as the position of the wall of interest. Fig. 4 depicts an example in which the radar was taken away from the wall, which can be seen by the growing propagation time. Other reflectors (ceiling, floor, back wall etc) change their distance to the radar differently and hence they can be suppressed by averaging the signals along the "wall track". But note, the spreading losses due to spherical wave propagation have to be removed before averaging. The simplest way to reduce the clutter is to synchronize all impulse responses on the first wall reflection (it is always very well visible), normalize each signal to its main peak and average all of them (Fig. 4). The antenna crosstalk should be removed

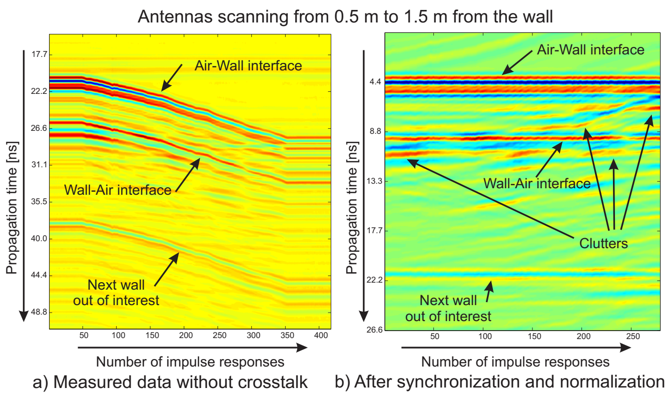


Fig. 4. B-scans. Antennas were moved from 0.5 m to 1.5 m from the wall. a) Measured data, oversampled and without crosstalk. b) After synchronization and normalization. Next wall is 1.8 m from measured wall.

beforehand and the data should be densely sampled in order to gain a precise synchronization between all measurements. Averaging the data from Fig. 4b) in the horizontal direction leads to a cleaned impulse response $h(n)$ of the wall (see Fig. 5a) which we will separate in two parts - one originating from the reflection of the outer surface $h_1(n)$ and one caused by the inner surface $h_2(n)$. The two reflections are clearly visible. A third reflection is also indicated by the data. It is produced by a target which is out of interest here.

## IV. Algorithm Description

As mentioned above, the first step is to determine the reflection coefficient $\Gamma$ of the outer surface in order to be able to determine the wall permittivity. Since the incident wave is not known in practice, a reference measurement $h_m(n)$ was made beforehand and stored in the device memory. For that purpose, we used a large sheet of metal $\Gamma = -1$ and measured the reflection at 1 m distance. Since the wall parameters are not frequency dependent, we can determine $\Gamma$ of the first surface from the peak values of the measured data:

$$\Gamma = -\frac{\|h_1(n)\|_\infty}{\|h_m(n)\|_\infty} = -\frac{\|h(n)\|_\infty}{\|h_m(n)\|_\infty}. \tag{3}$$

The reflection coefficient of a wall is always negative (compare (1) and see Fig. 4). The infinity norm is a positive number, hence the minus in (3). The determination of $h(n)$ has to be done carefully by using the same wall distance for synchronization as in the $h_m(n)$ measurement in order to respect the spreading loss of the waves. However, a distance measurement

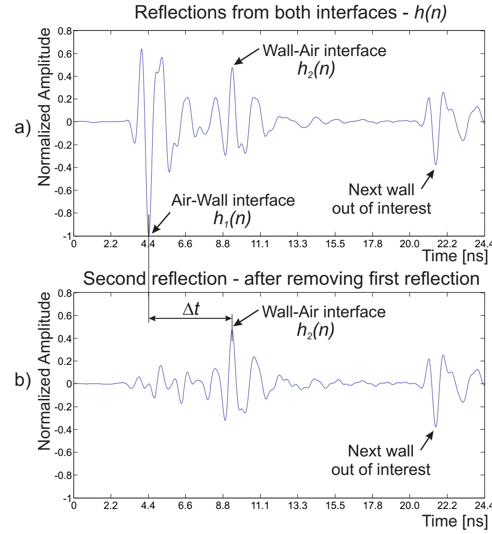


Fig. 5. Mean of reflections from wall interfaces, a) Reflection from both interfaces, b) Reflection from wall-air interface, after removing first reflection.

to the wall is not required, it can be easily obtained from position of $h_1(n)$.

Now, we can calculate the wall permittivity and the propagation speed within the wall:

$$\varepsilon_{rw} = \frac{(1-\Gamma)^2}{(1+\Gamma)^2}; \qquad v_w = \frac{c}{\sqrt{\varepsilon_{rw}}}. \tag{4}$$

The propagation time $\Delta t$ (see Fig. 4) within the wall will give the wall thickness:

$$D_w = \frac{v_w \Delta t}{2}. \tag{5}$$

Time $\Delta t$ results from the time position of the maximum of $h_2(n)$ referred to the first reflection. However, the $h_1(n)$ and $h_2(n)$ may overlap each other. Therefore, we first subtract the first reflection $h_1(n)$ from the data in order to gain the improved reflection from the inner surface. Since the wall parameters are frequency independent, we can suppose that $h_1(n)$ and $h_m(n)$ have the same time shape, hence

$$h_2(n) \approx h(n) - \frac{\|h_1(n)\|_\infty}{\|h_m(n)\|_\infty} h_m(n). \tag{6}$$

The norm of $h_1(n)$ may be approximated by norm of $h(n)$.

## V. Results from Measurements

The proposed method was tested on 13 different types of the walls. The walls were made from various types of bricks, concrete and reinforced concrete. The wall thicknesses ranged from 13 cm to 50 cm. Most of the walls were measured indoor, four walls were measured from outside. An M-sequence UWB radar device with 4.5 GHz sampling rate [14], frequency range 0.5 GHz to 2.25 GHz and double ridged Horn antennas were used for the measurements. Five walls were also investigated with circular antennas.

For data capturing, the (handheld) radar device was simply moved towards or from the wall. Reasonable distances cover about 0.5 m to 1.5 m. The processing is completely automated and takes less than 2 seconds on a standard laptop

TABLE I
ESTIMATION OF THE PERMITTIVITY, THICKNESS AND CONDUCTIVITY OF 13 DIFFERENT WALLS.

| **Type of the wall** | Environment Inside/Outside of the building | Estimated permittivity $\epsilon_{rw}$ | Estimated thickness $D_w$[cm] | Real thickness $D_w$[cm] | **Error in thickness [%]** |
|---|---|---|---|---|---|
| White brick with plaster | I | 3,141 | 41,91 | 40 | **4,77** |
| Brick with plaster | I | 4,11 | 29,24 | 29 | **0,83** |
| Red small brick with plaster | I | 3,46 | 13,24 | 13 | **1,85** |
| Brick with plaster | I | 4,95 | 20,97 | 20 | **4,85** |
| Gray reinforced brick | O | 2,46 | 18,46 | 18 | **2,56** |
| Gray reinforced brick | O | 2,71 | 47,75 | 50 | **4,5** |
| White brick | I | 3,04 | 22,56 | 25 | **9,76** |
| Reinforced concrete with wallpaper | I | 7,7 | 14,64 | 15,5 | **5,55** |
| Reinforced concrete | O | 7,69 | 14,77 | 15 | **1,53** |
| Concrete | I | 5,89 | 15,51 | 17 | **8,76** |
| Concrete with plaster | I | 4,72 | 15,48 | 15,7 | **1,4** |
| Small inhomogeneous hard brick with thick mortar | I | 5,58 | 44,14 | 38 | **16,16** |
| 4 cm Stone pavement, then 40 cm light brick | O | 10,17 | 3,97 | 44 | **-** |

in MATLAB. The results are shown in the Table I. It can be seen, that the proposed algorithm is very robust and the error in the thickness estimation is less than 10% for most of the walls. The wall parameters can be estimated precise enough for many practical applications even when the thin layer of plaster is present.

The occurred deviations are mainly caused by erroneous determination of the wall reflection resulting in permittivity and conductivity values of reduced reliability. The approach assumes an ideally flat surface and a homogeneous wall structure. If the surface is too rough or coated by some substances, there are also other quantities beside the volume material which determines the wall reflection. The use of more complex wall models may partially reduce these errors. However under field conditions it will usually not be possible to determine all the required parameters.

## VI. CONCLUSION

In this paper we have presented a new and practicable approach for estimation of wall parameters such as permittivity and thickness. The algorithm is suitable for handheld device operation without use of any additional equipment or prior knowledge. It can be applied under real conditions, the method is very robust and useful for typical walls that occur in the real environment. The whole algorithm is very fast, fully automatic and applicable under realtime conditions. The estimated parameters can be used to improve UWB through wall SAR imaging as well as moving person detection.

## ACKNOWLEDGMENT

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## REFERENCES


[1] M. Aftanas, J. Rovnakova, M. Drutarovsky, and D. Kocur, "Efficient Method of TOA Estimation for Through Wall Imaging by UWB Radar," *International Conference on Ultra-Wideband, ICUWB 2008*, vol. 2, pp. 101–104, Sep. 2008.

[2] 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.

[3] A. Muqaibel, A. Safaai-Jazi, A. Bayram, A. Attiya, and S. Riad, "Ultrawideband through-the-wall propagation," *Microwaves, Antennas and Propagation, IEE Proceedings*, vol. 153, pp. 581– 588, Dec. 2005.

[4] 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.

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

[6] 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.

[7] 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.

[8] 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.

[9] 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.

[10] 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.

[11] 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.

[12] 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.

[13] 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.

[14] J. Sachs, P. Peyerl, R. Zetik, and S. Crabbe, "M-Sequence Ultra-Wideband-Radar: State of Development and Applications," *Radar 2003, Adelaide, Australia*, pp. 224–229, Sep. 2003.