Through Wall Imaging of the Objects Scanned by M-sequence UWB Radar System

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Abstract. *UWB radar system facilitates us to estimate positions and shapes of objects behind the wall. We have made real through the wall SAR measurements with bistatic M-sequence UWB radar system. A metal plate, an aquarium filled with water and a wooden cupboard inside the room with concrete wall have been scanned. The simple and fast algorithm for compensation of different wave velocity inside the wall is described. Measured data are processed with 2-dimensional geometrical based SAR migration in time domain. Conductive materials behind the wall scanned with M-sequence UWB radar system are clearly visible.*

Keywords

Through Wall Imaging, Objects Behind Wall, UWB Radar, SAR, Migration, M-sequence.

1. Introduction

Through wall imaging is a highly interesting topic since there is a number of situations where the entering of a room or a building is considered as hazardous. It is desired to inspect its interior from outside through the walls. The utilization is very wide, e.g. during security activity with terrorists and hostages to locate people and weapons, through rubble imaging following an earthquake, explosion etc, through wall imaging during fire to locate people, through snow imaging to locate people after avalanche, to control border for the detection of illegal immigrants, substances or contraband and a lot of other applications. These technologies can save many lives during rescue and security actions because work would be more safe and location of the victims would be faster.

2. M-sequence UWB Radar System

We use UWB Maximum Length Binary Sequence (M-sequence) radar system [1], [2], because it has many advantages in comparison with classical pulse, or continuous wave radar, 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: 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

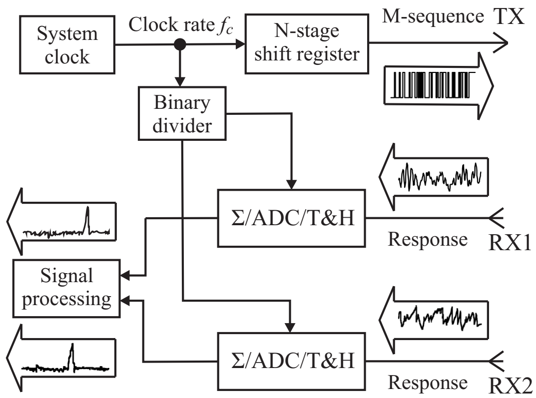

Fig. 1: Block diagram of M-sequence UWB radar system.

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.

3. Properties of the Waves Penetrating Through the Wall

Through 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 in through wall scenario attenuated several times due to free space loss, scattering from air-wall interface, loss in the wall and the scattering from objects [4]. The propagation loss inside the wall is a function of the frequency. Electromagnetic waves are able to penetrate through the concrete walls without massive attenuation up to approximately 3 - 4 GHz [5]. Practical measurements of through wall attenuation with M-sequence UWB radar system are shown in Fig. 2 [6]. In this figure through

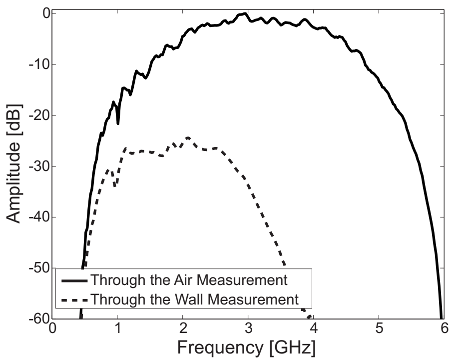

Fig. 2: Through the air and through the wall measurement.

the air measurement is shown in comparison with through the wall measurement. Both measurements were made under the same conditions, the only difference was the 60 cm thick concrete wall between antennas in through wall measurement. In Tab. 1 the pathlosses through the 0.3 m thick wall from concrete, brick and plywood for several frequencies are shown [4].

Pathloss (dB)				
Material	1 GHz	2 GHz	3 GHz	4 GHz
Concrete	15.3	21.9	22.1	23
Brick	7.5	10.7	13.8	16.6
Plywood	12.6	17.9	21.6	24.4

Tab. 1: Pathlosses of 0.3m thick walls.

In addition to looses, the waves penetrating trough the wall change their velocity of propagation. The velocity inside the wall can be described as:

$$v_{wall} = \frac{c}{\sqrt{\varepsilon_{rwall}}} \tag{1}$$

where c is velocity of the light in vacuum and ε_{rwall} is relative permittivity of the wall. According to Snell's law, the waves also change their direction during entering and leaving the materials with different permittivity. The wave path

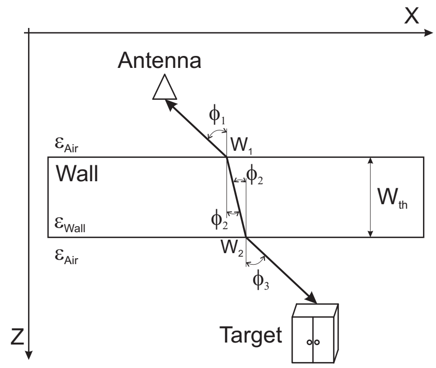

Fig. 3: The model of the wave penetrating through the wall.

for through the wall model is shown in Fig. 3. The angle of the wave inside the wall ϕ_2 can be computed as:

$$\phi_2 = \arcsin\left(\frac{v_{wall}\sin\phi_1}{c}\right). \tag{2}$$

The coordinates of W_1 and W_2 are not known and cannot be computed directly. To compute the true propagation distance between antenna and target, like it is shown in Fig. 3, some minimization method needs to be used [7], [8]. Such optimization procedures are based on the principle of minimization of the travel time, what is very complex and time consuming process. Therefore, we have made a simplification in the computation of time of propagation inside the wall by approximation. A small error will be introduced, but the time of computation will be greatly decreased. The time of propagation inside the wall can be approximated as:

$$t_{wall\_apr} = \frac{W_{th}}{v_{wall}}. \tag{3}$$

The additional time that has to be subtracted from the whole measured Time Of Arrivals (TOA) to compensate the smaller velocity in the wall can be approximated as:

$$t_{sub} = 2\left(\frac{W_{th}}{v_{wall}} - \frac{W_{th}}{c}\right) = \frac{2W_{th}}{c}\left(\sqrt{\varepsilon_{rwall}} - 1\right). \tag{4}$$

The target position for SAR imaging can be estimated more precisely with so adjusted TOA, like with the original TOA. When the antenna beam width is taken into the account, the wall is near the antenna and the relative permittivity of the wall is small, this approximation error can be neglected for imaging of relative big objects. The very fast computations allow to implement the method on a realtime hardware.

4. Preprocessing and Through Wall Imaging Algorithm

There are several migration algorithms which can be used to image the objects behind the wall [6]. In order to transform time domain into the depth domain, where the depth means the direction from antenna to the target (Z direction), the simple 2-dimensional SAR imaging in time domain was applied [6]. It is a migration with simple geometrical approach often called as back projection [9] or diffraction summation [10] and it does not take into account wave equation. The antenna beam width is taken into the account in the algorithm.

Before SAR imaging was applied, several preprocessing steps were undertaken: time zero estimation, crosstalk removing, deconvolution and oversampling. Such preprocessing is necessary for imaging the objects behind the wall and greatly improve the resultant image. Time zero is the time instant in which the transmit 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 flies directly from transmitting antenna to the receiving antenna. It does not contain any information about scanned object, but mostly represents the biggest part of 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. 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 softly improve the image after SAR imaging.

5. Measurement Scenario and Experimental Results

The measurements were done with the M-sequence UWB radar system [2] described above with the 9 GHz clock frequency and 511 M-sequence chips. Bistatic model with the double-ridged horn antennas was used. Distance between the centers of antennas was 0.45 m vertically, the scanned plane was in the middle of them. The oversampling in time domain was set to four. The every 1792 impulse responses were averaged in radar device before the preprocessing was applied, so the output frequency was approximately 19 impulse responses per second. The velocity of the antenna movement was approximately 0.2 m/s in X direction. The antenna beam width of 60 degrees was considered in the migration algorithm. The measurement room was approximately 4 m $\times$ 5 m large, with the wall thickness of about 0.2 m. The wall was made from brick with relative permittivity approximately $\epsilon_{rwall} = 4$. The antenna system was moved in parallel to the wall along 2 m at distance 0.5 m from the wall. The objects were placed 1 m behind the wall inside the room (Fig. 4). A metal plate, a wooden cupboard and a aquarium filled with water were chosen as examined objects behind the wall. The metal plate had size 1 m $\times$ 0.5 m and thickness of a few millimetres. The aquarium filled with water had size 0.5 m $\times$ 0.3 m $\times$ 0.3 m. The wooden cupboard had size 1.6 m $\times$ 0.9 m and thickness of about 0.4 m with small glassy doors.

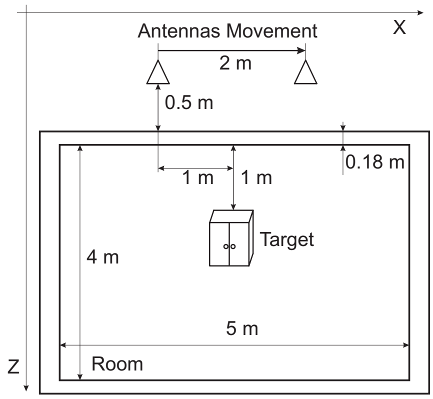

Fig. 4: SAR measurement scenario.

The metal plate, wooden cupboard and aquarium filled with water behind the wall scanned with M-sequence UWB radar system with and without the compensation of different velocity in wall are shown in Fig. 5 - 10, respectively. It can be seen that correction of different velocity in wall shifts all scanned objects approximately 18 cm closer to the antenna system to their correct positions, what results from (4). The first wall is also shifted, what causes that rear side of this wall is imaged at correct position, but the front side is shifted 18 cm closer to the antenna position from its correct position. The best visible object behind the wall is metal plate. The aquarium filled with water is also clearly visible. The wooden cupboard is almost not visible, even if the size of this object is much bigger than the size of the previous objects. These results from the conductivity of the scanned materials. Conductive materials reflect electromagnetic waves much better than insulating materials.

6. Conclusion

In this paper we present the through wall imaging of objects scanned with M-sequence UWB radar system. Three types of objects have been scanned through the brick wall and imaged. The simple method for compensation of the different wave velocity inside the wall has been described. When the wall thickness and permittivity is known, the objects behind the wall can be imaged at correct positions.

Acknowledgement

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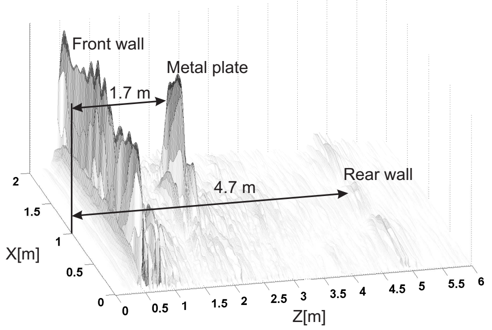

Fig. 5: Image of the metal plate behind the wall with compensation of different velocity in wall.

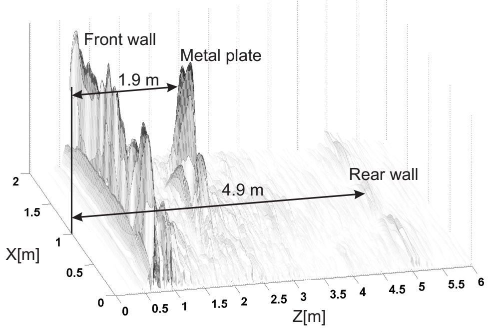

Fig. 6: Image of the metal plate behind the wall without compensation of different velocity in wall.

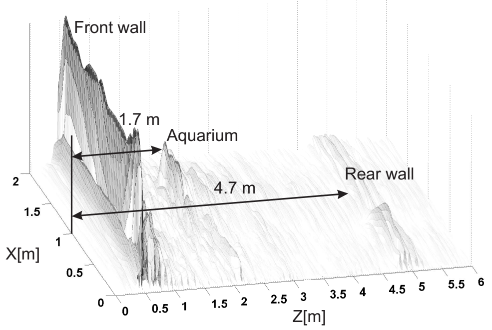

Fig. 7: Image of the aquarium filled with water behind the wall with compensation of different velocity in wall.

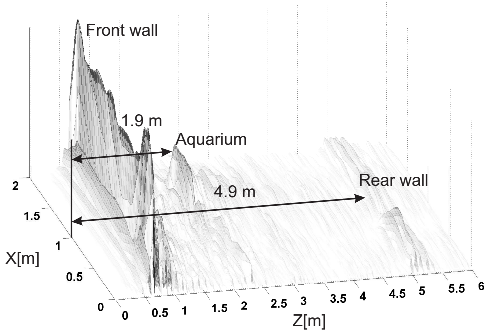

Fig. 8: Image of the aquarium filled with water behind wall without compensation of different velocity in wall.

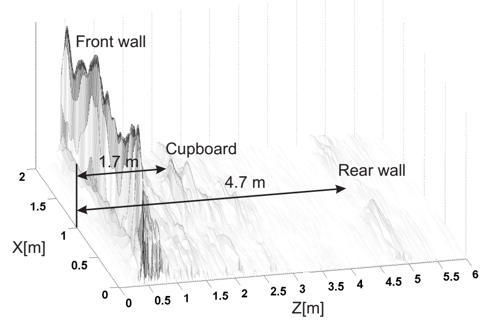

Fig. 9: Image of the wooden cupboard behind the wall with compensation of different velocity in wall.

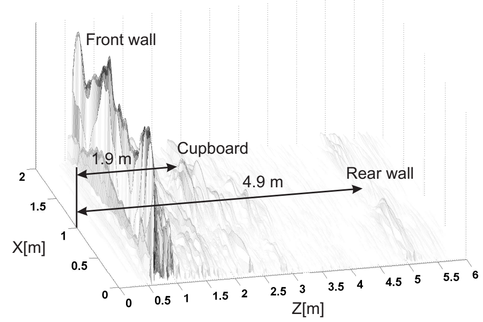

Fig. 10: Image of the wooden cupboard behind the wall without compensation of different velocity in wall.

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