Parallel Implenetation of the GPR Techniques for Detecting and Mapping Ancient Buildings by Using CUDA

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Öz

Yere nüfuz eden radar (GPR), bir duvarın arkasına gizlenebilen veya duvarın içine yerleştirilebilen nesnelerin algılanması için kullanılan ultra geniş bantlı bir elektromanyetik sensördür. GPR yöntemi, arayüzde yer alan yüksek hızda bir anten tarafından yatay yönde yeraltına gönderilen elektromanyetik dalgaların, yine alıcı tarafından yatay yönde yansıtılmasının kaydedilmesi prensibi üzerine çalışır. Gömülü yapılar; toplanan veriler, bilgisayar programları ve çeşitli filtreler kullanılarak algılanır. Hava cepleri gibi duvarlar arasında gizlenmiş hedeflerin bulunması arkeologlara yardımcı olur. Bu çalışmada, toprağın dağılımı için Lorentz modeli kullanılmıltır. Sınır koşullarını sönümleyip açık bir alanı simüle etmek için mükemmel uyumlu katman (PML) kullanılmış ve dağıtıcı medyaya uyacak şekilde genişletilmiştir. Sonlu farklı zaman alanı (FDTD) yöntemi, elektromanyetik alanların zaman basamaklamasındaki kısmi diferansiyel denklemleri ayrıştırmak için kullanılır. FDTD hesaplaması çok yavaş çalışmaktadır. Bu sorunu çözmek için grafik işlem biriminde (GPGPU) genel amaçlı programlama yapılabilmektedir. Bu çalışmada GPU'ya CUDA kullanılarak 3-B FDTD yöntemi uygulanmış ve 10 kat hızlanmıştır.

Anahtar Kelimeler: Sonlu fark zaman alanı (FDTD), Yere nüfuz eden radar (GPR), Mükemmel uyumlu katman (PML), Gömülü nesneler, Paralel Programlama.

Abstract

Ground-penetrating radar (GPR) is an ultra-wideband electromagnetic sensor used for the detection of objects which may be hidden behind a wall or inserted within the wall. The GPR method works on the principle of recording the reflection of electromagnetic waves sent to the underground at high speed from the interfaces by an antenna located in the horizontal direction, again by the receiver in the horizontal direction. Embedded structures are detected using collected data, computer programs, and various filters. Search for the presence of designated targets hidden between the walls, such as air pockets is help to archaeologists. In this work the Lorentz model was used for the distribution of the soil. The perfectly matched layer (PML) used for absorbing boundary conditions to simulate an open space and its expanded to match dispersive media. The finite-difference time-domain (FDTD) method is used to decompose partial differential equations for time cascading of the electromagnetic fields. FDTD calculation works very slowly. General-purpose programming can be done on the graphics processing unit (GPGPU) to solve this problem. In this work, the 3-D FDTD method was applied to the GPU by using CUDA and it was 10 times faster.

Keywords: Finite difference time-domain (FDTD), Ground penetrating radar (GPR), perfectly matched layer (PML), buried objects, Parallel Programming.

1. Introduction

Ground Penetrating Radar (GPR) is a useful and extensive research technique for detecting underground sub-surface layers and buried objects. High-frequency electromagnetic waves (between 10 MHz and 3GHz) are sent to the underground via a transmitting antenna, and radar grams created using the round-trip times of their reflections in the ground and underground structures are examined in high discrimination. The waves are sent underground in a center frequency, and this source frequency has great importance in the

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phenomenon of wave penetration depth, scattering and absorption in the environment. Besides, the dielectric permeability, electrical conductivity and magnetic permeability values of the underground materials have essential effects on the wave areas travelling underground. Considering all these reasons together, the nature of the GPR method is complicated, and interpretation difficulties arise, especially considering that the underground is significantly heterogeneous.

The usage areas of the GPR technique are widespread and applied on almost all shallow geophysical problems (stratigraphy, fault determinations, landslide, karstic space determinations, shallow groundwater aquifer surveys, etc.):

- Archaeological structures and cultural heritage,
- Engineering applications (pipelines research, tunnel highway and railway lines, building equipment and problems in the building, etc.),
- Unexploded military material and mine detection.

In addition to those, it has a wide range of applications in forensic and natural disasters, pollution and underground chemical fluid leaks detection, research on solid waste areas, mineral deposits detection, ore exploration and marble studies.

However, the natural situation undergrounds and very mixed properties especially in shallow environments, difficulties arising from the nature of the method, ecosystems having lost, scattered, wave-absorbing and emitting properties cause significant problems and misinterpretations in the way of interpretation. For this reason, numerical modelling of the underground feature of interest before starting research will provide a considerable benefit in terms of strengthening the presentation. The rapid increase in computer hardware and possibilities in recent years have also enabled the development of modelling techniques of the GPR method. Modelling of the GPR consists of single frequency models, time environment models, ray tracing, transmission and reflection techniques (transmission reflection), integral techniques (MOM – moments method) and discrete element methods. Finite-difference time-domain (FDTD) technique is the most popular among them and can be realized with the help of a desktop computer in a relative competence.

In this work, the CUDA implementation of 2D-FDTD modelling of GPR detection for archaeological excavations [1-7] is proposed. Section 2 gives a brief information about GPR modelling, the FTDT algorithms are presented in Section 3. In the following Section, the CUDA implementation of 2D-FDTD model is proposed. Data analysis and simulation results are summarized in Section 5. Finally, Section 6 concludes the work.

2. GPR Modelling

Since the geometry of embedded objects such as air pockets and clay walls is constant in the third dimension, electromagnetic wave propagation modelling of GPR detection can be analyzed the 2-D problem.
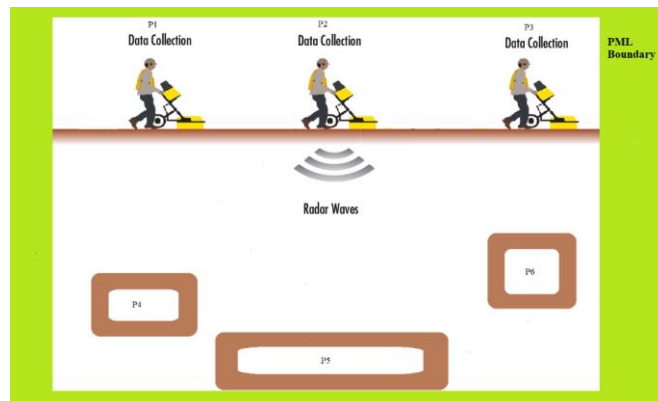

Fig. 1 The modelling of FDTD for GPR detecting of medium layers

On the ground, a transmitting source is placed in the middle of the soil surface. The horizontal and vertical distances of the medium are 7m. The medium has two layers, the upper side is air which thickness is 1m, and the lower side is soil whose width is 6m. Three different size rooms are buried at a depth of 3m, 2m, and 4m in the soil layer which has air pockets at its inside clay walls. The outer of the FDTD medium is perfectly matched layer (PML) boundary [8].

3. FDTD Algorithms

The FDTD algorithm allows analysis of all distribution types in one form. The Lorentzian algorithm is a frequently used distribution form and the polarization field in the frequency domain, P

$$P(w) = \frac{a}{b + jcw - dw^2} \quad (1)$$

Shifting to the time domain with inverse Fourier Transform

$$bP(t) + cP'(t) + dP''(t) = aE(t) \quad (2)$$

An essential step towards the formulized of a consistent and main FDTD algorithm is to approach the times derived from (2) the n-1 time instantly. So, the following update equation is obtained:

$$bP^{n-1} + c\frac{P^n - P^{n-2}}{2\Delta t} + d\frac{P^n - 2P^{n-1} + P^{n-2}}{\Delta t^2} = aE^{n-1} \qquad (3)$$

or

$$P^n = \frac{4d - 2b\Delta t^2}{2d + c\Delta t}P^{n-1} + \frac{-2d - c\Delta t}{2d + c\Delta t}P^{n-2} + 2\frac{2a\Delta t^2}{2d + c\Delta t}E^{n-1} \qquad (4)$$

can be written as

$$P^n = C_1 P^{n-1} + C_2 P^{n-2} + C_3 E^{n-1} \qquad (5)$$

The fixed C_1, C_2, C_3 values and can be found for any immersion relationship form. In the case of multipolar distribution, the same constant is written with three constants values for each pole.

Table 1. Dispersion Relation

Distribution term in frequency domain	C_1	C_2	C_3
Lorentz Pole $$P = \frac{a}{b + jcw - dw^2}E$$	$\frac{4d - 2b\Delta t^2}{2d + c\Delta t}$	$\frac{-2d - c\Delta t}{2d + c\Delta t}$	$\frac{2a\Delta t^2}{2d + c\Delta t}$

The Electric field intensity equation is given by;

$$E^n = \frac{D^n - \sum_i^N P_i^N}{\varepsilon_0 \varepsilon_\infty} \qquad (6)$$

Where N is the number of poles and D^n electric flux density is attained using Yee's algorithm in Figure 2. The order in which the calculations are performed in the general algorithm is shown in the flowchart of Figure 3 [9].
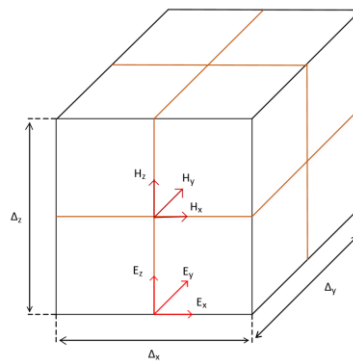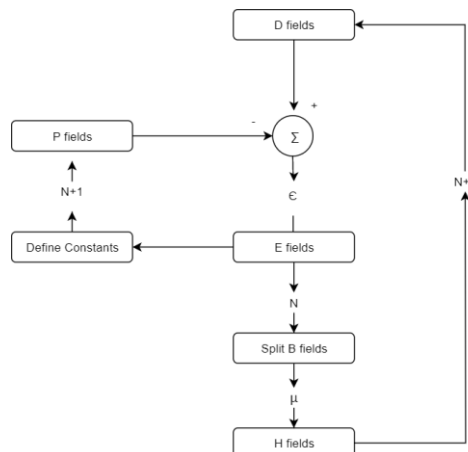

Fig.2 Discrete Yee Cellular of FDTD

Fig. 3 Computations of General Algorithm

4. Realization of The FDTD Model on GPU

The 3-D FDTD area is divided into two-dimensional planes. Figure 4 shows that the division of the 5×5x5 structural FDTD area. FDTD equations for a given plane are resolved in parallel using a core on the GPU, however, all plane is calculated in a single time step, in turn, to the others, with its core invocation. The given all plane is converted into two-dimensional unit blocks, and therefore all blocks have standard CUDA parameters which *blockIdx.x* and *blockIdx.y*. All block units are also divided into threads into two dimensions, so all threads have the standard *threadIdx.x* and *threadIdy.y* CUDA parameters. Figure 5 performs this decomposition method for the 3-D FDTD plane shown in Figure 4 [10-13].
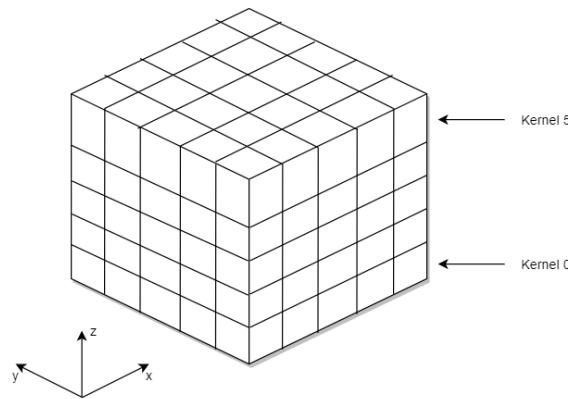

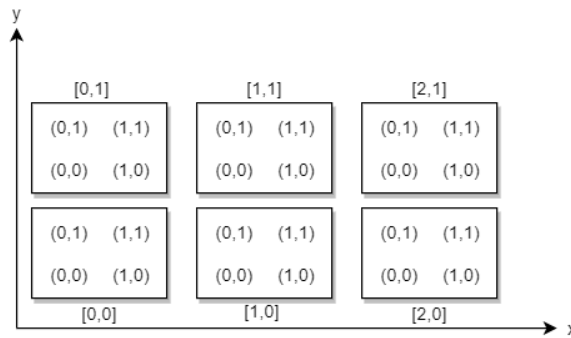Fig. 4 Division of the three-dimensional FDTD space

Fig. 5 Division of two-dimensional using blocks

Due to its simple algorithm and very high calculation efficiency in modern computers, the FDTD method is commonly used in the computational electromagnetic simulation [14]. The flow diagram in Figure 6 shows the operation of the FDTD method in the GPU. There are four main computation steps made at each time step in GPU side:

- E field computation (e_field),
- PML computation for E field (epml) as the absorbent boundary condition [15],
- H field (h_field) computation and,
- PML for H field (hpml).

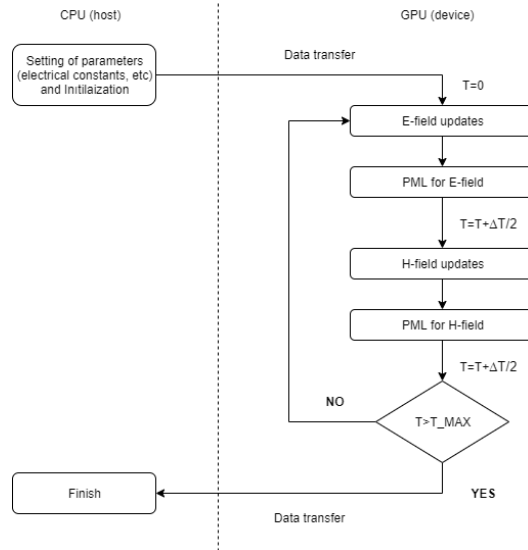All field updates in each time step can be parallelized and are offloaded to the GPU.

Fig. 6 FDTD computation flow chart

The original program which performs the 3-D FDTD algorithm was written in MATLAB and converted to CUDA code for performing its parallel calculation on the GPU. The computation process of the 3-D FDTD algorithm on the GPU starts with memory assignment, parameters definition and GPU setup. During the GPU setup part, memory assignment and defining of the variables allocated to the GPU are performed. In the next step, the information used in the computations of electromagnetic fields is transformed. In the FDTD algorithm operations performed on the GPU, so there is no data transfer process because all calculations are performed on the GPU [16-19].

5. Simulation Results and Data Analysis

First, calculation of five pole Lorentz equation parameters for 40% moist soil are given in Equation 7 [20]

$$\varepsilon_n(w) = \varepsilon_\infty + (\varepsilon_s - \varepsilon_\infty) + \sum_{p=1}^{5} \frac{G_p w_p^2}{w_p^2 + j\delta_p w - w^2} \qquad (7)$$

where 40% moist soil parameters are;

$$a = 0.2\varepsilon_0(\varepsilon_s - \varepsilon_\infty)w_0^2 \qquad (8)$$
$$b = w_0^2 \qquad (9)$$
$$c = 2\Delta \qquad (10)$$
$$d = 10^{-25} \qquad (11)$$

where pole coefficients are given in Table 2. Simulation results of six receivers in different locations as shown in Figure 7.

Table 2. Dispersion Relation

Pole Coefficients	ε_∞	ε_s	w_0	Δ
First Pole	13.7	15	15	9×10^{-7}
Second Pole	13.7	25	15	1×10^{-7}
Third Pole	13.7	26	15	1×10^{-7}
Fourth Pole	13.7	33	11	6×10^{-9}
Fifth Pole	13.7	25	17	6×10^{-9}

To achieve high accuracy and acceleration performance of the FDTD method, we preferred to use a GPU. NVIDIA Quadro M1200 graphics card is utilized as the GPU with HP ZBook Workstation for the simulation platform. The cluster configuration is shown below. In the simulation process, a workstation is used for serial and parallel computing of the FDTD computation. The execution time of both serial and parallel computations are listed and compared in Table 3.

The data of the computation are listed in Table 3. As a result of the study, it was observed that FDTD calculation accelerated ten times with the use of parallel implementation on CUDA platform.

Simulation Platform

HP-ZBook 15 G4\

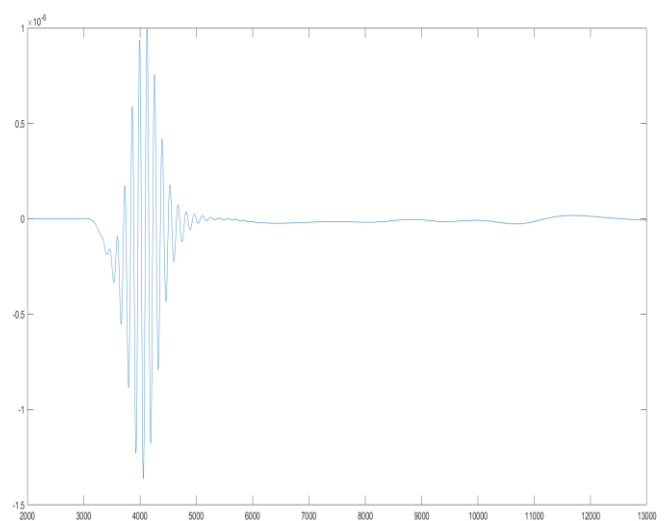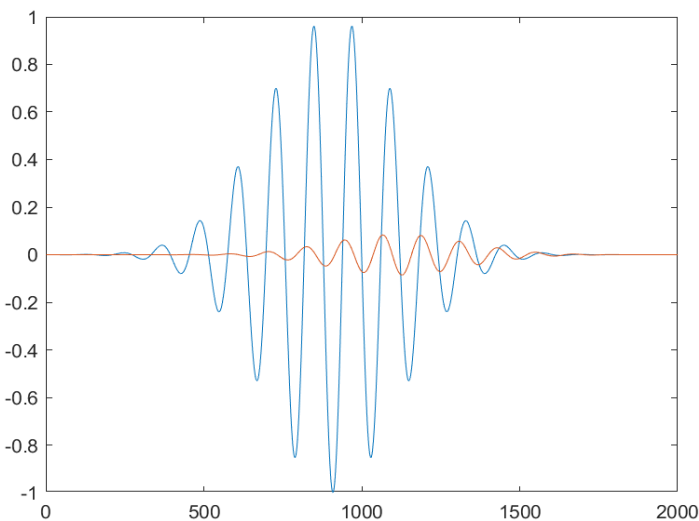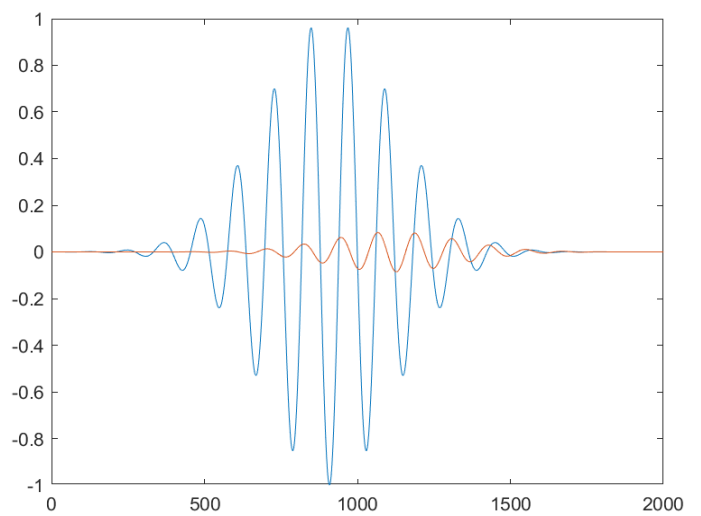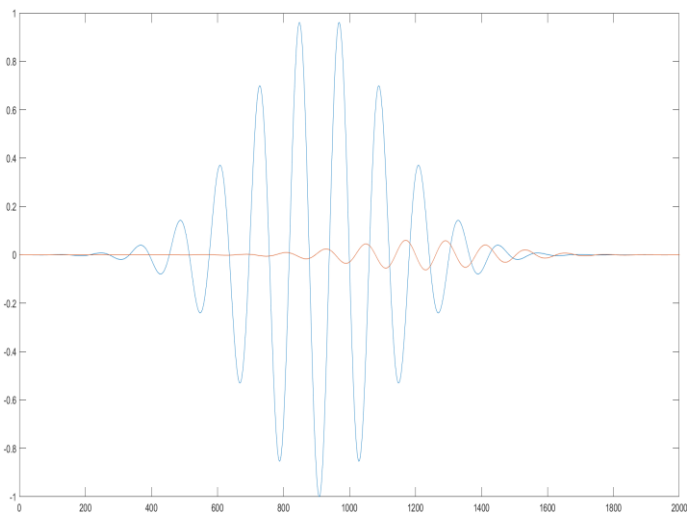CPU: Intel (R) Core (TM) i7-7700HQ @ 2.80GHz (8 CPUs)

RAM:16 GB

Graphics Card: NVIDIA Quadro M1200

VRAM: 4 GB

Table 3. FDTD calculation and comparasion of different scenarios

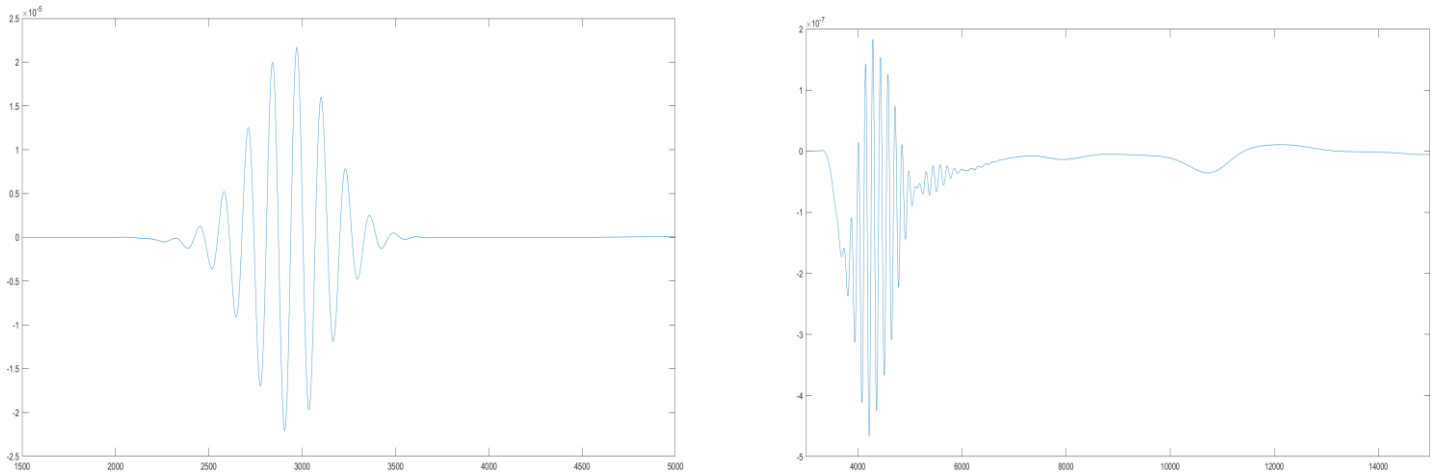| Calculation Method	Time(s)	CPU usagerate(%)
Serial	2613.377	49
Parallel	217.850	16

Fig. 7 Simulation Result of GPR Modelling

6. Conclusion

In this study, mathematical modelling and simulation of GPR systems for the detection of buried rooms are done using FDTD method, and CUDA implementation is carried out for performance improvement.

According to the results obtained, we can state that the parallel implementation of the GPR system is ten times faster than the serial implementation on CPU. This method helps to archaeologists to scan the ancient sites during archaeological excavations very fast.

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