Implementation of Two Different Moving Window FDTD Methods to Simulate the Electromagnetic Propagation in Tunnel with Parallel Computing

Yun-Fei Mao, Jia-Hong Chen, Liang Pan, and Xiao-Ming Wang

China Satellite Maritime Tracking and Control Department
Jiangyin, 2144000, China
myf4494@163.com, stone_cjh@sina.com, panliang@163.com, wangxiaoming@163.com

Abstract **─** Tunnel engineering is electrically large compared with the GHz electromagnetic pulse (EMP), it is difficult to simulate the EMP propagation in large-scale and long-distances vaulted tunnel by using the conventional finite-difference time-domain (FDTD) method. In this work, based on the parallel computing, two kinds of moving window FDTD (MW-FDTD) methods are presented to simulate the EMP propagation in tunnel, the results are validated by comparing with the results of the conventional parallel FDTD method. The convolution PML (CPML) is adopted to truncate the computation domain, which reduces the reflection error greatly. The accuracy and the efficiency of the proposed method are proposed by comparing with the conventional method. Results show that the relative errors for the Alternate MW-FDTD (AMW-FDTD) and the Chain MW-FDTD (CMW-FDTD) are 0.11% and 0.43%, respectively. The CPU time for the AMW-FDTD method can be reduced to about 45% of the conventional FDTD method, while the CMW-FDTD method can be reduced to about 35%.

Index Terms **─** EMP, Finite-Difference Time-Domain (FDTD), moving window, parallel computing, tunnel.

I. INTRODUCTION

Modeling the radio wave propagating over long distance in tunnel is significant for the tunnel-communication system design and the electromagnetic pulse (EMP) interference protection [1]-[6]. Recently, a new radio wave propagation model based on the finite difference time domain (FDTD) method is prevailing. However, being subject to the restriction of the stability condition and Courant criterion, the FDTD method faces severe difficulties in modeling some long distance or large-scale propagation problems for great computing requirements [7]-[8]. However, as the pulse propagates only over confined domain, large amount of computational power is wasted to update the domain that the pulse has propagated over and the domain that the pulse has not arrived.

It allows us to make the best use of the limited memory to design the FDTD mesh to move with the pulse, so as to insure the limited mesh long enough to overcast the pulse. According to this, many papers have designed the moving-window finite-difference time-domain FDTD (MW-FDTD) or the segmented (SFDTD) method [9]-[19] to solve the similar problems, but none of them are applicable for all. Of course we also could take the advantage of parallel computing using the message passing interface, but huge numbers of PCs and long computational time will be required as the modeling domain increases. Apparently, it is not a good solution to the problem.

In this paper, based on the parallel computing, two kinds of moving window FDTD (MW-FDTD) methods are presented to simulate the EMP propagation in tunnel, the results are validated by comparing with the results of the conventional parallel FDTD method. The convolution PML (CPML) is adopted to truncate the computation domain, which reduces the reflection error greatly. For the tunnel's vaulting boundary is a piece of curved dielectric surface which cannot be simulated with the conventional FDTD algorithm,

Submitted On: October 6, 2014
Accepted On: December 12, 2014

1054-4887 © 2015 ACES

here we take the technique of conformal FDTD (CFDTD) [20] to deal with it. The accuracy and the efficiency of the proposed method are proposed by comparing with the conventional parallel FDTD method. Results show that the relative errors for the AMW-FDTD 0.11%and the CMW-FDTD are $e_{rA} = 0.11\%$ and $e_{rC} = 0.43\%$, respectively. The CPU time for the AMW-FDTD method can be reduced to about 45% of the conventional FDTD method, while the CMW-FDTD method can be reduced to about 35%.

II. THEORY

A. The calculation model

The tunnel engineering always has long distance, its computational model can be seen in Fig. 1.

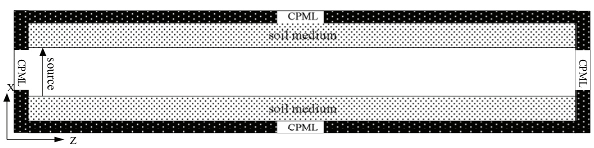


Fig. 1. The computational model of the tunnel.

Its section can be seen in Fig. 2 on the left side. The sizes of the hemline and the height are 4 m. The vault can be approximately regarded as hemi-cycle, its semi-diameter is 2 m. The relative permittivity is $\varepsilon_{rs} = 10.0$. The conductivity is $\delta = 1.0E-3$. Both ends of the tunnel and the soil domain around the tunnel are terminated by the CPML. For the tunnel's vaulting boundary is a piece of curved dielectric surface which cannot be simulated with the conventional FDTD algorithm, here we take the technique of CFDTD to deal with it, the results can be seen on the right hand of Fig. 2.

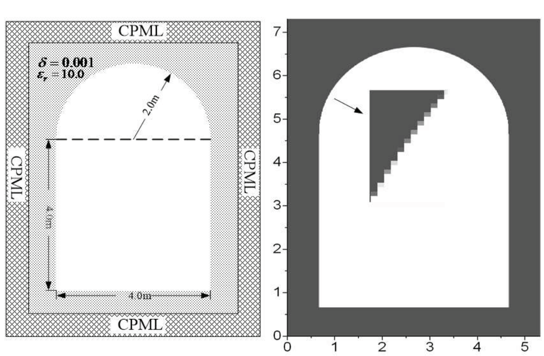


Fig. 2. The section of the tunnel.

B. Modeling of the source

In the wave-guide system, we usually use hard source to introduce the incident wave. Because the soil around the tunnel is not ideal conductor and the section is not typical wave-guide section such as cycle or rectangle, we can't obtain the field expression easily. To solve this problem, we can suppose the section as rectangle approximately, then use the mode distribution to introduce the source. Note that the mode of the pulse propagating in tunnel is not the same as the mode in wave-guide, we could assume that there are many modes at beginning, but as the wave propagating only those standing wave patterns which satisfy the boundary conditions at certain frequency will exist. Take typical mode TE10 and TM11 as example, the sizes of the rectangle are a, b.

(1) TM11 mode:

It has five field components, the field equations are as follows:

$$\begin{cases} E_x = -\dfrac{j\beta_{11}}{k_c^{\,2}}\dfrac{\pi}{a}A\cos(\dfrac{\pi}{a}x)\sin(\dfrac{\pi}{b}y)\,e^{-j\beta_{11}z} \\ E_y = -\dfrac{j\beta_{11}}{k_c^{\,2}}\dfrac{\pi}{b}A\sin(\dfrac{\pi}{a}x)\cos(\dfrac{\pi}{b}y)\,e^{-j\beta_{11}z} \\ E_z = A\sin(\dfrac{\pi}{a}x)\sin(\dfrac{\pi}{b}y)\,e^{-j\beta_{11}z} \\ H_x = \dfrac{j\omega\varepsilon}{k_c^{\,2}}\dfrac{\pi}{b}A\sin(\dfrac{\pi}{a}x)\cos(\dfrac{\pi}{b}y)\,e^{-j\beta_{11}z} \\ H_y = -\dfrac{j\omega\varepsilon}{k_c^{\,2}}\dfrac{\pi}{a}A\cos(\dfrac{\pi}{a}x)\sin(\dfrac{\pi}{b}y)\,e^{-j\beta_{11}z} \\ H_z = 0 \end{cases} . \quad (1)$$

(2) TE10 mode:

It has three field components, the field equations are as follows:

$$\begin{cases} E_y = -\dfrac{j\omega\mu a}{\pi}A\sin(\dfrac{\pi}{a}x)\,e^{-j\beta_{10}z} \\ H_x = \dfrac{\beta_{10}a}{\pi}A\sin(\dfrac{\pi}{a}x)\,e^{-j\beta_{10}z} \\ H_z = A\cos(\dfrac{\pi}{a}x)\,e^{-j\beta_{10}z} \\ E_x = E_z = H_y = 0 \end{cases} . \quad (2)$$

Suppose the source is located at $z = k_s\Delta z$, the field distribution functions $f(x,y,z)$ are shown in (1) and (2), the time function is $g(t)$, so the source can be set as:

$$E^{n+1}(i,j,k_s)=E^n(i,j,k_s)+f(x,y,z)g(t). \quad (3)$$

Usually, the time function $g(t)$ is set as high power microwave (HPM) or ultra wide-band (UWB).

HPM can be expressed as:

$$E_i(t)=\begin{cases} E_0\dfrac{t}{t_1}\sin(2\pi f_0 t) & 0<t<t_1 \\ E_0\sin(2\pi f_0 t) & t_1<t<t_1+\tau \\ E_0(\dfrac{\tau+2t_1}{t_1}-\dfrac{t}{t_1})\sin(2\pi f_0 t) & t_1+\tau<t<2t_1+\tau \end{cases}, \quad (4)$$

where, τ is the width of the pulse, t_1 is the ascending time, f_0 is the frequency of the carrier wave.

UWB can be expressed as:

$$E_i(t)=E_0 k(t-t_0)e^{-\frac{4\pi(t-t_0)^2}{\tau^2}}, \quad (5)$$

where $k=e^{0.5}\sqrt{8\pi}/\tau$. Its waveform is shown in Fig. 3.

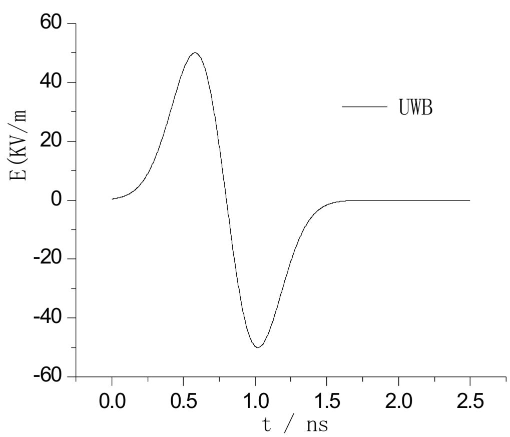


Fig. 3. The waveform for the UWB.

C. Introduction of the parallel implementation

Parallel FDTD is a kind of algorithm that the computational domain is divided into several sub-domains and each node only handle for the corresponding sub-domain calculation. As we can see from Fig. 1, that the tunnel is elongated in one direction. For simplicity, the one-dimensional parallel FDTD division is used in this paper. Along the z direction, the whole domain can be divided into several sub-domains, which can be seen in Fig. 4.

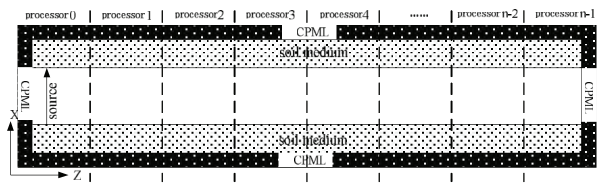


Fig. 4. The parallel model of the tunnel.

The Message Passing Interface (MPI) is a standard specification of a set of libraries call for passing messages between computers interconnected via a data communication network. According to the domain decomposition, each sub-domain can be treated as a process, and MPI connects these processes together.

By using this method, only the first and the last process need to be disposed specially, because of the CPML. Other processes can be implemented all the same. In one iterative only needs to exchange the magnetic field in the nearby processes. The data exchanging can be seen in Fig. 5.

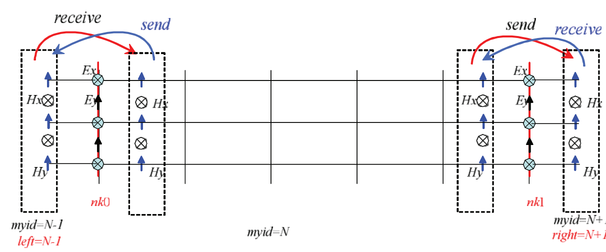


Fig. 5. The data exchanging between two nearby processes.

D. Calculation results

Take TE10 mode as the source, the field components are shown in equation (2) $a=6.0\text{m}$. We choose UWB as the time function. $\tau=3.0\text{ns}$, $t_0=2\tau$. $\Delta x=\Delta y=\Delta z=0.01333\text{m}$, $\Delta t=\Delta z/(2v_p)$, v_p is the velocity of the pulse in tunnel.

The length of the tunnel is 40 m. The results are shown in Fig. 6. On the left side it is the distribution of E_y , on the right side the waveforms for different distances are given. It can be seen in Fig. 6 (a) that the energy is concentrated in a small region. From Fig. 6 (b), we can find when the distance is increasing the waveform broadened.

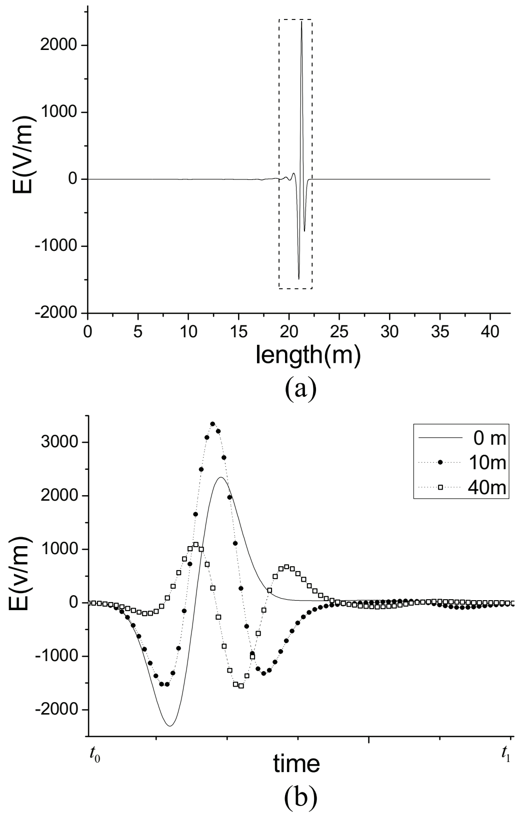


Fig. 6. The waveform of the calculation results.

III. IMPLEMENTATION OF THE MW-FDTD METHOD

From the forgoing section we know that the energy is concentrated in a small region when the wave is propagating in 40 m tunnel, in the other region we can nearly set as zero. However, we calculate the whole region including the zero region, so large amount of computational resources are wasted to update the domain that the pulse has propagated over and the domain that the pulse has not arrived. It allows us to make the best use of the limited memory to design the FDTD mesh to move with the pulse, so long as to insure the limited mesh long enough to overcast the pulse. In this section two different MW-FDTD methods are introduced to solve this problem.

A The alternate MW-FDTD method

The calculation model for the Alternate MW-FDTD (AMW-FDTD) method is shown in Fig. 7. Compare with the conventional parallel FDTD method, the AMW-FDTD has four CPMLs, CPML1 and CPML4 are the same with the conventional method, CPML2 and CPML3 are in the middle of the tunnel, by using the alternate of the four CPMLs the iterative can be implemented.

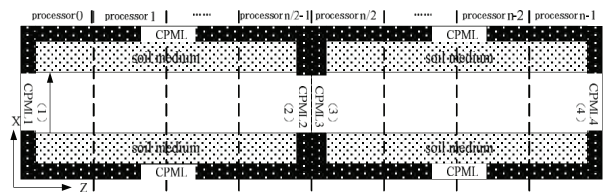


Fig. 7. The calculation model for the AMW-FDTD method.

The procedures of the AMW-FDTD method are list as follows.

First step, join interface 2 to interface 3, CPML2 and CPML3 are out of work, see in Fig. 8. Run the conventional FDTD updating with the source of the pulse added at the source interface.

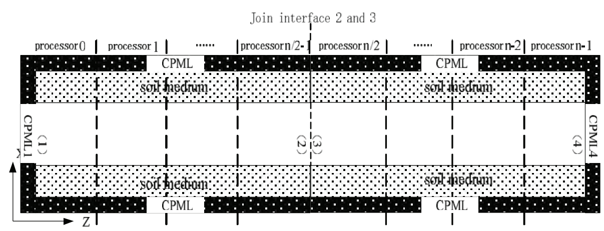


Fig. 8. The first step for the AMW-FDTD method.

Second step, when the pulse move to interface 4, set the domain including CPML between interface 1 and interface 2 to be zeros, join interface 4 to interface 1 conducting the pulse propagate to interface 2, take the CPML2 and CPML3 into function, set CPML4 and CPML1 out of work and stop the source adding at the source interface, see in Fig. 9.

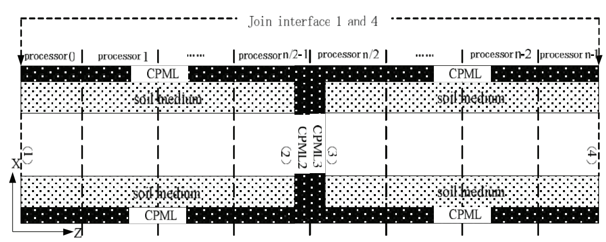


Fig. 9. The second step for the AMW-FDTD method.

Third step, when the pulse arrives at interface 2, set the field between interface 3 and interface 4 to be zeros, join interface 2 to interface 3 to conduct the pulse move to interface 4, and take CPML1 and CPML4 into function, see in Fig. 8.

Fourth step, follow the second step when the pulse arrives at interface 4. And the around-CPML of the tunnel is in function through the procedures.

To verify the efficiency and accuracy of the AMW-FDTD method, the calculation results are compared with the conventional parallel FDTD method. For the constraint of the computational resources, the conventional method can only calculate limited distances. For the AMW-FDTD method, the reflection error of the CPML and the cut error of the window are the main error. So when we expand the window the error can be reduced. First, we run the code with 500 grids. Figure 10 (a) shows the waveform for the AMW-FDTD method and the conventional method at 40 m, results show they agree well with each other. When we change the window to 1000 grids, the results in Fig. 10 (b) show good agreement with each other. So we can conclude that the reflection error and the cut error are negligible.

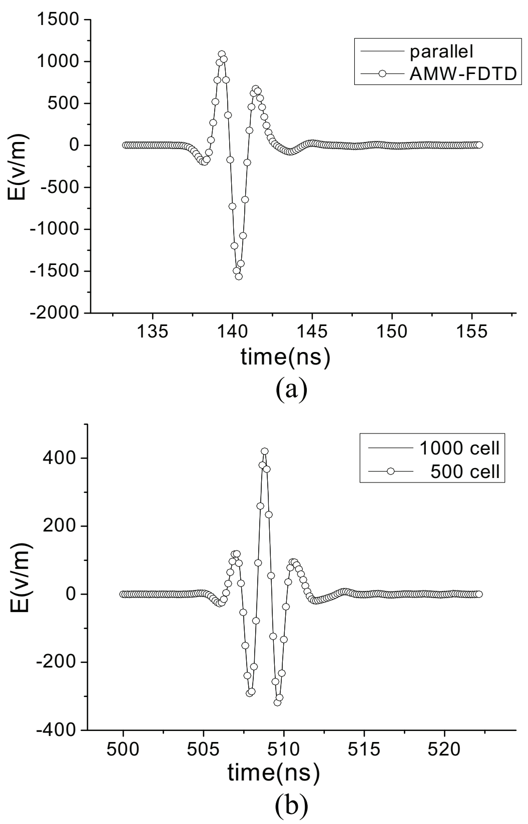


Fig. 10. The waveform for AMW-FDTD method at 40 m and 150 m.

Figure 11 shows the field attenuation at 40 m and 150 m. Results show the high frequency part attenuates slowly than the low frequency, which is consistent with the physical process.

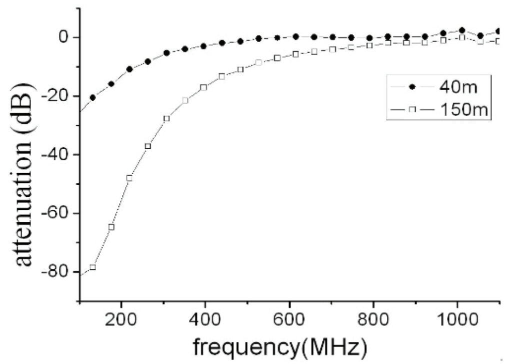


Fig. 11. The field attenuation at 40 m and 150 m.

B. The chain MW-FDTD method

The calculation model for the Chain MW-FDTD (CMW-FDTD) method is shown in Fig. 12. Instead of the right CPML in the conventional parallel FDTD method, it has a moving reset area, which is used to set the tail of the pulse to be zero, so that we can reduce the error.

The procedures of the CMW-FDTD method are list as follows.

First step, run the conventional FDTD method, the moving reset area moves along with time step.

Second step, when the left propagating pulse is totally absorbed by the CPML, join interface 1 and interface 2, form an annular iterative domain, which can be seen in Fig. 13.

To verify the efficiency and accuracy of the CMW-FDTD method, the calculation results are also compared with the conventional parallel FDTD method. Figure 14 (a) shows the waveform for the CMW-FDTD method and the conventional method at 40 m, results show they agree well with each other. The results for 150 m in Fig. 14 (b) show good agreement with the AMW-FDTD method.

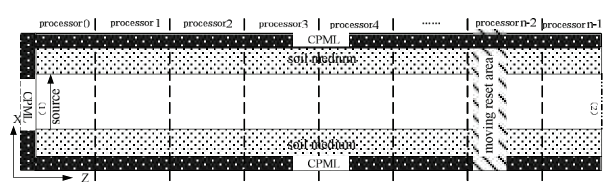


Fig. 12. The calculation model for the CMW-FDTD method.

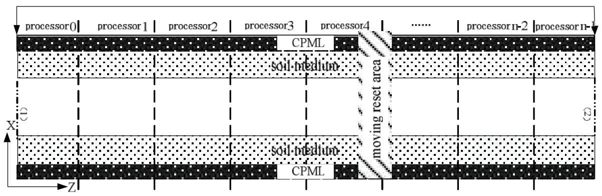
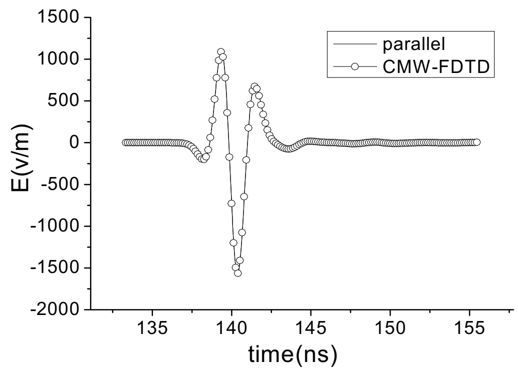
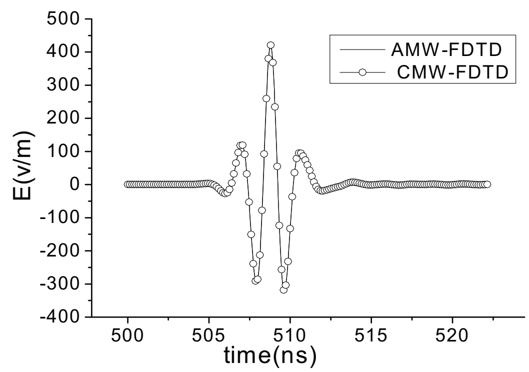


Fig. 13. The second step for the CMW-FDTD method.



(a)



(b)

Fig. 14. The waveform for CMW-FDTD method at 40 m and 150 m.

IV. ANALYSIS OF THE ACCURACY AND THE EFFICIENCY

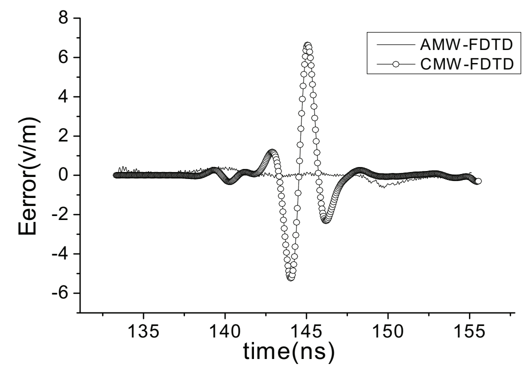
A. The calculation error for two different methods

To compare the calculation error of the two different MW-FDTD methods, we choose the conventional FDTD method as the reference. The relative error can be given as:

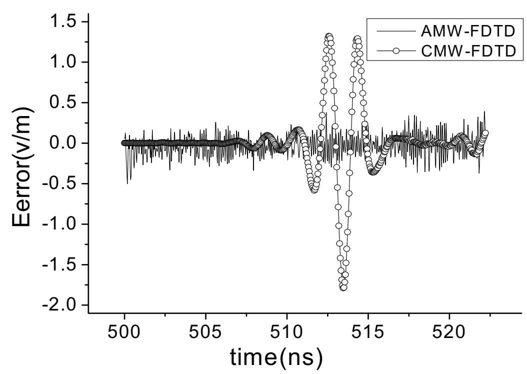
$$e_r = \frac{\left|E^*(t) - E(t)\right|_{\max}}{\left|E(t)\right|_{\max}}, \tag{6}$$

where $E(t)$ is the reference results, $E^*(t)$ is the MW-FDTD results.

Figure 15 shows the absolute error for two different MW-FDTD method. Substitute the results into equation (5), we can obtain the relative error for 40 m are $e_{rA} = 0.0415\%$ and $e_{rC} = 0.42\%$, respectively. And the relative error for 150 m are $e_{rA} = 0.11\%$ and $e_{rC} = 0.43\%$, respectively. So we can conclude that the calculation error for the AMW-FDTD method is smaller than the CMW-FDTD method. The relative error for the CMW-FDTD method is about 0.4%.



(a)



(b)

Fig. 15. The absolute error for two different CMW-FDTD methods at 40 m and 150 m.

B. The calculation efficiency for two different methods

In this section, the calculation efficiency is proposed. Table 1 shows the calculation resources and time for the AMW-FDTD, the CMW-FDTD and the conventional method at 40 m. From Table 1 we can see that the relative error for the AMW-FDTD method is less than 0.12%, for the CMW-FDTD method is about 0.43%, which means both the two proposed MW-FDTD methods have high accuracy. On a core2 2.4-GHz machine, it took the FDTD method 27.3h and the AMW-FDTD method

12.4h, which is 9.8h in the CMW-FDTD method. So compare with the conventional FDTD method the CMW-FDTD method has the highest efficiency. When the propagating distance is 200 m the calculation resources and efficiency for the two different MW-FDTD methods are shown in Table 2. For the limited of the computational resource this time the conventional method can't run. The memory for the AMW-FDTD and the CMW-FDTD method is 295 MB and 161.5 MB, respectively. The running time is 24.5h for the AMW-FDTD method and 14.0h for the CMW-FDTD method.

Table 1: The resource and efficiency for different methods at 40 m

	FDTD	AMW-FDTD	CMW-FDTD
Memory (MB)	1145	483	348
Time (hour)	27.3	12.4	9.8
Relative error	—	0.12%	0.43%

Table 2: The resource and efficiency for different methods at 200 m

	AMW-FDTD	CMW-FDTD
Memory (MB)	295	161.5
Time (hour)	24.5	14.0

V. CONCLUSION

In this paper, we present two different MW-FDTD methods to simulate the electromagnetic propagating in tunnel. Numerical results indicate that the proposed methods are accurate and efficient. The CPU time for the AMW-FDTD method can be reduced to about 45% of the conventional FDTD method, while the CMW-FDTD method can be reduced to about 35%. The relative error for the AMW-FDTD method is less than 0.12%, for the CMW-FDTD method is about 0.43%, which means both the two proposed MW-FDTD methods have high accuracy.

ACKNOWLEDGMENT

This work was supported by Chinese National Science Foundation under Grant No. 60971063.

REFERENCES

[1] D. G. Dudley, M. Lienar, S. F. Mahmud, and P. Degauque, "Wireless propagation in tunnels," *IEEE Antennas Propag. Magazine*, vol. 49, 11-26, 2007.

[2] Y. P. Zhang, "Novel model for propagation loss prediction in tunnels," *IEEE Trans. Veh. Technol.*, vol. 52, 1308-1314, 2003.

[3] E. Heyman, R. Kastner, and R. W. Ziolkowski, "Hybrid Ray-FDTD moving window approach to pulse propagation," *Journal of Computational Physics*, vol. 138, 480-500, 1997.

[4] J. F. Liu, X. L. Xi, G. B. Wan, and L. L. Wang, "Simulation of electromagnetic wave propagation through plasma sheath using the moving window finite-difference time-domain method," *IEEE Trans. on Plasma Science*, vol. 39, 852-855, 2011.

[5] G. S. Ching, M. Ghoraishi, M. Landmann, and H. Sakamoto, "Wideband polarimetric directional propagation channel analysis inside an arched tunnel," *IEEE Trans. Antennas Propagat.*, vol. 57, 760-767, 2009.

[6] K. Guan, Z. Zhong, B. Ai, and C. Briso-Rodriguez, "Complete propagation model in tunnels," *IEEE Antennas and Wireless Propagation Letters*, vol. 12, 741-743, 2013.

[7] K. S. Yee, "Numerical solution of initial boundary value problems involving Maxwell's equations in isotropic media," *IEEE Trans. Antennas Propagat.*, vol. 14, 302-307, 1966.

[8] A. Taflove and S. C. Hagness, *Computational Electrodynamics: The Finite-Difference Time-Domain Method*, 2nd ed., Boston, MA: Artech House, 2000.

[9] J. W. Schuster, K. C. Wu, R. R. Ohs, and R. J. Luebbers, "Application of moving window FDTD to predicting path loss over forest covered irregular terrain," *Antennas and Propagation Society International Symposium*, 1607-1610, 2004.

[10] Y. Wu and Ian Wassell, "Introduction to the segmented finite-difference time-domain method," *IEEE Trans. on Magnetics*, vol. 45, 1364-1367, 2009.

[11] M. Masud Rana and A. Sanagavarapu Mohan, "Segmented locally one dimensional FDTD method for EM propagation inside large complex tunnel environments," *IEEE Trans. on Magnetics*, vol. 48, 223-226, 2012.

[12] F. Akleman and L. Sevgi, "Realistic surface modeling for a finite difference time domain

wave propagator," *IEEE Trans. Antennas Propagat.*, vol. 51, no. 7, July 2003.

[13]F. Akleman and L. Sevgi, "A novel finite difference time domain wave propagator," *IEEE Antennas and Propagat.*, vol. 48, no. 5, 839-841, 2000.

[14]S. A. Torrico, H. L. Bertoni, and R. H. Lang, "Modeling tree effects on path loss in a residential environment," *IEEE Trans. Antennas Propagat.*, vol. 46, 1998.

[15]K. Wu and J. Schuster, "Application of moving window FDTD to modeling the effects of atmospheric variations and foliage on radio wave propagation over terrain," *IEEE Military Communications Conference*, 2004.

[16]B. Fidel and E. Heyman, "Hybrid Ray-FDTD moving window approach to pulse propagation," *Journal of Computational Physics*, vol. 138, 480-500, 1997.

[17]M. O. Ozyalcin, F. Akleman, and L. Sevgi, "A novel TLM-based time-domain wave propagator," *IEEE Trans. Antennas Propagat.*, vol. 51, no. 7, 2003.

[18]Z. Kang, et al., "An efficient 2-D compact precise integration time domain method for longitudinally invariant waveguiding structures," *IEEE Trans. Microwave Theory and Techniques*, 2013.

[19]M. Hadi and S. Mahmoud, "A high order compact-FDTD algorithm for electrically large waveguide analysis," *IEEE Trans. Antennas and Propagation*, 2008.

[20]K. K. Mei, A. C. Cangellaris, and D. J. Angelakos, "Conformal time domain finite differentce method," *Radio Science*, 1145-1147, 1984.

Yun-Fei Mao was born in Zhejiang Province, China, in 1984. He received the B.S. degrees, the M.S. degree and the Ph.D. degree in Electric Systems from Nanjing Engineering Institute, Nanjing, China, in 2006, 2009 and 2013 respectively. He is currently working with China Satellite Maritime Tracking and Control Department, Yuan Wang Ⅲ, Jiangyin 214400, China. His research interests include computational electromagnetic and electromagnetic tracking.

Jia-Hong Chen was born in Jiangsu, China, in 1969. He received the B.S. and M.S. degrees from National University of Defense Technology, Changsha, China, in 1982 and 1987, respectively, and the Ph.D. degree in Control Engineering from Xi'an Jiao Tong University, Xi'an, China. His research interests include electromagnetics and electromagnetic tracking.

Liang Pan was born in Zhejiang Province, China, in 1967. He received the B.S. degrees from Zhejiang University, Zhejiang, China, in 1988. He received the M.S. degrees from Nanjing University of Science and Technology, Nanjing, China, in 2007. He is currently working with China Satellite Maritime Tracking and Control Department, Jiangyin 214400, China. His research interests include inertial navigation and electromagnetic tracking.

Xiao-Ming Wang was born in Jiangsu Province, China, in 1980. He received He received the B.S. in Industrial Automation from Jiangsu University, Zhenjiang, China, in 2002, and the M.S. degree in Control Theory and Control Engineering from Southeast University, Nanjing, China, in 2005. He is currently working with China Satellite Maritime Tracking and Control Department, Jiangyin 214400, China. His research interests include electromagnetics and electromagnetic tracking.