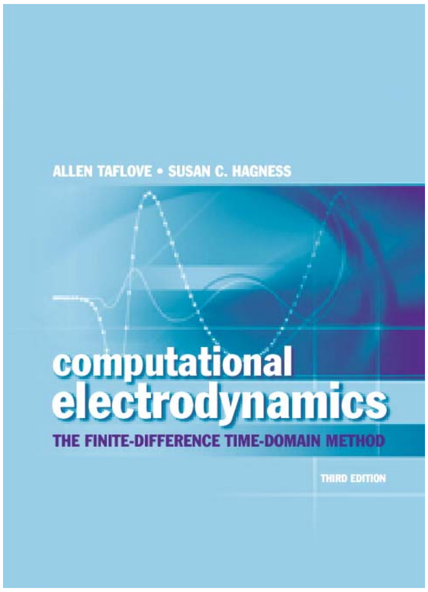
Book Review

By Guest Associate Editor: James L. Drewniak, Electromagnetic Compatibility Laboratory, University of Missouri-Rolla

Title: Computational Electrodynamics: The Finite-Difference Time-Domain Method, Third Edition
Authors: Allen Taflove and Susan C. Hagness
Publisher: Artech House
Year Published: 2005
ISBN: 1-58053-832-0
Number of pages: 1006

The third edition of Allen Taflove's and Susan Hagness's FDTD book is a thousand pages providing a comprehensive treatment of the method from fundamental principles and formulation to the latest developments and applications. As the development and application of the FDTD method has grown, so has the scope of the material in this book. Four new Chapters have been added that relate to new developments in the field since the second edition, and revisions and/or material have been added to existing Chapters to enhance clarity or expand the treatment. Overall, it is a wonderful text for a newcomer to the method suitable to practicing engineers and scientists, as well as a university course for senior level undergraduates or beginning graduate students. Further, it is sufficiently comprehensive and provides a good reference on aspects of the latest developments in the FDTD method. The fundamental material comprises Chapters 2-10, and applications and more recent developments in FDTD are given in Chapters 11-20. The preface to the Third Edition provides a very nice overview of the new material added.

The FDTD method in the past 40 years has grown from an academic endeavor, kept alive by a handful of people, including the senior author of this book, for at least the first 20 of these, to being widely applied across a wide range of engineering and scientific problems. The list of applications is long and includes antennas, EM and acoustic propagation, shielding, packaging, signal integrity, power distribution design in printed circuits, RF and microwave circuits, photonics, and many more. The primary attributes of the method are that it is easy to understand and can be formulated directly from the integral form of the Maxwell equations, is simple to implement, can handle all types of media, and electrodynamic phenomena



that can be incorporated into the Maxwell equations, and can be, and is typically robust and accurate, for a very wide class of problems and range of applications. It is not without its "warts", however, including the computational resources required to model practical problem spaces, and the numerical rate of the problem solution associated with marching the wave in time throughout the computational domain. This can be typically onerous for problems where the mesh dimension is dictated by geometry feature sizes. As the cost of FLOPs and RAM continues to decrease, so does this problem. Further, FDTD lends itself very well to parallel implementation. With a Linux cluster, and public domain MPI routines, developing a parallel implementation of FDTD is cheap and easy.

Chapter 1 begins with an overview of the FDTD method. Part of the Chapter is "gee-whiz" examples of applications that show the power of the method with complex applications. The examples chosen are complex and diverse to give the reader a notion of the span of applications. A timeline of the FDTD development is also given that provides some perspective on the history and exploding interest in, and applications of, the method. Chapter 1 also gives an overview of the nature of space-grid time-domain methods that is very helpful for newcomers to the FDTD method. The extensive references in Chapter 1 are also very nice. It is easy for one to skip the introductory Chapter in a book, however, this is one well worth reading!

Chapters 2-5 present fundamental material of the FDTD method that begins with a 1D formulation in Chapter 2 by finite differencing the wave equation, and proceeding with a discussion of stability and dispersion. Stability and dispersion are at the heart of whether a result is achieved or the merits of the result with FDTD, and an insightful choice of treatment is provided here that gives the reader new to the method a good perspective on numerical stability and dispersion. Well-chosen examples are illustrative. Proceeding to Chapter 3, it is worth jumping to Section 3.6.8 -3.6.9, after reading Section 3.2, which gives a formulation of the explicit implementation that begins with the Maxwell equations in integral form, and shows the divergence less nature of the method. Seeing the formulation beginning from the integral equations gives a very clear picture on the implementation in space and time of the circulation integrals. The preservation of the zero divergence inherent in the Ampere and Faraday laws as written in the Maxwell equations is a critical aspect, and well worth noting. The basic Yee algorithm (rectangular grid) and the explicit difference equations for the FDTD method are given in Chapter 3 as well. Chapter 3 concludes with an application of alternate gridding options within the method as applied to ELF wave propagation around the earth. The implementation of these alternate grids is very clear if the method is considered from the discretization of the Maxwell equation circulation integrals, and any such grid where the E and H circulation integrals are at right angles to each other.

Chapter 4 provides a substantial treatment and discussion of numerical dispersion and stability. Numerical dispersion will limit the accuracy of the FDTD solution. The dispersion relation gives the propagation constant for the wave as a function of direction. For a traveling wave, this is related to wave speed. Since the FDTD method is a discretization of the exact equations, the wave speed as compared to the actual continuous value is lower, and depends on the number of mesh cells per wavelength, but does approach the continuous value, as the mesh is made finer. Further, the dispersion is direction dependent, i.e., propagating along one of the grid axes, as opposed to at an angle with them will result in different numerical wave speeds. The treatment is sufficiently detailed to give the reader a good understanding of dispersion, yet very readable. Stability is also discussed in Chapter 4 and the CFL stability criterion shown, which essentially states that the explicit FDTD algorithm can not be stepped in time any faster than the wave should be moving out in space and time. If a speed = distance/time calculation yields a delay for the wave from one point to another, the wave cannot be stepped in time, given a specific grid, to arrive numerically before this time. A cautionary note is given in Section 4.8 that I greatly appreciate, which indicates that augmenting algorithms introduced on the basis of approximations into the Yee scheme can in general lead to late time instabilities. This is not to say that in many engineering applications good results cannot be achieved prior to this occurrence. Chapter 4 concludes with an overview of the alternating-direction-implicit FDTD (ADI-FDTD) where the time integrations are done implicitly (matrix solution) as opposed to the usual explicit time-marching equations.

Implementing source conditions into the FDTD method is presented in Chapter 5. Sources can be introduced in two ways in wave motion, either directly into the equations of motion, here the Maxwell equations, or the wave equation as a forcing function. Alternatively, the sources can be introduced as forcing functions through the boundary conditions. In the first case, these sources do not cause any scattering for waves incident on them, and are referred to as "soft" sources. Any wave incident on this type of source moves right through it as if it was transparent, and the local field is a superposition of any incoming waves and the soft source. Alternatively, the electric or magnetic fields can be specified at some location(s) in the grid, referred to as "hard" sources, and constitute a boundary condition that results in wave scattering from those grid cells. Local hard- and soft-sources are discussed in the first portion of the Chapter. Plane wave excitation through a total-field/scattered-field formulation is presented in the last half of the Chapter. Plane wave excitation arises in applications that include shielding, radar cross-section, and antenna reception on complex structures, and the detailed discussion is helpful to understand how a plane wave can be synthesized within the FDTD method.

Absorbing boundary conditions for terminating the FDTD mesh are given in Chapters 6-7. Analytical methods for terminating the mesh are presented in Chapter 6. In one sense, the Chapter is a historical overview of these approaches. Since the FDTD grid must be truncated at some point outside the scattering region for the problem of interest, early methods sought to ensure the Sommerfeld radiation condition, or out-going waves, at the truncation boundary. These conditions were typically formulated analytically. Accuracy and stability were always issues with these methods, though the additional computational burden imposed for these cases was modest. The perfectly-matched-layer (PML) absorbing boundary condition introduced by Berenger is presented in Chapter 7. Essentially these layers terminate the FDTD grid by applying a set of layers such that there is zero reflection at the interface between the terminated computational domain and the PML region over all angles of incidence, while attenuating the wave as it propagates in the PML layers. Then, a conducting sheet with perfect electric conductor boundary conditions terminates the PML layers. An overview of Berenger's original split field formulation is given. Another formulation for perfectly matched layers, i.e., uniaxial PMLs is detailed in Chapter 7, and a computationally efficient approach is provided in detail. This material is more than academic, since the original Berenger formulation can consume an inordinate portion of the computation time in many practical problems.

Near-field-to-far-field transformation is presented in Chapter 8. Equivalent currents on a virtual surface obtained from the fields on that surface, which in the FDTD method is a rectangular box around the scatterers, can be used to transform the near fields to the far fields. This can be done after the time-domain simulation is concluded, and Fourier transforming the time history of the equivalent currents, or by a direct time-domain transformation. Both are discussed in Chapter 8.

Incorporation of dispersive, non-linear, and gain materials into the FDTD method are discussed in Chapter 9. There are many aspects of the FDTD method that distinguishes it from integral equation or finite element formulations, and ease of handling these kinds of materials is one. The dispersive properties over frequency for many materials can be described as Debye, Lorentzian, or a linear combination of these types of terms. The corresponding circuit behaviors are RC, or RLC circuits – both under damped and critically damped. Since the material behavior satisfies the Kramers-Kronig relations (ensuring causality), it can be incorporated into the FDTD equations in a self-consistent, and stable manner. Two methods have been developed for doing this, i.e., a recursive convolution approach that is well suited to FDTD, or an auxiliary differential equation (ADE) approach, and both are detailed in Chapter 9. Modeling of non-linear phenomena using an ADE is demonstrated with optical solution propagation, and the ADE approach for modeling lasing in a four-level, two-electron atomic system is also presented.

Another distinguishing feature of the FDTD method is the ease of developing and integrating local sub-cell models, which are presented in Chapter 10 for several significant cases including slots, curves on conducting surfaces, thin wires, thin material sheets, and conductor skin-effect losses. With these models, feature sizes smaller than the grid dimensions can be modeled without having to mesh down to fine dimensions. Section 10.5, which presents a sub-cell model for a thin wire, illustrates very well the manner in which appropriate field behavior asymptotics can be integrated into the FDTD method, as long as the physics are self-consistent. The examples given in Chapter 10 are important, but the underlying methodology is more widely applicable. A selected biography at the end of the Chapter provides wider reading in this regard.

The second half of the book in Chapters 11-20 are devoted to applications, recent developments, and more specialized topics. Non-uniform, non-orthogonal unstructured grids, and sub-grids are discussed in Chapter 11. A limitation in the time-honored Yee FDTD algorithm is accurate boundary fitting within a scattering problem. Because the algorithm is on a structured mesh where the E and H circulation integral loops are interleaved, and in planes that are orthogonal to each other, typically a rectangular coordinate system, material boundaries are approximated in a stair-step fashion. This leads to either crudely approximated boundaries, or a very fine mesh to approximate a boundary that may have small radii of curvature, as well as potential electromagnetic artifacts of the stair casing itself, all of which are undesirable. A generalized Yee algorithm is discussed in Chapter 11 that allows for non-orthogonal hexahedral cells used in a general, unstructured mesh. These general cells can then be used for boundary fitting with a planar or linear approximation in a similar fashion that is a strength of the finite element method. Sub-gridding is also discussed in Chapter 11, where a locally reduced mesh is embedded in a larger mesh dimension.

Chapter 12 and 13 are more specialized Chapters that present FDTD applied to bodies of revolution and periodic structures. The FDTD method for bodies of revolution that are most naturally modeled in a cylindrical coordinate system is given in Chapter 12. The discussion proceeds by discretizing the Ampere and Faraday laws in integral form of the Maxwell equations. The discussion is detailed and easy to follow for this class of problems. Modeling of periodic structures is presented in Chapter 13. Typical applications are frequency selective surfaces and electromagnetic bandgap structures for selective shielding and filtering applications, as well as large antenna arrays. Different approaches for modeling periodic structures are presented, as well as discussions of stability and dispersion. Again, this Chapter is more specialized, but covers a class of problems of growing importance in a clear and concise fashion.

Modeling of antennas with FDTD is presented in Chapter 14. The first portion of the Chapter focuses on modeling the antenna feed and the temporal variation of the source. The discussion and figures provide good insight into modeling with FDTD in general, though the application is specific to antennas. The specific examples are probe-fed bow-tie monopoles, and probe-fed waveguide horn antennas. Other specific antenna examples are given, including a detailed case-study for a tri-band cellular telephone radiating near a human head model, which gives not only an example of the power and utility of the method, but how to apply it for practical engineering.

Modeling of printed circuits with linear passive and non-linear active loads is detailed in Chapter 15. Integrating lumped circuit elements into the FDTD formulation is shown in detail, including general two terminal lumped networks. Direct linking of FDTD and SPICE is also discussed. Specific examples are given for modeling of power distribution in a multi-layer printed circuit board, and a 6 GHz MESFET amplifier. Extrapolation of an FDTD time-history, and interpolation of frequency spectra are also considered in a section of this Chapter.

Chapter 16 on photonics applications of FDTD is the longest Chapter in the book, with a very extensive set of references. The Chapter focuses on FDTD modeling and results for specific optical devices including coupled micro cavity ring and disk resonators, a coupled race-track device, distributed Bragg reflector devices, a VCSEL device, and photonic bandgap structures. The FDTD method is ideally suited to modeling the dispersive nature of the optical materials either through an auxiliary differential equation, or using recursive convolution, methods given in Chapter 9. FDTD modeling, and the results for the various structures are presented and discussed with an emphasis on extracting relevant physics and performance analysis. Analysis and design of optical components and devices has historically relied on analytical solutions. Chapter 16 clearly details the suitability of FDTD for these problems and the engineering design discovery that it allows.

Chapter 17 and Chapter 18 are on topics that are at the research boundary in the time-domain solutions of the Maxwell equations. Chapter 17 on advances of pseudo-spectral time domain techniques gives an overview of other approaches besides central differencing for approximating the spatial derivatives in the differential form of the Maxwell equations. The advantage is a more rapid decrease in numerical dispersion error as the mesh dimension decreases. An underlying framework for unconditionally stable time-domain algorithms is given in Chapter 18. The discussion is entirely mathematical in nature, but provides a nice treatment on properties of these algorithms in a concise manner.

A hybrid FDTD/time-domain finite element approach is described in Chapter 19. One of the shortcomings of the classic Yee algorithm is the need for a structured, rectangular mesh. A significant advantage of the finite element method is that it in general is applied to an unstructured mesh, and a great deal of effort has been invested over the years in developing suitable mesh generators. A hybrid FDTD-FE method seeks to take advantage of the suitability of finite elements for boundary fitting in an unstructured mesh, while using FDTD in all its simplicity in dealing with the spatial derivatives, and robustness in the larger volume of the computational domain. An overview of the chronology of attempts at a hybrid FDTD-TDFEM approach is given. Typically these approaches have exhibited late-time instabilities. A brief overview of the FE method is given including a description of several element geometries. Treatment of the FDTD-TDFEM interface is discussed, and a proof of stability is given.

Implementing the Yee algorithm in hardware is discussed in Chapter 20. A brief overview of efforts in this area is given, as well as a discussion of the hardware implementation. The merits of FPGA and graphical processing units as the underlying hardware platforms are presented. In short, the approach is to exploit the inherent parallelism in the FDTD method and to achieve gains over paralleling on multiple PC platforms using software by implementing the method on silicon over several processors. These ideas and the implementation are still somewhat embryonic, however, the importance of considering electromagnetic interactions in the development and design of high-speed and wireless electronics and the large computational burden of such problems as one example will continue to provide impetus in this area.

Overall, I find this to be a wonderful book, both as a learning resource and a reference. The treatment of fundamental concepts and historical developments in the first half of the book are detailed and easy to follow. The second half of the book detailing applications and recent developments is a good ready reference, and in general the references at the end of each Chapter provide good guidance on exploring a topic in more detail. **EMC**