ELEC 621 NUMERICAL TECHNIQUES IN ELECTROMAGNETICS

Wolfgang J.R. Hoefer, Professor
Department of Electrical and Computer Engineering
University of Victoria, Victoria, B.C.
Canada V8W 3P6
Tel. (250) 721-6030
Fax (250) 721-6230
EMail: WHoefer@ece.uvic.ca

Fall 2005

Assessment: Project and Seminar Presentation: 25% Mid-term : 25% Final: 50%

Office hours: Tuesdays and Thursdays from 14:00 to 16:00 h
Location: EOW 419

Lectures:

Sept. 09 – Dec. 03:	Tuesdays and Thursdays	16:00 to 17:30 h	MAC D114

(Scheduling Info is available at http://uvvm.uvic.ca/~zzsyst01/ttservx.*cgi)

Sep. 8, 2005	First lecture:	16:00 to 17:30 h	MAC D114
Oct. 11, 2005:	Midterm Examination,	16:00 to 17:30 h	MAC D114
Nov. 10, 2005	Reading Break, no lecture		

For a detailed schedule of lectures see the Lecture Timetable on Page 4.

Text: (required)
Richard C. Booton, Jr.
Computational Methods for Electromagnetics and Microwaves
John Wiley & Sons, New York, 1992

References: (optional)

Tatsuo Itoh (Editor)
Numerical Techniques for Microwave and Millimeter-Wave Passive Structures
John Wiley & Sons, New York, 1989

Matthew N.O. Sadiku
Numerical Techniques in Electromagnetics
CRC Press, Roca Baton, 1992

Eikichi Yamashita (Editor)
Analysis Methods for Electromagnetic Wave Problems
Artech House, Boston, 1990

Roberto Sorrentino (Editor)
Numerical Methods for Passive Microwave and Millimeter Wave Structures,
IEEE Press, New York 1989:

Wolfgang J.R. Hoefer, Poman P.M. So
The Electromagnetic Wave Simulator
John Wiley & Sons, Chichester, 1991

Various Selected Journal and Conference Publications

Grading Scheme

The final grade obtained from the above marking scheme will be based on the following percentage-to-grade point conversion.

90	≤	A+	≤	100	
85	≤	A	<	90	
80	≤	A-	<	85	
75	≤	B+	<	80	
70	≤	B	<	75	
65	≤	B-	<	70	
60	≤	C+	<	65	
55	≤	C	<	60	
50	≤	D	<	55	
35	≤	E	<	50	Fail, conditional supplemental exam – <u>for undergraduate courses only</u>
		F	<	35	Fail, no supplemental.
		N			Fail, did not write examination or otherwise complete course requirements by the end of the term or session; no supplemental exam.

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1. Where classes or examinations are scheduled on the holy days of a religion, students may notify their instructors, at least two weeks in advance, of their intention to observe the holy day(s) by absenting themselves from classes or examinations.
2. Instructors will provide reasonable opportunities for such students to make up work or missed examinations.
3. Students will cooperate by accepting the provision of reasonable opportunities for making up work or missed examinations.
4. The University Secretary's Office will distribute a multi-faith calendar to each academic unit annually.

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Syllabus, Course Objective and General Description

To introduce participants to the numerical modeling of electromagnetic fields in both the time and frequency domains. Emphasis will be on the solution of electromagnetic wave problems as encountered in microwave/millimeter-wave/optical engineering. The course focuses on the formulation of modeling algorithms and procedures as well as their implementation. The relation between the numerical formulation and the classical analytical presentation of electromagnetics will be stressed throughout the course. At the same time, typical guiding and radiating structures as well as EMI/EMC situations will be solved to demonstrate the capabilities of the methods. During the course, two- and three-dimensional dynamic field simulators will be demonstrated to facilitate the understanding of the various algorithms by observing their effect directly on the computer screen.

1 Theoretical Foundations

2 Models of Electromagnetic Wave Propagation

3 Introduction to Numerical Methods

4 Method of Moments

5 Finite Difference Method

6 Finite Difference Time Domain Method

7 TLM Method

8 Finite Element Method

9 Spectral Domain Method

10 Student Projects

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Time Table for ELEC 621
Numerical Techniques in Electromagnetics
2005

Date	Day	Room	From	To	# hrs	L#	Topic
08 Sept.	Thu	MAC D114	16:00	17:30	1.5 h	01	Theoretical Foundations
13 Sept.	Tue						No lecture (Travel)
15 Sept.	Thu						No lecture (Travel)
20 Sept.	Tue	MAC D114	16:00	17:30	1.5 h	02	Huygens' Principle and Maxwell's Eqs
20 Sept.	Tue	MAC D114	17:30	19:00	1.5 h	03	Wave Equations and Propagation
22 Sept.	Thu	MAC D114	16:00	17:30	1.5 h	04	Scalar and Vector Potentials
22 Sept.	Thu	MAC D114	17:30	19:00	1.5 h	05	Green's Functions
27 Sept.	Tue	MAC D114	16:00	17:30	1.5 h	06	Method of Moments 1
27 Sept.	Tue	MAC D114	17:30	19:00	1.5 h	07	Method of Moments 2
29 Sept.	Thu	MAC D114	16:00	17:30	1.5 h	08	Finite Differences Frequency Domain 1
29 Sept.	Thu	MAC D114	17:30	19:00	1.5 h	09	Finite Differences Frequency Domain 2
04 Oct.	Tue						No lecture (Travel)
06 Oct.	Thu						No lecture (Travel)
11 Oct.	Tue	MAC D114	16:00	17:30	1.5 h		Midterm Examination
13 Oct.	Thu	MAC D114	16:00	17:30	1.5 h	10	Finite Differences Time Domain 2D-1
13 Oct.	Thu	MAC D114	17:30	19:00	1.5 h	11	Finite Differences Time Domain 2D-2
18 Oct	Tue	MAC D114	16:00	17:30	1.5 h	12	Finite Differences Time Domain 3D-1
20 Oct.	Thu	MAC D114	16:00	17:30	1.5 h	13	Finite Differences Time Domain 3D-2
25 Oct	Tue	MAC D114	16:00	17:30	1.5 h	14	TLM-2D-1
27 Oct.	Thu	MAC D114	16:00	17:30	1.5 h	15	TLM-2D-2
01 Nov.	Tue						No lecture (Travel)
03 Nov.	Thu	MAC D114	16:00	17:30	1.5 h	16	TLM-3D 1
08 Nov.	Tue	MAC D114	16:00	17:30	1.5 h	17	TLM-3D 2
10 Nov.	Thu						Reading Break
15 Nov.	Tue	MAC D114	16:00	17:30	1.5 h		No lecture (Travel)
17 Nov.	Thu	MAC D114	16:00	17:30	1.5 h		No lecture (Travel)
22 Nov	Tue	MAC D114	16:00	17:30	1.5 h	18	Finite Element Methods 1
24 Nov	Thu	MAC D114	16:00	17:30	1.5 h	19	Finite Element Methods 2
24 Nov.	Thu	MAC D114	17:30	19:00	1.5 h	20	Spectral Domain Methods 1
29 Nov.	Tue	MAC D114	16:00	17:30	1.5 h	21	Spectral Domain Methods 2
29 Nov.	Tue	MAC D114	17:30	19:00	1.5 h	22	Student Project Presentations
01 Dec	Thu	MAC D114	16:00	19:00	3.0 h		Final Examination

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Lecture 1   1.5h   Theoretical Foundations

Objectives:

1.1) Meet the students, get their names and addresses, discuss modalities, assessment, etc.

1.2) Introduce course philosophy and content. Distribute material. Give references.

1.3) Explain significance of electromagnetic modeling in modern CAD design. Stress the importance of modeling both in frequency and time domains.

1.4) Compare traditional and alternative approaches to modeling. Discuss challenges and limitations.

1.5) Introduce students to the models of light propagation throughout the ages.

1.6) Discuss Huygens' model in detail.

Lecture Structure:

1 Theoretical Foundations

1.1 Introduction, motivation and historical perspective
Importance of numerical modeling. Driving forces in field modeling. Why computers are needed in modern electromagnetic design. Understanding CAD. Functions performed by CAD programs. Typical CAD problem. First and second generations of CAD. Traditional and alternative solution of electromagnetic problems. Models of light propagation throughout the ages.

1.2 Huygens' Principle
Huygens' theory of light emission, propagation, and scattering. Extracts of "Traité de la Lumière". Modern interpretation and application of Huygens' principle.

Lecture 2 1.5h Huygens' Principle and Maxwell's Equations

Objectives:

2.1 Discuss Huygens' model of light propagation in detail.

2.2 Recall Maxwell's equations in integral form and understand their physical meaning.

2.3 State the condition for which Maxwell's equations describe an electrostatic field

2.4 State the condition for which Maxwell's equations describe a DC electromagnetic field.

Lecture Structure

2.2 Huygens' Principle. Huygens' theory of light emission, propagation, and scattering. Extracts of "Traité de la Lumière". Modern interpretation and application of Huygens' principle.

2.3 Maxwell's Equations in integral form. Derivation of the differential form using Stoke's theorem. Physical significance of Maxwell's equations. Boundary and interface conditions. Condition for which Maxwell's equations describe an electrostatic field.

Lecture 3 1.5h Wave Equations and Propagation

Objectives:

3.1 Discuss Maxwell's equations in differential form, as well as boundary conditions, material equations and continuity equation. Clearly understand the idealized nature and the limitations of this model.

3.2 Derive the homogeneous Helmholtz wave equation (absence of sources).

3.3 Derive the inhomogeneous wave equations for electric and magnetic fields in the presence of both charges and currents.

3.4 Discuss solutions of these wave equations such as uniform plane waves, cylindrical and spherical TEM waves, and recall important concepts such as phase and group velocity, surface of constant phase, and power flux density (Poynting) vector.

Lecture Structure

3.1 Mathematical Models of Wave Propagation

3.2 Derivation of the Homogeneous Wave Equation

3.3 Derivation of the Inhomogeneous Wave Equation

3.4 Solutions of the Wave Equations (of interest in this course)

Uniform Plane Wave (TEM Wave)
Phase Velocity
Spherical Wave (TEM Wave)

Lecture 4 1.5h Scalar and Vector Potentials

Objectives:

4.1 Formulate a general solution of the wave equations using the concept of Green's function.

4.2 Recall the properties of the Dirac Delta function and the Kronecker delta function. Assign a voluntary exercise to test the proficiency of students in handling the Dirac delta function.

4.3 Extend the Green's function approach to the general space-time case. Discuss the significance of the homogeneous and the particular solution of the wave equation.

4.4 Introduce the concepts of scalar and vector retarded potentials and clarify their advantages in terms of simplification of the source terms in the inhomogeneous wave equations. Discuss the Lorentz and Coulomb gauge conditions.

Lecture Structure:

4 The Search for a General Solution of the Wave Equations

i) The Solution of the One-Dimensional Wave Equation,
ii) Extension of the Green's Function to the Three-Dimensional, Time Dependent Case

Partial integral
Homogeneous solution

iii) The Vector and Scalar Retarded Potentials
Lorentz gauge
Coulomb gauge

<u>Lecture 5</u> 1.5h Green's Functions

Objectives:

5.1 Derive the Green's function for an arbitrary time dependence using the time domain Fourier transform.

5.2 Obtain the free-space time domain Greens function for a single frequency.

5.3 Express the retarded scalar and vector potentials in terms of this Green's function, resulting in the so-called Helmholtz integrals, and summarize the usefulness of these quantities in practical solutions of electromagnetic problems.

Lecture Structure:

5.1 Green's Function for an Arbitrary Time Dependence
Express arbitrary time variation in terms of its Fourier components,
Obtain the frequency domain Greens function for a single Fourier component in the frequency domain,
Obtain the time domain Green's function via inverse Fourier transform.

5.2 The Helmholtz integrals
Derive the expressions for the retarded scalar and vector potentials using the time domain Green's function.

Lecture 6/7 3h Method of Moments 1 and 2

Objectives:

6/7.1 Introduce the concept of expansion of an unknown function into known basis functions

6/7.2 Discuss the difference between entire-domain and subdomain basis functions

6/7.3 Discuss solution of differential equations using the moment method

6/7.4 Discuss solution of integral equations using the moment method

6/7.5 Apply solution method to determine the capacitance of a parallel plate capacitor

Lecture Structure: (Numbering of items corresponds to Booton: Computational Methods ...)

1) 7.1 Linear Operators

2) 7.2 Approximation by Expansion in Basis Functions

3) 7.3 Determination of Parameters

4) 7.4 Differential Operators

5) 7.5 Integral Operators

6) 7.6 Pulse Functions

7) 7.7 Parallel-Plate Capacitor in Two Dimensions

Lecture 8 1.5h Finite Differences in Frequency Domain 1

Objectives:

8.1 Discretize a one-dimensional function in terms of finite differences using Taylor expansion. Approximation of differentials with first and higher order accuracy.

8.2 Solve a one-dimensional second-order differential equation using finite differences.

8.3 Extend this concept to two-dimensional equations.

8.4 Implement Dirichlet and Neumann boundary conditions in the discrete computational space.

Lecture Structure

(Numbering of items corresponds to Booton: Computational Methods ....)

Finite-Difference Method

1) 2.1 Finite Differences in One Dimension

2) 2.2 One-Dimensional Differential Equation Example

3) 2.3 Finite Differences in Two Dimensions

Lecture 9 1.5h Finite Differences in Frequency Domain 2

Objectives:

9.1 Solve Laplace's equation in two dimensions for the example of a parallel plate transmission line in a shielded box

9.2 Solve unbounded (open region) problems by Richardson extrapolation of results obtained for increasingly large bounded regions.

9.3 Model curved boundaries using internal and external stair-step approximations.

9.4 Discuss computer project 2-1: Calculation of capacitance per unit length of a square coaxial transmission line using finite differences.

9.5 Solve one-dimensional and two-dimensional eigenvalues with finite differences

9.6 Demonstrate this approach by finding the propagation parameters of modes in rectangular waveguides.

9.7 Discuss LU-factorization as a method for finding the eigenvalues of the characteristic matrix.

9.8 Discuss iterative solution methods for the direct calculation of the eigenvalues as an alternative.

Lecture Structure
(Numbering of items corresponds to Booton: Computational Methods ....)

1) 2.4 A Two-Dimensional Capacitance Example

2) 2.5 Open Regions

3) 2.6 Generalizations

4) 2.7 Computer Project 2-1

5) 3.1 Eigenvalues in One Dimension

6) 3.2 Waveguide-Mode Example

7) 3.3 Numerical Evaluation of the Determinant

8) 3.4 Iterative Solution Methods

<u>Lecture 10/11</u> 3h Finite Differences Time Domain 2D

Objectives:

10.1 Discretize the one-dimensional wave equation in space and time using finite differences.

10.2 Demonstrate the introduction if initial conditions for time-dependent discrete formulations of the wave equation.

10.3 Extend these concepts to two and three space dimensions.

Lecture Structure (Numbering of items corresponds to Booton: Computational Methods ...)

1) 4.1 Wave Equation in One Spatial Dimension

2) 4.2 Time Quantization

3) 4.3 Initial Conditions

4) 4.4 Waves in Two and Three Spatial Dimensions

Midterm Exam 1.5h

Lecture 12/13 3h Finite Differences Time Domain 3D

Objectives:

12.1 Demonstrate the direct discretization in space and time of Maxwell's equations (as opposed to the discretization of the Helmholtz wave equation).

12.2 Discuss Yee's scheme in two and three dimensions.

12.3 Discuss Computer Project 4-1 (Wave propagation in two-dimensional space with finite differences)

Lecture Structure: (Numbering of items corresponds to Booton: Computational Methods ...)

1) 4.5 Maxwell's Equations

2) Problem

3) Computer Project 4-1

Lecture 14/15 3h 2D Transmission-Line Matrix Method (TLM-2D)

Objectives:

14.1 Demonstrate implementation of 2D-TLM algorithm in a simulator

14.2 Illustrate the features and limitations of discrete time domain field models

14.3 Demonstrate modeling of dispersive boundary conditions using numerical convolution

14.4 Show solutions of typical field problems with the 2D-TLM Electromagnetic Simulator

Lecture Structure

1) Execute basic pulse propagation in 2D-TLM network on the simulator

2) Demonstrate Fourier transform of impulse responses and their characteristics

3) Show examples of S-Parameter computations of filters

4) Demonstrate Johns Matrix generation and convolution on the computer

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Lecture 16/17 3h 3D Transmission Line Matrix Method (TLM 3D)

Objectives:

16.1 Extend shunt- and series-node 2D TLM to 3D

16.2 Derive properties of expanded 3D TLM node

16.3 Derive properties of symmetrical condensed 3D-TLM node

16.4 Discuss differences between 3D-TLM schemes and compare with 3D-FDTD.

Lecture Structure

1) Recall of 2D shunt and series nodes

2) Scattering matrix and wave properties of expanded 3D-TLM node

3) Scattering matrix and wave properties of symmetrical condensed 3D-TLM node

4) Comparison between TLM schemes and FDTD schemes

Lecture 18 1.5h Finite Element Method (FEM) 1

Objectives:

18.1 Discuss the definition of a functional and stationary conditions

18.2 Illustrate the significance of a functional in the case of electrostatic energy

18.3 Formulate eigenvalues of a function in terms of a variational expression.

18.4 Discuss the Rayleigh-Ritz method for finding an approximation to the function that makes a functional stationary.

Lecture Structure (Numbering of items corresponds to Booton: Computational Methods ...)

Variational and Related Methods

1) 5.1 Stationary Conditions for Functionals

2) 5.2 Example of Electrostatic Field Energy

3) 5.3 Variational Expression for Eigenvalues

4) 5.4 Rayleigh - Ritz Method

Lecture 19 1.5h Finite Element Method (FEM) 2

Objectives:

19.1 Introduce the concept of finite elements as subregions of a functional space.

19.2 Use linear functions to approximate a function over a small isosceles right triangular subregion.

19.3 Discuss subdivisions using square elements.

19.4 Derive finite element solutions in 2D-space using general triangular elements and first-order interpolation

Lecture Structure: (Numbering of items corresponds to Booton: Computational Methods ...)

Finite-Element Method

1) 6.1 Basic Concept of Finite Elements

2) 6.2 Finite Elements in One Dimension

3) 6.3 Linear Interpolation for Isosceles Right Triangles

4) 6.4 Square Elements

5) 6.5 General Triangular Elements

Lecture 20/21 3h Spectral Domain Method 1 and 2

Objectives:

20.1 Explain the expansion of hybrid waveguide fields in terms of transverse modes

20.2 Show application of Galerkin's Method in the spectral domain

20.3 Discuss the choice of appropriate basis functions

20.4 Discuss eigenvalue solutions in quasi-planar waveguides

Lecture Structure: Special handout will be distributed)

Spectral Domain Method

1) Formulation of Eigenvalue problems in the spectral domain

2) Eigenvalue solutions with Galerkin's procedure

3) Choice of Basis Functions

   3.1 Approximation of slot field or strip current by a constant basis function

   3.2 Approximation of slot field or strip current by pulse basis function

   3.3 Approximation of slot field or strip current by Gegenbauer polynomials

   3.4 Approximation of slot field or strip current by Legendre polynomials

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Final Exam 1.5h

The remaining lecture hours are devoted to student presentations of their projects and to their discussion. Every student prepares a 45 minute presentation on a specific numerical technique and its application to the solution of technically relevant problems. Individual project assignments will be made during the first few lectures.