Time domain simulation and the FDTD method

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OUTLINE

- PART I: TUTORIAL ON FDTD

- PART II: SEMBA & OPEN-SEMBA: YET ANOTHER SOLVER FOR EMC ANALYSIS

PART I: TUTORIAL

- ☐ Deterministic methods in EMC
- ☐ FDTD fundamentals
- ☐ DGTD: an affordable alternative to FDTD
- ☐ Dispersion, dissipation, stability, convergence
- ☐ Requirements for a practical tool: PMLs, sources, materials & sub-cell models
- ☐ Computer implementation
- ☐ Applications
- ☐ Towards affordable sensitivity analyses

NUMERICAL METHODS IN EMC

- Low Frequency Band (<100 λ)

3D FULL-WAVE

- o Time Domain: Differential (FDTD, FIT, TLM), Variational (DGTD, FVTD, FETD), hybrid (FE-FDTD), Integral TDIE (EFIE, MFIE –PWTD-)
- o Frequency Domain: Variational (FEFD), Integral (EFIE, MFIE, MPIE) MoM w/o MLFMA

CIRCUITAL: LUMPED AND MTLN

- High Frequency Band (> 100 λ)
  - o Frequency Domain: PO, GTD, UTD, PW

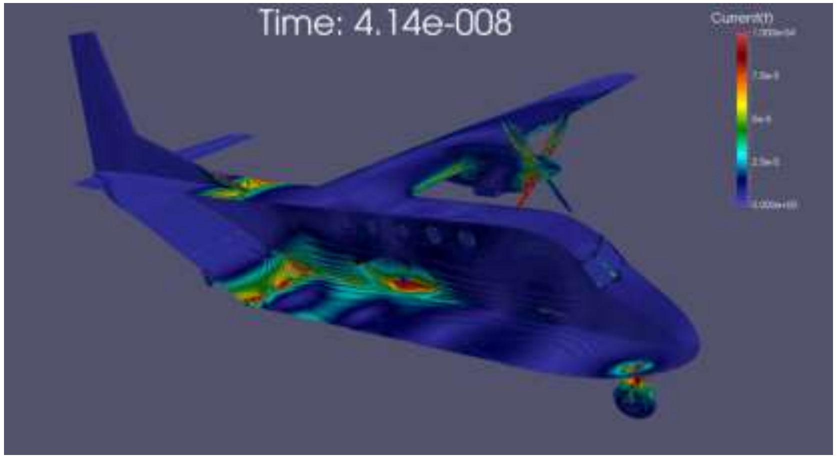
FDTD, DGTD, FVTD

SPACE

- Differential (FD): for maturity, scalability, ease of meshing, PARALLELIZABILITY …
- Variational (DG, FV): for higher order accuracy and hp-adaptivity

TIME

- Differential & Explicit: for HPC, Marching-on-in-time: LF, RK4…



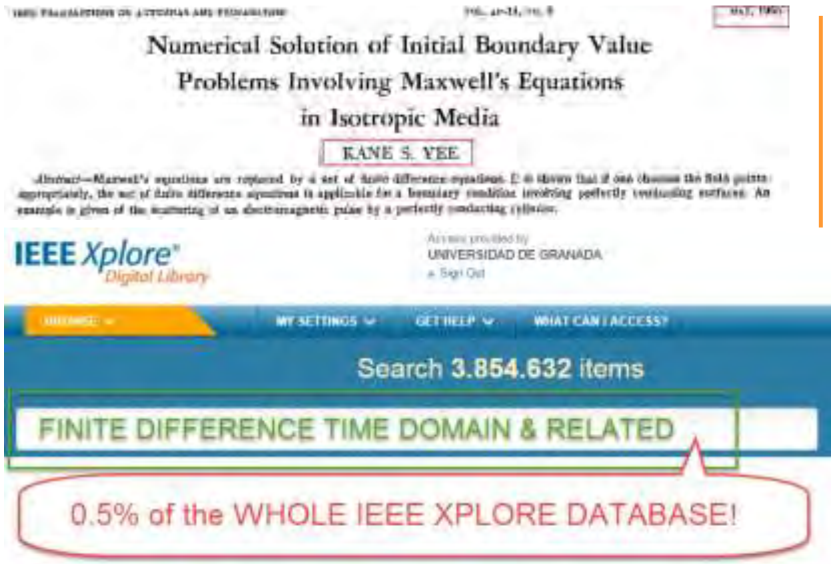
EXPLICIT SCHEMES IN TD: ADVANTAGES

- **Local Marching-on-in-time** algorithm: updating the unknowns only require past unknowns at neighbour cells
- **Simple** formulation (no matrix inversions).
- **Physics** (materials, currents...) naturally treated: dielectric, magnetic, frequency dependent, nonlinear, anisotropic,…
- A single run can cover the **whole frequency band**
- Straightforwardly **parallelizable**

EXPLICIT SCHEMES IN TD: DRAWBACKS

- Overall order dominated by time integration: eg: **2nd-order for Leap-frog**.
- **Conditionally stable**: Maximum time-step bounded by space-step (unconditionally stable alternatives exist: implicit!)
- May last to **converge for LF** (can be combined with prediction techniques: Prony, permittivity scaling ...)
- **Large CPU**: brute-force sensitivity analysis

THOUSANDS OF PAPERS. DOZENS OF BOOKS



IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION VOL. AP-14, NO. 3 MAY, 1966

Numerical Solution of Initial Boundary Value
Problems Involving Maxwell's Equations
in Isotropic Media

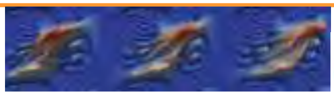
KANE S. YEE

Abstract—Maxwell's equations are replaced by a set of finite difference equations. It is shown that if one chooses the field points appropriately, the set of finite difference equations is applicable for a boundary condition involving perfectly conducting surfaces. An example is given of the scattering of an electromagnetic pulse by a perfectly conducting cylinder.

Search 3.854.632 items

FINITE DIFFERENCE TIME DOMAIN & RELATED

0.5% of the WHOLE IEEE XPLORE DATABASE!



MAXWELL'S EQUATIONS

James Clerk Maxwell.

$$\vec{D} = \varepsilon \vec{E} \quad , \quad \vec{B} = \mu \vec{H}$$

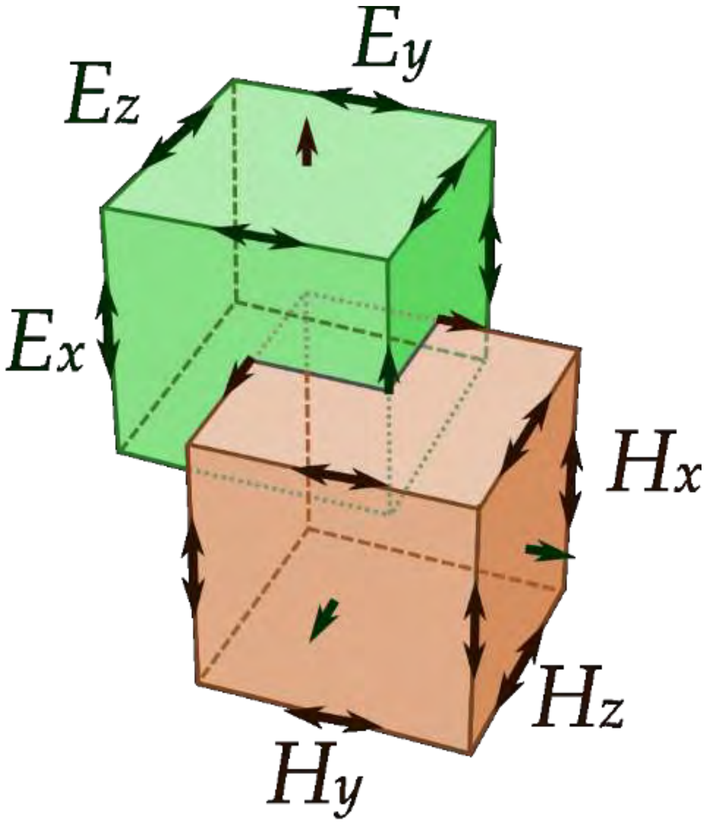
$$\nabla \cdot \vec{D} = \rho \quad , \quad \nabla \cdot \vec{B} = 0$$

$$\varepsilon \partial_t \overrightarrow{E} = \nabla \times \overrightarrow{H} - \sigma \overrightarrow{E} - \overrightarrow{J}$$

$$\mu \partial_t \overrightarrow{H} = \nabla \times \overrightarrow{E} - \sigma^* \overrightarrow{H} - \overrightarrow{M}$$

FDTD: FINITE DIFFERENCE TIME DOMAIN METHOD

Direct discretization of **Maxwell curl equations** by 2nd-order finite diferences for all derivatives, in a non co-located staggered space-time mesh



FINITE DIFFERENCE/AVERAGES

Continuum	Discrete
$\partial_u f(u,\ldots)$	$D_u f(u,\ldots) = \dfrac{f(u+\Delta u/2,\ldots) - f(u-\Delta u/2,\ldots)}{\Delta u}$
$f(u,\ldots)$	$P_u f(u,\ldots) = \dfrac{f(u+\Delta u/2,\ldots) + f(u-\Delta u/2,\ldots)}{2}$

E.g.: For a single-component

$$\frac{\partial E_x}{\partial t} = \frac{1}{\varepsilon}\left(\frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z} - \sigma_x{}^e E_x - J_x\right)$$

with field averaging:

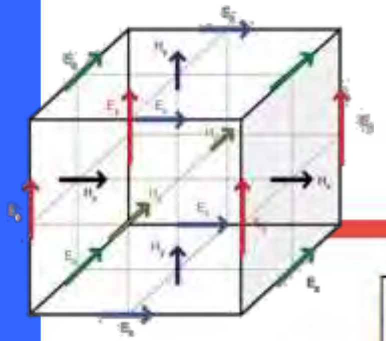
$$E_x^{n+\frac{1}{2}} = \tfrac{1}{2}\left[E_x^{n+1} + E_x^{n}\right]$$

Apply **finite difference** approximations:

$$\frac{E_x^{n+1}(i,j,k) - E_x^{n}(i,j,k)}{\Delta t} = \frac{1}{\varepsilon_x(i,j,k)}\left[\frac{H_z^{n+1/2}(i,j,k) - H_z^{n+1/2}(i,j-1,k)}{\Delta y}\right]$$

$$-\frac{1}{\varepsilon_x(i,j,k)}\left[\frac{H_y^{n+1/2}(i,j,k) - H_y^{n+1/2}(i,j,k-1)}{\Delta z}\right]$$

$$-\boxed{\frac{\sigma_x^e(i,j,k)}{2\varepsilon_x(i,j,k)}\left[E_x^{n+1}(i,j,k) + E_x^{n}(i,j,k)\right]} - \frac{1}{\varepsilon_x(i,j,k)} J_{xi}^{n+\frac{1}{2}}(i,j,k)$$



$$E_x^{n+1}(i,j,k) = \frac{\left[\frac{1}{\Delta t} - \frac{\sigma_x^e(m)}{2\varepsilon_x(m)}\right]}{\left[\frac{1}{\Delta t} + \frac{\sigma_x^e(m)}{2\varepsilon_x(m)}\right]} E_x^{n}(i,j,k) + \frac{\frac{1}{\varepsilon_x(m)\Delta y}}{\left[\frac{1}{\Delta t} + \frac{\sigma_x^e(m)}{2\varepsilon_x(m)}\right]}\left[H_z^{n+1/2}(i,j,k) - H_z^{n+1/2}(i,j-1,k)\right]$$

$$-\frac{\frac{1}{\varepsilon_x(m)\Delta z}}{\left[\frac{1}{\Delta t} + \frac{\sigma_x^e(m)}{2\varepsilon_x(m)}\right]}\left[H_y^{n+1/2}(i,j,k) - H_y^{n+1/2}(i,j,k-1)\right] - \frac{\frac{1}{\varepsilon_x(m)}}{\left[\frac{1}{\Delta t} + \frac{\sigma_x^e(m)}{2\varepsilon_x(m)}\right]} J_{xi}^{n+\frac{1}{2}}(i,j,k)$$

DGTD, FVTD

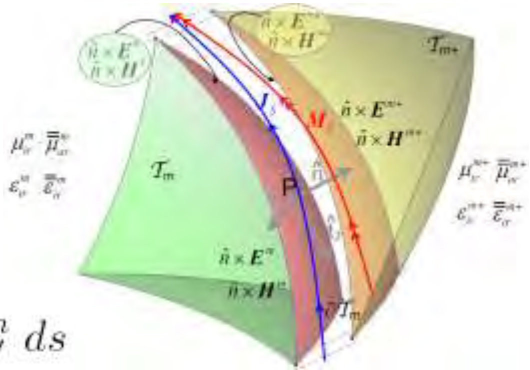
DISCONTINUOUS GALERKIN TIME DOMAIN

Maxwell curl E-H equations in **variational** form tested/expanded (**Galerkin**) in **HIGH-ORDER hierarchal** basis on **1st/2nd-order tetrahedrons**

$$\varepsilon_r \varepsilon_0 \frac{\partial \boldsymbol{E}}{\partial t} = \nabla \times \boldsymbol{H} \quad , \quad \mu_r \mu_0 \frac{\partial \boldsymbol{H}}{\partial t} = -\nabla \times \boldsymbol{E}$$

The field is allowed to be DISCONTINUOUS at the boundary, but its flux is CONTINUOUS

$$\oint_{\partial T_m} (\hat{\mathbf{n}}^m \times \boldsymbol{E}^{m*}) \cdot \phi_{q'}^m \, ds$$



$$\mu \mathbb{M} d_t H^m + (\sigma_m \mathbb{M} - \mathbb{F}_{\nu h}) H^m + \mathbb{F}^+_{\nu h} H^{m+} = -(\mathbb{S} - \mathbb{F}_{\kappa e}) E^m - \mathbb{F}^+_{\kappa e} E^{m+} - M_{s\kappa} + J_{s\nu}$$

$$\varepsilon \mathbb{M} d_t E^m + (\sigma_e \mathbb{M} - \mathbb{F}_{\nu e}) E^m + \mathbb{F}^+_{\nu e} E^{m+} = (\mathbb{S} - \mathbb{F}_{\kappa h}) H^m + \mathbb{F}^+_{\kappa h} H^{m+} - J_{s\kappa} - M_{s\nu}$$

Explicit marching-in-time

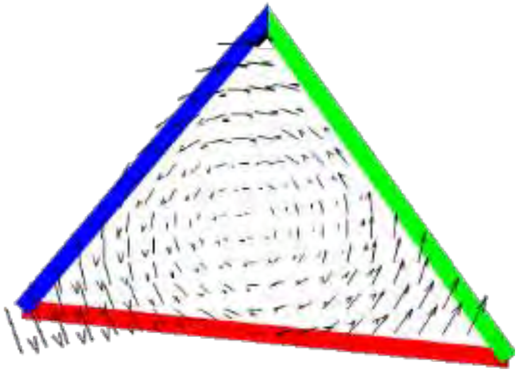
$$c_o \Delta t < \min \left(\frac{h_l}{2} \sqrt{\varepsilon_{r_l} \mu_{r_l}} \frac{1}{(p+1)^2} \right)$$

NODAL AND VECTOR DGTD

Testing & expanding (**Galerkin**) in **vector**

$$\vec{E}(\vec{r}) = \sum_{i=1}^{N_{edges}} E_i \vec{W}_i \quad , \text{ e.g. Whitney's } \vec{W}_i = \xi_j \nabla \xi_k - \xi_k \nabla \xi_j$$

Curl-conforming



or (**nodal**) functions: Lagrange polynomials

SIMILAR BEHAVIOR: **RIEMANN-LIKE** FLUXES ATTENUATE SPURIOUS (BADLY RESOLVED) SOLUTIONS REPORTED IN NODAL CONTINUOUS FEM

KEY FEATURES IN A NUMERICAL SCHEME

- CONSISTENCY
- CONVERGENCE
- STABILITY

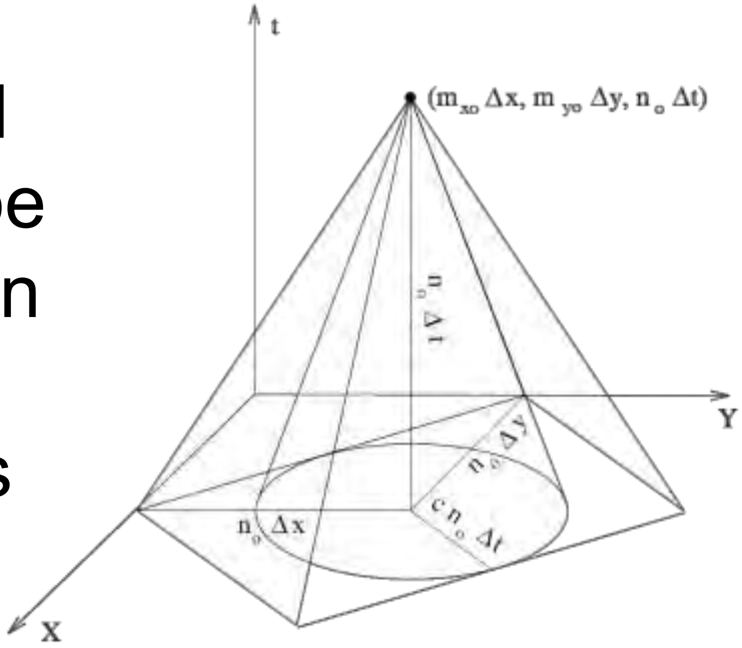
Lax theorem

For a consistent scheme, stability and convergence are equivalent

STABILITY & CAUSALITY: COURANT-FRIEDRICHS-LEWY

4D numerical causal hypercone (Minkowski's) must COMPRISE the analytical one (based in Lax convergence-stabilty equivalence theorem).

Practical corollary: E and H field components must be ALWAYS inter-dependent in the numerical scheme. E.g. if a E component uses some H, the latter must also use it.



CONSISTENCY: GLOBAL 2ND-ORDER

Consistency

truncation error must converge to 0 for increments tending to 0

Analytical

$$\boxed{\partial_t \vec{\psi} = \tilde{\mathcal{R}}_T \vec{\psi} - \vec{\mathcal{K}}}$$

Yee FDTD

$$\boxed{\frac{\vec{\Psi}^{n+1} - \vec{\Psi}^{n}}{\Delta t} = \tilde{R}_T \vec{\Psi}^{n+1/2} - \vec{K}^{n+1/2}}$$

Analytical

$$\boxed{0} = \partial_t \vec{\psi}^{n+1/2} - \tilde{R}_T \vec{\psi}^{n+1/2}$$

Yee FDTD

$$O(\boxed{\Delta t^2 \partial_t^3, \Delta x^2 \partial_x^3, \Delta y^2 \partial_y^3, \Delta z^2 \partial_z^3}) = \frac{\vec{\psi}^{n+1} - \vec{\psi}^{n}}{\Delta t} - \tilde{R}'_T \vec{\psi}^{n+1/2}$$

DISPERSION & STABILITY: VON NEUMANN ANALYSIS

Plane waves are propagated by lossless source-free Maxwell's equations in propagate in TEM modes

$$\vec{\Psi}(x,y,z,t)=\vec{\Psi}_0 e^{j(\omega t-\vec{\beta}\cdot\vec{r})}$$

$$\vec{\beta}=\left(\beta_x,\beta_y,\beta_z\right),\ \vec{r}=(x,y,z)$$

With an analytical dispersion relationship

$$\mu\varepsilon\omega^2=\left(\beta_x^2+\beta_y^2+\beta_z^2\right)$$

DISPERSION & STABILITY: VON NEUMANN ANALYSIS

$$\frac{1}{c^2\Delta t^2}\sin^2\left(\Omega\frac{\Delta t}{2}\right) = \frac{1}{\Delta x^2}\sin^2\left(\beta_x\frac{\Delta x}{2}\right) + \frac{1}{\Delta y^2}\sin^2\left(\beta_y\frac{\Delta y}{2}\right) + \frac{1}{\Delta z^2}\sin^2\left(\beta_z\frac{\Delta z}{2}\right)$$

For a Cauchy problem with given wavenumber

$$\sin\left(\Omega\frac{\Delta t}{2}\right) \le c\Delta t\sqrt{\frac{1}{\Delta x^2}+\frac{1}{\Delta y^2}+\frac{1}{\Delta z^2}}$$

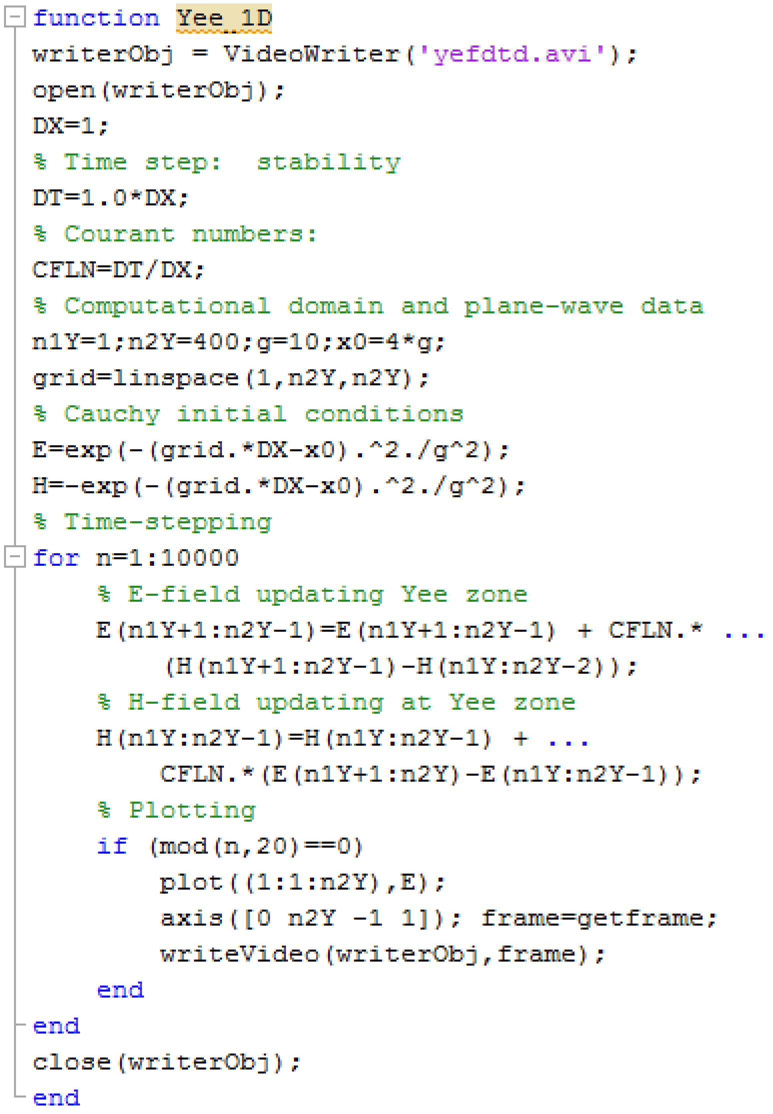
$$\mathrm{Im}\{\Omega\} < 0 \Leftrightarrow s = CFLN = c\Delta t\sqrt{\frac{1}{\Delta x^2}+\frac{1}{\Delta y^2}+\frac{1}{\Delta z^2}} \le 1 \Rightarrow \boxed{\mathrm{Im}\{\Omega\} = 0}$$

STABILITY IMPLIES NON-DISSIPATION

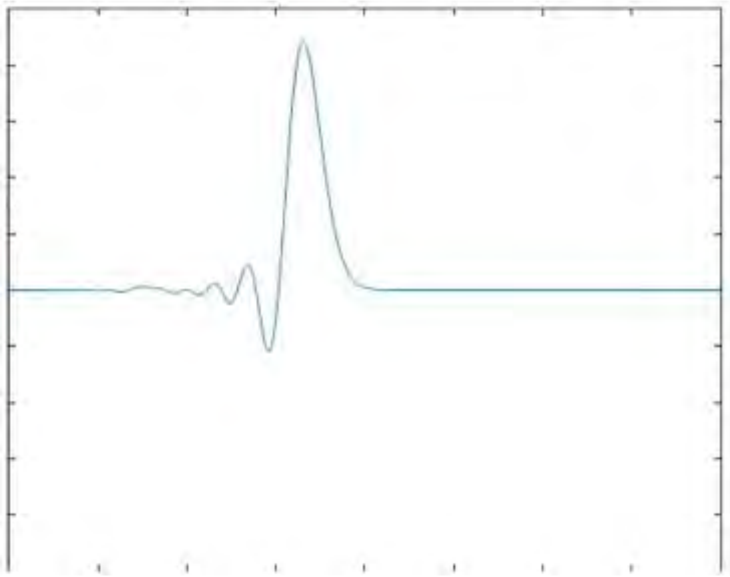
Von-Neumann stability requires a non-increasing exponential, and hence imposes an UPPER LIMIT for the time-step determined by the spatial discretization steps.

EXAMPLE: A 1D MATLAB CODE

DISPERSION $\frac{c\Delta t}{\Delta x} = 0.7$



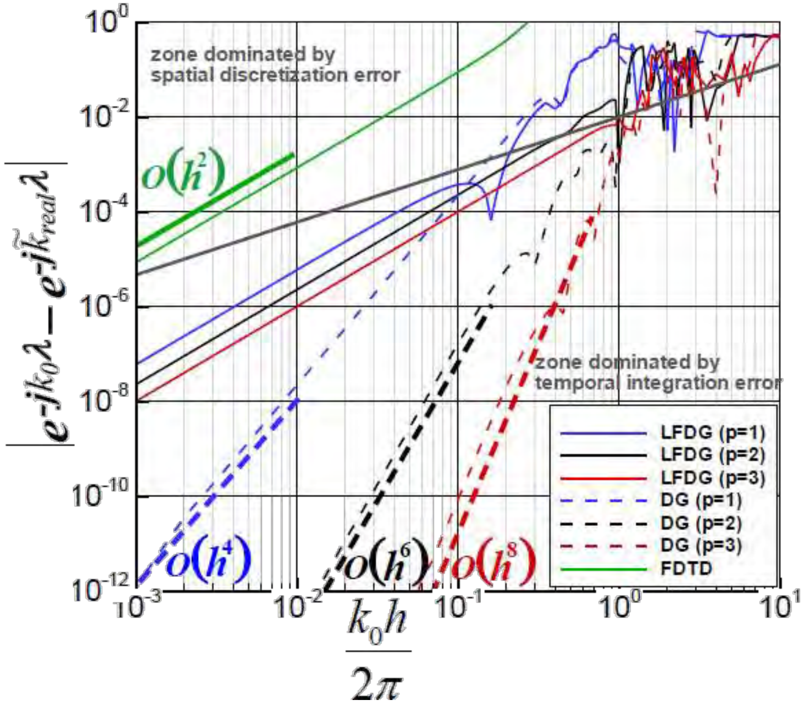
```
function Yee_1D
writerObj = VideoWriter('yefdtd.avi');
open(writerObj);
DX=1;
% Time step:  stability
DT=1.0*DX;
% Courant numbers:
CFLN=DT/DX;
% Computational domain and plane-wave data
n1Y=1;n2Y=400;g=10;x0=4*g;
grid=linspace(1,n2Y,n2Y);
% Cauchy initial conditions
E=exp(-(grid.*DX-x0).^2./g^2);
H=-exp(-(grid.*DX-x0).^2./g^2);
% Time-stepping
for n=1:10000
    % E-field updating Yee zone
    E(n1Y+1:n2Y-1)=E(n1Y+1:n2Y-1) + CFLN.* ...
        (H(n1Y+1:n2Y-1)-H(n1Y:n2Y-2));
    % H-field updating at Yee zone
    H(n1Y:n2Y-1)=H(n1Y:n2Y-1) + ...
        CFLN.*(E(n1Y+1:n2Y)-E(n1Y:n2Y-1));
    % Plotting
    if (mod(n,20)==0)
        plot((1:1:n2Y),E);
        axis([0 n2Y -1 1]); frame=getframe;
        writeVideo(writerObj,frame);
    end
end
close(writerObj);
end
```



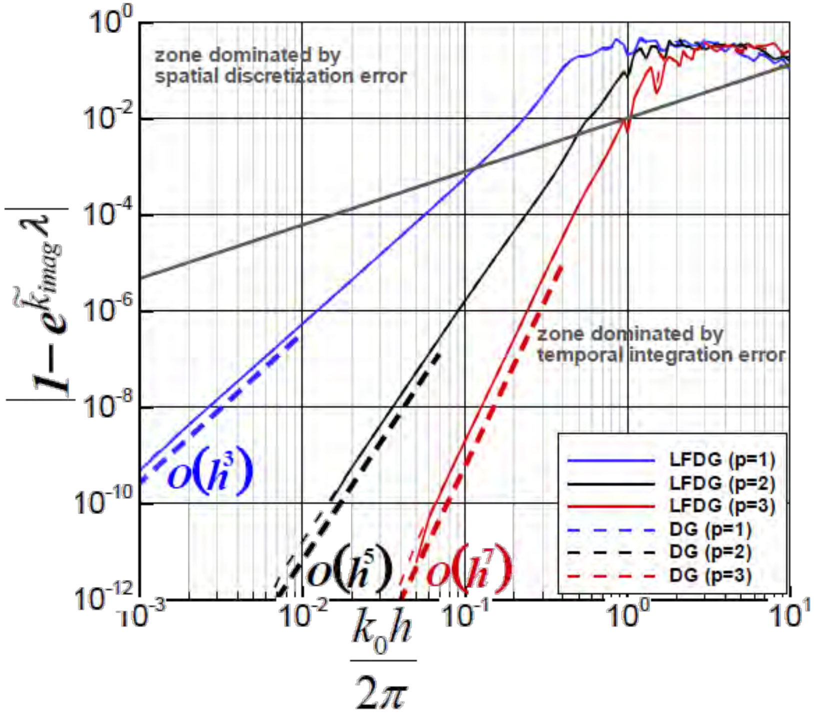
DISPERSION & DISSIPATION

FDTD: 2nd ORDER. ~10º / λ AT 10 PPW !

DGTD: h^{th} ORDER

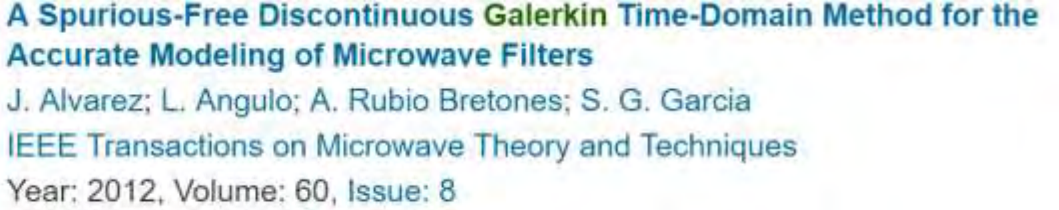


DISPERSION: DOMINATED BY TIME INTEGRATION ORDER (LF2 or RK4)



DISSIPATION: Inherent to penalized fluxes. Worsened by RK4

GOOD TO DAMP SPURIOUS FEM MODES (REPORTED IN NODAL CONTINUOUS FEM)



A Spurious-Free Discontinuous Galerkin Time-Domain Method for the Accurate Modeling of Microwave Filters

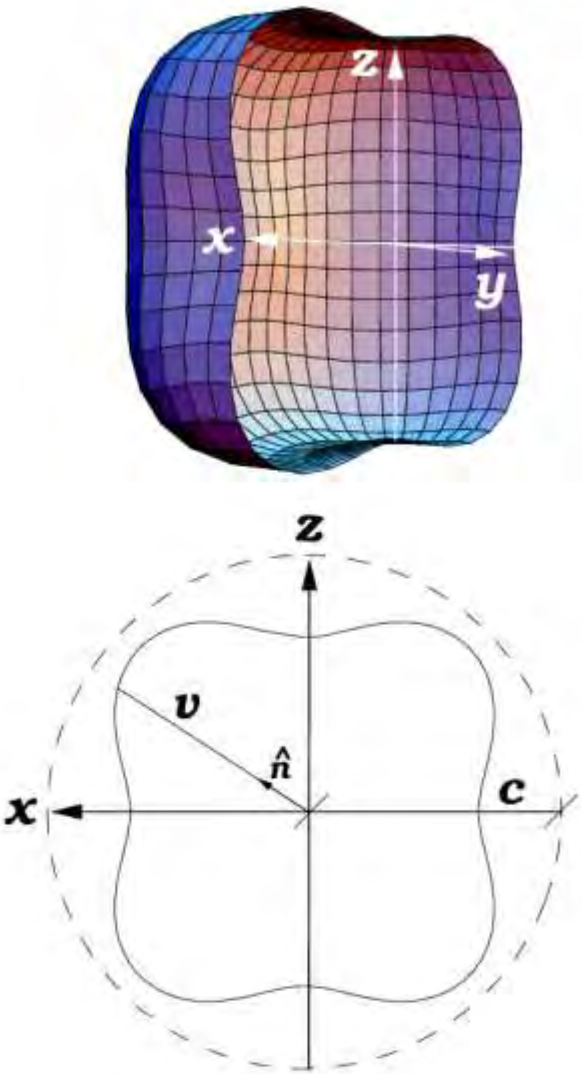
J. Alvarez; L. Angulo; A. Rubio Bretones; S. G. Garcia

IEEE Transactions on Microwave Theory and Techniques

Year: 2012, Volume: 60, Issue: 8

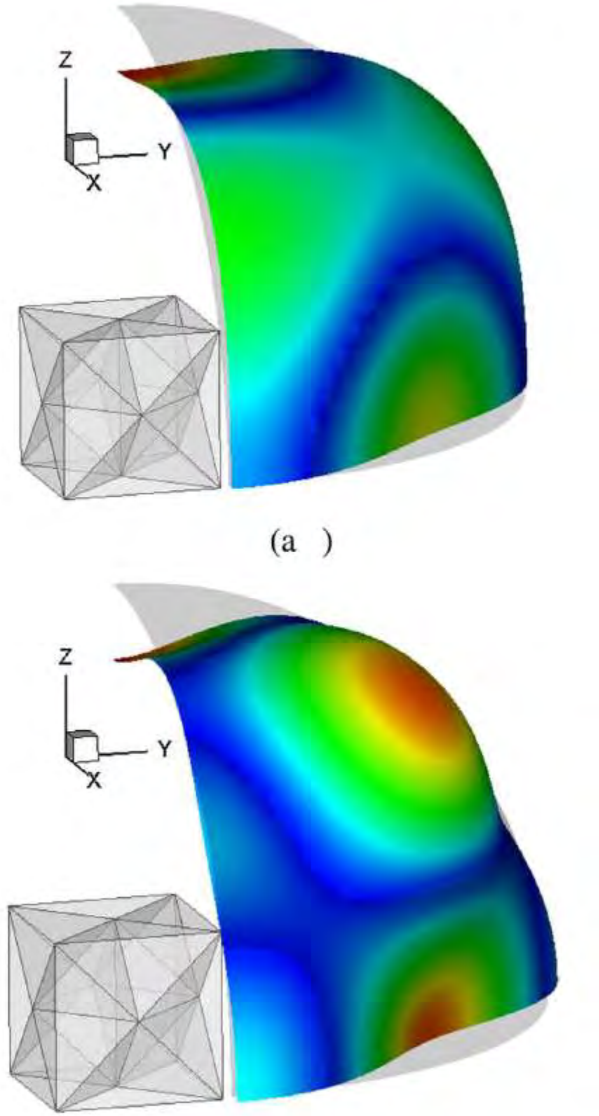
ANISOTROPY IN DISPERSION

FDTD



DGTD

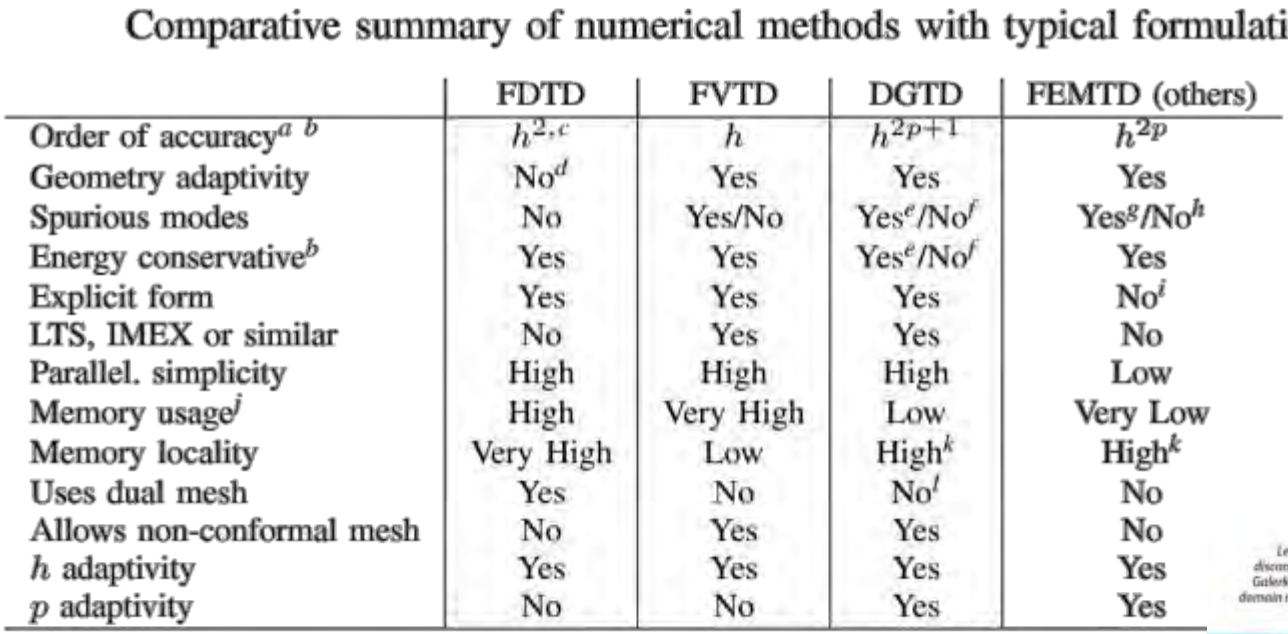
$\tau = 0.1,\ h = 0.25$. (a) $p = 1$ and (b) $p = 3$



(a)

(b)

FDTD vs DGTD: PROs & CONs



Comparative summary of numerical methods with typical formulations

	FDTD	FVTD	DGTD	FEMTD (others)
Order of accuracy[a] [b]	$h^{2,c}$	h	h^{2p+1}	h^{2p}
Geometry adaptivity	No[d]	Yes	Yes	Yes
Spurious modes	No	Yes/No	Yes[e]/No[f]	Yes[g]/No[h]
Energy conservative[b]	Yes	Yes	Yes[e]/No[f]	Yes
Explicit form	Yes	Yes	Yes	No[i]
LTS, IMEX or similar	No	Yes	Yes	No
Parallel. simplicity	High	High	High	Low
Memory usage[j]	High	Very High	Low	Very Low
Memory locality	Very High	Low	High[k]	High[k]
Uses dual mesh	Yes	No	No[l]	No
Allows non-conformal mesh	No	Yes	Yes	No
h adaptivity	Yes	Yes	Yes	Yes
p adaptivity	No	No	Yes	Yes

Leap-frog discontinuous Galerkin time-domain method.

Efficient Antenna Modeling by DGTD

DGTD method has a comparable computational cost to FDTD for practical applications, but preserving most of the advantages of finite element methods

Forum for Electromagnetic Research Methods and Application Technologies (FERMAT)

ART-2015-Vol10-Jul_Aug

Discontinuous Galerkin Time Domain Methods in Computational Electrodynamics: State of the Art

L. D. Angulo, J. Alvarez, M. F. Pantoja, S. G. Garcia, and A. R. Bretones

FDTD: TOWARDS A PRACTICAL SIMULATION TOOL

SOME IMPLEMENTATION DETAILS

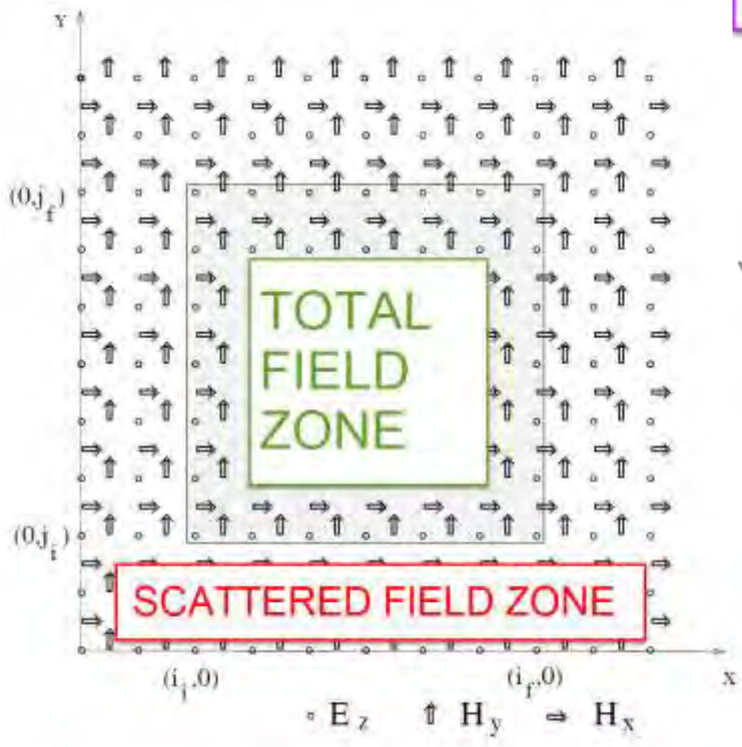
HOW TO CHOOSE THE SAMPLING?

Rule of the thumb for the number of cells per wavelength (PPW) in FDTD:

$$\frac{\lambda}{\mathrm{Min}\{\Delta s\}} \geq 10 \;\&\; \frac{T}{\Delta y} \geq 10 \,\text{(automatic in time if fulfilled in space)}$$

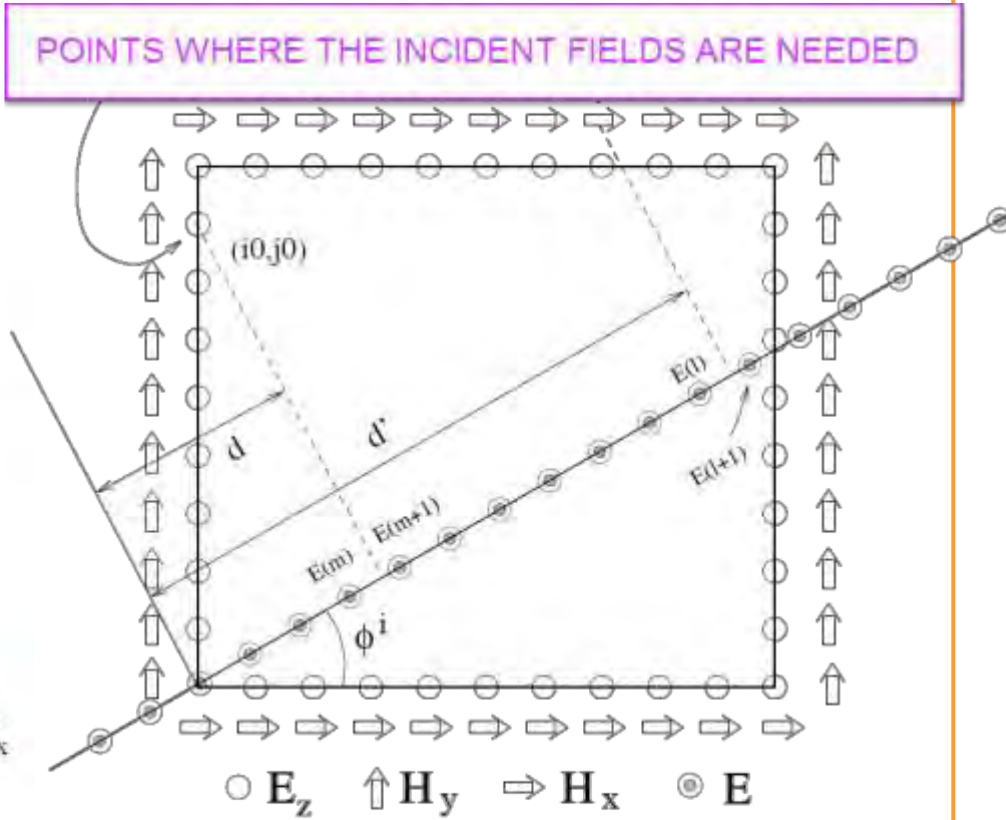
$$\lambda = \frac{\lambda_0}{\sqrt{\frac{1}{2}\left(\sqrt{1+Q^{-2}}+1\right)}}, \quad \lambda_0 = \frac{c}{f} \qquad Q = 1/\tan\delta = \frac{\omega\varepsilon}{\sigma}$$

SOURCES: TOTAL/SCATTERED FIELD ZONING



TOTAL FIELD ZONE

SCATTERED FIELD ZONE

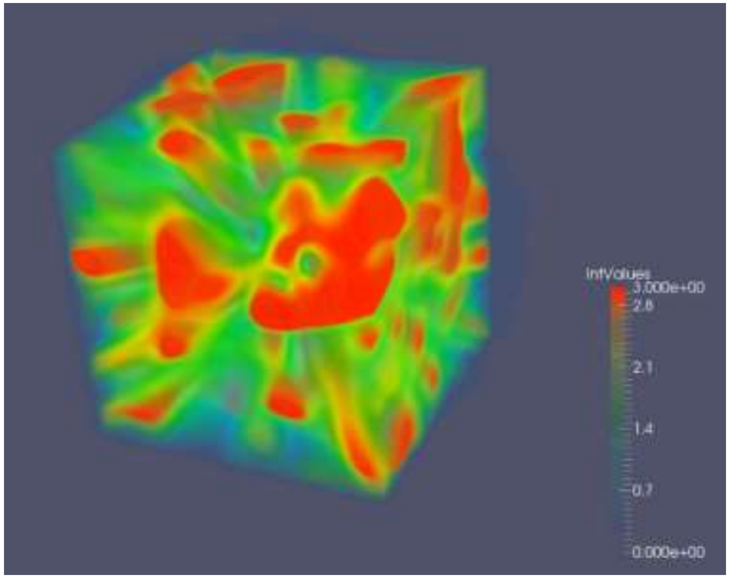


POINTS WHERE THE INCIDENT FIELDS ARE NEEDED

TAFLOVE'S LINEARITY INTERPRETATION

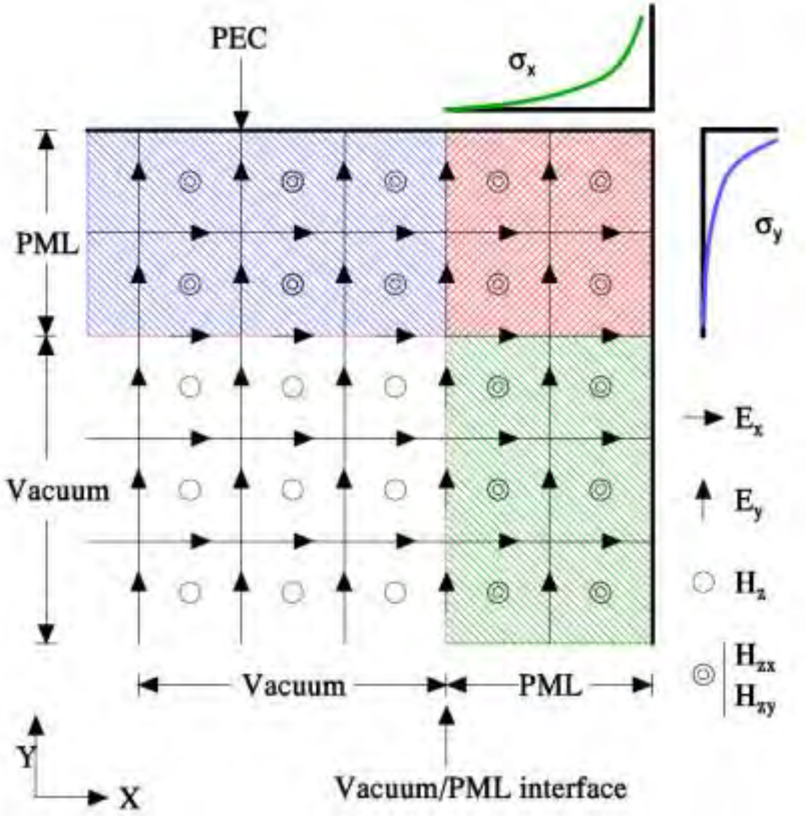
$$
\begin{aligned}
E_z^{n+1}(i_i,j)\,\Big|\boxed{\text{TOTAL}} &= C_a(i_i,j)E_z^{n}(i_i,j)\,\Big|\boxed{\text{TOTAL}} + C_b(i_i,j)\\
&\Big(H_y^{n+\frac{1}{2}}(i_i+\tfrac{1}{2},j)\,\Big|\boxed{\text{TOTAL}} - H_y^{n+\frac{1}{2}}(i_i-\tfrac{1}{2},j)\,\Big|\boxed{\text{SCATTERED}} +\\
&H_x^{n+\frac{1}{2}}(i_i,j-\tfrac{1}{2})\,\Big|\boxed{\text{TOTAL}} - H_x^{n+\frac{1}{2}}(i_i,j+\tfrac{1}{2})\,\Big|\boxed{\text{TOTAL}}\Big)\\
&\boxed{-C_b(i_i,j)H_y^{n+\frac{1}{2}}(i_i-\tfrac{1}{2},j)\,\Big|\boxed{\text{INCIDENT}}}
\end{aligned}
$$

REVERBERATING CHAMBER STOCHASTIC SOURCES



PERFECTLY MATCHED LAYER ABSORBING BOUNDARY CONDITIONS

A fictious shell is added to the 3D FDTD domain with “impedance” matched free-space for **ALL FREQUENCIES** and for **ALL ANGLES OF INCIDENCE**




JOURNAL OF COMPUTATIONAL PHYSICS **114**, 185–200 (1994)

A Perfectly Matched Layer for the Absorption of Electromagnetic Waves

JEAN-PIERRE BERENGER

STRETECHED PML INSTEAD OF SPLIT BERENGER PMLs

$$j\omega\varepsilon_x E_x + \sigma_x^e E_x = \frac{1}{s_{ey}}\frac{\partial H_z}{\partial y} - \frac{1}{s_{ez}}\frac{\partial H_y}{\partial z}$$

$$j\omega\varepsilon_y E_y + \sigma_y^e E_y = \frac{1}{s_{ez}}\frac{\partial H_x}{\partial z} - \frac{1}{s_{ex}}\frac{\partial H_z}{\partial x}$$

$$j\omega\varepsilon_z E_z + \sigma_z^e E_z = \frac{1}{s_{ex}}\frac{\partial H_y}{\partial x} - \frac{1}{s_{ey}}\frac{\partial H_x}{\partial y}$$

CAN ALSO ABSORB EVANESCENT WAVES BY TUNING:

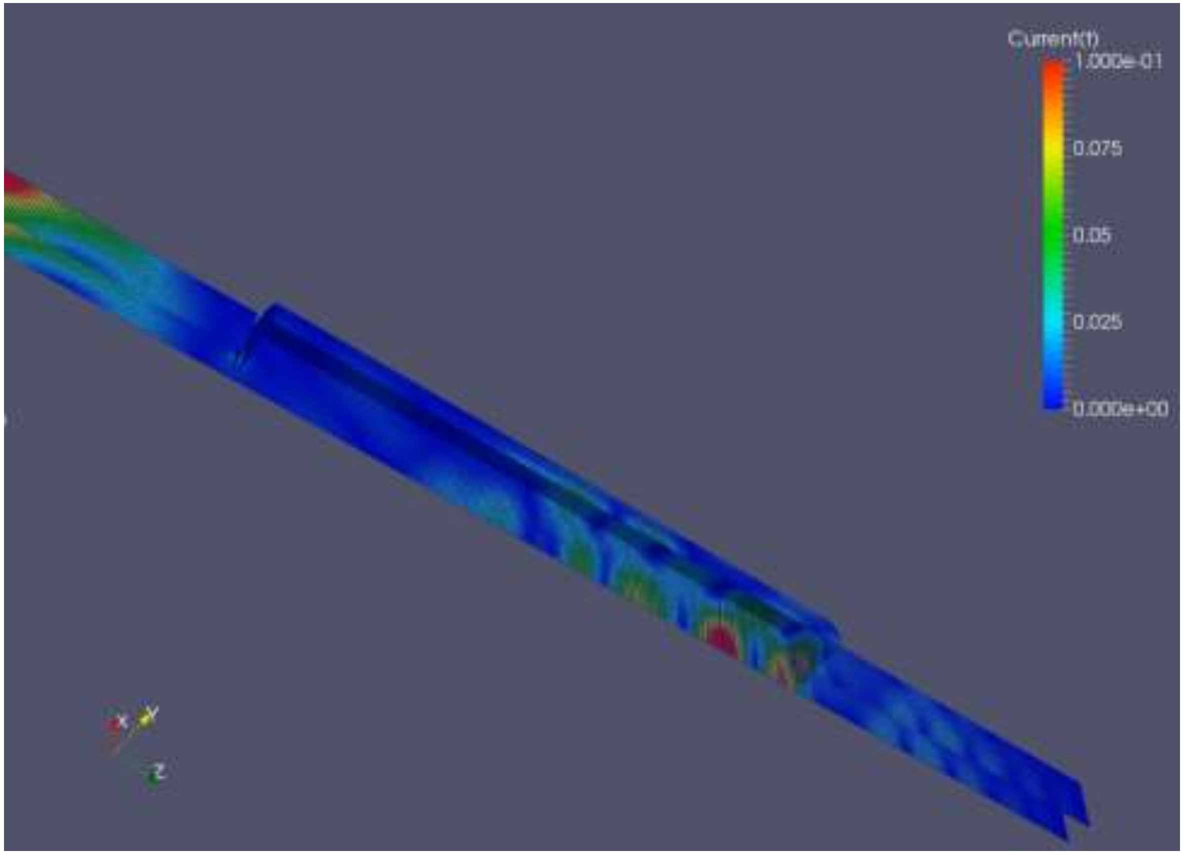
$$s_\alpha = \kappa_\alpha + \frac{\sigma_\alpha}{\eta_\alpha + j\omega\chi_\alpha}$$

CONVOLUTION PML (CPML): AN EFFICIENT FDTD IMPLEMENTATION OF THE CFS – PML FOR ARBITRARY MEDIA

J. Alan Roden[1] and Stephen D. Gedney[2]

MICROWAVE AND OPTICAL TECHNOLOGY LETTERS / Vol. 27, No. 5, December 5 2000

MODAL ABSORPTION IN WAVEGUIDES WITH PML



DISPERSIVE MATERIALS

VECTOR FITTING: poles/residues (complex conjugate pairs)

$$\nabla\times\vec{H}(\omega)=j\omega\varepsilon(\omega)\vec{E}(\omega)\ \Rightarrow\nabla\times\vec{H}(t)=\varepsilon_{\infty}\partial_t\vec{E}(t)+\sigma\vec{E}(t)+\sum_{k=1}^{N}\vec{P}_k(t)$$

VECTOR FITTING

$$\chi(\omega)=\sum_{k=1}^{N}\frac{R_k}{j\omega-p_k}$$

$$\mathrm{Re}\{p_k\}\le 0\ \ (\text{Stable})$$

Into discrete TD, either:

- **P**iecewise **L**inear **R**ecursive **C**onvolution
- **A**uxiliary **D**ifferential **E**quation

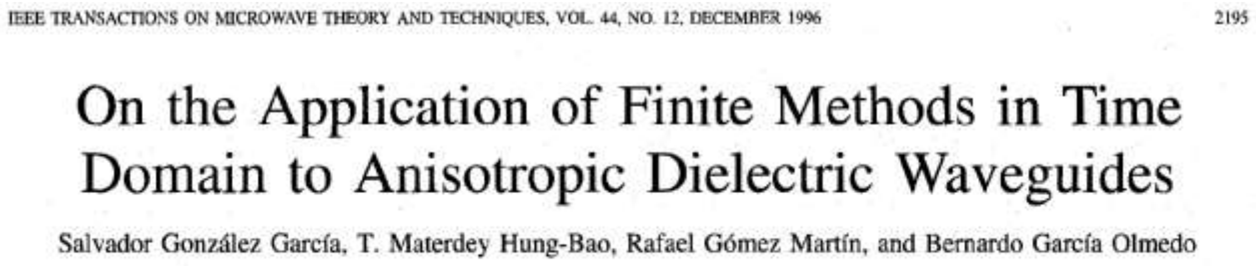
$$\begin{cases}\vec{P}_k(t)=R_k\vec{E}(t)+R_k p_k\displaystyle\int_{t'=-\infty}^{t'=t}e^{p_k(t-t')}\vec{E}(t')\,dt' \\ \partial_t\vec{P}_k(t)-p_k\vec{P}_k(t)=R_k\partial_t\vec{E}(t)\end{cases}$$

PLRC

ADE

ANISOTROPIC MATERIALS

$$
\begin{aligned}
&\underbrace{E_x^{n+1}(i+\frac{1}{2},j,k)}=\underbrace{E_x^{n}(i+\frac{1}{2},j,k)}+\frac{\Delta t}{\Delta}\Bigg\{ \\
&\xi_{xx}\quad \Bigg(\underbrace{H_z^{n+\frac{1}{2}}(i+\frac{1}{2},j+\frac{1}{2},k)}-\underbrace{H_z^{n+\frac{1}{2}}(i+\frac{1}{2},j-\frac{1}{2},k)}\Bigg)\quad - \\
&\xi_{xx}\quad \Bigg(\underbrace{H_y^{n+\frac{1}{2}}(i+\frac{1}{2},j,k+\frac{1}{2})}-\underbrace{H_y^{n+\frac{1}{2}}(i+\frac{1}{2},j,k-\frac{1}{2})}\Bigg)\quad + \\
&\xi_{xy}\quad \Big(H_x^{n+\frac{1}{2}}(i+\tfrac{1}{2},j,k+\tfrac{1}{2})-H_x^{n+\frac{1}{2}}(i+\tfrac{1}{2},j,k-\tfrac{1}{2})\Big)\quad - \\
&\xi_{xz}\quad \Big(H_x^{n+\frac{1}{2}}(i+\tfrac{1}{2},j+\tfrac{1}{2},k)-H_x^{n+\frac{1}{2}}(i+\tfrac{1}{2},j-\tfrac{1}{2},k)\Big)\quad + \\
&\xi_{xz}\quad \Big(H_y^{n+\frac{1}{2}}(i+1,j,k)-H_y^{n+\frac{1}{2}}(i,j,k)\Big)\quad - \\
&\xi_{xy}\quad \Big(H_z^{n+\frac{1}{2}}(i+1,j,k)-H_z^{n+\frac{1}{2}}(i,j,k)\Big)\Bigg\}
\end{aligned}
$$



IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. 44, NO. 12, DECEMBER 1996 2195

On the Application of Finite Methods in Time Domain to Anisotropic Dielectric Waveguides

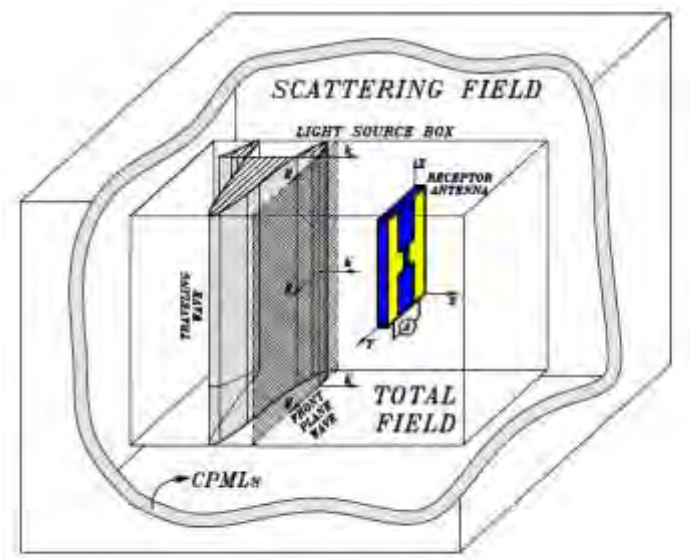
Salvador González García, T. Materdey Hung-Bao, Rafael Gómez Martín, and Bernardo García Olmedo

MULTIPHYSICS: SEMICONDUCTOR MODELING

$$\mu\partial_t\vec{H}(\vec{r},t) = -\vec{\nabla}\wedge\vec{E}(\vec{r},t), \qquad \varepsilon\partial_t\vec{E}(\vec{r},t) = \vec{\nabla}\wedge\vec{H}(\vec{r},t) - \vec{J}_T(\vec{r},t)$$

$$\partial_t n(\vec{r},t) = q^{-1}\vec{\nabla}\cdot\vec{J}_{nT}(\vec{r},t) + G(\vec{r},t) - R(\vec{r},t)$$

$$\partial_t p(\vec{r},t) = -q^{-1}\vec{\nabla}\cdot\vec{J}_{pT}(\vec{r},t) + G(\vec{r},t) - R(\vec{r},t)$$



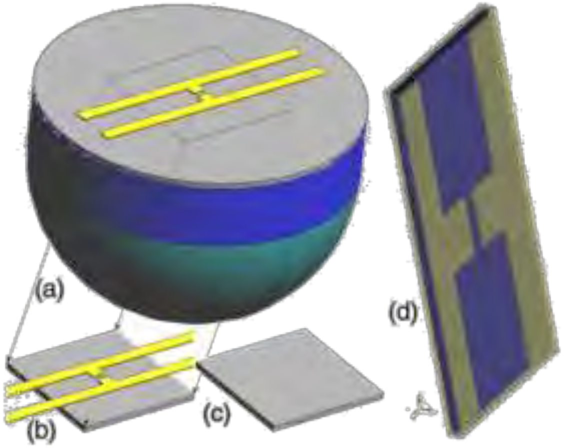


Fig. 1. (a) Photoconductive antenna formed by a photolayer of LT-GaAs on SI-GaAs substrate and a dielectric lens under the substrate. (b) PEC contact on the photozone. (c) The photozone. (d) Computational domain simulated.

Vol. 32, No. 10 / October 2015 / *Journal of the Optical Society of America B*

Time-domain numerical modeling of THz receivers based on photoconductive antennas

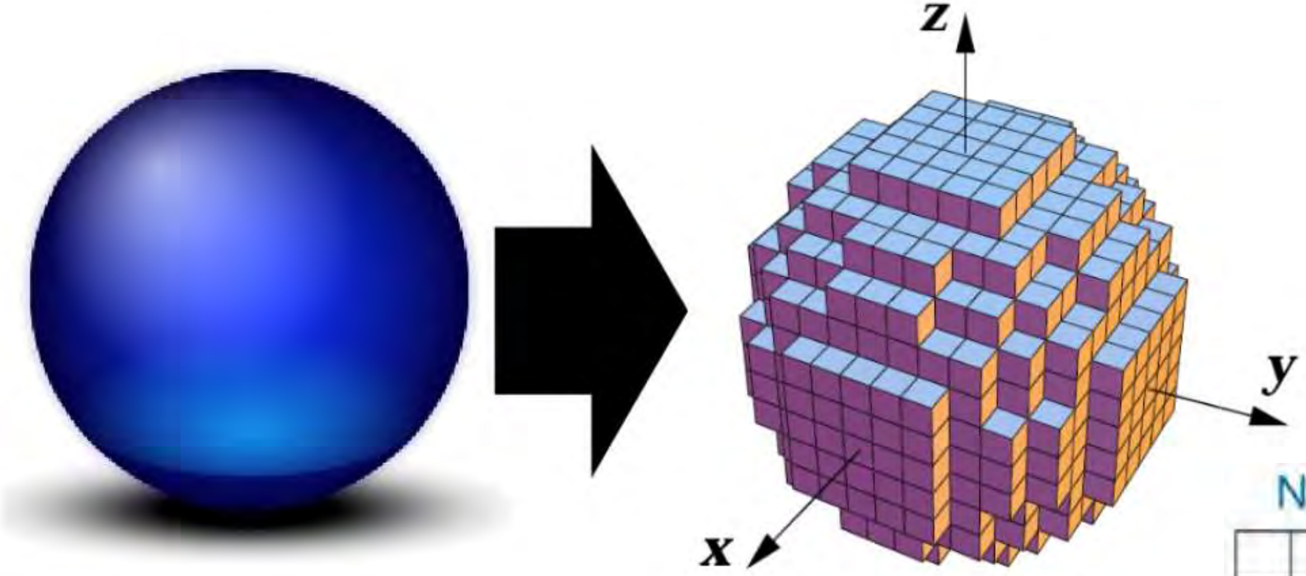
E. MORENO[1,*], Z. HEMMAT[2,*], J.B. ROLDÁN[3,*], M. F. PANTOJA[1,*], A. R. BRETONES[1,*], AND S. G. GARCÍA[1,*]

FDTD: TOWARDS A PRACTICAL SIMULATION TOOL

SUB-CELL EXTENSIONS COMMON IN EMC

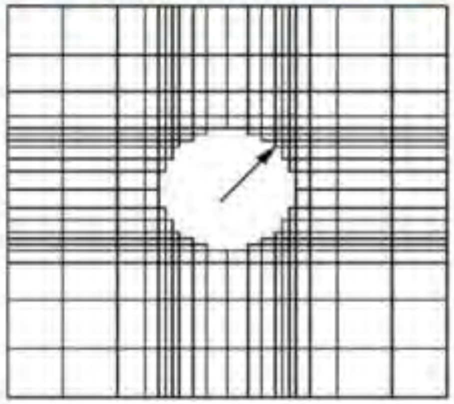
STAIRCASE MESHING

Staircasing error. It is the error introduced of the cubical spatial discretization of the FDTD method.



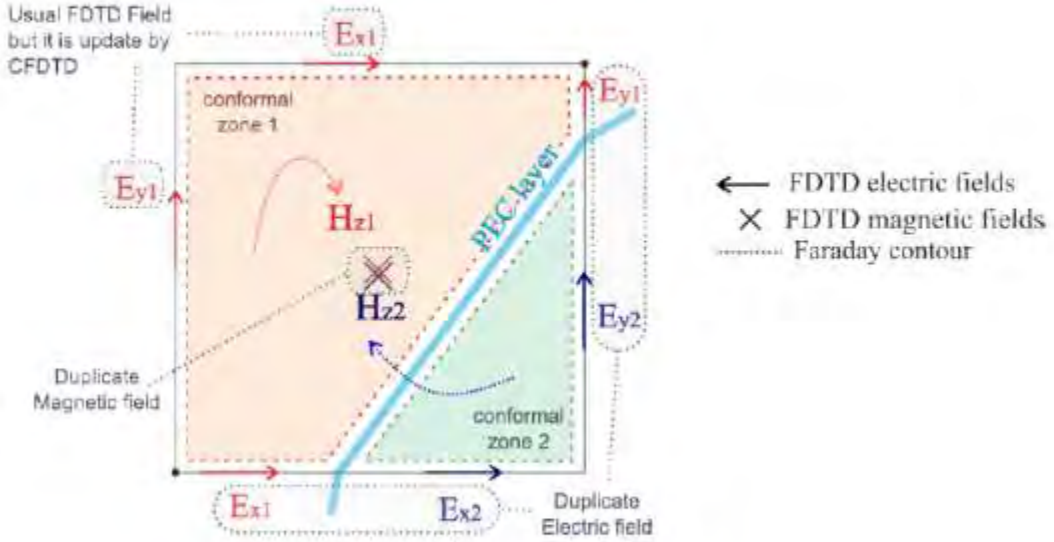
FDTD classic discretization.

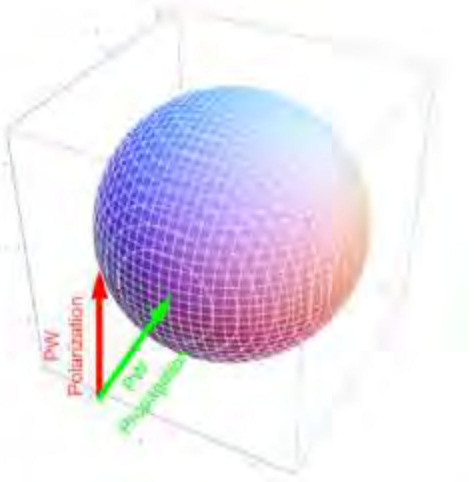
Non-uniform FDTD



STAIRCASE ALTERNATIVES

Conformal methods aim to mitigate staircasing error.

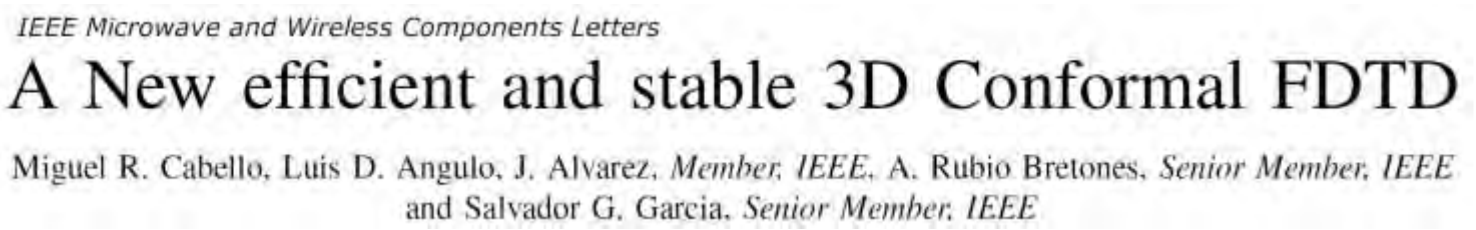




Applying a conformal meshing algorithm. (Dey/Yu-Mittra)

S. Dey and R. Mittra, “A locally conformal finite-difference time-domain (FDTD) algorithm for modeling three-dimensional perfectly conducting objects,” IEEE Microwave Guided Wave Lett., vol. 7, pp.273–275, Sept. 1997.

CONFORMAL FDTD

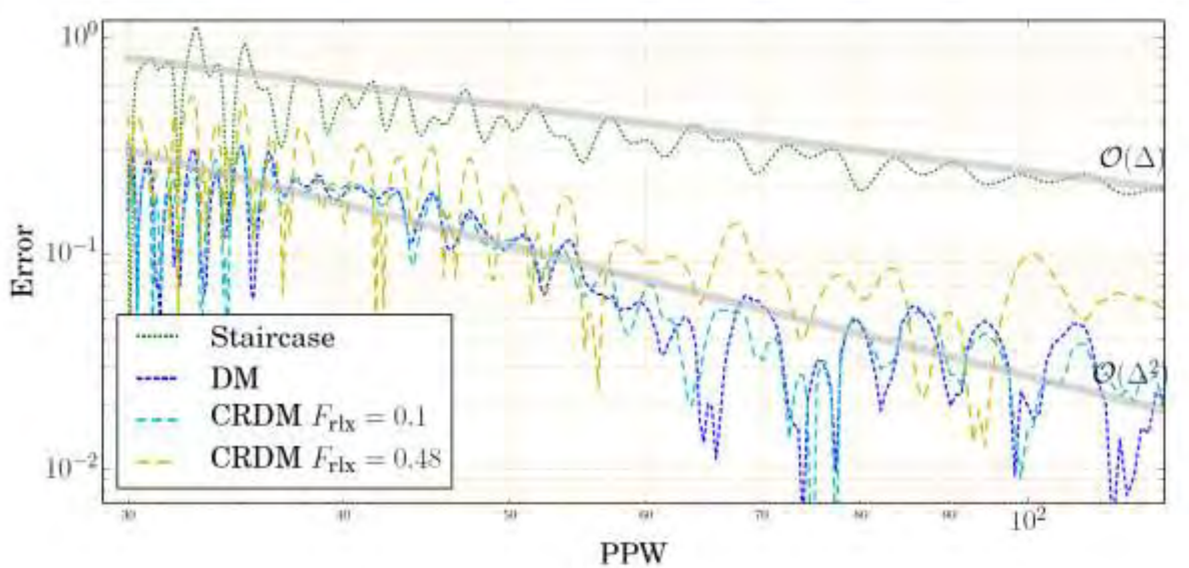


IEEE Microwave and Wireless Components Letters

A New efficient and stable 3D Conformal FDTD

Miguel R. Cabello, Luis D. Angulo, J. Alvarez, *Member, IEEE*, A. Rubio Bretones, *Senior Member, IEEE*
and Salvador G. Garcia, *Senior Member, IEEE*

Bistatic RCS of a NASA almond at *1* GHz. Comparison results between staircase, conformal relaxed and MoM/DGTD.

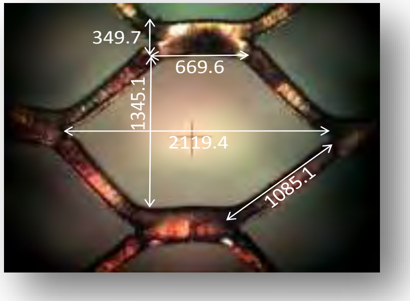


L2 **error norm with respect to MoM/DGTD versus the number of Points Per Wavelength (PPW)**

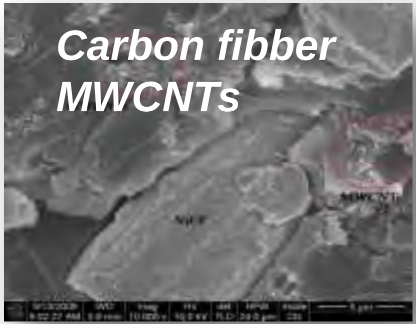
DISPERSIVE SURFACES / METASURFACES

- Carbon-fibber composites, laminates & sandwiches

- Protective metallic meshes

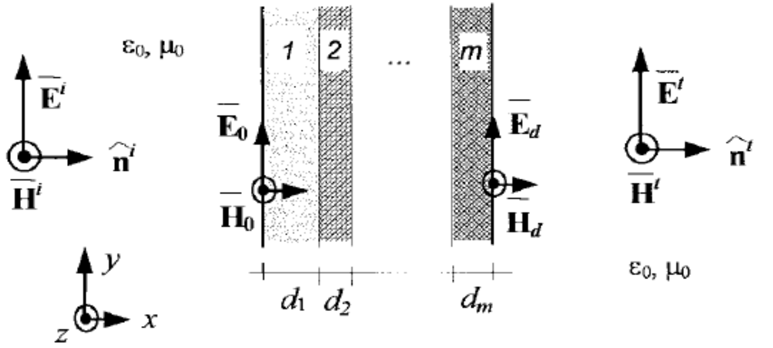


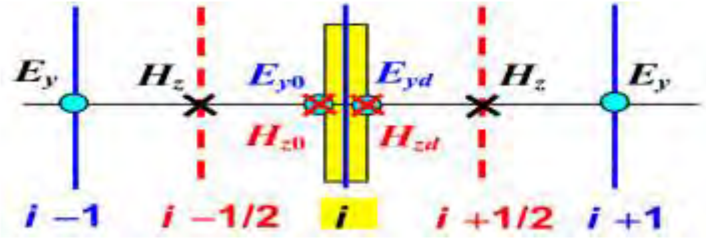
- Micro / nanocomposites



ANISOTROPIC DISPERSIVE THIN-PANELS

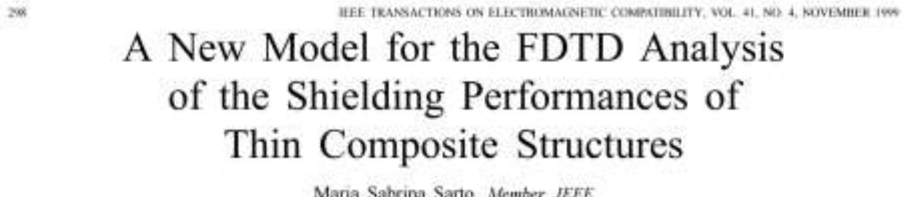
2-SIDED SURFACE IMPEDANCE BOUNDARY CONDITIONS (IBC) (LOSSY MULTILAYERS)





$$\begin{bmatrix} E_{y0}(\omega) \\ H_{z0}(\omega) \end{bmatrix} = \prod_{i=1}^{m} [\Phi_i(\omega)] \begin{bmatrix} E_{yd}(\omega) \\ H_{zd}(\omega) \end{bmatrix} \Rightarrow \begin{bmatrix} E_{y0}(\omega) \\ E_{yd}(\omega) \end{bmatrix} = [Z(\omega)] \begin{bmatrix} H_{z0}(\omega) \\ -H_{zd}(\omega) \end{bmatrix}$$

$$[\Phi_i(\omega)] = \begin{bmatrix} \cosh(\gamma_i d_i) & \sinh(\gamma_i d_i) \\ \eta_i^{-1} \sinh(\gamma_i d_i) & \cosh(\gamma_i d_i) \end{bmatrix} \qquad \eta_i = \sqrt{\mu_i \left(\varepsilon_i + \frac{\sigma_i}{j\omega} \right)^{-1}}, \; \gamma_i = j\omega \sqrt{\mu_i \left(\varepsilon_i + \frac{\sigma_i}{j\omega} \right)}$$



298 IEEE TRANSACTIONS ON ELECTROMAGNETIC COMPATIBILITY, VOL. 41, NO. 4, NOVEMBER 1999

A New Model for the FDTD Analysis of the Shielding Performances of Thin Composite Structures

Maria Sabrina Sarto, *Member, IEEE*

VECTOR FITTING

$$Z(\omega) = Z_\infty + \sum_{k=1}^{N} \frac{R_k}{j\omega - p_k} \in \text{Reals}$$

STABILITY

Boundedness

$$\lim_{t\to\infty}\left[\text{Z(t)}\right] \neq \infty \quad \Leftrightarrow \text{Re}\left\{p_k\right\} \le 0$$

PASSIVITY

NO Energy generation

$$\Leftrightarrow \lambda(\omega)\text{=eig}\left\{\tilde{Z}(\omega) \; + \tilde{Z}^H(\omega)\right\} > 0$$

$$Z_k\text{(t)=Fourier}^{-1}\left\{\frac{R_k}{j\omega - p_k} + \frac{R_k^*}{j\omega - p_k^*}\right\} =$$

$$e^{\text{Re}\{p_k\}t}\, 2R_k \cos\left(\text{Im}\left\{p_k\right\}t\right)$$

CAUSALITY

Response AFTER excitation

$$Z(\omega) \quad \text{analytic} \quad \forall \omega > 0 \quad \Leftrightarrow$$

$$\lim_{\omega\to\infty} \frac{Z(\omega)}{\omega} = 0 \;\&\; Z_{r,i}(\omega) = \mp \frac{1}{\pi} P_{Cauchy}\left[\int_{-\infty}^{+\infty} \frac{Z_{i,r}(\omega)}{\omega' - \omega} d\omega'\right]$$

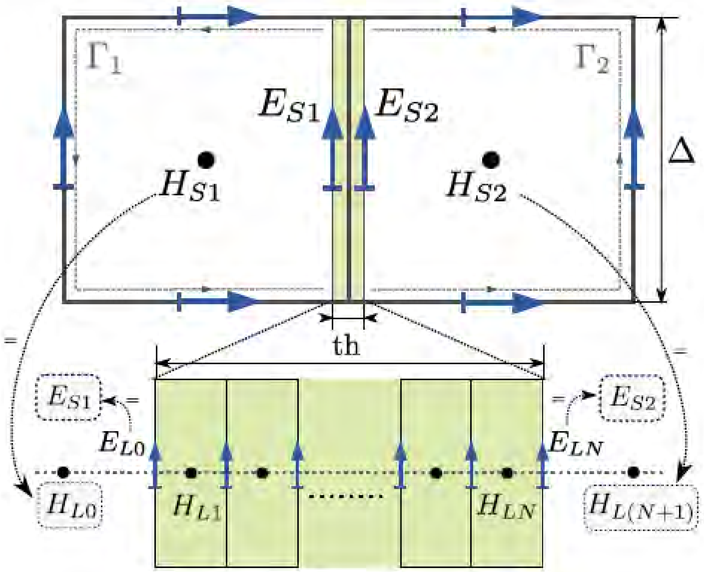
KRAMER-KRONIG

https://www.sintef.no/projectweb/vectfit/

The Vector Fitting Web Site

ALTERNATIVE TO SIBC

SUBGRIDDING BOUNDARY CONDITIONS (SGBC)



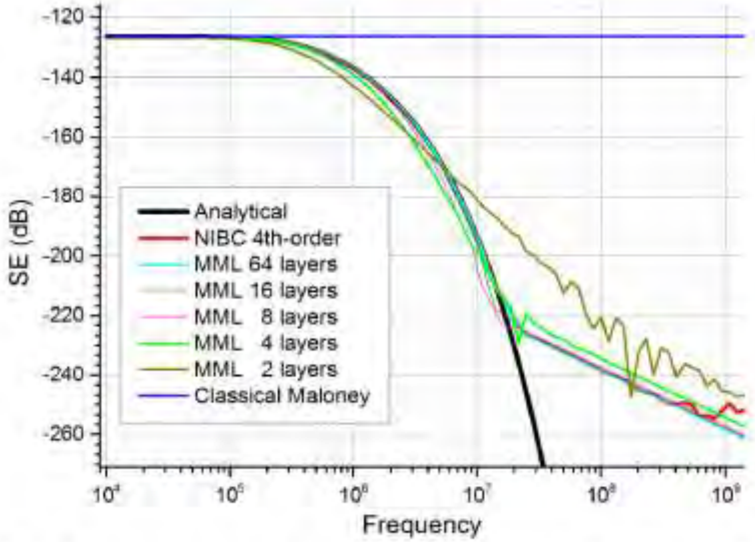
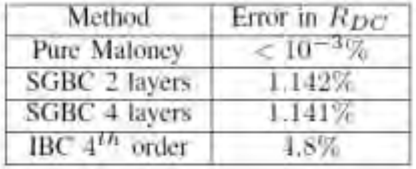
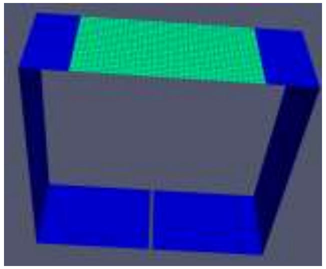


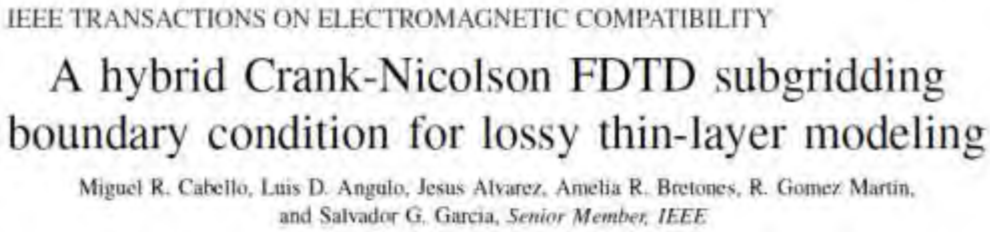
Fig. 3: Shielding effectiveness for an aluminum planar slab with a conductivity $\sigma = 3.456 \cdot 10^7\ S/m$ and a thickness $h = 0.3mm$. Space-step $\Delta = 2.5mm$.



Method	Error in R_{DC}
Pure Maloney	$< 10^{-3}\%$
SGBC 2 layers	1.142%
SGBC 4 layers	1.141%
IBC 4^{th} order	4.8%

TABLE I: Errors in DC prediction of a ($\sigma = 20S/m$), 216mm long x 120 mm width x 2 mm thick meshed with $\Delta = 6mm$.



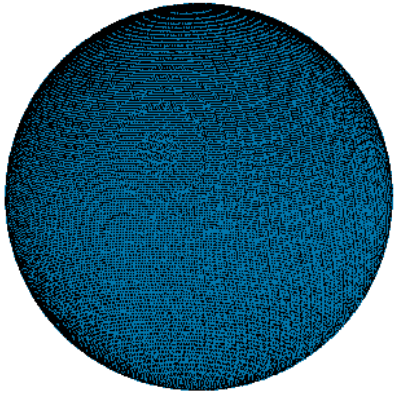


IEEE TRANSACTIONS ON ELECTROMAGNETIC COMPATIBILITY

A hybrid Crank-Nicolson FDTD subgridding boundary condition for lossy thin-layer modeling

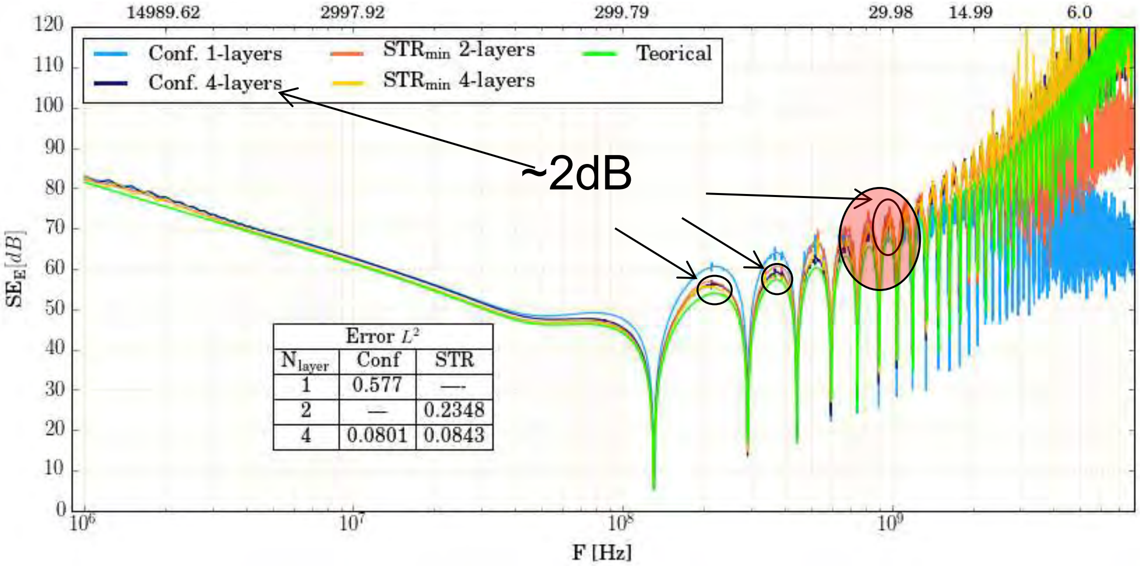
Miguel R. Cabello, Luis D. Angulo, Jesus Alvarez, Amelia R. Bretones, R. Gomez Martin, and Salvador G. Garcia, *Senior Member, IEEE*

CONFORMAL THIN-PANELS



Cell size=10 mm.

thickness is 5mm, and its conductivity is 200 S/m.

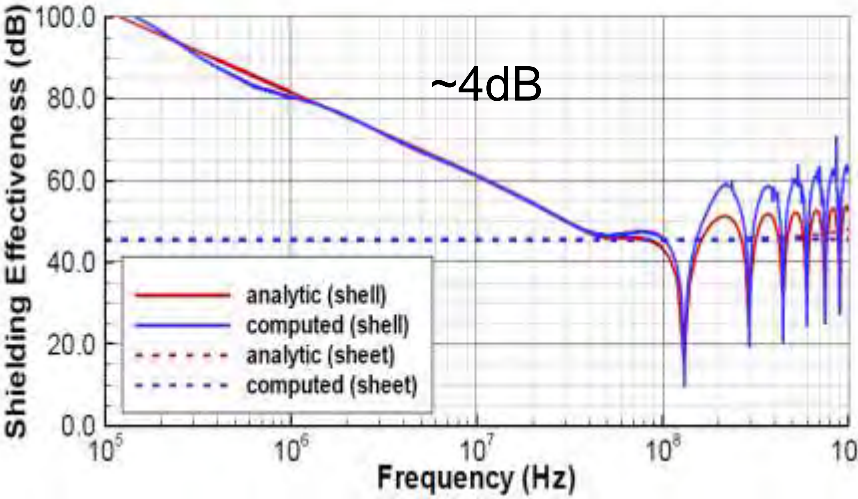


~2dB

Error L^2		
N$_{layer}$	Conf	STR
1	0.577	—
2	—	0.2348
4	0.0801	0.0843

Effective Parameters

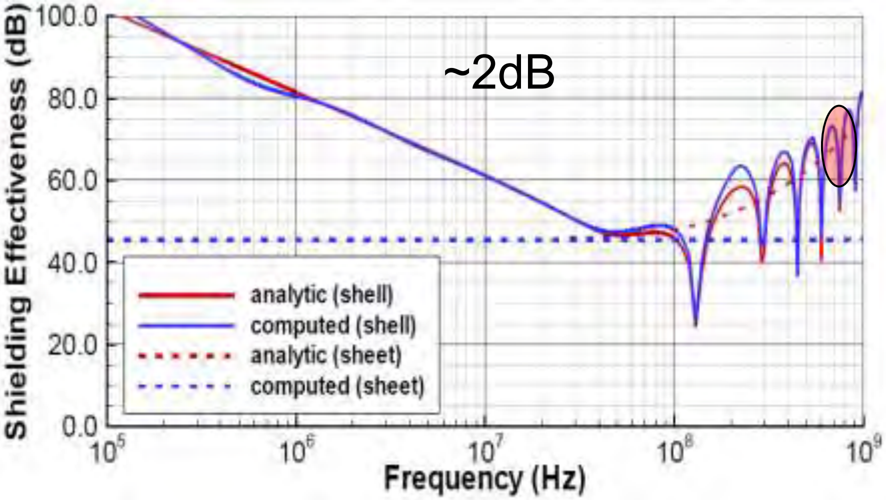
thin shell	1 mm	1000 S/m



~4dB

(a) Thin shell.

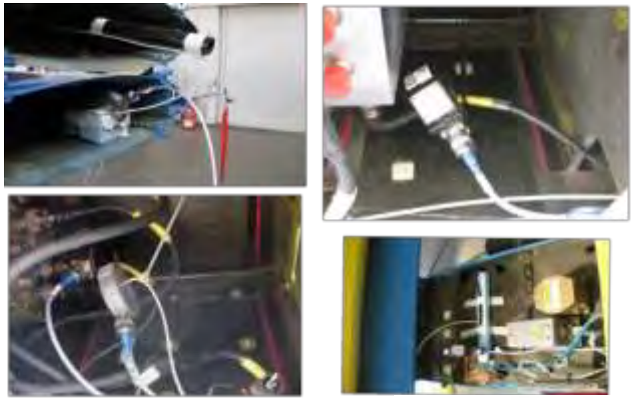
medium shell	10 mm	100 S/m

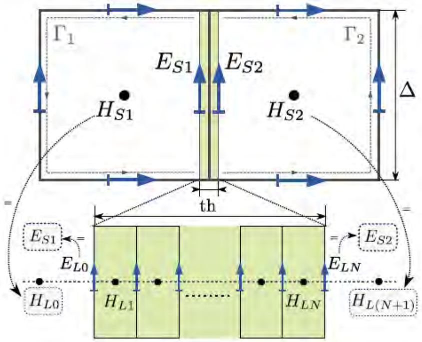


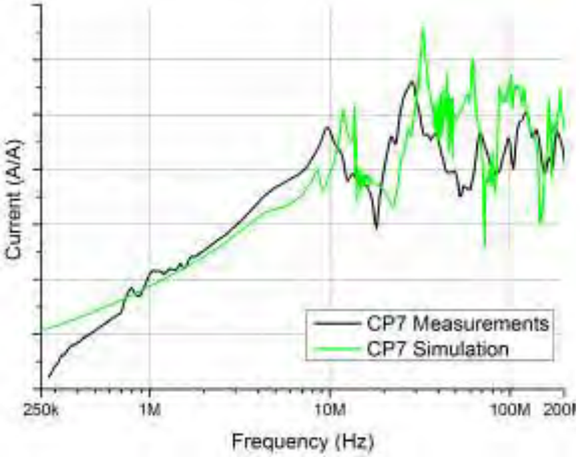
~2dB

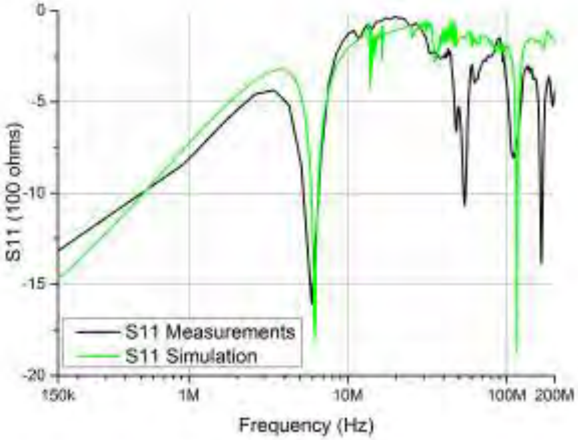
(b) Medium shell.

APPLICATIONS: INTA's SIVA









FSV

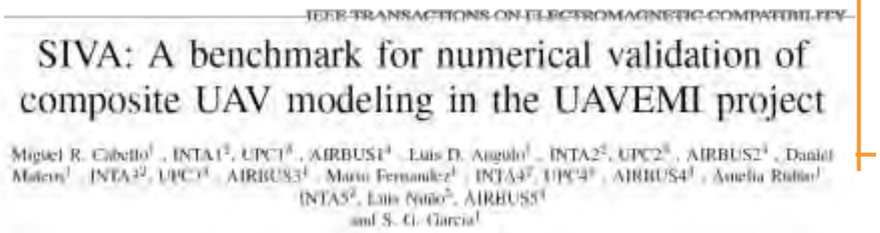
	ADM	FDM	GDM	Expert impression
CP1	0.2038	0.5315	0.6243	Excellent
CP3	0.2659	0.6137	0.742	Excellent
CP7	0.2642	0.5336	0.6685	Excellent

R. Jauregui, M. Pous and F. Silva, "Use of reference limits in the Feature Selective Validation (FSV) method," Electromagnetic Compatibility (EMC Europe), 2014 International Symposium on, Gothenburg, 2014, pp. 1031-1036.

esa 2016 esa workshop on aerospace emc
23 - 25 May 2016

UAVEMI PROJECT: NUMERICAL AND EXPERIMENTAL EM IMMUNITY ASSESSMENT OF UAV FOR HIRF AND LIGHTNING INDIRECT EFFECTS

Salvador G. Garcia(1), Ferran Silva(2), David Escot(3), Enrique Pascual(1),Mario F. Pantoja(1), Pere Riu(2), Manuel Añón(3), Jesús Álvarez(4), M. Cabello(1), Marc Pous(2), Sergio Fernandez(2), Rafael Trallero(3), Luis Nuño(5)

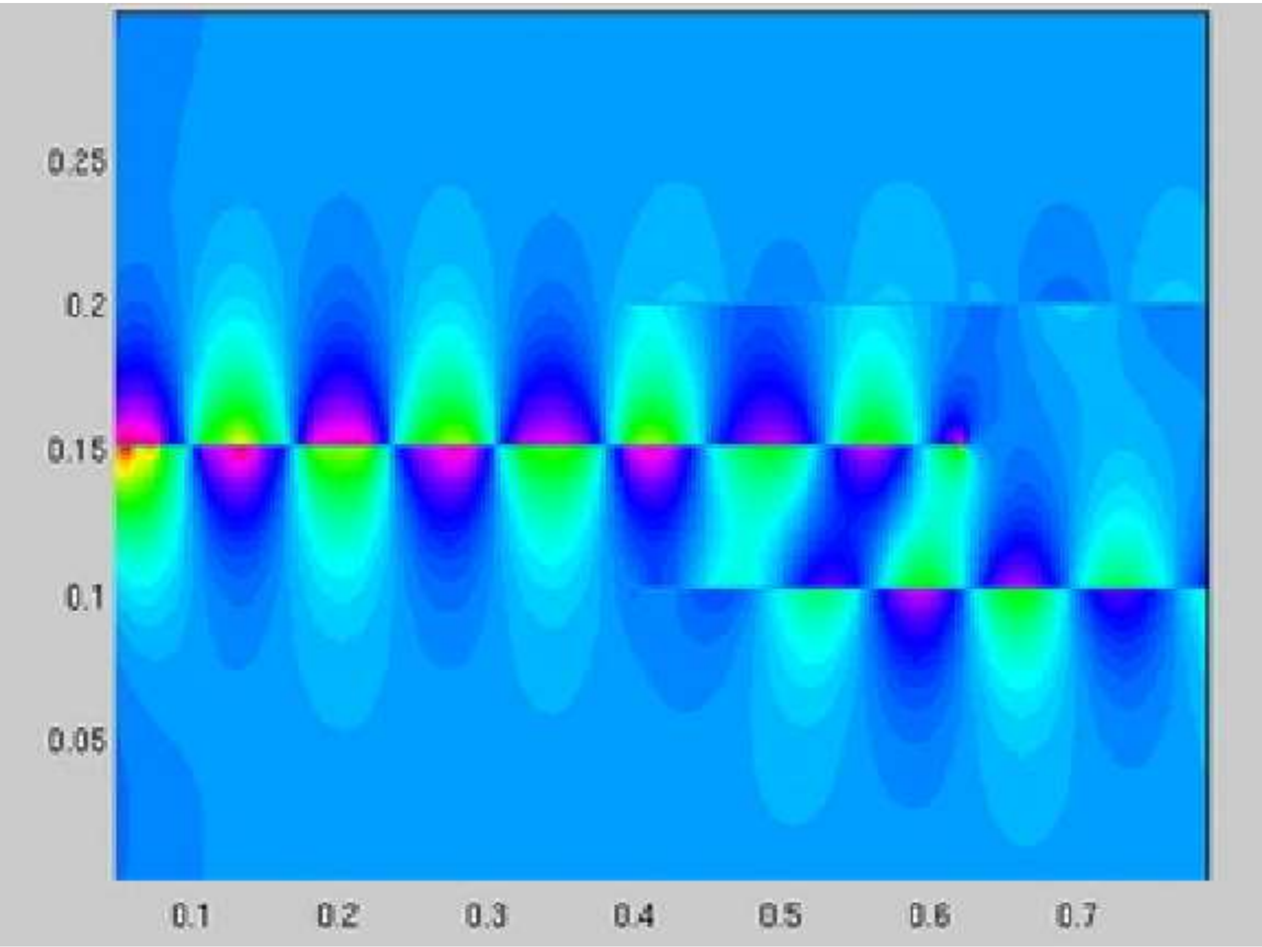


IEEE TRANSACTIONS ON ELECTROMAGNETIC COMPATIBILITY

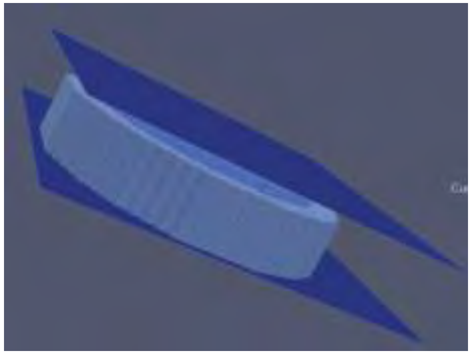
SIVA: A benchmark for numerical validation of composite UAV modeling in the UAVEMI project

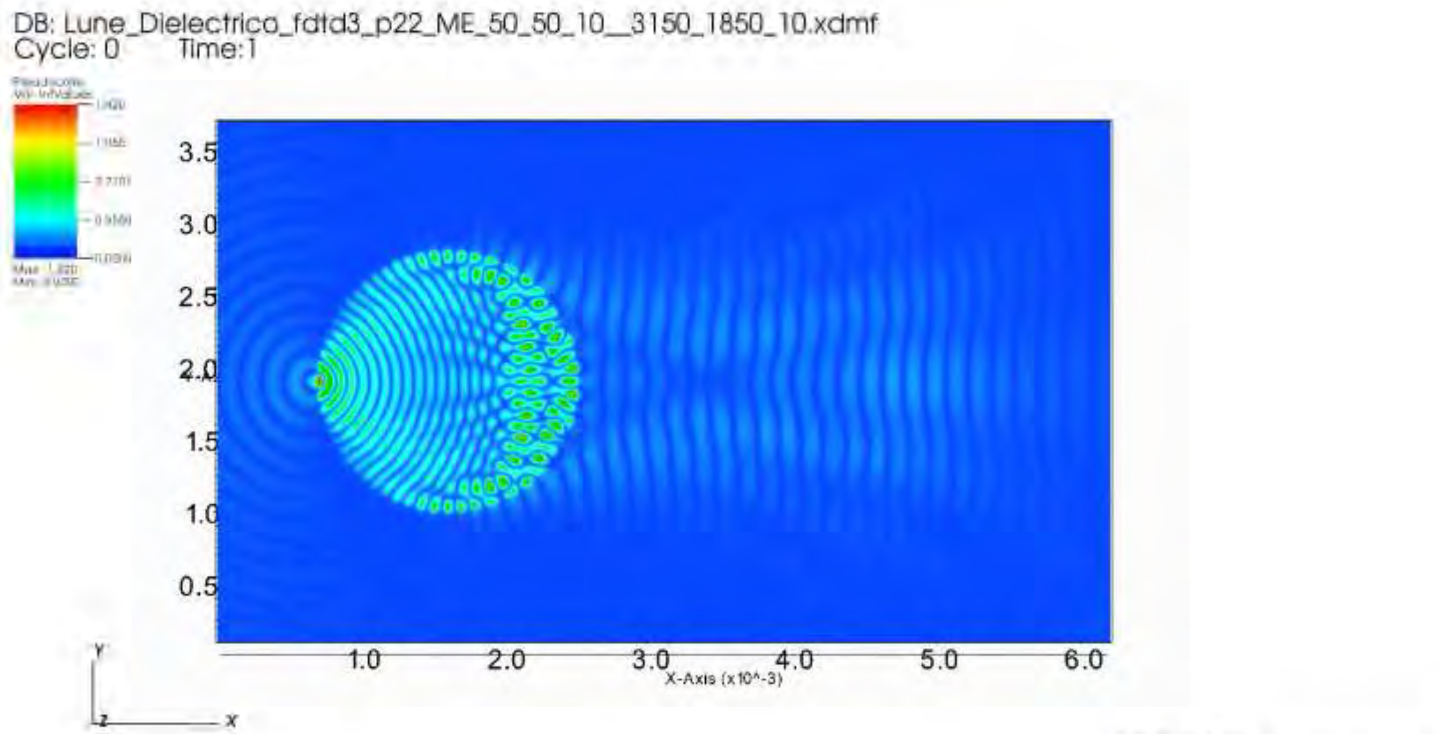
Miguel R. Cabello[1], INTA1[2], UPC1[3], AIRBUS1[4], Luis D. Angulo[1], INTA2[2], UPC2[3], AIRBUS2[4], Daniel Mateos[1], INTA3[2], UPC3[3], AIRBUS3[4], Mario Fernandez[1], INTA4[2], UPC4[3], AIRBUS4[4], Amelia Rubio[1] INTA5[2], Luis Nuño[2], AIRBUS5[4] and S. G. Garcia[1]

DISPERSIVE METASURFACES GRAPHENE



DISPERSIVE PERIODIC METASURFACES: LUNEBURG LENS





DB: Lune_Dielectrico_fdtd3_p22_ME_50_50_10__3150_1850_10.xdmf
Cycle: 0 Time:1

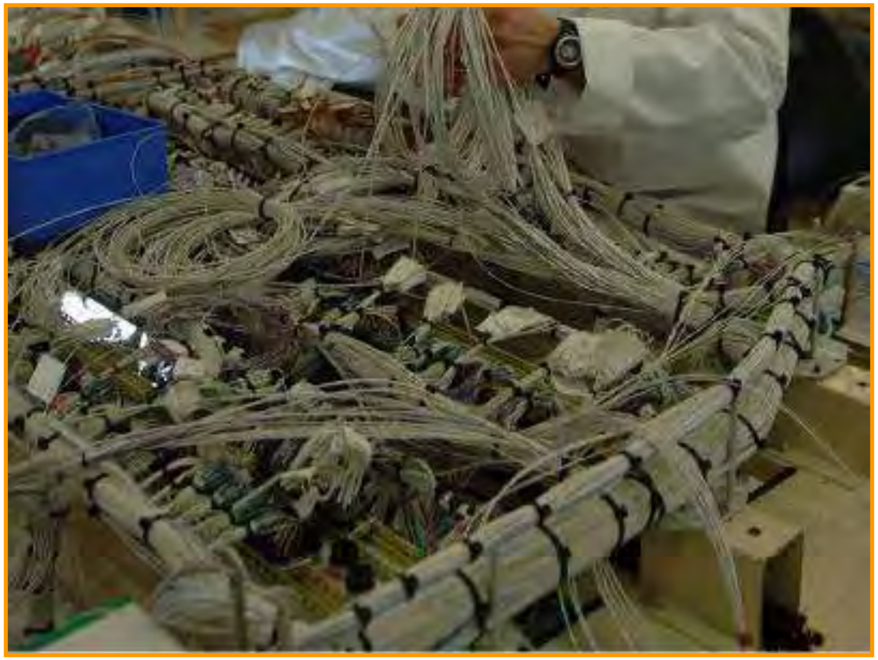
user: salva
Thu May 14 21:02:58 2015

IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, VOL. 60, NO. 9, SEPTEMBER 2012 4065

Non-Uniform Metasurface Luneburg
Lens Antenna Design

Marko Bosiljevac, Massimiliano Casaletti, *Member, IEEE*, Francesco Caminita, Zvonimir Sipus, *Member, IEEE*, and Stefano Maci, *Fellow, IEEE*

CABLE BUNDLE AND HARNESS SOLVING



HYBRID MTLN – 3D FDTD SOLVER

$$\tilde{L}\frac{\partial \bar{I}}{\partial t} + \tilde{R}\bar{I} + \tilde{L}\tilde{C}\frac{\partial \bar{V}}{\partial \xi} = \left\langle \bar{E}_{\xi} \right\rangle , \quad \tilde{C}\frac{\partial \bar{V}}{\partial t} + \frac{\partial \bar{I}}{\partial \xi} = 0$$

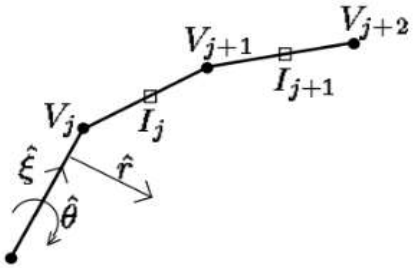
TWO-WAY FIELD-TO-TL

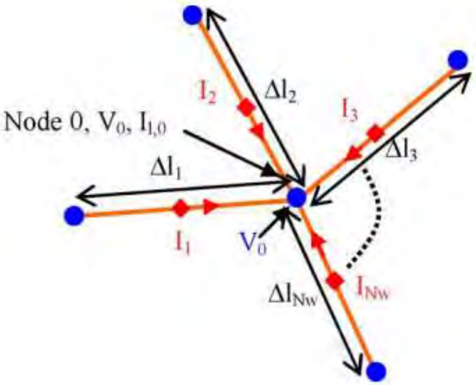
$$\vec{J} = \varepsilon\frac{\partial \vec{E}}{\partial t} + \sigma\vec{E} - curl\,\vec{H} , \quad \mu\frac{\partial \vec{H}}{\partial t} + curl\,\vec{E} = 0$$

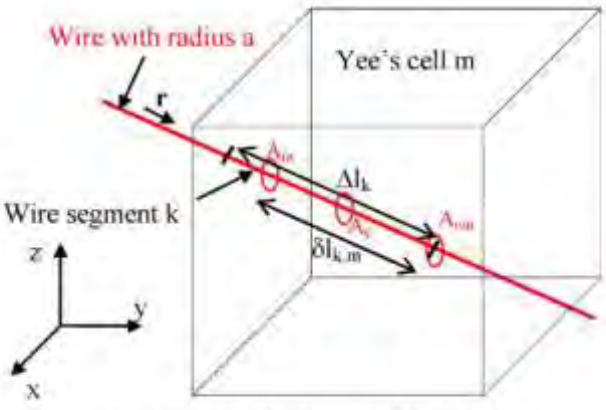
- The return path is provided by the solution of Maxwell equations *at the adjacent space*, *in terms of the displacement current flowing around a section transversal to the path*

- The assumption of transmission line propagation is no longer restricted to common-mode TL solutions, and they obtain both antenna-mode differential (radiation), and common-mode TL solutions

CONFORMAL CABLE SOLVER







A_{in}: input point of the segment k in the cell m
A_{out}: output point of the segment k in the cell m
A_c: center point of the segment part belonging to the cell m

$$L_{u,j,m} = \frac{\mu_0}{2\pi}\frac{\iiint_{V_{u,j,m}} \ln\left(\frac{\rho(x,y,z)}{a}\right)dxdydz}{\Delta x\Delta y\Delta z}$$

$$\bar{I}_{k+1/2}^{n+1/2} = \tilde{b}_{1I,k}\bar{I}_{k+1/2}^{n-1/2} + \tilde{b}_{2I,k}\left(\bar{V}_{k+1}^{n} - \bar{V}_k^{n}\right) + \tilde{b}_{3I,k}\langle \bar{E}_k^n\rangle$$

$$V_k^{n+1} = b_{1V,k}V_k^n + b_{2V,k}\sum_{q=1}^{N_w} I_q^{n+1/2}$$

$$\tilde{b}_{1I,k} = (\tilde{L}+\tilde{R}\Delta t/2)^{-1}(\tilde{L}-\tilde{R}\Delta t/2)$$

$$\tilde{b}_{2I,k} = -c^2\frac{\Delta t}{\Delta\xi}(\tilde{L}+\tilde{R}\Delta t/2)^{-1}\tilde{L}\tilde{C}$$

$$\tilde{b}_{3I,k} = \Delta t(\tilde{L}+\tilde{R}\Delta t/2)^{-1}$$

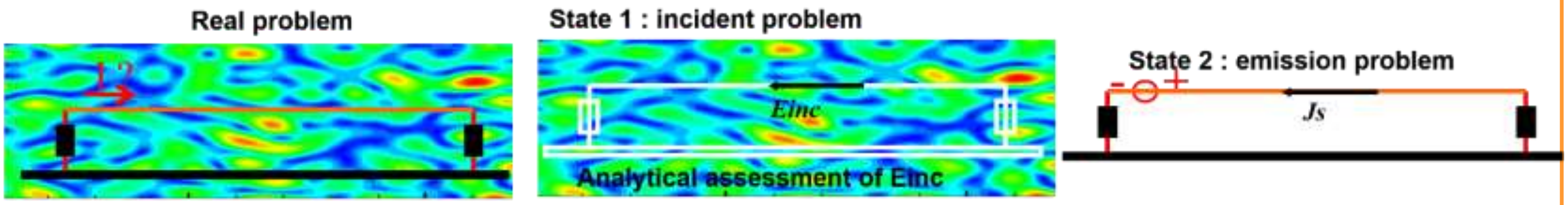
1458 IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, VOL. 60, NO. 3, MARCH 2012

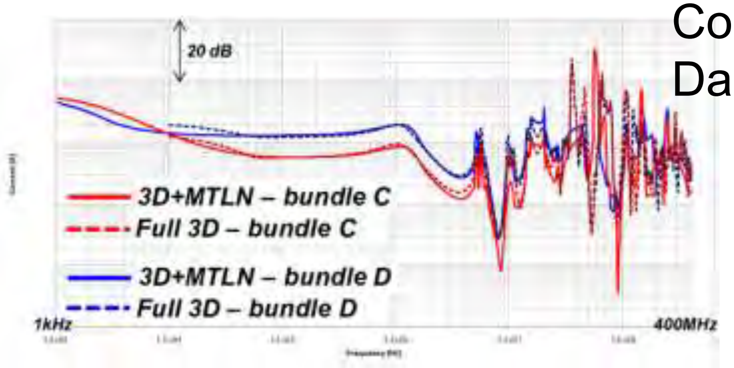
New Oblique Thin Wire Formalism in the FDTD Method With Multiwire Junctions

Christophe Guiffaut, *Member, IEEE*, Alain Reineix, *Member, IEEE*, and Bernard Pecqueux

FIELD-TO-TL CABLE SOLVER

ONE-WAY FIELD-TO-TL:
CO-SIMULATION (NO GEOMETRY)





Courtesy of
Dassault

- OK: Field-to-TL is especially suited for complex bundles
- KO: Disregards the re-radiation effects of cables flowing along cables. Depends on E/H coupling predominancy

F. Rachidi, "A Review of Field-to-Transmission Line Coupling Models With Special Emphasis to Lightning-Induced Voltages on Overhead Lines," in IEEE Transactions on Electromagnetic Compatibility, vol. 54, no. 4, pp. 898-911, Aug. 2012.

PARALLEL COMPUTER IMPLEMENTATIONS

FDTD Parallelization possibilities

Shared memory

- Several cores per CPU: **Multithreading**.
- Just needs compiler preprocessing directives to distribute loops
- Shared memory in **single CPU**.
- Performance **scales linearly** with number of threads.
- The standard is **OpenMP**. Included by default in c++.

Distributed memory

- **Several CPUs**.
- Needs **specific code**.
- Needs **mesh partition** to distribute the data among CPUs. Relatively simple partition in FDTD.
- Performance **scales linearly** with number of threads with special hardware.
- **MPI** is the standard. Several implementations available.

FDTD Parallelization possibilities

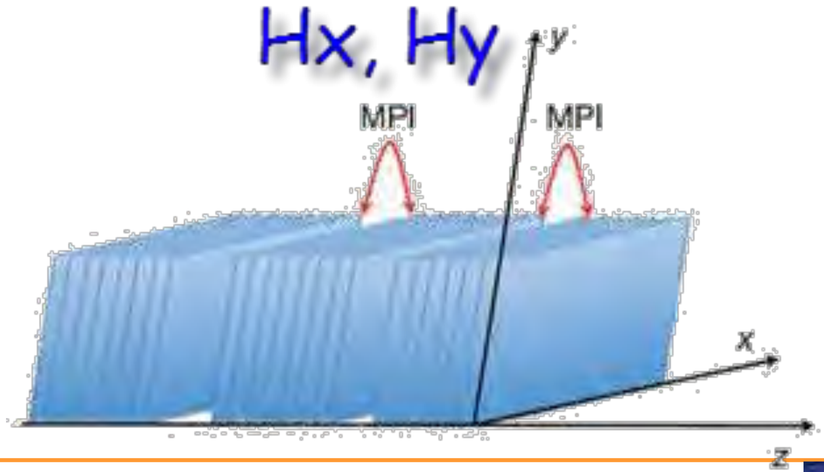
GPU, co-processors

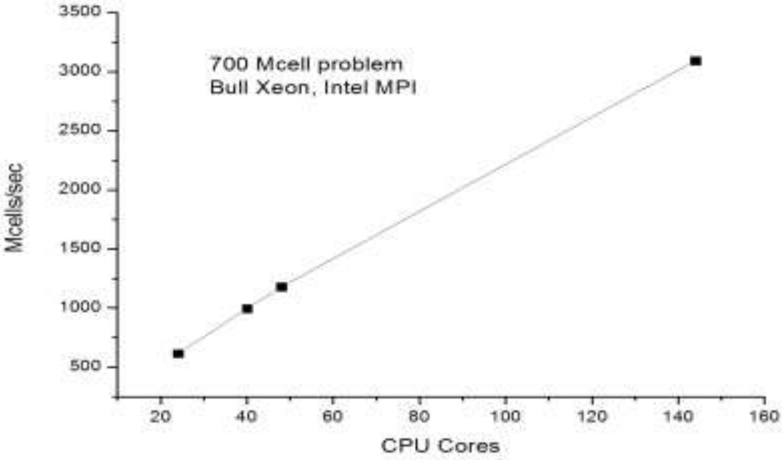
- Code runs on special processing units such as the **GPU**, Intel's Phi co-processors.
- Usually **hardware specific code**.
- Performs a Single Instruction in Multiple Data threads (**SIMD**).
- Massive number of threads.
- Fast intra-GPU memory bandwidth. Slow GPU-Main memory bandwidth.
- Relatively new, there is **no standard yet**. Several implementations available: CUDA, OpenCL, **OpenACC**.

PRACTICAL APPROACH: SPLIT ALONG 1D DIRECTION TO MAINTAIN MEMORY LOCALITY

- **OPEN-MP: Several cores intra-node. Directives to distribute DO-ENDDO loops**
- **MPI: Problem sliced among several nodes. Specific code to communicate data. Good scalability.**

> 20 Mcells/second/core

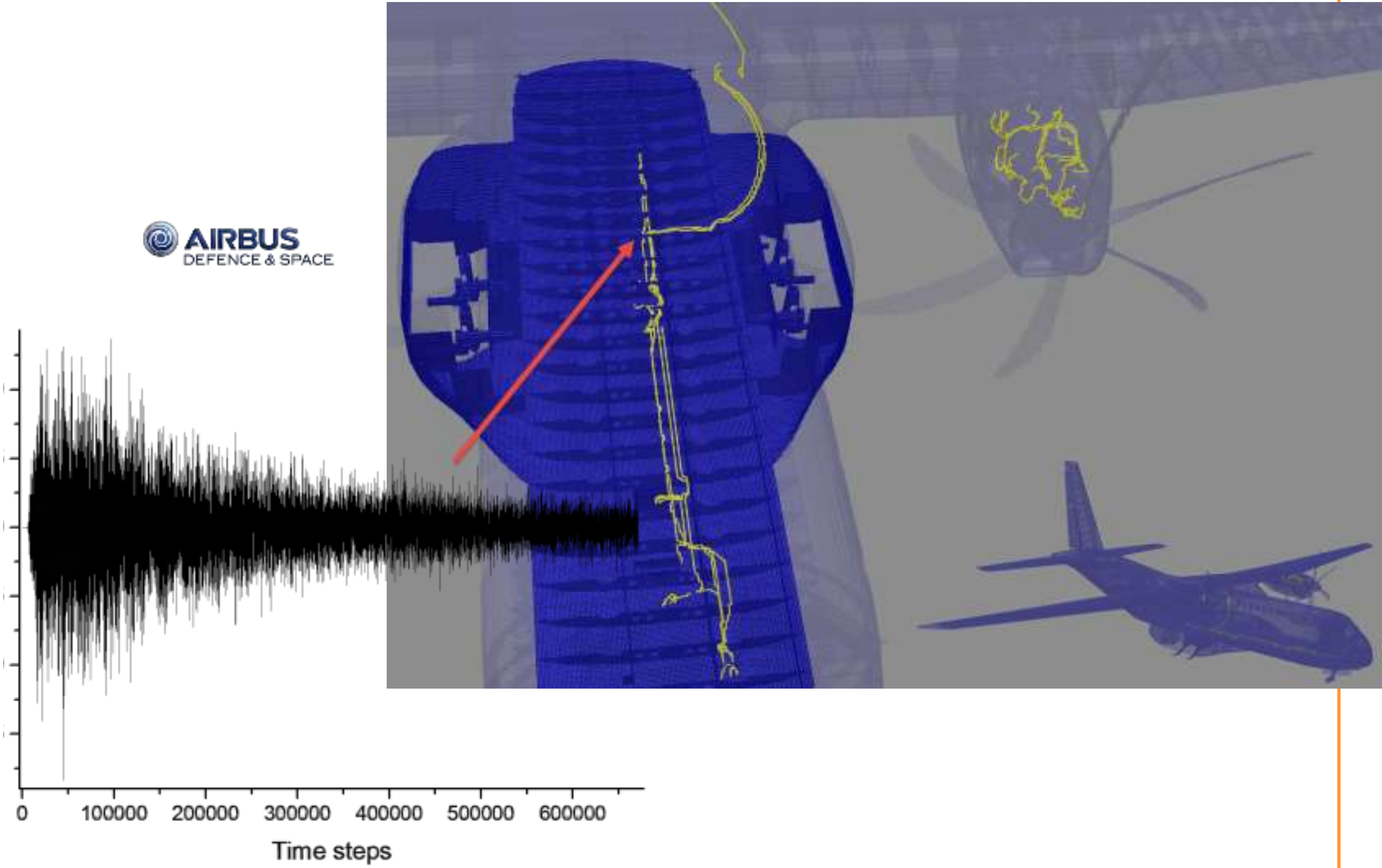




LARGE CPU:

AN OPEN ISSUE IN DETERMINISTIC EMC TD MODELING

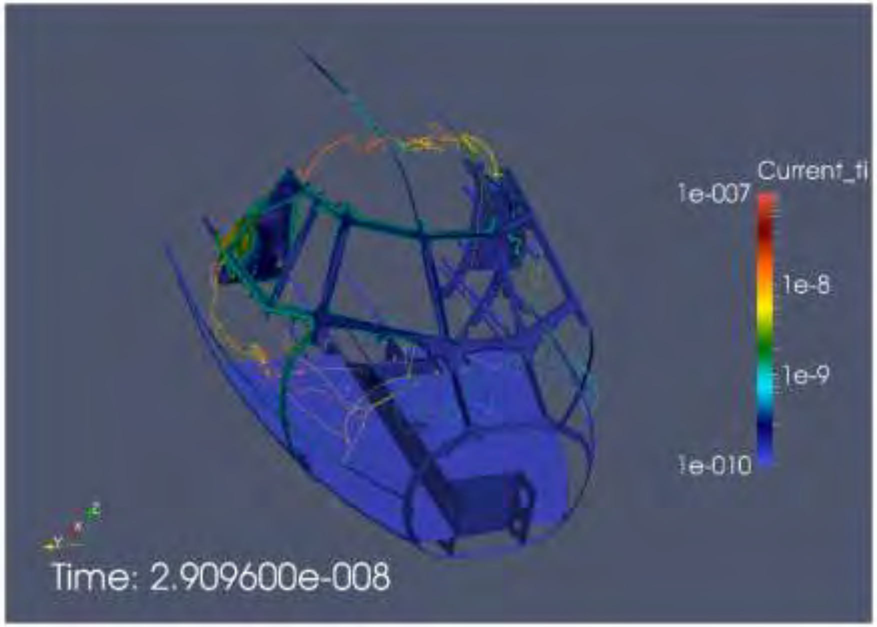
LARGE CPU FOR LF AND HIGH-Q

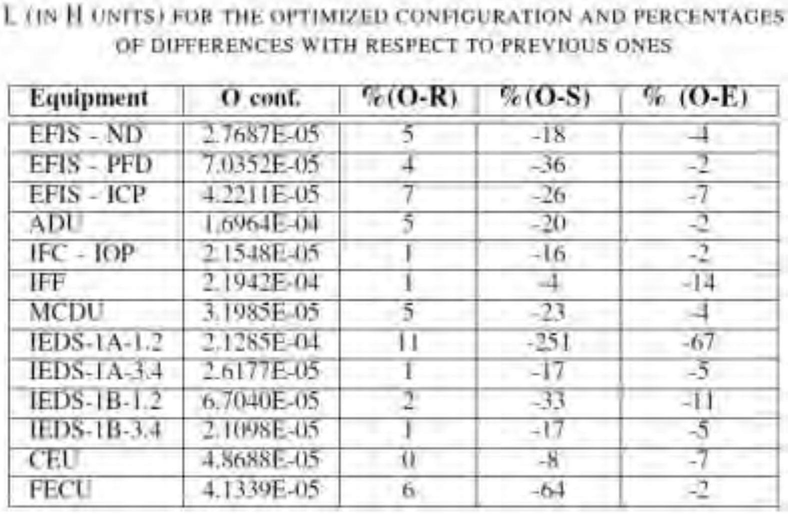


LARGE CPU REQUIREMENTS FOR

- HIGH-Q ENCLOSURES & LOW FREQUENCY PROBLEMS

SENSITIVITY





L (IN H UNITS) FOR THE OPTIMIZED CONFIGURATION AND PERCENTAGES OF DIFFERENCES WITH RESPECT TO PREVIOUS ONES

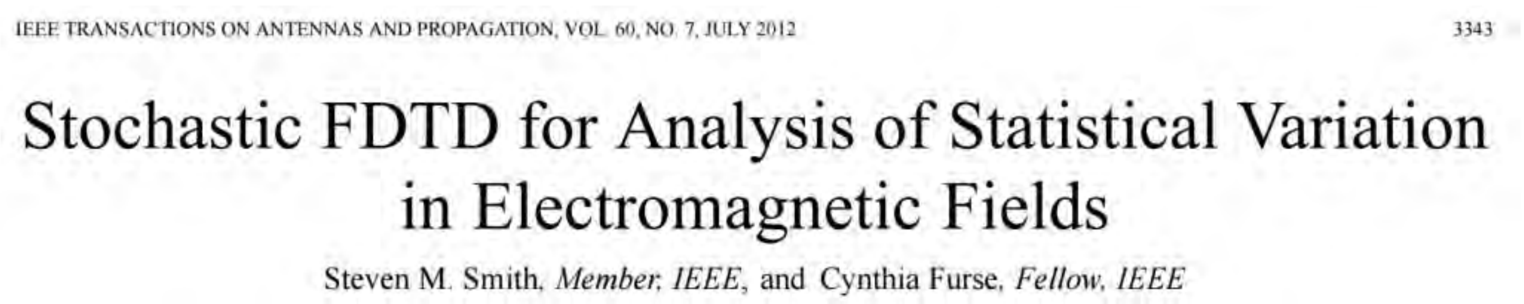
Equipment	O conf.	%(O-R)	%(O-S)	% (O-E)
EFIS - ND	2.7687E-05	5	-18	-4
EFIS - PFD	7.0352E-05	4	-36	-2
EFIS - ICP	4.2211E-05	7	-26	-7
ADU	1.6964E-04	5	-20	-2
IFC - IOP	2.1548E-05	1	-16	-2
IFF	2.1942E-04	1	-4	-14
MCDU	3.1985E-05	5	-23	-4
IEDS-1A-1.2	2.1285E-04	11	-251	-67
IEDS-1A-3.4	2.6177E-05	1	-17	-5
IEDS-1B-1.2	6.7040E-05	2	-33	-11
IEDS-1B-3.4	2.1098E-05	1	-17	-5
CEU	4.8688E-05	0	-8	-7
FECU	4.1339E-05	6	-64	-2

IEEE TRANSACTIONS ON ELECTROMAGNETIC COMPATIBILITY

On the Design of Aircraft Electrical Structure Networks

Guadalupe G. Gutierrez, Daniel Mateos Romero, Miguel Ruiz Cabello, Enrique Pascual-Gil, *Member, IEEE*, Luis Diaz Angulo, and Salvador Gonzalez Garcia, *Senior Member, IEEE*

NEXT STEP: STATISTICAL FDTD



IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, VOL. 60, NO. 7, JULY 2012 3343

Stochastic FDTD for Analysis of Statistical Variation in Electromagnetic Fields

Steven M. Smith, *Member, IEEE*, and Cynthia Furse, *Fellow, IEEE*

FDTD CAN PROPAGATE EXPECTED VALUE & VARIANCE

$$\underset{\sim}{E}\left\{B_y^{n+1/2}(k+1/2)\right\}=\underset{\sim}{E}\left\{B_y^{n-1/2}(k+1/2)\right\} - \frac{\Delta t}{\Delta z}\left[\underset{\sim}{E}\left\{E_x^n(k+1)\right\}-\underset{\sim}{E}\left\{E_x^n(k)\right\}\right]$$

$$\sigma\left\{H_y^{n+1/2}(k+1/2)\right\}\approx\sigma\left\{H_y^{n-1/2}(k+1/2)\right\}+\frac{\Delta t}{\mu\Delta z}\left(\sigma\left\{E_x^n(k+1)\right\}-\sigma\left\{E_x^n(k)\right\}\right)$$

Introduction to the SEMBA Framework

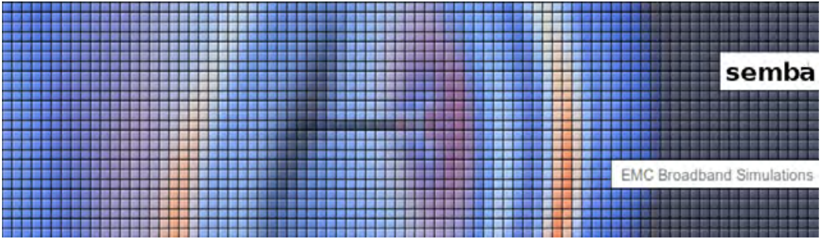
Time domain simulations and the FDTD method

PART II

Nottingham, United Kingdom
April 4th-6th, 2016

Outline

SEMBA (Broadband Electromagnetic Simulator)



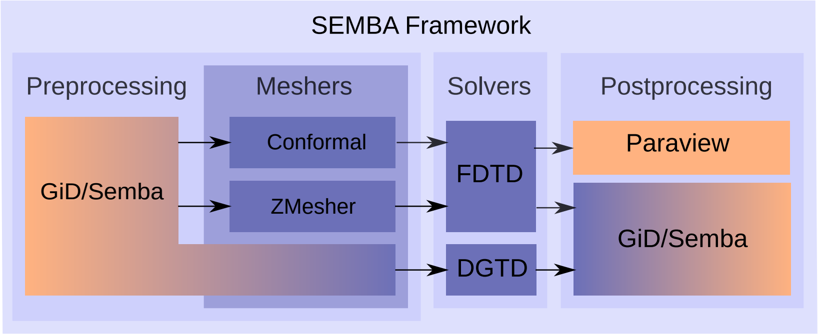
SEMBA

SEMBA is a collection of integrated tools for TD CEM that can work coordinately.

- It includes DGTD and FDTD solvers.
- Uses common structures originally created for DGTD to store information that is used by the meshers and FDTD solvers. Now released as an OpenSource project (OpenSEMBA)

It has been developed essentially in the framework of these projects:

- High Intensity Radiated Field Synthetic Environment (European FP7, '08-'13, 44 partners: BAEs, ALA, ONERA, EADS, THALES, etc).
- A-UGRFDTD: Advanced UGRFDTD EM computer simulation tool (Airbus Mil., '12-'15).



SEMBA Framework

Preprocessing

Meshers

Solvers

Postprocessing

GiD/Semba

Conformal

ZMesher

FDTD

DGTD

Paraview

GiD/Semba

Collection of integrated tools. Darker colors are developments carried on within the UGR.

SEMBA and Cutoo

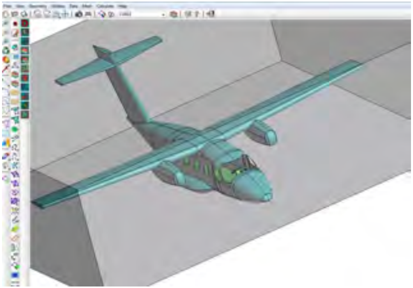
Pre and post-processing

Pre-processing

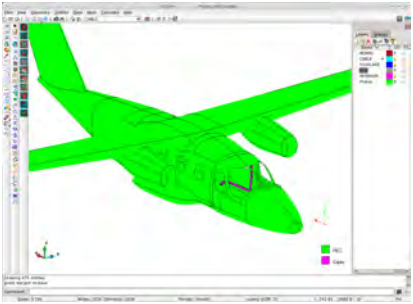
The preprocessing is made with an **extension of GiD** having the following features:

1. Direct use of **CAD data**: import, repair, collapse,...
2. **Geometric modeling** facilities.
3. Allows to choose among **several meshers and solvers**.
4. Easy and **user friendly** interface.
5. **Physical models**: materials, thin layers, wires.
6. **Electromagnetic sources**: plane-wave, dipoles, voltage generators.
7. **Probes**: time/frequency domain, bulk currents, different geometries.

Pre-processing



CAD preprocessing with GiD-Semba

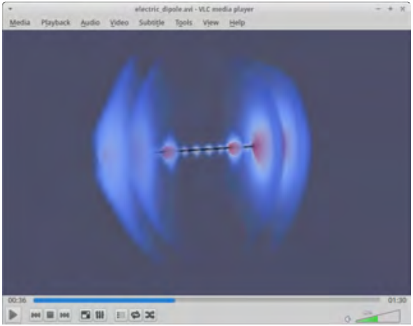


Material assignment with GiD-Semba

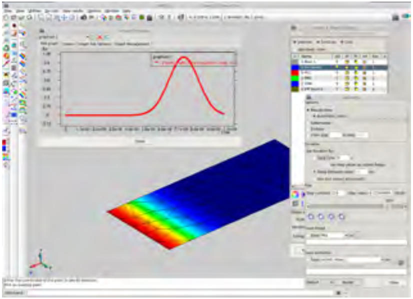
Post-processing

Post-processing can be done with GiD and/or Paraview.

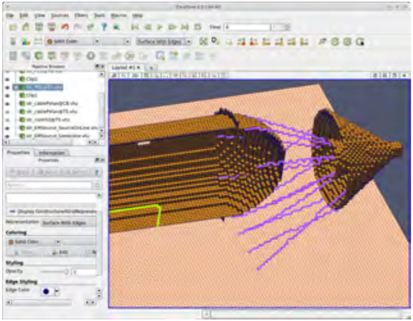
1. Visualization of fields and currents at different time-steps.
2. Can generate time animations to show evolution of fields and currents.
3. Results are also given in plain-text for additional preprocessing with custom programs.



Post-processing



GiD-Semba postprocessing view



Paraview post-processing view

Meshers

Meshers are important

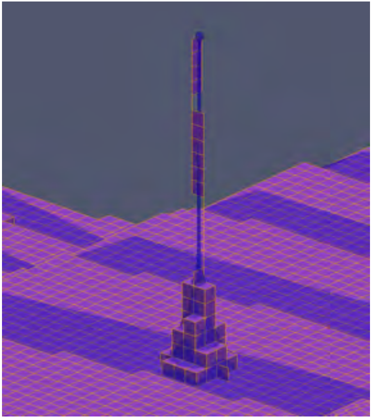
- Good meshers can dramatically **reduce engineering time** need for preprocessing.
- Simulation results will be as good as your mesh is.

Features of our solutions

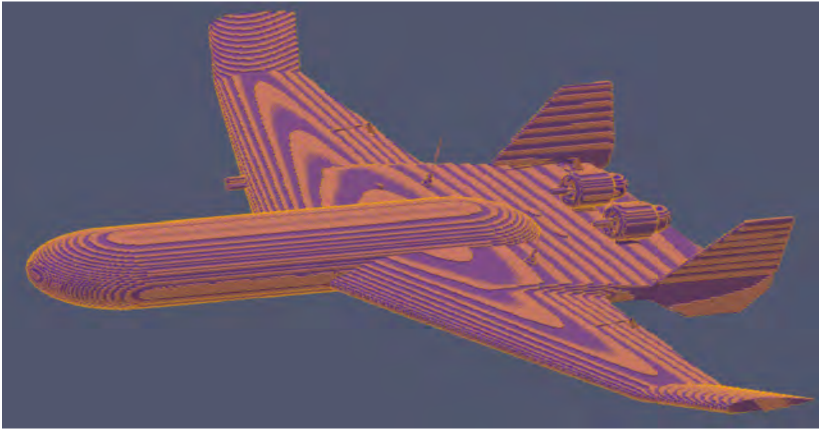
- **Mind the Physics of the problem**: preserves ohmic connections, model sub-cell features, ...
- Mesh **complex wirings**, preserving connectivities.
- Can work with **uncleaned CADs**.
- **Extremely large meshes**, billions of cells with a PC.
- **Fastest**: Closest competitor is one order of magnitude slower.
- **Minimal memory requirements**, under 1 GB of RAM for typical meshes.

ZMesher

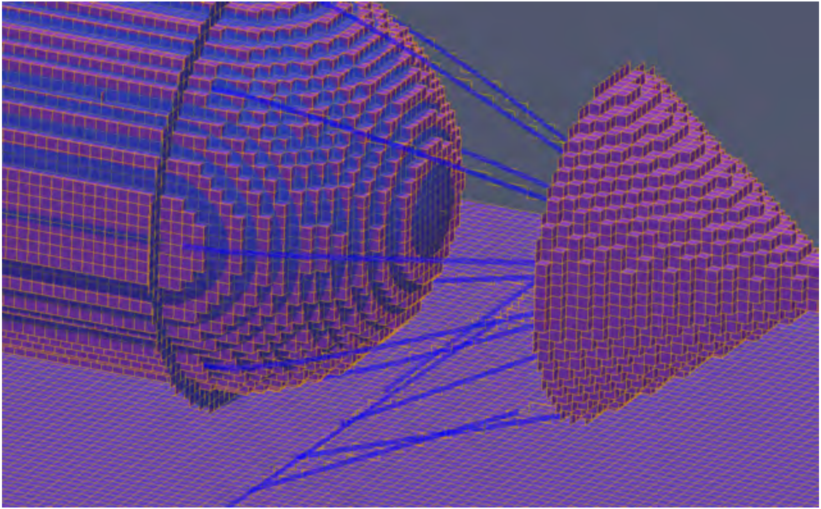
- Generates **structured regular and Cartesian meshes**.
- Mimics the geometry problem even for **sub-cell features**.
- **Deeply tested** in several architectures, operating systems and compilers.
- Licensed for distribution within GiD, to appear in next version.



Antenna geometry is preserved despite having a subcell geometry



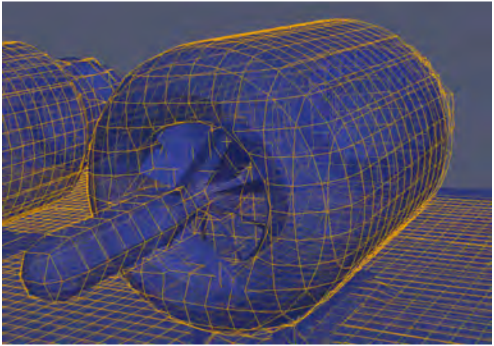
UAV mesh with 14.5 MCells. Obtained with a desktop computer in less than 5 minutes.



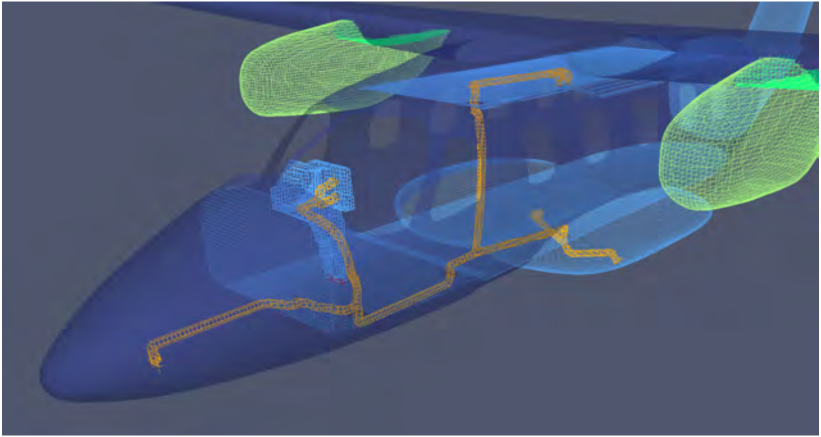
Wire handling example. The connectivity among structures is preserved.

Conformal mesher

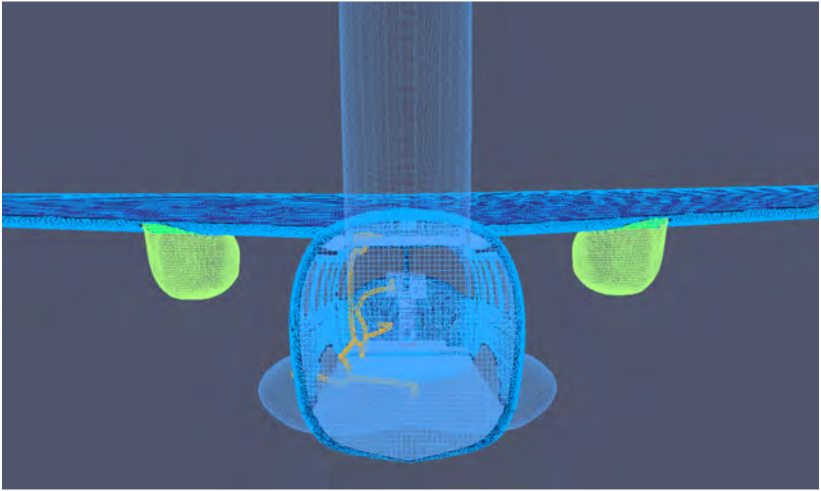
- Mesh adapts better to geometry, **improved accuracy**.
- **Geometric adaptation can be graded** to optimize the computational time-step by the solver.
- Captures geometrical sub-cell details.



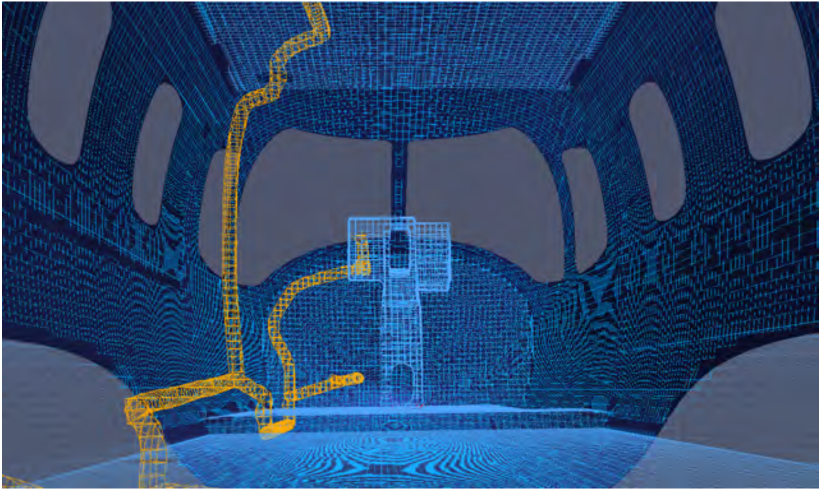
UAV motor detail



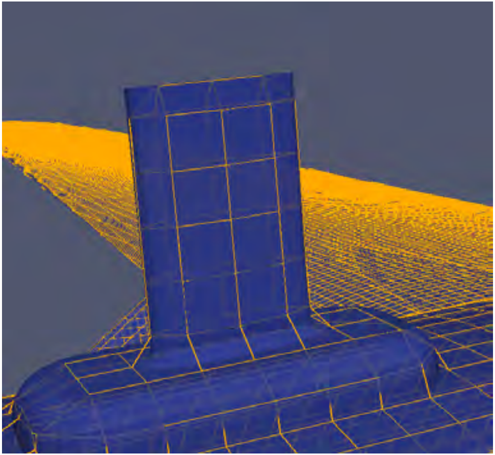
Isometric view of EV55 airplane. Conformal mesher offers better adaptation to curved objects. Morphed Evektor EV55 Used under the HIRF-SE EU FP7 project.



Rear view of EV55 airplane conformal mesh. Different layers highlighted with colors.



EV-55 meshed with ConformalMesher, internal view of the cockpit.



Example of the solution adopted by the Conformal Mesher to deal with sub-cell geometric details.

SOLVERS

Summary of solvers capabilities

	UGRFDTD	LFDG	CUDG3D
Space discretization			
Algorithm	Finite Differences	Discontinuous Galerkin	
Num. Fluxes	-	Centered, Upwind, Penalized	
Element types	Rectilinear, conformal	Linear or quadratic tet.	
Type of basis	-	Vector	Nodal
p-adaptivity	-	Yes	No
Time integration			
Algorithm	LF2	LF2, LSERK4	LF2, LSERK4, Verlet
LTS	-	Dosopoulos, Optimized ass.	Montseny, CPLTS
Physical models			
EM Sources	Any	Any	Any
Anisotropic mat.	Yes	Yes	No
PMLs	Cartesian (CPML)	Conformal (ADE)	Cartesian (ADE)
Other absorbing BC.	Mur 1st and 2nd Order	Silver-Mueller ABC	
Dispersive mat.	Any (CCPR)	Simply conductive	Any (CCPR)
Thin layers	Yes	No	Yes
Thin wires	Yes	No	No
Thin slots	Yes	No	No
Other			
Language	Fortran (Intel)	Fortran (Intel)	C++ (gnu)
OS	Windows, Linux	Windows, Linux	Linux
Parallelization	MPI/OMP	MPI/OMP	MPI/OMP w. balance
Operator deduplication	Intrinsic	No	Yes
GUI	GiD-Semba, Cutoo	GiD	GiD-Semba

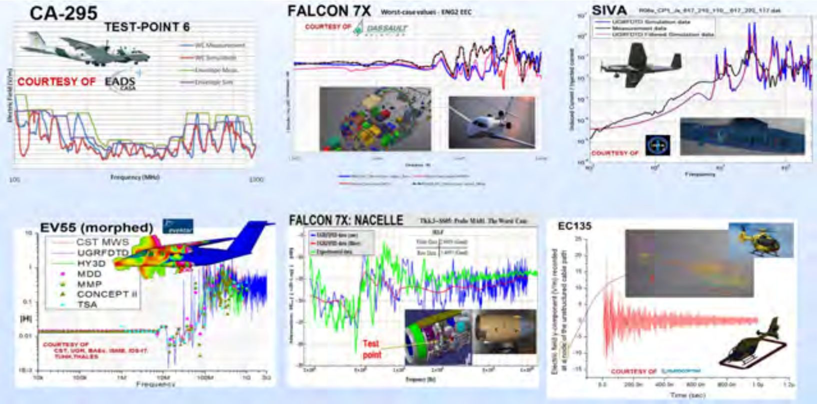
UGRFDTD

UGRFDTD features

UGRFDTD is a general-purpose time-domain simulator, specially suited to deal with HIRF, Lightning, NEMP... electrically-large EMC problems involving complex structures, complex materials and cables.

1. Multi-CPU (MPI) and multicore (OpenMP) capabilities.
2. Very large problems (billions of cells).
3. Improved accuracy with conformal meshing.
4. Materials with **frequency dependent permittivity and/or permeability**, with an arbitrary number of complex-conjugate pole-residue pairs.
5. Bulk **anisotropic materials**, lossless and lossy dielectrics.
6. **Cable bundles and harnesses**.
7. Graphene, carbon nanotubes.
8. **Multilayered composites**, FSS, lossy surfaces, skin-depth, ...

Validations: HIRF on several aircrafts



Validated at **aircraft level** with **experimental data** under HIRF-SE by INTA, Airbus, Dassault.

CUDG3D

Our DGTD solver, CUDG3D is now part of the OpenSEMBA project. OpenSEMBA is an opensource set of tools for electromagnetic simulations. It includes the following:

- CUDG3D: A **full wave electromagnetic solver based on the Discontinuous Galerkin** in Time Domain (DGTD) technique.
- SEMBA-GiD. A GiD based Graphical User Interface (GUI).
- libopensemba. A set of tools for storing, importing, exporting electromagnetic data. Including mesh manipulation capabilities.

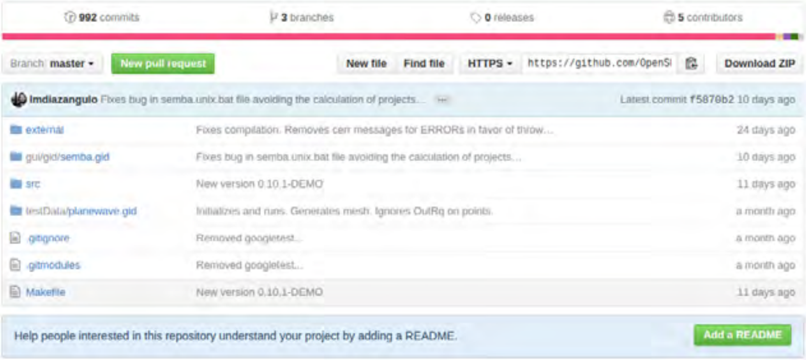
This is all the minimum necessary to do simulations using a DGTD scheme.

Coding standard

OpenSEMBA is implemented in the C++ language using an OOP paradigm. Includes unit tests for many pieces of code.

Code repository is in GitHub:

`https://github.com/OpenSEMBA/OpenSEMBA`



lmdiazangulo Fixes bug in semba.unix.bat file avoiding the calculation of projects… Latest commit f5870b2 10 days ago

external	Fixes compilation. Removes cerr messages for ERRORs in favor of throw…	24 days ago
gui/gid/semba.gid	Fixes bug in semba.unix.bat file avoiding the calculation of projects…	10 days ago
src	New version 0.10.1-DEMO	11 days ago
testData/planewave.gid	Initializes and runs. Generates mesh. Ignores OutRq on points.	a month ago
.gitignore	Removed googletest…	a month ago
.gitmodules	Removed googletest…	a month ago
Makefile	New version 0.10.1-DEMO	11 days ago

Help people interested in this repository understand your project by adding a README.

Screenshot of the project in GitHub, an opensource code repository that facilitates collaboration.

CUDG3D is an open-source Discontinuous Galerkin Time Domain Solver specifically developed to solve Maxwell curl equations.

- **World unique DGTD Open-Source code for Maxwell's equations** (to the best of our knowledge) with close to commercial features.
- The code is being re-factored and is **currently not operational**. We expect to have a renewed, fully operational, version by September 2016.
- This re-factorization aims to make contributions and code expansion more easy in the future.

CUDG3D features

Spatial discretization

- Supports centered, upwind, and partially-penalized numerical fluxes.
- Linear or **quadratic tetrahedrons**.
- Scalar nodal basis, tested to work up to order 3.
- Does not support p-adaptivity.

Time Integration

- Supported time integrators: LF2, LSERK4, Verlet.
- Local Time Stepping: Montseny's and CPLTS.

Physical models

- Electromagnetic sources: dipoles and planewaves.
- Cartesian non-homogeneous PMLs and SMA Boundary conditions.
- Dispersive materials (CCPR).
- Thin layers (SIBC, CCPR).

Implementation details

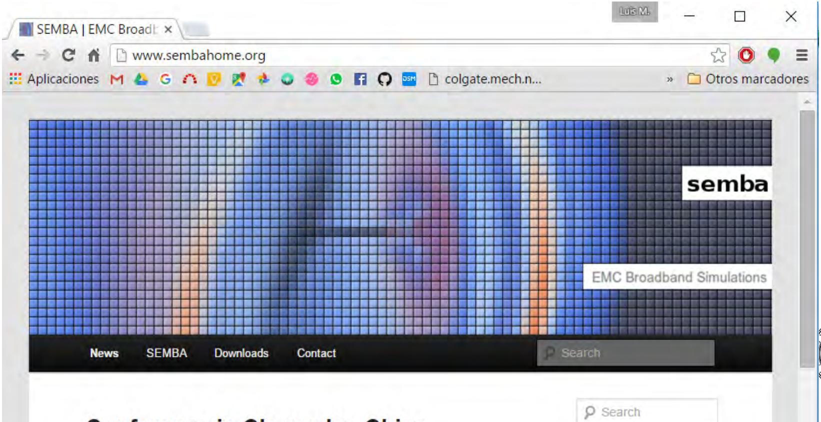
- MPI and OpenMP parallelization. Includes load balance for MPI.
- Includes operator de-duplication (extremely important for when using semi-structured meshes).

Conclusions

More information available in webpage:

`www.sembahome.org`

Video tutorials are available in the SEMBA channel in YouTube.



Thank you for your attention !
Questions?

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