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Transmission of Microwaves Through Vegetation/Trees for SWE Applications

Leung Tsang and Huanting Huang

Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, MI, USA.

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Radiation Laboratory

Physical Models of Microwave Transmission

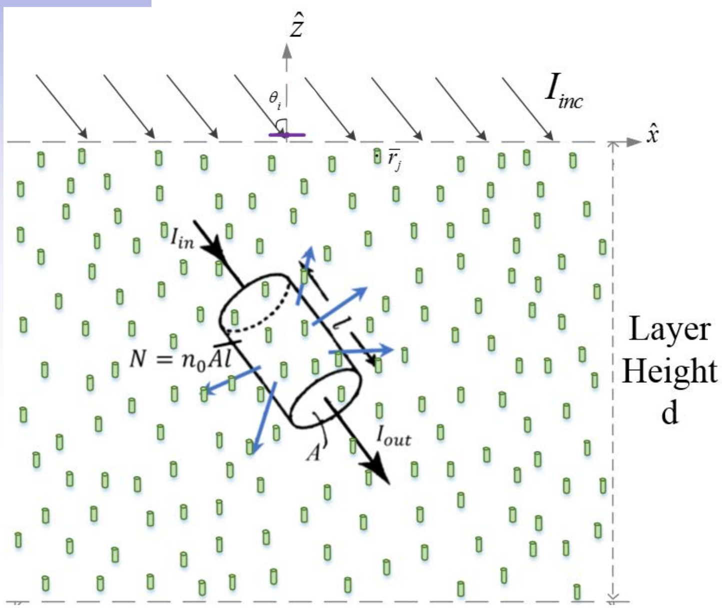
- Vegetation/Trees
  - Radiative Transfer Equation (RTE) , questions/issues

- Recent Model: NMM3D (Numerical Maxwell Equations 3D)
  - Examples: extended cylinders show much larger transmission than RTE

- NMM3D for trees: hybrid method: combining
  - Off-the-shelf technology for single objects
  - Foldy-Lax (FL) technology (our Group) for coherent wave Interactions among single objects

Radiative Transfer Equation (RTE) Physical Picture and Derivation

RTE elemental volume



$$\Delta P = (I_{out} - I_{in})A$$

Power change.

σ_a and σ_s absorption and scattering cross section of single object

$$\boldsymbol{\kappa_e = n_0(\sigma_a + \sigma_s)}$$

$$\frac{dI}{ds} = -\boldsymbol{\kappa_e} I$$

Attenuation rate per unit distance

$$\frac{dI}{ds} = -\boldsymbol{\kappa_e} I + \int d\hat{s}' \, p(\hat{s}, \hat{s}') I(\hat{s}')$$

Physical Picture of RTE:

a) Single objects are “Droplets”

b) “Droplets” uniformly spread out in positions

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Transmission: RTE, Extensively Used

$$\kappa_e = n_0(\sigma_a + \sigma_s)$$

$$\tau = \langle \kappa_e \rangle d$$

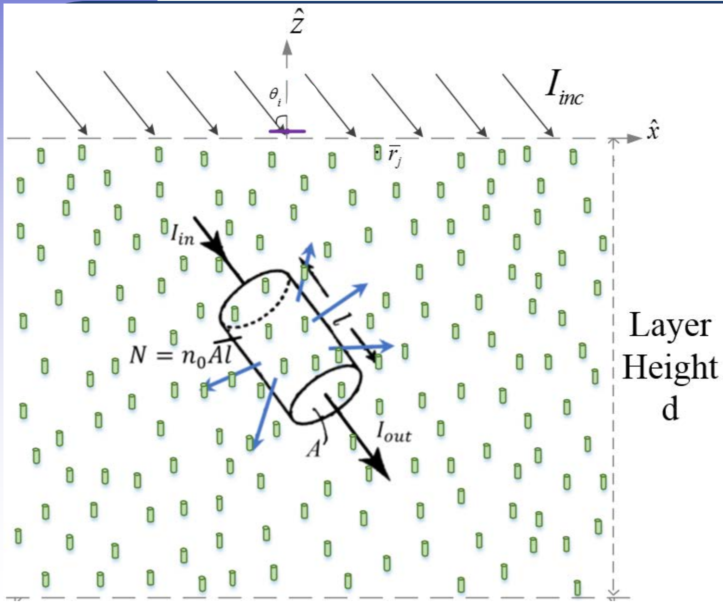
Transmission: $t = exp(-\tau \sec\theta_i) = exp(-\langle \kappa_e \rangle d \sec\theta_i)$

d = height of vegetation/tree layer

- Count number densities n_0 for each type, branches, leaves; size, shape
- Calculate cross sections σ_a and σ_s for each type

Formula often gives large attenuation rate meaning small transmission.

Vegetation/Trees: Comparing pictures



a) Are the objects (branches, stalks, trunks, leaves) "droplets"?

b) Are these objects uniformly spread out in positions?

Trees

Grass

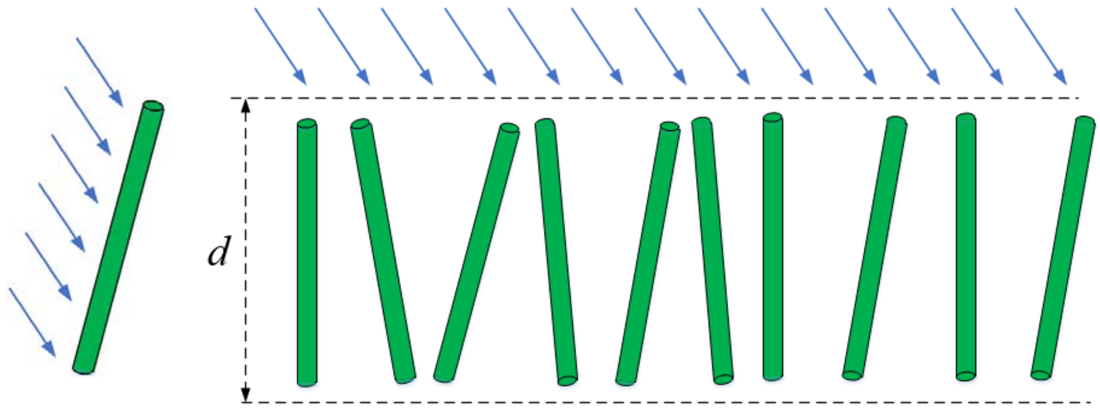
Tree Trunks

5 Questions for RTE

1. Uniform illumination ?

Scattering cross section σ_s uniformly illuminating the entire cylinder.

influence by other cylinders



2. Is there a difference when there are gaps?

- RTE does not account for gaps
- Same transmission: gaps / no gaps

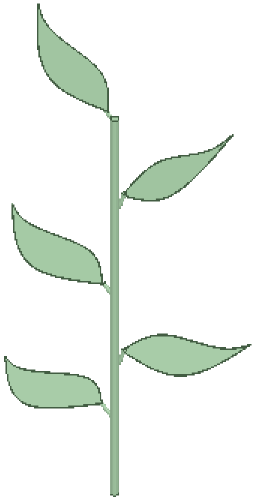
$$\kappa_e = n_0(\sigma_a + \sigma_s)$$

Questions for RTE

3. What is a single object ?

- 6 objects or 1 object ?
- σ_s not additive
- Different results for 6 objects and 1 object

Branch with 5 leaves



$$\sigma_{s,1} + \cdots + \sigma_{s,6} \neq \sigma_s(6)$$

4. κ_e : RTE assumes attenuation rate per unit distance. Does that exist?

Questions for RTE

5. RTE uses far field approximation, is it valid?

- Far field distance = L^2/λ
  - L: length of cylinder
  - λ: wavelength
- Example :
  - L-band λ =0.24 m, L=10m (trunk), far field = **416 m.**
  - Distance between tree trunk and ground much less than 416 m.

RT, RTE and Maxwell Equations

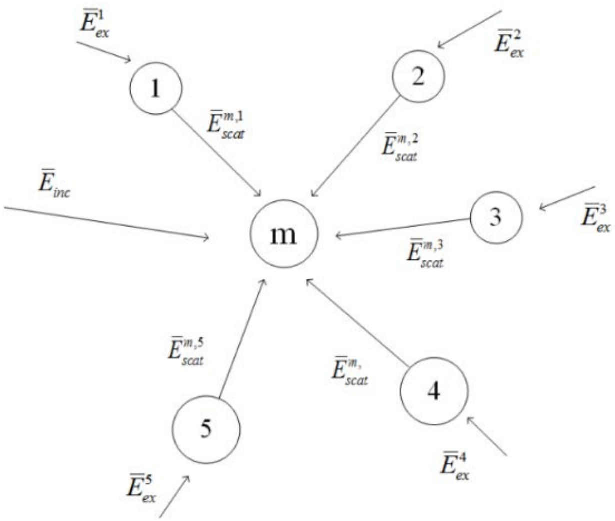
- RT (Radiative Transfer): Physical Process
- RTE: Radiative Transfer Equation is an approximate model to Radiative Transfer (RT) based on assumptions
- Maxwell Equations: Govern Radiative Transfer (RT)

NMM3D (Numerical Maxwell 3D)

Foldy Lax (FL) Multiple Scattering Theory:

- Exact, Derived from Maxwell equations
- $\bar{\bar{G}}_0$ = Green's function propagator
- $\bar{\bar{T}}$ = Scattering T matrix
- Solve exciting field self-consistently

$$\bar{E}_{ex}^{m} = \bar{E}_{inc} + \sum_{\substack{n=1 \\ n\neq m}}^{N} \bar{\bar{G}}_0 \bar{\bar{T}}_n \bar{E}_{ex}^{n}$$



NMM3D has 2 parts
Divide into single objects

A) Calculate single object T matrix ($\bar{\bar{T}}_n$)

B) Calculate coherent wave interactions among single objects

Cylinders: T Matrix from BOR Code

Example: Single object is a cylinder
T matrix calculated by BOR (Body of Revolution).

FL-BOR: $\bar{\bar{T}}_n \longrightarrow \bar{\bar{Z}}_n^{-1}$ Inverse impedance matrix of BOR

BOR

- Off-the-shelf code
- Rotationally symmetric objects: cylinders and disks

Maxwell Equations: Answers 5 Questions

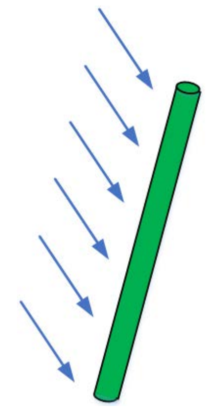
1. Illumination

– Can be non-uniform illumination

$$\bar{E}_S^n = \bar{\bar{G}}_0 \bar{\bar{T}}_n \bar{E}_{ex}^n$$

Scattered Wave

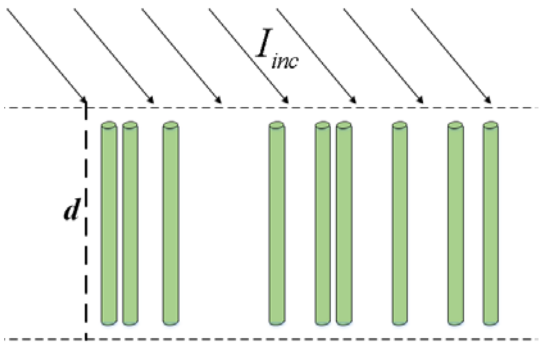
Exciting Wave
Can be non-uniform.



2. Heterogeneity and gaps

- Wave interactions sense the gaps

$$\bar{E}_{ex}^m = \bar{E}_{inc} + \sum_{\substack{n=1 \\ n \neq m}}^{N} \bar{\bar{G}}_0 \bar{\bar{T}}_n \bar{E}_{ex}^n$$

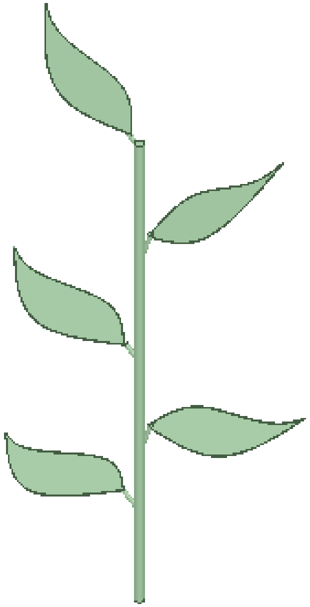


NMM3D: Single Object

3. What is a single object ?

- Wave interactions among the 6 objects

$$\bar{E}_{ex}^{m} = \bar{E}_{inc} + \sum_{\substack{n=1 \\ n\neq m}}^{6} \bar{\bar{G}}_0 \bar{\bar{T}}_n \bar{E}_{ex}^{n}$$



- 6 objects or 1 object: same results

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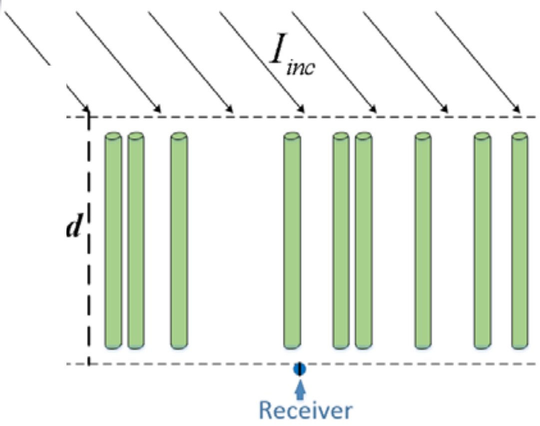
NMM3D Answers

4. No attenuation rate per unit distance

Calculate transmission from Maxwell equations



Transmission

5. Does not use far field approximation

- Use $\bar{\bar{G}}_0$, propagator, all distance ranges

$$\bar{E}_{ex}^{m} = \bar{E}_{inc} + \sum_{\substack{n=1 \\ n\neq m}}^{N} \bar{\bar{G}}_0 \bar{\bar{T}}_n \bar{E}_{ex}^{n}$$

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NMM3D Simulation Procedures and Results

- 500 extended cylinders
  - Extended cylinders: cylinder lengths comparable to height
- Randomly shuffled
- Uniform and clusters (gaps)

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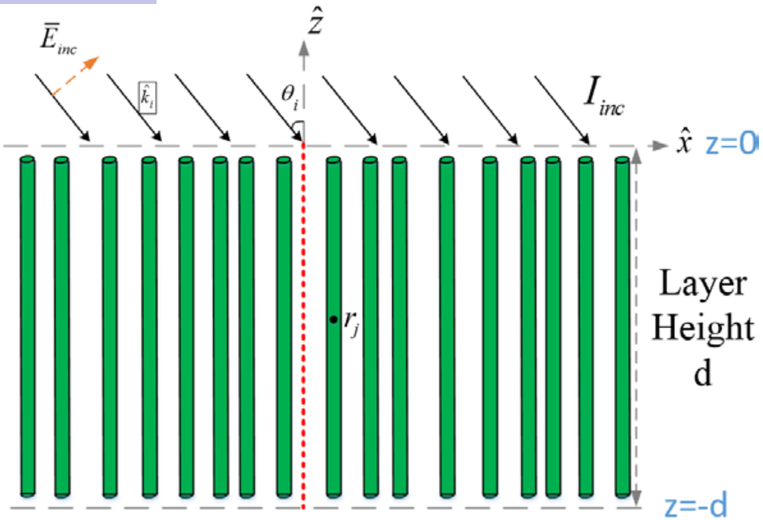
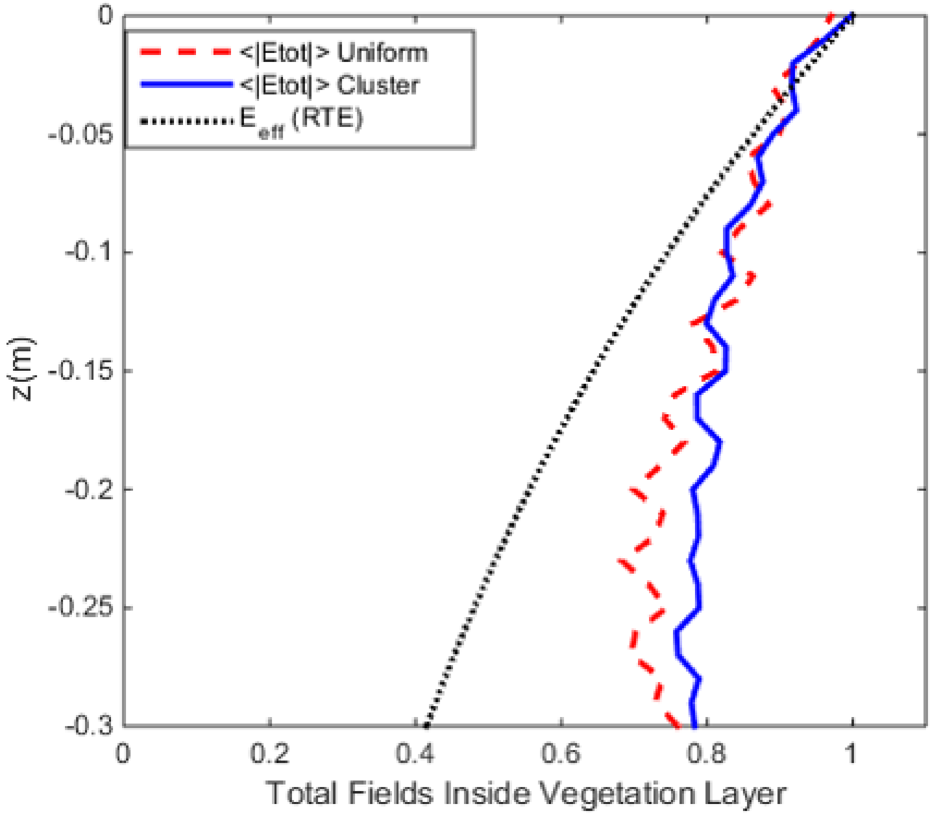
Electric Field Profile Simulations

RTE: $\left|\bar{E}_{eff}^{tot}(\bar{r}_o)\right| = exp\left(-\frac{1}{2}\kappa_e|z_o|sec\theta_i\right)$





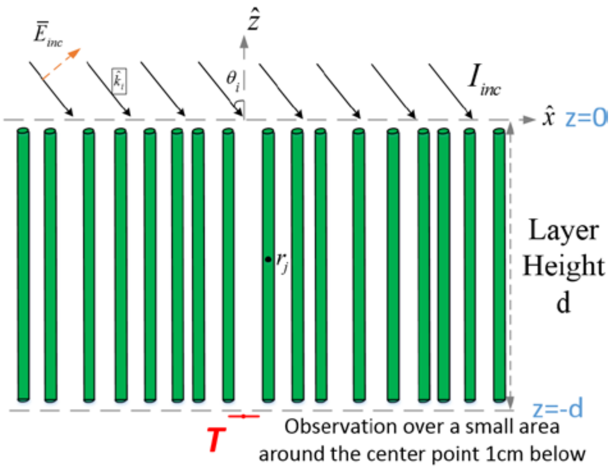
Factor of 2 difference in electric field.
Factor of 4 difference in Intensity.

Transmission Simulations

- NMM3D receiver **below** canopy
  receiver size: $\lambda \times \lambda$ area.

  Normalized by without cylinders

$$T_s = \iint_{\lambda^2} I_t \Big/ \iint_{\lambda^2} I_t(without\ cylinders)$$



- Taking average over realizations

$$t = \left(\sum_{r=1}^{N_r} T_s\right) \Big/ N_r \qquad \tau_{NMM3D} = -ln(t) * cos(\theta_i)$$

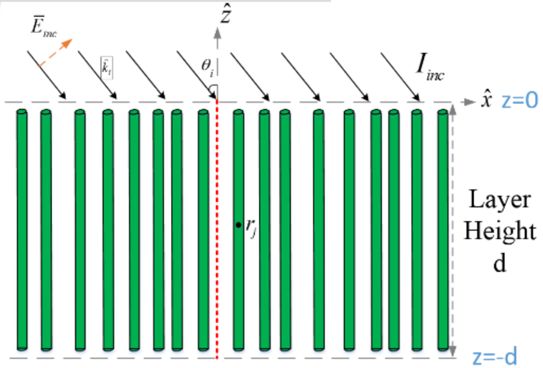
$$t = \exp(-\tau sec(\theta_i))$$

Realizations:

Shuffling the cylinders

Transmission Comparison: 500 Cylinders

Layer height d=5.4 λ, radius = 0.018 λ;
Area: 8.8λ × 8.8λ (500 cylinders);
100 Realizations.



RTE: $t = exp(-\langle \kappa_e \rangle d \sec \theta_i)$

t : RTE	t : NMM3D Uniform	t : NMM3D Clustered (Gaps)
0.1722	**0.6142**	**0.7044**

RTE: 17% transmission
NMM3D: cluster/gaps: 70% transmission
Uniform: NMM3D 3.6 times larger than RTE.
Cluster (gaps): NMM3D 4.1 times larger than RTE

Trees: Hybrid Method: Decomposition into 2 Steps

1) Single object: $\bar{\bar{T}}_n$ off-the-shelf technology:

- BOR: trunk, leafless branch
- HFSS: branches with leaves

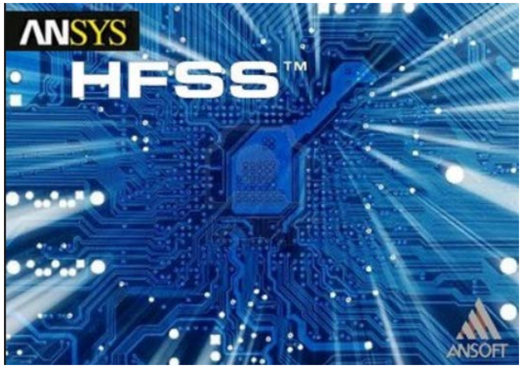
2) Wave Interactions (Our Group) among single objects

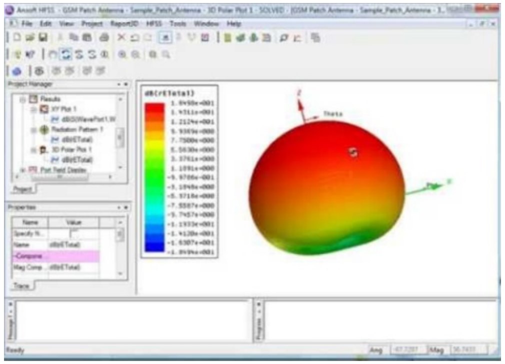
- Foldy-Lax (FL) technology

$$\bar{E}_{ex}^{m} = \bar{E}_{inc} + \sum_{\substack{n=1 \\ n \neq m}}^{N} \bar{\bar{G}}_0 \bar{\bar{T}}_n \bar{E}_{ex}^{n}$$

HFSS (Commercial Software)

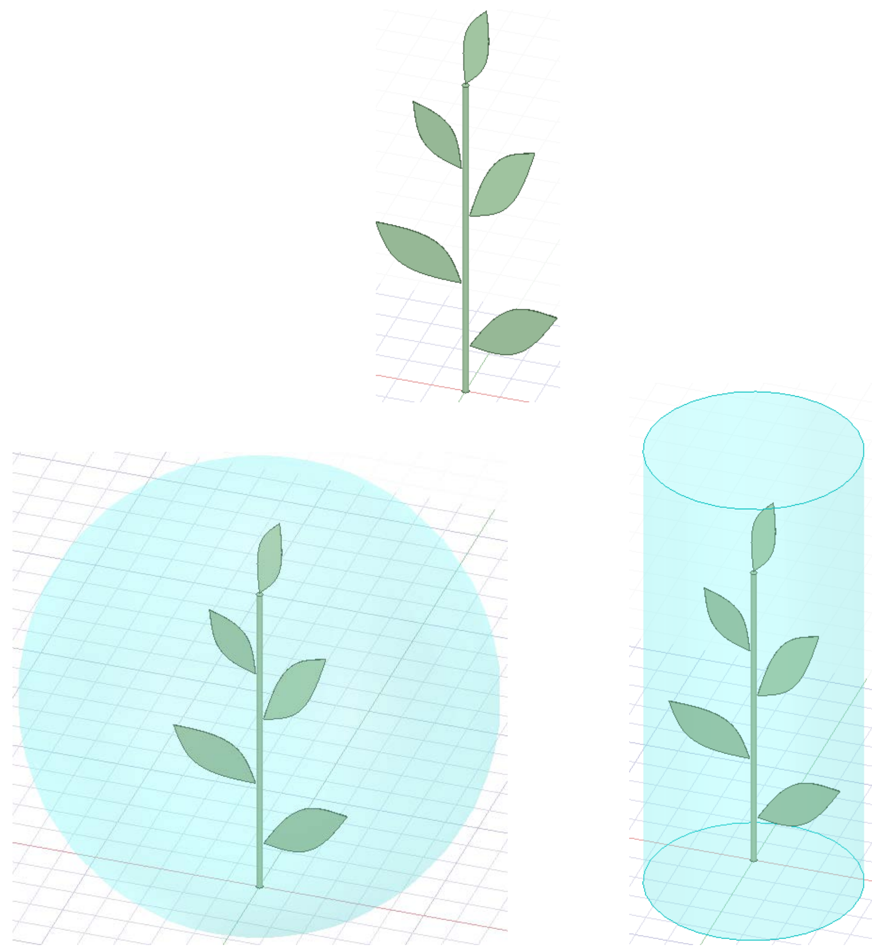
- Full-wave electromagnetics simulation tool
- Object enclosed by box: Use Finite Element Method (FEM) to solve Maxwell equations inside the box
- 10 cubic wavelengths box/domain size: CPU in minutes
- EE undergraduate/graduate classes





Box/domain, 10 Cubic Wavelengths

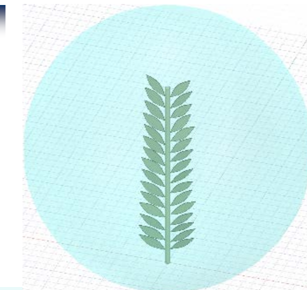
HFSS Technology

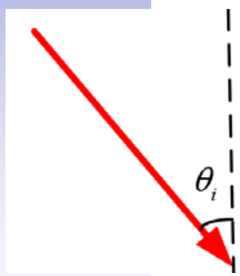


Single Branch : Extract T Matrix. $\theta_i = 40^o$, V-pol

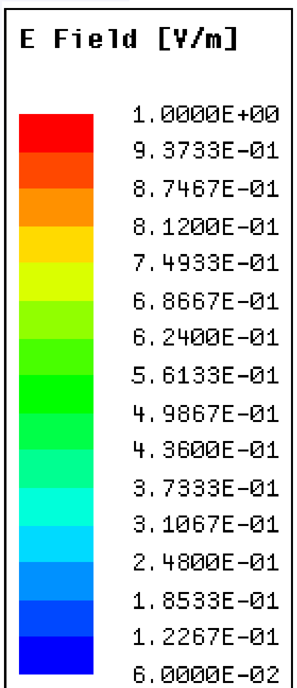
Stalk diameter: 0.024 λ, length: 0.95 λ. epsr=27.2-5.2i. Size of leaves: ~ 0.1 λ.
enclosing sphere: 1.3 λ

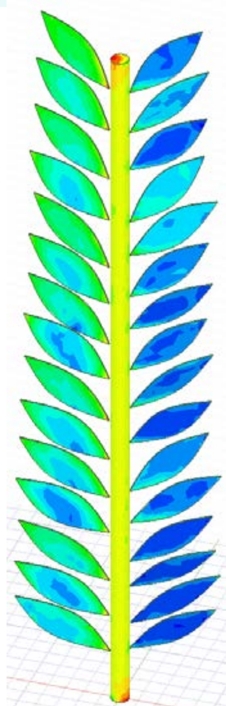
Internal electric fields complicated,
T matrix much less complicated



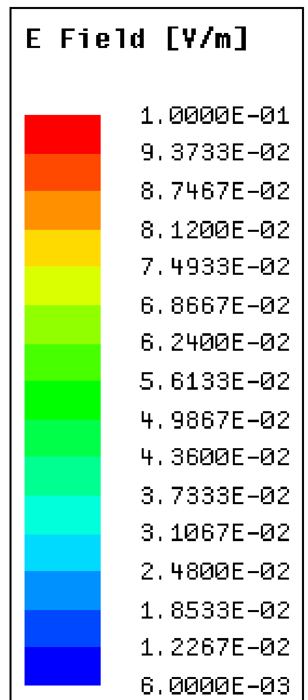


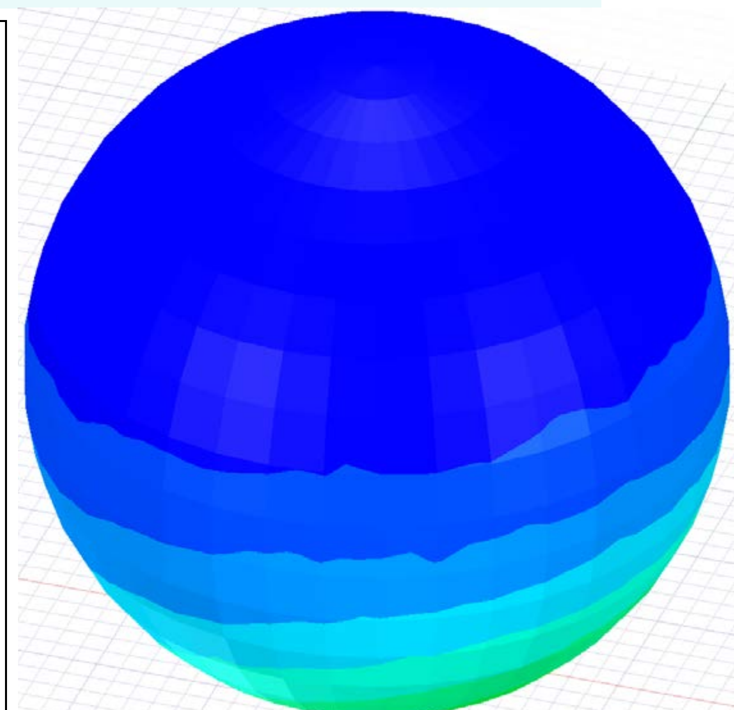
Total Fields
on the object ∂S





Total Fields on
the enclosing sphere: ∂S_S





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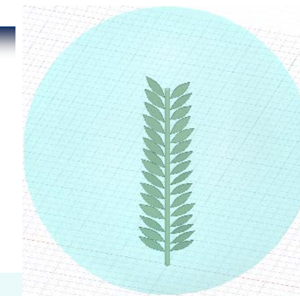
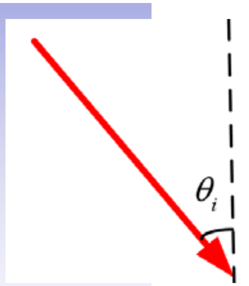
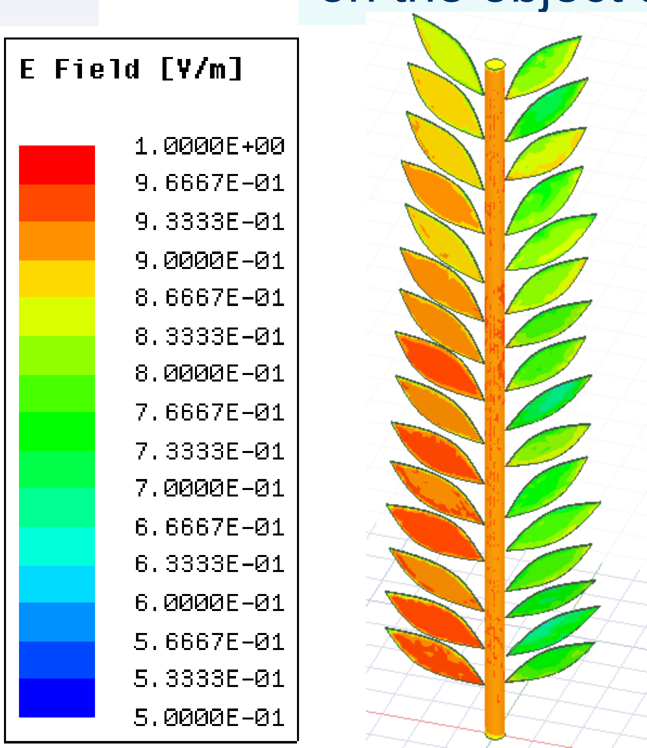


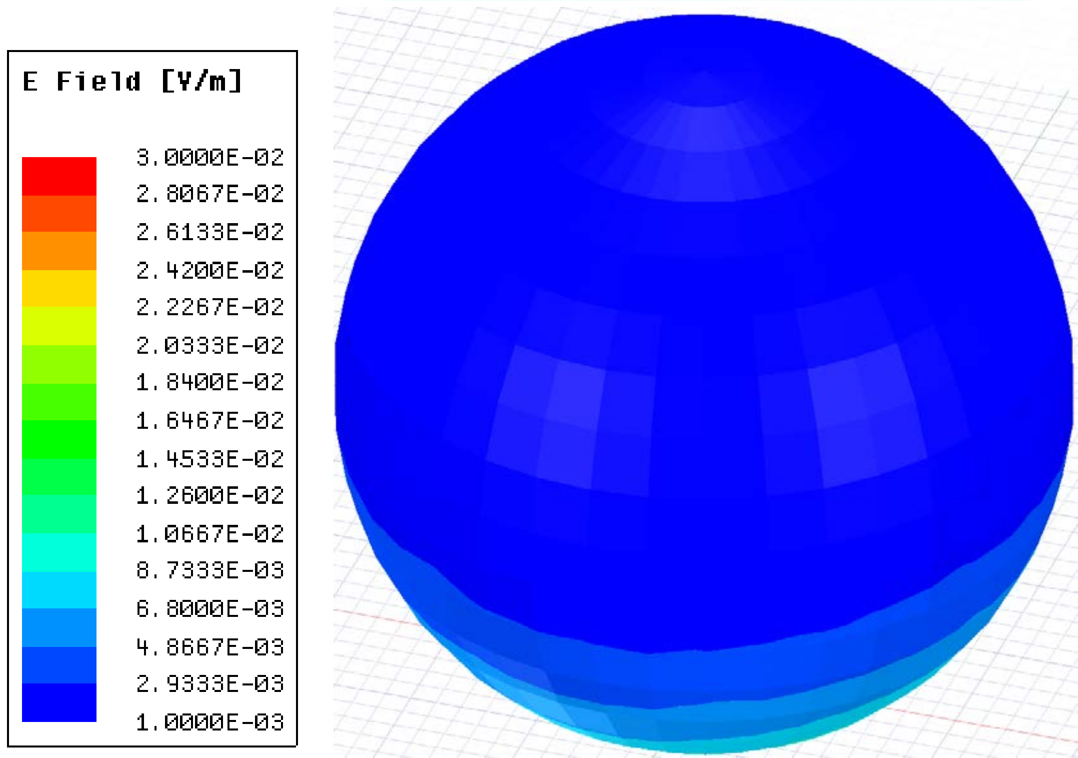
Internal electric fields complicated, T matrix much less complicated



Total Fields on the object ∂S



Total Fields on the enclosing sphere: ∂S_S



CPU of HFSS for Single Object

- Single object "structure matrix": CPU Does Not increase with number of incident angles
  - Extract T matrix with multiple incident angles

- Same enclosing box/domain: CPU Does Not increase with number of leaves attached

Hybrid Method of a Tree: Decompose into single objects

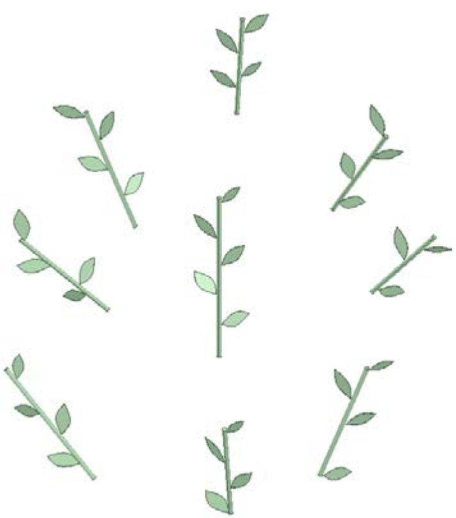
Step 1:

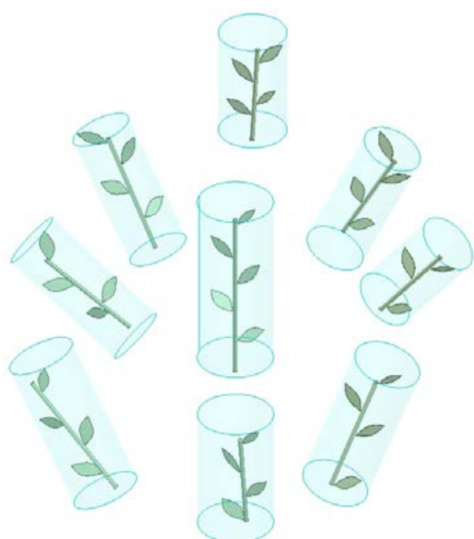
- **Enclose each object with cylindrical box.**
- **Use HFSS/BOR, extract T matrix.**

Step 2: Wave interactions among objects

Foldy-Lax(FL) Multiple Scattering Equation:

$$\overline{E}_{ex}^{m} = \overline{E}_{inc} + \sum_{\substack{n=1 \\ n\neq m}}^{N} \overline{\overline{G}}_0 \overline{\overline{T}}_n \overline{E}_{ex}^{n}$$





$$\overline{E}_{ex}^{1} = \overline{E}_{inc} + \overline{\overline{G}}_0 \overline{\overline{T}}_2 \overline{E}_{ex}^{2} + \overline{\overline{G}}_0 \overline{\overline{T}}_3 \overline{E}_{ex}^{3}$$

$$\overline{E}_{ex}^{2} = \overline{E}_{inc} + \overline{\overline{G}}_0 \overline{\overline{T}}_1 \overline{E}_{ex}^{1} + \overline{\overline{G}}_0 \overline{\overline{T}}_3 \overline{E}_{ex}^{3}$$

$$\overline{E}_{ex}^{3} = \overline{E}_{inc} + \overline{\overline{G}}_0 \overline{\overline{T}}_1 \overline{E}_{ex}^{1} + \overline{\overline{G}}_0 \overline{\overline{T}}_2 \overline{E}_{ex}^{2}$$

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Summary: Transmission of Microwaves

- RTE assumes objects are droplets and the droplets are uniformly spread out
  - Flaws/Issues: extended cylinders, gaps
- Maxwell equations (NMM3D) simulations
  - Examples: extended cylinders: much larger transmission
- Maxwell equations (NMM3D) : a tree, multiple trees
  - Hybrid method: combining
    - Off-the-shelf technology (BOR, HFSS) for single objects to extract T matrix
    - Foldy-Lax (FL) technology (our Group) for coherent wave Interactions among single objects
  - Experiments of measuring transmission