A Nomenclature for Classifying Multiscale Electromagnetic Problems (All Multiscale Problems are Hard, Some are Harder)

Y. BRICK[1], J. MASSEY[2], K. YANG[3], and A. E. YILMAZ[1,2]

[1]Institute for Computational Engineering & Sciences
[2]Department of Electrical & Computer Engineering
[3]Department of Petroleum Engineering & Geosciences
The University of Texas at Austin

IEEE APS International Symposium
USNC/URSI National Radio Science Meeting
Fajardo, Puerto Rico, June 26-July 1, 2016

Outline

- Motivation
  - A bit of literature/philosophy
  - Why now?
- Observations
  - Different perspectives on multiscale modeling and analysis
  - Basic definition for classical EM analysis
  - Are there multiscale problems in classical EM analysis?
- Proposed Nomenclature
  - Major problem with basic definition
  - Proposed categories for multiscale problems
- Conclusion

Why Care About Nomenclature?

What's in a name? That which we call a rose by any other name would smell as sweet.

(Act II, Scene II, Romeo & Juliet, William Shakespeare)

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Why Care About Nomenclature?

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type 4 multiscale problem

What's in a name? That which we call a ~~rose~~ by any other name would ~~smell as sweet.~~

be just as hard/interesting to solve

(Act II, Scene II, Romeo & Juliet, William Shakespeare)

Why Care About Nomenclature?

type 4 multiscale problem

What's in a name? That which we call a ~~rose~~ by any other name would ~~smell as sweet.~~

be just as hard/interesting to solve

(Act II, Scene II, Romeo & Juliet, William Shakespeare)

- Reasons to use names

  + Speed up communication
  + Improve understanding
  + Ease thinking

Why Care About Nomenclature?

’Tis but thy name that is my enemy.

Thou art thyself, though not a Montague.

What’s Montague? It is nor hand, nor foot,

Nor arm, nor face, nor any other part

Belonging to a man. O, be some other name!

What’s in a name? That which we call a rose by any other name would smell as sweet.

(Act II, Scene II, Romeo & Juliet, William Shakespeare)

- Reasons to use names
  + Speed up communication
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Aims & Scope

The *IEEE Journal on Multiscale and Multiphysics Computational Techniques* publishes papers related to a broad range of electromagnetic engineering problems that rely on theoretical developments and computational techniques to solve problems spanning different physical properties or scales. Papers shall describe or use multiphysics or multiscale modeling in physics and electromagnetic engineering, including the calculation of system behavior on one scale using information or models derived from a different scale. Papers describing numerical inversion methods, parallel processing methods, high-order basis functions, and other advanced mathematical or numerical methods to perform multiphysics co-simulations for applied problems are published.

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Published by:

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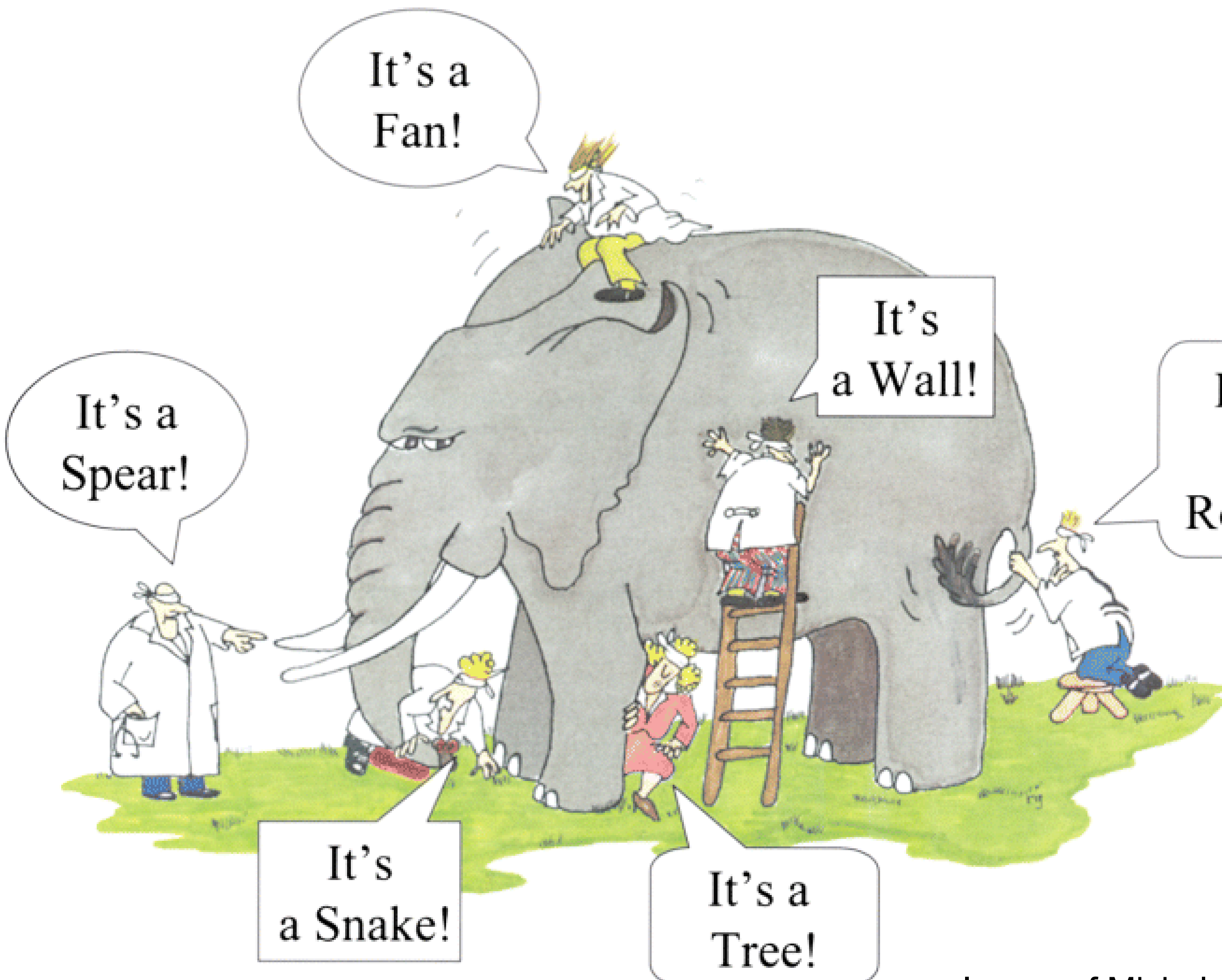
OBSERVATIONS

- Different Perspectives on Multiscale Modeling and Analysis
- Basic Definition for Classical EM Analysis
- Are there Multiscale Problems in Classical EM Analysis?

Multiscale Modeling and Analysis



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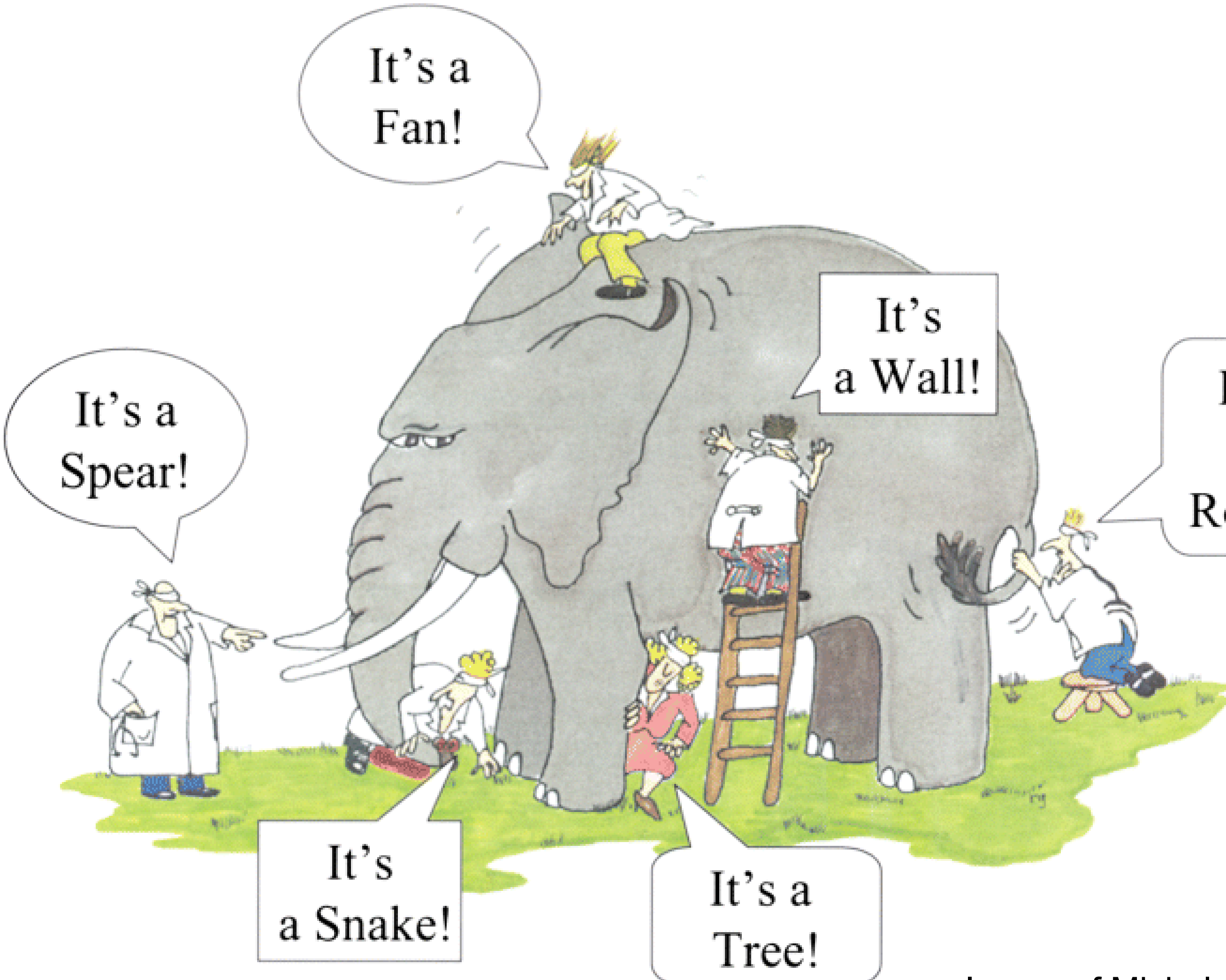
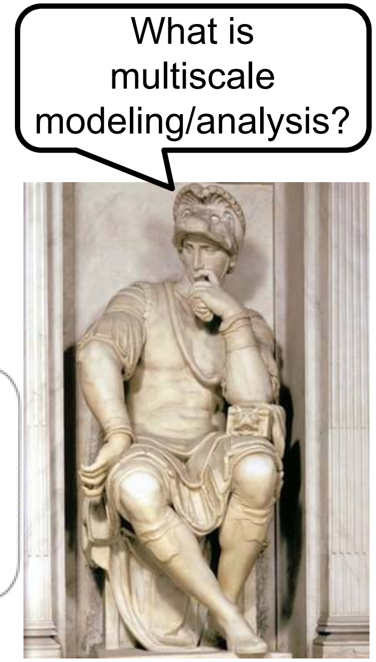
Multiscale Modeling and Analysis





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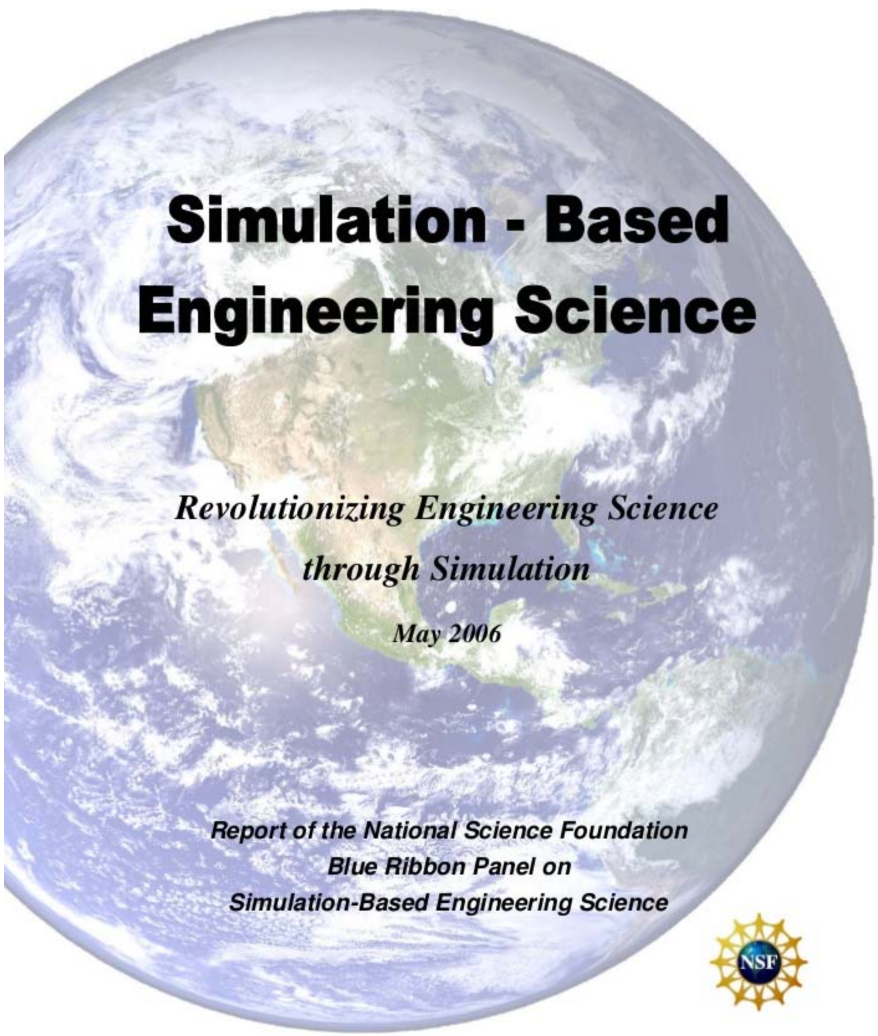
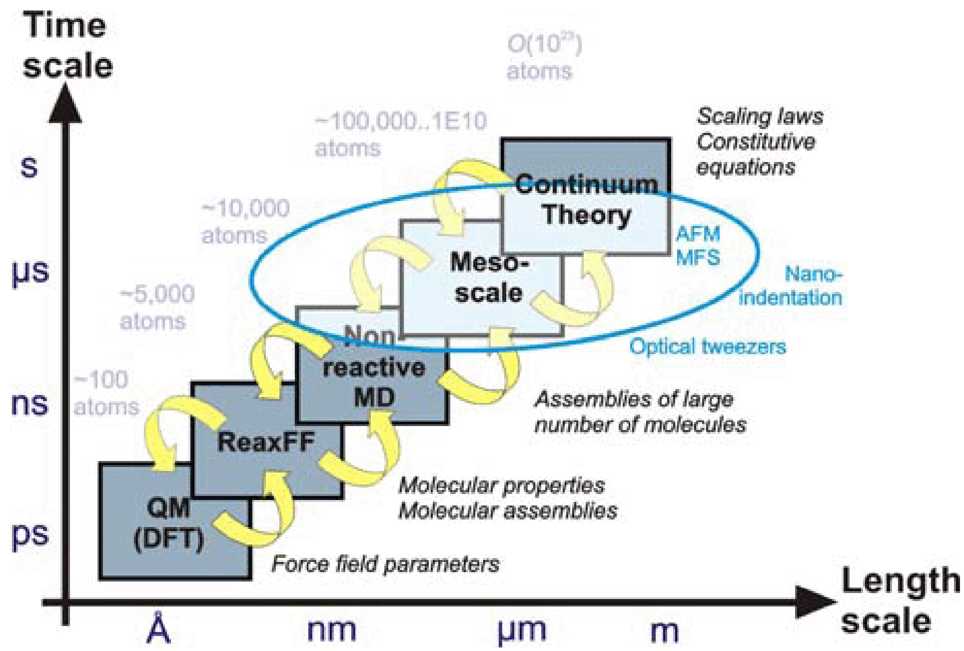
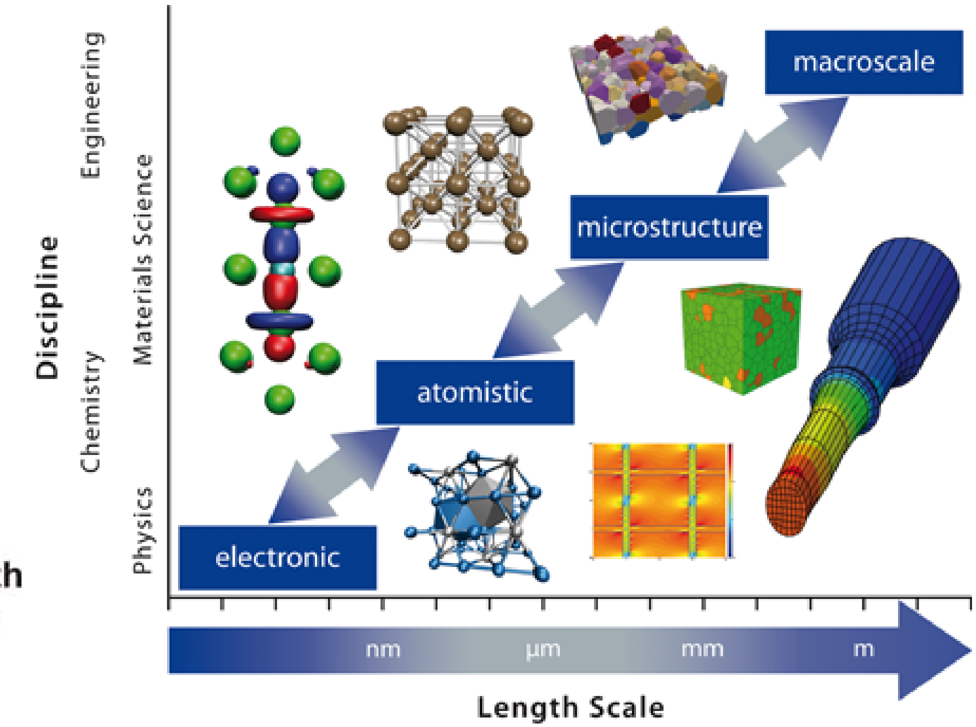
The View from Computational Science



- NSF Blue-Ribbon Committee on Simulation-Based Engineering Science, May 2006:
  - SBES is **the discipline that provides the scientific and mathematical basis for the simulation of engineered systems**.
  - **Formidable challenges** stand in the way of progress in SBES research. These challenges involve resolving **open problems** associated with **multiscale and multi-physics modeling**, real-time integration of simulation methods with measurement systems, model validation and verification, handling large data, and visualization.
  - Formidable obstacles remain in **linking highly disparate length and time scales** and bringing together the disciplines involved in researching simulations methods…

The View from Material Science





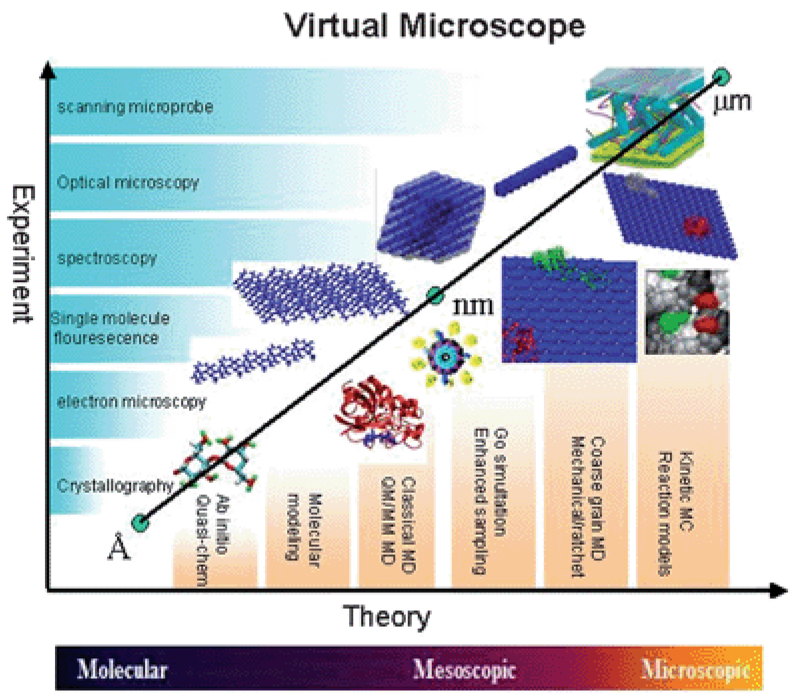
"To calculate materials properties, fundamental information is obtained from the QM level, and then used to train the ReaxFF level, which in turn is used to train ordinary FF and mesoscale levels to inform the macroscale simulations needed for engineering design"

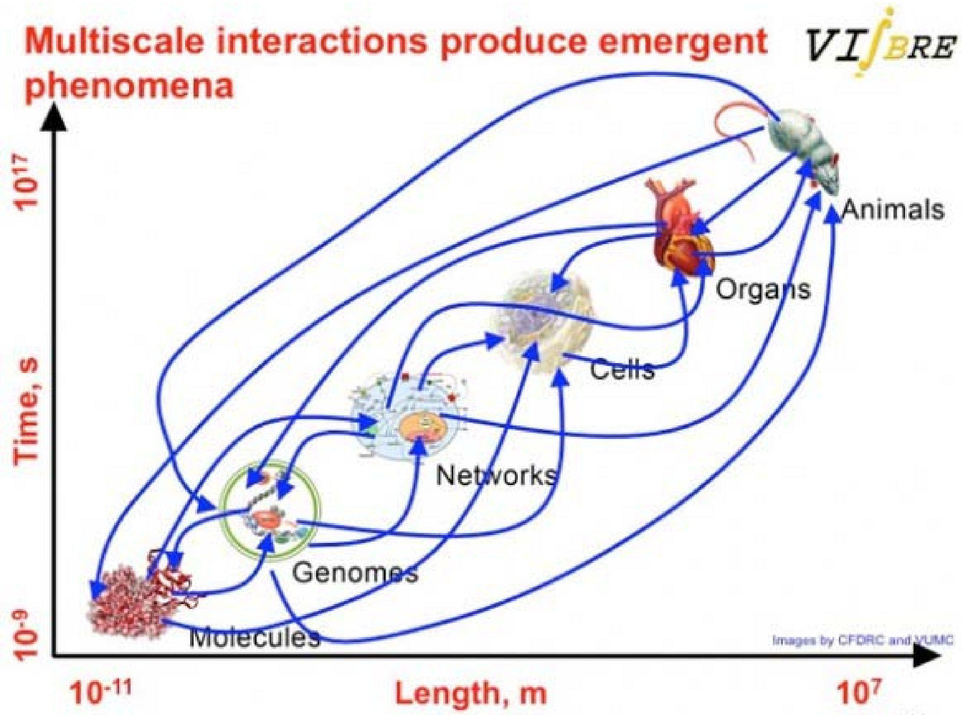
from:
http://materialstechnology.tms.org/TECarticle.asp?articleID=1480

"Traditionally different disciplines focus on different length scales. Multiscale modeling of materials across the length scales requires…a seamless integration of the models on different length scales into one coherent multi-scale modelling framework"

from:
http://materialstechnology.tms.org/TECarticle.asp?articleID=1480

The View from Chemistry & Biology





"An array of complementary experimental techniques is being used to characterize biomass at different length scales…different theoretical approaches are being developed and applied to interpret experimental data at each length scale…Coarse graining … used to integrate individual theoretical models that traverse length scales…"

from:
http://pubs.rsc.org/en/Content/ArticleHtml/2011/EE/c1ee01268a

"One of the things that makes biology so complicated is that processes at different scales ranging from the molecular to whole animals are continually interacting with each other…"

from:
http://www.kurzweilai.net/robot-biologist-solves-complex-problem-from-s

The View from ECE

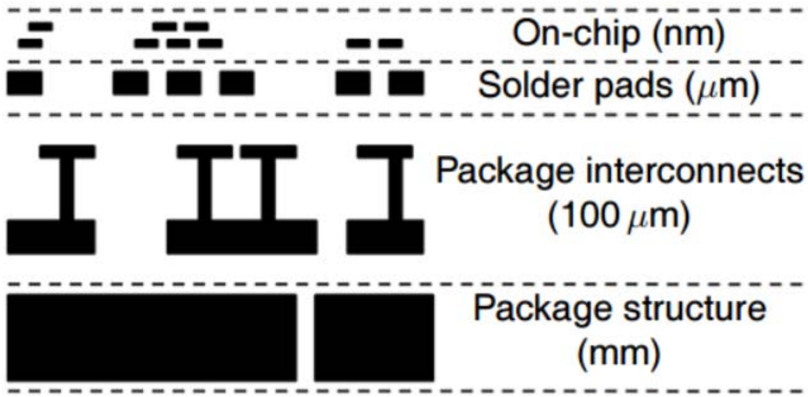


Figure 1: Multiscale package-to-chip structure.

$$\nabla \times \vec{E}(\vec{r},t) = -\frac{\partial \vec{B}(\vec{r},t)}{\partial t}$$

$$\nabla \times \vec{H}(\vec{r},t) = \frac{\partial \vec{D}(\vec{r},t)}{\partial t} + \vec{J}_{\mathrm{cond}}(\vec{r},t) + \vec{J}_{\mathrm{imp}}(\vec{r},t)$$

$$\vec{B}(\vec{r},t) = \mu(\vec{r},t) * \vec{H}(\vec{r},t)$$

$$\vec{D}(\vec{r},t) = \varepsilon(\vec{r},t) * \vec{E}(\vec{r},t)$$

$$\vec{J}_{\mathrm{cond}}(\vec{r},t) = \sigma(\vec{r},t) * \vec{E}(\vec{r},t)$$

from:
L. Tobon, J. Chen, J. Lee, M. Yuan, B. Zhao, and Q. H. Liu, “Progress in multiscale computational electromagnetics in time domain,” 2013

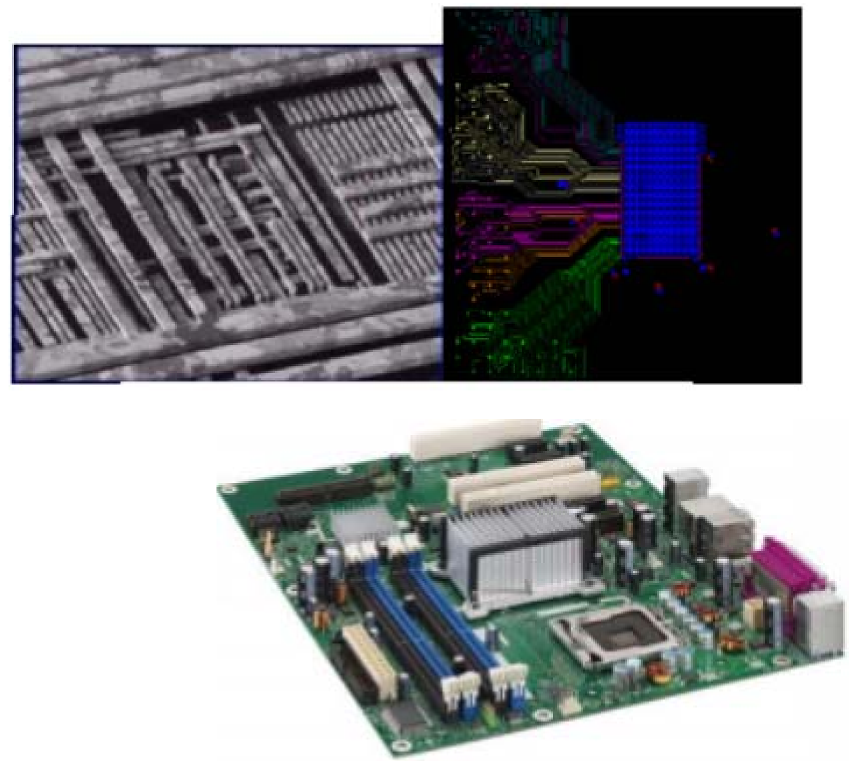


Figure 2. (Top left) XY lines. (Top right) Interconnects and package. (Bottom) Buses and motherboard. The multiscale of dimensions exists in an integrated circuit and computer circuit. The devices and XY lines are of nanometer dimension. The package and interconnects are of mm dimension, and the buses and board are of cm dimension. Maxwell's equations hold true in these length scales differing in seven orders of magnitude. (images from Wikipedia and Intel)

from:
W. C. Chew *et al.* “Fast and accurate multiscale electromagnetic framework: an overview,” 2013.

OBSERVATIONS

- Different Perspectives on Multiscale Modeling and Analysis
- Basic Definition for Classical EM Analysis
- Are there Multiscale Problems in Classical EM Analysis?

Multiscale Problems in Classical/Macroscopic EM Analysis

- Definition

  A problem that has important EM field variations in the domain of analysis at multiple time or length scales

  * Presumes: Maxwell's equations (or their simplified forms) are governing at all the relevant scales <= otherwise, "multiphysics"

  * Undefined: Important? Domain of analysis? <= Application & model dependent

  * Presumes: Appropriate scales are used

- Categories

  Multi-time-scale problem (stiff problems) => often (not always) can be avoided
  Multi-length-scale problem => focus here

- Appropriate scales?

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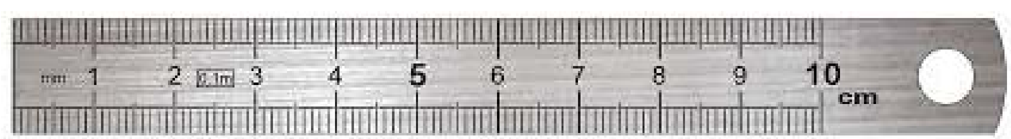
  Multi-time-scale problem (stiff problems) => often (not always) can be avoided
  Multi-length-scale problem => focus here

- Appropriate scales?

  Length scale: A single ruler with 11 major/101 minor tick marks

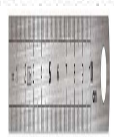
  1-cm scale (10-cm ruler)

  $$[0.1 - 10]\ \mathrm{cm} \mp 0.1\ \mathrm{cm}$$



  1-mm scale (10-mm ruler)

  $$[0.1 - 10]\ \mathrm{mm} \mp 0.1\ \mathrm{mm}$$



Appropriate Length Scales

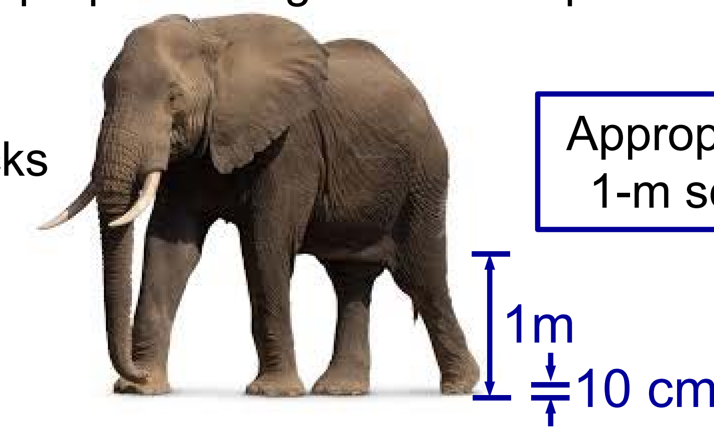
- Minor issue: Any length scale can be used to describe any field variation

  Scales smaller than the “appropriate length scale” require >>1 ruler

  Scales larger than the “appropriate length scale” require >>101 tick marks

Very large features!?
~10^9 rulers with 1-nm ticks

Very small features!?
One 1-Gm ruler with
~10^{10} ticks



Appropriate length scale
1-m scale (10-m ruler)

Appropriate Length Scales

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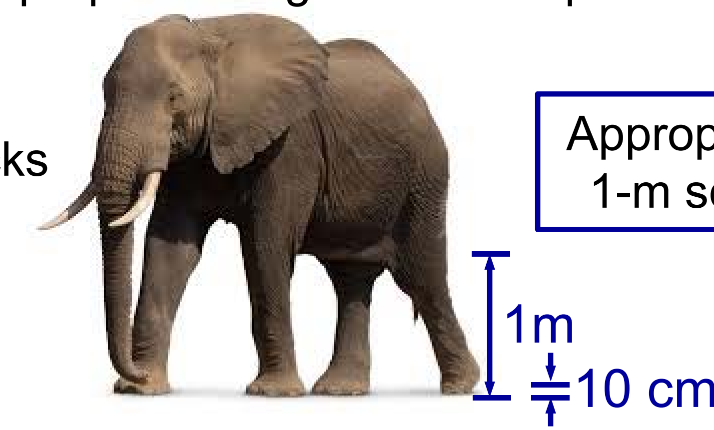
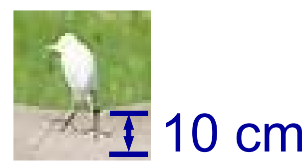


Appropriate length scale
1-m scale (10-m ruler)

- Minor issue: Any multi-scale field variation can be described with one scale

Single scale!?
One 10-m ruler with
1001 tick marks

Single scale!?
~100 1-m rulers

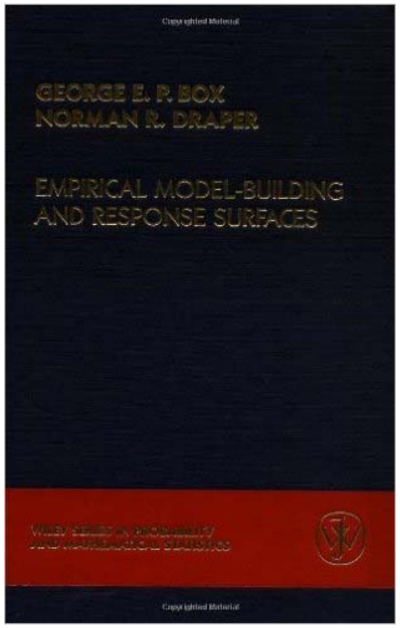


# of appropriate length
scales: 2
1-m (One 10-m ruler)
10-cm (One 1-m ruler)

OBSERVATIONS

- Different perspectives on multiscale modeling and analysis
- Basic definition for classical EM analysis
- Are there multiscale problems in classical EM analysis?

Source of Multiscale Problems in Classical/Macroscopic EM Analysis



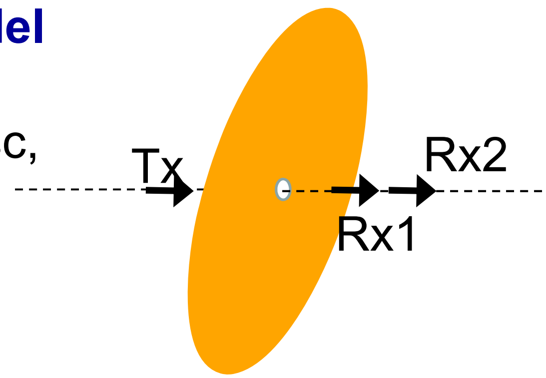
Remember that all models are wrong; the practical question is how wrong do they have to be to not be useful. (p. 74)

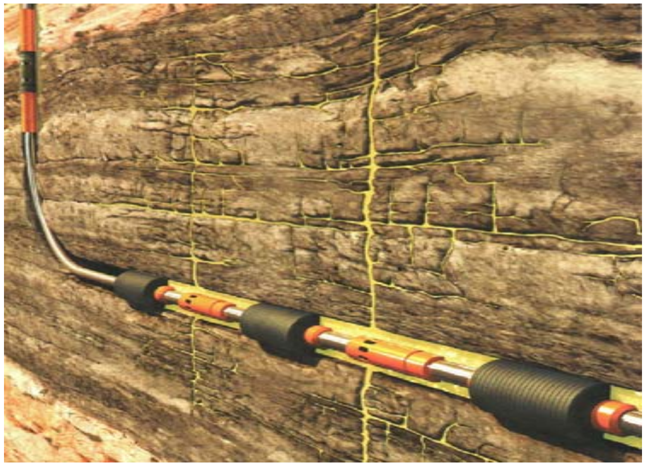
Essentially, all models are wrong, but some are useful. (p. 424)

(G. E. P. Box and N. R. Draper)

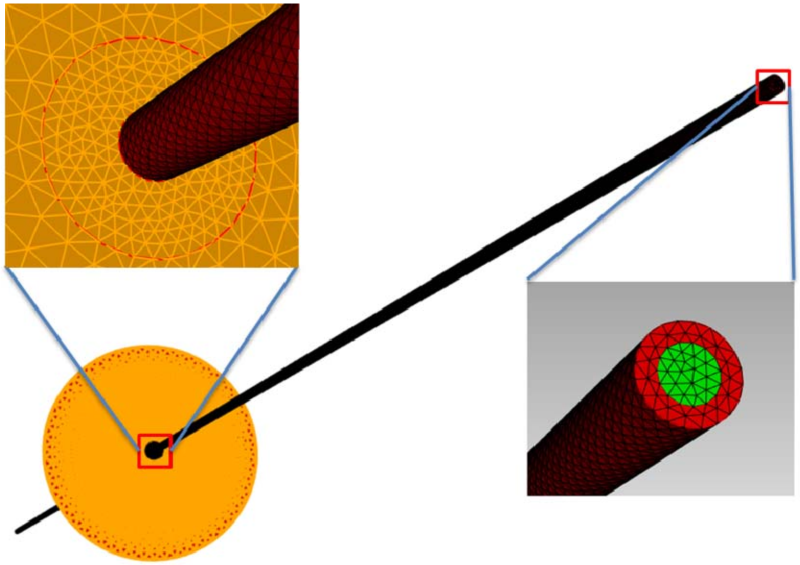
Higher Fidelity Models => Multiscale Problems

(Over?)Simplified model
- Simple fracture
- Circular conductive disc, uniform features/mesh
- Borehole not modeled

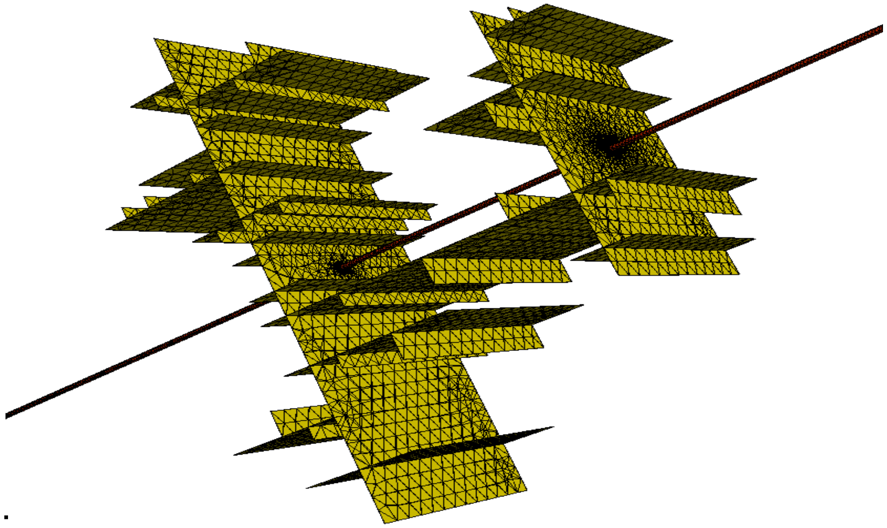




Refined model
- Simple fracture + borehole model



Higher-fidelity model
- Complex fracture + borehole model

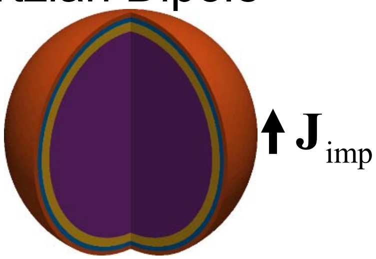


from:
K. Yang, A. E. Yilmaz, *IEEE Trans. Geosci. Remote Sensing*, Aug. 2015.

Higher Fidelity Models => Multiscale Problems

(Over?)simplified model

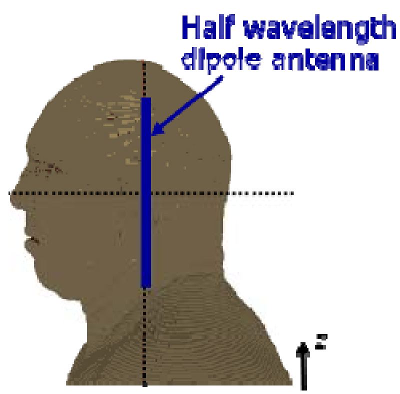
Multilayered head-sized sphere + Hertzian Dipole



Refined models

AustinWoman + Hertzian Dipole

AustinMan +Half-Wavelength Dipole



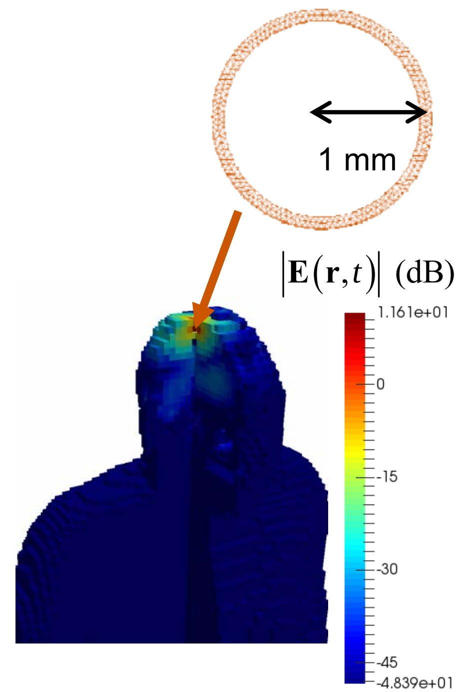
F. Wei and A. E. Yilmaz, in *Proc. ICEAA*, Sep. 2012.

Higher-fidelity models

AustinMan + AMF Antenna

J. W. Massey *et al*., in *Proc. EuCAP*, Apr. 2016.

AustinWoman + Implanted Sensor



J. W. Massey and A. E. Yılmaz, in *Proc. URSI NRSM*, Jan. 2016.

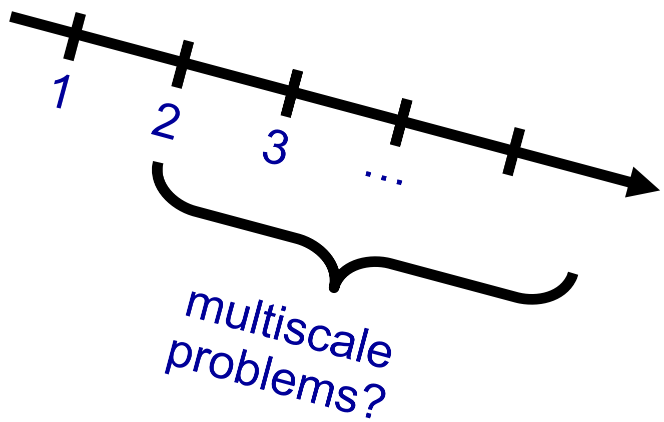
Proposed Nomenclature

- Major problem with basic definition
- Proposed categories for multiscale problems

Multiscale Problems in Classical/Macroscopic EM Analysis

• Multiscale problem

A problem that has important EM field variations in the domain of analysis at multiple time or length scales

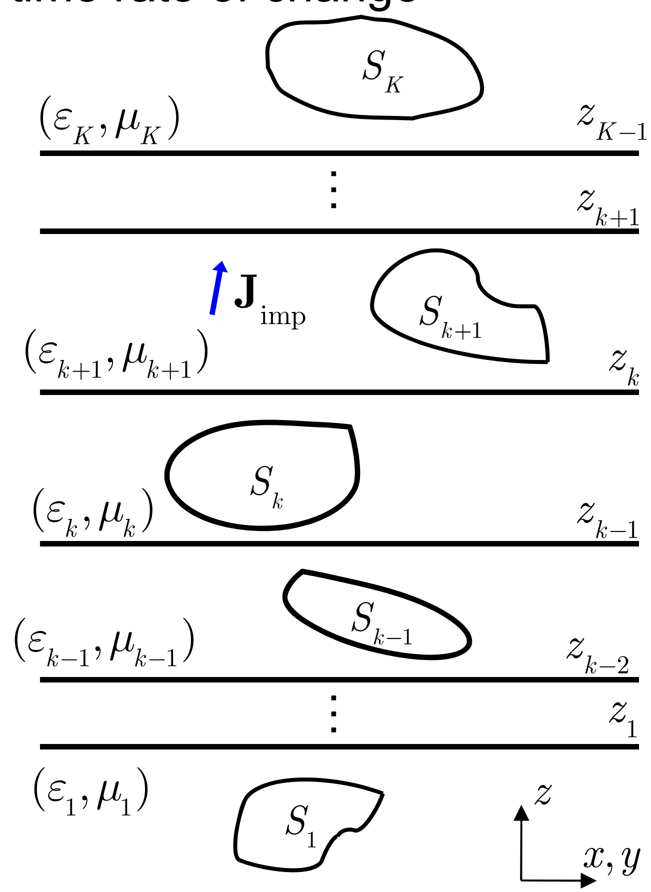


# of appropriate length scales
to resolve
important field variations
in the domain of analysis

- Major problem: Not enough information about
  - What factors determine field variations?
  - Are all (2, 3, …)-scale problems equally difficult?
  - What is a single-scale EM problem anyway?

Multiscale Problems in Classical/Macroscopic EM Analysis

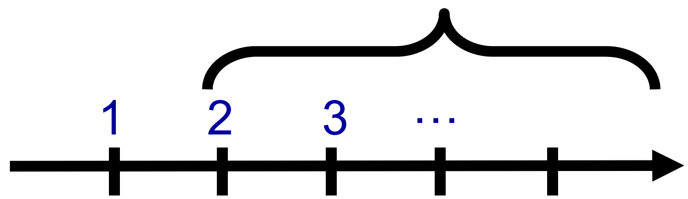
- Three important factors to consider
  - Structure length scales
  - Primary (impressed) source time rate of change
  - Background length scales



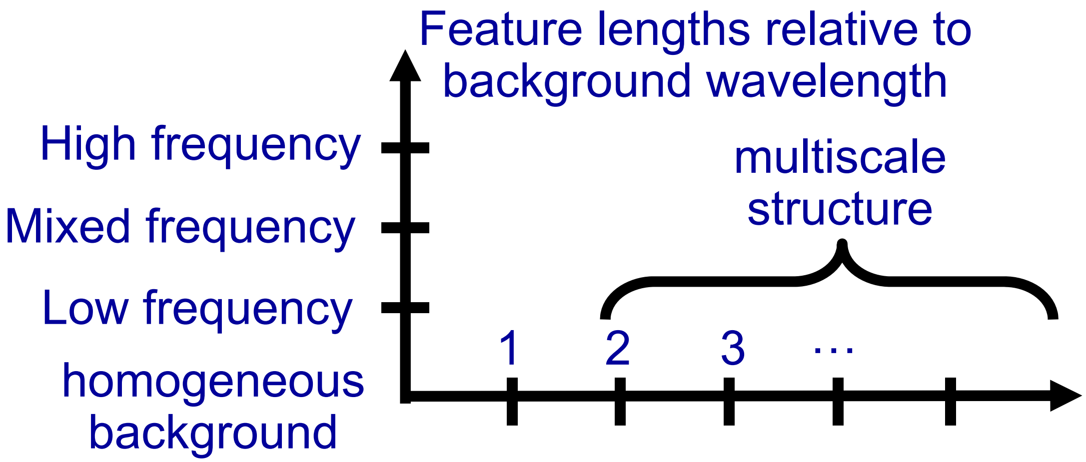
Multiscale Problems in Classical/Macroscopic EM Analysis

- Multiscale structure

A structure that has important features in the domain of analysis at multiple length scales



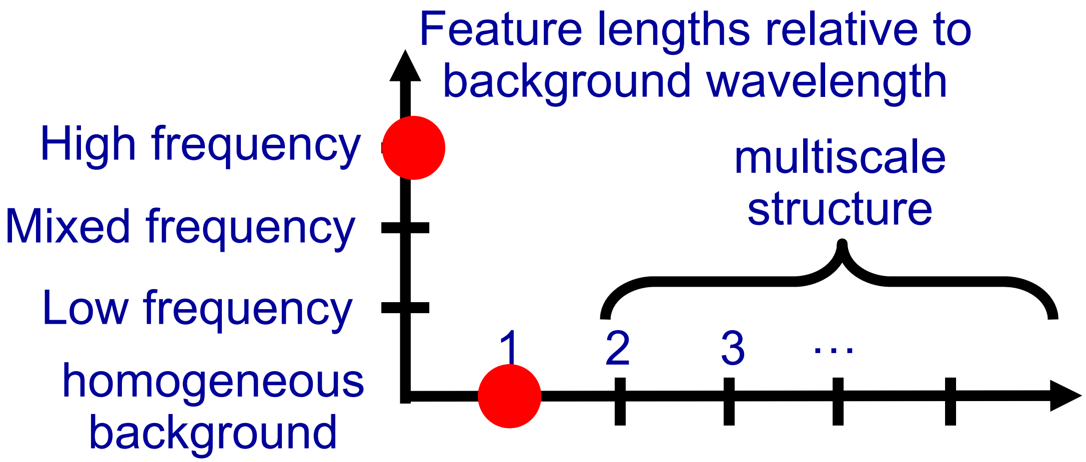
Multiscale Problems in Classical/Macroscopic EM Analysis



- Frequency regime

Field variations dictated by structure features (LF), background wavelength (HF), or combination (MF)

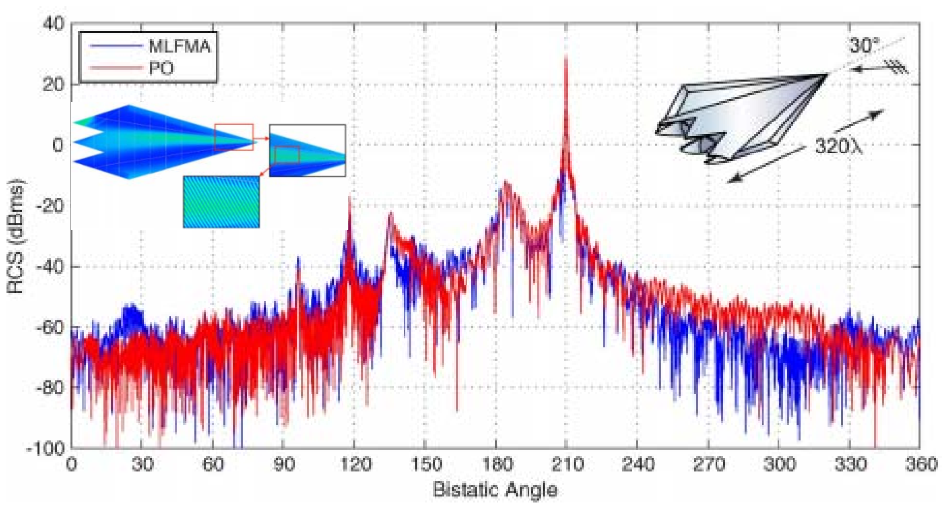
Multiscale Problems in Classical/Macroscopic EM Analysis



- Type 1 multiscale problem

1c: High-frequency
1a: Low-frequency

Two-scales :One scale for structure, one for fields



O. Ergul, L. Gurel, *Proc. IEEE*, Feb. 2013.

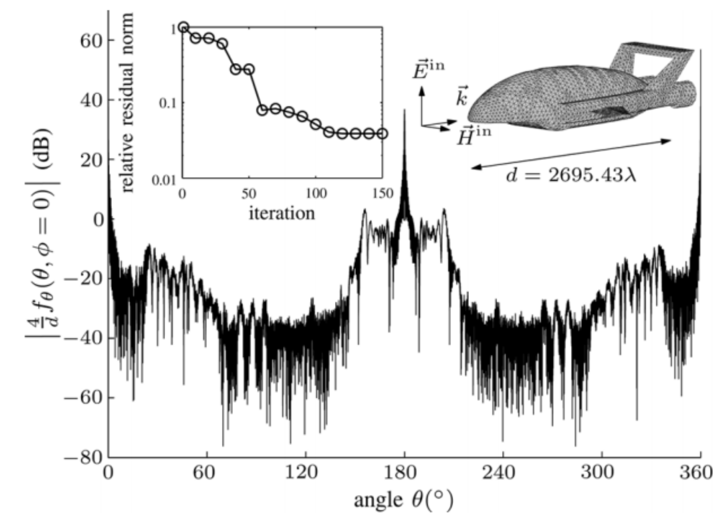
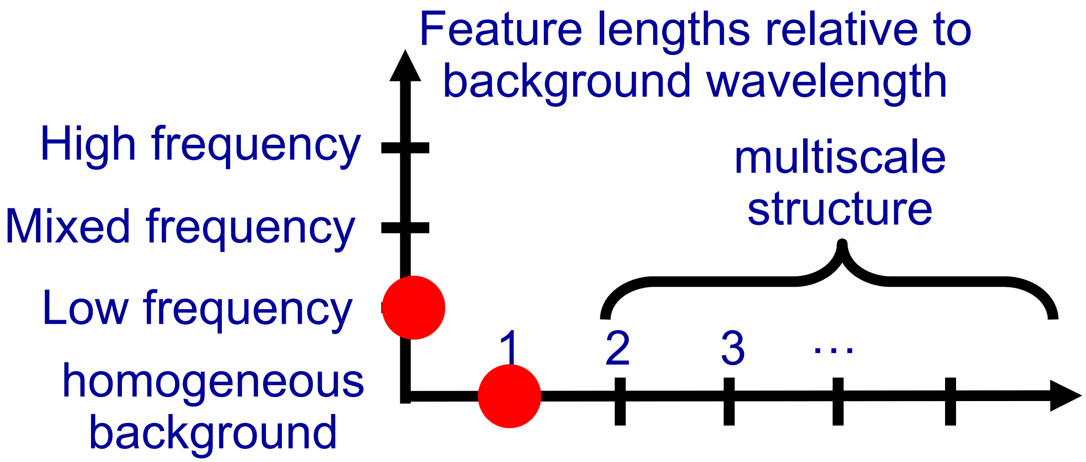


Fig. 4. The normalized radiation pattern for a PEC 'Thunderbird' discretized in over 2.5 billion unknowns. Inset: convergence behavior over 150 iterations.

B. Michiels, J. Fostier, I. Bogaert, D. D. Zutter, *IEEE Trans. Antennas Propag.*, Feb. 2015.

Multiscale Problems in Classical/Macroscopic EM Analysis



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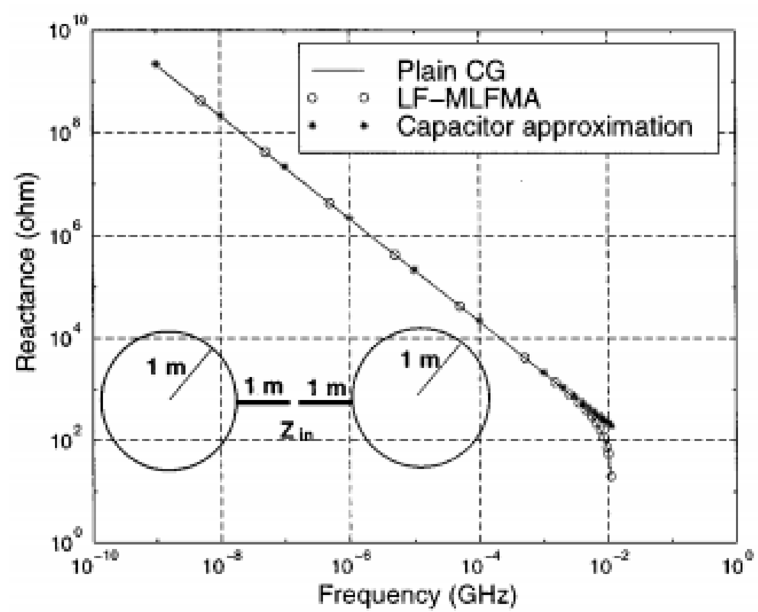
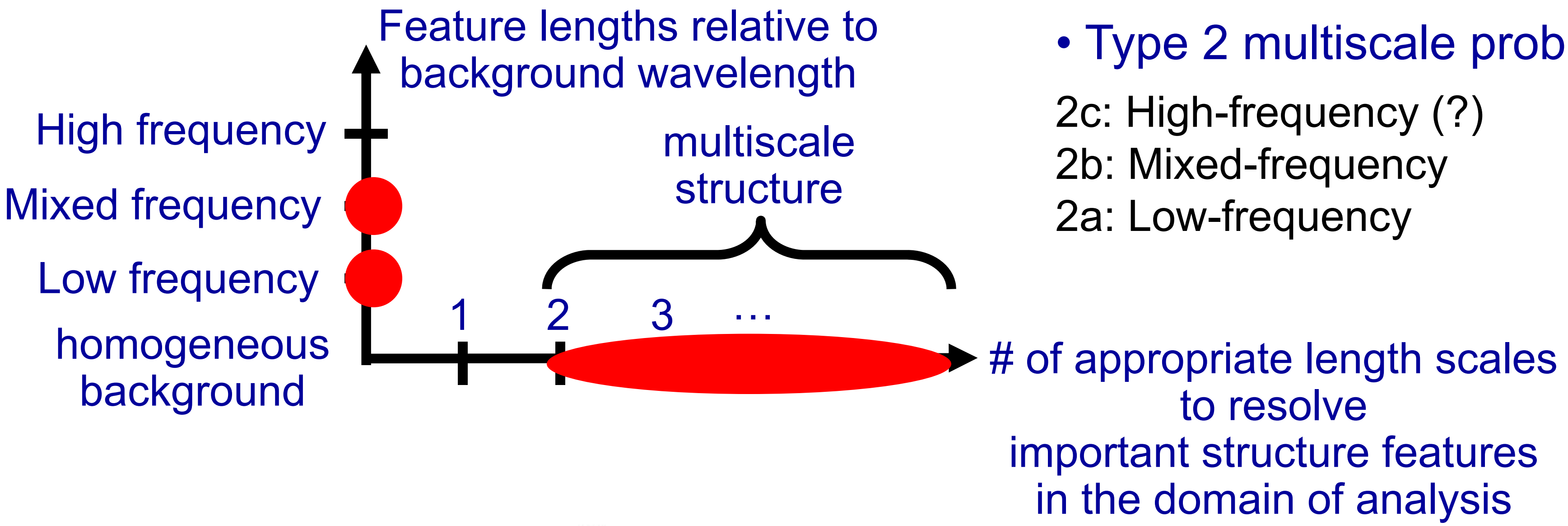


J. S. Zhao, W. C. Chew, *IEEE Trans. Antennas Propag.*, Oct. 2000.

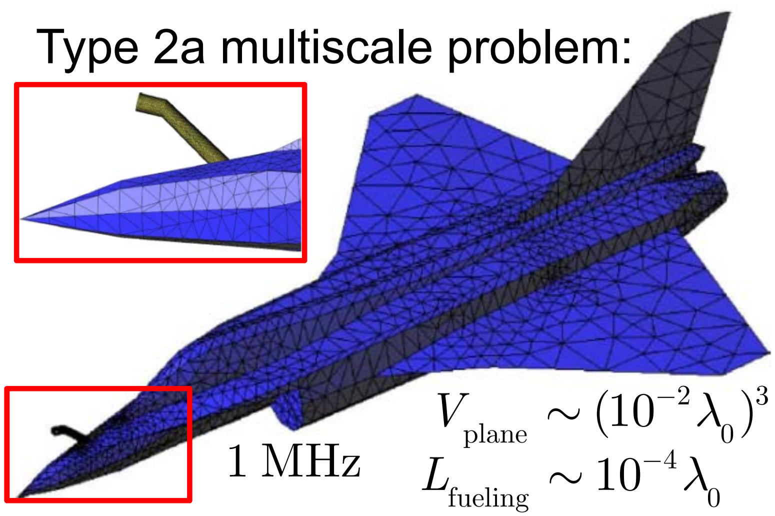
Multiscale Problems in Classical/Macroscopic EM Analysis



- Type 2 multiscale problem

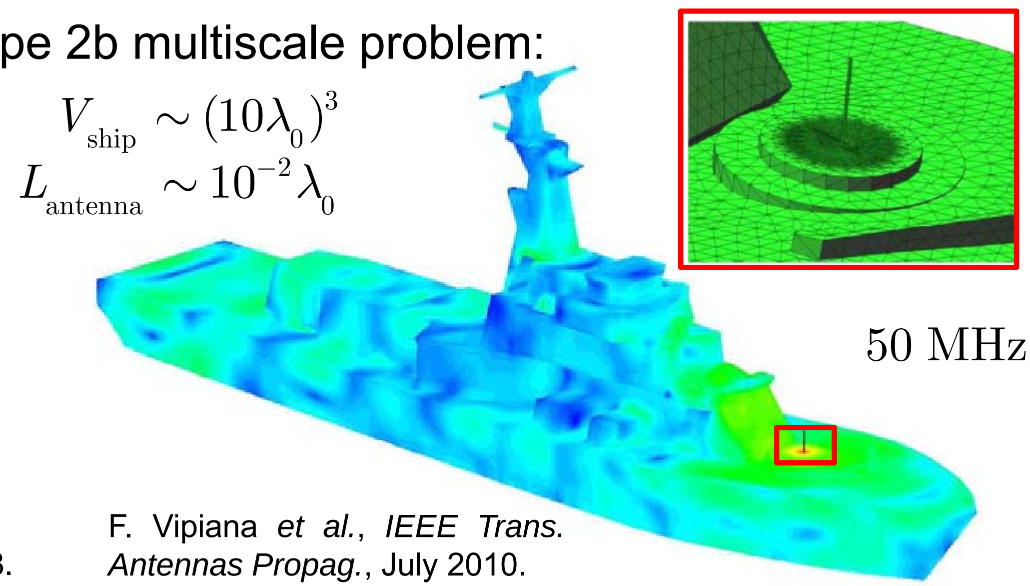
2c: High-frequency (?)
2b: Mixed-frequency
2a: Low-frequency

Type 2a multiscale problem:



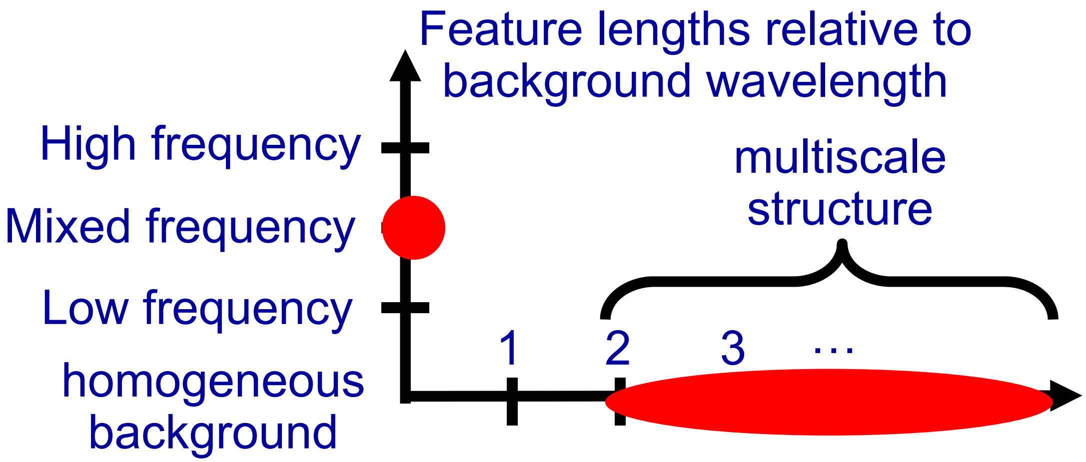
F. P. Andriulli *et al.*, *IEEE Trans. Antennas Propag.*, Aug. 2008.

Type 2b multiscale problem:



F. Vipiana *et al.*, *IEEE Trans. Antennas Propag.*, July 2010.

Multiscale Problems in Classical/Macroscopic EM Analysis



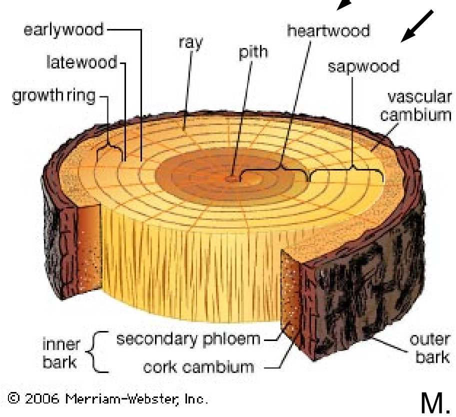
- Type 2 multiscale problem

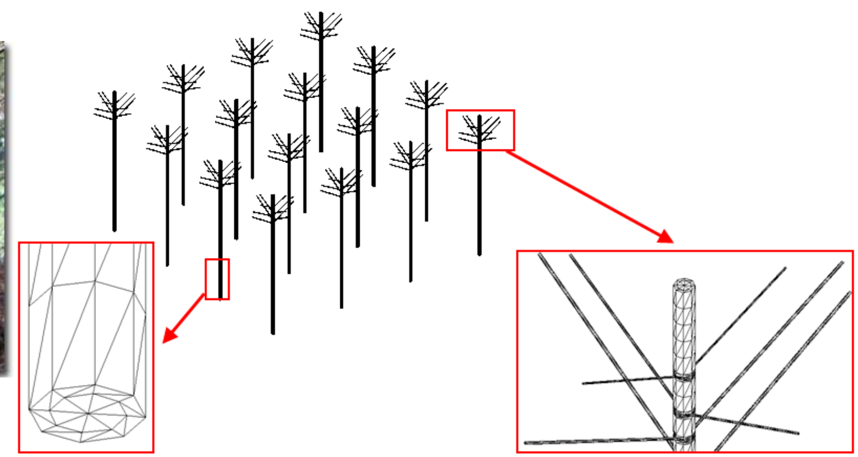
2c: High-frequency (?)
2b: Mixed-frequency
2a: Low-frequency

Type 2b multiscale problem:

$\varepsilon_r = 12.2,\ \sigma{=}0.002$

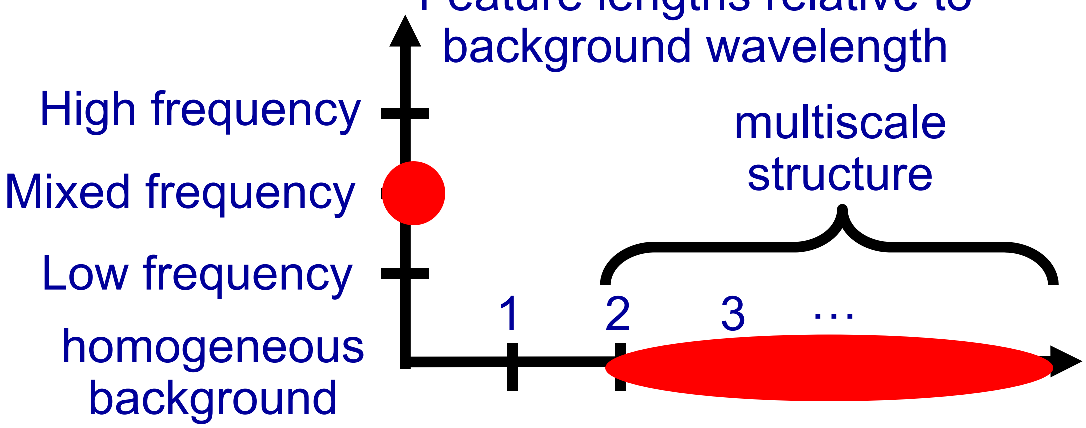
$\varepsilon_r = 56.7,\ \sigma{=}0.013$





M. F. Wu, G. Kaur, A. E. Yilmaz, *IEEE Trans. Antennas Propag.*, May 2010.

Multiscale Problems in Classical/Macroscopic EM Analysis

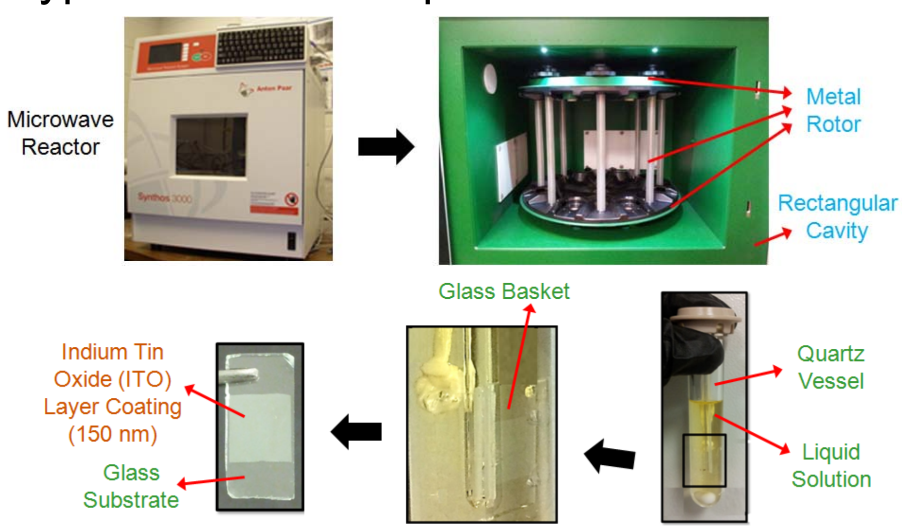


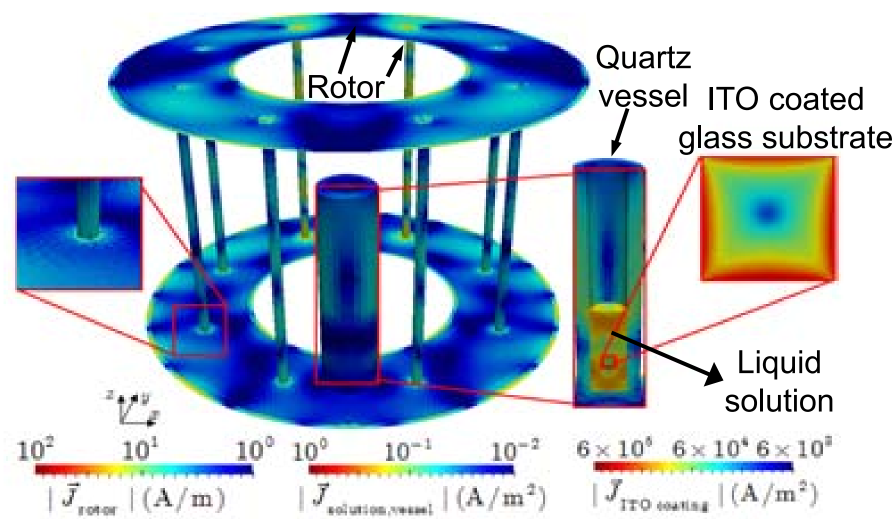
# of appropriate length scales to resolve important structure features in the domain of analysis

- Type 2 multiscale problem

2c: High-frequency (?)
2b: Mixed-frequency
2a: Low-frequency

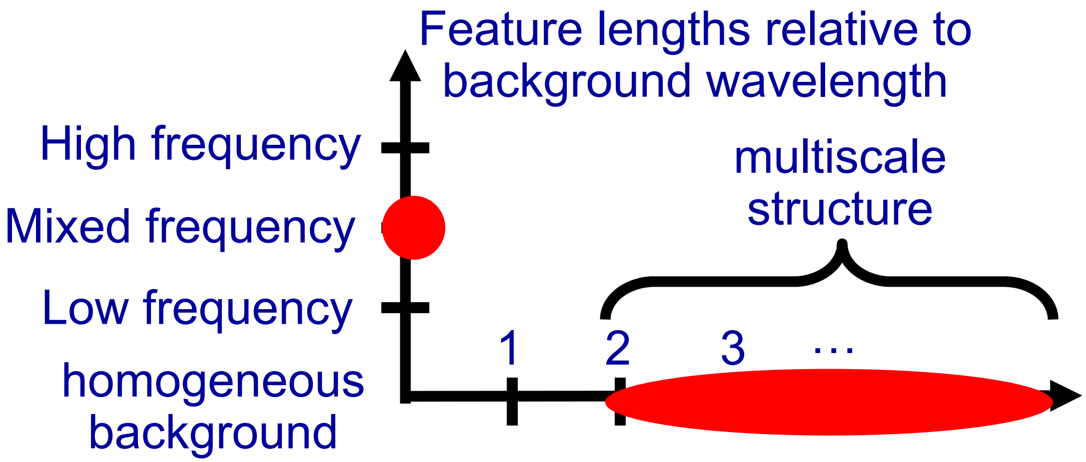
Type 2b multiscale problem:





B. Reeja-Jayan *et al.*, *Sci. Rep.*, Dec. 2012.

Multiscale Problems in Classical/Macroscopic EM Analysis



# of appropriate length scales to resolve important structure features in the domain of analysis

- Type 2 multiscale problem

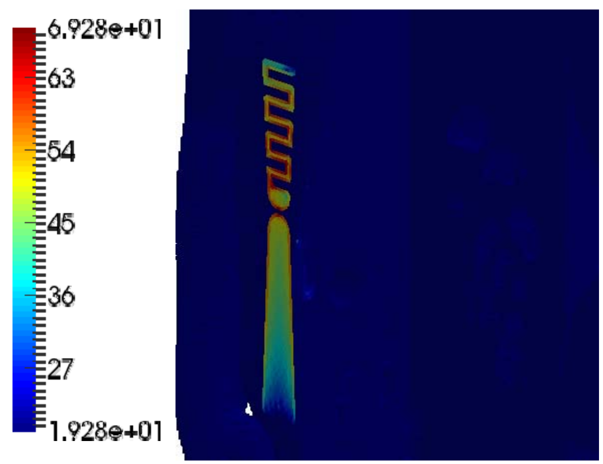
2c: High-frequency (?)
2b: Mixed-frequency
2a: Low-frequency

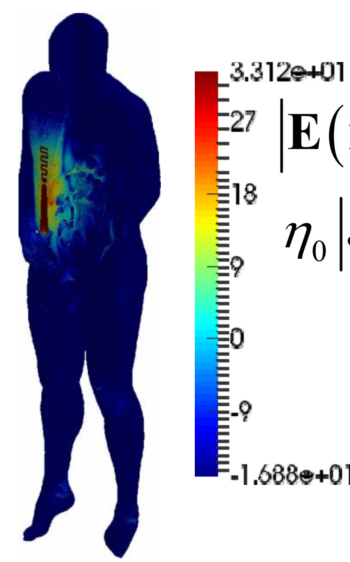
Type 2b multiscale problem:

$f = 350\text{MHz}$

J. W. Massey,
V. Subramanian,
C. Liu,
A. E. Yilmaz,
in *Proc. EUCAP*,
Apr. 2016.

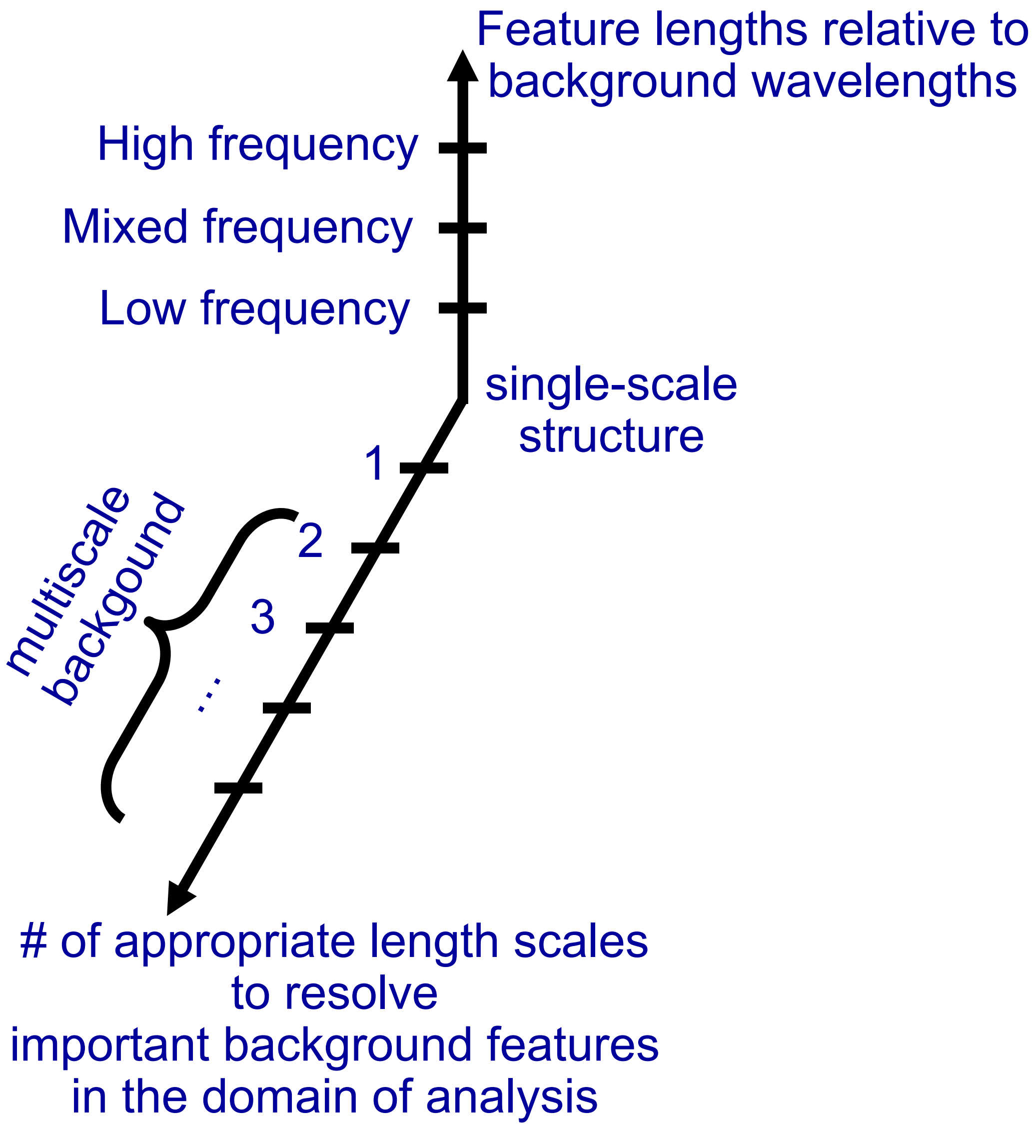
$|\mathbf{E}(\mathbf{r},t)|$ or $\eta_0 |\mathbf{J}_s(\mathbf{r},t)|$ (dB)





$|\mathbf{E}(\mathbf{r},t)|$ or $\eta_0 |\mathbf{J}_s(\mathbf{r},t)|$ (dB)

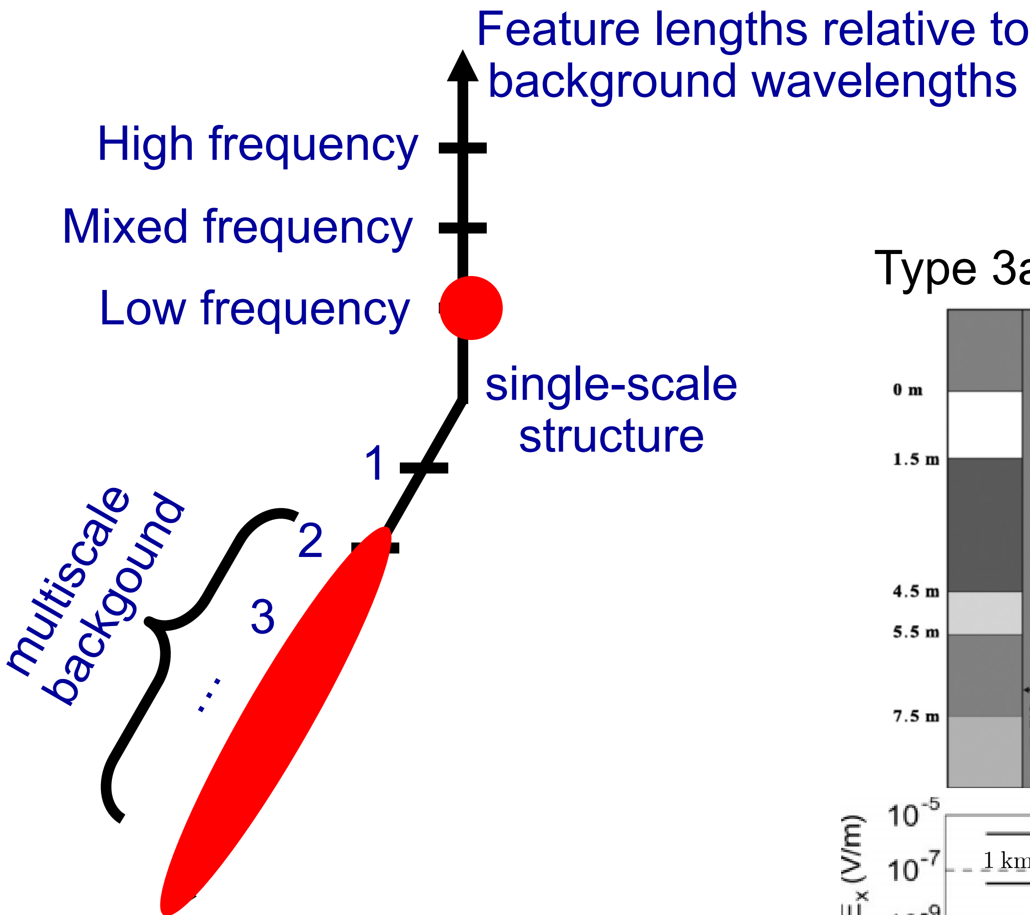
Multiscale Problems in Classical/Macroscopic EM Analysis



- Multiscale background

A background medium that has important features in the domain of analysis at multiple length scales

Multiscale Problems in Classical/Macroscopic EM Analysis

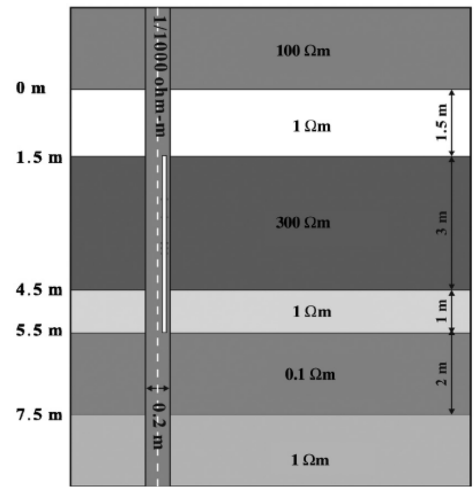


# of appropriate length scales to resolve important background features in the domain of analysis

- Type 3 multiscale problem

3c: High-frequency
3a: Low-frequency

Type 3a multiscale problem:

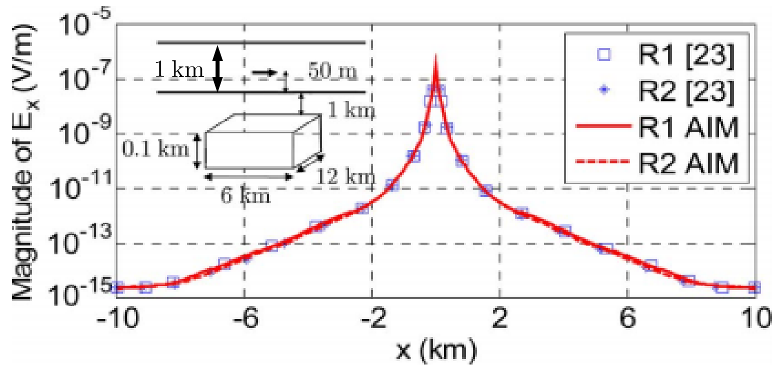


26 kHz

$$\frac{\lambda_0}{\delta_{\text{background}}} \sim 10^2 - 10^4$$

$$\frac{R_{\text{borehole}}}{\delta_{\text{background}}} \sim 10^{-3} - 10^{-1}$$

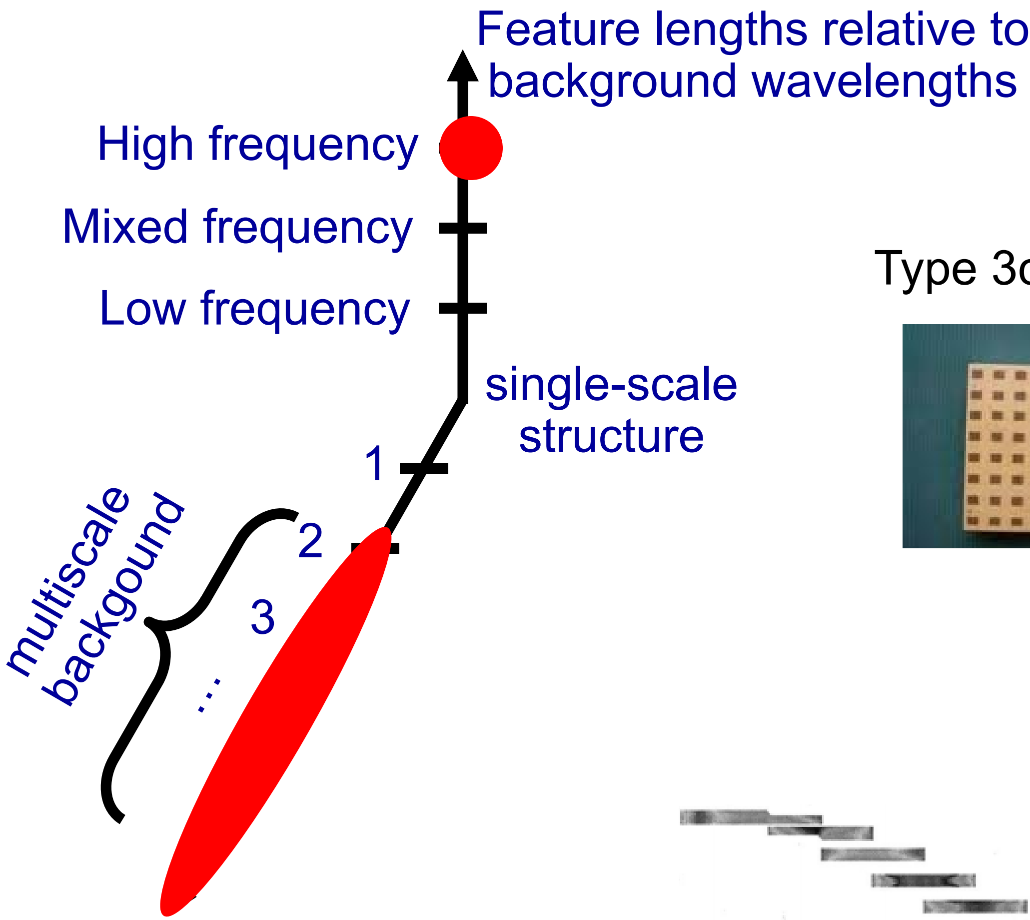
M. J. Nam *et al.*, *Geophysics*, Jan.-Feb. 2013.



0.25 Hz

K. Yang, A. E. Yilmaz, *IEEE Geosci. Remote Sens. Lett.*, July 2013.

Multiscale Problems in Classical/Macroscopic EM Analysis



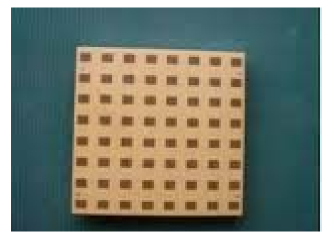
# of appropriate length scales to resolve important background features in the domain of analysis

- Type 3 multiscale problem

3c: High-frequency
3a: Low-frequency

Type 3c multiscale problem:

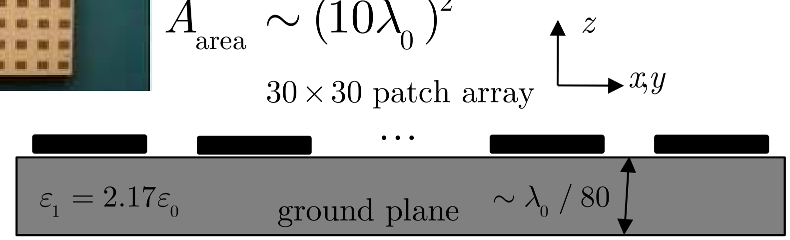
J. S. Zhao, W. C. Chew, C.-C. Lu, E. Michielssen, J. Song, *IEEE Trans. Microw. Theory Tech.*, Apr. 1998.



2.2 GHz

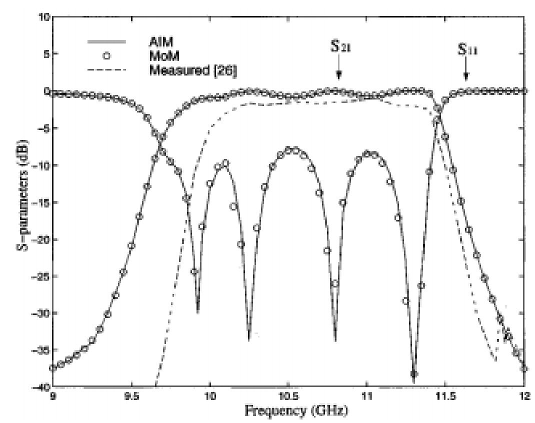
$A_{\text{area}} \sim (10\lambda_0)^2$

30×30 patch array

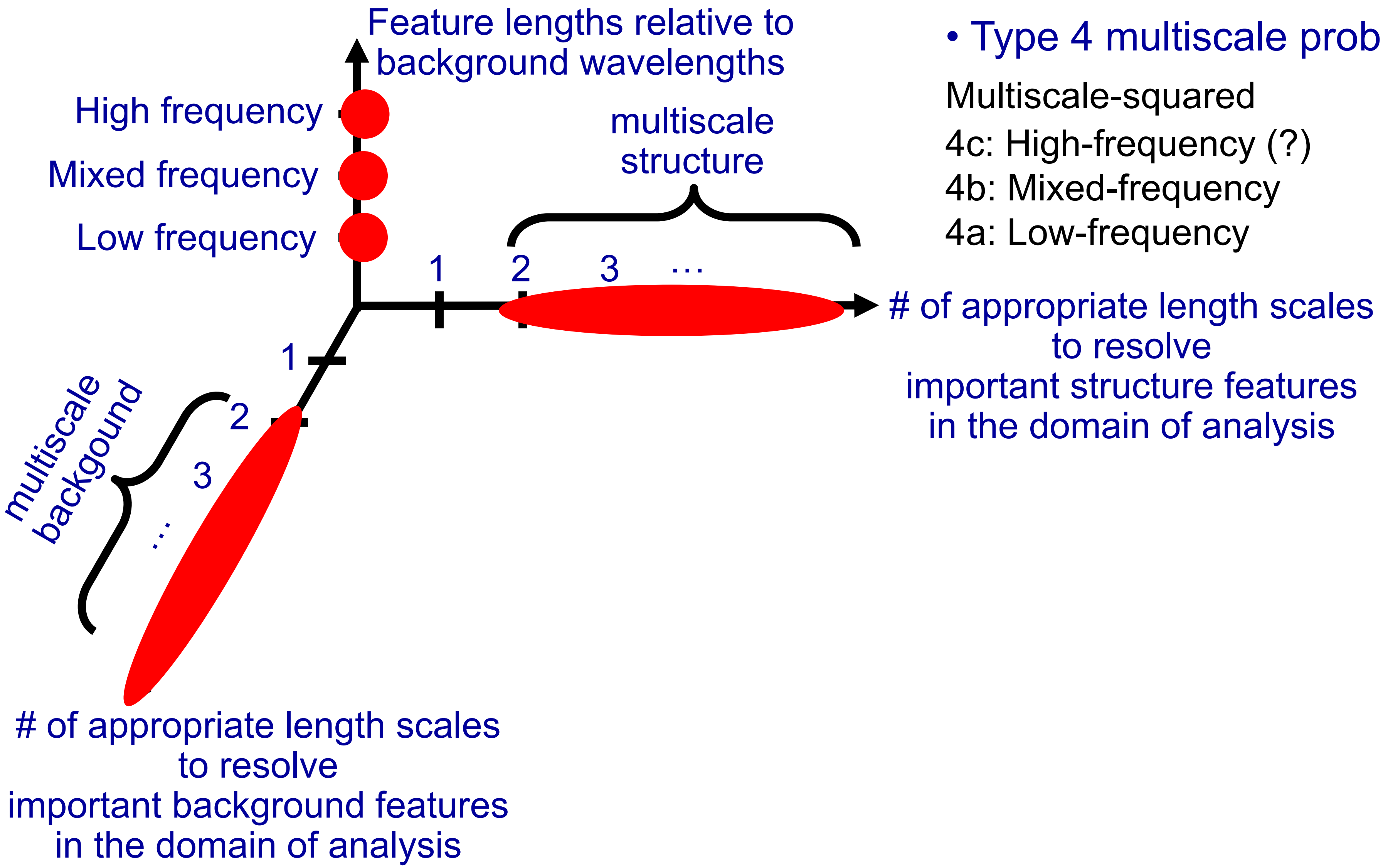


F. Ling, C. F. Wang, J. M. Jin, *IEEE Trans. Microw. Theory Tech.*, May 2000.

11 GHz



Multiscale Problems in Classical/Macroscopic EM Analysis



- Type 4 multiscale problem

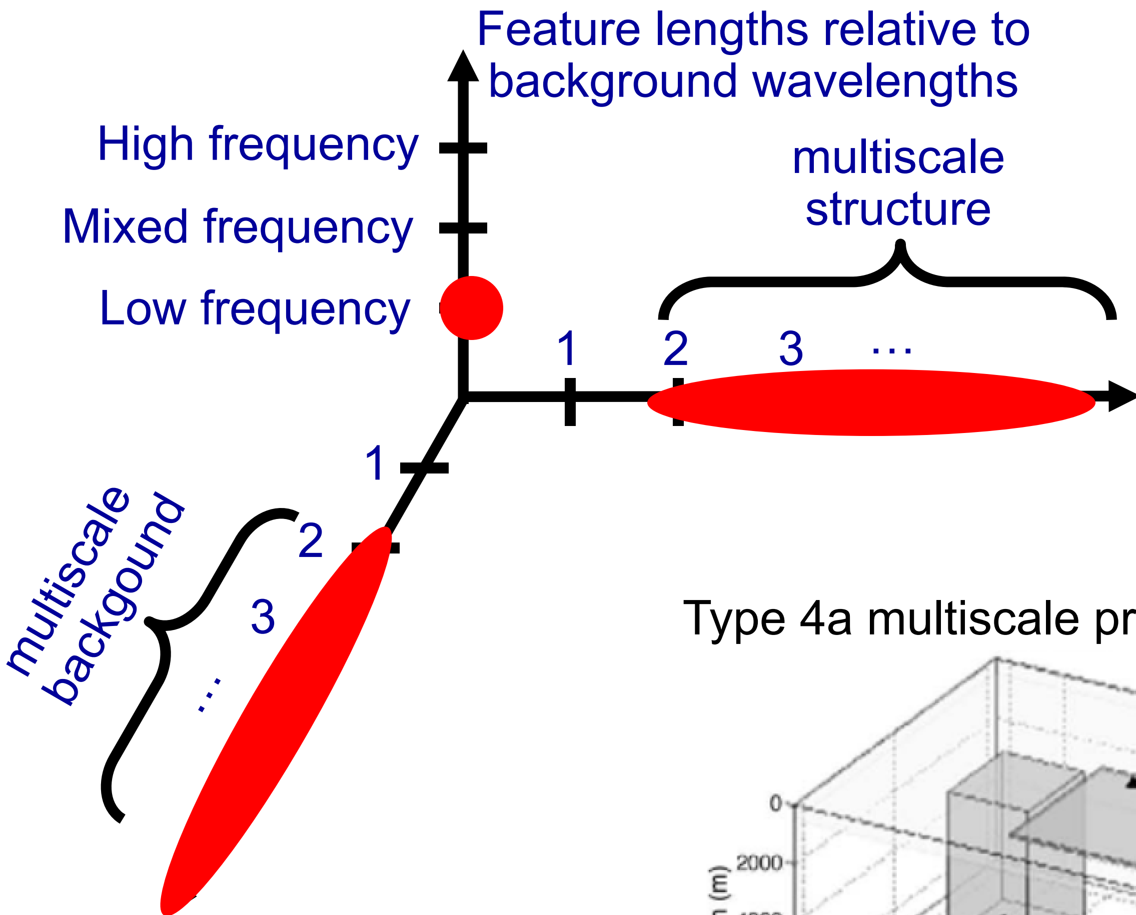
Multiscale-squared

4c: High-frequency (?)

4b: Mixed-frequency

4a: Low-frequency

Multiscale Problems in Classical/Macroscopic EM Analysis



- Type 4 multiscale problem

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4c: High-frequency (?)

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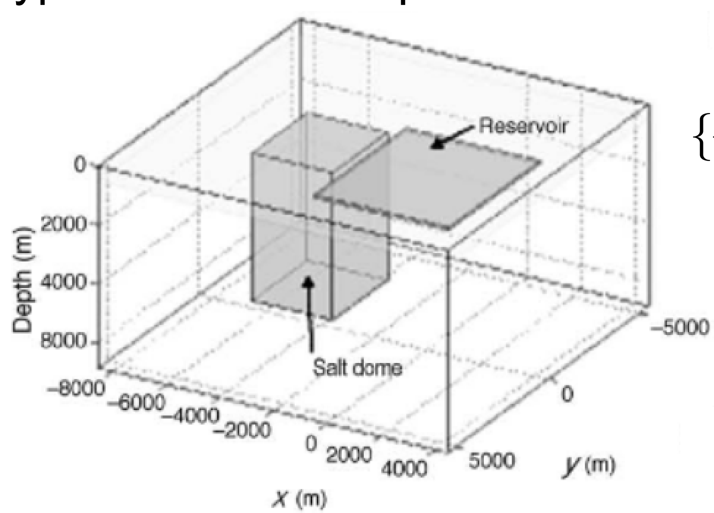
Type 4a multiscale problem:



$$1\ \mathrm{mHz}$$

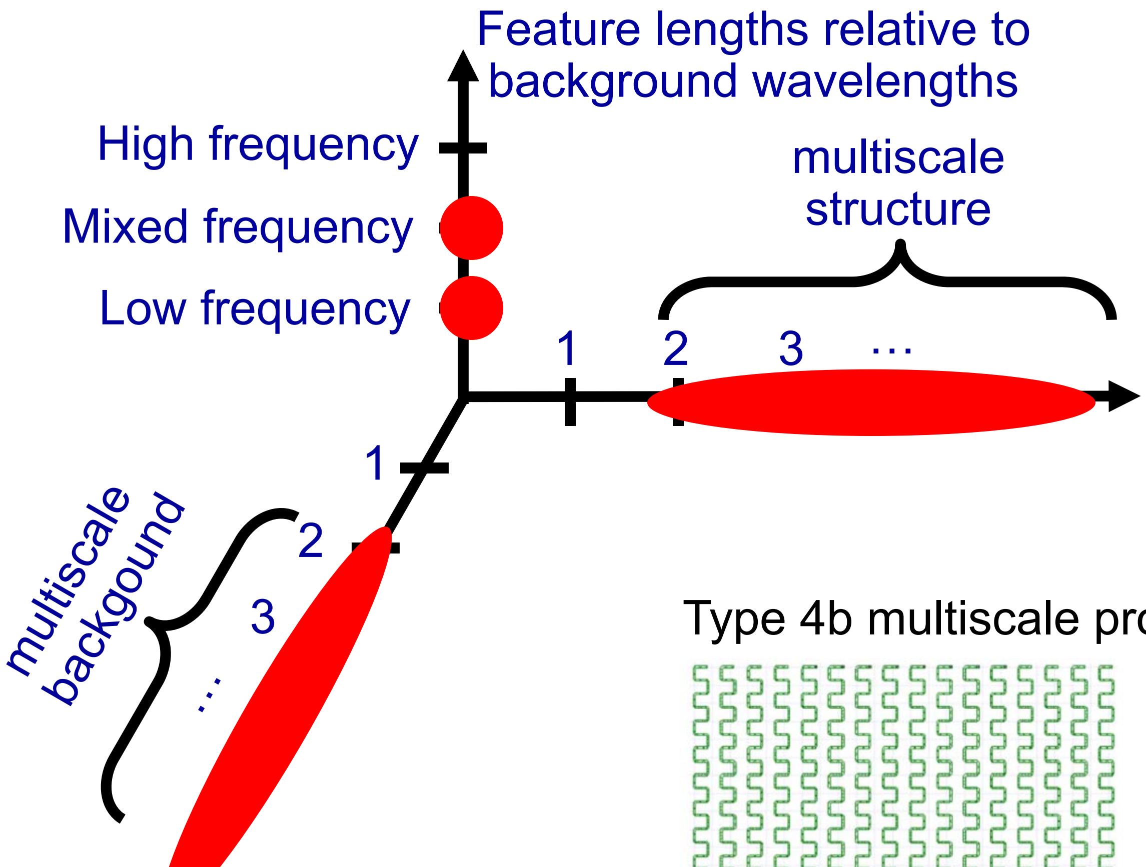
$$\left\{\frac{\lambda_0}{\delta_{\mathrm{rock}}}, \frac{\lambda_0}{\delta_{\mathrm{sea}}}\right\} = \{10^7, 10^7\}$$

$$V_{\mathrm{dome}} \sim \left(\frac{\delta_{\mathrm{rock}}}{10}\right)^3$$

$$h_{\mathrm{reservoir}} \sim 10^{-3}\delta_{\mathrm{rock}}$$

M. S. Zhadanov *et al.*, *Geophysics*, Nov.-Dec. 2006.

Multiscale Problems in Classical/Macroscopic EM Analysis



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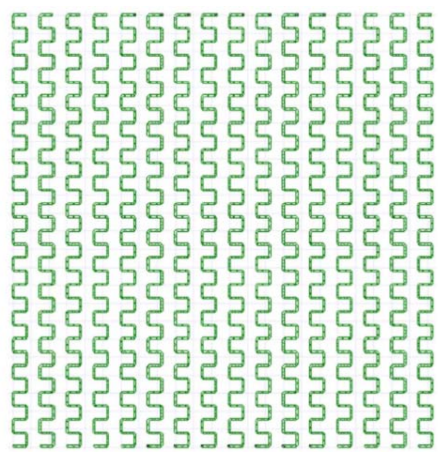
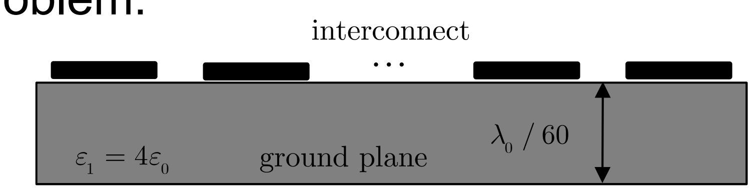
Type 4b multiscale problem:





20 GHz

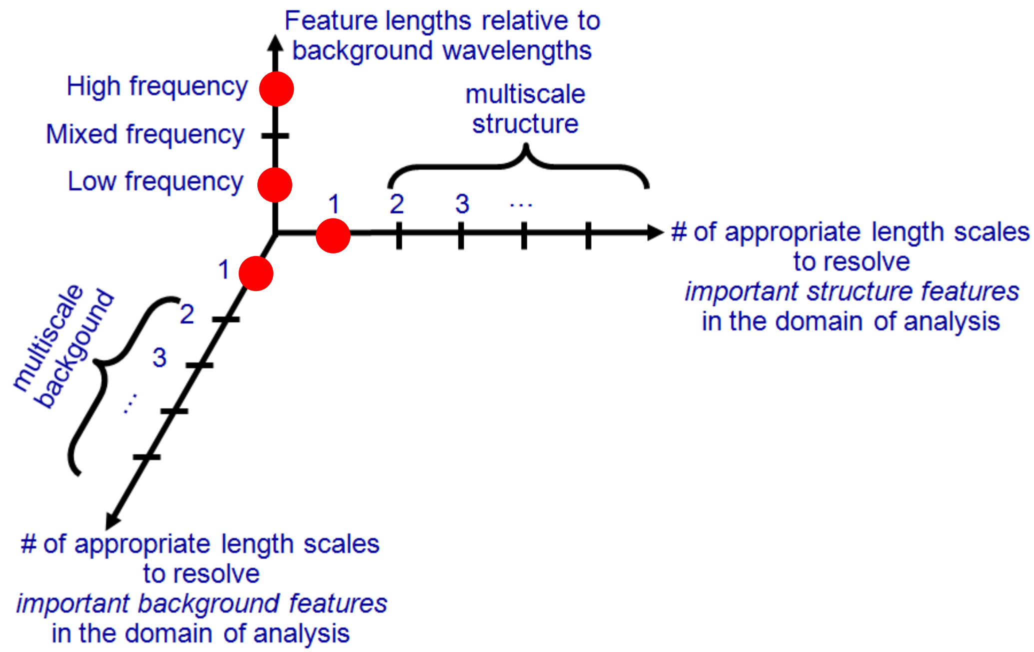
$$W_{\text{interconnect}} \sim \frac{\lambda_0}{10^{-2}} \qquad \frac{\lambda_0}{h_{\text{substrate}}} \sim 60$$

$$A_{\text{area}} \sim (10\lambda_0)^2$$

C. J. Ong, L. Tsang, *IEEE Trans. Adv. Pack.*, Nov. 2008.

Conclusion

- Not all multi-scale EM problems are the same, some are harder
  - Must consider structure, background, rate of change of fields
  - 4 types of problems stand out:
    - Type 1a,1c (two-scale)
    - Type 2a,2b,2c
    - Type 3a,3c
    - Type 4a,4b,4c



- What we haven't talked about
  - Multi-time-scale problems
  - How much *should* one model vs. how much *can* one model?
  - Which methods are more promising for which types of problems?
  - How different solution methods can recast the problem to a different type…
    - A type 2c problem for FDTD can become a type 3c problem for MOM
    - A type 2b problem can become many type 1a+1c problems using equivalence principle

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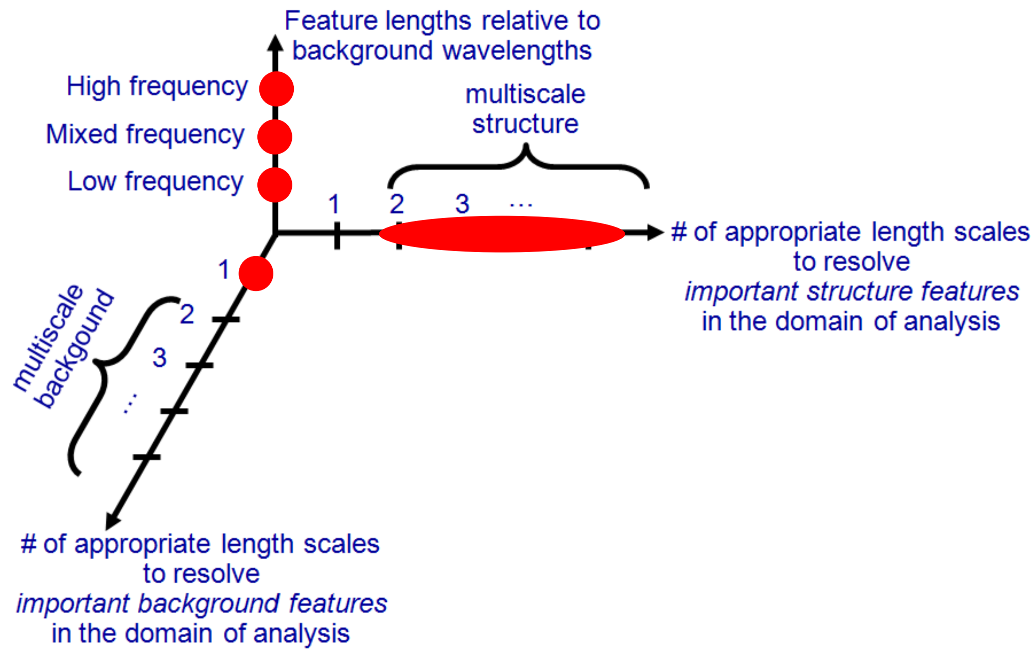

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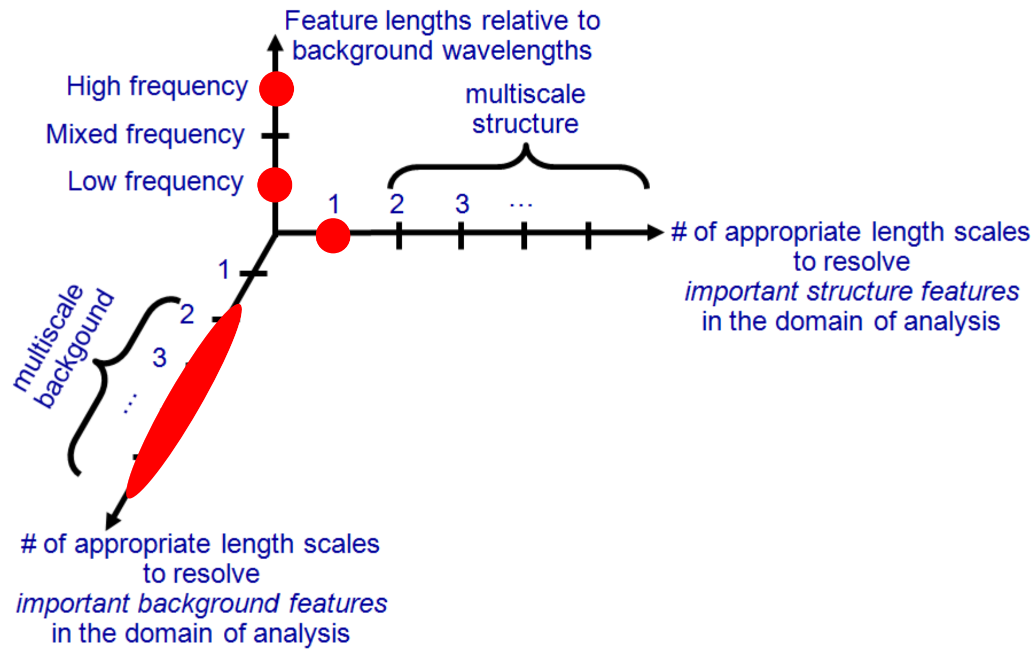

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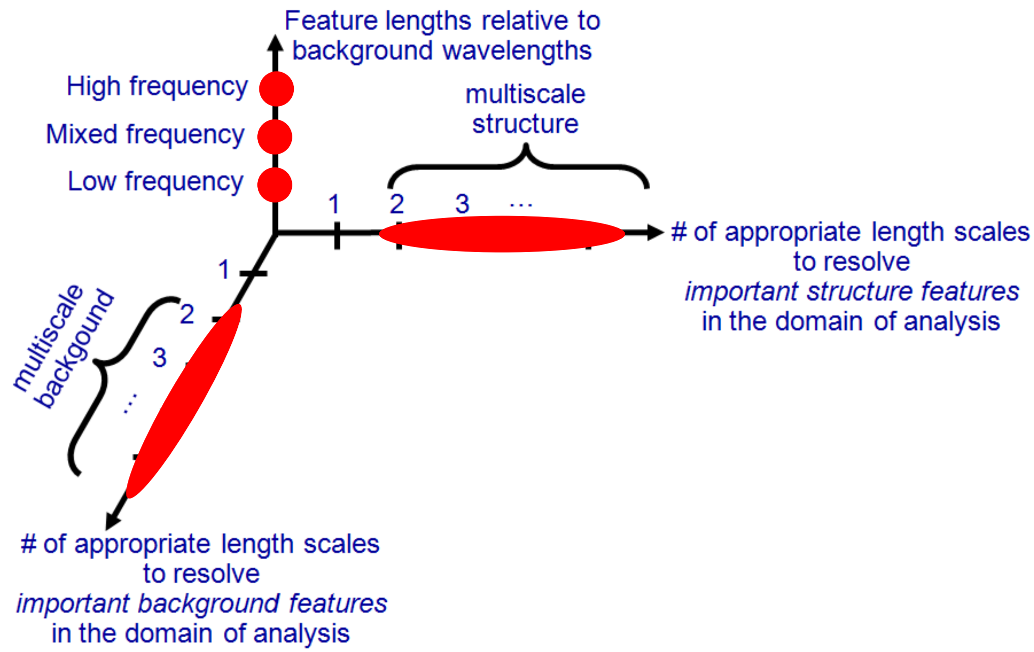

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