Finite Frequency Sensitivity Kernels For Multi Scale Electromagnetic Imaging Applications

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Electromagnetic (EM) imaging is gaining importance as an effective method to inspect low-loss dielectric materials and fluids.

1- 100 GHz (mm)

100 MHz- 1 GHz (cm - m)

1- 100 MHz (m - Km)

Source

NDE

Oil

CO_2

Funded by LLNL Carbon Storage program

Benefits of the imaging method:

- Multi-scale applications,
- Non-iterative kernel based imaging,
- Kernels provide contrasting sensitivity of EM waves to different properties.

Basic approach

EM forward propagation

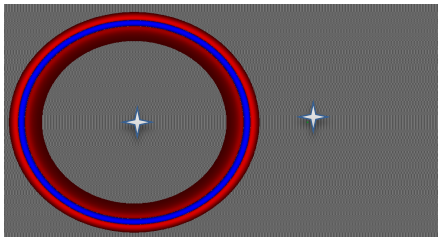
Adjoint source computed from forward fields

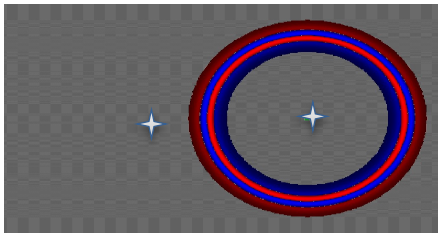
EM back-propagation

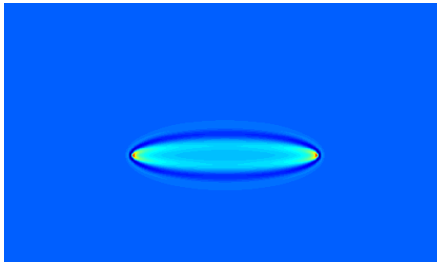
Kernel computed based on interaction between forward and adjoint fields.

Sensitivity kernels

Kernels used for imaging and form basis of tomographic inversion.

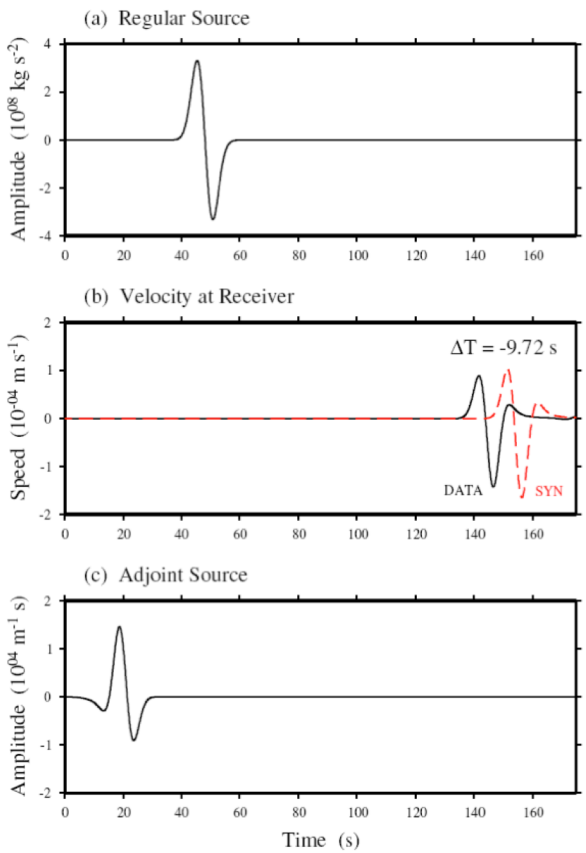




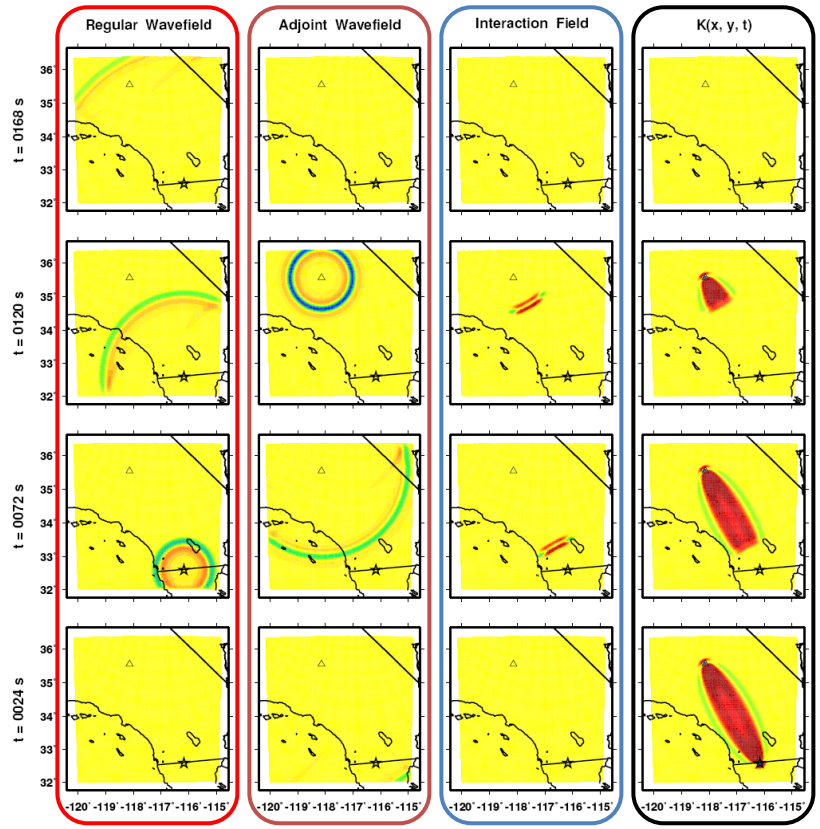


Schematic Kernel Construction

Adjoint source construction:



$$K_i(\mathbf{x}) = \int_0^T \mathbf{D}(\mathbf{x},\, t) \,:\, \mathbf{D}_i^\dagger(\mathbf{x},\, T-t)\, dt$$



(after Tape et al., GJI 2007)

Adjoint inversion method

- ***Forward equation***:

$$\varepsilon^e \cdot \partial_t^2 \mathbf{E} = \nabla \cdot (\partial_t \tilde{\mathbf{H}}) - \sigma^e \cdot \partial_t \mathbf{E} - \partial_t \mathbf{j}_s$$

$\boldsymbol{E}$ and $\widetilde{\boldsymbol{H}}$ are the electric and magnetic fields, $\mathbf{j_s}$ is the source current density [1].

- ***Adjoint equation***:

$$\varepsilon^e \cdot \partial_t^2 \mathbf{E}^\dagger = \nabla \cdot \left(\partial_t \tilde{\mathbf{H}}^\dagger\right) - \sigma^e \cdot \partial_t \mathbf{E}^\dagger - \partial_t \mathbf{j}_s^\dagger$$

$\boldsymbol{j_s}^\dagger, \boldsymbol{E}^\dagger$ and $\widetilde{\boldsymbol{H}}^\dagger$ are the adjoint counterparts, $\boldsymbol{j_s}^\dagger$ can be constructed by different ways [2].

- ***Finite frequency sensitivity kernels***:

$$K_\varepsilon = -\int_0^T \varepsilon^e \boldsymbol{E}^\dagger(T-t) \,.\, \partial_t^2 \boldsymbol{E}(t)\ dt$$

$$K_\mu = -\int_0^T 2\,\mu^{-1}\,\boldsymbol{\tau}(t) :\ \boldsymbol{\varphi}^\dagger(T-t)\,dt$$

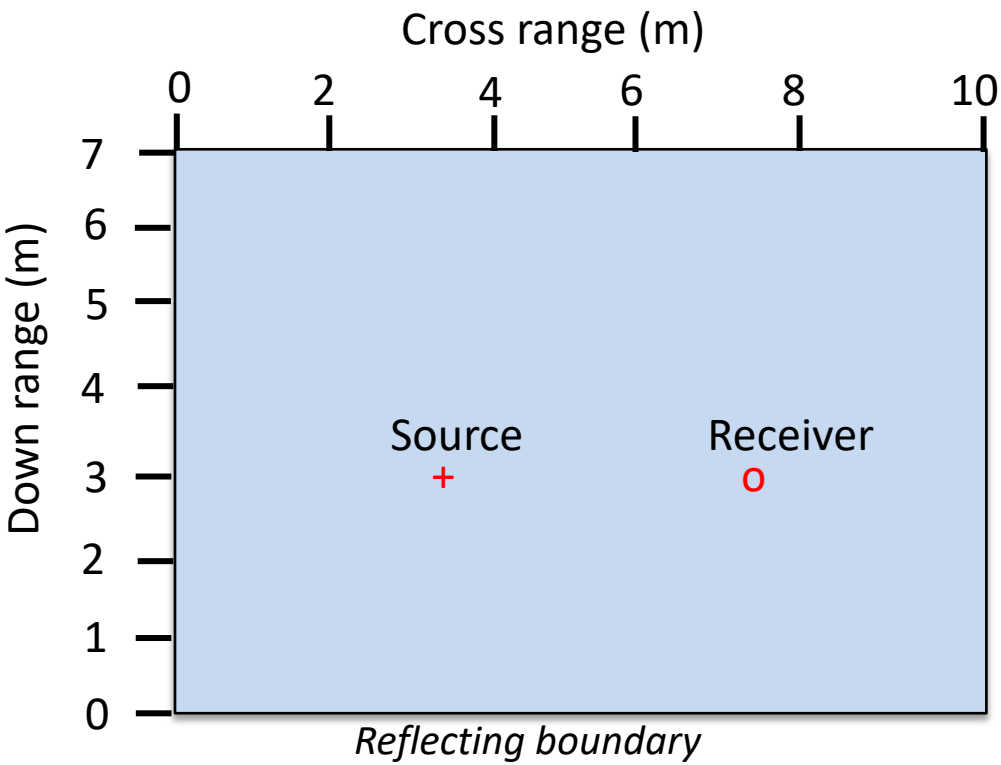
$$K_\sigma = -\int_0^T \sigma^e \boldsymbol{E}^\dagger(T-t) \,.\, \partial_t\, \boldsymbol{E}(t)\ dt$$

$$\boldsymbol{\tau} = \frac{1}{2}[\nabla \boldsymbol{E} - (\nabla \boldsymbol{E})^T],\ \boldsymbol{\varphi}^\dagger = \frac{1}{2}[\nabla \boldsymbol{E}^\dagger - (\nabla \boldsymbol{E}^\dagger)^T]$$

[1] Morency, C. "Electromagnetic wave propagation based upon spectral-element methodology", (2018) submitted to Geophysical Journal International.
[2] Mukherjee, S., Morency, C., "Finite frequency sensitivity kernels for electromagnetic wave propagation based on adjoint methods" (in preparation).

Source imaging

Geometry

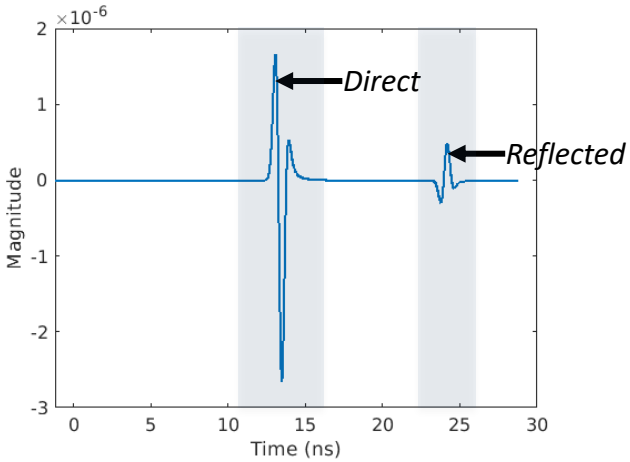


Model Geometry: Source detection

- Dielectric medium : ε_r =3, σ=0.02 S/m.
- Spatial domain: 10 m × 7 m
- Locations:
  - Source (3 m,3 m)
  - Receiver (7 m,3 m)
- Absorbing boundary conditions imposed on left, right and top boundaries.
- Bottom boundary is assumed to be a reflecting boundary

Source imaging

Radargram



Electric fields recorded by the receiver array.

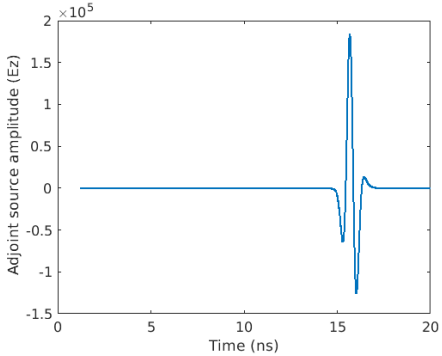
- direct interaction.
- reflected fields from boundary.

Adjoint source :

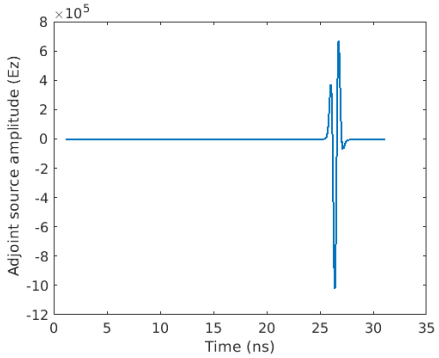
$$j_s^{\dagger}(x,t) = \frac{w_r(T-t)}{N_r}\partial_t \mathbf{E}(x,T-t)\delta(x-x_r)$$

Adjoint source

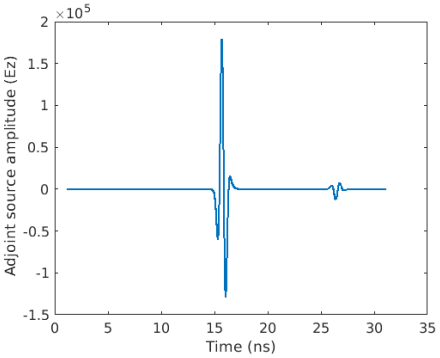
Direct



Reflected

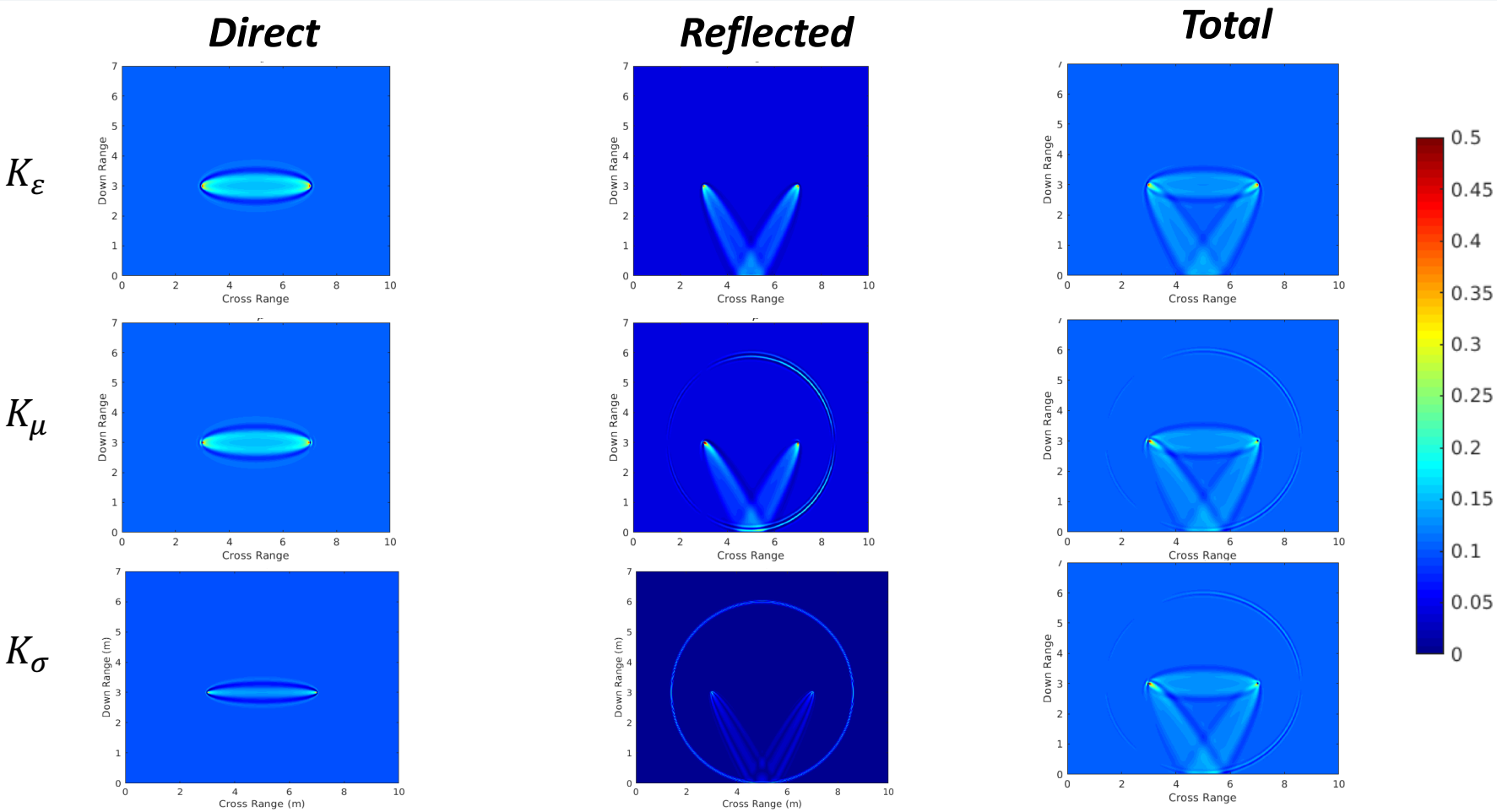


Total



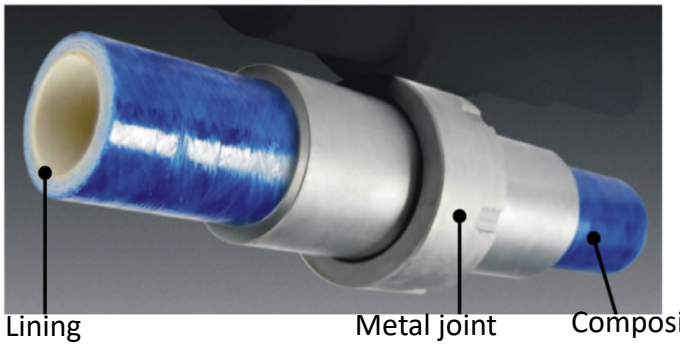
Source configuration

Kernels



The kernels highlight the primary EM wave path.

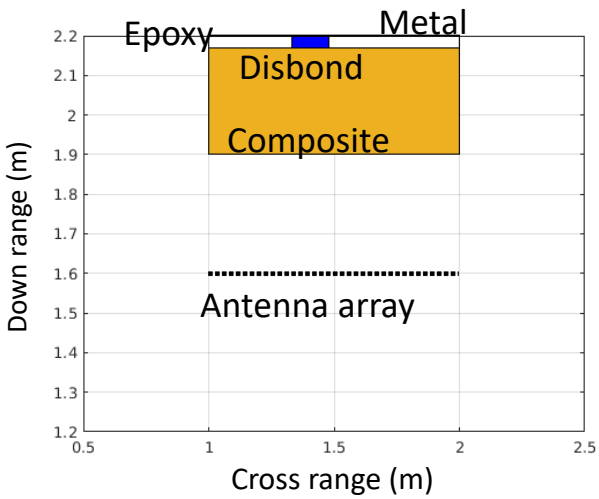
Application: NDE of composites



Metal-composite tube for buildings [3]

- **Composite:** Light weight, High stiffness, strength..
- **Industries:** Aerospace, automotive, civil.

GOAL: Detect disbond in metal composite joint.



Model Geometry: Far field EM imaging system for NDE of metal composite joints

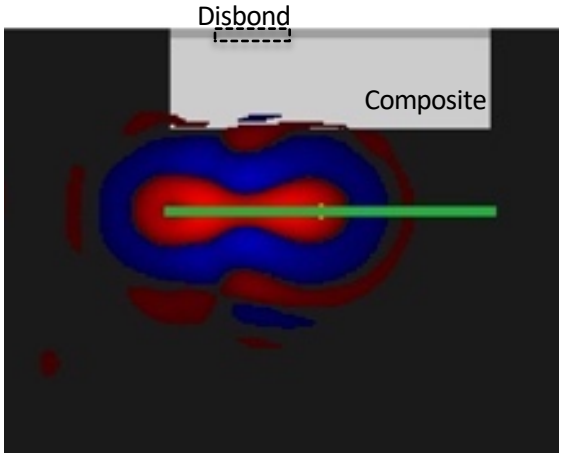
Material	Electrical Property		Size
	ε_r	$\tan\delta$	m × m
Composite	3.8	0.017	1 × 0.3
Epoxy	3.6	0.032	1 × 0.03
Disbond	1	0	0.3 × 0.03 ($2\lambda \times \lambda/5$)

- Transceiver system: 20 sources, 50 receivers.

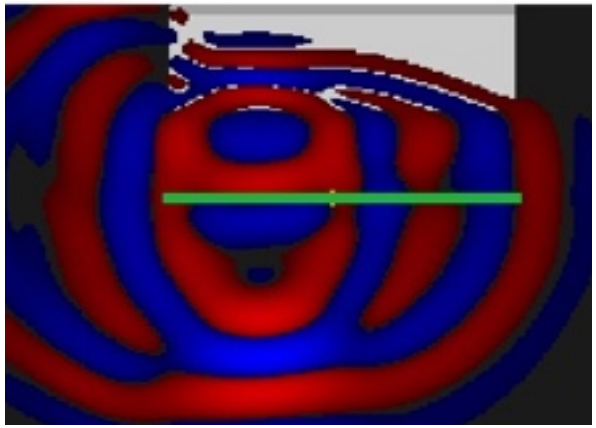
[3] Li, H., Zhang et al., 2015. Failure analysis of the adhesive metal joint bonded on anticorrosion plastic alloy composite pipe. *Engineering Failure Analysis*, *47*, pp.49-55.

Visualization of the back-propagated adjoint fields

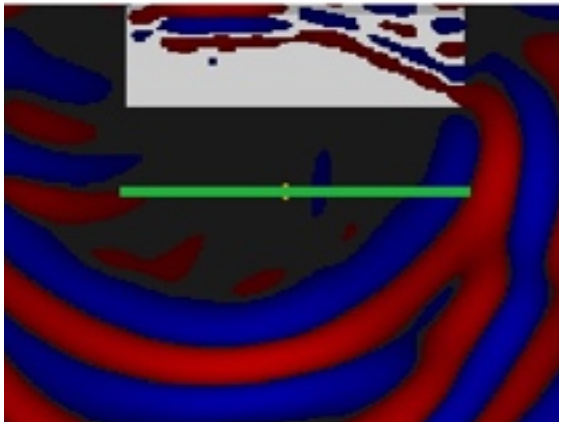
Wave initiating from receiver array (t=1 ns)



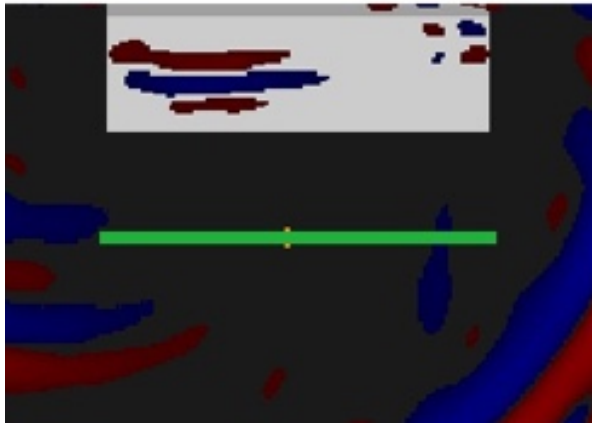
Wave starts converging (t=6 ns)



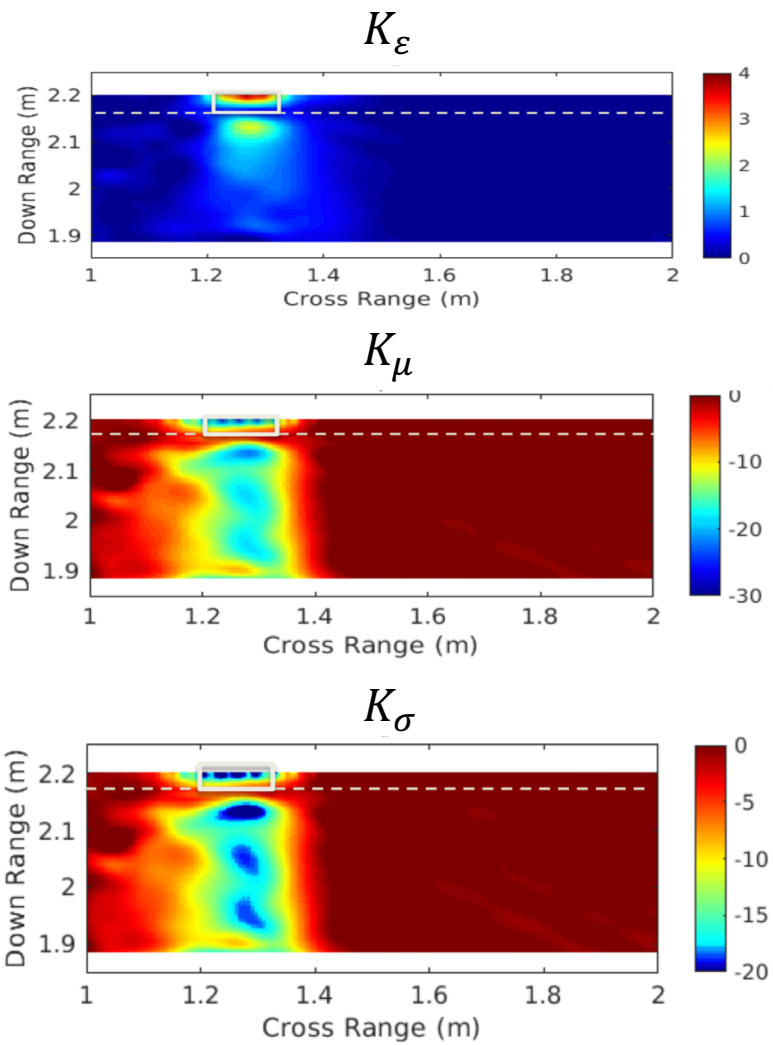
Wave focused at disbond (t=8 ns)

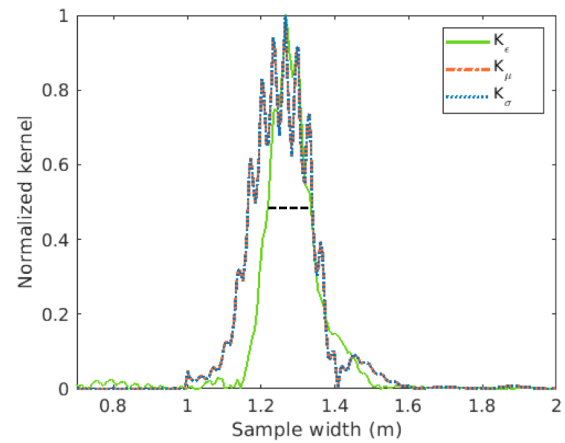


Wave diverges (t=10 ns)



Sensitivity Kernels for imaging defects

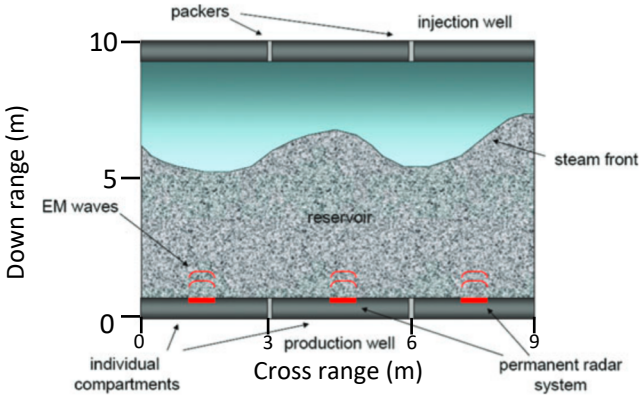




Comparison of kernels (*Black dashed line is the predicted disbond length*)

- K_ε shows the maximum contrast.
- Down range resolution limited due to diffraction limits.
- Full width at half maxima of the row of maximum intensity of the kernels (0.25 m) correlate with disbond length.

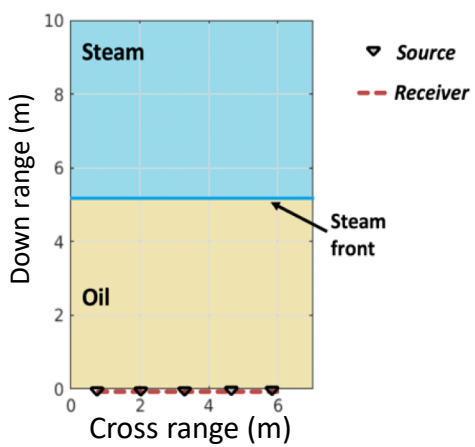
Application: Oil monitoring during steam injection process



Schematic representation of a potential downhole radar system in a SAGD process [4]

- Steam assisted gravity drainage (SAGD) is an enhanced oil recovery method.
- Advanced diagnostics needed to monitor an oil reservoir during steam injection.

GOAL: Image steam front in an oil reservoir.



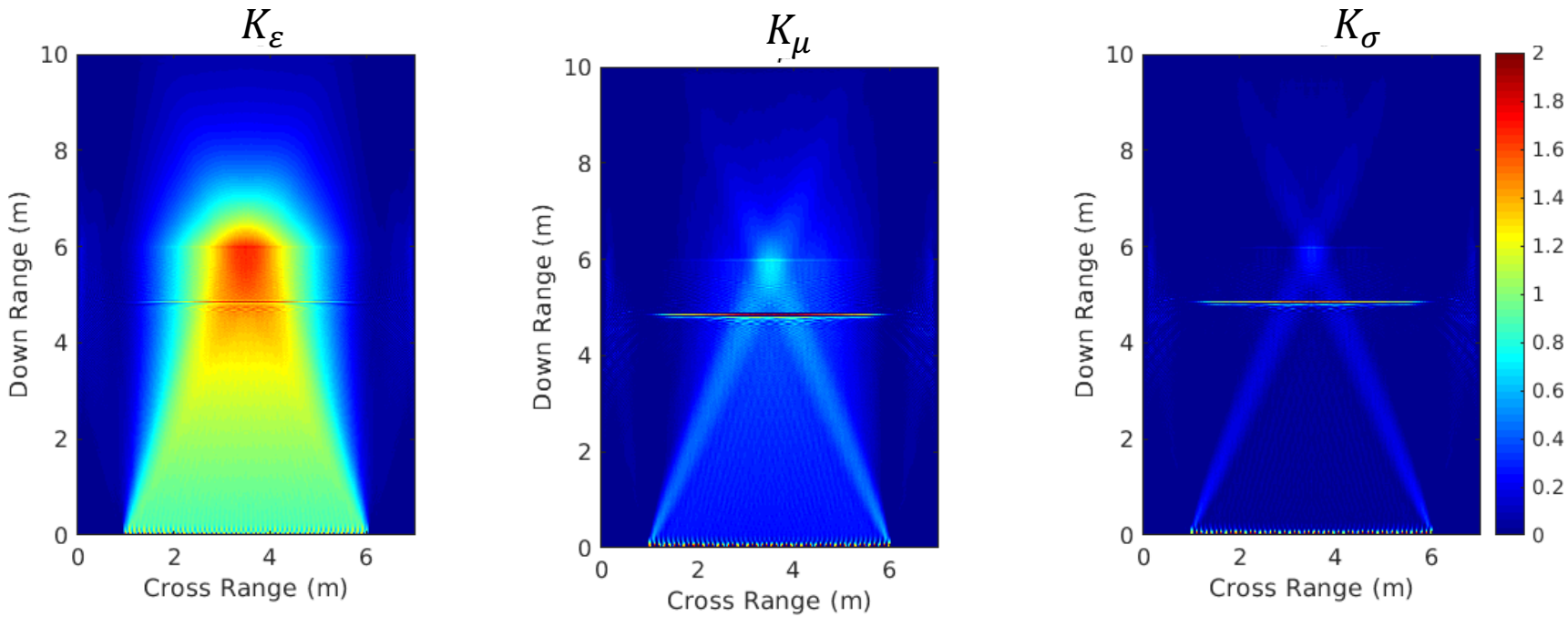
Model Geometry: Steam injected in oil reservoir to enhance production

Material	Electrical Property	
	ε_r	σ (S/m)
Oil	8	0.01
Steam	20	0.01

- Downhole radar system: 20 sources, 50 receivers

[4] Miorali, M. et al., 2011. A feasibility study of borehole radar as a permanent downhole sensor. *Geophysical Prospecting*, *59*(1), pp.120-131.

Sensitivity Kernels for oil monitoring

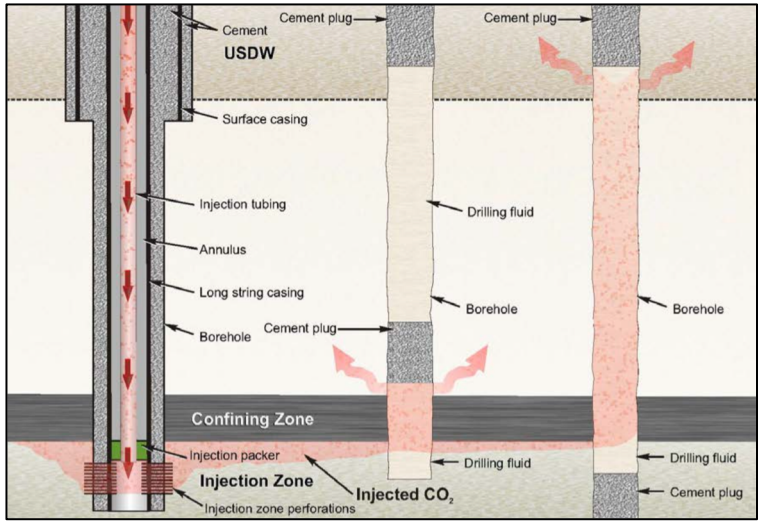


- The steam boundary can be clearly detected in the kernels.
- Primarily sensitivity in the center of the model due to radar configuration.
- Permeability and conductivity kernels extremely sensitive to interface discontinuities.
- Permittivity kernel provides more volumetric information, showing a permittivity anomaly.

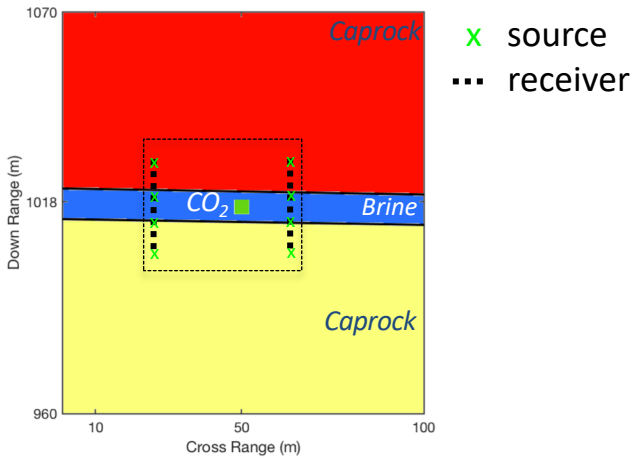
Application: CO_2 sensing during sequestration

Funded by LLNL Carbon Storage program

Example of CO_2 leakage of abandoned wells [5]



Model Geometry : CO_2 injected in a brine-saturated aquifer environment



- Accurate monitoring during CO_2 sequestration needed for detecting and tracking CO_2.
- Cross-bore radar can be used for CO_2 detection in brine saturated aquifers.

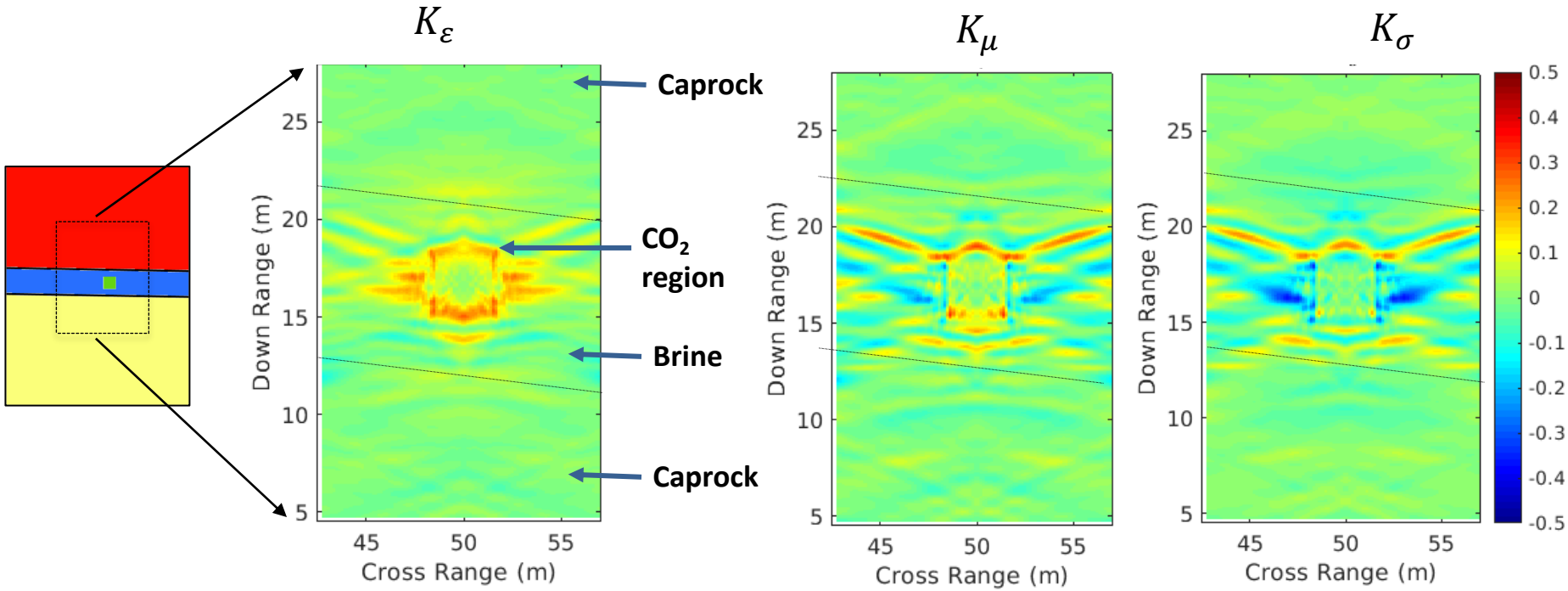
GOAL: Detect CO_2 in brine saturated aquifer.

Material	Electrical Property	
	ε_r	σ (S/m)
Brine	10	0.01
Caprock	7	0.002
CO_2	3	0.03

- Crossbore radar system: 8 sources, 80 receivers *(need reflection and transmission data)*

[5] Geologic Sequestration of Carbon Dioxide Underground Injection Control Program Class VI Well Testing and Monitoring Guidance, Environment Protection Agency 2013.

Sensitivity Kernels for CO_2 sensing



- The CO_2 interface can be clearly detected in the kernels.
- K_ε shows the maximum sensitivity.

Conclusions and future work

- The adjoint method is used to compute finite frequency sensitivity kernels.
- The newly developed kernels demonstrate their sensitivity for diverse imaging applications:
  - Detection of source,
  - NDE of composites [6],
  - oil monitoring [7],
  - CO_2 sensing.
- Preliminary simulation results are promising, show high efficiency from scales ranging from millimeters to 100s of meters.
- *Future work: Use the kernels in an adjoint iterative framework for direct inversion of EM properties.*

[6] Mukherjee, S., Morency, C., "Finite Frequency Sensitivity Kernels For Microwave NDE Of Metal-composite Joints" , QNDE 2019 (to be presented).
[7] Mukherjee, S., Morency, C., "Investigation of a radar based adjoint imaging method for oil monitoring applications", SEG Workshop 2019 (to be presented).

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