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2 Apr 2007

Enhancements in Electrical Impedance Tomography (EIT)

Image Reconstruction for 3D Lung Imaging

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School of
Information Technology
and Engineering

Aim of this work

- Develop enhancements in EIT image reconstruction for 3D lung imaging; to remove some of the limitations that continue to impede its routine use in the clinic

- The aim is attained through the systematic achievement of four main objectives:

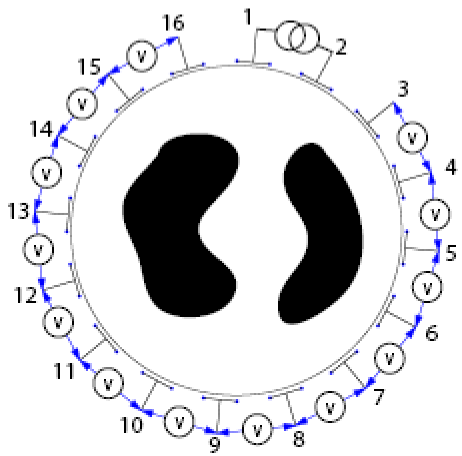
Objectives

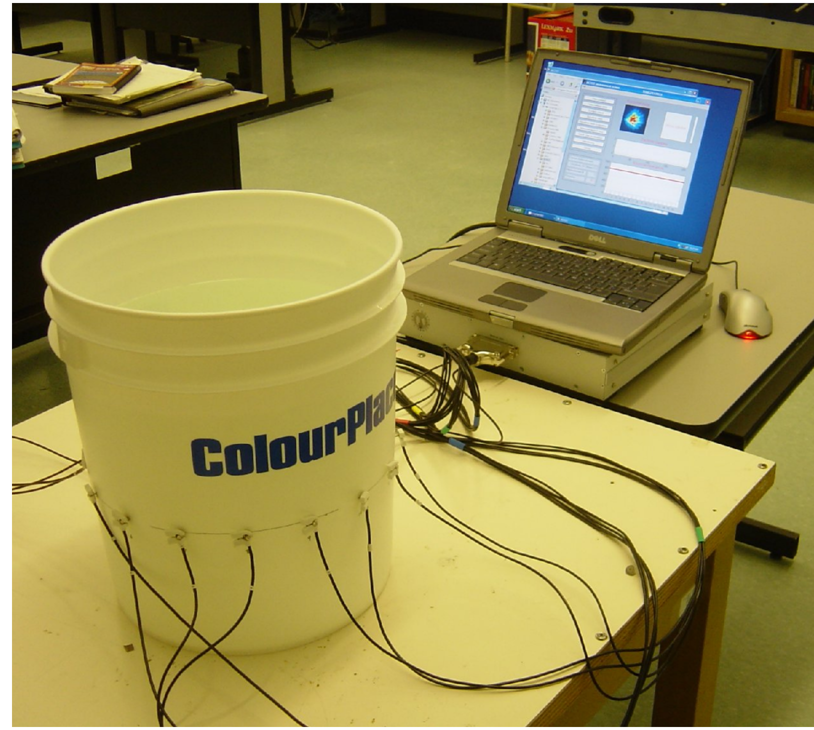
1. Improve the method of hyperparameter selection in order to eliminate case by case tweaking of parameters, provide repeatability of experiments, and reduce the number of reconstructions needed to find the best reconstruction for a given data set.

3. Increase the resolution of 3D models by increasing the number of elements in the FEM. This requires the development of an algorithm to solve the large inversion using readily available computers.

5. Determine how to collect 3D data from the chest given some equipment limitations and a specific set constraints concerning electrode placement.

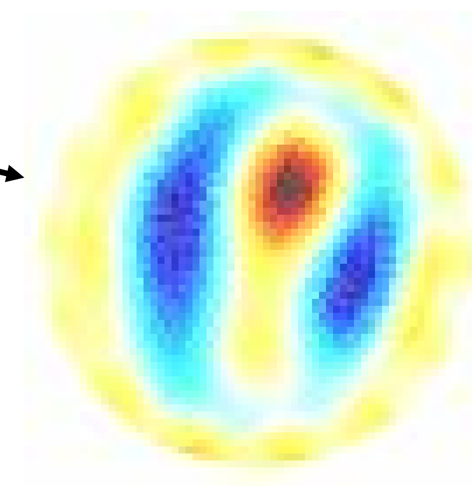
7. Determine the viability of non-blurring regularization for 3D lung imaging.

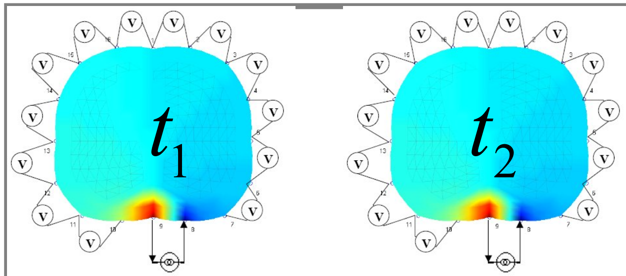




Signal Processing

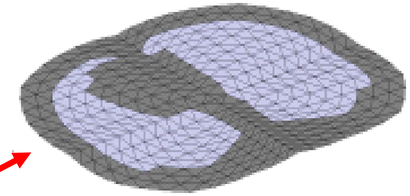
- Dimension
- Electrode Arrangement
- Data collection protocol
- Prior
- Weighing (Noise)
- Norm
- Hyper-parameter
- Algorithm
- Display and Interpretation





$$z_i = v_i^2 - v_i^1$$

$$\hat{x} = \sigma^2 - \sigma^1 = \Delta\sigma$$



Sensitivity Relationship

$$z = Hx + n$$

Associated Optimization

$$\arg\min_x \; \|Hx - z\|_2^2 + \lambda \, \|Rx\|_2^2$$

Regularized Inverse

$$x = (H^T H + \lambda R)^{-1} H^T z$$

Basic idea but many variations…

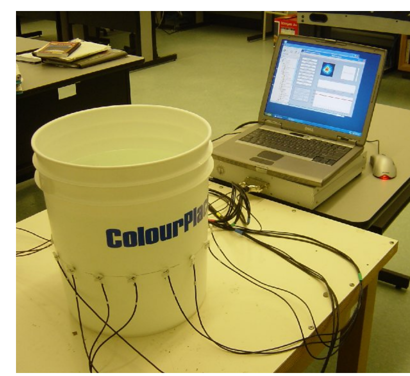
Challenges

- Large body of work available
  - Lots of information but few recommendations
    - Little rigorous evaluation
  - What parts are important?
      - why do people still use back projection?
  - Repeatability
    - "Expert/Heuristic Selection" is pervasive
  - Empirical Verification
    - Lots of work is simulated only


Regularized Reconstruction in Electrical Impedance Tomography Using a Variance Uniformization Constraint

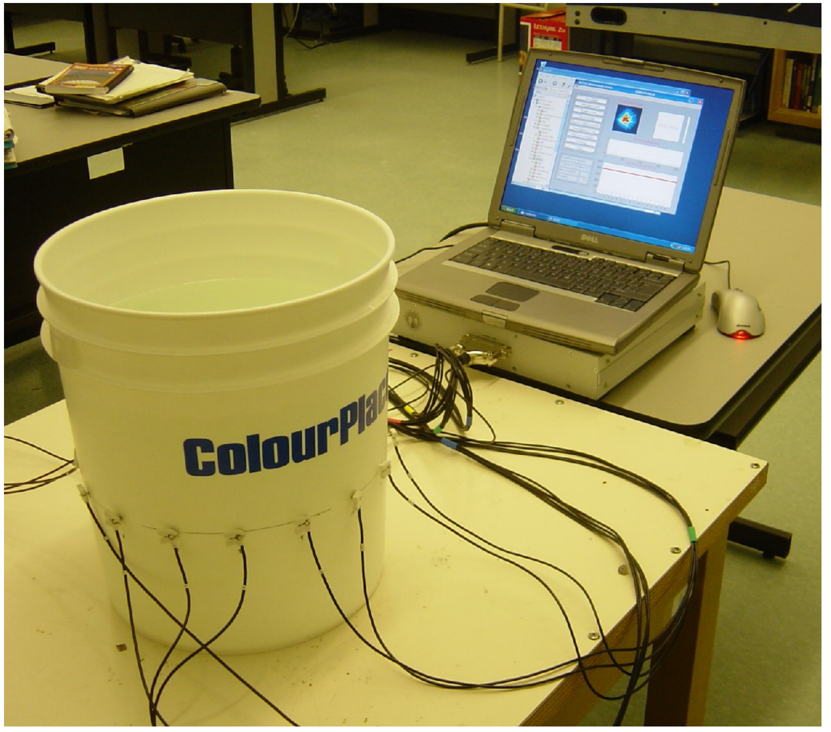
Impedance Imaging of Lung Ventilation: Do We Need to Account for Chest Expansion?

Dimension
Electrode Arrangement
Data collection protocol
Prior
Weighing (Noise)
Norm
Hyper-parameter
Algorithm
Display and Interpretation



Constraints

- Primarily Lung Imaging
- Empirical Confirmation
  - GOE MF II Type Tomography System



Contributions.

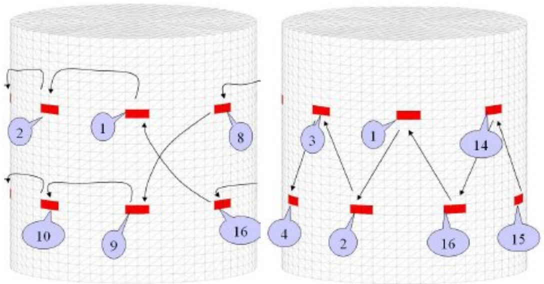
$$x = (H^T H + \lambda R)^{-1} H^T z$$

- O1 - Development of an objective HP selection method (*BestRes*)
  - Is as good or better than existing methods while being repeatable and intuitive
  - First paper only addressed *BestRes* for 2D

- O2 - Development of a solver that enables the cheap solution of large 3D models
  - Convert Elemental Jacobian to Nodal Jacobian and reduce the size of $H^T H$
  - Can solve with direct inversion.
  - Nodal display is fast
  - Also verified *BestRes* for 3D elemental and 3D Nodal

Contributions..

- O3 - Determine the best way to collect 3D data from the chest given some constraints.
  - Proposed several “regular” 3D electrode placement (EP) configurations tailored to a 16 electrode adjacent drive EIT system are proposed and evaluated in terms of several figures of merit, immunity to noise and performance in the presence of electrode placement errors.
  - Decision to use only 2 plane arrangements
  - Verified with lab equipment
  - Provide a recommendation

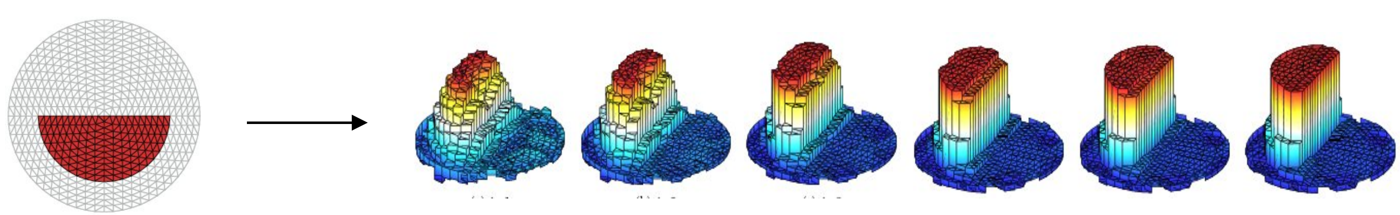


$$\arg\min_{x} \quad \|Hx - z\|_2^2 + \lambda \|Rx\|$$

ℓ^1 norm

Contributions…

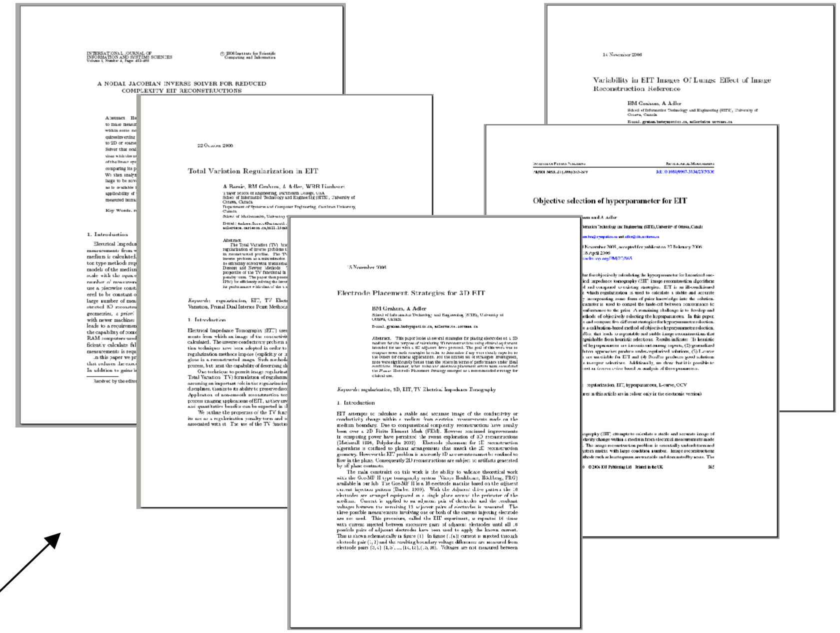
- O4 - Evaluation of TV Prior
  - The development of the PD-IPM algorithm, it's explanation and implementation are the original work of Andrea Borsic and can be found in [22].
  - The analysis of the algorithm's performance, including the improvement in convergence, the simplification of the β decay schedule as well as the design and execution of the algorithm's performance evaluation and subsequent conclusions are the original contribution of this thesis.
  - Works well for 2D but 3D needs more work

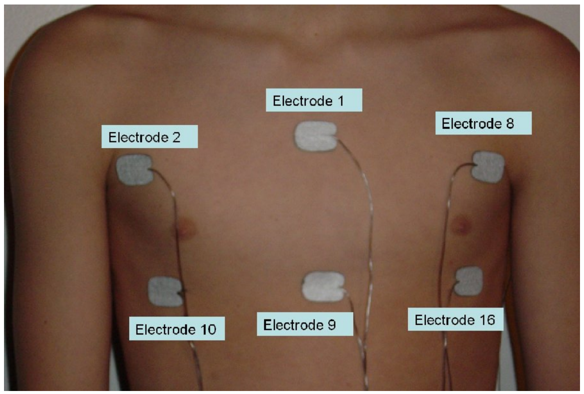


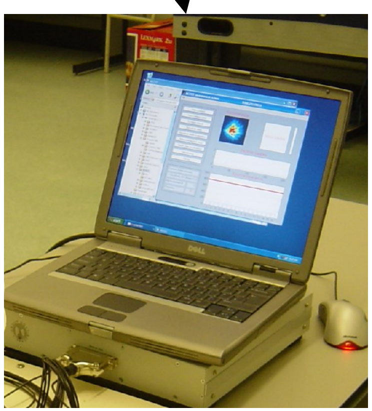
Other Contributions

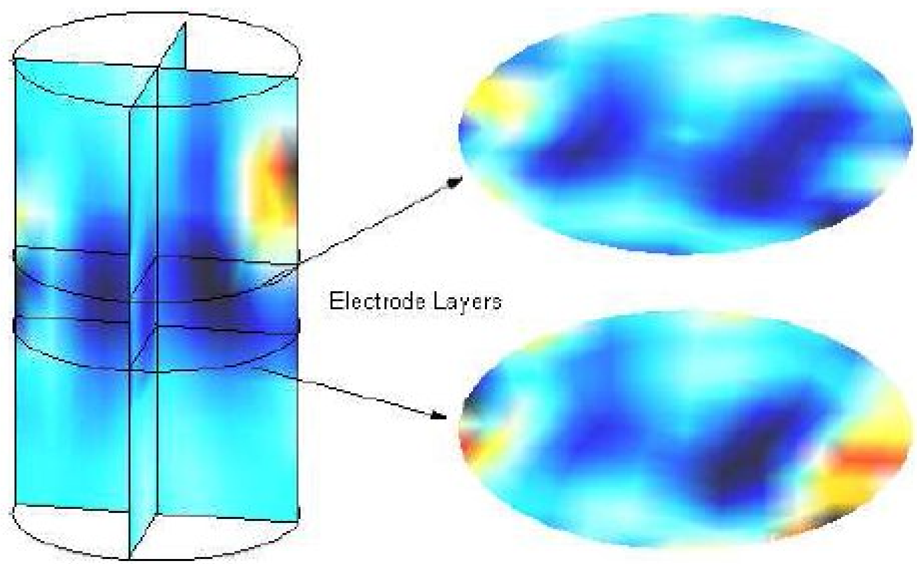
- Routine use of 3D
- Inverse Crime Detection
- Provide a recommendation based on the 4 main contributions
- supported by empirical verification

Contributions









Questions

Contact Information

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Institute of Physics Publishing — Physiological Measurement

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Objective selection of hyperparameter for EIT

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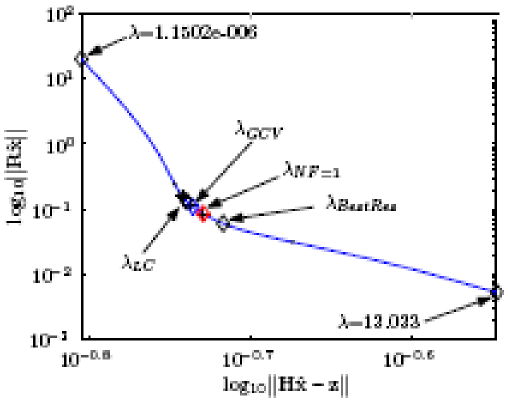
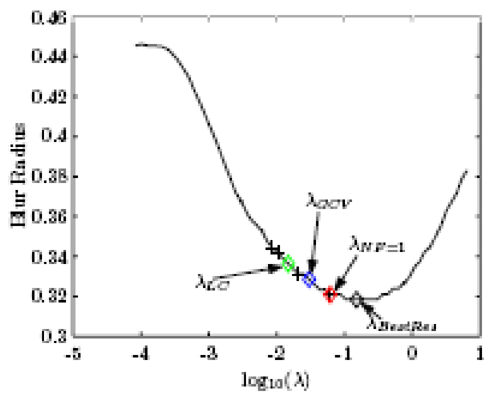
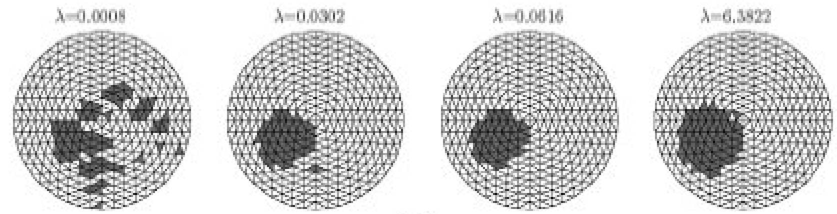


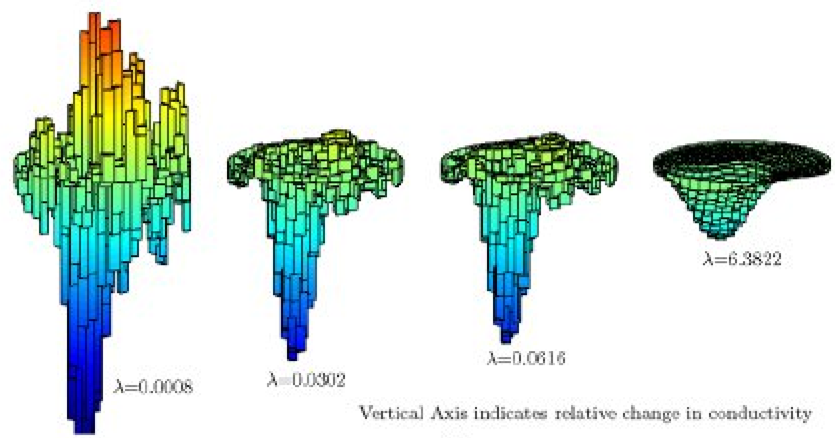
(a)



(b)



(a)

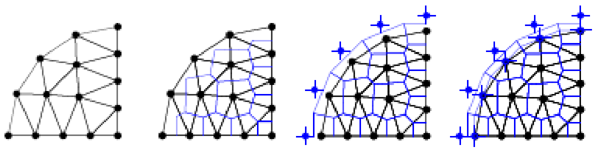


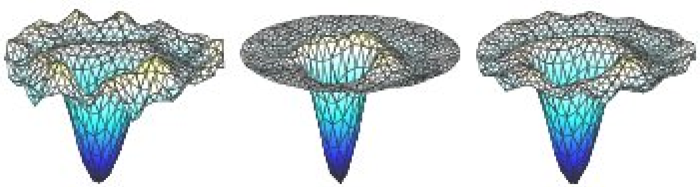
(b)

INTERNATIONAL JOURNAL OF
INFORMATION AND SYSTEMS SCIENCES
Volume 2, Number 4, Pages 453–468

A NODAL JACOBIAN INVERSE SOLVER FOR REDUCED COMPLEXITY EIT RECONSTRUCTIONS

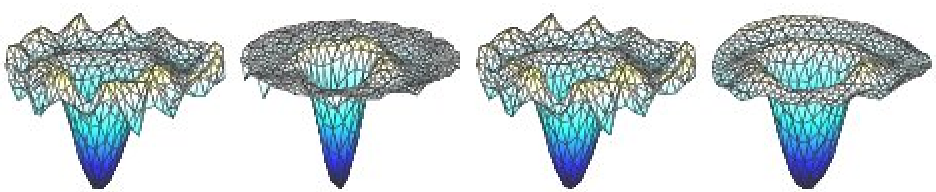
B. M. GRAHAM AND A. ADLER





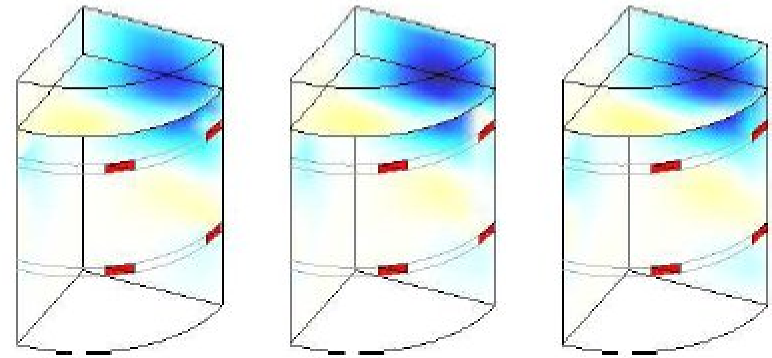
(a) $\mathbf{R}_{Tik}$ *BR=.309, SNR=.450* (b) $\mathbf{R}_{diag}$ *BR=.233, SNR=.337* (c) $\mathbf{R}_{HPF}$ *BR=.279, SNR=.444*

FIGURE 3. *Comparison of 2D Elemental reconstructions using*

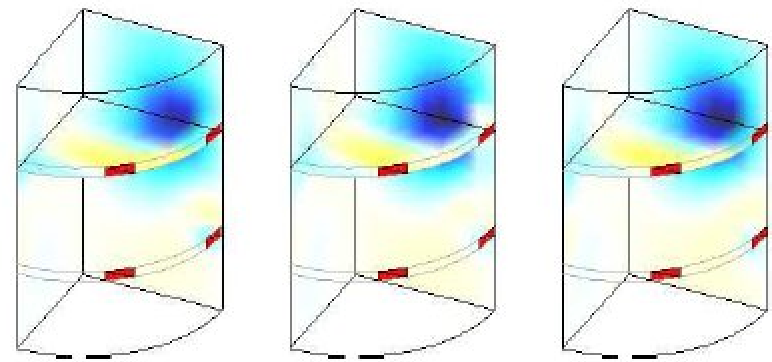


(a) $\mathbf{R}_{Tik}$ *BR=.328, SNR=.462* (b) $\mathbf{R}_{diag}$ *BR=.236, SNR=.332* (c) $\mathbf{R}_{HPF}$ *BR=.324, SNR=.440* (d) $\mathbf{R}_{Lap}$ *BR=.296, SNR=.485*

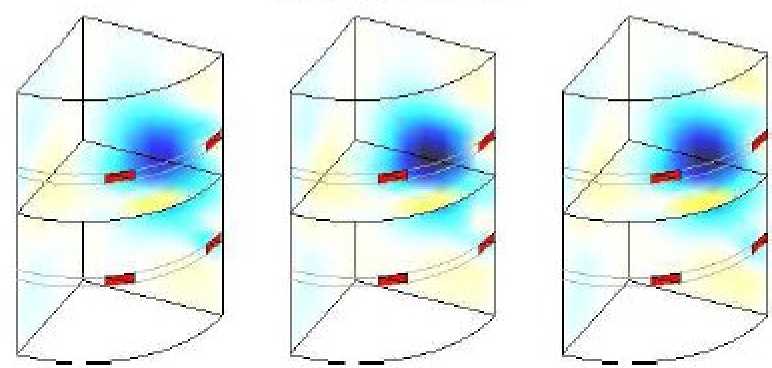
FIGURE 4. *Comparison of 2D Nodal reconstructions using tank*



(a) *Target Height 23cm*



(b) *Target Height 19cm*



(c) *Target Height 15cm*

Total Variation Regularization in EIT

A Borsic, BM Graham, A Adler, WRB Lionheart
Thayer School of Engineering, Dartmouth College, USA
School of Information Technology and Engineering (SITE), University of Ottawa, Canada
Department of Systems and Computer Engineering, Cartleton University, Canada
School of Mathematics, University of Manchester, University of Manchester, UK

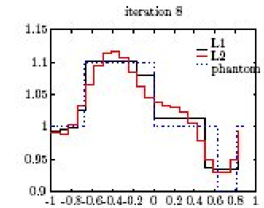
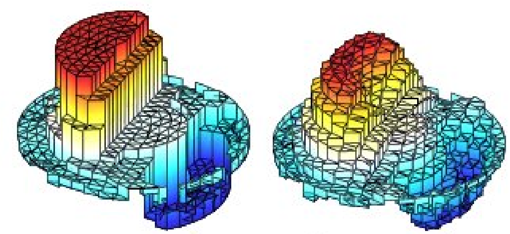
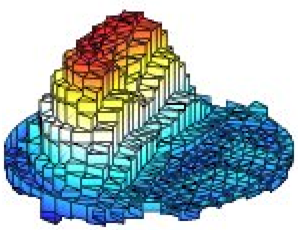


Figure 10: *Phantom B profiles.*

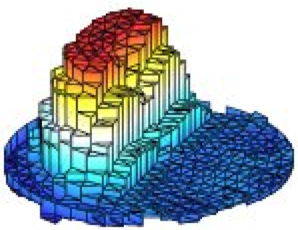


(a) *TV solution at* 8^{th} *iteration* (b) L^2 *solution at* 8^{th} *iteration*

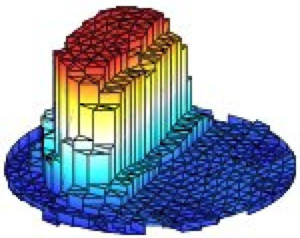
Figure 11: *Reconstructions of Phantom B with 2.5% AWGN.*



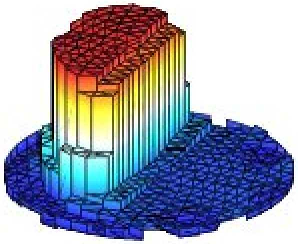
(a) i=1



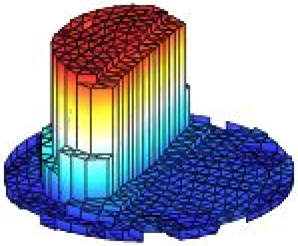
(b) i=2



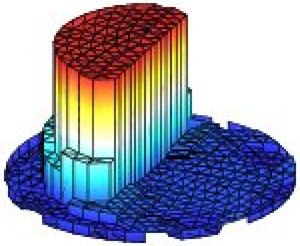
(c) i=3



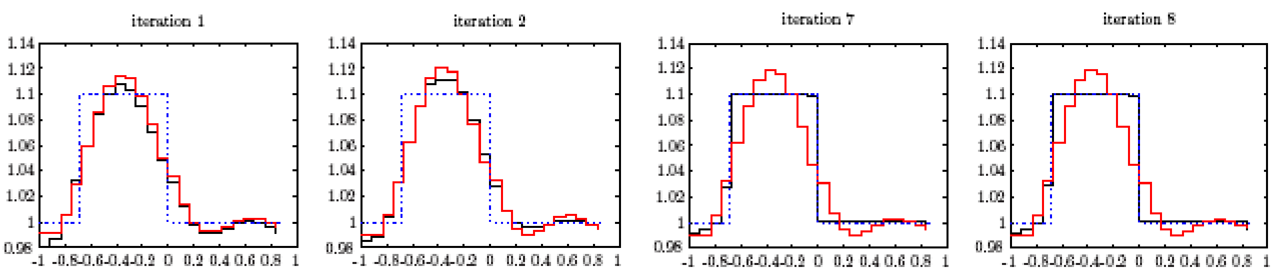
(d) i=4

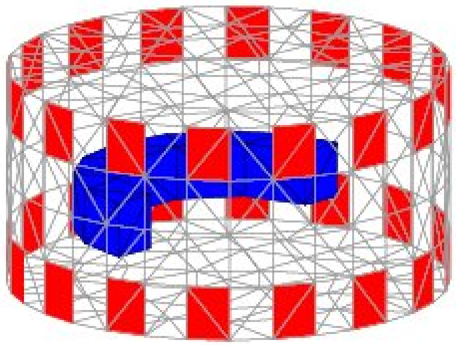


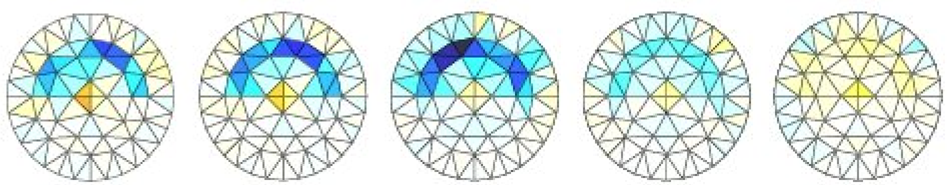
(e) i=5



(f) i=7

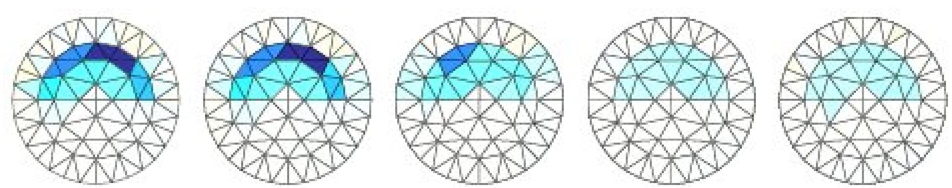






(a) *z=0 (bottom)* (b) *z=1* (c) *z=2* (d) *z=3* (e) *z=4 (top)*

Figure 3: *Slices of 3D reconstructions for Iteration 1. No noise added.*



(a) *z=0 (bottom)* (b) *z=1* (c) *z=2* (d) *z=3* (e) *z=4 (top)*

Figure 4: *Slices of 3D reconstructions for Iteration 8. No noise added.*

Electrode Placement Strategies for 3D EIT

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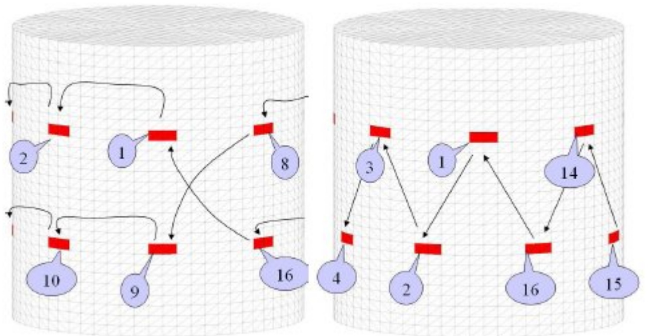
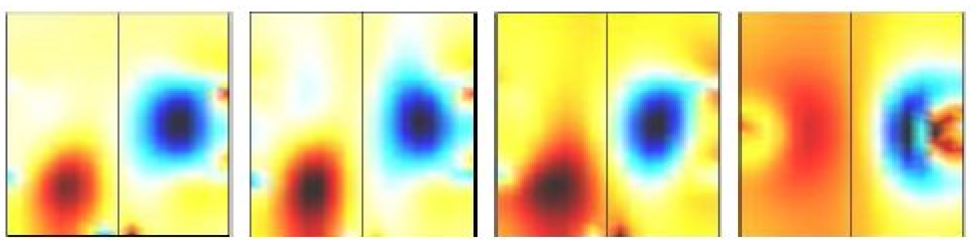


(a) *Planar EP strategy* (b) *Zigzag Offset EP strategy*

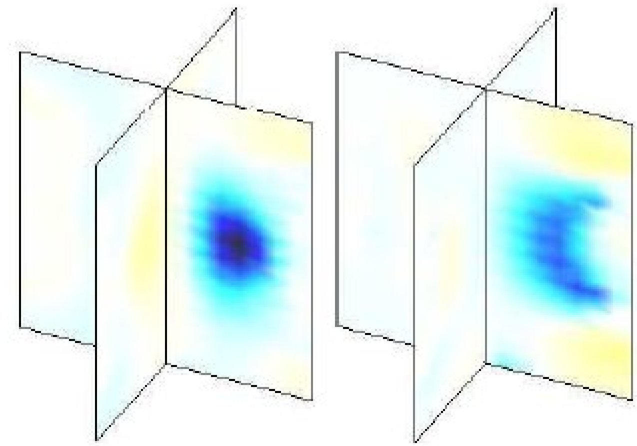
Figure 3. *Diagrams to assist in interpretation of Table 1 to understand electrode sequencing*



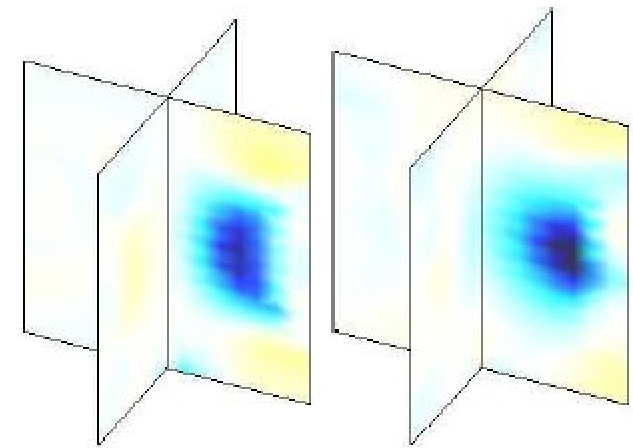
(a) *Zigzag-Offset, Square* (b) *Planar, Zigzag, Planar-Offset* (c) *Planar-Oposite* (d) *2D Adjacent*

Figure of Merit Reference	Res Fig 7(a)	VPE Fig 7(b)	Qual Sect 3.2	Noise Sect 3.3	Offset Err Sect 3.4	Sep Err Sect 3.5	VPE (Radial) Fig 8(b)
Planar			+	+	+	+	
Planar-Offset			+	+	+	+	+
Planar-Opposite	-		+		- -	- -	+
Zigzag		- -	-	- -	+	-	
Zigzag-Offset		- -	- -	- -	-	-	
ZigZag-Opposite	-		-			- -	
Square		- -	+	-		- -	

Table 2. *Comparison Summary of EP Strategies - in the ROI.*



(a) *Planar-Offset, Planar, Planar-Opposite, and Square are similar* (b) *Zigzag-Offset*



(c) *Zigzag* (d) *Zigzag-Opposite*

Revisions to EP Config paper

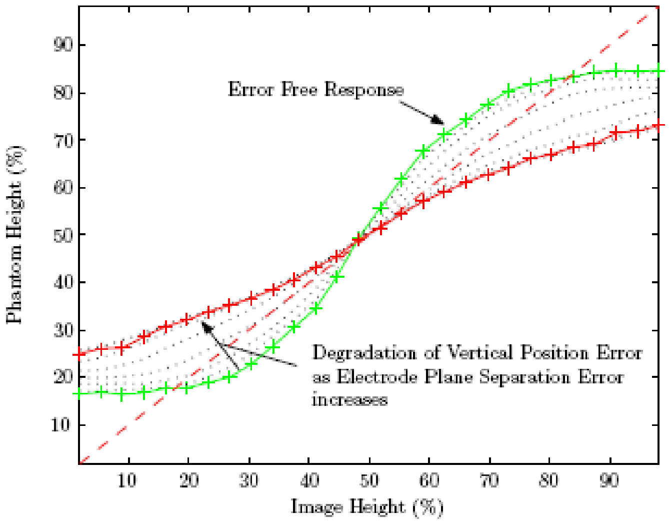
Table 2. Comparison of EP configurations in terms of SNR and Jacobian condition number.

EP configuration	SNR (normalized)	SNR (db)	Cond($H^T H$) ($\times 10^{23}$)
Planar	1.0000	−3.9568	0.7826
Planar-offset	0.9709	−4.0849	3.8234
Planar-opposite	0.3852	−8.0997	0.4019
Zigzag	0.2965	−9.2365	2.0639
Zigzag-offset	0.2702	−9.6406	2.6358
Zigzag-opposite	0.2924	−9.2971	0.6721
Square	0.3907	−8.0380	5.8860

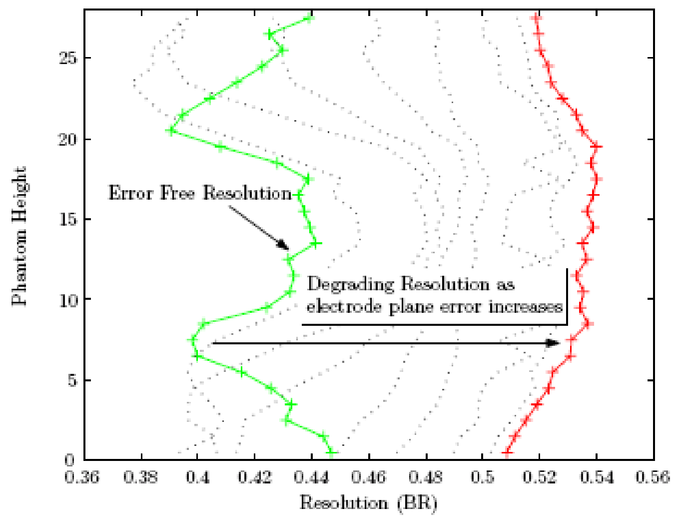
Table 3. Comparison summary of EP configurations—in the ROI.

Figure of merit Reference	Res Figure 6(a)	VPE Figure 6(b)	Qual Section 3	Noise Section 3	Offset err Section 3	Sep err Section 3	VPE (radial) Figure 7(b)
Planar			+	+	+	+	
Planar-offset			+	+	+	+	+
Planar-opposite	-		+		- -	- -	+
Zigzag		- -	-	- -	+	-	
Zigzag-offset		- -	- -	- -	-	-	
ZigZag-opposite	-		-			- -	
Square		- -	+	-		- -	

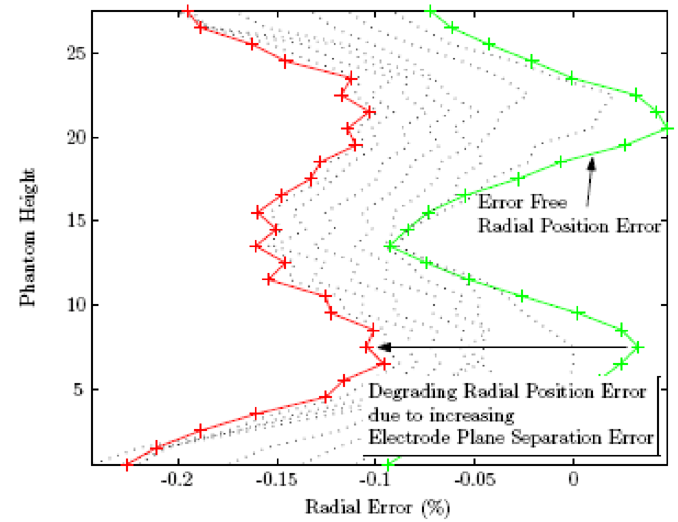
Revisions to EP Config paper



(a) *Planar, Vertical Position Error*



(b) *Zigzag, Resolutic*

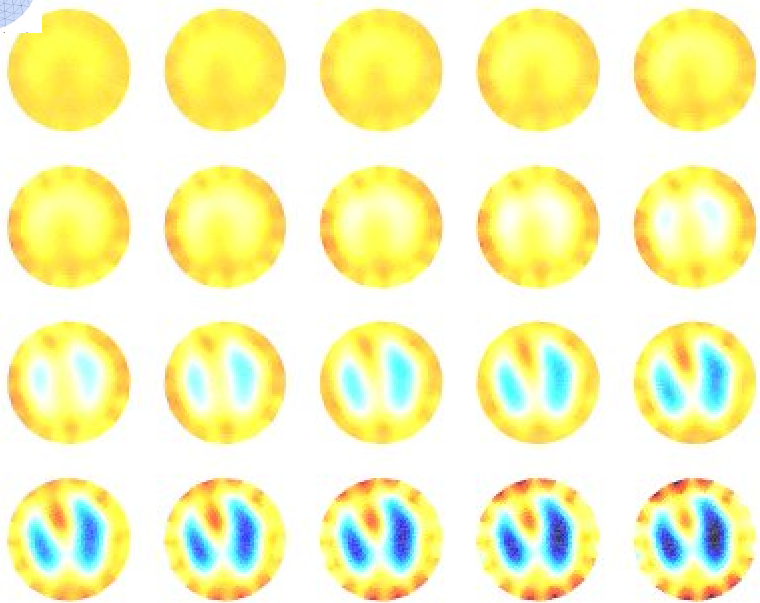


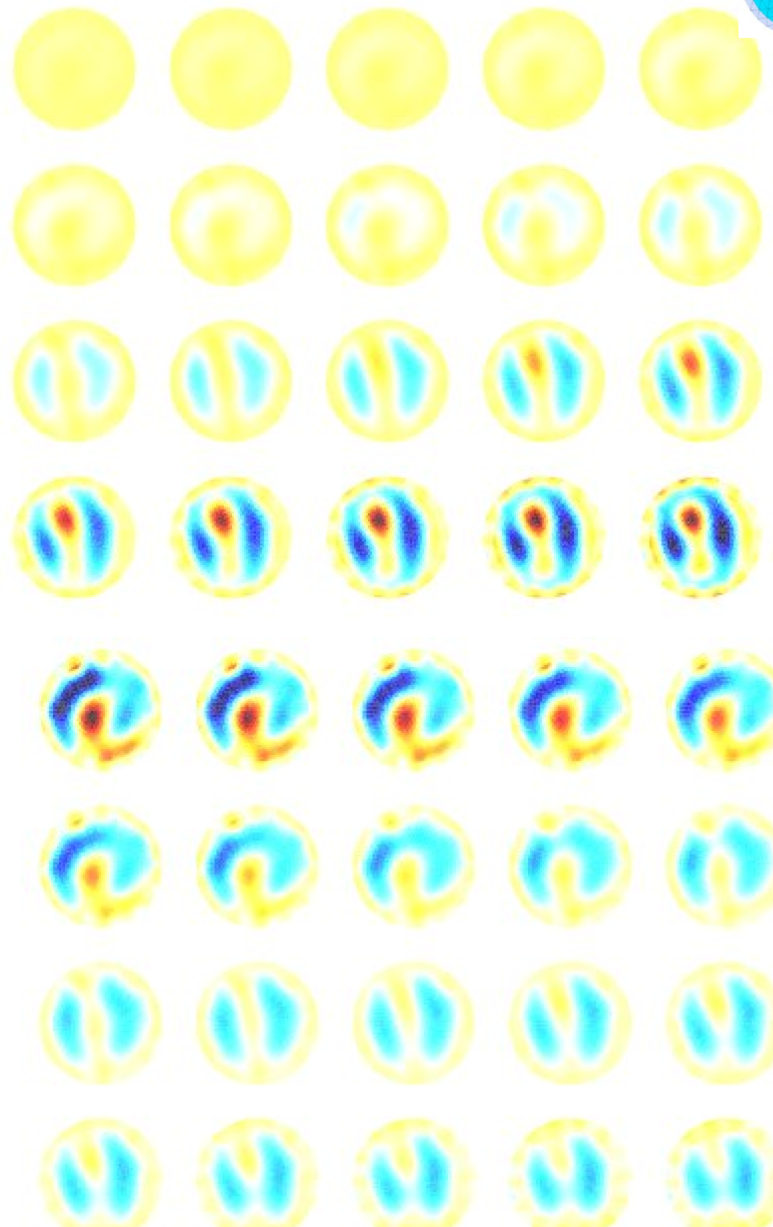
(c) *Planar-Opposite, Radial Position Error*

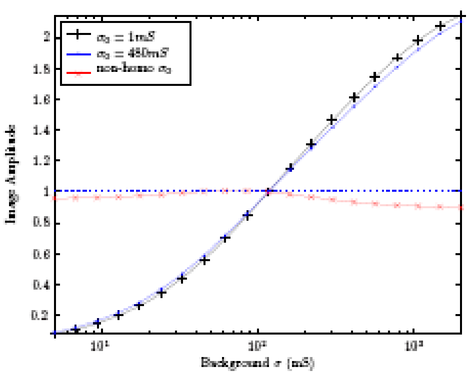
Figure 10. Degradation of selected performance measures for selected configurations due to electrode plane separation error. The error free curves represent no electrode plane separation error. The dotted curves represent increasing electrode plane separation to a maximum of 10 cm error represented by the red solid line.

Variability in EIT Images Of Lungs: Effect of Image Reconstruction Reference

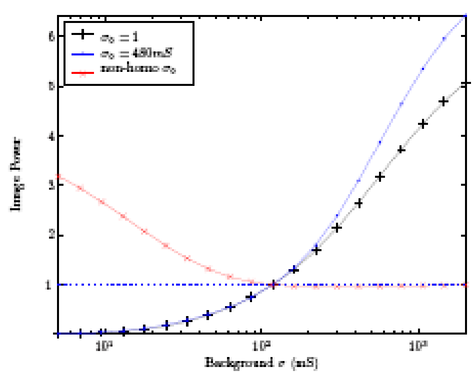
BM Graham, A Adler
School of Information Technology and Engineering (SITE), University of Ottawa, Canada





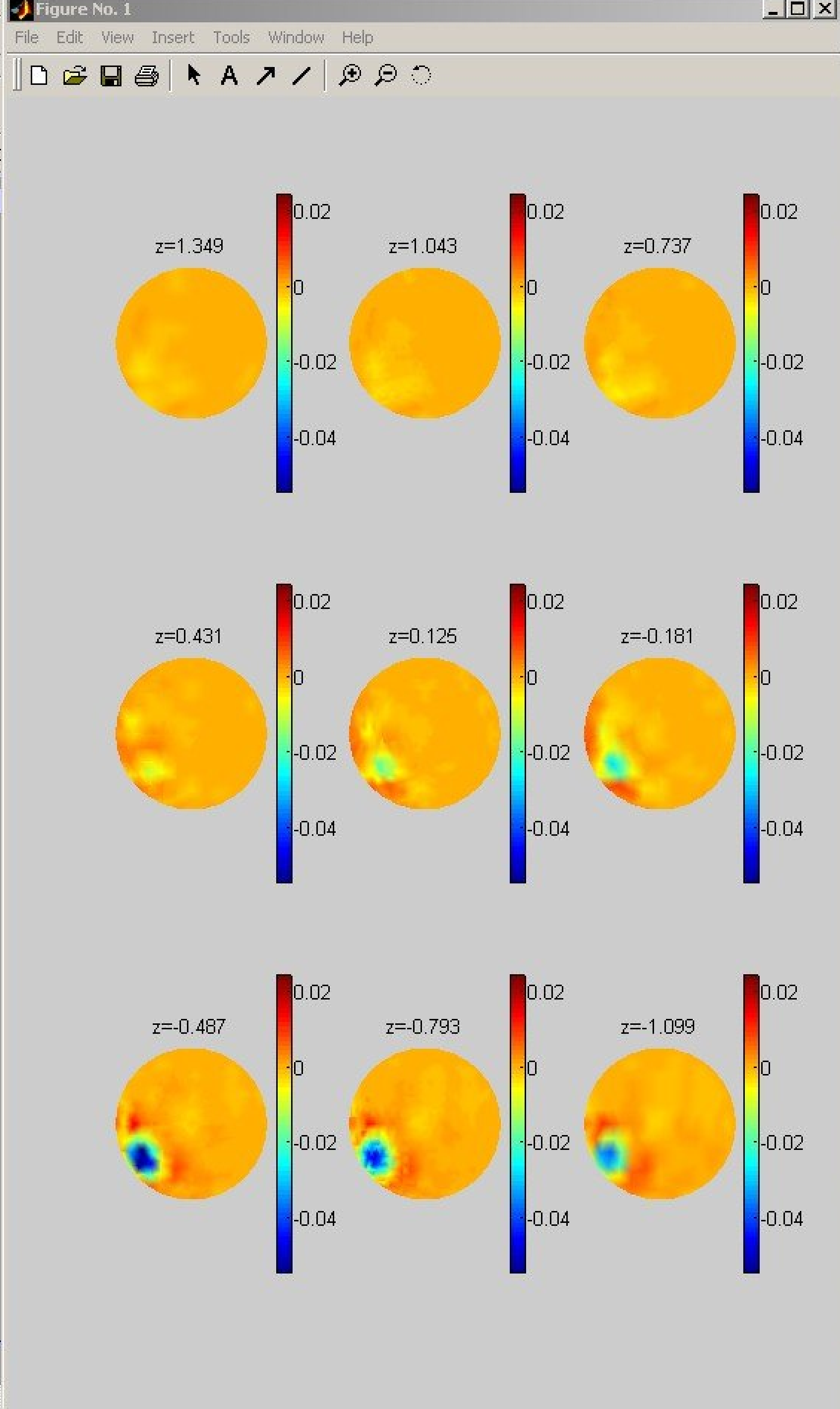


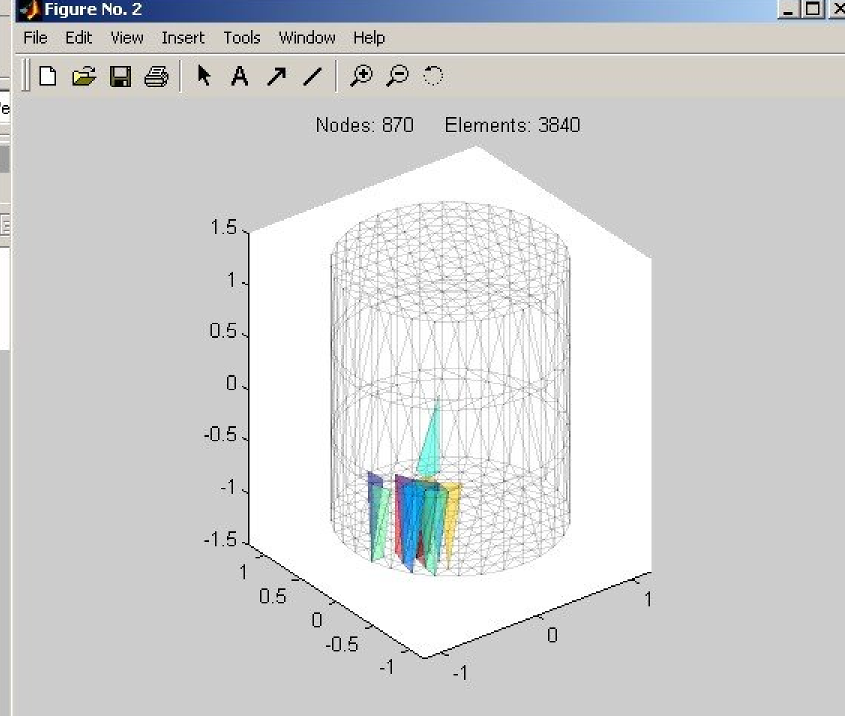
(e) *Image Amplitude inner area=73%*



(f) *Image Power inner area=73%*

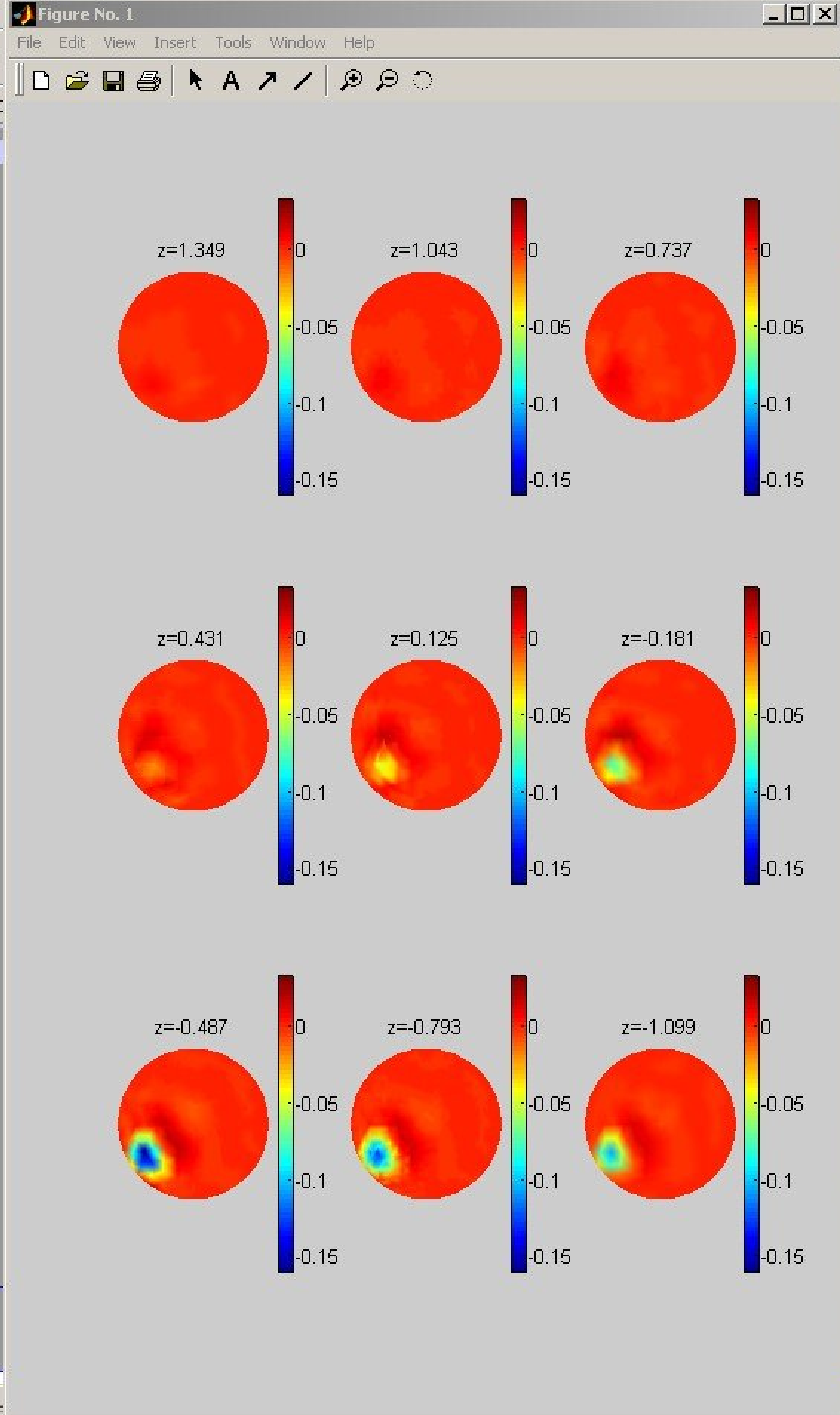
Extra Extra

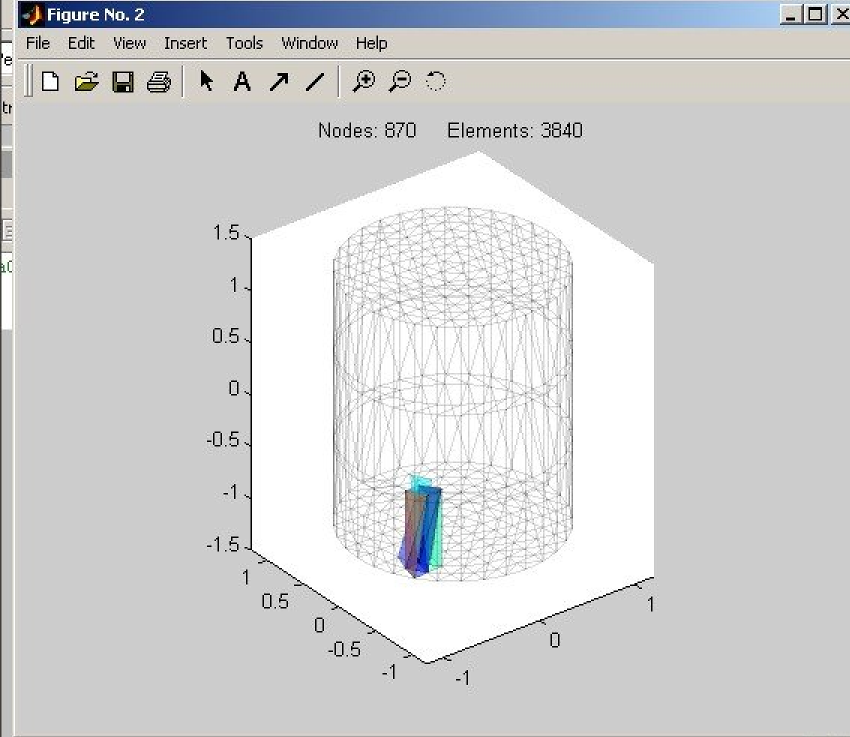




Element based Jacobian

This is the standard eidors3D method. Have to invert a 3840*3840 matrix. Slow and requires pcg run in a matlab command line





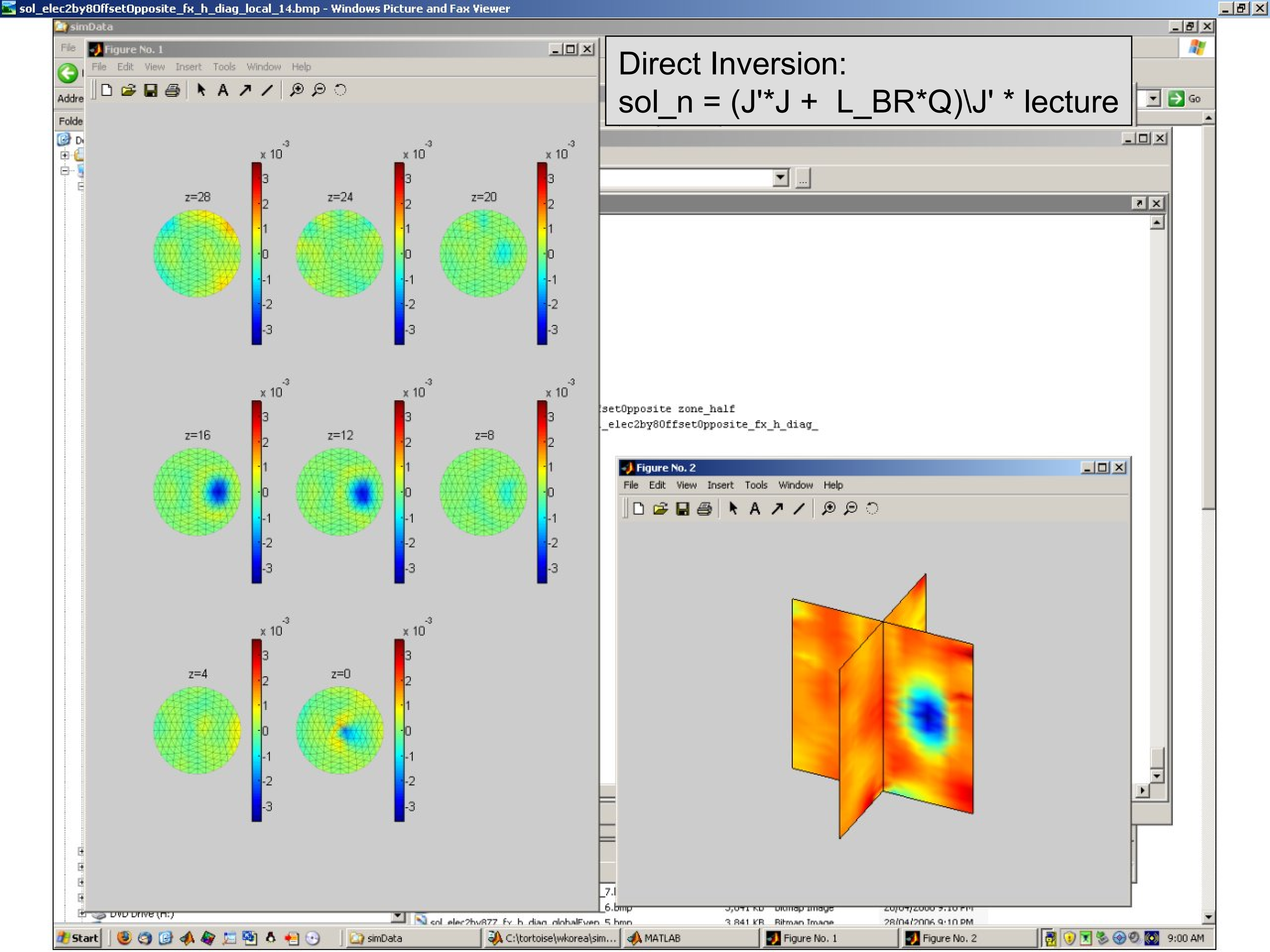
Nodal Jacobian Basis (pre-filtered Jacobian)

Only have to invert a 870*870 matrix.

Ran in the full matlab environment using backslash operator

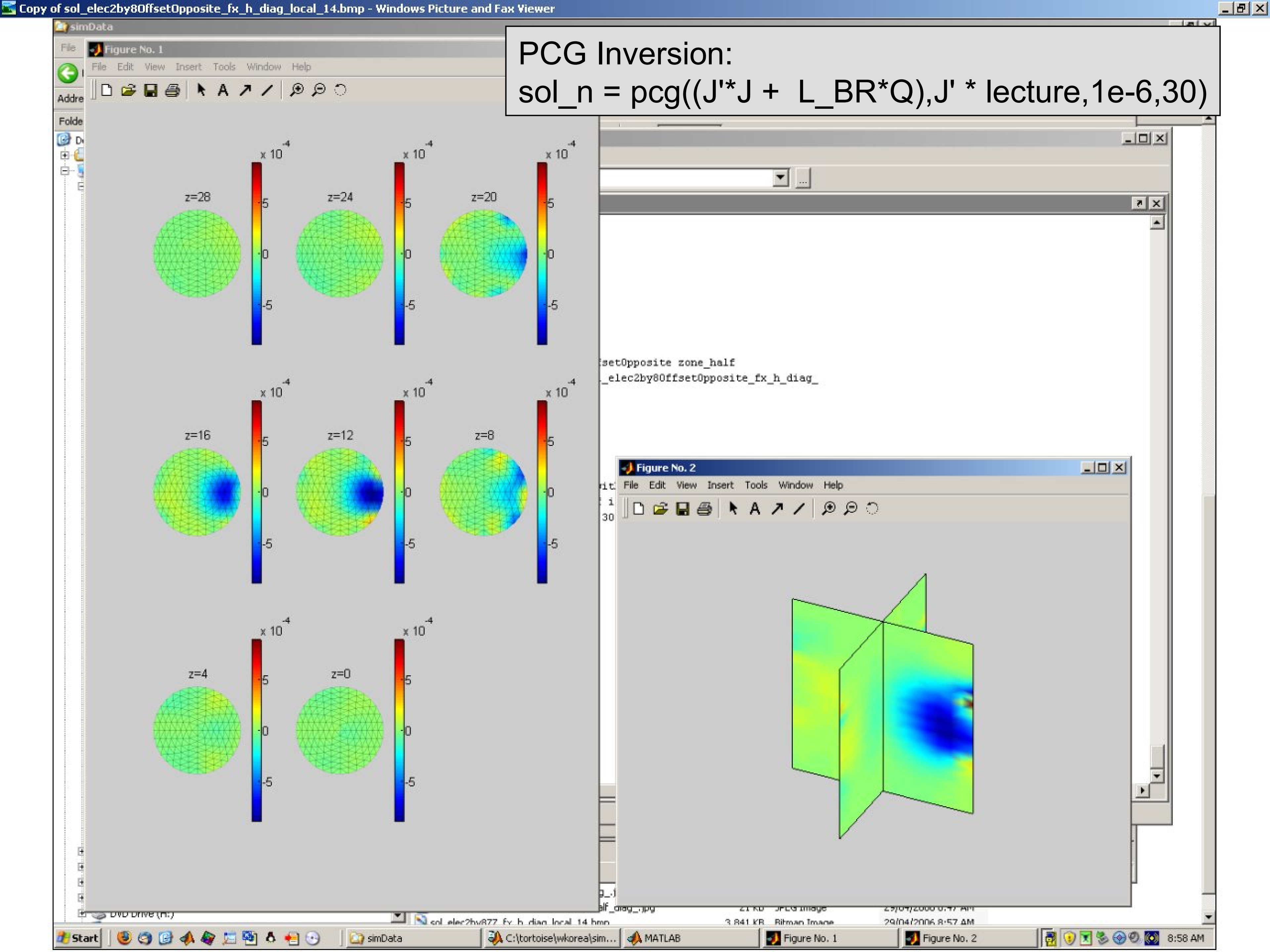
Direct Inversion:

sol_n = (J'*J + L_BR*Q)\J' * lecture

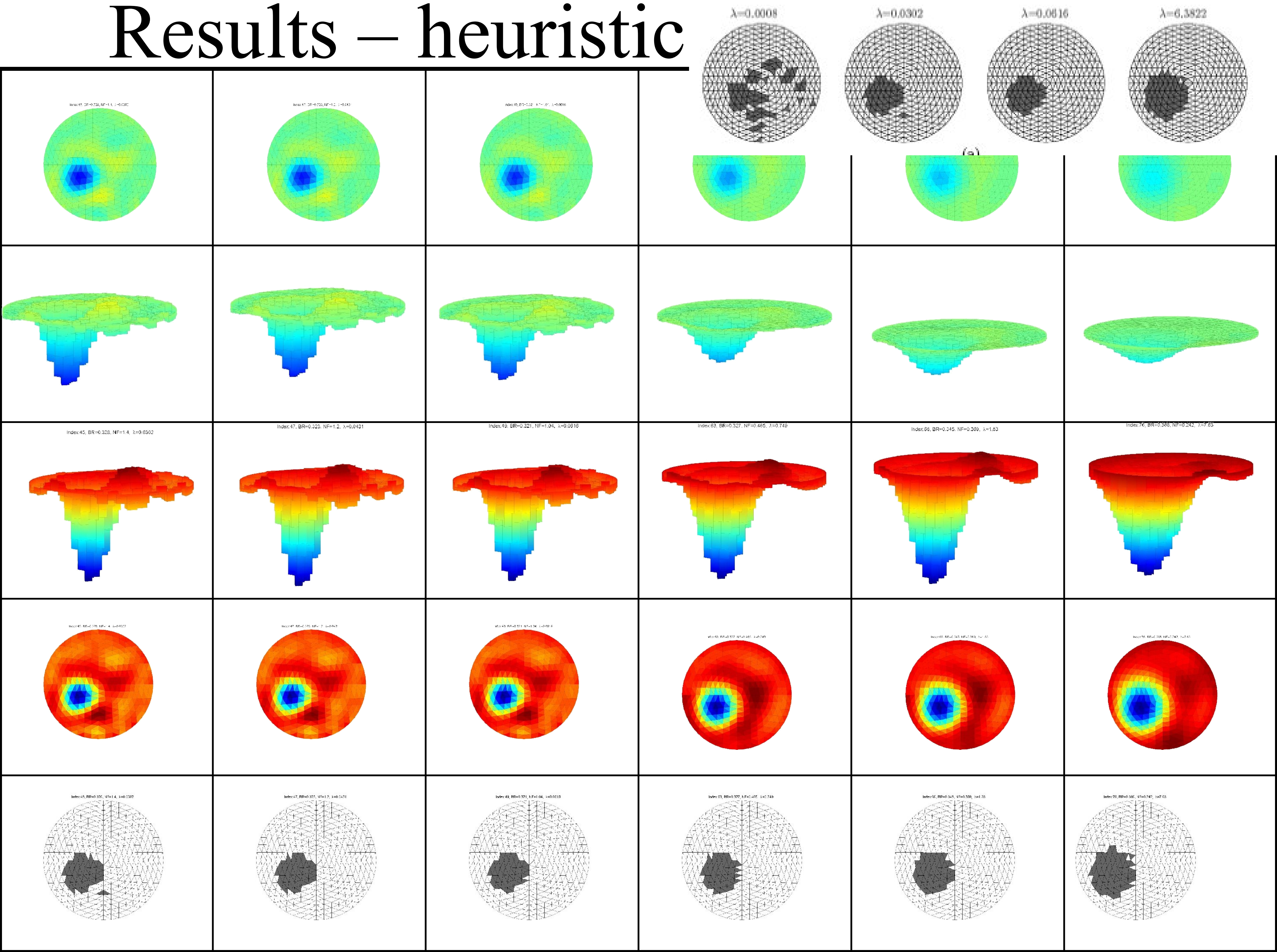


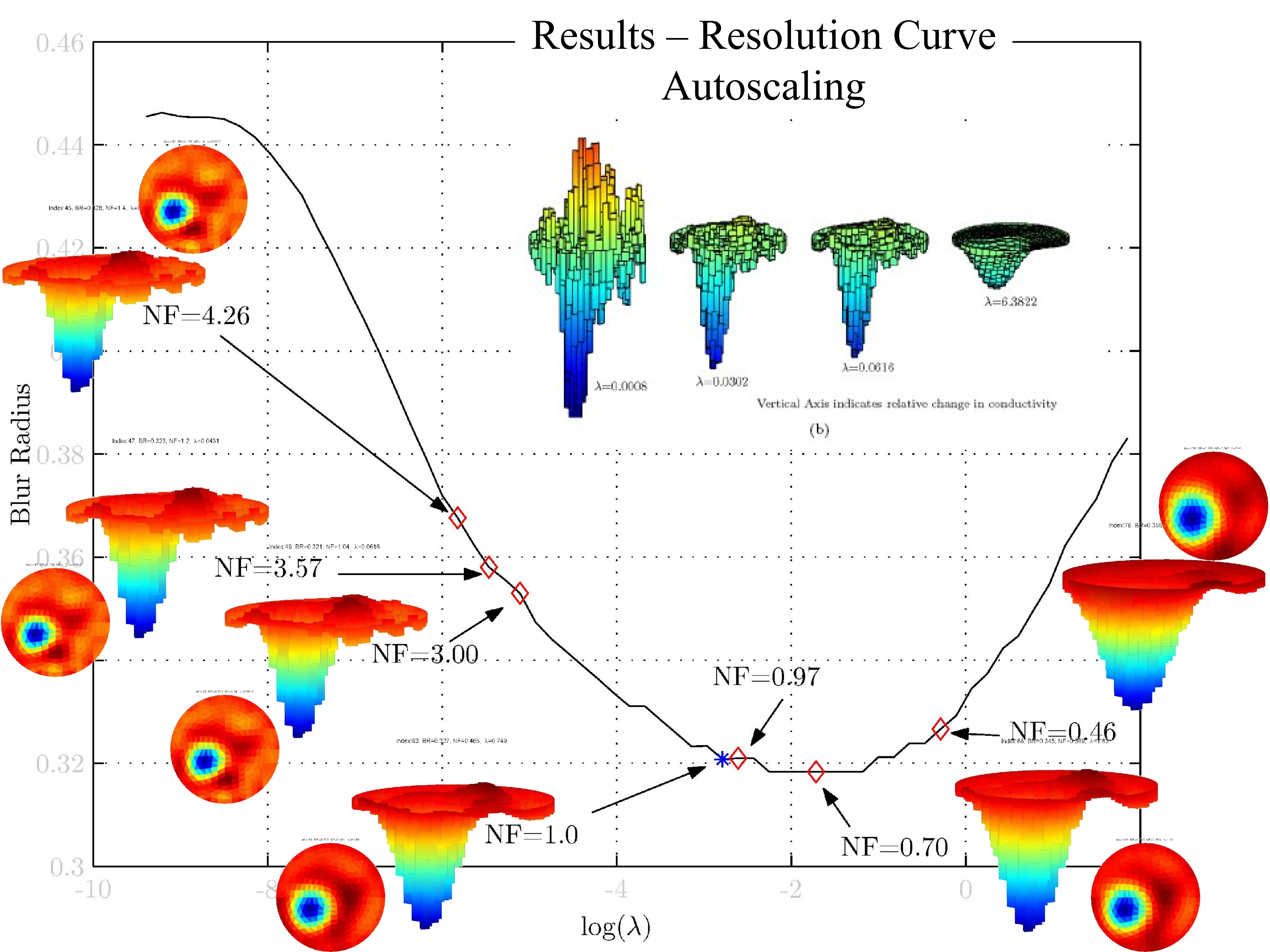
PCG Inversion:

sol_n = pcg((J'*J + L_BR*Q),J' * lecture,1e-6,30)



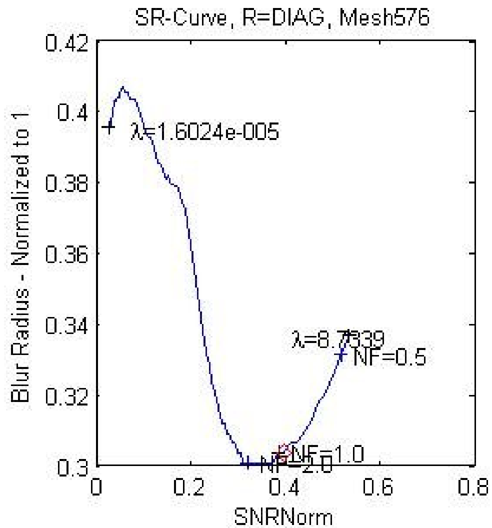
Results – heuristic

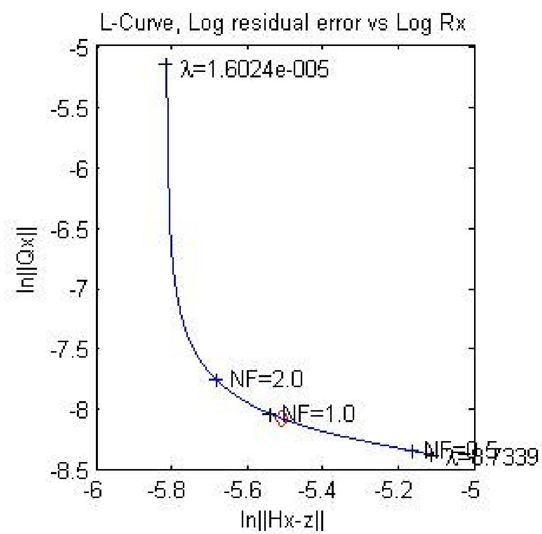


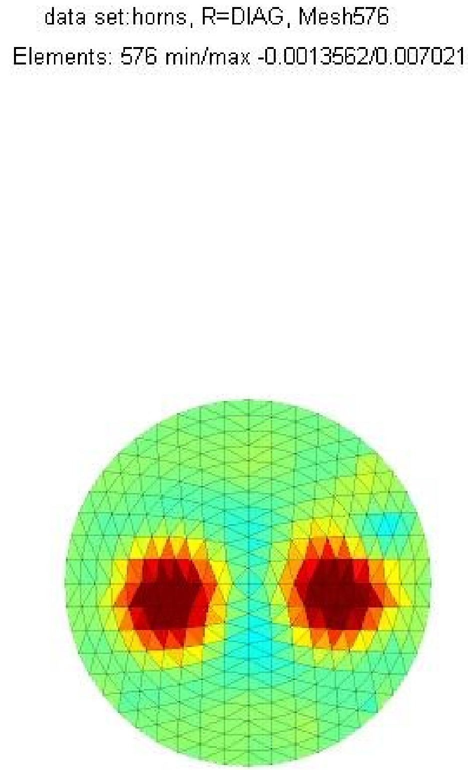


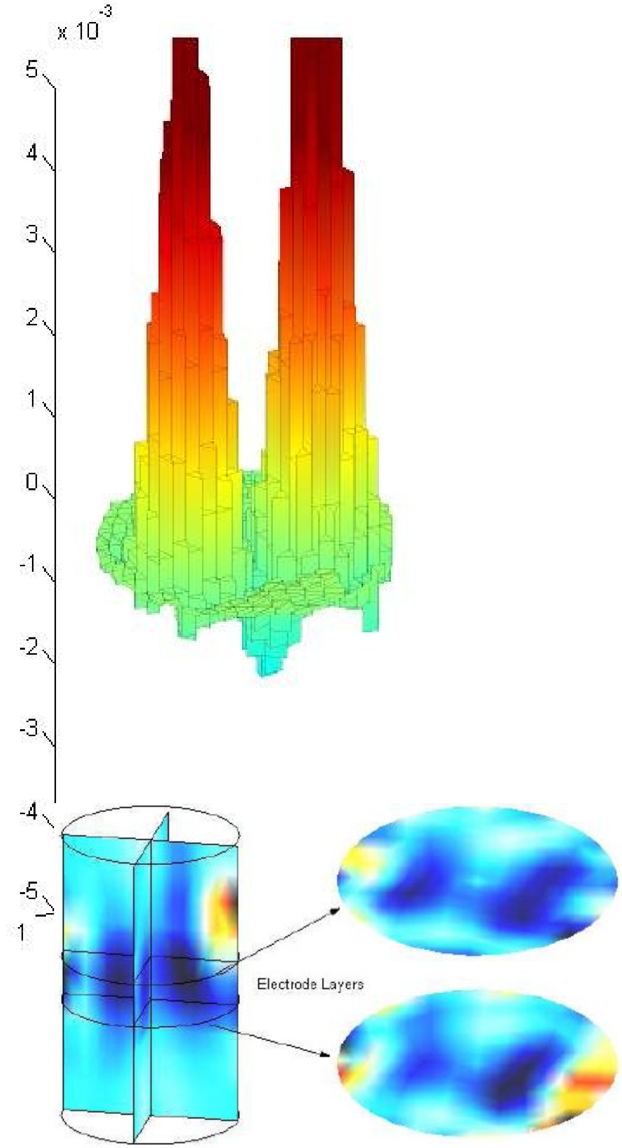
Results – Resolution Curve
Autoscaling
Blur Radius
log(λ)
0.46
0.44
0.42
0.38
0.36
0.32
0.3
-10
-4
-2
0
NF=4.26
NF=3.57
NF=3.00
NF=1.0
NF=0.97
NF=0.70
NF=0.46
Index:47, BR=0.323, NF=1.2, λ=0.0431
Index:49, BR=0.321, NF=1.04, λ=0.0616
Index:63, BR=0.327, NF=0.465, λ=0.749
λ=0.0008
λ=0.0302
λ=0.0616
λ=6.3822
Vertical Axis indicates relative change in conductivity
(b)

Not Just for an Impulse









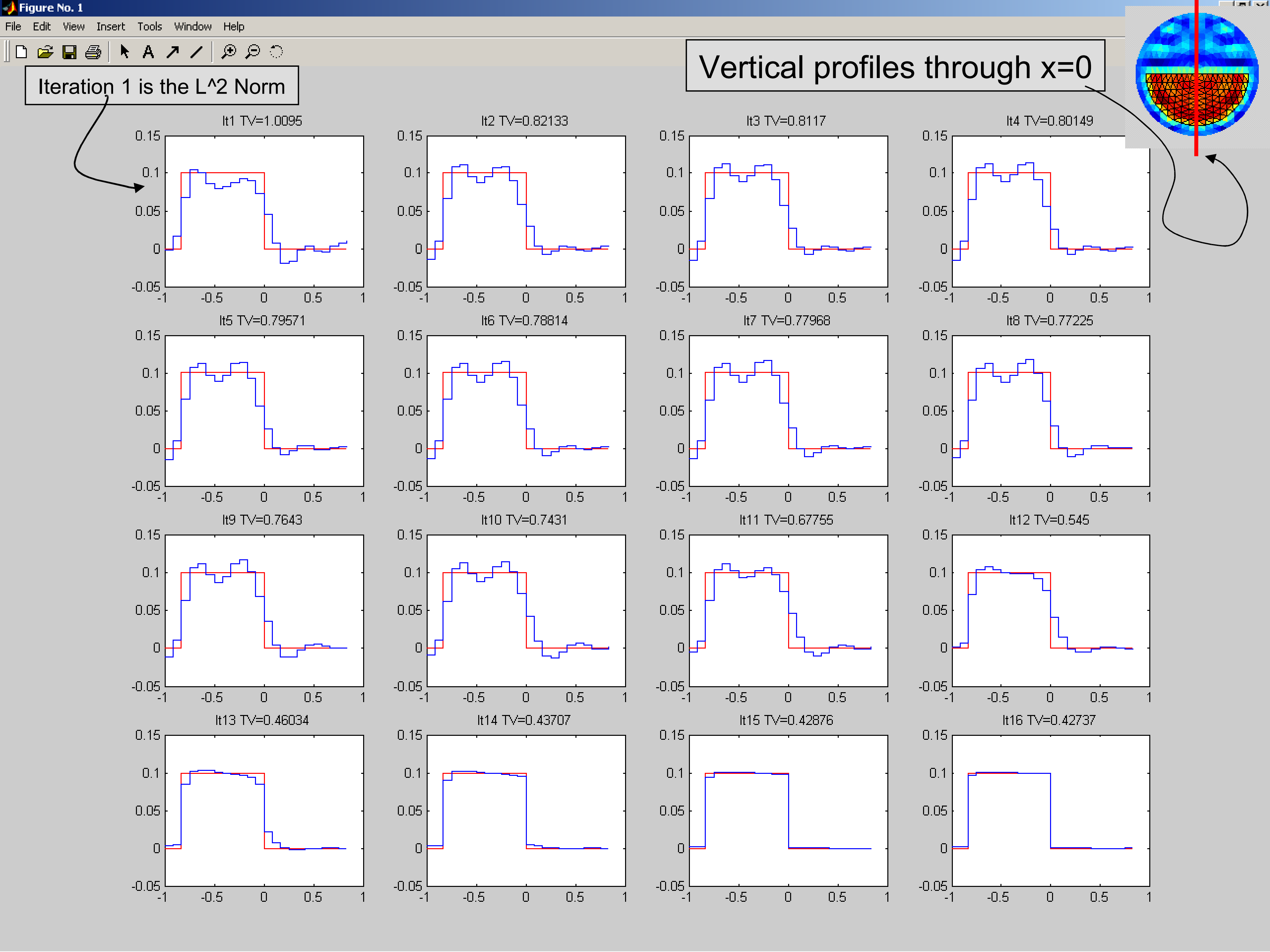


Figure No. 1
File Edit View Insert Tools Window Help
Iteration 1 is the L^2 Norm
Vertical profiles through x=0
It1 TV=1.0095
It2 TV=0.82133
It3 TV=0.8117
It4 TV=0.80149
It5 TV=0.79571
It6 TV=0.78814
It7 TV=0.77968
It8 TV=0.77225
It9 TV=0.7643
It10 TV=0.7431
It11 TV=0.67755
It12 TV=0.545
It13 TV=0.46034
It14 TV=0.43707
It15 TV=0.42876
It16 TV=0.42737

Recommendation

- The regularization hyperparameter, λ, is selected using the BestRes method
- The norm of the prior is the 2-norm. Use of the 1-norm via the TV PD-IPM algorithm requires further work to extend it to the nodal basis.
- The prior matrix, R, is the prior from diagonal matrix of the NOSER algorithm, $R=\mathrm{diag}(H^T H)$, due to its performance in 3D. The Gaussian prior performs slightly better in 2D but does not have a suitable analog for 3D.
- The data weighting matrix W is left as the identity matrix, and is therefore removed from the algorithm. In the case that erroneous electrode data has been revealed through a method such as that of Asfaw and Adler [6] the problem measurements can be accounted for by zeroing each column of the matrix B

Recommendation

- The initial conductivity, σ_0, is left at a homogenous value of 1. Alternatively one can obtain a crude estimate of a static homogenous equivalent conductivity through the method discussed in chapter 8.

- The background conductivity used to calculate the Jacobian, σ^*, is left at a homogenous value of 1.

- Using the Nodal inverse solver requires that the FEM parameters include tetrahedral meshes with linear conductivity on each element.

- For pulmonary imaging we recommend the Planar Electrode Placement Strategy discussed in chapter 6. This is an adjacent current injection and measurement protocol.