Adaptive Electrical Capacitance Volume Tomography for Real Time Measurement of Solid Circulation Rate at High Temperatures

Project Investigator: Tech4Imaging LLC, 1910 Crown Park ct., Columbus OH 43235

PI: Qussai Marashdeh, marashdeh@tech4imaging.com

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Subcontractors: The Ohio State University (Professor Fernando Teixeira & Zeeshan Zeeshan)

TECH4IMAGING

Project Goals & Objectives

- The main technical objective of Phase II is to develop a functional AECVT demonstration system for real-time imaging and measurement of multiphase flows at high temperature.

Year 1 Milestones:

1. Finalize AECVT sensor design- end of 2nd quarter.
2. Development of software for SART reconstruction technique- end of 4th quarter.
3. Fabrication of adaptive data acquisition system- end of 5th quarter.

Year 2 Milestones:

1. Fabrication of AECVT sensor- end of 5th quarter.
2. Finalize image reconstruction and feature extraction- end of 7th quarter.
3. Demonstrate integrated system- end of 7th quarter.
4. Finalize GUI- end of project.
5. Finalize demonstration unit and develop virtual experience- end of project.

Presentation Outline

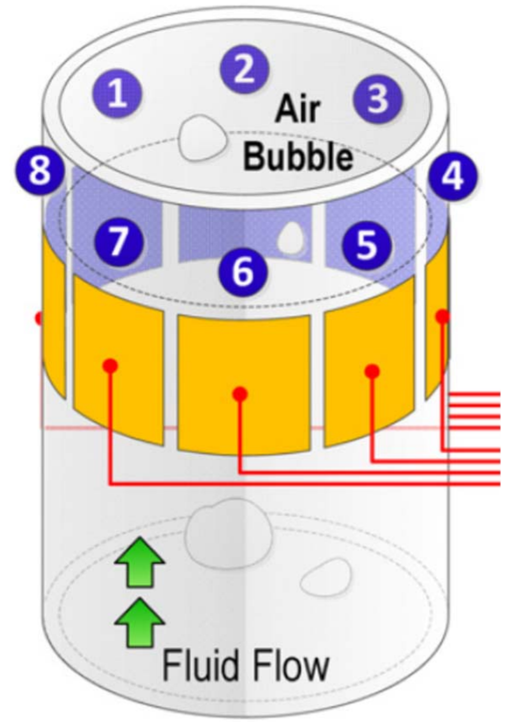
- Introduction to ECVT & AECVT
- Electronic Design
- Simulations
- Experimental validation
- Schedule

Electrical Capacitive Volume Tomography

- ❖Electrical Capacitance Volume Tomography (ECVT) is a low cost noninvasive imaging technique to find the volumetric dielectric distribution from inter-electrode capacitance measurements.

- ❖Electrodes respond differently to the change in permittivity distribution inside the sensing domain. These mutual capacitances are used to reconstruct the dielectric distribution in the sensing domain.

- ❖ECVT is used in nondestructive testing, imaging of multiphase flows and for imaging of combustion flames and fluidized beds.
- ❖Adaptive ECVT (AECVT) is a high resolution sensor formation that can form many electronic synthetic plates.



ECVT Sensor Model

The inter electrode capacitance is computed by

$$C = -\frac{1}{V}\iint_{\Gamma} \varepsilon(x,y)\nabla\phi(x,y)\cdot n dS\,.$$

The first order linear approximation $\Delta C = \frac{d\xi}{d\varepsilon}(\Delta\epsilon) + O((\Delta\epsilon)^2)$

$$\mathbf{C}_{\mathbf{M}\times\mathbf{1}} = \mathbf{S}_{\mathbf{M}\times\mathbf{N}}\mathbf{G}_{\mathbf{N}\times\mathbf{1}},$$

Where $M = \frac{n(n-1)}{2}$ are the number of independent sensor measurements, N is the number of pixels in the sensing domain and the sensitivity matrix S is defined as

$$S_{ij}[n] = \frac{1}{V_i V_j}\int_{v[n]} \nabla\varphi_i \cdot \nabla\varphi_j dv$$

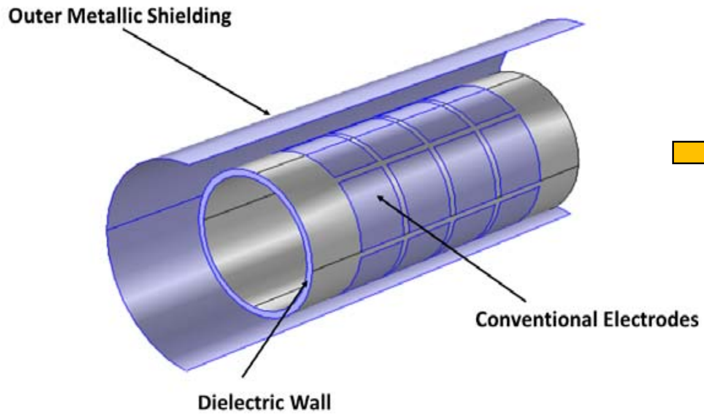
ECVT Challenges

- ECT image reconstruction is an ill-posed and ill-conditioned inverse problem.
- Solution is very sensitive to measurement errors.
- Number of independent measurements are limited due to SNR considerations (setting a minimum electrode plate size) hence problem is underdetermined.
- Image reconstruction algorithm does not cater for soft-field nature of the ECT sensing field (quasi-static Laplacian field).
- Limited spatial resolution.
- Fast and robust reconstruction algorithms for real time applications.

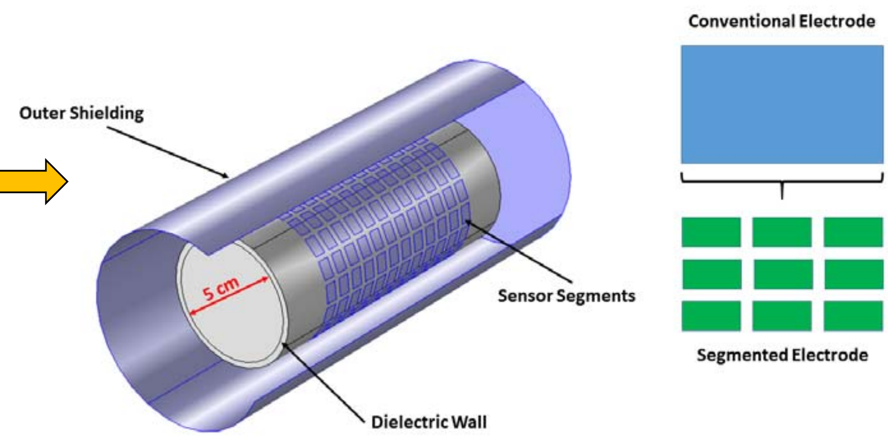
Adaptive ECVT Sensor

- Adaptive ECVT sensor allows the small segments to be electronically combined in an arbitrary fashion into synthetic electrodes.
- Individual segments can also be excited differently.
- The number of independent measurements can be increased while maintaining a minimum (synthetic) electrode size from SNR considerations.
- AECVT sensor is easily reconfigurable.

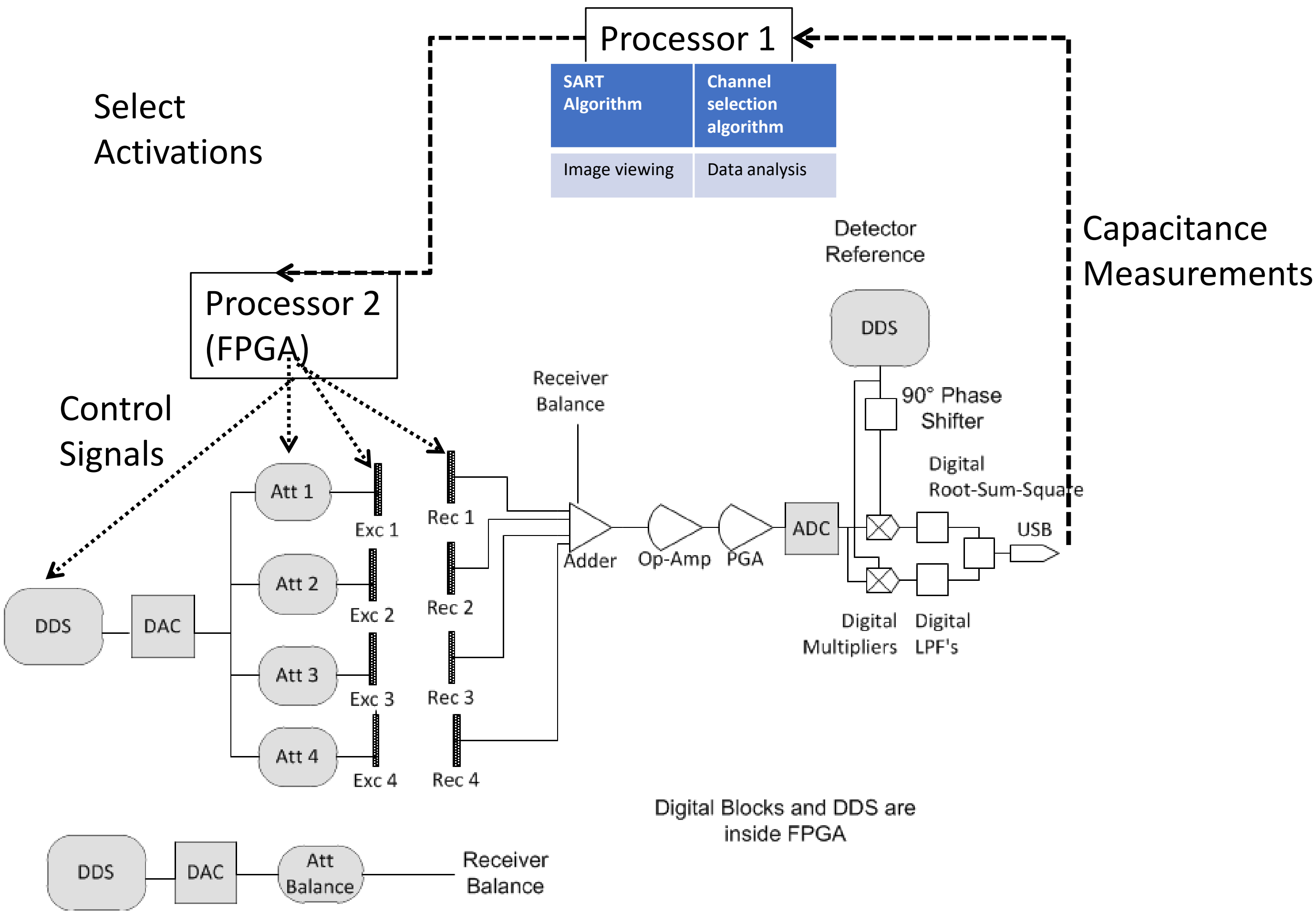
Conventional ECVT Sensor



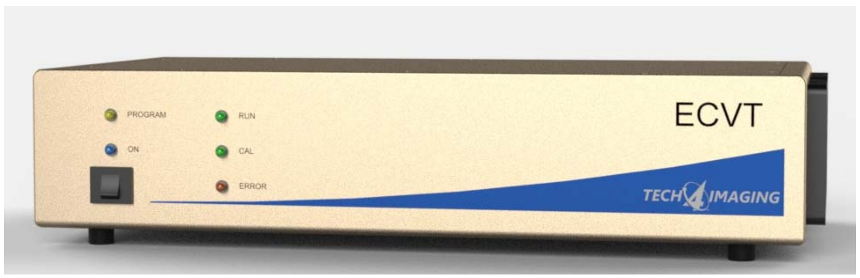
Adaptive ECVT Sensor: AECVT



Electronic Design Activation Scheme



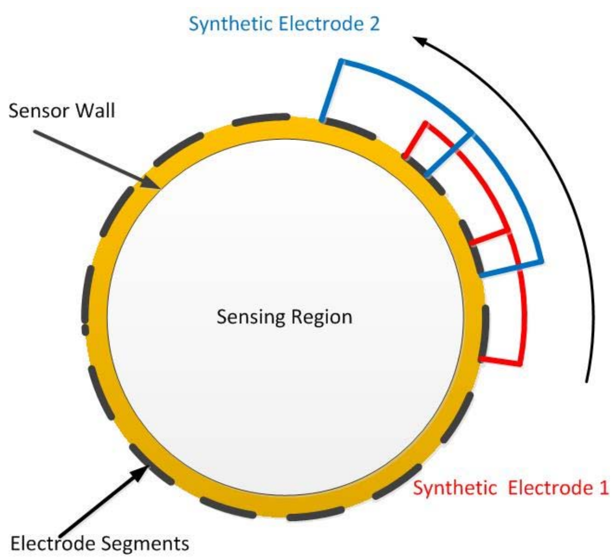
Adaptive Data Acquisition System (DAS)



ECVT DAS: 36 channels

ECVT DAS: 288 channels

Sensor: Spatial Resolution in AECVT

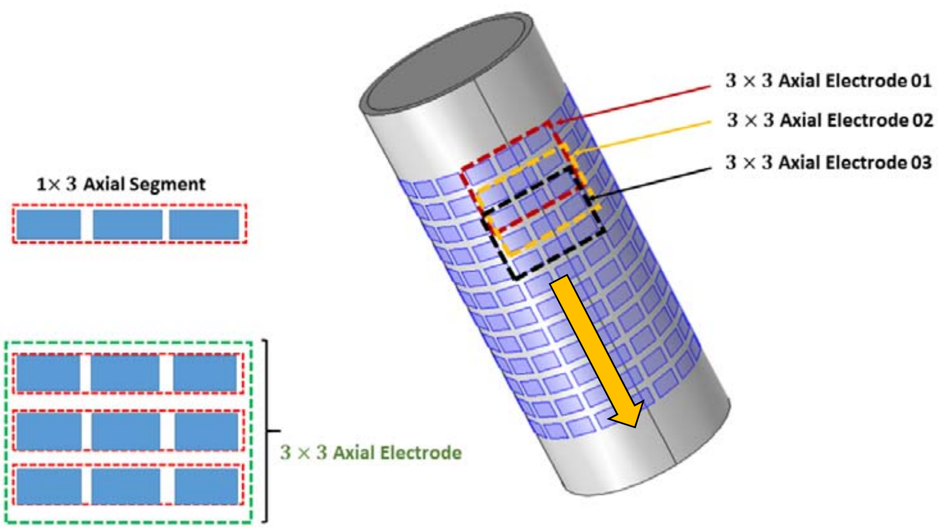


AECT SENSOR CONFIGURATIONS

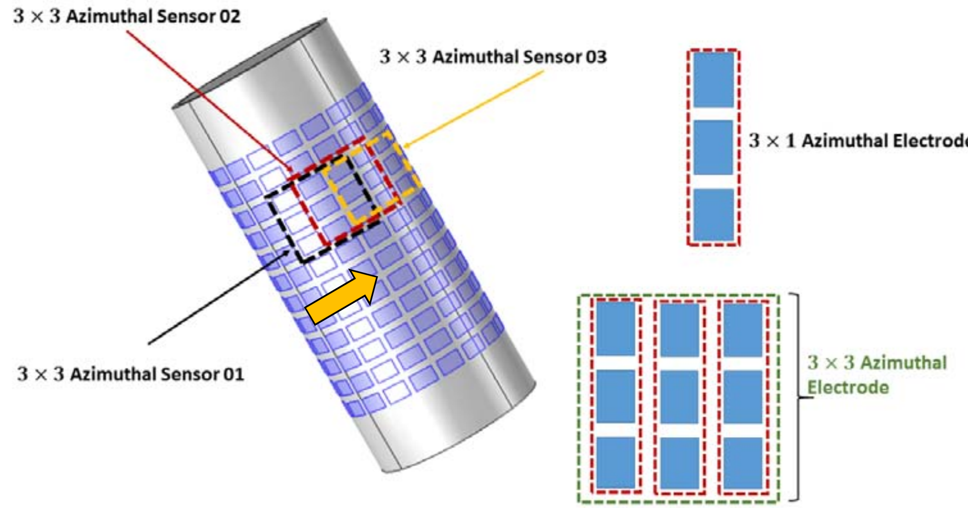
Sensor	No. of Electrodes	Measurements
ECT	12	66
AECT: 2 Segment	36	594
AECT: 3 Segment	36	558
AECT: 4 Segment	36	522
AECT: 6 Segment	36	450

Simulated AECVT Sensor Scanning Modes

Axial Scan

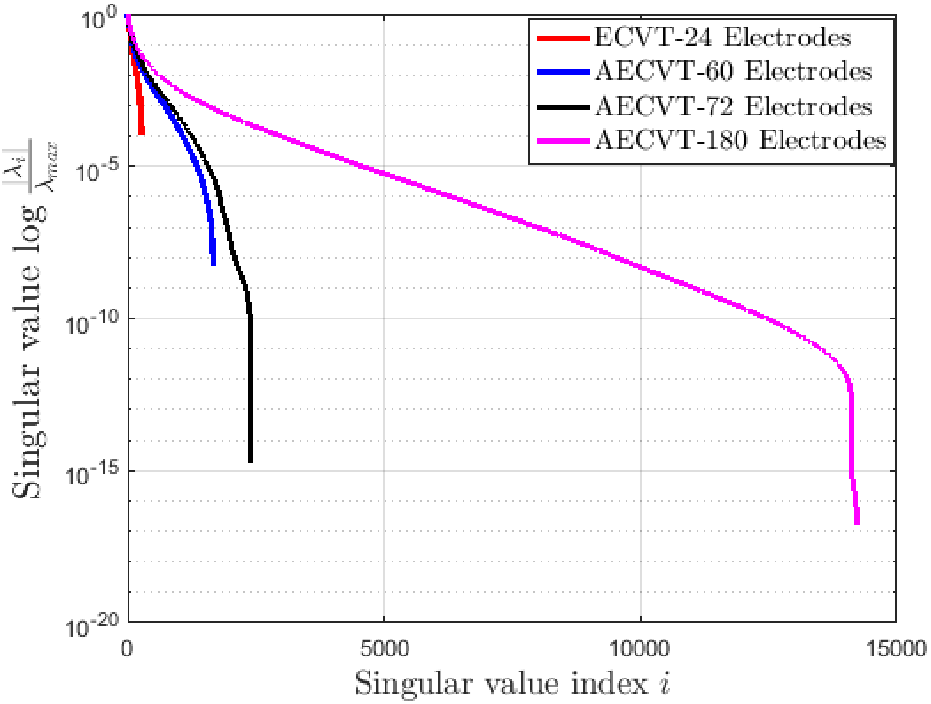


Azimuthal Scan



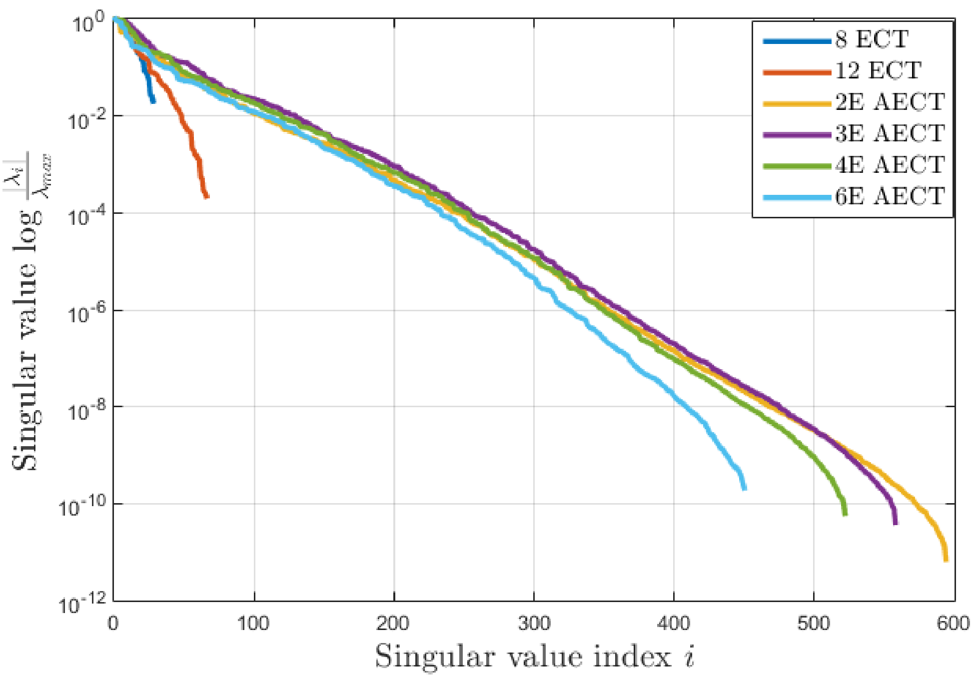
- AECVT sensor can be activated using the axial and azimuthal scanning modes.
- These electronic scanning modes increase the number of measurement while retaining the (synthetic) electrode size and hence the minimum SNR.

AECVT Sensor Model Analysis

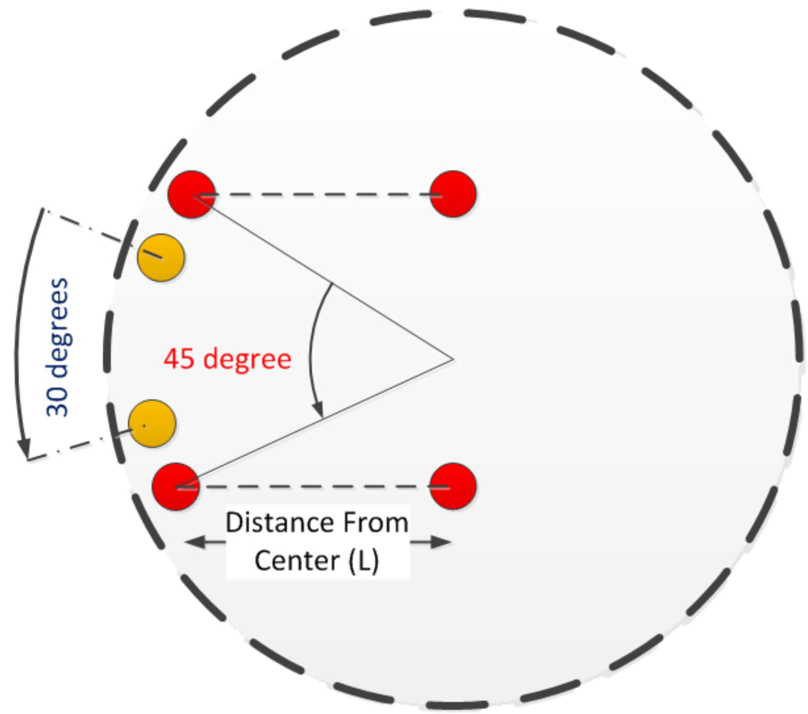


Sensor	No of Electrodes	Condition Number
Conventional	24	9.034×10^{3}
Axial 3×3	60	1.753×10^{8}
Azimuthal 3×3	72	5.492×10^{14}
Full-scan 3×3	180	6.065×10^{16}

Imaging Resolution in AECT

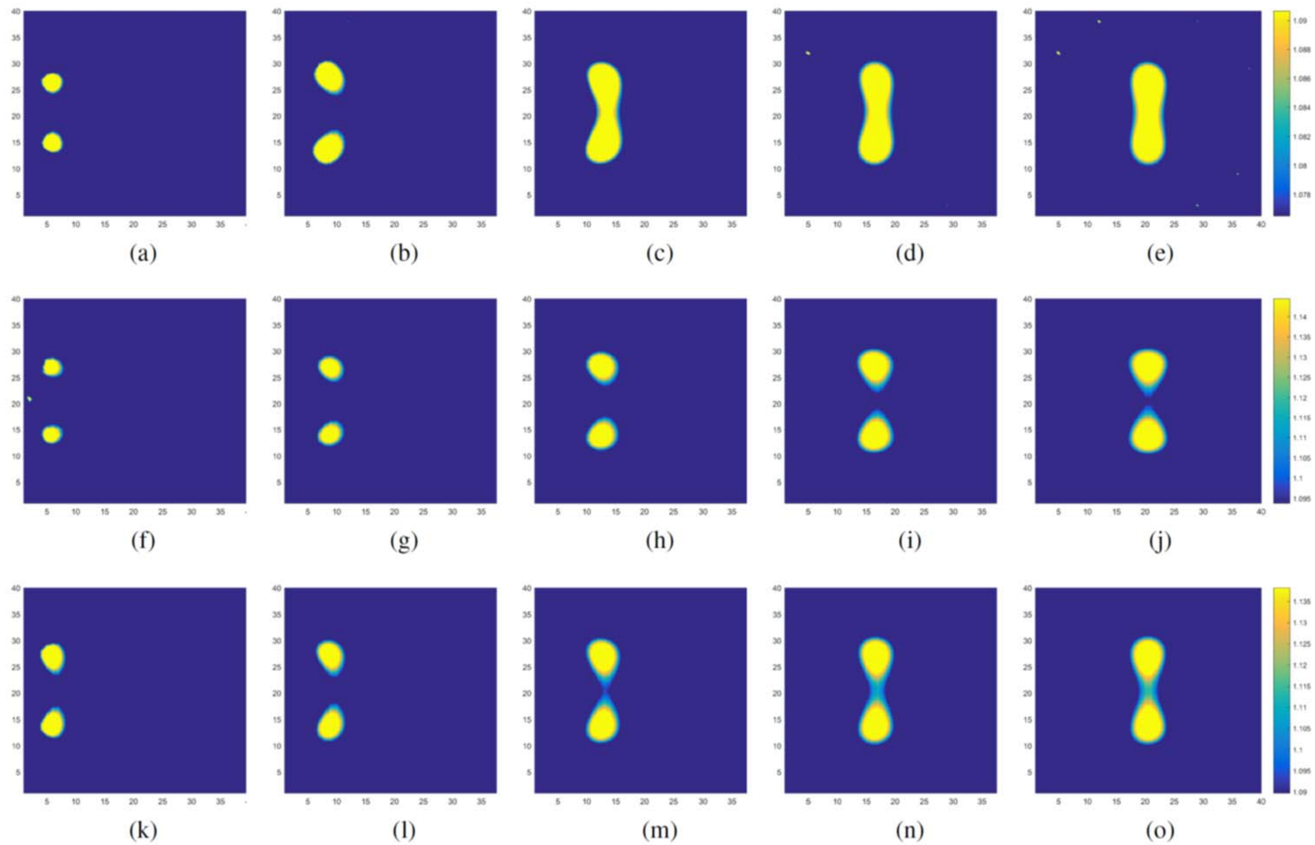


Spectral Plot for AECT



Resolution Test Configuration

Imaging Resolution

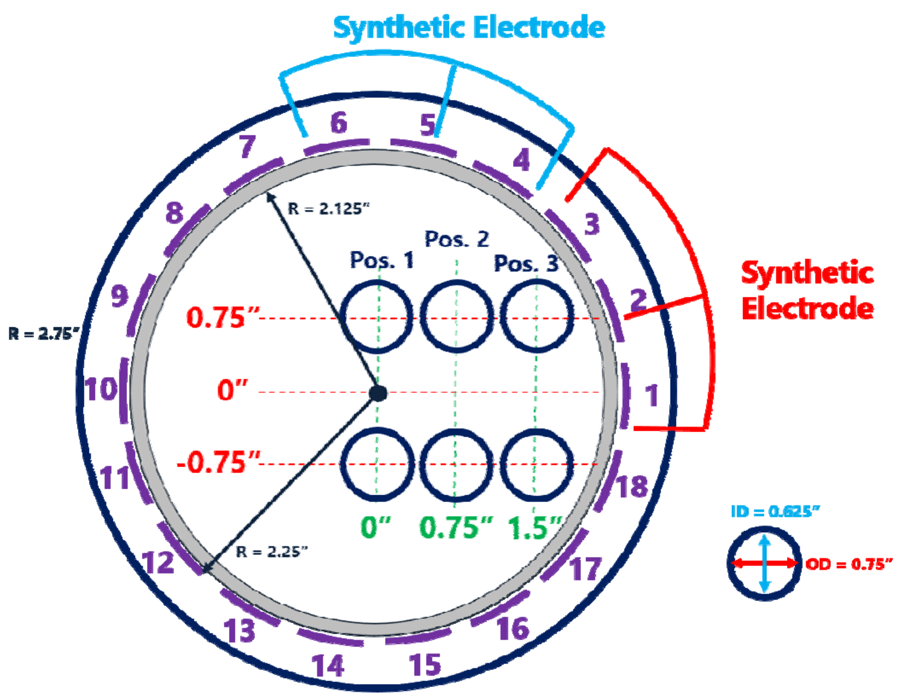


ECT12 Electrode Sensor

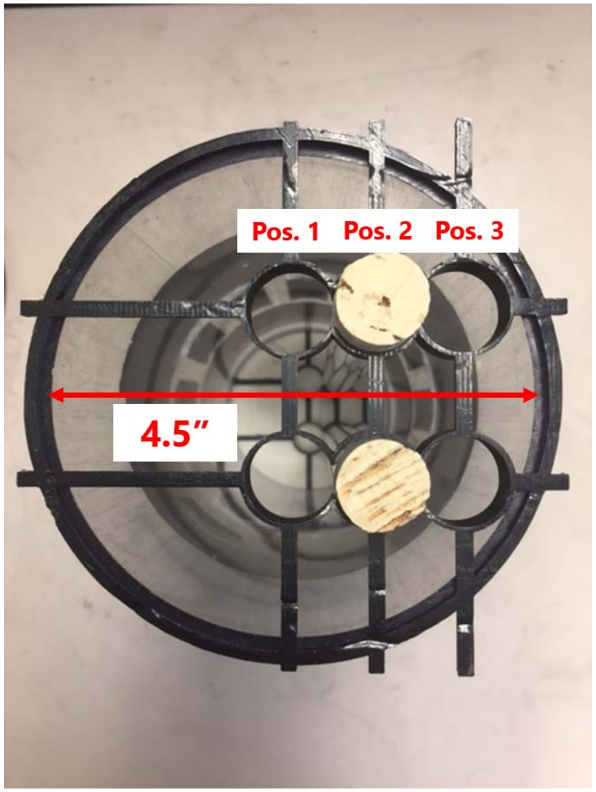
AECT18 Electrode 3 Segment Sensor

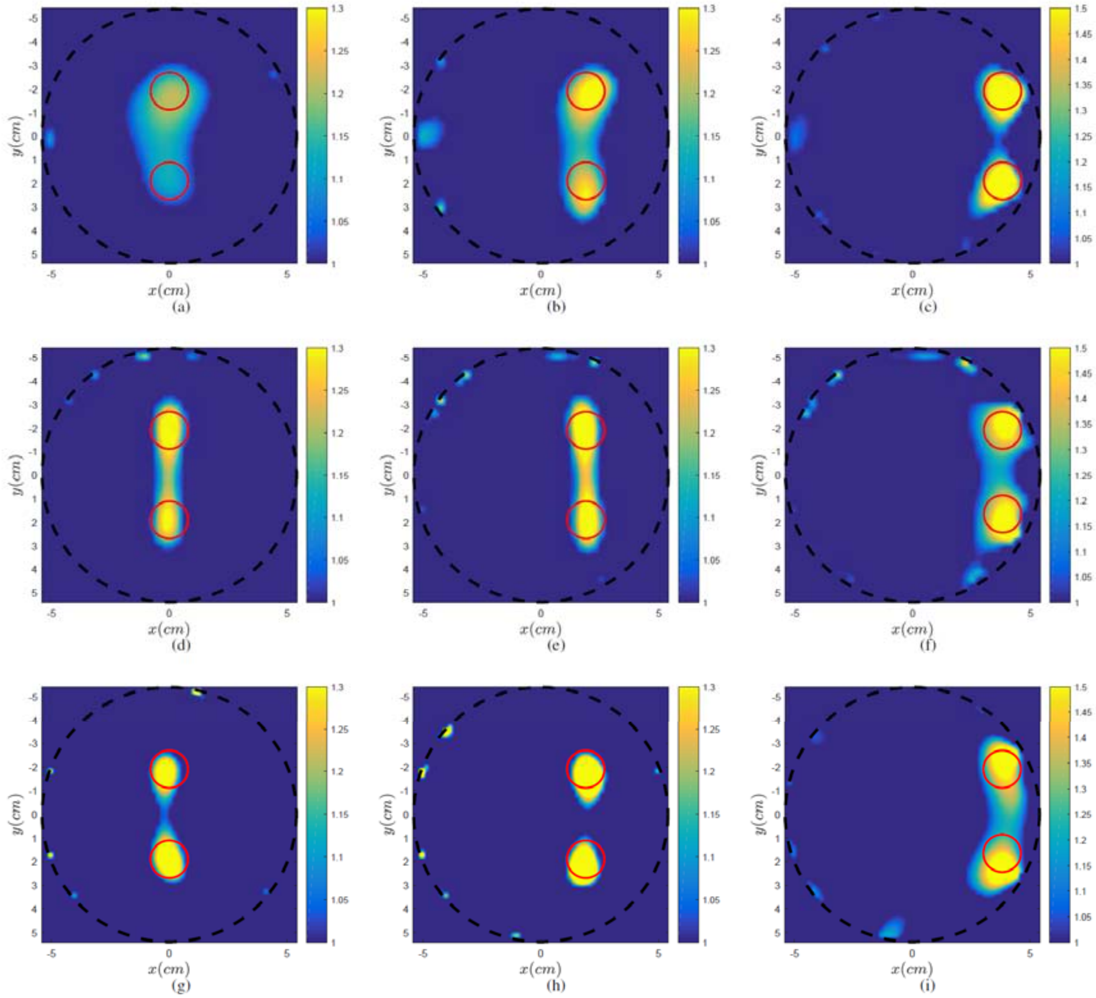
AECT18 Electrode 2 Segment Sensor

AECT Experimental Results with 18 Electrode Sensor



Experimental Setup





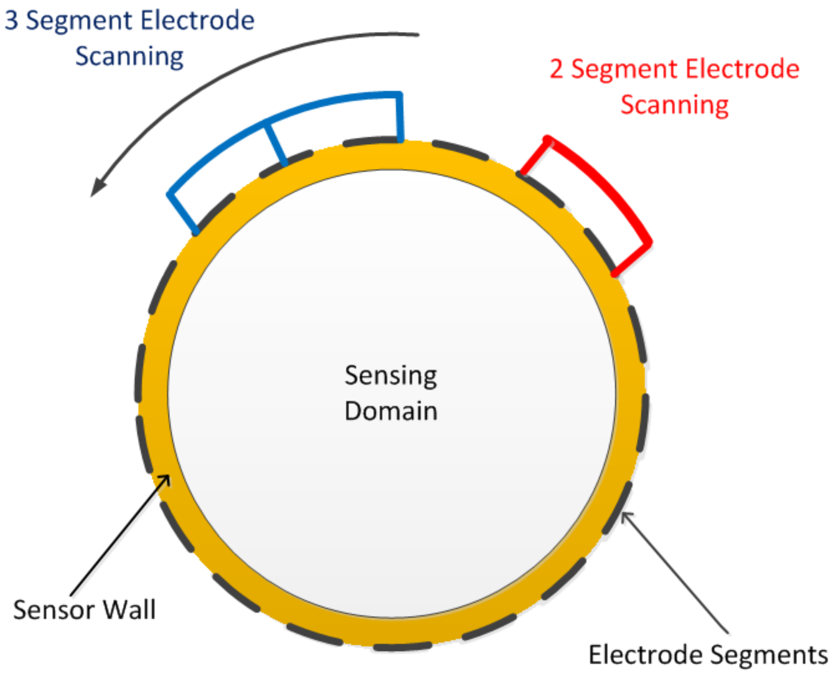
ECT12 Electrode Sensor

AECT18 Electrode 3 Segment Sensor

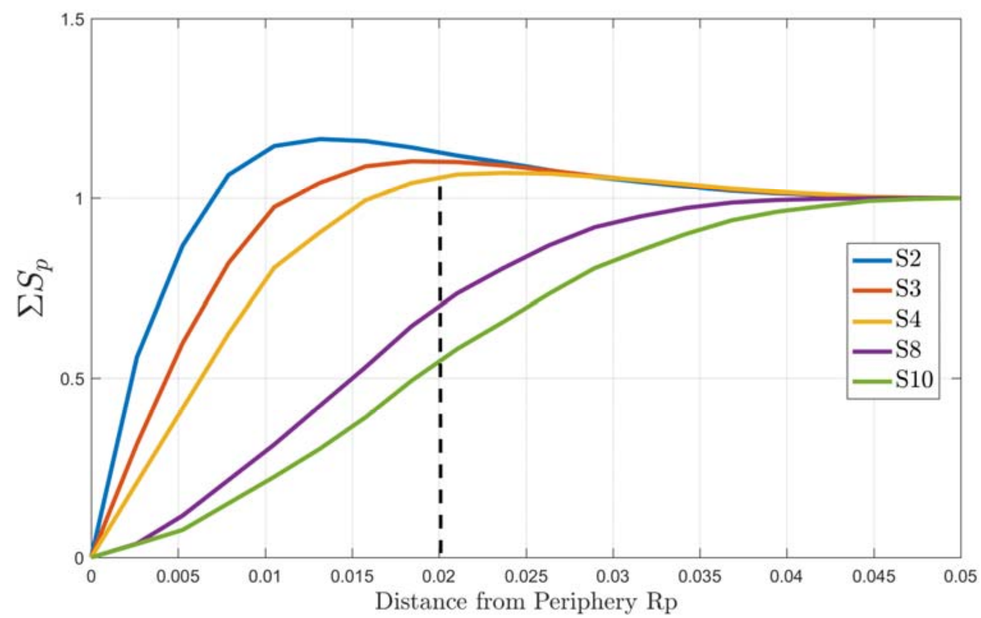
AECT18 Electrode 2 Segment Sensor

Image reconstruction results based on the Landweber algorithm for two test objects at the three sucessive positions indicated in Fig. 12 for: (a)-(c) Conventional12-electrode ECT sensor, (d)-(f) 18-segment AECT sensor with synthetic electrodes comprised of 3 segments, and (g)-(i) 18-segment AECT sensor with synthetic electrodes comprised of 2 segments.

Space Adaptive & Field Imaging

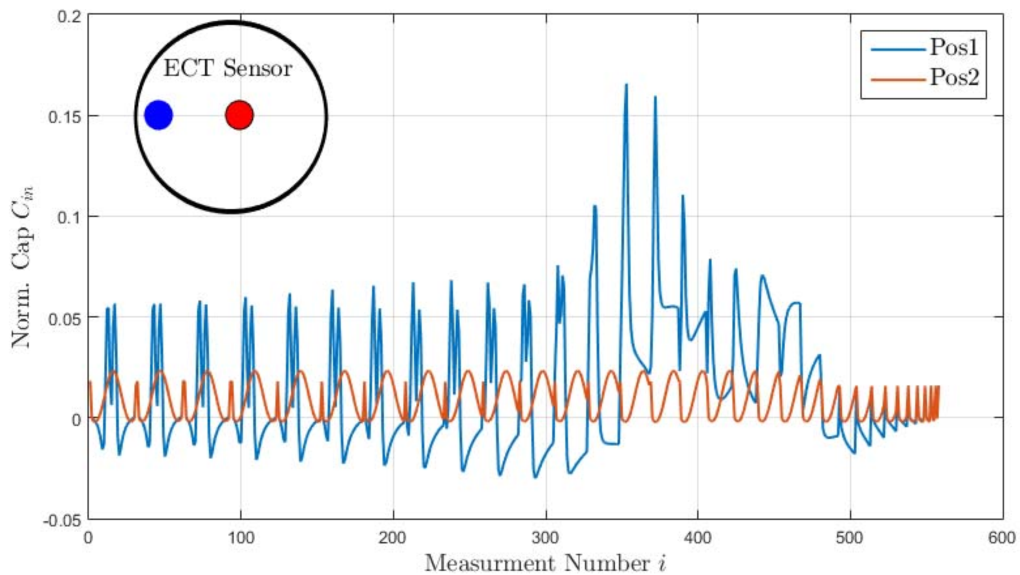


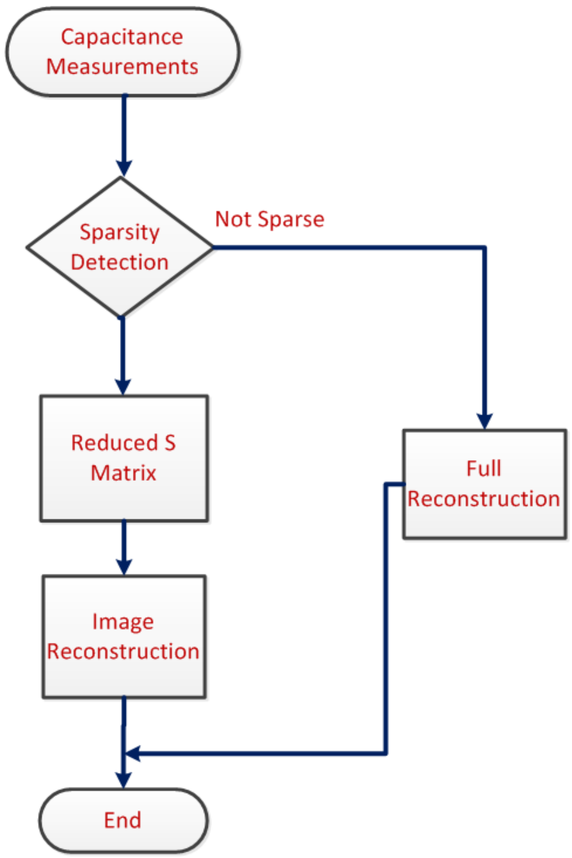
Sensor Scanning



Cumulative Sensitivity Distribution

Sparse Measurements and Near Field Imaging





High Resolution Imaging-Objectives

ECT Imaging resolution can be quantified by

1. Spatial Resolution
2. Permittivity Contrast (Radiometric Resolution)

The other Parameters of interest include Center of the Object

1. Shape and Size
2. Correlation between the true and reconstructed image

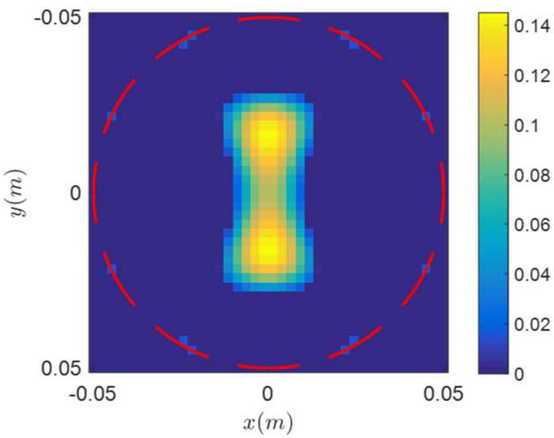
Sensor Parameters to Select are:

1. Electrode Size
2. Imaging Domain Size
3. Number of Measurements

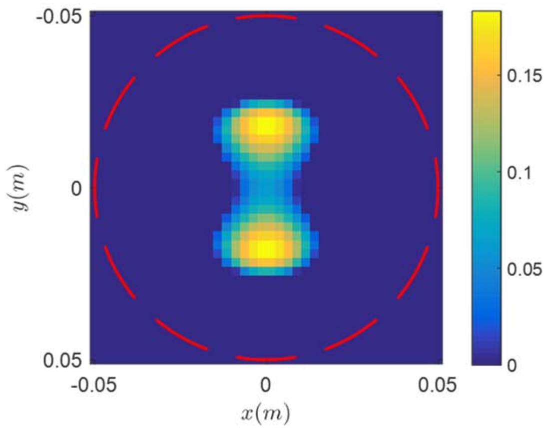
Reconstruction Methods

1. LandWeber
2. DROP

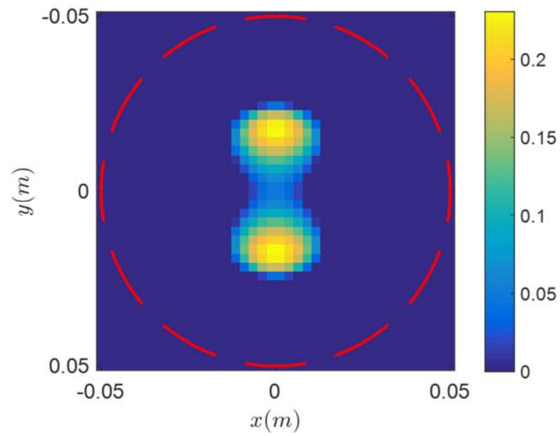
Spatial Resolution Enhancement using SART



Conventional



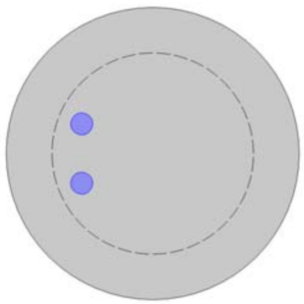
SART

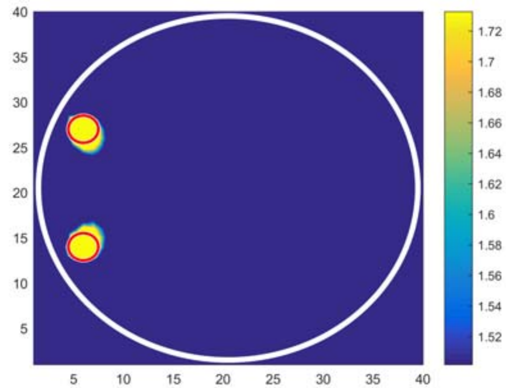


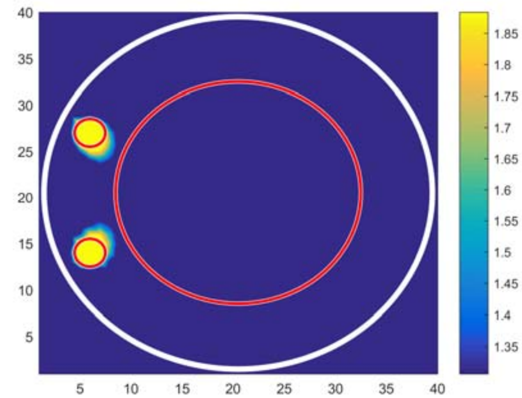
SART1

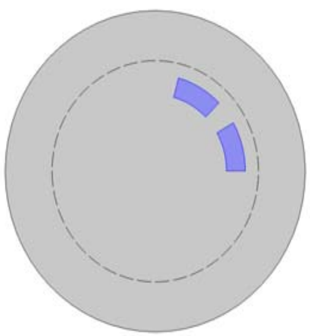
Image reconstruction results. Test objects.

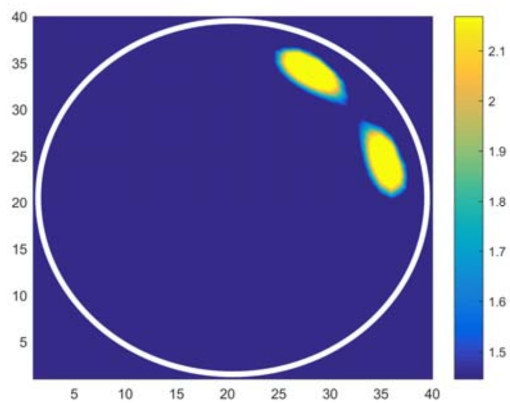
Full | Reduced

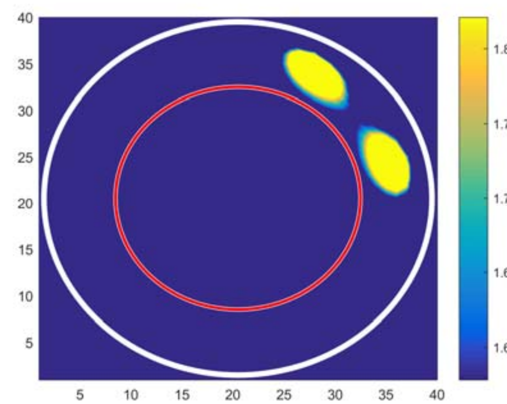




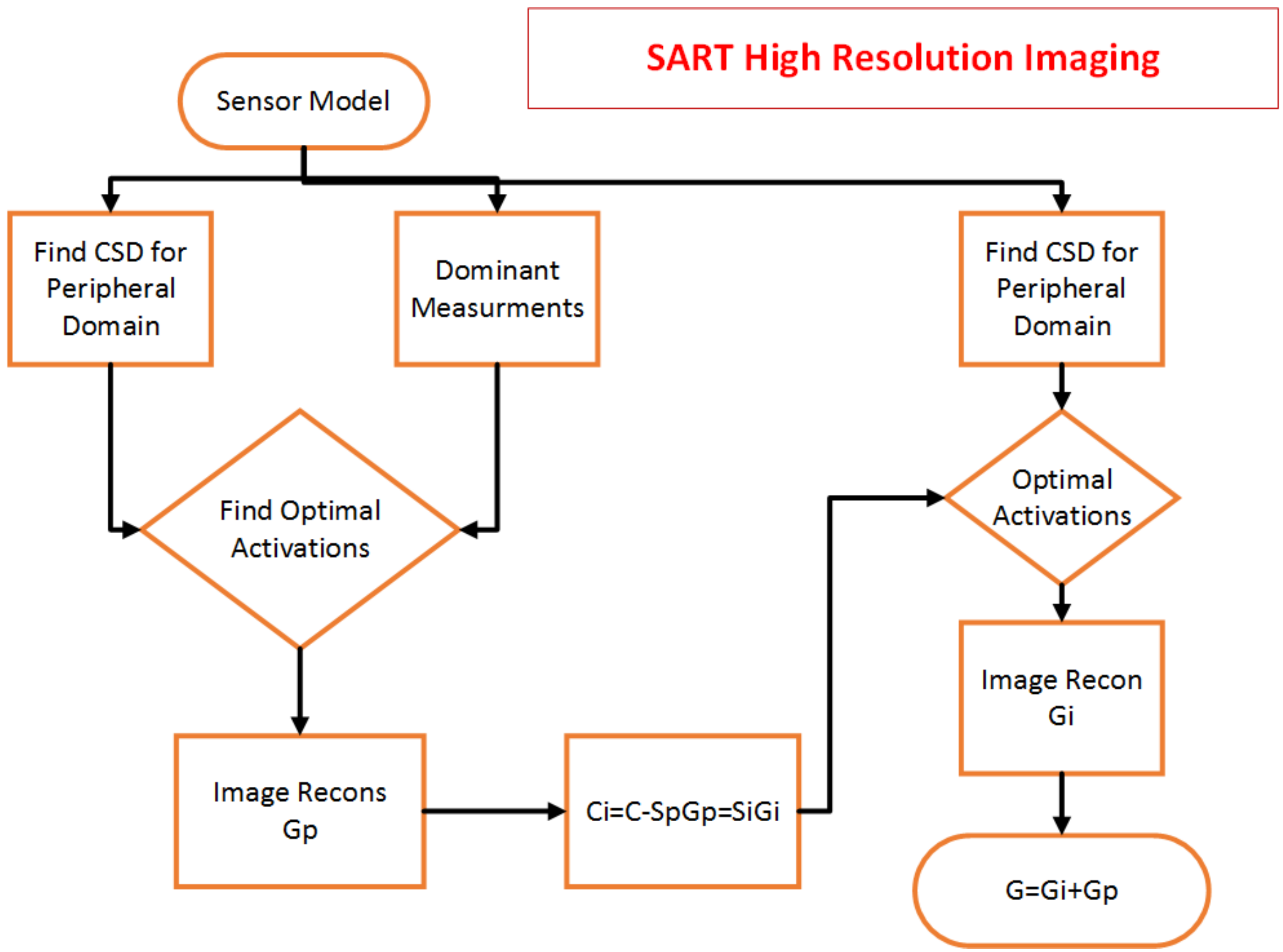




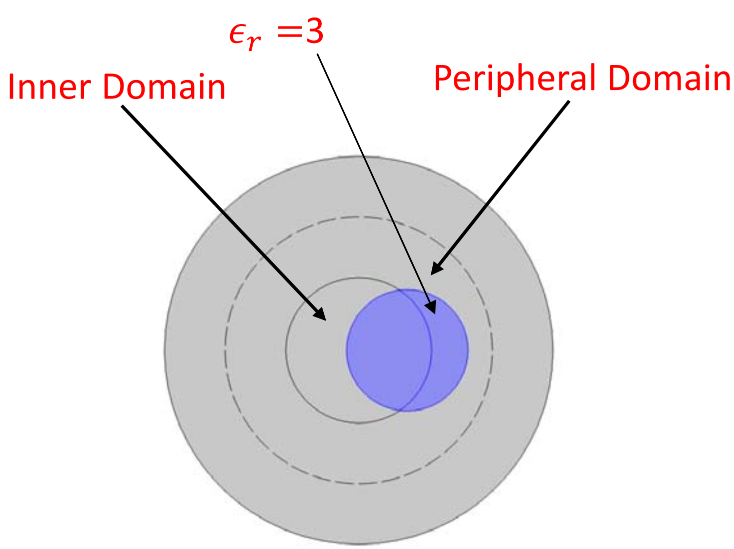


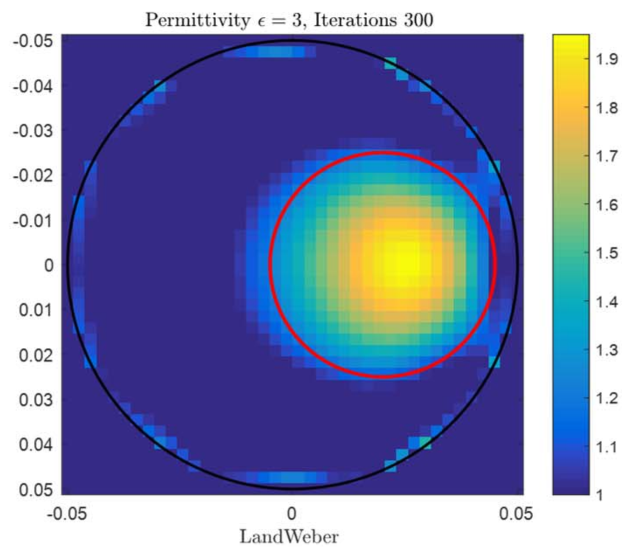


High Resolution Imaging-Problem Formulation

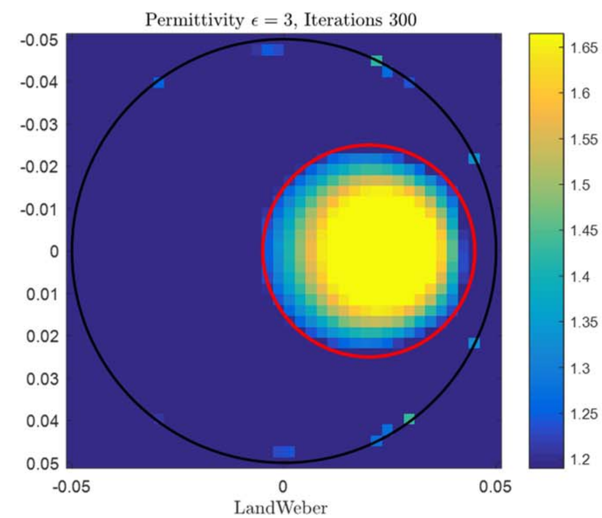


SART Reconstruction Results





Conventional Reconstruction



SART Reconstruction

Phase II Schedule

Task 1: *Electrical design of AECVT sensor for high temperatures*
Task 2: *ECVT sensor mechanical design for high temperatures*
Task 3: *ECVT sensor fabrication*
Task 4: *Build test chamber*
Task 5: *Data Acquisition System (DAS) firmware and electronic design*
Task 6: *Testing*
Task 7: *Implement image reconstruction algorithm based on developed SART technique*
Task 8: *Develop feature extraction*
Task 9: *System integration and testing in real-time*
Task 10: *Software interface*
Task 11: *Finalize demonstration unit*

Tasks	Project period (Quarter)							
	1	2	3	4	5	6	7	8
Task 1	■							
Task 2	■	■	■	■				
Task 3	■	■	■	■	■			
Task 4	■	■	■	■	■			
Task 5	■	■	■	■	■			
Task 6						■	■	■
Task 7	■	■	■	■	■	■	■	
Task 8					■	■	■	
Task 9							■	■
Task 10						■	■	■
Task 11								■

Phase II Milestones

Year 1 Milestones:

1. Finalize AECVT sensor design- end of 2^{nd} quarter.
2. Development of software for SART reconstruction technique- end of 4^{th} quarter.
3. Fabrication of adaptive data acquisition system- end of 5^{th} quarter.

Year 2 Milestones:

1. Fabrication of AECVT sensor- end of 5^{th} quarter.
2. Finalize image reconstruction and feature extraction- end of 7^{th} quarter.
3. Demonstrate integrated system- end of 7^{th} quarter.
4. Finalize GUI- end of project.
5. Finalize demonstration unit and develop virtual experience- end of project.

Conclusion

- Higher ECVT resolution is directly proportional to increased number of plates.
- Adaptive ECVT (AECVT) is based on substantial increase in number of synthetic plates using plate segmentation.
- Adaptive ECVT is a new technology at the frontier of higher resolution capacitance imaging:
  - Infinite options of plate arrangements and independent number of measurements
  - Maintain High SNR of acquired measurements
  - Ability to beam ECVT resolution toward a desired region
  - Ability to Zoom ECVT resolution toward a desired region
- More work is required for Algorithm development and testing.

Acknowledgement

U.S. DEPARTMENT OF ENERGY

THE OHIO STATE UNIVERSITY