Tech4Imaging Training

36-Channel Electrical Capacitance Volume Tomography Data Acquisition System and Image Reconstruction Software

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Tomography

Sectioning of a volume by means of a penetrating wave. Produces image of a cross-section in volume.

- **Radiology** – X-rays through volume (radiation concerns)
- **Computer-Assisted Tomography (CAT)** – Computer-processed x-rays (radiation, expensive)
- **Magnetic Resonance Imaging (MRI)** – Magnetically-disturbed atoms scanned (expensive, large)
- **Positron Emission Tomography (PET)** – Gamma ray detection for 3-D imaging (ionizing radiation)
- **Electrical Capacitance Tomography (ECT)** – Electric field disturbances analyzed for 2-D imaging
- **Electrical Capacitance Volume Tomography (ECVT)** – ECT with 3-D imaging capabilities

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Electrical Capacitance Volume Tomography (ECVT)

- Array of capacitor plates
- Real-time capacitance measurements reconstructed into image
- Multi-phase flow systems and volumes
- ECVT includes 3-dimensional image reconstruction

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Benefits of ECVT

- Non-invasive, non-interfering tomography
- Affordable
- Designable for varying systems and vessel sizes
- Quick image reconstruction
- Runs on standard host PC
- Provides 3-D image of volume
- High space and time resolutions (milliseconds between images)

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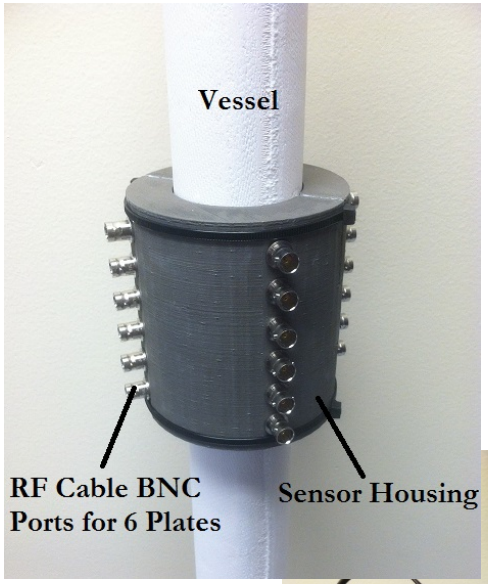
Tech4Imaging ECVT Data Acquisition System

- Unique capacitance sensor with up to 36 plates
- DAS-2 intermediary device between sensor and host PC
- USB connection to host PC
- All analysis and reconstruction occurs on PC



ECVT Sensor

DAS-2 Device

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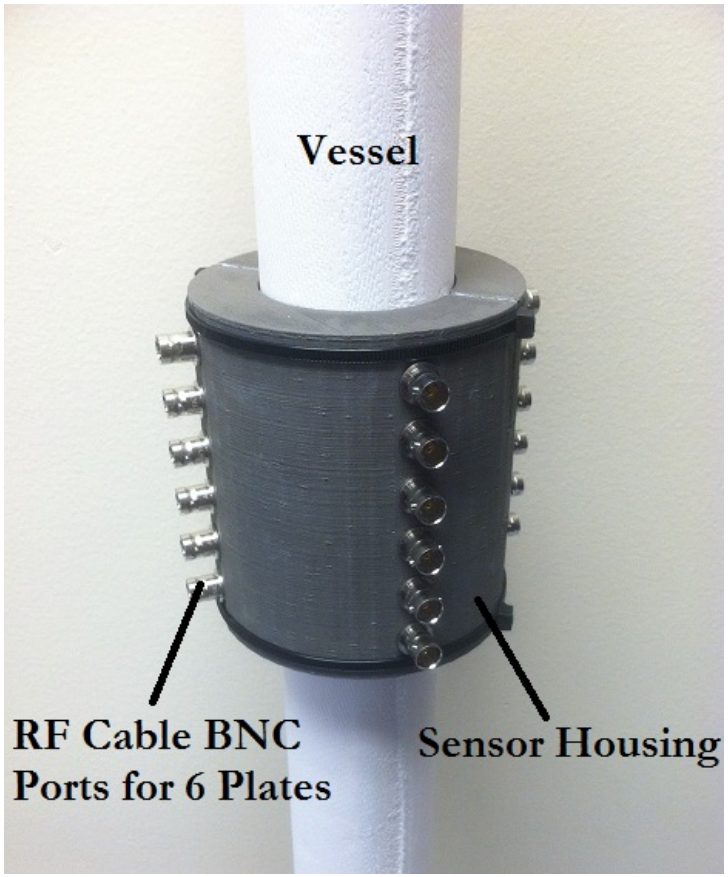
ECVT Sensor

- Capacitance plates wrapped around vessel inside sensor housing
- Common sensors have 12, 24, or 36 plates
- Plates connect to DAS-2 with RF cables



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Data Acquisition System-2

- Drives AC signals to and receives measurements from capacitor plates
- Uses USB to communicate with host computer
- Dynamic Link Library usage
- 5-Volt power source
- Download software on CD to host PC

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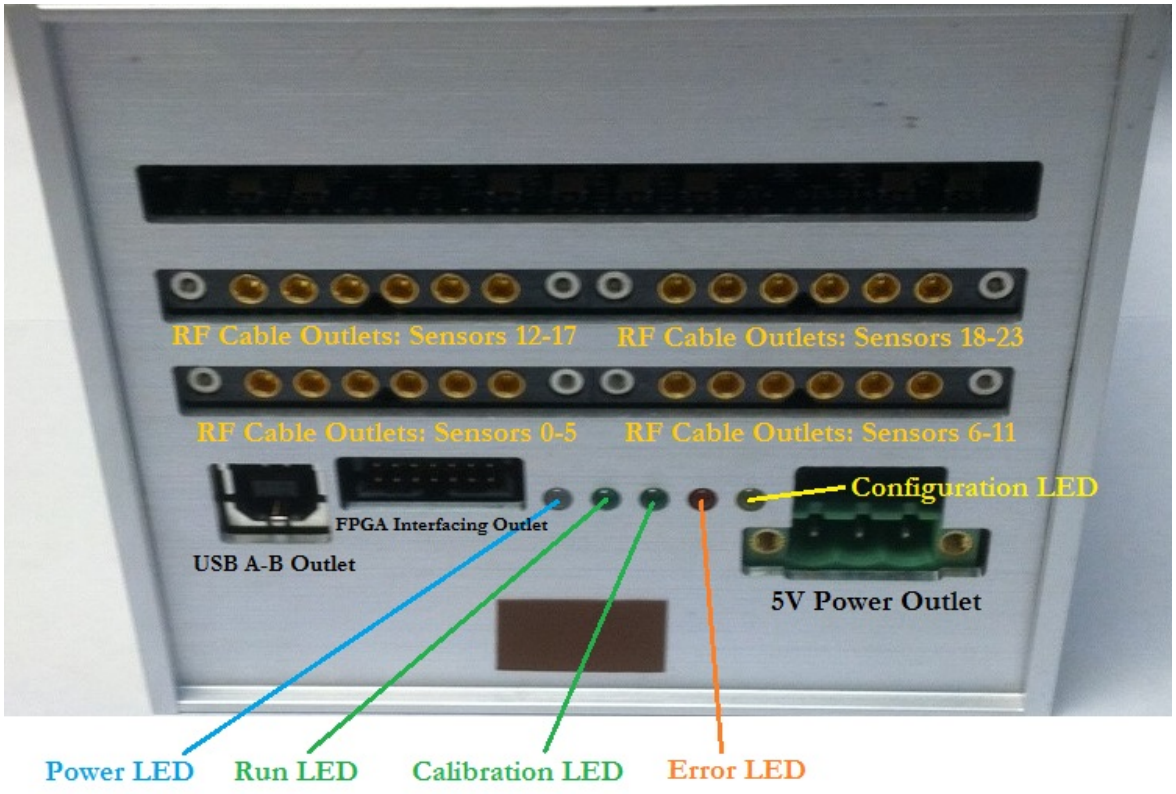
Data Acquisition System-2

- ECVT plate connections in groups of 6
- Three 12-plate receiver cards may be installed
- LEDs indicate power, run, and calibration status of DAS-2



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Data Acquisition System-2

- Capacitance Reading Range: 1.1 fF (10^{-15} F) to 11 pF (10^{-12} F), 1 fF resolution
- Relative Permittivity Range: 0.01 to 100 (Dynamic ratio of 1 to 10,000)
- Typical Measurement Time: 18.1 µs (10^{-6} s)
- For 24-plate setup, typical operating speed is 200 frames/second
- Receiver cards work in parallel to increase speed

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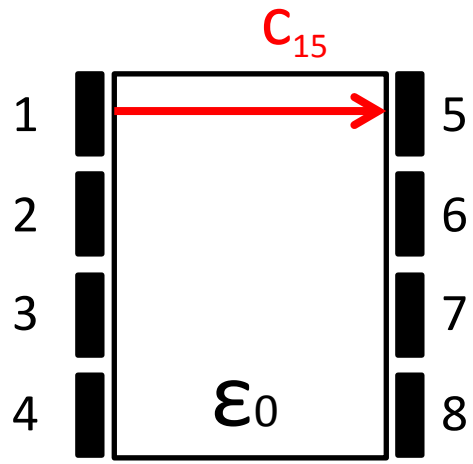
Capacitance Measurements

DAS-2 Measurement Process (for c_{15}):

1. Send 2 MHz AC signal to driver plate (Plate 1)
2. Receive AC signal from excite plate (Plate 5)
3. Modulate and process excite plate signal to determine capacitance



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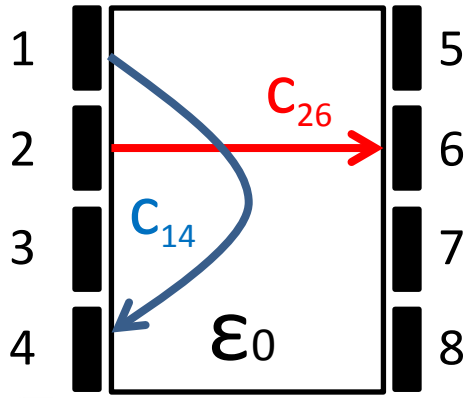
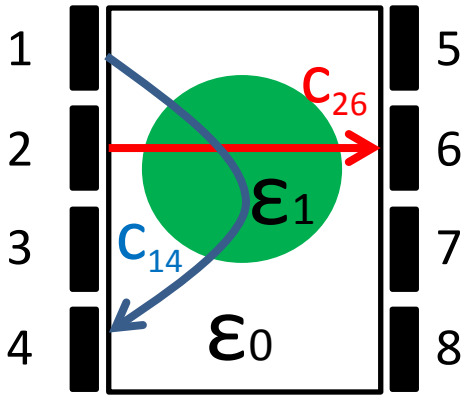
Capacitance Measurements

- For an n-plate sensor, the number of unique plate pairs (channels) M is given by:

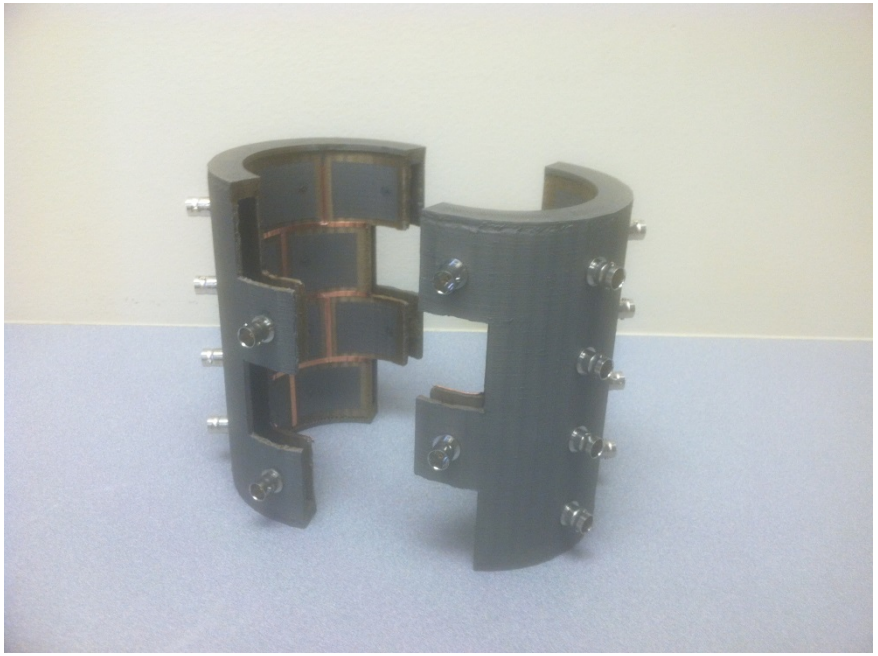
$$M = \frac{n \times (n-1)}{2}$$

- Vertically-distant plates (farther than 5 cm) have low signal-to-noise ratios
- c_{14} will not differentiate the presence of new objects inside sensor volume
- Such channels are not used in image reconstruction (channel vector rejects these plate pairs)

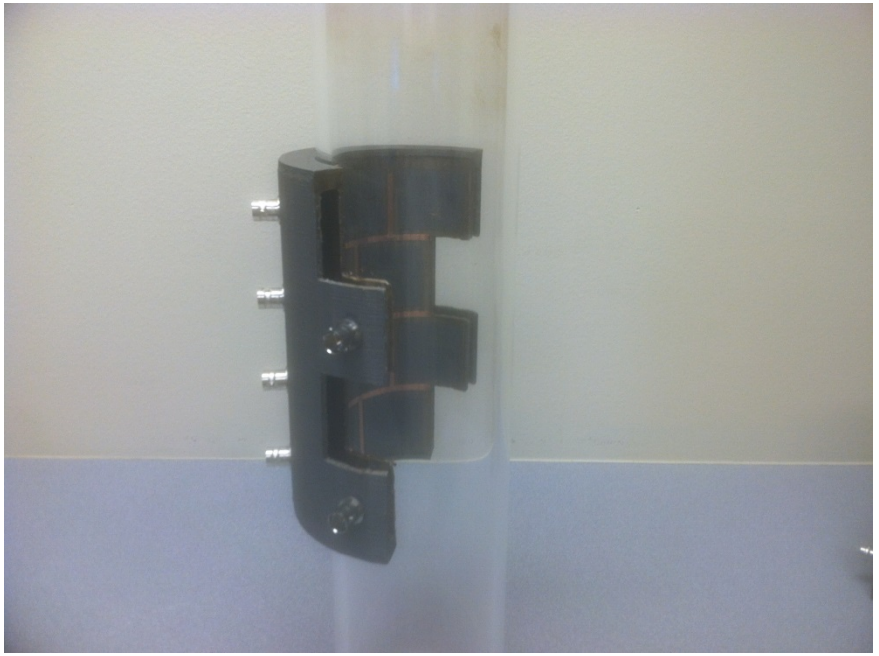




Equipment Connections



24-Plate ECVT Sensor Halves



Sensor Half around Vessel

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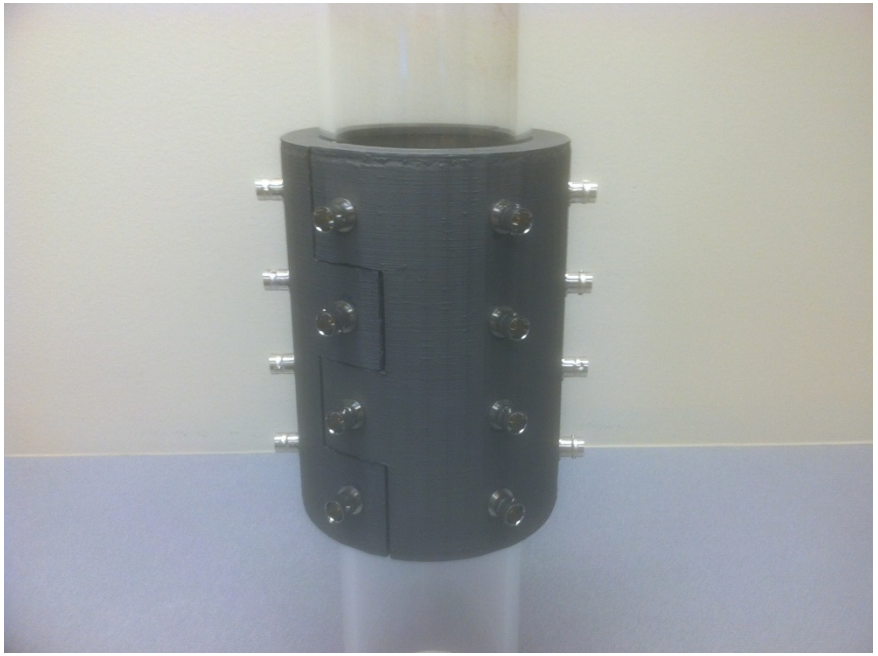
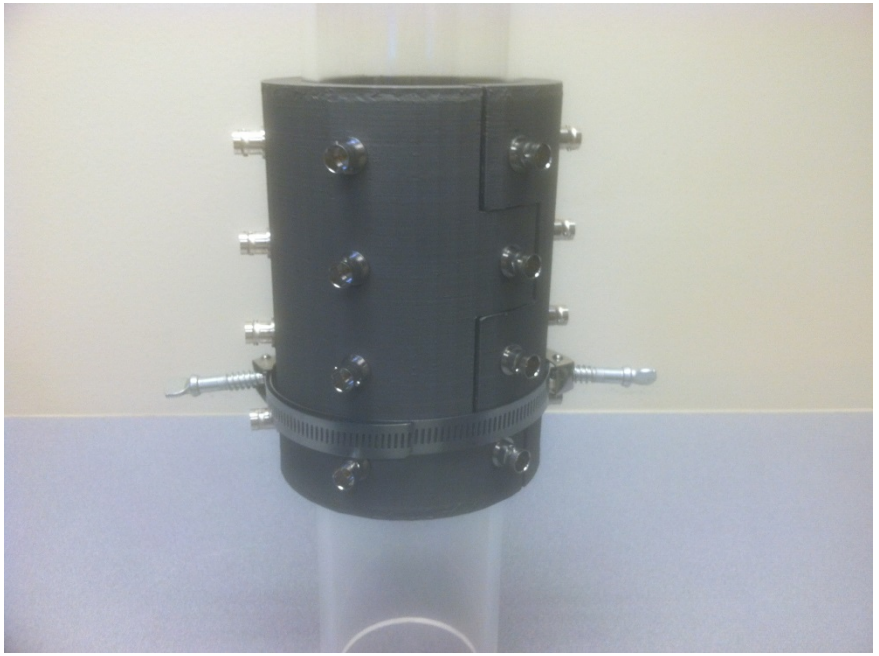
Equipment Connections



Full Sensor around Vessel



Metal Cable Tie around Sensor

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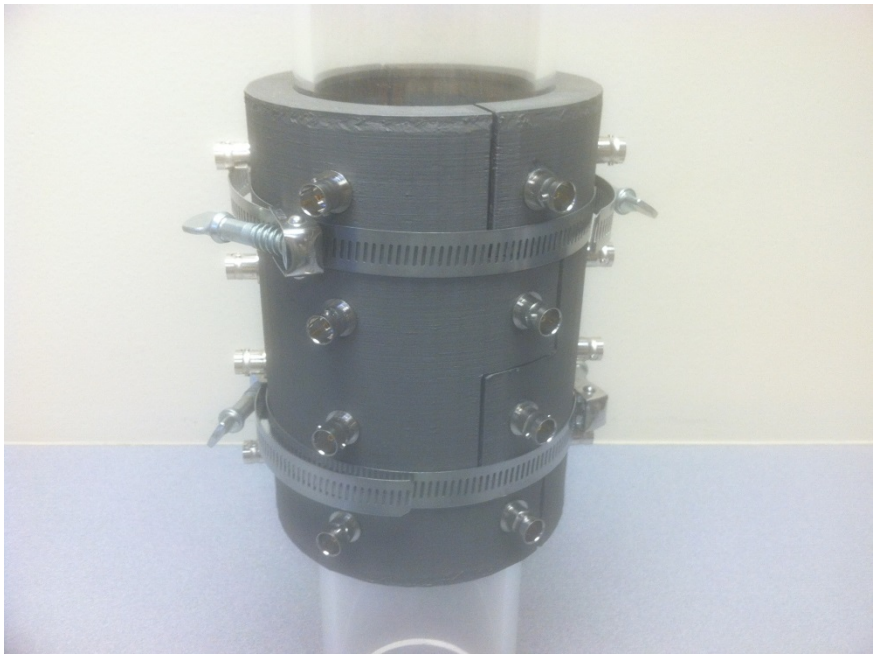
Equipment Connections

Fastened Cable Tie



Fully-Attached Sensor

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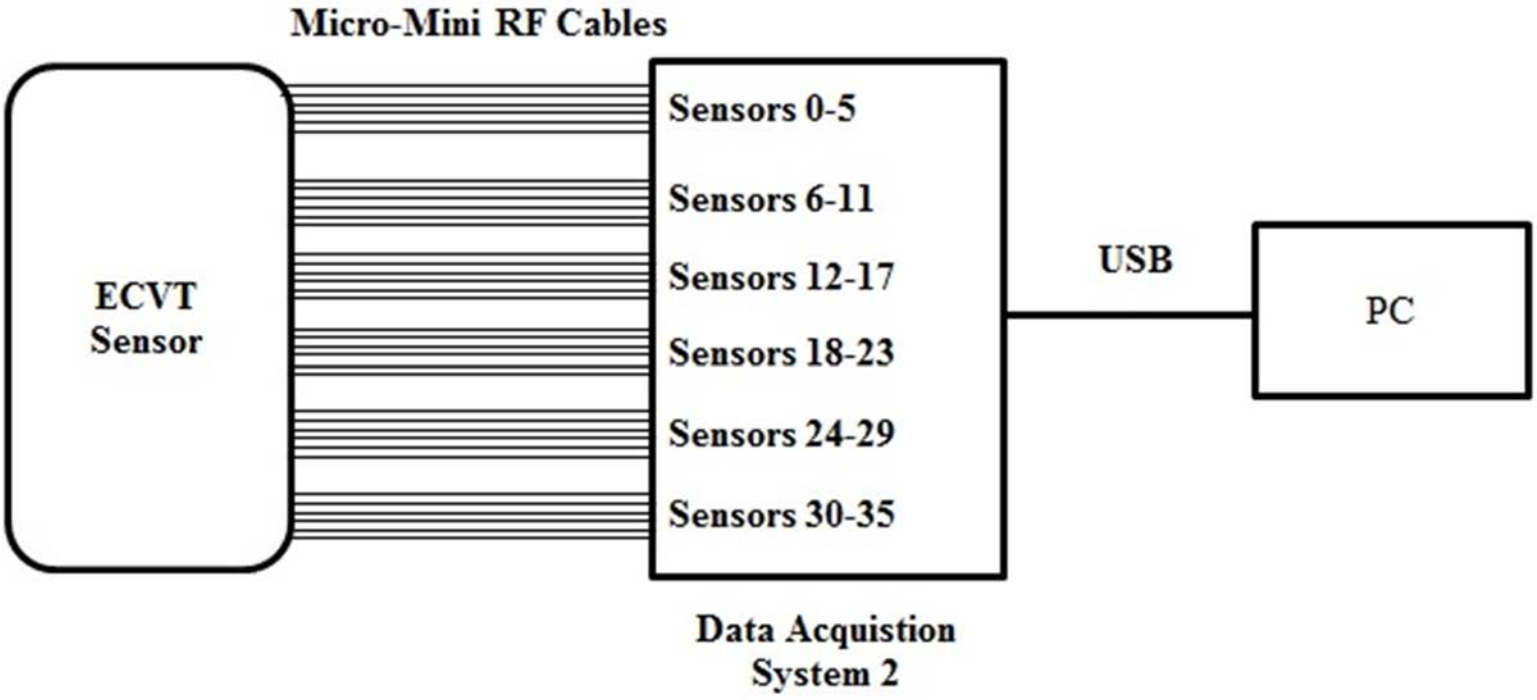
Equipment Connections



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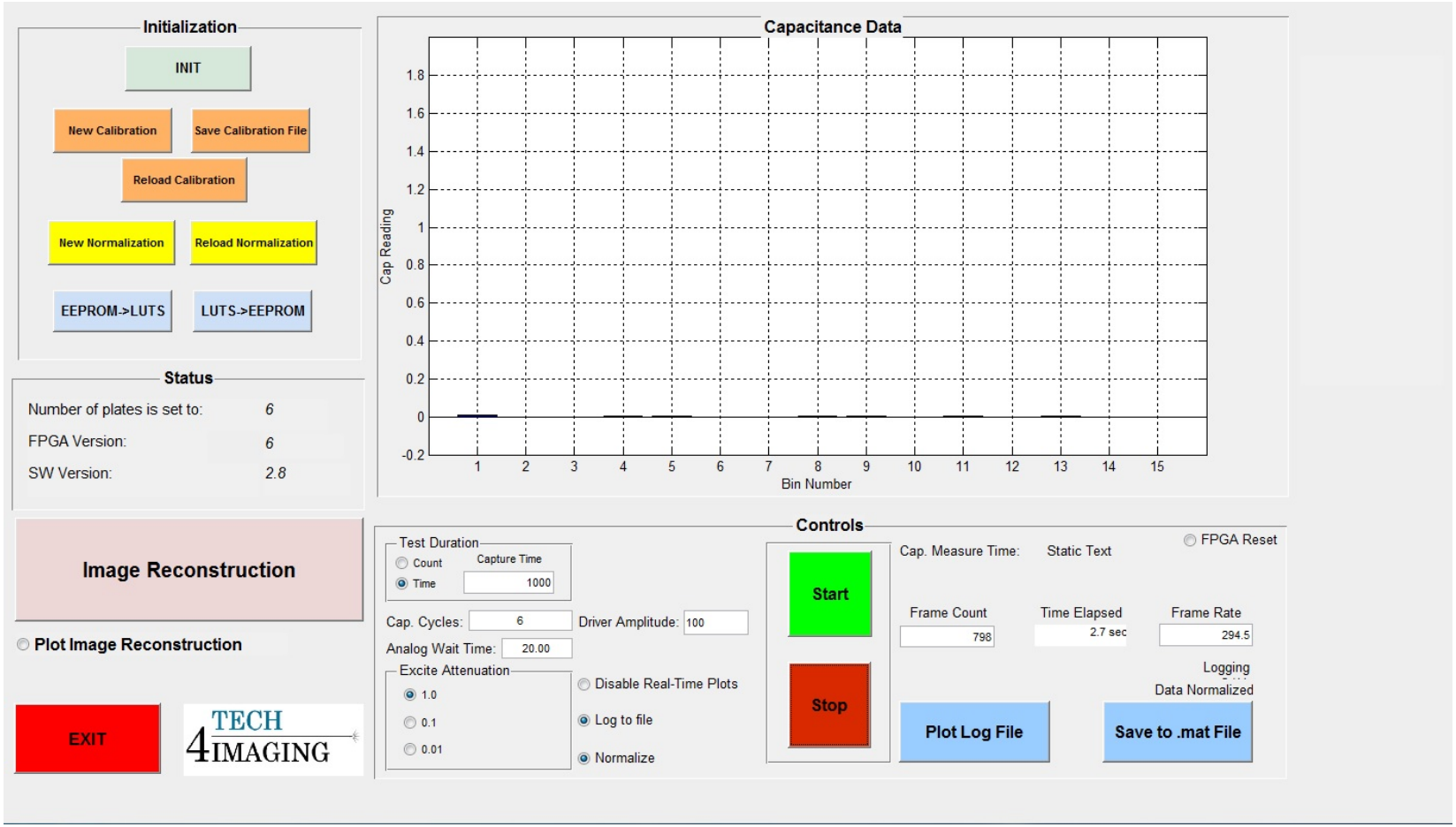
Data Acquisition Software



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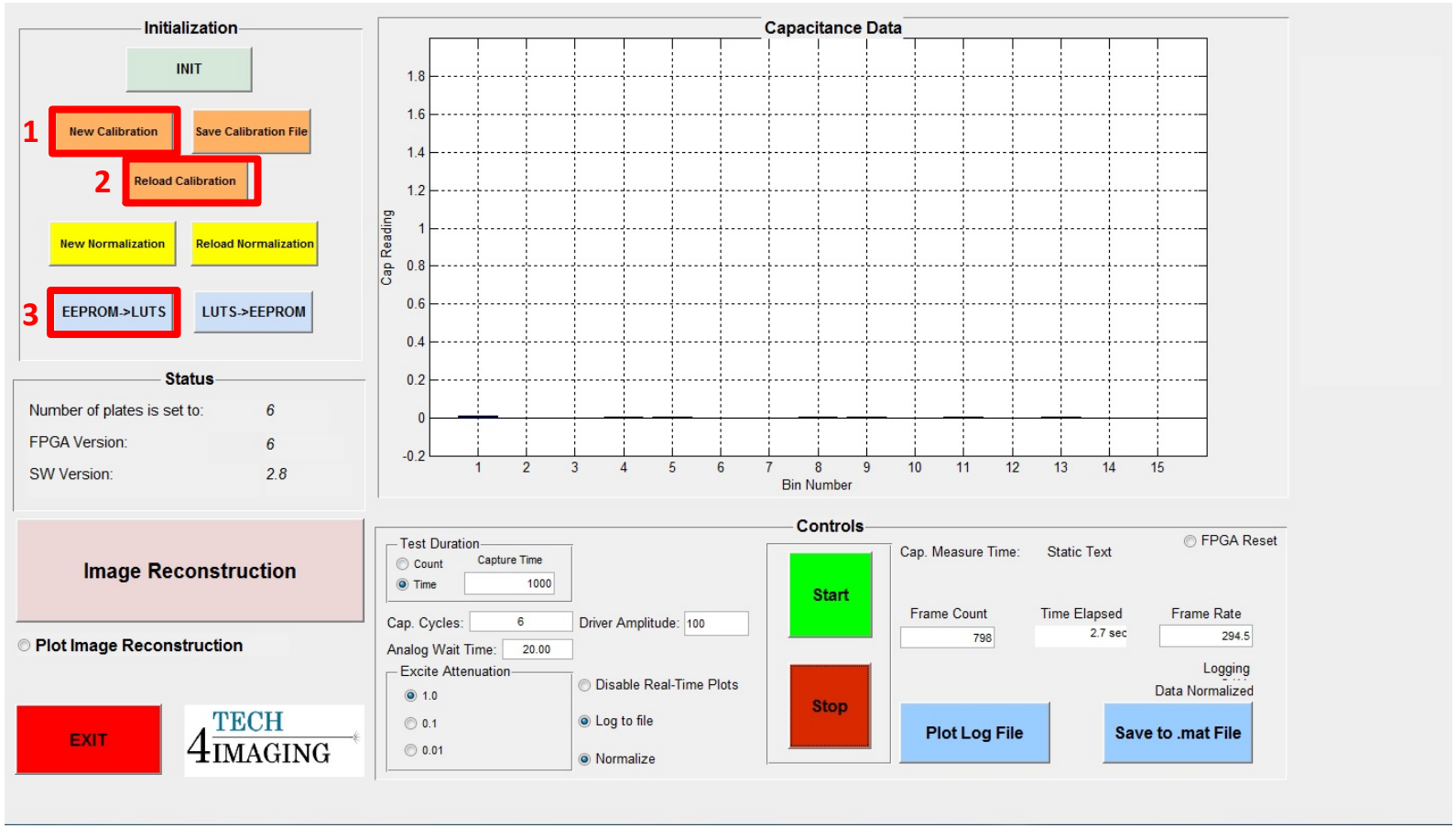
Calibration

- System must be calibrated for the types of materials to be seen in a measurement
- Three options for calibration:
  1. Perform new calibration
  2. Reload a saved calibration
  3. Load calibration values from device EEPROM

Calibration



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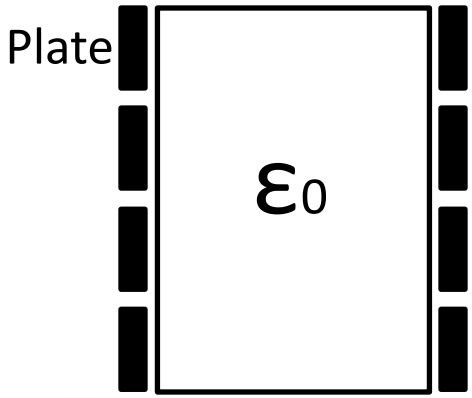
New Calibration

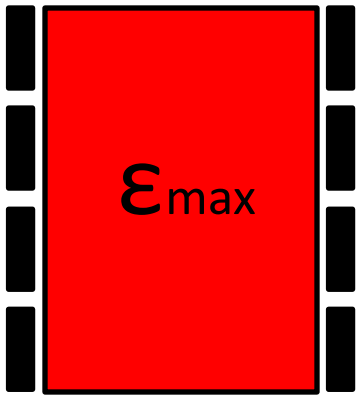
1. Select “New Calibration”
2. Input number of capacitor plates
3. Fill vessel with air or vacuum to calibrate minimum capacitance
4. Fill vessel with highest-dielectric material to calibrate maximum capacitance
5. Save calibration file if desired

*May take up to 30 minutes

**The orange “Error” LED on the DAS-2 front panel will be lit if calibration cannot be performed. Usually this is can be corrected by setting the Driver Amplitude to a lower value.



Step 3



Step 4

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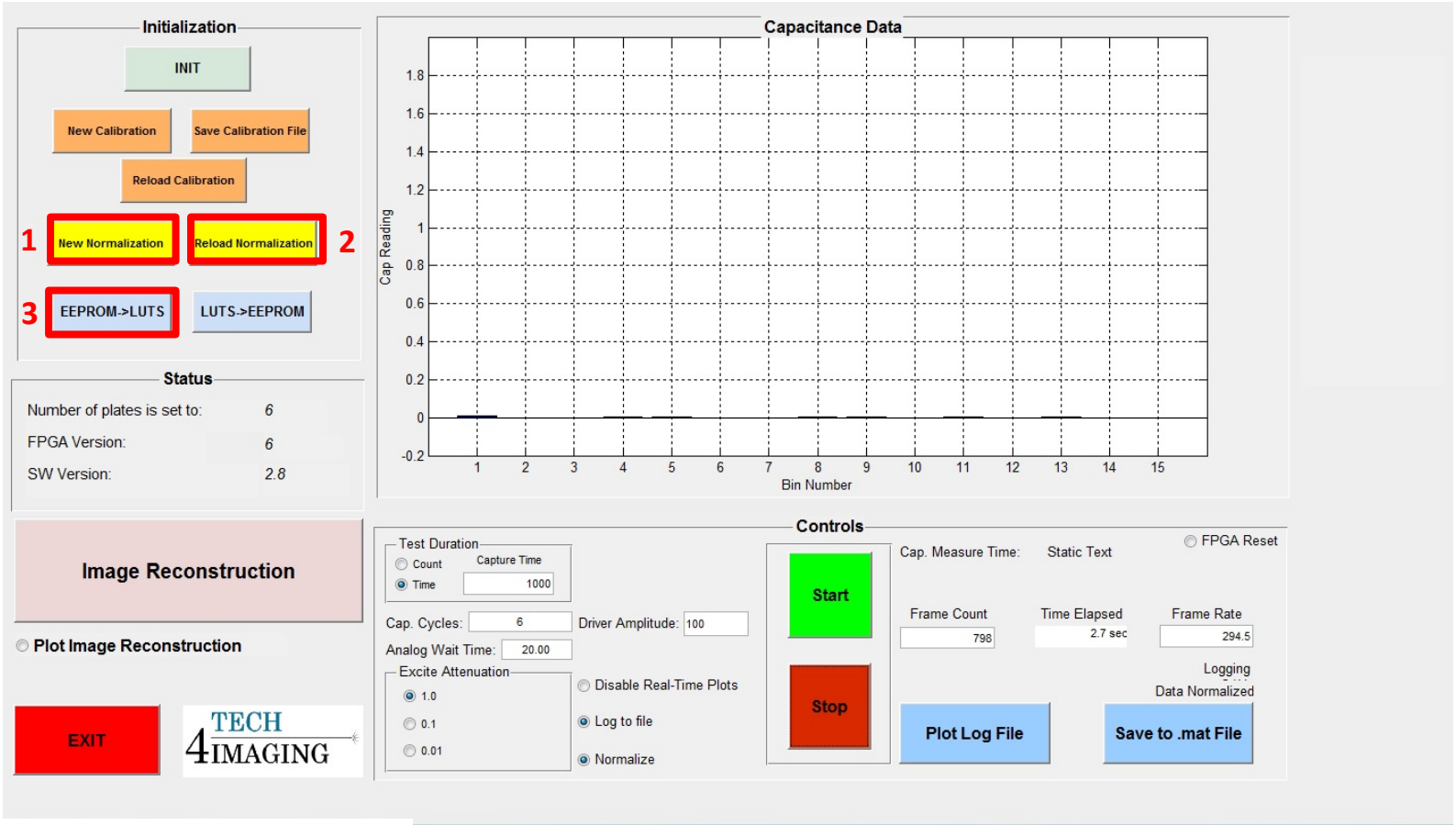
Normalization

- Host computer must be normalized to the range of expected capacitance readings
- Three options for normalization:
  1. Perform new normalization
  2. Reload a saved normalization
  3. Load normalization values from device EEPROM

Normalization



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Normalization

- Calibration determines minimum and maximum capacitances for each plate pair
- Normalization converts each plate pair reading to a percentage of its range:

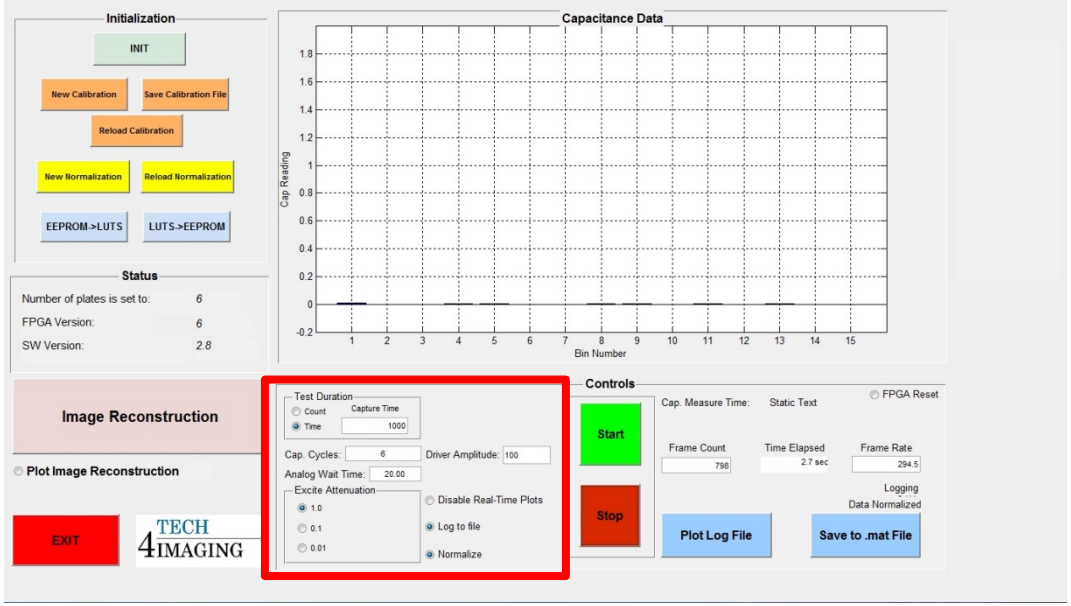
$$c_{pair} = \frac{measured\ value - \ empty\ value_{pair}}{full\ value_{pair} - empty\ value_{pair}}$$

- Allows comparison of different plate pair readings

Data Acquisition

Set test parameters for data acquisition:

- **Test Duration** (Num. of Frames or Time in Secs.)
- **Capacitance Measurement Duration** (Num. of Cycles)
- **Driver Signal Amplitude** (%)
- **Wait Period between Measurements** (µsecs.)
- **Excite Signal Attenuation**



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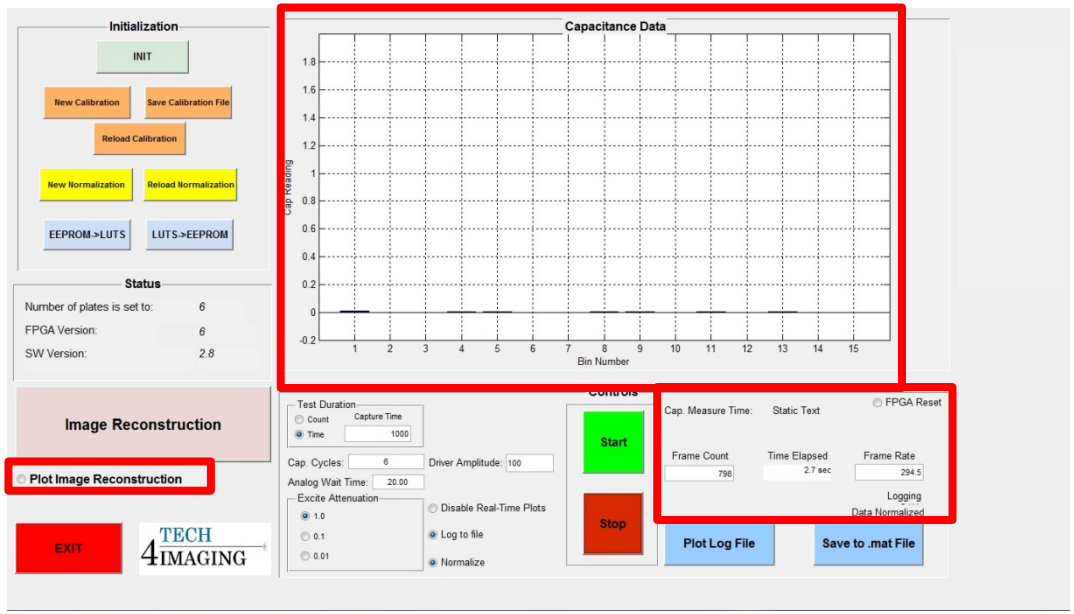
Data Acquisition

Begin test and observe collected data:

- Display capacitance readings for each plate in real time
- Can also display rough reconstructed images in real time (slows down acquisition)
- Displays frames captured, run time, frame rate
- Shows logging status and location



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Data Acquisition

- **Plot Log File**- shows evolution of capacitances over test
- **Save to .mat File**- saves all data frames for later reconstruction
- **Image Reconstruction**- opens new interface

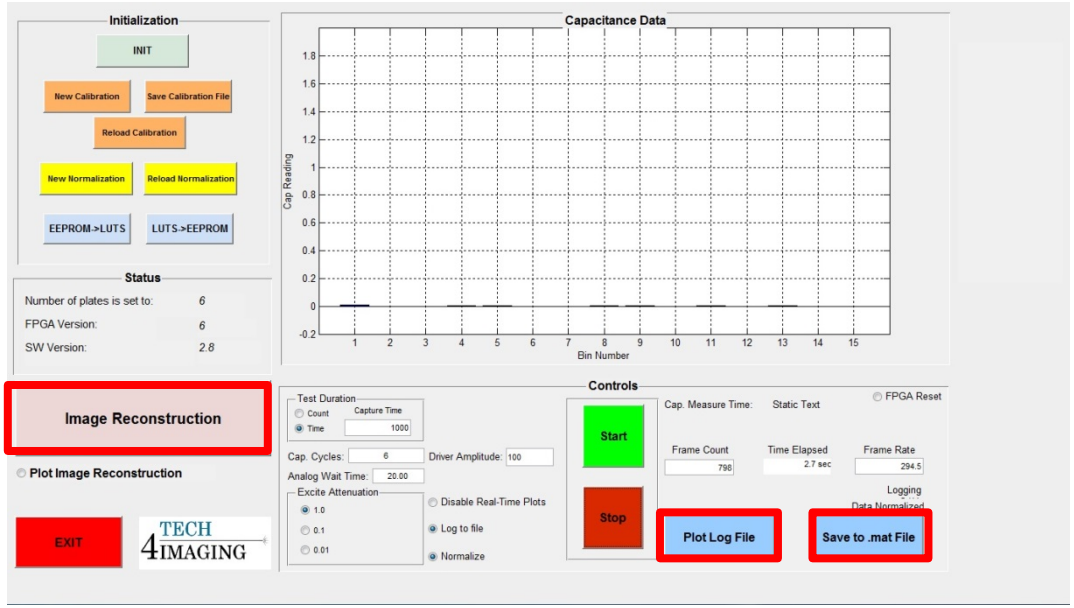

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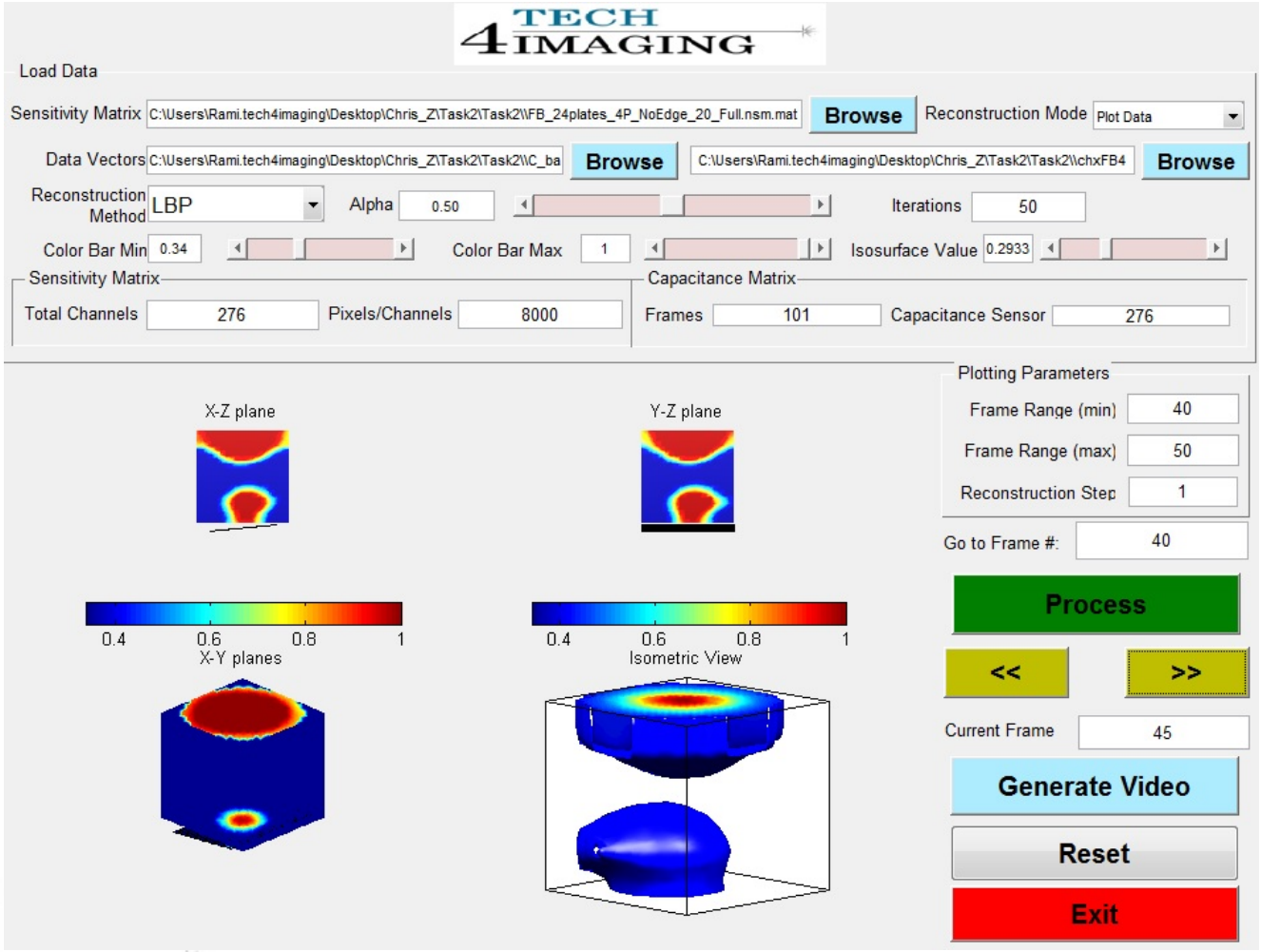
Image Reconstruction Software



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Sensitivity Matrix

- Determines relationship between sensor plates and changes in capacitance
- Studied volume divided into many small volumes (voxels)
- Matrix shows each plate pair response to capacitance change in each voxel
- Used in reconstruction algorithms to relate data to image

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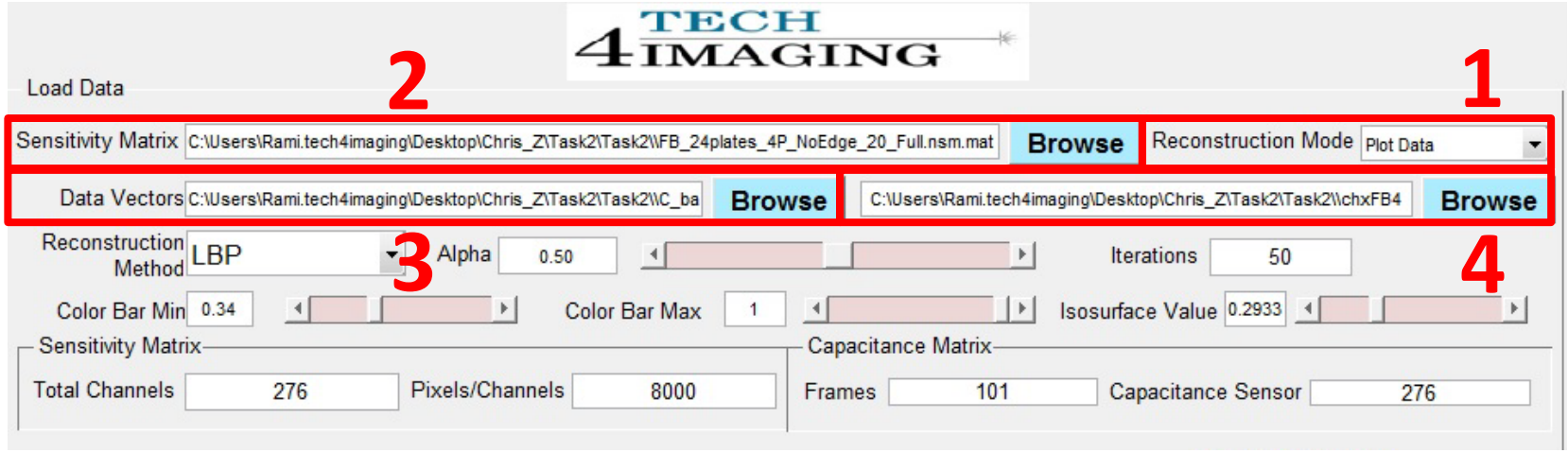
Loading Data

1. Select **“Plot Data”** as current mode
2. Select sensitivity matrix
3. Select previously-saved capacitance data vector
4. Select channel vector



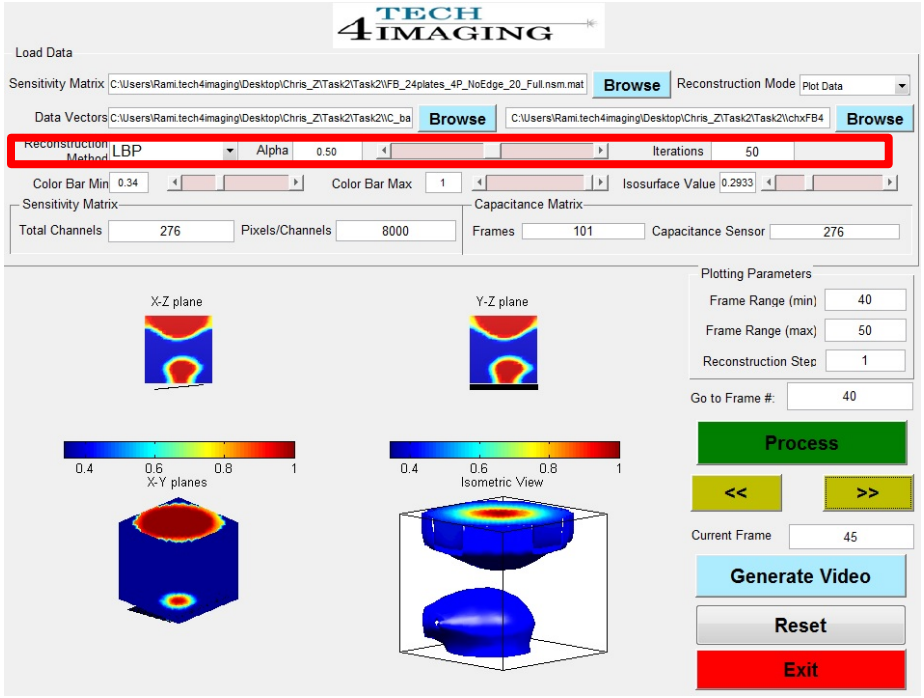
Reconstruction Methods

Three methods are available for image reconstruction:

1. **Linear Back Projection (LBP)** – Fastest, least accurate
2. **Landweber Iteration** – Slower, more accurate
3. **3-D Neural Network Multicriterion Optimization Image Reconstruction Technique (NNMOIRT)** – Slowest, most accurate

Method Parameters:

- **Alpha**
  - Landweber Method
  - Sets step size
  - Between 0 and 1
- **Iterations**
  - Landweber and NNMOIRT Methods
  - Determines iteration count for algorithm
  - Positive integer



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Linear Back Projection (LBP)

- Fastest, least accurate method
- One-equation solution:

$$\hat{g} = \boldsymbol{S}^{T} \boldsymbol{\lambda}$$

$\hat{g}$ = image vector [N terms for N voxels in image]

$\boldsymbol{\lambda}$ = normalized capacitance vector [M terms for M plate pairs]

$\boldsymbol{S}$ = sensitivity matrix [M x N]

Landweber Iteration

- Slower but more accurate method
- Image vector equation solved a set number of times:

$$\hat{g}_{k+1} = \hat{g}_k - \alpha S^T (S\hat{g}_k - \lambda)$$

k = iteration number
$\hat{g}_k$= kth image vector
$\hat{g}_0$ = initial condition zero vector = [0,0,0, … ,0]
α = relaxation factor (Between 0 and 1)
$\boldsymbol{\lambda}$ = normalized capacitance vector [M terms for M plate pairs]
$\boldsymbol{S}$ = sensitivity matrix [M x N]

- More iterations = longer solving time and more accurate image
- Alpha determines step size between iterations

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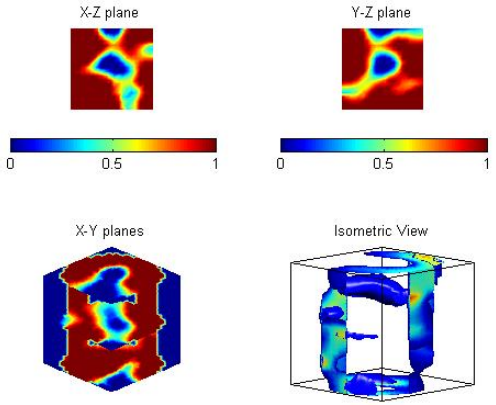
3-D Neural Network Multicriterion Optimization Image Reconstruction Technique (NNMOIRT)

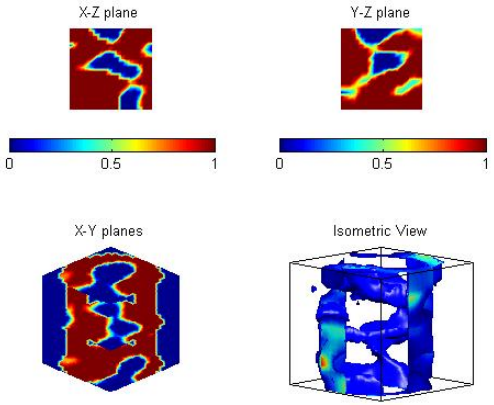
- Slowest, most accurate method
- Finds image vector $\hat{g}$ that simultaneously minimizes four objective functions:
  1. Negative Entropy
  2. Least Square Error
  3. Smoothness and Small-Peakedness
  4. 3D-to-2D Matching
- Enhances quality of 3-D image reconstruction
- Best noise filtering

Reconstruction Method Signal-to-Noise Ratio Effects

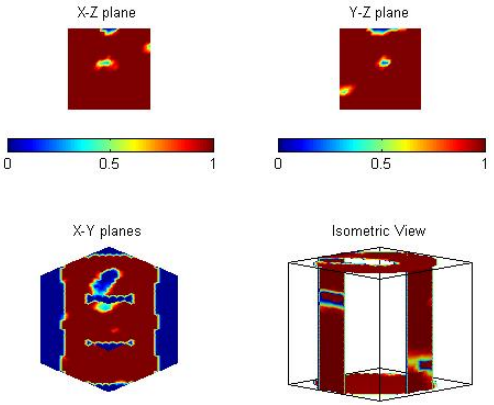
0 dB SNR



Linear Back Projection
MSE = 0.4729



Landweber*†
MSE = 1.1794



3-D NNMOIRT†
MSE = 0.2485

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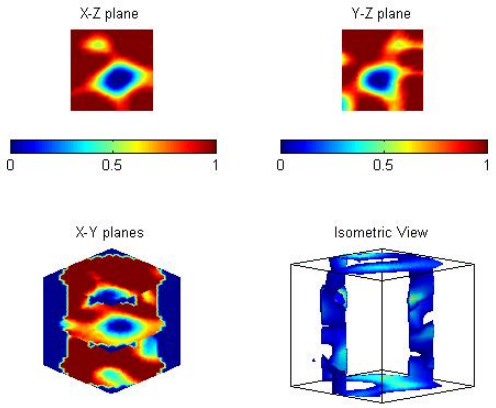
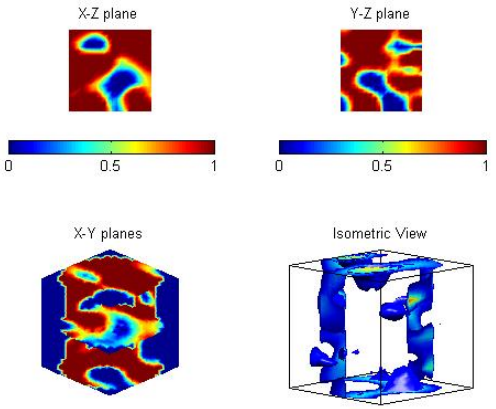
*Alpha = 0.025
†Iterations = 150

Reconstruction Method Signal-to-Noise Ratio Effects

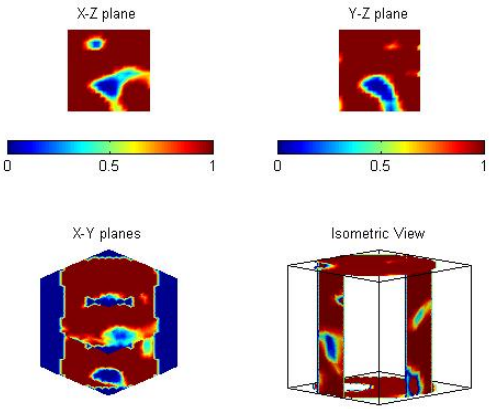
5 dB SNR



Linear Back Projection
MSE = 0.3175



Landweber*†
MSE = 0.5656



3-D NNMOIRT†
MSE = 0.2644

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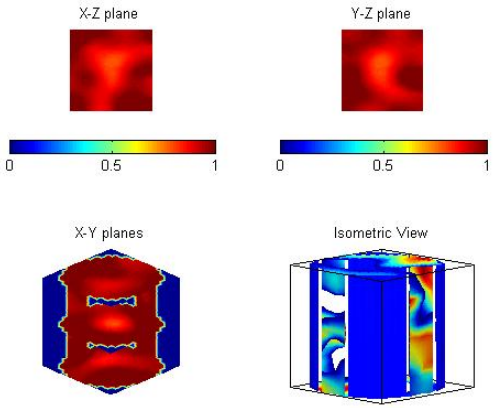
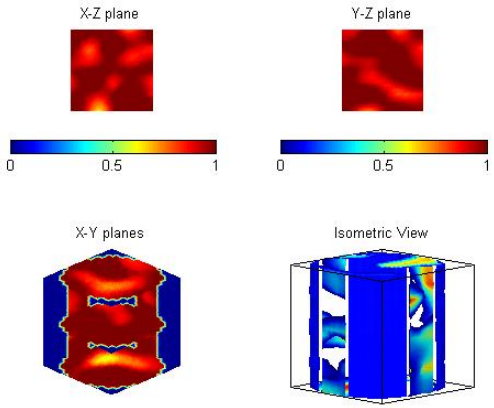
*Alpha = 0.025
†Iterations = 150

Reconstruction Method Signal-to-Noise Ratio Effects

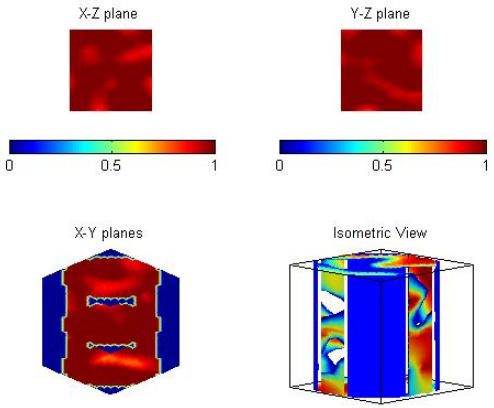
20 dB SNR



Linear Back Projection
MSE = 0.2134



Landweber*†
MSE = 0.2172



3-D NNMOIRT†
MSE = 0.2317

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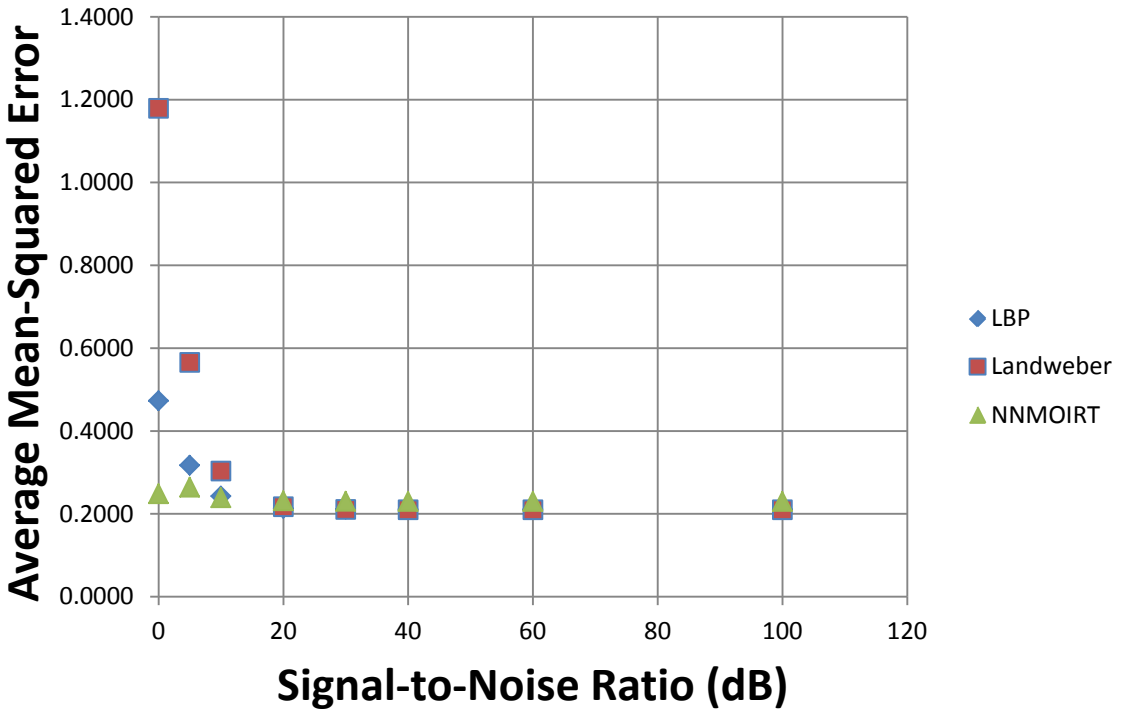
*Alpha = 0.025
†Iterations = 150

Reconstruction Method Signal-to-Noise Ratio Effects

- 3-D NNMOIRT method least affected by low SNRs
- Three methods reach maximum performance at 20 dB
- Standard DAS-2 signal-to-noise ratio is 60 dB



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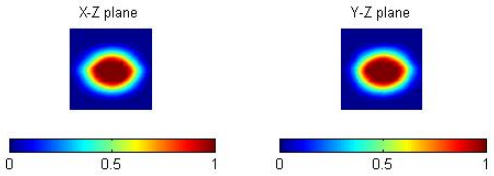
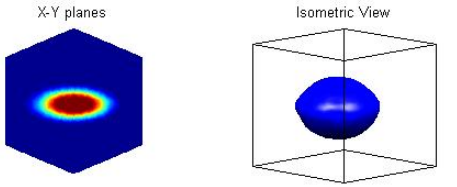
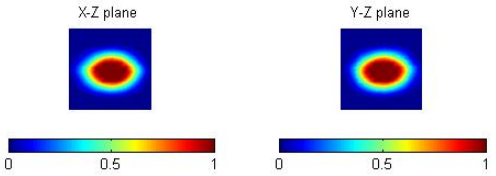
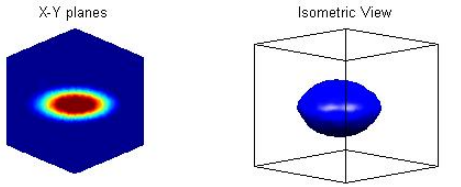
Reconstruction Method Landweber Iteration Effects



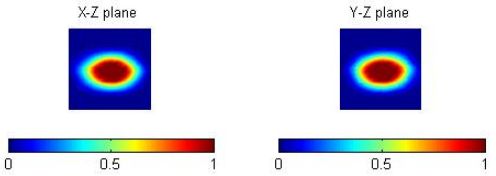


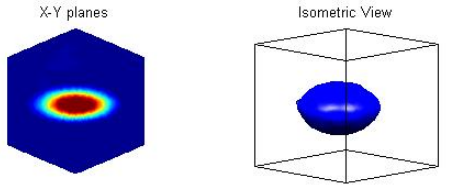
5 Iterations





25 Iterations





50 Iterations

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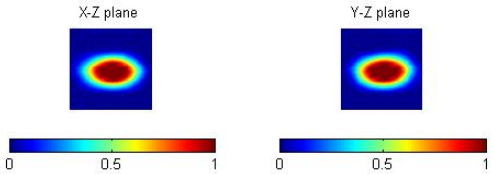
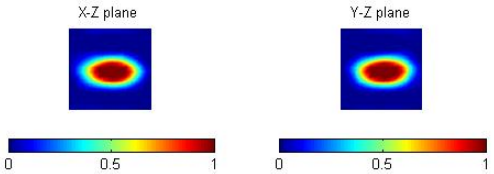
Alpha = 0.025

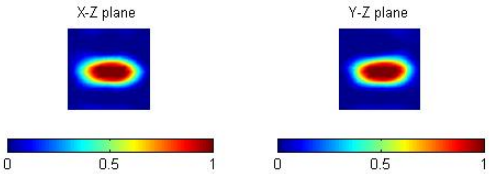
Reconstruction Method Landweber Iteration Effects



100 Iterations



200 Iterations



500 Iterations

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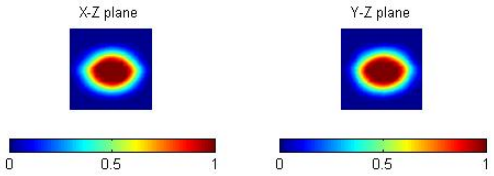
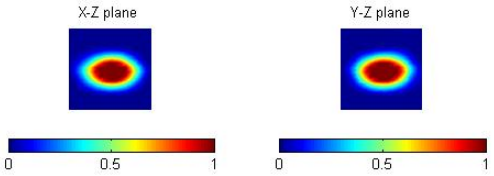
Alpha = 0.025

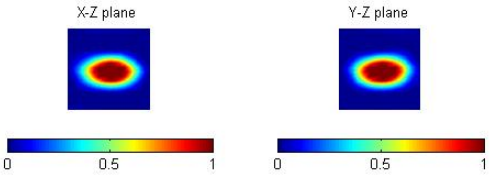
Reconstruction Method Landweber Alpha Effects



Alpha = 0.001



Alpha = 0.010

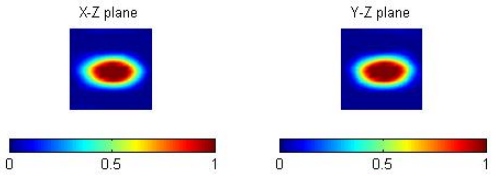


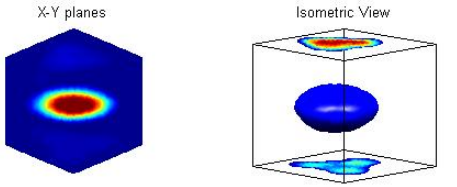
Alpha = 0.020

4TECH IMAGING

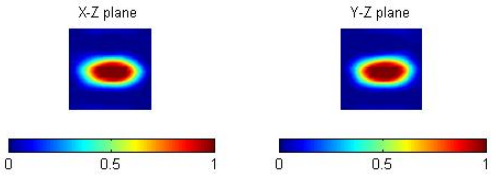
150 Iterations

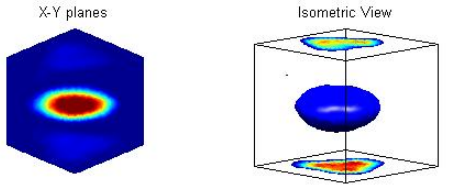
Reconstruction Method Landweber Alpha Effects



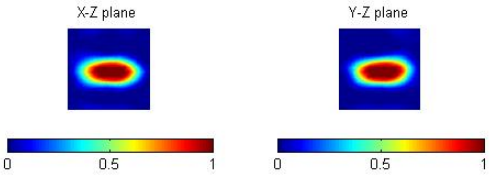


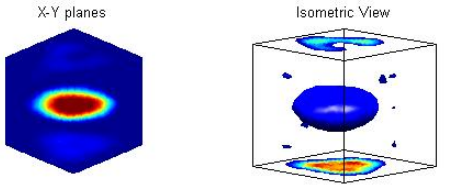
Alpha = 0.025





Alpha = 0.050



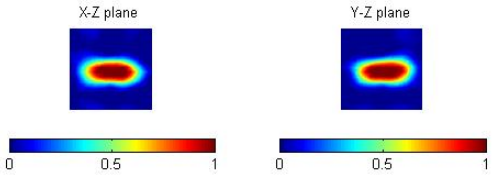


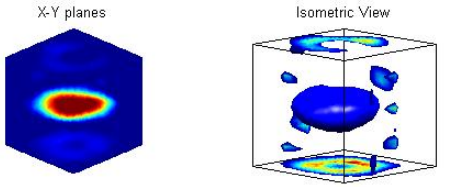
Alpha = 0.100

4TECH IMAGING

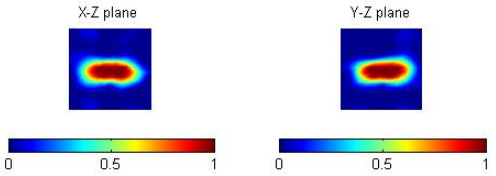
150 Iterations

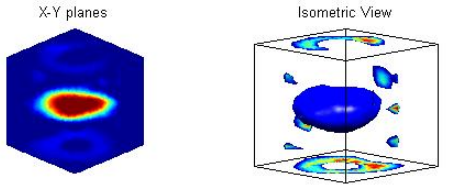
Reconstruction Method Landweber Alpha Effects



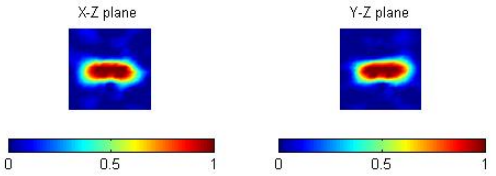


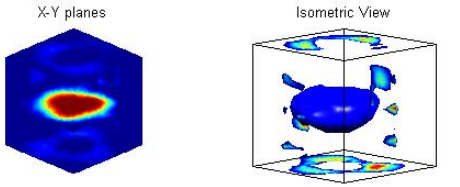
Alpha = 0.250





Alpha = 0.500



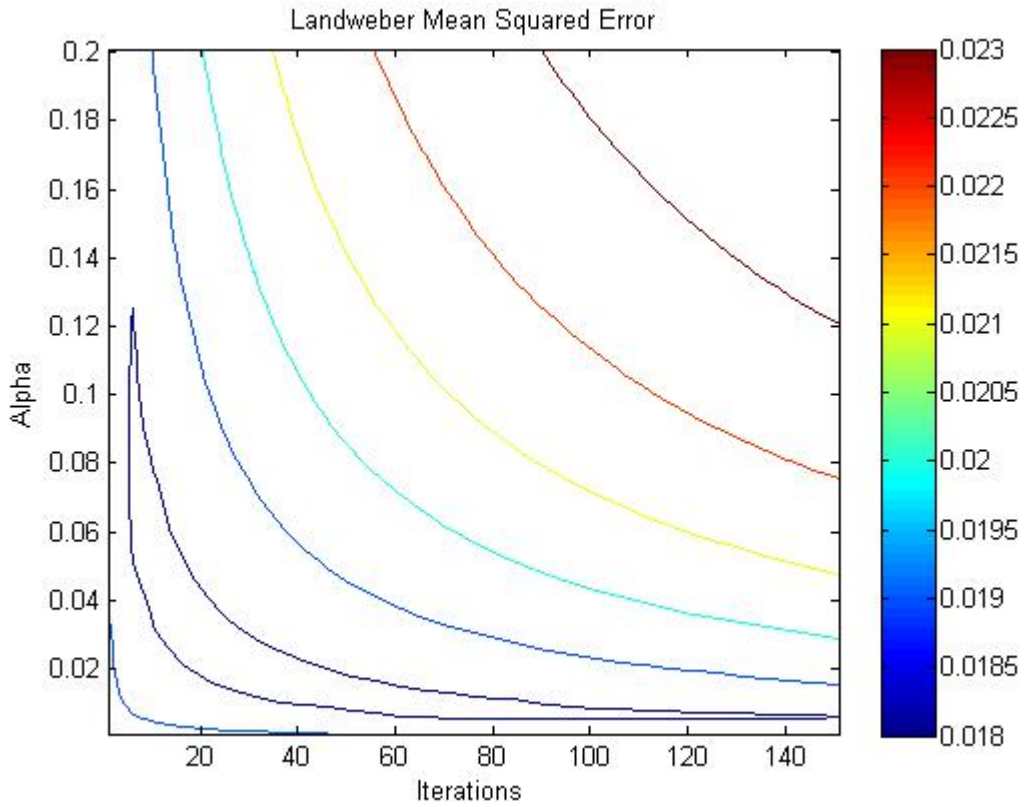


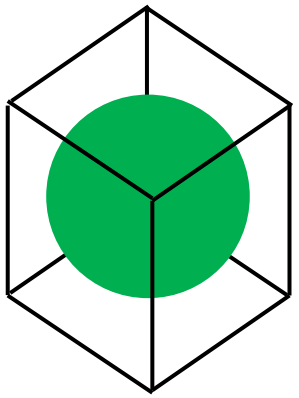
Alpha = 1.000

TECH 4IMAGING

150 Iterations

Reconstruction Method Landweber Parameter Effects



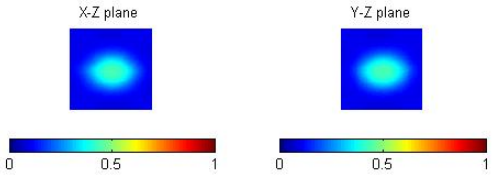


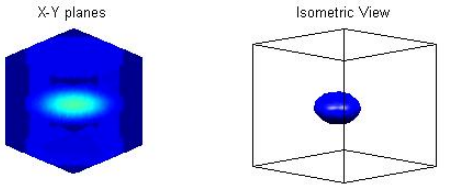
True Image:
Centered Ball

Alpha and iteration count effects on algorithm mean-squared error from ideal image

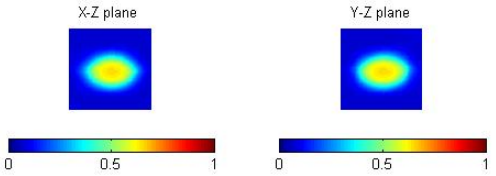
4 TECH IMAGING

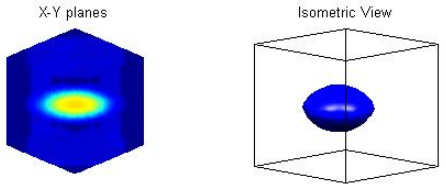
Reconstruction Method 3-D NNMOIRT Iteration Effects



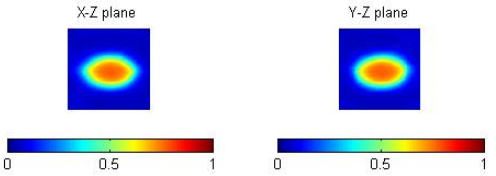


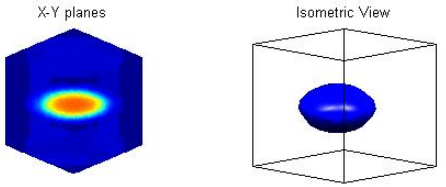
10 Iterations





25 Iterations

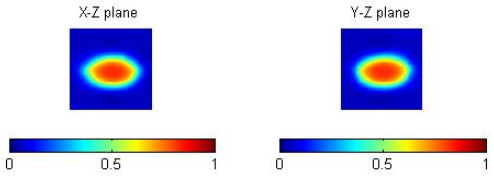


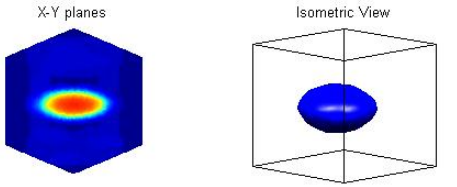


50 Iterations

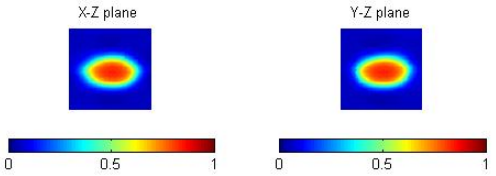
TECH 4IMAGING

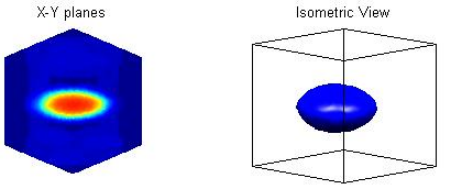
Reconstruction Method 3-D NNMOIRT Iteration Effects



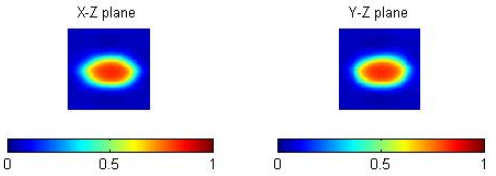


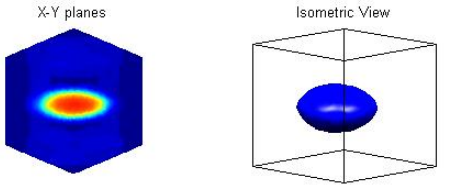
100 Iterations





200 Iterations

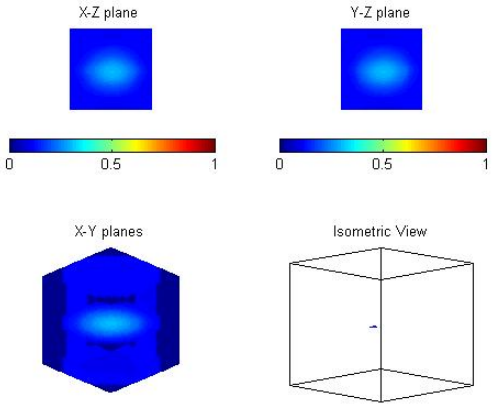




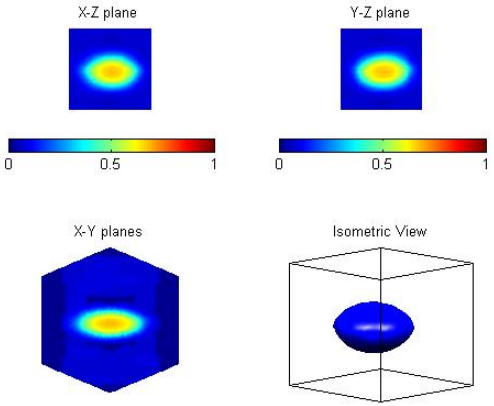
500 Iterations

TECH 4IMAGING

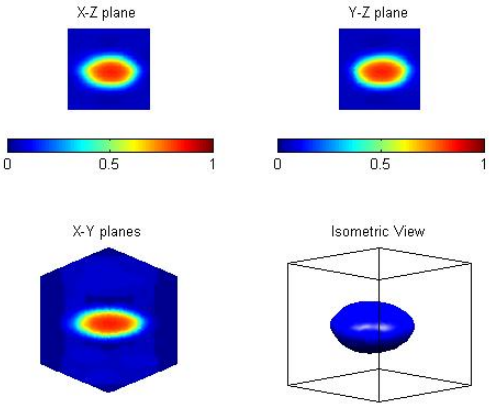
Reconstruction Method 3-D NNMOIRT Alpha* Effects



Alpha = 1



Alpha = 10



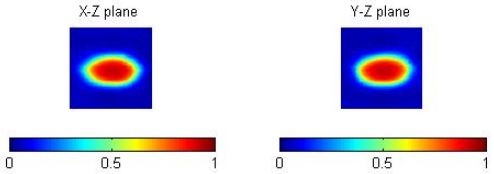
Alpha = 20

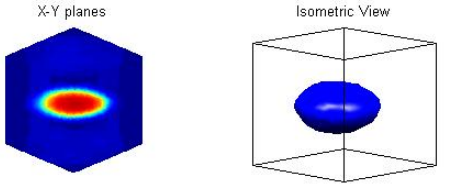
*The 3-D NNMOIRT Alpha parameter is another variable used during image reconstruction that is normally held at 20; it is not usually a controllable variable

TECH 4IMAGING

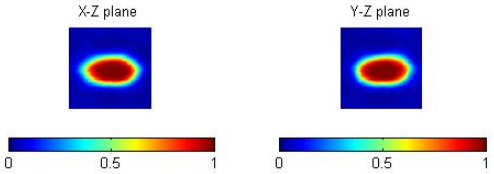
150 Iterations

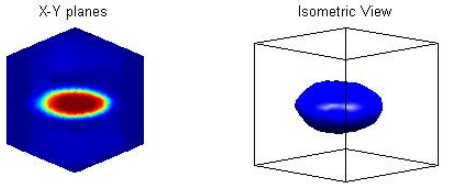
Reconstruction Method 3-D NNMOIRT Alpha Effects



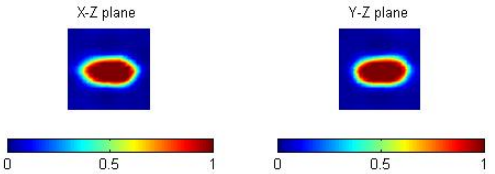


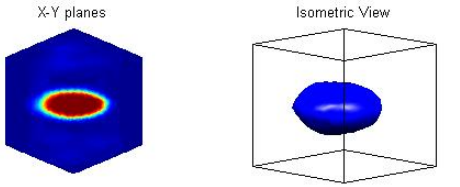
Alpha = 30





Alpha = 50



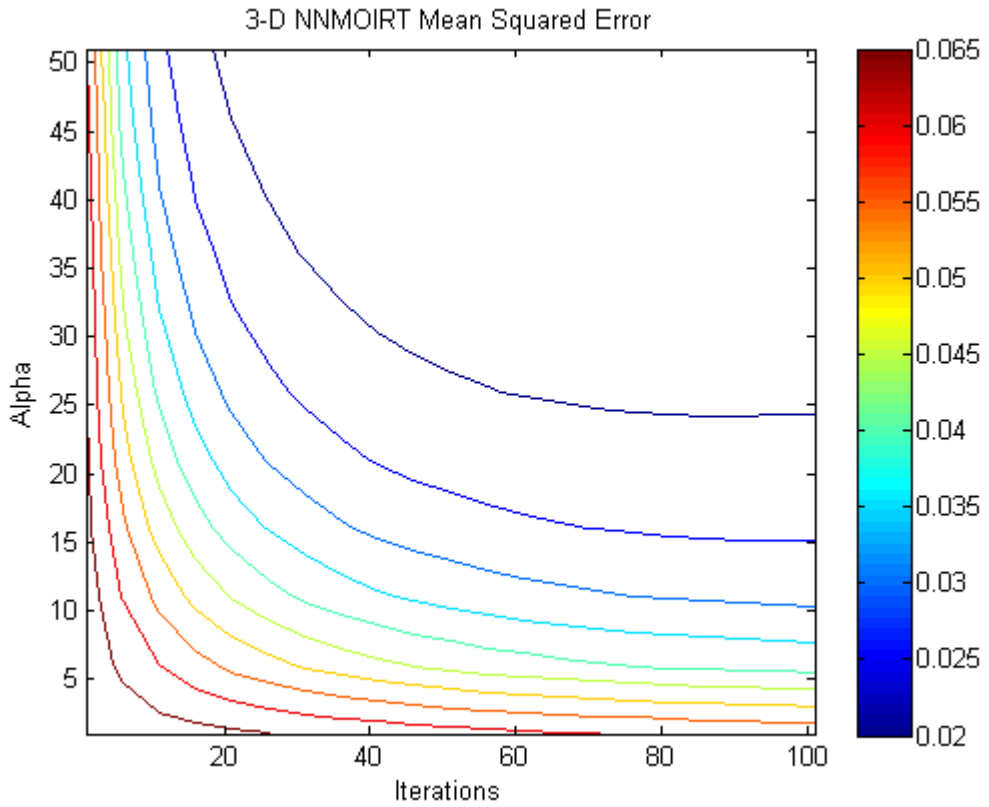


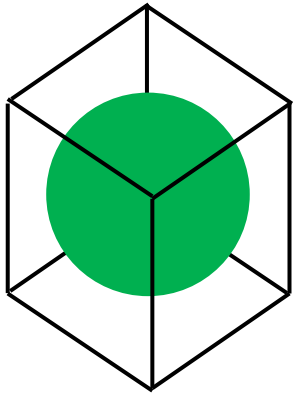
Alpha = 100

TECH 4IMAGING

150 Iterations

Reconstruction Method NNMOIRT Parameter Effects





True Image:
Centered Ball

Alpha and iteration count effects on algorithm mean-squared error from ideal image

TECH 4IMAGING

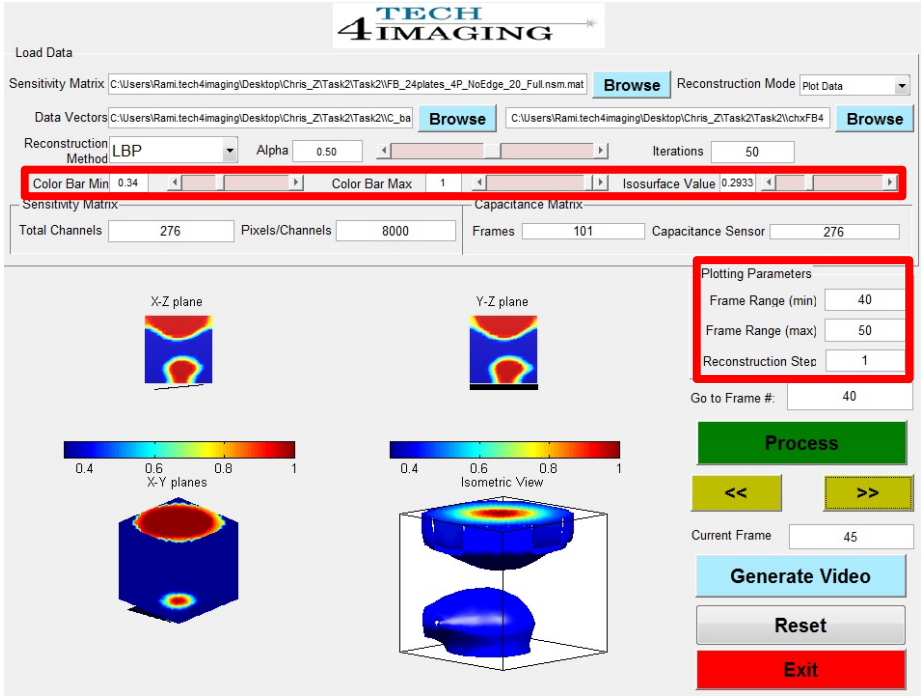
Image Reconstruction

Set plotting parameters:

- **Color Bar Min:** Normalized capacitance value that will appear dark blue
- **Color Bar Max:** Normalized capacitance value that will appear bright red
- **Isosurface Value:** 3-D isometric view scaling
- All values are between 0 and 1

Set plot range:

- **Frame Min**
- **Frame Max**
- **Reconstruction Step:** Number of frames to increment between images



TECH 4IMAGING

Image Reconstruction

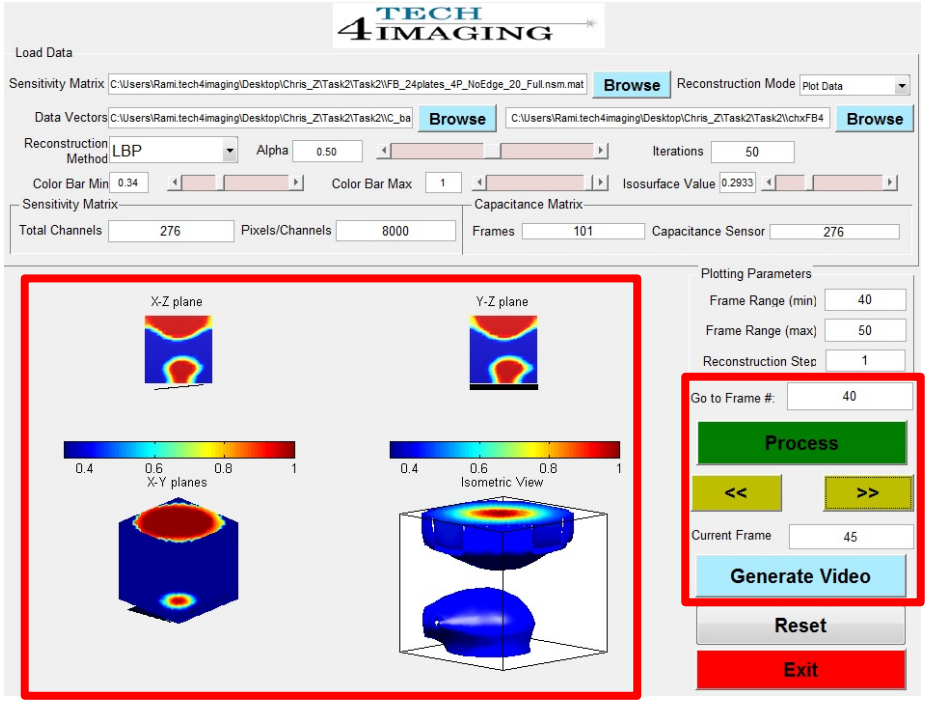
Four views of 3-D volume presented

- **XZ Plane**
- **YZ Plane**
- **Multiple XY-Plane Slices**
- **3-D Isosurface View**

Move through images

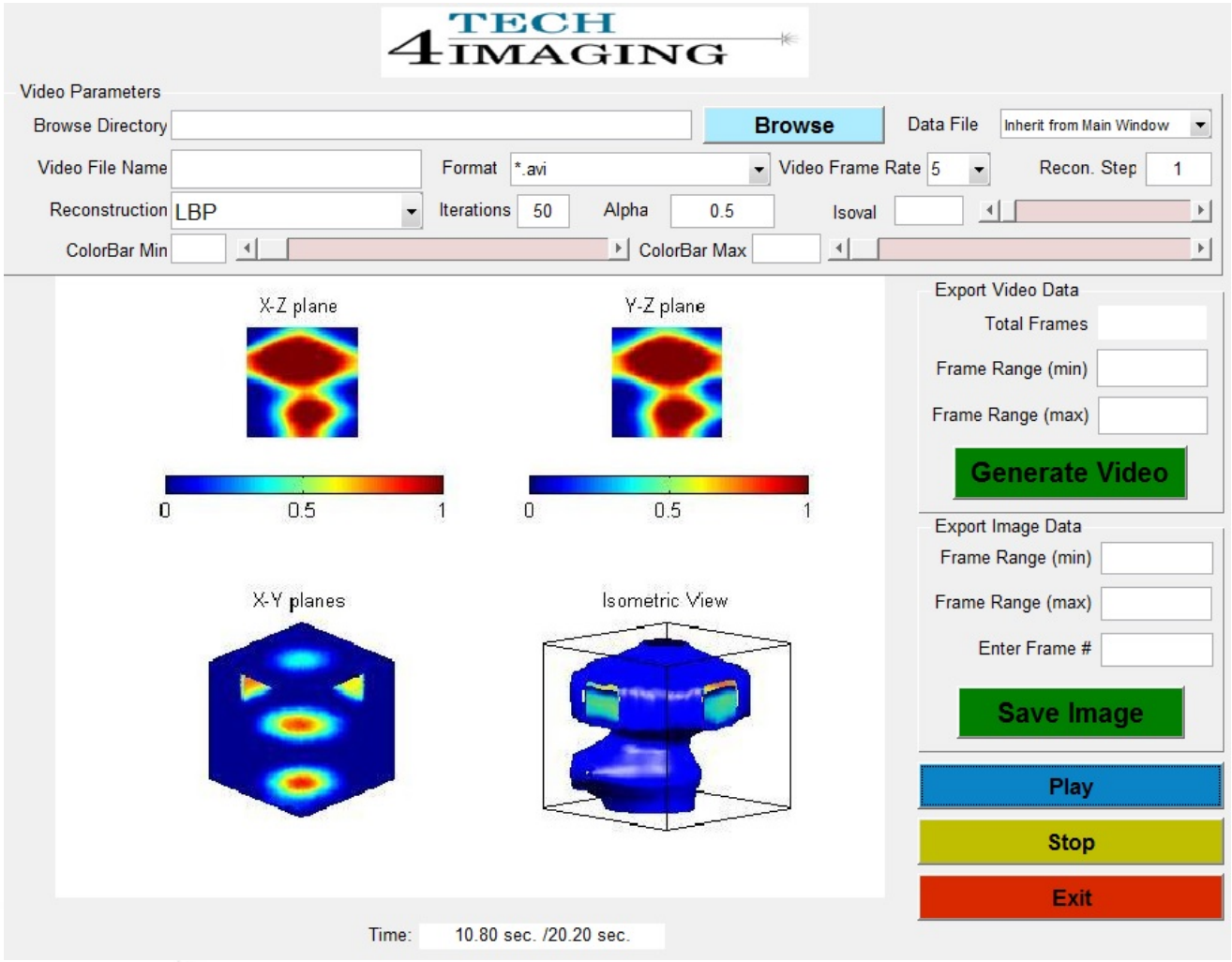
- Jump to specific frame
- Move forwards/backwards through frame range
- Only frames in defined range can be viewed

Generate Video opens new interface



TECH 4IMAGING

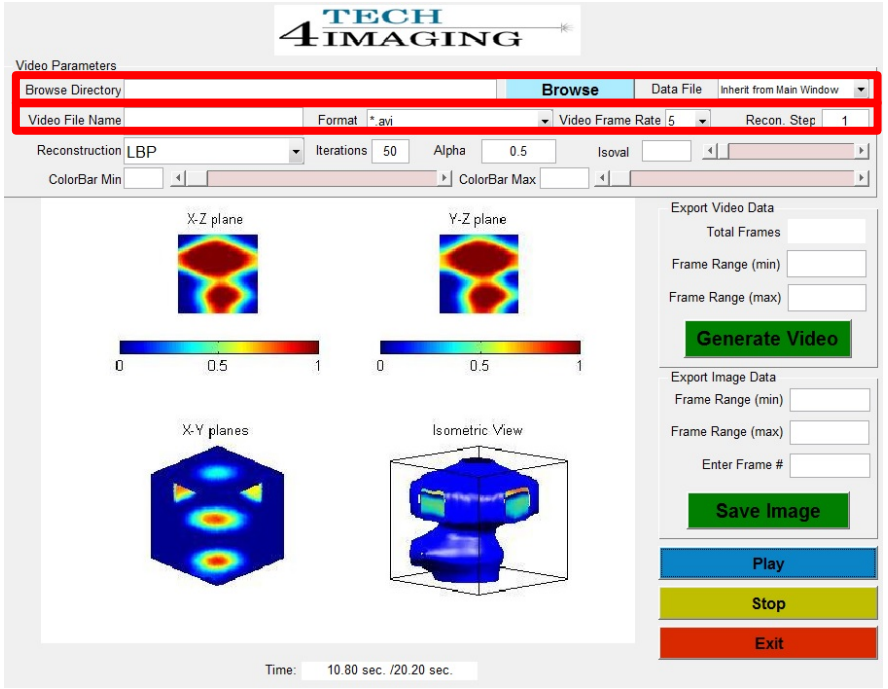
Video Generation Software



TECH 4IMAGING

Video Generation

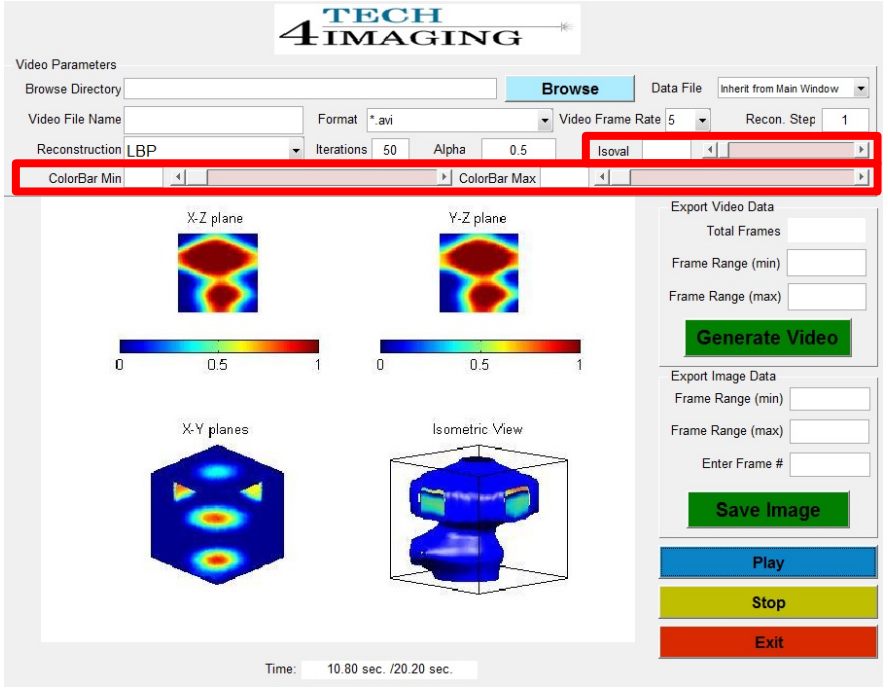
1. **Load data to use** - .mat file containing previously-reconstructed images
2. **Name video file**
3. **Select video type** - .avi, .flv, .mp4, or .mpeg
4. **Choose frame rate** - 5 to 50 frames per second
5. **Set reconstruction step** - number of frames to increment between images



TECH 4IMAGING

Video Generation

6. Set plotting parameters
   - Color Bar Min
   - Color Bar Max
   - Isosurface Value



TECH 4IMAGING

Video Generation

Generate Video

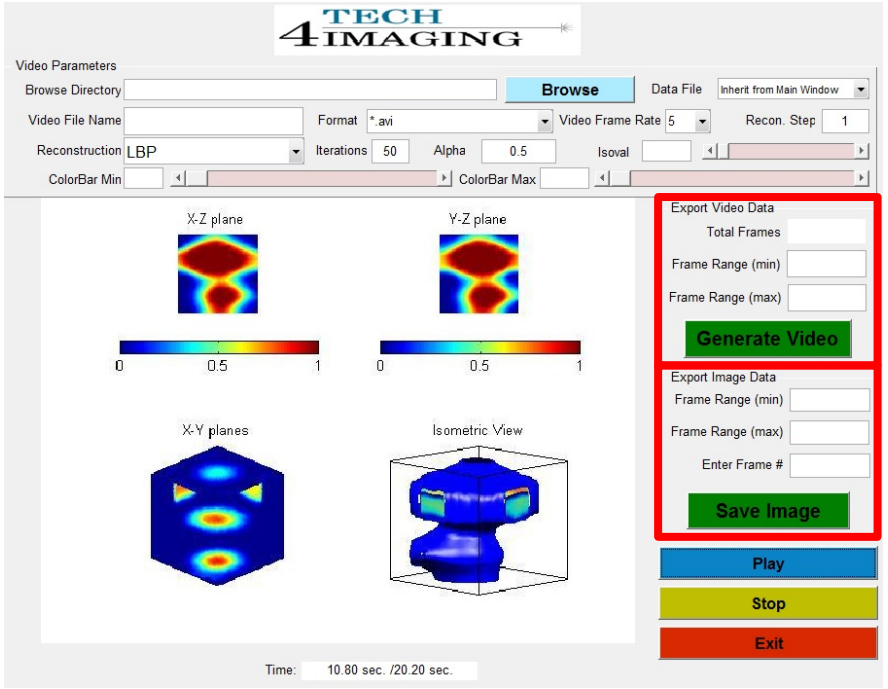
- Set range of frames to include
- All frames included if range not specified
- Press "**Generate Video**"

Generate Images

- Set range of frames to generate

  or

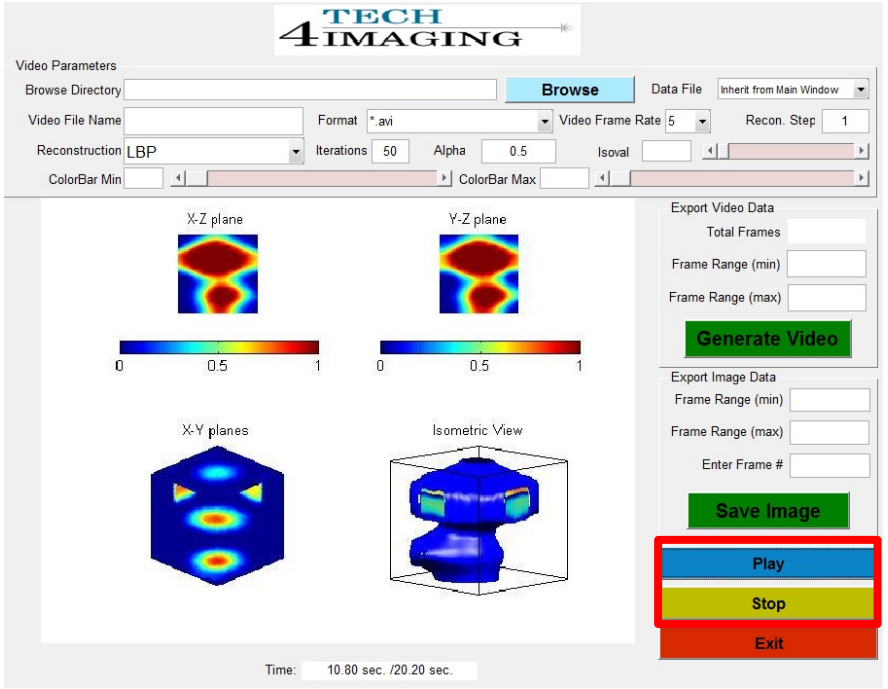
- Enter specific frame number
- Press "**Save Image**"



TECH 4IMAGING

Viewing Videos

1. Press yellow button (will display "**Browse**")
2. Select video
3. Press blue button (will display "**Play**")
4. Play video
   - Blue button now displays "**Pause**"
   - Yellow button now displays "**Stop**"
5. Stop current video to select another



TECH 4IMAGING

ECVT Video