*** IMPORTANT ***

*** OPERATING AND SAFETY PRECAUTIONS ***

*** STATIC CHARGE WARNING ***

The use of an ECT sensor with moving dielectric fluids in an insulating pipe can give rise to the development of high electrostatic potentials on the sensor and pipe which could create a safety hazard for both the operator and the plant. Any implications for the safety of the plant being monitored should be carefully considered before using the ECT system. In particular, the sensor metalwork should be solidly grounded and connected electrically to any adjacent metallic pipework to protect the operator. If installation of the sensor causes an insulated break in a run of metallic pipework, the two sections of pipe should be bonded together using a substantial electrical link which must also be connected electrically to the outer shield of the sensor.

The input channels of the DAM200E Capacitance Measurement Unit (CMU) contain CMOS circuitry. Because of the nature of the measurement of very small values of capacitance used in the system, it is not possible to fully protect these inputs. It is therefore very important that any sensors connected to the inputs of this unit are fully discharged before connections are made. All sensors used with the DAM200E unit should include built-in discharge resistors of no more than 1 Mohm in value, connected between the individual sensor electrodes and the screens of the coaxial connecting leads, to ensure that static charge cannot build up on the sensor electrodes.

ELECTROMAGNETIC COMPATIBILITY

The PTL300E ECT system is a sensitive scientific instrument. Under normal operating conditions, the system will not cause problems to other electronic equipment provided that the ECT sensor used with the system is adequately screened and grounded.

However, the PTL300E system may be adversely affected by high levels of electrical interference because of its high measuring sensitivity. If these problems persist, please contact PTL for advice on solutions to these problems.

INTRINSIC SAFETY DISCLAIMER

The PTL300E ECT system has not been certified for use in applications which require intrinsic safety certification and must not be used in applications where intrinically-safe equipment is mandatory.
ACKNOWLEDGEMENTS

The PTL300E Electrical Capacitance Tomography System is manufactured under licence from the University of Manchester Institute of Science and Technology (UMIST). The design is protected by British and foreign patents.

WARRANTY

This equipment is warranted by Process Tomography Ltd., (the Company) against any defects of materials or workmanship for a period of one year from the date of despatch. In the case of components employed in this equipment but not manufactured by the Company, the manufacturer's warranty will apply.

During the warranty period, the Company will repair or, at the Company's option, replace any warranted item that proves on examination to be defective, provided the equipment is returned, carefully packed and carriage prepaid to the Company, together with full details of the claimed fault.

This warranty is in all cases limited to the cost of making good the defect in the equipment itself. It does not apply to defects caused by abnormal conditions of working, accident, misuse, neglect, wear and tear, or to equipment which has been repaired or altered other than by a person authorised by the Company.

In no event shall the Company be liable for any damages or injury which may result from the use or misuse of this product by the purchaser, his employees or others, or for any incidental or consequential damages.

To register a claim under the provisions of this warranty, please contact the Company for instructions for returning the equipment.

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ELECTRICAL CAPACITANCE TOMOGRAPHY

Electrical Capacitance Tomography (ECT) is a technique for measuring the permittivity distribution of a mixture of 2 dielectric materials inside a closed vessel, from which the concentration distribution can be found. It is a research tool which allows measurements to be made on process plant which were previously either difficult or impossible to realise. This instruction manual contains a broad spectrum of information about electrical capacitance tomography, as well as specific operating instructions for the PTL300E single and twin-plane ECT systems. The PTL300E-SP-G system allows data from one axial plane of electrodes to be imaged while the PTL300E-TP-G system allows data from one or two planes to be imaged simultaneously.

HOW TO USE THIS MANUAL

This manual applies to both single and twin-plane PTL300E ECT systems. Where appropriate, data which applies only to twin-plane systems is contained within square brackets [ ] and should be ignored by users of single-plane systems. The manual is divided into nine main sections.

Section 1, consisting of chapters 1 and 2 contains basic information about how to set up the ECT system and check it for correct operation. Full detailed operating instructions are given in section 5.

Section 2, consisting of the single chapter 3, contains an overview of ECT technology and provides a brief introduction to Electrical Capacitance Tomography.

Section 3 (chapters 4-7) gives further detailed information about the PTL300E ECT system, including the principle of operation of the ECT hardware and explains how the ECT system measures the inter-electrode capacitances of the ECT sensor.

Section 4, which contains chapters 8 to 15, explains how ECT images are reconstructed from the capacitance measurements.

Section 5, consisting of chapters 16 to 30 gives detailed information about the operation of the ECT system using the ECT32v2 software.

Section 6 (Chapter 31) Describes the operation of a file conversion utility for converting data files from previous versions of PTL ECT systems into ECT32v3 format.

Section 7 (Chapter 32) describes the ECT Toolkit utilities which provide diagnostic and maintenance facilities for the ECT system software and firmware and which allow the ECT system to be used directly for capacitance and other measurements.

Section 8 Contains a set of Frequently Asked Questions (FAQs) and answers about ECT technology.

Section 9 contains a number of Appendices which give further detailed information about the ECT system, including data file formats, circuit constants and additional software utilities.

First time users should read sections 1 and 2. When the system has been successfully set up and tested, the remainder of the manual should be read to familiarise the user with the details of the ECT system and its operation. Most of the functions of the system can be checked using the demonstration sensor[s] supplied with each system. Once the ECT hardware and software have been mastered using the demonstration sensor[s], users will want to apply the system to custom sensors on their own plant. Process Tomography Ltd can provide advice to users to enable them to design their own custom sensors or can arrange for custom sensors to be designed and supplied to customers on request.
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SECTION 1 BASIC INFORMATION

This initial section, consisting of chapters 1 and 2, explains how to unpack and set up the ECT system and gives simplified instructions for testing the system using one of the demonstration sensors supplied with the system.
1. POST-DELIVERY INSTRUCTIONS

1.1 UNPACKING THE SYSTEM

Following delivery of the ECT system, the system components should be unpacked, identified and checked for shortages against the delivery note. Any damage or shortages should be notified to the carrier and to PTL immediately.

1.2 SYSTEM COMPONENTS

Figure 1.1 shows the main components of a Twin-plane PTL300E ECT system. Figure 1 shows a DAM200E Capacitance Measurement Unit (CMU) a personal computer and two 12 element demonstration capacitance sensors.

A standard PTL300E ECT system consists of the following items:

- Desktop or Notebook personal computer loaded with PTL ECT software.
- DAM 200E single [or twin-plane] Capacitance Measurement Unit.
- 1 [2] X demonstration 12 element capacitance sensor[s].
- 3 X IEC mains leads (for PC, monitor and DAM200E).
- This instruction manual.
- Set of 4 x PTL application notes.

Software Manuals as follows:

- IU2000 off-line image reconstruction software
- MatPTL off-line software utilities
- CD ROM(s) containing software.

1.3 POWER SUPPLY INFORMATION

The DAM200E unit will accept voltages from 90-240V, 50 or 60Hz. The desktop PC will be supplied with a power supply suitable for the country in which the PC is to be used.
Figure 1.1 A PTL300E Twin-plane ECT system
2. QUICK START INSTRUCTIONS

This chapter gives a rapid introduction to some of the important features of the PTL300E ECT system and demonstrates how to calibrate, capture and playback data using the ECT32 software and one of the demonstration sensors supplied with the ECT system. Full details of the ECT system hardware and software are given in subsequent sections of this manual.

******* STATIC CHARGE PRECAUTIONS *******

The input channels of the DAM200E CMU contain sensitive CMOS electronic circuitry. Because of the nature of the measurement of very small values of capacitance used in the system, it is not possible to fully protect these inputs. It is therefore very important that the electrodes of capacitance sensors are not allowed to become electrically charged with respect to earth before they are connected to the DAM200E unit. All capacitance sensors used with the DAM 200E unit must include built-in discharge resistors of no more than 1 Mohm in value, permanently connected between the individual sensor electrodes and the screens of the coaxial connecting leads, to ensure that static charge cannot build up on the sensor electrodes.

2.1 THE DAM200E CAPACITANCE MEASUREMENT UNIT (CMU)

The front panel layout of the CMU is shown in figure 2.1.1. There are 5 indicator lamps (LEDs) and 4 sets of 12 x SMB miniature coaxial connectors, two sets for the Plane 1 and Plane 2 Measurement Electrode channels and a further two sets for the Plane 1 and Plane 2 Driven Guard Electrode channels.

The connectors for the Capacitance Measurement channels are located on the lower half of the front panel and are labelled M1 to M12. The Plane 1 set are at the bottom of the panel with the Plane 2 set located directly above those for Plane 1.

The connectors for the Driven Guard channels are located on the top half of the panel and are labelled G1 to G12. Again the Plane 1 set is located below the Plane 2 set.

The rear panel of the CMU is shown in figure 2.1.2. The mains power input (IEC) socket, switch and fuse are located at the RHS of the panel when viewed from the rear of the unit. Other items on the rear panel are a LAN 10/100 MB/S Ethernet connector, a 3-pin DIN trigger input/output connector and a diagnostic serial (RS232) port.
Figure 2.1.1 DAM200E CMU Front panel layout
Figure 2.1.2. DAM200E CMU Rear panel layout
2.2 SETTING UP THE ECT SYSTEM

1. Assemble the demonstration sensors as described in Appendix 2 (first time of use after unpacking only).

2. Connect the mains lead supplied with the ECT system to the power input connector on the rear panel of the DAM200E CMU. Do not switch on the CMU yet.

3. Connect the coaxial leads from one of the sensors to the Plane 1 Measurement Electrodes input channel connectors (the lower row of connectors) on the front panel of the CMU, ensuring that each numbered sensor lead is connected correctly to the appropriate numbered input channel connector (M1 to M12) on the DAM200E unit. Note that the channel numbers start at 2 on the right hand end of the front panel and that channel 1 is next to channel 12 on the CMU. As the demonstration sensors do not contain driven guard electrodes, no connections should be made to the Guard channels on the DAM200E unit.

3. Connect the crossed ethernet cable supplied with the ECT system between the CMU (standard LAN ethernet socket on rear panel labelled “10/100 Ethernet Port”) and the ethernet port on the Control PC. If the PC contains 2 LAN connectors, use the one on the rear panel of the the separate LAN plug-in circuit board. Do not use the one on the PC motherboard.

Note that additional information about using the ECT system when the CMU and the control PC are connected to a local area network can be obtained from PTL on request.

3. Connect up the remainder of the system as shown in figure 2.2.1. Do not make any connection to the trigger input/output connector or the diagnostic serial port on the rear panel.

![Figure 2.2.1 ECT system interconnection diagram](image-url)
2.3 POWERING UP THE SYSTEM

1. Switch on the PC and the DAM200E Capacitance Measurement Unit (mains switch on rear panel). Both the Embedded PC inside the DAM200E unit and the Control PC will start their boot-up sequences.

At the start of the Embedded PC boot sequence, all of the front panel LEDs, (apart from the Trigger Input LED) will illuminate on the DAM200E unit. Approximately 10 seconds later, 2 beeps will sound from the embedded PC and after another 10 seconds, all of the front panel LEDs, apart from the Supply On LED, will extinguish. After a further 2 seconds, when the embedded PC has completed its boot sequence, the internal software on the embedded PC will start to run and the firmware status LED on the front panel will start to flash on and off at 1 second intervals.

When the control PC has completed its start-up sequence, the PC monitor will display the Windows Desktop.

Once both computers have completed their start-up sequences and the Firmware status LED is flashing on the CMU, proceed to step 2 below.

2. Double-click on the ECT software shortcut on the Desktop. The ECT software group window shown in figure 2.3.1 will appear.

![ECT Program Group window](image)

Figure 2.3.1 ECT Program Group window
2.4 THE CONFIGURATION WINDOW

1. Double click on the ECT32v2 icon in the ECT program group window. The Configuration window, shown in figure 2.5.1 below, appears each time the ECT32 software is run and allows some of the important software set up parameters to be defined and/or initialised.

![ECT32 Configuration Window](image)

**Figure 2.4.1 ECT32E Configuration Window**

2. Left click the **Restore Defaults** button at the bottom of the Configuration window, then click in the Plane 2 box in the Data Sources parameter group to deselect plane 2.

3. Check the Configuration parameters and, if necessary, modify any parameters which differ from those shown in figure 2.4.1. The most likely change needed will be to the Sensor Information file which should be set to SSM12_32.sif using the Browse button.

4. Left click the **Setup System** button at the bottom of the Configuration window. The network connection window shown in figure 2.4.2 will appear.
5. If necessary, reset the correct network address for the DAM200E CMU and click on OK.

The Link Status LED on the CMU front panel will light and the 2-point ECT Calibration window shown in figure 2.4.1 below, will appear.

2.5 SYSTEM CALIBRATION

The demonstration sensor is calibrated by following the instructions which appear in the calibration windows. The sensor is first filled with the lower permittivity material (in this case air) by standing the sensor vertically on end with the electrodes at the top of the tube. It is next filled with the higher permittivity material (polypropylene beads) by inverting the tube so that it is again vertical, but this time with the electrodes at the bottom of the tube. This is carried out as follows:

1. With the PC displaying the calibration window shown in figure 2.5.1, fill the demonstration sensor with the lower permittivity material (air) by inverting the sensor so that the electrodes are at the top of the sensor tube and click the Next button. After a short pause, followed by a beep, the screen changes to that shown in figure 2.5.2.
2. Now fill the demonstration sensor with the higher permittivity material (plastic beads) by inverting the sensor tube so that the electrodes are at the bottom of the tube and again click the Next button. After a short pause, followed by a beep, the screen changes to that shown in figure 2.5.3.

3. Click on the Save file button and save the calibration data to a suitable file name in the Working folder. Note that the file extension .cal is added automatically to saved calibration file names.

4. Click on the Done button to complete the calibration process. The ECT system and sensor are now calibrated and ready to carry out on-line measurements, so the screen changes to the main ECT32 window shown in the next paragraph.
2.6 DATA CAPTURE

Once calibration has been completed, the main **ECT32 window** (the **ECT32 Desktop**) appears and a **live image** of the contents of the sensor contents is displayed as shown in **figure 2.6.1** at the **default frame rate** (50 fps). This image is likely to be that of a **full sensor**, as it follows immediately after sensor calibration with the **higher permittivity material**. This **data is being captured** on a continuous basis, to a **circular buffer file in memory**.

![Figure 2.6.1 Main ECT32 window (ECT32 Desktop)](image)

An **image** of the **full tube** is displayed in **red** using a **colour scale** which goes from **blue (filled with lower permittivity material)** via **green**, to **red (filled with higher permittivity material)** The user should experiment by tilting and/or twirling the **demonstration sensor** to see the images produced by a partially-filled sensor.

The data display format can be varied as follows:

1. **Left click the Plane 1 capacitances icon** (icon 18). This will open a new window, displaying the **normalised capacitances** as shown in **figure 2.6.2**
These capacitances are displayed as sets of **vertical lines** (with a gap between each set) where each line represents the **normalised capacitance** on a nominal scale from 0 to 100%, with facilities for 30% over and under-range values. The first set of lines are the capacitances $C_{12}$ to $C_{1E}$ in order (where $E$ is the total number of electrodes), the second set is $C_{23}$ to $C_{2E}$ and so on.

The **volume ratio** calculated from the normalised capacitances is displayed on a scale at the right hand edge of the capacitance window.

2. Move the **sensor** so that the image changes. Data is being **continuously captured** to a **rolling memory buffer**, whose size is determined by the figures set in the **Frames** and **Time** boxes in the **control panel**. The buffer is **continuously overwritten** as it is filled.

3. Click the **Stop button** in the **control panel** (shown in detail in **figure 2.7.1**). Data collection will cease and the system will automatically revert to **Playback mode**. Note that the **Playback button** is now depressed and that the number of frames captured and the **Time** in seconds are displayed in the **control panel**.

4. The **data** in the **memory buffer** is automatically saved to the **hard disk** each time that the system changes from **Capture mode** to **Playback mode**. The default file name is **buffer.cap**.
2.7 REPLAYING CAPTURED DATA

![ECT32 Control Panel](image)

Figure 2.7.1 ECT32 Control Panel

1. Click the **forward play** [>] button on the **control panel** (second button from the right). The image data will be replayed and the **current image number** and the **time from the start of data collection** are displayed at the top of the image window and also on the right hand end of the **status bar** at the **bottom** of the window.

2. Click the **reverse play** [<] button (to left of **stop** button) on the **control panel**. The captured data will be replayed in **reverse order**.

3. Click the **Go to last frame** [>] and **Go to first frame** [<] buttons at the edges of the **control panel** in turn. Note that these set the **displayed image** to the **last** and **first** captured **frames** respectively.

4. Click the **increment one frame** button [\(\Delta t\)]. The image will advance to the next frame. Similarly, click the **decrement one frame** button [\(<\Delta t\)]. The image will change to the previous frame.

5. Position the **mouse cursor** inside the **permittivity image** and left click the cursor. The **pixel under the cursor** is highlighted as a **white square** (the **pixel probe**) and the **normalised pixel permittivity** is displayed at the **bottom of the image**. A **sample permittivity image** is shown in figure 2.7.2 where the **pixel probe** indicates a **pixel value** of **0.99**. Move the mouse cursor outside the image and click again to turn off the pixel probe.

6. Note that the **Record button** has not been active so far. The function of this button is described later in chapter **25**.

7. **Exit** the ECT32 software by clicking on the **X box** at the **top right hand corner** of the screen. The system will prompt with the message “**Do you really want to exit from ECT32?**” Respond by clicking the **Exit ECT32** button.
2.8 TESTING THE SYSTEM USING A SENSOR CONNECTED TO PLANE 2

The sensor connected to plane 2 can be tested in a similar manner by repeating the steps in paragraph 2.4 but by connecting a sensor to plane 2 and selecting plane 2 rather than plane 1 in the Configuration window.

2.9 TESTING BOTH SENSOR PLANES SIMULTANEOUSLY

Similarly, with demonstration sensors connected to each measurement plane on the DAM200E unit, 2 measurement planes can be displayed simultaneously by repeating the steps in paragraph 2.4 but selecting both Planes 1 and Plane 2 in the Configuration window.

2.10 THE NEXT STEPS

This completes the quick tour of the ECT32 software. Detailed operating instructions, including a full description of the various windows and controls are given in section 5.

N.B In case of difficulty, please re-check the set up of the hardware and check that the software settings are correct as described above. If the problems persist, please read the detailed operating instructions given in section 5.
SECTION 2.

INTRODUCTION TO ELECTRICAL CAPACITANCE TOMOGRAPHY

In this section, consisting of a single chapter (3), the fundamental principles of Electrical Capacitance Tomography (ECT) are explained in a concise format. Further, more detailed information can be found later in this manual and also in the PTL software manuals and application notes which are included with each ECT system.
3. INTRODUCTION TO ELECTRICAL CAPACITANCE TOMOGRAPHY (ECT)

3.1 OVERVIEW OF ECT

ECT is used to obtain information about the spatial distribution of a mixture of dielectric materials inside a vessel, by measuring the electrical capacitances between sets of electrodes placed around its periphery and converting these measurements into an image showing the distribution of permittivity as a pixel-based plot or image. The images produced by ECT systems are approximate and of relatively low resolution, but they can be generated at relatively high speeds. Although it is possible to image vessels of any cross section, most of the work to-date has been carried out on circular vessels.

ECT can be used with for any arbitrary mixture of different non-conducting dielectric materials such as plastics, hydrocarbons, sand or glass. However, an important application of ECT is viewing and measuring the spatial distribution of a mixture of two different dielectric materials (a two-phase mixture) as in this case, the permittivity distribution can be made to correspond to the concentration distribution of the two components over the cross-section of the vessel.

The permittivity image resolution achievable depends on the number of independent capacitance measurements, but is generally low. However, images can be generated at high frame rates, typically 100fps. Successful applications of ECT include imaging 2-phase liquid/gas mixtures in oil pipelines and solids/gas mixtures in fluidised beds and pneumatic conveying systems. Where the mixture is flowing along the vessel, measurements of the concentration distributions at two axial planes permit the velocity profile and the overall flow rate to be found in some cases.

A typical ECT permittivity image format uses a square grid of 32 x 32 pixels to display the distribution of the normalised composite permittivity of each pixel. For a circular sensor, 812 of the available 1024 pixels are used to approximate the cross-section of the sensor. The values of each pixel represent the normalised value of the effective permittivity of that pixel. In the case of a mixture of two dielectric materials, these permittivity values are related to the fraction of the higher permittivity material present (the volume ratio (or voidage)) at that pixel location.

An ECT system produces one or more cross-sectional images of the permittivity profile of the contents of a pipe or vessel from measurements of capacitance between combinations of sensor electrodes which surround the vessel.

The overall volume ratio, which defines the ratio of the two materials present, averaged over the volume of the sensor, can also be obtained. The overall volume ratio of the materials inside the sensor at any moment in time is defined to be the percentage of the volume of the sensor occupied by the higher permittivity material. The volume of the sensor is the product of the cross-sectional area of the sensor and the length of the sensor measurement electrodes.

In all of the following we shall be referring to the relative permittivity (or dielectric constant) of materials. The relative permittivity of a material is its absolute permittivity divided by the permittivity of free space (or air). Hence the relative permittivity of air is 1 and typical values for other materials in solid or liquid format are polystyrene (2.5), glass (6.0) and mineral oil (2.3).
In this manual, we have used three different terms to describe the same concept, as they are all in common use. These are volume ratio, voidage and concentration, which we define to be the fraction of the higher permittivity material present in the mixture. These terms are inter-changeable in the following text. A typical application of ECT is for the real-time monitoring of the motion of fluids, including multi-phase flows, in process engineering plants. In general ECT can be used to monitor any process where the fluid to be observed has low electrical conductivity and a varying permittivity.

3.2. ECT MEASUREMENT SYSTEM CONFIGURATION

An ECT system consists of a capacitance sensor, measurement circuitry and a control computer. For imaging a single vessel type with a fixed cross-section and with a fixed electrode configuration, the measurement circuitry can be integrated into the sensor and the measurement circuits can be connected directly to the sensor electrodes. This simplifies the measurement of inter-electrode capacitances and is potentially a good design solution for standardised industrial sensors.

However, most current applications for ECT are in the research sector, where it is preferable to have a standard capacitance measuring unit which can be used with a wide range of sensors. In this case, screened cables connect the sensor to the measurement circuitry, which must be able to measure very small inter-electrode capacitances, of the order of $10^{-15}$ F (1 fF), in the presence of much larger capacitances to earth of the order of 200,000 fF (mainly due to the screened cables). A diagram of a very simple ECT system of this type is shown in figure 3.2.1.

![Figure 3.2.1 Basic PTL300E ECT System](image-url)
If the vessel wall is non-conducting, electrodes can be located inside, within or outside the wall as shown in figure 3.2.2. However, if the tube wall is a conductor, internal electrodes must be used. The convention we use to identify electrodes is to number them anticlockwise, starting at the electrode at or just before 3 o’clock.

![Figure 3.2.2 Circular sensor electrode configurations](image)

The number of sensor electrodes that can be used depends on the range of values of inter-electrode capacitances and the upper and lower measurement limits of the capacitance measurement circuit. The capacitance values when the sensor contains air are referred to as “standing capacitances” and their relative values are shown in figure 3.2.3 for a 12-electrode circular sensor with internal electrodes.

![Figure 3.2.3. Inter-electrode capacitances](image)

Sequential electrodes are referred to as adjacent electrodes, and have the largest standing capacitances, while diagonally opposing electrodes (opposite electrodes) have the smallest capacitances. Because of the wide range of these capacitances, they are usually normalised to lie within a standard range of values, as described in paragraph 3.9. As the number of electrodes increases, the electrode surface area per unit axial length decreases and the inter-electrode capacitances also decrease. When the smallest of these capacitances (for opposite electrodes), reaches the lowest value that can be measured reliably by the capacitance circuitry, the number of electrodes, and hence the image resolution, can only be increased further by increasing the axial lengths of the electrodes. However, these lengths cannot be increased indefinitely because the standing capacitances between pairs of adjacent electrodes will also increase and the measurement circuitry will saturate or overload once the highest capacitance measurement threshold is exceeded.
3.3. CAPACITANCE MEASUREMENT PROTOCOLS

Many different ECT measurement protocols are possible (Reinecke, 1994), as capacitances can be measured between many combinations of groups of electrodes (which effectively become new “virtual electrodes”). Most work to-date with circular vessels has used the simplest arrangement (which we refer to as protocol 1) where capacitances are measured between single pairs of electrodes. The measurement sequence for protocol 1 involves applying an alternating voltage from a low-impedance supply to one (source) electrode. The remaining (detector) electrodes are all held at zero (virtual ground) potential and the currents which flow into these detector electrodes (and which are proportional to the inter-electrode capacitances) are measured. A second electrode is then selected as the source electrode and the sequence is repeated until all possible electrode pair capacitances have been measured. This generates M independent inter-electrode capacitance measurements, where:

\[
M = \frac{E(E - 1)}{2}
\]  

and E is the number of electrodes located around the circumference. For example for E = 12, M = 66. As the measurements for a single frame of data are made sequentially, the capacitance data within the frame will be collected at different times and there will be some skewing of the data. Interpolation techniques can be used to de-skew this data if this effect is likely to produce significant errors.

Other possible protocols involve grouping electrodes and exciting them in pairs (protocol 2) and triplets (protocol 3) etc. The formula for the number of independent measurements for grouped electrodes is :

\[
M = \frac{(E)(E - (2P - 1))}{2}
\]  

where P (the protocol number) is the number of electrodes which are grouped together. The advantage of using these more complex protocols is that they can generate a larger number of independent measurements for a given electrode size and capacitance measurement sensitivity than the simple single-pair protocol 1. Improved image resolution is therefore achievable, although at the expense of the maximum image frame rate, which falls as the protocol number or number of electrodes increases.

3.4. CAPACITANCE SENSOR ELECTRODE DESIGN

ECT can be used with vessels of any cross-section, but most work to-date has used circular geometries. For a sensor with internal electrodes, the components of capacitance due to the electric field inside the sensor will always increase in proportion to the material permittivity when a higher permittivity material is introduced inside the sensor. However for sensors with external electrodes, the permittivity of the wall causes non-linear changes in capacitance, which may increase or decrease depending on the wall thickness and the permittivities of the sensor wall and contents. In general, ECT sensors with external electrodes are easier to design and fabricate than internal electrode sensors and they are also non-invasive.

Axial resolution and overall measurement sensitivity can be improved by the use of driven axial guard electrodes, located either side of the measurement electrodes, as shown in the flexible laminate design of figure 3.4.1.
Figure 3.4.1 Partial PCB layout for an 8-electrode single-plane sensor

The driven axial guard electrodes are excited at the same electrical potentials as the associated measurement electrode and prevent the electric field from being diverted to earth at the ends of the measurement electrodes. For large diameter vessels, axial guard electrodes are normally an essential requirement to ensure that the capacitances between opposing electrodes are measurable.

With the current state of capacitance measurement technology, it is possible to measure capacitance changes between 2 unearthed electrodes of 0.2 fF in the presence of stray capacitance to earth of 200pF at a rate of 2000 measurements per second. This sets a practical lower design limit on the capacitance between any pair of electrodes of around 5fF, which equates to measurement electrodes of minimum axial length 3.5cm for an 8 electrode sensor or 5 cm for a 12 electrode sensor. These dimensions assume that effective driven axial guards are used. For this condition to be met, the sum of the lengths of the axial guard and the measurement electrodes must equal or exceed the sensor diameter.

3.5. CAPACITANCE SENSOR FABRICATION

The required electrode pattern can be designed using CAD software and the electrodes fabricated using photolithographic techniques from a flexible copper-coated laminate, which is then wrapped around the outside of an insulating tube to form the sensor. Part of a design for an 8-electrode single plane sensor with driven axial guards is illustrated in figure 3.4.1, which shows earthed screening tracks between the sets of electrodes (to reduce the adjacent electrode capacitances) together with earthed areas at the ends of the sensor (to allow the cable screens to be terminated). Coaxial leads (with a maximum length of 2m to minimise capacitance to ground) are connected to the electrodes and an earthed screen is located around the sensor to exclude any external signals. Discharge resistors (typically 1 MOhm) must be connected between each electrode and the cable screen to ensure that no static charge can build up on the electrodes and connecting leads, otherwise damage may occur when the sensor is connected to the capacitance measurement circuit. These basic techniques can be used to construct static or sliding sensors with internal or external electrodes. More complex fabrication techniques are needed for sensors for operation at elevated temperatures and pressures.
ECT systems can be operated in many different ways but in this introductory section, we will describe
the simplest method which involves using the simplest capacitance measurement protocol together
with a simple image reconstruction algorithm. The sequence of actions required to measure the
permittivity distribution of a mixture of 2 dielectric fluids inside an ECT sensor is as follows:

1. The properties of the capacitance sensor are measured or calculated initially to produce a sensitivity
map of the sensor. This is a set of numerical matrices whose elements correspond to the individual
pixels in a rectangular grid which is used to define the sensor cross-section.

2. The sensor is normally calibrated at each end of the range of permittivities to be measured by
filling the sensor with the lower permittivity material initially and measuring all of the individual
inter-electrode capacitances. This operation is then repeated using the higher permittivity material.
The data obtained during the calibration procedure is used to set up the measurement parameters
for each measuring channel and is stored in a calibration data file.

3. Once the system has been calibrated, the capacitances between all unique pairs of sensor electrodes
are measured continuously at high speed, giving N(N-1)/2 unique values per measurement or
image frame, where N is the number of sensor electrodes.

4. The measured capacitance values are normalised to the values measured during the calibration
process.

5. An image reconstruction algorithm, together with an appropriate sensor permittivity-concentration
model is used to compute the cross sectional distribution of the permittivity of the material inside
the pipe. Images can be constructed from the capacitance measurements either at the time of
measurement (on-line) or from stored or captured data (off-line). The algorithm supplied as
standard in the PTL300E system is the so-called linear back-projection (LBP) algorithm. This is a
fast but approximate algorithm which uses the capacitance measurements, together with the
sensitivity map to produce the image. Other alternative algorithms can be used with the stored data
to produce more accurate images.

The various stages in this measurement process are described in more detail in the following chapters.
### 3.7 THE SENSITIVITY MATRIX

The sensitivity matrix describes how the measured capacitance between any combination of electrodes changes when a change is made to the dielectric constant of a single pixel inside the sensor. This can be better understood by considering the case where one electrode is connected to a positive potential $V$ and all of the other electrodes are connected to earth.

![Equipotential lines inside ECT sensor](image1)

**Figure 3.7.1 Equipotential lines inside ECT sensor**

The electric field distribution for this situation is shown in figure 3.7.1 (the figure shows the equipotential lines) and is relatively uneven, the field being strongest near to the excited electrode and weakening with increasing distance from this electrode. The corresponding electric field lines are shown in the figure below.

![Electric field distribution inside ECT sensor](image2)

**Figure 3.7.2 Electric field distribution inside ECT sensor**
The effect of this uneven field distribution is that the change in capacitance measured between any two electrodes caused by an object with a given permittivity will vary depending on the location of the object. When used with a circular cross section sensor, the ECT system is most sensitive when an object is placed near the walls of the vessel and is least sensitive at the centre of the vessel. Allowance is made for this effect from knowledge of the variation of sensitivity with position for each pixel. This information is stored in the sensitivity map file. When the ECT system constructs images, it reads the sensitivity map and compensates the image pixels accordingly.

The sensitivity matrix must be calculated (or measured) for each individual sensor as a separate exercise prior to using the sensor with an ECT system. One method for calculating the sensitivity coefficient \( S \) of a pixel for an electrode-pair (i-j) is based on the use of equation 6.

\[
S = \int_{A} E_i \cdot E_j \cdot dA \quad (3.7.3)
\]

where \( E_i \) is the electric field inside the sensor when one electrode of the pair i is excited as a source electrode, \( E_j \) is the electric field when electrode j is excited as a source electrode and the dot product of the two electric field vectors \( E_i \) and \( E_j \) is integrated over the area \( A \) of the pixel. The set of sensitivity coefficients for each electrode-pair is known as the sensitivity map for that pair. For circular sensors with either internal or external electrodes, it is possible to derive an analytical expression for the electric fields and in this case, the sensitivity coefficients (and also the electrode capacitances) can be calculated accurately. For more complex geometries, numerical methods can be used to calculate the sensitivity coefficients. It is normally only necessary to calculate a few primary sensitivity maps for the unique geometrical electrode pairings, as all of the other maps can be derived from these by reflection or rotation. A set of primary maps for an 8-electrode sensor operating under protocol 1 is shown in figure 3.7.3.

![Figure 3.7.3 Primary Sensitivity Maps for an 8-electrode sensor](image)

The maps show the relative pixel sensitivities on a compressed colour scale, where blue represents negative sensitivity, green represents zero sensitivity and red represents positive sensitivity regions.
3.8 ECT SYSTEM CALIBRATION

In the normal method of operation, an ECT system is calibrated by filling the sensor with the two reference materials in turn and by measuring the resultant inter-electrode capacitance values at these two extreme values of relative permittivity. This situation is shown diagramatically in figure 3.8.1 which illustrates how the measured inter-electrode capacitances change between the higher and lower values of permittivity used for calibration, for two materials of relative permittivity $K_L$ and $K_H$. For simplicity, it has been assumed that the variation is linear.

![Diagram of ECT System Calibration](image)

**Figure 3.8.1 Principle of ECT System Calibration**

This method of calibration defines the two nominal end points of the measurement range for most types of ECT measurement.

All subsequent capacitance values $C_M$ are then normalised to have values $C_N$ between zero (when the sensor is filled with the lower permittivity material) and 1 (when filled with the higher permittivity material) as described in the next paragraph.

3.9 CAPACITANCE MEASUREMENT AND NORMALISATION

Once the ECT system has been calibrated, the ECT system is ready to capture image data. When data capture is initiated, the capacitances between all unique pairs of sensor electrodes are measured continuously at high speed. These capacitance values are stored, initially in binary format in the control PC memory and are then available to construct an image of the permittivity distribution inside the sensor.

In PTL ECT systems, use is made of normalised parameters to represent the inter-electrode capacitance measurements and also the displayed values of pixel permittivity. This is carried out using the reference data in the calibration file which is generated during the calibration process.

This process is carried out as follows:
The inter-electrode capacitances measured at the lower permittivity calibration point \( (C_L) \) are assigned values of 0 while the inter-electrode capacitances measured at the higher permittivity calibration point \( (C_H) \) are assigned values of 1. This relationship is shown in graphical format in figure 3.9.1.

\[
C_n = \frac{(C - C_L)}{(C_H - C_L)} \quad (3.9.1)
\]

where \( C_n \) is the set of normalised inter-electrode capacitances and \( C \) are the set of absolute capacitances measured with the sensor containing a material of arbitrary permittivity, \( C_H \) are the set of capacitances measured at the higher permittivity calibration point and \( C_L \) are the set of capacitances measured at the lower permittivity calibration point.

### 3.10 NORMALISATION OF PIXEL PERMITTIVITY VALUES

The pixel values in the permittivity image are similarly normalised, so that they have the value 0 for the lower permittivity material and 1 when the sensor is filled with the higher permittivity material using equation 3.10.1.

\[
K_n = \frac{(K - K_L)}{(K_H - K_L)} \quad (3.10.1)
\]

where \( K_n \) is the set of normalised permittivities (pixel values) when the sensor is filled with a material of permittivity \( K \), \( K_H \) is the effective permittivity of the material used to calibrate the sensor at the higher permittivity calibration point and \( K_L \) is the permittivity of the material used to calibrate the sensor at the lower permittivity calibration point.

The relationship between absolute and normalised permittivities is shown in figure 3.10.1.
3.11 CAPACITANCE/PERMITTIVITY/CONCENTRATION MODELS

The relationship between the permittivity distribution and the capacitance measured between a pair of electrodes must be considered carefully if accurate permittivity/concentration images are to be obtained. If the two dielectric materials exist as discrete stratified permittivity layers between the two electrodes, then two component capacitances, each due to one of the dielectric materials, and effectively connected in parallel, will exist between the electrodes. The sum of these capacitances will therefore accurately reflect the relative proportions of the 2 materials present.

However, if the materials exist as alternating bands of permittivity between the electrodes, the capacitances measured between the electrodes will be constituted from component capacitances which are effectively connected in series. In this case, the reciprocal rule must be used to obtain the component permittivities and concentration from the measured capacitances. If there is a combination of these two basic material distributions, more complex relationships, such as the method described by Maxwell, must be used to define the permittivity/ concentration/ capacitance relationships. It is therefore very important to use the correct permittivity model (parallel/series/Maxwell etc) if accurate concentration values are to be obtained from the permittivity image. Further information on capacitance/ permittivity models (including Maxwell's method) is given in the paper by Yang and Byars (1999).

![Diagram](image-url)
3.12 LIMITS ON IMAGE RESOLUTION

The resolution of an ECT permittivity image is limited by the number of independent inter-electrode capacitance measurements that can be made and this relationship can be considered to be an example of spatial filtering, as shown in figure 3.12.1.

![Figure 3.12.1 Resolution limits imposed by spatial filter.](image)

The resolution limit is difficult to define mathematically, but a simple engineering estimate can be made by assuming that the number of independent measurements $M$ corresponds to a similar number of discrete regions inside the sensor. If we assume that the angular resolution is equal to the number of electrodes $E$, then the radial resolution will equal $M/E$. For protocol 1 and a 12 electrode sensor, this gives a radial resolution limit of 5.5. For protocol 2 and 24 electrodes, this figure increases to 10.5.

It is not possible to obtain a unique solution for each image pixel when the number of pixels in the image exceeds the number of capacitance measurements. Furthermore, image distortion can occur because ECT is an inherently soft-field imaging method (the electric field is distorted by the material distribution inside the sensor). However, in many cases, the contrast between the permittivities of the materials inside the sensor is small, resulting in only limited image distortion. This allows approximate linear algorithms to be used to relate the capacitance measurements to the pixel values in the image and vice-versa. The method which has been used with greatest success to-date is known as Linear Back Projection (LBP).
3.13 IMAGE RECONSTRUCTION USING THE LBP ALGORITHM

The LBP algorithm is based on the solution of a set of forward and reverse (or inverse) linear transforms.

The forward transform is a matrix equation which relates the set of inter-electrode capacitance measurements \( C \) to the set of pixel permittivity values \( K \). This transform assumes that the measured inter-electrode capacitances resulting from any arbitrary permittivity distribution \( K \) inside the sensor will be identical to those obtained by summing the component capacitance increases which occur when each pixel has its defined permittivity, with all other pixels values set to zero.

This forward transform is defined in equation 3.13.1, where bold characters represent matrices:

\[
C = S.K \tag{3.13.1}
\]

\( C \) is an \((M \times 1)\) dimensioned matrix containing the set of \( M \) inter-electrode pair capacitances (where \( M \) is typically 66 for a 12-electrode sensor or 28 for an 8-electrode sensor for protocol 1).

\( K \) is an \((N \times 1)\) dimensioned matrix (where \( N \) is 1024 for a 32 x 32 grid) containing the set of \( N \) pixel permittivity values which describe the permittivity distribution inside the sensor (the permittivity image).

\( S \) is the forward transform, usually known as the sensor Sensitivity Matrix. \( S \) has dimensions \((M \times N)\) and consists of \( M \) sets (or maps) of \( N \) (typically 1024) coefficients, (1 map for for each of the \( M \) capacitance-pairs), where the coefficients represent the relative change in capacitance of each capacitance pair when an identical change is made to the permittivity of each of the \( N \) (1024) pixels in turn.

In principle, once the set of inter-electrode capacitances \( C \) have been measured, the permittivity distribution \( K \) can be obtained from these measurements using an inverse transform \( Q \) as follows.

\[
K = Q.C \tag{3.13.2}
\]

\( Q \) is a matrix with dimensions \((N \times M)\) and, in principle, is simply the inverse of the matrix \( S \). However, it is only possible to find the true inverse of a square matrix (where \( M = N \)). In physical terms, this is confirmation that it is not possible to obtain the individual values of a large number of pixels (eg 1024) from a smaller number of capacitance measurements (eg 66). As an exact inverse matrix does not exist, an approximate matrix must be used. The LBP algorithm uses the transpose of the sensitivity matrix, \( S' \) which has the dimensions \((N \times M)\) and this is justified by the following reasoning:

Although we have no means of knowing which pixels have contributed to the capacitance measured between any specific electrode-pair, we know from the sensitivity matrix \( S \) that certain pixels have more effect than others on this capacitance. Consequently, we allocate component values to each pixel proportional to the product of the electrode-pair capacitance and the pixel sensitivity coefficient for this electrode-pair. This process is repeated for each electrode-pair capacitance in turn and the component values obtained for each pixel are summed for the complete range of electrode-pairs.
This simple algorithm produces approximate, but very blurred permittivity images, and a typical image is shown in figure 3.1.4.2. The LBP algorithm acts as a spatial filter with a lower cut-off frequency than that of the fundamental filter (as shown in figure 3.12.1) and produces sub-optimal images from a given set of input data.

3.14 FORMAT OF PERMITTIVITY IMAGES

The permittivity distribution of a mixture of two fluids is often displayed as a series of normalised pixels located on either a (32 x 32) or (64 x 64) square pixel grid. If the sensor cross-section is circular, this circular contour must be projected onto the square grid containing typically 1024 pixels. Some of the pixels will lie outside the vessel circumference and the image is therefore formed from those pixels that lie inside the vessel. A typical arrangement which is commonly used is shown in figure 3.14.1, where the circular image is constructed using 812 of the available 1024 pixels.

Figure 3.14.1  32 x 32 square pixel grid

Figure 3.14.2  ECT image for contents of a circular sensor. Note that the colour scale progresses from zero (blue) through green to (1) red.

The permittivity distribution (image) is plotted using an appropriate colour scale to indicate the normalised pixel permittivity. A simple example is a graduated blue/green/red colour scale, where pixel values corresponding to the lower permittivity material used for calibration have the value zero and are shown in blue, while pixels corresponding to the higher permittivity material have the value 1 and are shown in red. A typical 32 x 32 ECT image, obtained using the methods described in paragraph 3.13, is shown in figure 3.14.2.

The normalised permittivity distribution corresponds to the fractional concentration distribution of the higher permittivity material.

3.15 SUMMARY

This completes the brief overview of ECT technology. Further detailed information is given in subsequent sections of this manual.
3.16 REFERENCES

A small selection of papers on electrical capacitance tomography is given below.


SECTION 3

This section contains information about Electrical Capacitance Tomography (ECT) which is specific to the PTL300E ECT system.

Chapter 4 gives a brief overview of the ECT system.

Chapter 5 discusses capacitance sensors.

Chapter 6 describes the capacitance measurement unit.

Chapter 7 discusses system calibration and normalisation
4. PTL300E ECT SYSTEM OVERVIEW

4.1 THE PTL300E ECT SYSTEM

The PTL300E is an enhanced ECT system controlled by Windows-based software running on an Intel-compatible PC. It can be used to monitor any process where the fluid to be observed has low electrical conductivity and a varying permittivity. A typical application is the real-time monitoring of the motion of fluids, including multi-phase flows, in process engineering plant. Specific applications where ECT has been successfully used to-date include the monitoring of powder conveying, flames, combustion and explosions, mineral processing, fluidised beds, wood rot, hydrate formation and catalyst structures, and for checking product uniformity.

PTL300E ECT systems consists of a capacitance sensor unit, a Capacitance Measurement Unit (CMU) and a personal computer equipped with custom communications and control software. A photograph of the complete ECT system is shown in figure 1.1 and a detailed specification is given in Appendix 1.

4.1 SYSTEM OPTIONS

Two versions of the PTL300E ECT system are available, suitable for use with sensors containing either one or two planes of measuring electrodes and one or two sets of driven guard electrodes.

The single plane system (type PTL300E-SP-G) consists of an industry-standard PC together with a Capacitance Measurement Unit (CMU) type DAM200E-SP-G and a demonstration 12 element single-plane unguarded single-plane ECT sensor. Capacitance sensors containing sets of between 2 and 12 measurement electrodes, together with up to 2 sets of driven axial guard electrodes, can be used with the system.

The twin-plane version (type PTL300E-TP-G) is intended for imaging in two axial planes and is similar to the single plane system but uses a dual-plane Data Acquisition Module type DAM200E-TP-G and is supplied with an additional demonstration single-plane capacitance sensor. This version can be used to measure the velocity profile of the sensor contents under suitable flow conditions, by correlating the permittivity data between the two image planes of a suitable twin-plane capacitance sensor.

4.2 MEASUREMENT CAPABILITIES

PTL300E ECT systems are intended primarily for use with mixtures of two materials having different dielectric constants (permittivities). These are known as two-phase mixtures and for mixtures of this type, PTL300E ECT systems can provide approximate information about the relative proportions of the two materials inside the ECT sensor at any given time (voidage) as well as displaying their approximate distribution across the sensor plane.

PTL300E ECT systems can be used with ECT sensors containing either one or two sets of between 2 and 12 measurement electrodes and up to 2 sets of driven guard electrodes and capture capacitance data in accordance with measurement protocol 1.

The PTL300E-SP-G ECT system can be used to view the contents of closed pipes or vessels at one axial location while the PTL300E-TP-G system can be used to image at two separate axial locations simultaneously. If the vessel walls are non-metallic external sensor electrodes can be used. If the vessel walls are metallic, the sensor electrodes must be placed inside the vessel walls. The materials
to be imaged must be essentially non-conducting dielectric materials such as oils, plastics, powders or other similar materials.

Measured inter-electrode capacitances can also be stored in a data file on a continuous basis at speeds up to 300 frames per second, depending on the number of electrodes on the sensor. Permittivity images are displayed over a cross section made up from a selected number of pixels contained (typically) in a 32 X 32 square grid. The colour of each individual pixel represents the average value of the normalised permittivity (in a range from 0 to 1) of the material in the cell.

The ECT system must be calibrated before it can be used. This involves filling the ECT sensor with two different materials having permittivities at the lower and higher ends of the permittivity range to be measured.

The equipment can be used in a number of different modes:

- In Capture mode, live images of materials can be displayed and captured at data rates selected by the user, while the inter-electrode capacitance measurements are streamed to a continuous buffer file which can then be saved to a data file following the cessation of data capture. This allows permittivity images to be reconstructed and replayed at a later date using other alternative software.

- In Playback mode, images can be replayed at the same or different rates, again selected by the user. Facilities are also provided for single-stepping through recorded images.

- In Record mode, capacitance data is streamed directly to a series of user-defined data files.

The normalised permittivity of individual pixels in the ECT image can be displayed either On-line during data capture or when the data is replayed. The values of the normalised inter-electrode capacitances can also be displayed in both Data Capture and Playback modes. The instantaneous volume fraction (or concentration) of the materials inside the sensor is displayed continuously on the image screen and a pixel probe allows the value of individual permittivity pixels to be displayed.

Alternative sets of sensitivity maps for different dielectric materials and/or sensors can be used and diagnostic software is provided which allows the measurement of absolute values of inter-electrode capacitances for sensor design and testing purposes.

Finally, the recorded capacitance data can be used for the independent calculation of volume ratio or for the calculation or display of images using other image reconstruction software.
4.3 PRINCIPLE OF OPERATION

The PTL300E ECT system produces one or more cross-sectional images of the permittivity profile of the contents of a pipe or vessel from measurements of capacitance between combinations of sensor electrodes which surround the vessel. The images are approximate and of relatively low resolution. Sensors of any cross-section can be imaged provided that a suitable sensitivity map for the sensor can be calculated.

Images are produced in the following way:

1. The properties of the sensor are measured or calculated initially to produce a sensitivity map of the sensor. This is a set of numerical matrices whose elements correspond to the individual pixels in a rectangular grid which is used to define the sensor cross-section.

2. The sensor is normally calibrated at each end of the range of permittivities to be measured by filling the sensor with the lower permittivity material initially and measuring all of the individual inter-electrode capacitances. This operation is then repeated using the higher permittivity material. The data obtained during the calibration procedure is used to set up the measurement parameters for each measuring channel and is stored in a calibration data file.

3. Once the system has been calibrated, the capacitances between all unique pairs of sensor electrodes are measured continuously at high speed, giving $E(E-1)/2$ unique values per measurement or image frame, where $E$ is the number of sensor electrodes.

4. An image reconstruction algorithm is used to compute the cross-sectional distribution of the permittivity of the material inside the pipe. Images can be constructed from the capacitance measurements either at the time of measurement (on-line) or from stored or captured data (off-line). The algorithm supplied as standard in the PTL300 system is the so-called linear back-projection (LBP) algorithm. This is a fast but approximate algorithm which uses the capacitance measurements, together with the sensitivity map to produce the image. Other alternative algorithms can be used with the stored data to produce more accurate images.

4.4 ECT PERMITTIVITY IMAGE FORMATS

ECT systems can be used to obtain images of the distribution of permittivity inside ECT sensors for any arbitrary mixture of different dielectric materials. However, an important application of ECT is viewing and measuring the spatial distribution of a mixture of two different dielectric materials (a two-phase mixture). For a two-phase mixture, ECT can be used to measure the spatial distribution of the composite permittivity of the two materials inside the sensor. From this permittivity distribution, it is possible to obtain the distribution of the relative concentration (volume ratio) of the two components over the cross-section of the vessel.

A typical ECT permittivity image format uses a square grid of 32 x 32 pixels to display the distribution of the normalised composite permittivity of each pixel. For a circular sensor, 812 pixels are used to approximate the cross-section of the sensor, as shown in figure 4.4.1.
The values of each pixel represent the normalised value of the effective permittivity of that pixel. In the case of a mixture of two dielectric materials, these permittivity values are related to the fraction of the higher permittivity material present (the volume ratio (or voidage)) at that pixel location.

The overall volume ratio, which defines the ratio of the two materials present, averaged over the volume of the sensor, can also be obtained. The overall volume ratio of the materials inside the sensor at any moment in time is defined to be the percentage of the volume of the sensor occupied by the higher permittivity material. The volume of the sensor is the product of the cross-sectional area of the sensor and the length of the sensor measurement electrodes.

In all of the following we shall be referring to the relative permittivity (or dielectric constant) of materials. The relative permittivity of a material is its absolute permittivity divided by the permittivity of free space (or air). Hence the relative permittivity of air is 1 and typical values for other materials in solid or liquid format are polystyrene (2.5), glass (6.0) and mineral oil (2.3).

In this manual, we have used three different terms to describe the same concept, as they are all in common use. These are volume ratio, voidage and concentration, which we define to be the fraction of the higher permittivity material present in the mixture. These terms are inter-changeable in the following test.
4.5 SOME TYPICAL PERMITTIVITY IMAGES

Figure 4.5.1 shows a sequence of images obtained from a number of applications, including the imaging of gas bubbles in oil, a fluidised bed experiment and a sensor imaging a flame. In all of the examples shown, the images are based on a normalised permittivity scale which progresses from zero (blue) through green, to a maximum value of 1 (red).

The first example shows a 15cm diameter clear plastic pipe containing a mixture of oil and gas. An external 12 element capacitance sensor is shown attached to the pipe. The ECT image shows a gas bubble passing through the sensor. The blue area of the image represents the gas bubble and the red area of the image represents the oil.

The second example shows a sequence of ECT images obtained using a fluidised bed consisting of a vertical pipe containing an epoxy powder. Air is blown vertically from the bottom of the bed, through a filter and the powder is fluidised by the air flow. An 8 element capacitance sensor with 2.5 cm long sensor electrodes was used to obtain the images. The image sequence shows the unfluidised initial state (red image) (A), partial fluidisation (green image) (B), excess fluidisation allowing the formation of an air hole (blue area) in the bed (C) and final state following the removal of the air supply (D).

The final example shows a 6 element capacitance sensor constructed inside an aluminium cylinder of internal diameter 10cm. The ECT image was obtained using a butane flame positioned approximately in the centre of the sensor.
Figure 4.5.1 Examples of ECT images from some typical applications
4.6 CONDUCTIVITY EFFECTS

The PTL300E ECT system uses a relatively simple method to measure the capacitance impedances between pairs of sensor electrodes. Consequently, the capacitance measurement will also respond to any conductive component present between the electrodes. For normal applications, where the ECT sensor contains ‘ideal’ dielectric materials such as oil, glass or plastics, the conductive component is negligible and the capacitance measurement is reasonably accurate. However, when the conductive component of the impedance between the electrodes becomes comparable to the capacitive component of impedance, errors will occur.

The problem is most severe for sensors with external electrodes, as it is very difficult to obtain any accurate information from sensors with external electrodes containing a fluid material which is not a perfect dielectric, for the reasons given later in this section. In the following few paragraphs, we will consider the case of an ECT sensor constructed with internal electrodes, which are in contact with an imperfect dielectric fluid, which will be assumed to have finite conductivity.

In these circumstances, problems will occur when the conductive component of the impedance between pairs of electrodes becomes comparable with the capacitive component of impedance. This situation will occur first between the pairs of opposite electrodes in the ECT sensor (where the capacitance is lowest). For a typical ECT sensor, the capacitance between opposite electrodes at the lower permittivity calibration point is around 10 fF, which corresponds to a capacitive impedance of \( \frac{1}{2\pi F C} \approx 12.7 \text{ Mohm at } 1.25 \text{ Mhz.} \)

If the conductive impedance between the pair of opposite electrodes is comparable with, or less than this figure, the ECT system will respond to the conductive component as well as the capacitive component of impedance. As the conductivity of the material inside the sensor increases, the conductive impedance between the electrodes will fall and will become much lower than the capacitive component of impedance. In these circumstances, the ECT system will start to behave as an Electrical Resistance Tomography (ERT) system, responding predominantly to changes in the conductivity of the material rather than its permittivity.

In practice, the effect of conductivity is just noticeable with pure distilled water, becomes a severe problem with tap water and becomes the dominant effect for even weak saline solutions. In these circumstances, any images obtained from the ECT system will be based on the conductive properties of the medium rather than its dielectric properties. In fact the ECT system can be considered to be operating as an ERT system when the conductivity reaches these levels.

As the conductivity increases further, two further effects occur which drastically reduce the accuracy and effectiveness of the ECT system in its ‘ERT’ mode. The first of these is a saturation effect. As the resistance between the pairs of electrodes falls, the current which flows into the detector electrodes overloads or saturates the detector circuitry and no further changes in current are measurable unless steps are taken to reduce the measurement sensitivity.

The second effect occurs because the ‘on’ resistances of the electronic switches in the ECT system rather than the resistance of the medium start to limit both the voltage which can be applied between the sensor electrodes and also the currents which flow between them. So even if the measurement circuitry is desensitised to allow larger currents to be measured, there will be a loss of sensitivity because of the resistances of the electronic switches. In these circumstances it is preferable to use a constant-current-injection measurement technique (rather than the applied voltage method which is used in ECT systems) to obtain the ERT image and this is indeed the method which is used in commercial ERT measurement systems.
As mentioned earlier, the problem of conductive fluids is much more serious if external electrodes are used. This is because there is relatively weak electrical coupling through the wall of the sensor between the electrodes and the sensor fluid when compared with the coupling across the fluid. Consequently the conductive fluid tends to act as a continuous and perfectly conducting object. If the sensor is full, the fluid acts as a circular conducting shield just inside the sensor wall and simply couples the electrodes together via the dielectric material of the sensor wall. When this happens, the image obtained is simply that of the outside surface of the fluid only. Experience suggests that it is not possible to image inside even slightly-conducting fluids using ECT sensors with external electrodes (although it is just possible if distilled water is used).
5. ECT CAPACITANCE SENSORS

5.1 ELECTRODE LOCATION

Capacitance sensors for use with PTL300E ECT systems will normally be customised items for each individual application, and can take one of two basic forms. The simplest arrangement, for a single plane sensor, consists of a non-conducting section of pipe surrounded by an array of equally-spaced screened capacitance sensor electrodes. A demonstration 12-element sensor of this type is supplied with each ECT system and photographs showing its construction are shown in figure A2.1. An alternative arrangement is an insulated pipe liner, fitted with sensor electrodes which is inserted into the pipeline. A twin-plane sensor will contain two sets of measuring electrodes located at different axial planes, together with guard electrodes.

In general, ECT sensors can be constructed with electrodes located on either the inner or outer surface of non-conducting pipes (or embedded within the pipe wall). Electrodes are often located on the outer surface for convenience of construction and because in this arrangement, the electrodes are non-invasive. However, sensors with electrodes on the outside of the sensor wall can exhibit considerable non-linearity in their response to dielectric materials introduced inside the sensor. This effect is caused by the presence of the sensor wall, which introduces an additional series coupling capacitance into the measurement. If more accurate measurements are required, sensors with electrodes on the inside surface of the sensor wall should be used.

As the inter-electrode capacitances are typically fractions of a picoFarad, an earthed screen is required around the electrodes to eliminate the effects of extraneous signals, which would otherwise predominate and corrupt the measurements. The overall sensor assembly can be encased for operation in high-pressure systems and is connected to the Data Acquisition Module by screened flexible coaxial leads.

5.2 NUMBER OF ELECTRODES

PTL300E ECT systems can be used with capacitance sensors having between 2 and 12 measurement electrodes and a similar number of driven guard electrodes. Capacitance measurements (using protocol 1 only) are made between each electrode and every other electrode. For a sensor containing E measurement electrodes, there are E(E-1)/2 unique capacitance measurements. This corresponds to 66 individual measurements for a 12 electrode sensor.

The number of electrodes used will depend on the measurement priorities. There is a trade-off between the axial and radial resolutions of ECT sensors, the capacitance measurement sensitivity and the maximum data capture rate. Shorter electrodes will give improved axial resolution but at the expense of an increase in system noise level. This can be compensated by using fewer electrodes so that the electrode area is maximised and this in turn will give faster maximum frame capture rates.

PTL300E systems can capture data at more than 100 frames per second when 12 electrodes are in use. For a smaller number of electrodes, less time is needed to measure all of the inter-electrode capacitances and higher data capture rates can be achieved. For example, for an 8 electrode system, the number of individual capacitance measurements falls to 28 and the maximum image capture rate increases accordingly.
As a rule of thumb, faster frame capture rates require the use of a small number of electrodes and this also improves the axial resolution. However, if good angular resolution is required a larger number of longer measurement electrodes will be needed but the axial resolution and maximum frame capture rate will be reduced.

5.3 NEED FOR DRIVEN GUARD ELECTRODES

If the sensor electrodes are short compared with the diameter of the sensor, axial guard electrodes must be used in addition to the measuring electrodes, to prevent the electric field from spreading excessively at the ends of the electrodes. These guard electrodes are connected to guard driving circuitry on the data acquisition module.

As a guide, if the length of measuring electrodes is less than than approximately twice the sensor diameter, axial guard electrodes, driven with the same potentials as the measuring electrodes will be needed as shown in figure 5.3.1. The use of driven guard electrodes dramatically improves both the axial resolution and signal-to-noise ratio of sensors with short electrodes.

![Driven guard electrode design for an 8-electrode sensor.](image)

5.4 ELECTRODE NUMBERING CONVENTION

For all PTL ECT sensors, we use the convention that electrodes are numbered anticlockwise when the capacitance sensor is viewed from the connector end (or the end from which the captive coaxial leads emerge), starting in the first quadrant above the horizontal, as shown in figure 5.4.1.

![Electrode numbering convention](image)
The location of each electrode on the boundary of the permittivity image is determined by the geometry of the sensor model used to define the sensor sensitivity map. Standard sensitivity maps for circular sensors with 6, 8 and 12 electrodes are provided with PTL300E ECT systems. For these maps and for sensors with 6 and 12 electrodes, the centre of electrode 1 lies on the horizontal axis (at 3 o clock) and the remaining electrodes are distributed at 30 or 60 degree intervals. For 8 electrode sensors, the centre of electrode 1 is at 22.5 degrees above the horizontal axis and the remaining electrodes are distributed at 45 degree intervals.

5.5 ELECTRODE EXCITATION

Channels 2 to 11 on the DAM200E unit can be selected to be either source or detector channels and the corresponding electrodes on the capacitance sensor will therefore also be excited as either source or detection electrodes. Channel 1 on the DAM200E sets electrode 1 to be either a source electrode or grounds it and channel 12 always sets electrode 12 to be a detector electrode. The driven guard electrodes follow the potentials of the corresponding measurement electrodes.

As it is necessary to maximise the surface area of each electrode to optimise the measurement sensitivity, it is tempting to cover the circumference of the sensor with electrodes with minimal spacing between adjacent electrodes. However, this can lead to problems, as the standing capacitance between adjacent electrodes will be very large and may saturate the capacitance measuring equipment. Consequently, thin earthed axial guard electrodes are normally located between adjacent electrodes to reduce this standing capacitance to manageable values. A typical electrode pattern of this type has already been shown in figure 5.3.1.

A consequence of this arrangement is that the electrical potential on every electrode is well-defined, which makes it relatively straightforward to calculate the sensor sensitivity map and also results in an electrically-optimum sensor design. An important point which must be understood is that, because of the finite axial length of each sensor electrode, the permittivity image will be the average over the volume of the sensor occupied by each set of measurement electrodes.

5.6 CAPACITANCE VALUES

The DAM200E CMU can measure inter-electrode capacitances in the range 0.3 to 2000fF. A good design rule is to design the sensor electrodes so that the capacitance per unit length between adjacent electrodes is minimised, with a target value for adjacent electrodes of the order of 500fF for 10 cm long electrodes with air inside the sensor. This allows for an increase in capacitance between adjacent electrodes by a factor of 4 when the sensor contains a dielectric material. This is normally sufficient for most materials which are likely to be imaged.

The capacitance between adjacent electrodes can be reduced by placing an earthed screening track between each electrode and by using an outer screen located at a set radial distance from the electrodes. With the outer screen located approximately 0.5 cm from the electrodes the capacitance between adjacent electrodes is approximately halved compared with the value in the absence of the screen, but there is little effect on the capacitance between non-adjacent electrodes. The inter-electrode capacitance can be further reduced by the addition of a radial screen between each sensor electrode, connected between the earthed screening track and the outer screen.

Having designed for minimum capacitance per unit length between adjacent electrodes, the absolute values of inter electrode capacitances can be adjusted by varying the axial length of the electrodes. For most ECT sensors, the capacitance between any pair of electrodes will consist of two components, a primary capacitance component via the internal volume of the sensor which contains the dielectric fluids and a secondary capacitance component due to coupling via external paths, for example, through the vessel walls and in the space between the electrodes and the external screen.
For sensors with internal electrodes, the primary capacitance components usually predominate and if
the sensor is filled with a dielectric material, the capacitances between all electrodes will increase
approximately by the dielectric constant of the material inside the sensor.

For sensors with external electrodes, the secondary capacitances can be of comparable magnitude or
larger than the primary capacitances. Experience shows that when these sensors are filled with a
dielectric material, only the capacitances between opposite electrodes increase by a factor equal to the
dielectric constant of the material. The capacitance increases between other electrode combinations
will be less, because of the effect of the secondary capacitances.

Typical measured capacitances between all electrode-pairs for a guarded 12-electrode sensor with and
without a vessel wall are shown in figure 5.7.1

**Sensor mounted on 63.5 mm o/d plexiglass tube with 3.2mm wall**

<table>
<thead>
<tr>
<th>Sensor mounted on 63.5 mm o/d plexiglass tube with 3.2mm wall</th>
<th>Capacitances (fF)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>src</strong></td>
<td></td>
</tr>
<tr>
<td>1 405.70</td>
<td>35.42 13.86 9.01 6.82 6.15 7.12 9.10 13.87 33.40 392.58</td>
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<tr>
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<td>34.69 15.78 10.37 8.03 7.42 8.06 10.37 15.36</td>
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<td>33.04 15.09 9.58 7.13 6.54 7.22 8.97</td>
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<td>5 407.08</td>
<td>33.61 15.09 9.09 6.89 6.47 7.03</td>
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<tr>
<td>11 413.30</td>
<td></td>
</tr>
<tr>
<td>Cinj</td>
<td>3.38 3.62 -1.15 3.59 -0.67 -7.66 1.72 -5.51 -7.84 5.48 -148.58</td>
</tr>
</tbody>
</table>

**Sensor with no wall. Sensor i/d 63.5mm**

<table>
<thead>
<tr>
<th>Sensor with no wall. Sensor i/d 63.5mm</th>
<th>Capacitances (fF)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>src</strong></td>
<td></td>
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<tr>
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<td>32.15 13.36 8.83 6.64 5.97 6.92 8.83 13.15 28.98 180.59</td>
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<td>3 217.75</td>
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<td>29.55 14.37 9.28 7.00 6.41 7.09 8.71</td>
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</tr>
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<tr>
<td>Cinj</td>
<td>3.71 3.98 -0.91 3.93 -0.44 -7.47 2.02 -5.33 -7.78 5.65 -148.25</td>
</tr>
</tbody>
</table>

**Figure 5.7.1 Inter-electrode capacitances with and without a vessel wall.**

In these figures, the first column shows the source electrode and the columns are for each detector
electrode using the normal measurement sequence C12, C13 etc.
5.7 AVOIDANCE OF STATIC CHARGE PROBLEMS

It is important to prevent static charge building up on the sensor electrodes, as this may damage the CMOS input circuitry of the DAM200 unit when the charged electrodes are connected to the unit. For this reason, discharge resistors must be permanently connected between each sensor and driven guard electrode and earth. A suitable value for these resistors is 1 M ohm. If printed circuit electrodes are used, it is usually convenient to solder the discharge resistors in circuit at the location where the coaxial leads are connected to the electrodes and earth.

5.8 THE DEMONSTRATION SENSORS

The demonstration sensors supplied with PTL300E ECT systems are 12 element unguarded sensors containing a quantity of glass or plastic beads inside a 51mm diameter PVC tube. The sensor electrodes are formed from flexible copper-clad laminate and are 100 mm long with axial earthed guard tracks between electrodes and an earthed screen at each end of the sensor. The whole assembly is screened by an outer copper tube formed from copper sheet which is formed around the electrode assembly and spaced approximately 5mm from the electrodes. The sensor contains 12 x 1Mohm discharge resistors connected between the sensor electrodes and the earthed section of the flexible PCB.

An image sequence showing the construction of the demonstration sensor is shown in Appendix 2 and a photograph of the completed sensor is shown in figure 5.8.1.

![Demonstration 12-electrode unguarded ECT sensor](image)

**Figure 5.8.1 Demonstration 12-electrode unguarded ECT sensor**

The total tube length of the sensor is more than twice the active sensor length and includes a transparent viewing section. The sensor is half-filled with beads and it is therefore possible to either fill or empty the capacitance sensor section simply by inverting the tube assembly.

The sensor has 12 individually-numbered 1.25 metre leads terminated in SMB connectors and these must be connected to the corresponding numbered channels on the Data Acquisition Module.

Further information on the design of ECT sensors can be found in PTL Application note AN3, copies of which are available on request.

6 THE DAM200E CAPACITANCE MEASUREMENT UNIT
6.1 OVERVIEW

The inter-electrode capacitances are measured by the Capacitance Measurement Unit (CMU), controlled by a standard Personal Computer (the Control PC) running proprietary PTL (ECT32) control software under the MS Windows operating system. The CMU contains an embedded PC running PTL embedded software under the Linux operating system and this embedded PC is linked to the control PC by a standard 10/100 ethernet connection.

The CMU contains 1 [or more] set[s] of capacitance measuring circuitry, together with circuitry for driving any guard electrodes. The presence of the earthed screen around the sensor and the screened connecting leads means that a stray-immune method must be used for measuring the inter-electrode capacitances. The technique used in the DAM200 unit is a development of the charge transfer method, operating at a switching frequency of 1.25 MHz, which allows capacitance values down to 0.0001pF (0.1 femtoFarads) to be resolved. Details of the capacitance measurement circuitry are given in paragraph 6.2.

All adjustments of the CMU are made from within the system software. These include adjustment of the circuit gain for individual capacitance measurements, calibration of the system, and continuous automatic monitoring and compensation for zero drift in the capacitance measuring circuitry.

The ethernet connection between the CMU and the host control computer can be implemented either by the use of a direct cross-over ethernet lead between the 2 units or by connecting the PC and CMU to an ethernet hub using conventional (uncrossed) ethernet leads.

The DAM200E CMU can carry out Protocol 1 capacitance measurement sequences in which one measurement electrode in each electrode plane and the equivalent driven guard electrode is set to be a source electrode, while the remaining (detector) electrodes are maintained at virtual earth potentials. Capacitance sensors having one (or two) planes of between 2 and 12 measurement electrodes and an optional set of driven guard electrodes can be used with the DAM200E CMU.

6.2 HARDWARE DETAILS

The CMU contains measurement circuitry for up to 2 planes of measurement electrodes and two sets of driven guard electrodes. Each plane of measurement electrodes is controlled and measured by an analogue measurement circuit board and an associated digital control board and the driven guard electrodes are controlled by circuitry on two further driven guard control boards. The CMU also contains an embedded PC with a digital interface and input/output triggering circuitry. A functional drawing of the CMU is shown in figure 6.2.1.
Figure 6.2.1 Component parts of the DAM200E-TP-G Capacitance Measurement Unit

Each analogue circuit board contains 12 capacitance measuring/control channels, an 11-way multiplexer circuit and a common analogue measuring circuit containing a DC bridge circuit and a 12-bit Analogue-to-Digital Converter (ADC). Each digital board contains the control and communications circuits for its associated analogue board. The driven guard boards provide an excitation signal to each driven guard electrode, identical to that applied to the equivalent measurement electrodes.

The CMU can measure capacitances in the range 0.1 - 2000fF (1fF = $10^{-15}$ F), and the inter-electrode capacitances of the capacitance sensor must therefore lie within this range when the sensor contains the dielectric materials to be imaged. The bridge circuit in the CMU is normally operated so that the 12-bit ADC (max output count 4095) operates between approximately 20% of full scale (900 counts) for all low-permittivity capacitance values (when the sensor is filled with the lower permittivity material) and 80% of full-scale (3200 counts) for all high permittivity capacitance values (when the sensor is filled with the higher permittivity material). This gives a measurement "headroom" of approximately 30% of the nominal measurement range above and below the nominal measurement range defined during the sensor calibration process. This headroom is needed to cope with soft field effects which can cause the measured capacitances to either exceed or fail to reach the values measured during calibration.
6.3. CAPACITANCE MEASUREMENT

6.3.1 Requirements For Capacitance Measurement System

The capacitance measuring system must be able to measure very small inter-electrode capacitances, of the order of $10^{-15}$ Farads (1 fF), in the presence of much larger capacitances to earth of the order of 200,000 fF (mainly due to the screened connecting cables and the outer screen of the sensor). It must be able to measure the small capacitances between opposing electrodes (10fF) as well as the much larger capacitances between adjacent electrodes (500fF) and must be able to do this at high speeds. The measurement circuit must noise-free as far as possible, immune to any interfering signals and must be stable and exhibit low long-term drift.

The technique used for measuring the capacitances between electrode pairs in the PTL300E ECT system uses a set of 11 charge/discharge capacitance/voltage converters and a common analogue measurement channel in the form of a programmable DC bridge as shown in figure 6.3.1.

![Capacitance measurement circuitry for a single plane of electrodes](image)

Figure 6.3.1 Capacitance measurement circuitry for a single plane of electrodes
6.3.2 Capacitance-To-Voltage Converter Circuits

The capacitance between electrode pairs is measured using a capacitance to voltage converter circuit which is largely unaffected by stray capacitance to earth. The basic measuring circuit is shown in figure 6.3.2 and works on the charge transfer principle, with one electrode of the pair (the \textbf{SOURCE} electrode) connected to a high frequency square wave source of amplitude \(V_s\) (15V) and frequency \(f\) (1.25 MHz), while the other electrode (the \textbf{DETECTOR} electrode) is held at virtual ground potential (0V). The current which flows into the second \(\textbf{DETECTOR}\) electrode of \(C_x\) (which is held at virtual ground potential) is measured using a synchronous demodulator. This measured current is proportional to the capacitance between the \textbf{SOURCE} electrode and the \textbf{DETECTOR} electrode of \(C_x\).

![Figure 6.3.2 Basic capacitance to voltage converter circuit](image)

Referring to figure 6.3.2, \(S_1\) and \(S_2\) are electronic switches which operate alternately at a frequency \(f\) (1.25 MHz) to generate a high frequency square excitation waveform of amplitude \(V_s\) (15V) which is applied to the source electrode of the unknown capacitance \(C_x\).

Switches \(S_3\) and \(S_4\) also operate alternately at the same frequency \(f\) but the phasing of the switching waveforms applied to \(S_3\) and \(S_4\) is in quadrature with the switching waveforms controlling \(S_1\) and \(S_2\). Consequently, the charging currents for the charging and discharging cycles of \(C_x\) are stored in the in the capacitances \(C\). The resultant stored charge causes the voltage across these capacitors to increase, which in turn causes the outputs of each amplifier to increase to provide a current through the feedback resistors \(R_f\) which cancels the charged stored in the capacitors \(C\). Hence the voltage across each capacitor \(C\) is maintained at zero (or virtual earth) potential. This method ensures that the detector electrode is also held at virtual ground potential (0V).
There are two separate outputs from this circuit, $V_a$ and $V_b$ corresponding to the **CHARGING** and **DISCHARGING** cycles of the circuit where:

$$V_a = -f.V_sR_f C_x + e_1 \quad (6.3.1)$$

$$V_b = f.V_sR_f C_x + e_2 \quad (6.3.2)$$

$R_f$ is the feedback resistance value used in the current detector circuits (figure 8.2.1), and $e_1$ and $e_2$ are output offset error voltages. The main cause of these offset voltages is leakage of charge from the control circuits of the CMOS switches (an effect known as charge injection). The two outputs are subtracted to give a net output from the circuit equal to:

$$V_o = 2f.V_sR_f C_x + e_2 - e_1 \quad (6.3.3)$$

If the charge injection voltages are equal, then the output simplifies to:

$$V_o = 2f.V_sR_f C_x \quad (6.3.4)$$

There are 11 identical circuits of this type for each of the measurement planes in the DAM200E CMU and this allows the capacitances between one source electrode and up to 11 detector electrodes to be measured simultaneously. This relatively simple measuring circuit has most of the desirable properties outlined in paragraph 6.1.
6.4 ELECTRODE CONTROL CIRCUITS AND OUTPUT MULTIPLEXER

In an ECT system, the electrodes must be switchable to be either source, detector or grounded electrodes. This is carried out using the arrangements shown in figure 6.4.1.

![Figure 6.4.1 Electrode control and output multiplexer circuits](image)

The electronic control system used within the DAM200 unit ensures that only one electrode at a time can be configured as a SOURCE electrode. The remaining electrodes are automatically set to be DETECTOR electrodes. In figure 6.4.1, electrode 1 is shown connected as a SOURCE and all of the other electrodes are shown connected as DETECTORS.

All measurement channels having the same channel number are always set to have the same function, so that for example, if channel 2 is set to be a source channel, then electrode 2 will be a source electrode in both planes 1 and 2 and also in the driven guard planes.

The electrodes connected to channels 2 to 11 of each measurement plane and the equivalent driven guard electrodes can be selected to be either SOURCE electrodes or DETECTOR electrodes (or grounded in the case of the driven guard electrodes) by the changeover switches shown in figure 6.4.1.

The limited number of measurements needed for protocol 1 excitation means that channels 1 and 12 can be simplified to conserve space on the analogue circuit boards. Under protocol 1, electrode 1 is always set to be either a SOURCE electrode or it is grounded and there is therefore no need for a capacitance measurement channel for electrode 1. Conversely, electrode 12 is never required to be a
source electrode and so it is always connected to its capacitance measurement channel as a **DETECTOR** electrode.

The outputs from the capacitance to voltage converter circuits are passed to a 2-pole 11-way selector switch (multiplexer), shown on the RHS of figure 6.4.1. The multiplexer operates under software control to select the outputs from one measuring channel at a time to the common analogue measurement circuit.

### 6.5 CAPACITANCE MEASUREMENT SEQUENCE

#### 6.5.1 Protocol 1

The DAM200E CMU is designed to measure capacitances under protocol 1, where one measurement electrode in each electrode plane and the equivalent driven guard electrode are set to be source electrodes, while the remaining (detector) electrodes are maintained at virtual earth potentials. This results in the following sequence of capacitance measurements for a 12-electrode sensor:

<table>
<thead>
<tr>
<th>Source channel</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{1-2}$, $C_{1-3}$, $C_{1-4}$, $C_{1-5}$, $C_{1-6}$, $C_{1-7}$, $C_{1-8}$, $C_{1-9}$, $C_{1-10}$, $C_{1-11}$, $C_{1-12}$</td>
<td>1</td>
</tr>
<tr>
<td>$C_{2-3}$, $C_{2-4}$, $C_{2-5}$, $C_{2-6}$, $C_{2-7}$, $C_{2-8}$, $C_{2-9}$, $C_{2-10}$, $C_{2-11}$, $C_{2-12}$</td>
<td>2</td>
</tr>
<tr>
<td>$C_{3-4}$, $C_{3-5}$, $C_{3-6}$, $C_{3-7}$, $C_{3-8}$, $C_{3-9}$, $C_{3-10}$, $C_{3-11}$, $C_{3-12}$</td>
<td>3</td>
</tr>
<tr>
<td>$C_{4-5}$, $C_{4-6}$, $C_{4-7}$, $C_{4-8}$, $C_{4-9}$, $C_{4-10}$, $C_{4-11}$, $C_{4-12}$</td>
<td>4</td>
</tr>
<tr>
<td>$C_{5-6}$, $C_{5-7}$, $C_{5-8}$, $C_{5-9}$, $C_{5-10}$, $C_{5-11}$, $C_{5-12}$</td>
<td>5</td>
</tr>
<tr>
<td>$C_{6-7}$, $C_{6-8}$, $C_{6-9}$, $C_{6-10}$, $C_{6-11}$, $C_{6-12}$</td>
<td>6</td>
</tr>
<tr>
<td>$C_{7-8}$, $C_{7-9}$, $C_{7-10}$, $C_{7-11}$, $C_{7-12}$</td>
<td>7</td>
</tr>
<tr>
<td>$C_{8-9}$, $C_{8-10}$, $C_{8-11}$, $C_{8-12}$</td>
<td>8</td>
</tr>
<tr>
<td>$C_{9-10}$, $C_{9-11}$, $C_{9-12}$</td>
<td>9</td>
</tr>
<tr>
<td>$C_{10-11}$, $C_{10-12}$</td>
<td>10</td>
</tr>
<tr>
<td>$C_{11-12}$</td>
<td>11</td>
</tr>
</tbody>
</table>

where, for example, $C_{1-2}$ means the capacitance measured between electrodes 1 and 2 with electrode 1 set to be a source electrode and electrode 2 set to be a detector electrode.

As the capacitances between pairs of electrodes are independent of the direction of measurement, reciprocal measurements (eg $C_{2-1}$) are not made in the interest of capturing frames of data at the highest possible capture rates.

The rate at which measurements can be made depends on the response time of the capacitance measurement circuits inside the CMU. The outputs of the electronic filters in the capacitance measurement channels must be allowed to reach their maximum values before the ADCs in each channel are read. For the filters in the DAM200E, a delay of approximately 380uS is needed after the source channel has been selected before the individual measurement channels can be read. Moreover, an additional delay of approximately 20 uS is required between selecting the output of each successive capacitance measurement channel to the common measurement channel via the multiplexer.
6.5.2 Capacitance Measurement Control Sequence

The table in paragraph 6.5.1 defines the required measurement sequence to capture a full frame of capacitance data. The actual measurement sequence implemented in the CMU is as follows:

1. Set channel 1 to be a source channel. Wait approximately 380uS to allow the outputs of the electronic filters in the measurement channels to settle.

2. Measure the capacitances between electrode 1 and the remaining electrodes in numerical order with a delay of 20uS between each of these measurements.

3. Set channel 2 to be a source channel. Wait approximately 380uS to allow the outputs of the electronic filters in the measurement channels to settle.

4. Measure the capacitances between electrode 2 and the remaining electrodes in numerical order with a delay of 20uS between each of these measurements.

Repeat this sequence for each source electrode channel in turn up to channel 11.

The capacitance data within a frame will be skewed in time as a result of this sequential data capture scheme. If this is important, supplementary software is available which can be used to "de-skew" the capacitance data.

A finite time is taken to capture a full frame of data and the total time delay is seen to be 380 x 11 + 20 x 66 = 5500 uS, corresponding to a maximum possible frame rate of 182 fps for a 12-electrode sensor. In practice, because of additional delays within the PC digital interface and the ethernet link, the fastest rates that can be achieved in practice are around 105 fps for a 12-electrode sensor, but this capture rate can be achieved using either one or 2 measurement planes.
6.6 THE COMMON ANALogue MEASURING CIRCUIT

In simple terms, the function of the common analogue measurement channel is to accept a DC input from a capacitance to voltage measurement circuit and convert this voltage into a count on a 12-bit Analogue to Digital Converter (ADC). However, because of the wide range of capacitance values which must be measured and the use of normalisation techniques, the operation of the circuit is relatively complex.

The circuit must be able to measure small changes in a wide range of standing capacitances. For a simple practical ECT sensor with internal electrodes, the standing capacitance between a pair of adjacent electrodes will be around 500 fF (0.5 pF) if the sensor contains air, while the capacitance between a pair of opposite electrodes will be 10 fF or less. If the sensor is now filled with a dielectric material, these values will increase by a factor anything up to the relative permittivity of the material. The measurement circuit must therefore have a wide measurement range.

The ECT system is designed to operate between an upper and lower set of permittivity values and is normally calibrated at these two extreme values of permittivity. Calibration is carried out by first measuring the capacitances between the various electrode combinations with the sensor filled with the lower permittivity material and then again with the sensor filled with the higher permittivity material. Reference parameters for each of these calibration conditions are stored in a calibration data file and this information is used to set the gain and offset voltages used in the common measurement channel.

The common analogue measurement circuit is made to operate so that the ADC count has approximately 20% of its maximum value at the lower permittivity calibration point and 80% of its maximum value at the upper permittivity calibration point. This means that the circuit normally operate over 60% of the ADC range but with a headroom of a further 33% of the nominal measurement range at each end to cope with out-of-range signals before the system saturates. A simplified representation of the circuit is shown in figure 6.6.1.

![Simplified common analogue measurement channel](image.png)

Figure 6.6.1 Simplified common analogue measurement channel
The circuit operates in the following manner:
1. The measurement circuit takes the form of a DC bridge, shown in simplified form in figure 6.6.1, which is balanced at the extreme ends of the measurement range. The bridge balancing is carried out using a programmable offset voltage, obtained from a Digital to Analogue Converter circuit (DAC) and also by adjusting the gain of a programmable attenuator if this is required.

2. This second programmable attenuator, in the form of a 10-bit (1024) multiplying DAC effectively extends the dynamic range of the measurement circuit beyond the nominal 12 bits of the ADC. The attenuator has a gain of 1 when the control data bus is set to its maximum count (1023) and a gain of zero when the count is set to 0.

3. The measurement circuit operates by adjusting the programmable attenuator and programmable offset voltage so that, as far as is possible, the ADC output counts are the same for all of the electrode-pair capacitances, whatever their actual values. The programmable offsets and attenuation figures are recorded during the calibration process and are recalled to measure the actual capacitances during normal operation of the ECT system.

A more detailed circuit diagram is given in figure 6.6.2 and a description is given in Appendix 4, which derives the measurement system equation which has been repeated below.

\[
C_{\text{meas}} = \left( \frac{1}{(K_1.G_1)} \right) \left[ \left( \frac{1024}{(M_2.G_3)} \right) \left( \frac{5.M_3}{4096.G_5} \right) - VR_2.G_4 \right] + VR_1.(M_1/1024 - G_1) 
\]

(6.6.1)

The parameters in equation 6.6.1 are defined in figure 6.6.2.
Figure 6.6.2 Common analogue measurement circuit (2)
6.7. MEASUREMENT OF ABSOLUTE CAPACITANCES

The system equation 6.6.1 converts the output voltage from the capacitance/voltage converter measuring circuits into a capacitance value in fF. However, the output voltages from the capacitance/voltage converter circuits will include any residual offset errors. Moreover, there may be further offset voltage errors in the common analogue measurement circuits. It is necessary to carry out a 3 sets of measurements to obtain the true values of absolute capacitances between an electrode-pair as follows:

6.7.1 System Zero Balance count M3BAL

The first task is to measure the balance point for the DC bridge circuit in the common analogue measurement channel with no input to the bridge circuit. This is the system zero balance voltage $V_{BAL}$ and is measured as as an equivalent ADC count $M_{3BAL}$.

$M_{3BAL}$ is measured by setting the gain of DACb in figure 6.6.2 to zero ($M_2 = 0$) and by measuring the output voltage $V_{BAL}$ as an equivalent ADC count $M_{3BAL}$. This value of $M_3$ is used in all subsequent measurements as the bridge balance point. This value is unique and is not affected by the choice of measuring channel.

When subsequent balancing operations are carried out during the capacitance measurements, balance is achieved when the ADC count reaches this value M3BAL, or the nearest value achievable by the balancing circuitry.

6.7.2 Charge Injection Capacitances

The next task is to measure the spurious output of the capacitance circuit when no electrode is set to be a source electrode. This output will consist of the offset voltages produced by the capacitance/voltage converter circuits and any residual offsets in the common measurement circuit. As the main effect is due to the charge injection leakage in the analogue switches, this spurious output is known as the charge injection capacitance of the circuit. As there are 11 capacitance/voltage converter circuits, there will be up to 11 charge injection capacitances and these are measured as follows:

The gain of DACb is set to 1 ($M_2=1023$) and electrodes 2 to 12 are set to be detector electrodes, with electrode 1 grounded. This ensures that the only output from the capacitance measuring circuits is that due to charge injected from the clock waveforms applied to the control gates of the analogue switches in the capacitance measuring circuits.

Each measuring channel is then selected in turn and the offset voltage $V_1$ is adjusted by varying the count $M_1$ applied to DACa until the ADC count $M_3$ equals the system zero balance value M3BAL (or as close to this value as can be achieved by the circuit).

The charge injection capacitances for each measuring channel $C_0(n)$ are then calculated using equation 6.6.1 and the values of $M_1$, $M_2$ and $M_3$ required to achieve balance as described above. There will be $(E-1)$ values of charge injection capacitance (11 maximum), where $E$ is the total number of measuring channels in use.
6.7.3 Inter-Electrode Capacitance Measurements

The final step is to measure the values of capacitances between the electrodes of a multi-electrode sensor system when each electrode is selected as a SOURCE electrode in turn. There will be \((E-1)E/2\) unique combinations of electrodes, resulting in the same number of values of measured capacitance \(C_{mij}\), where \(i\) refers to the source electrode and \(j\) refers to the detector electrode.

This is carried out by setting \(M2\) to 1024 (DACb gain = 1) and by adjusting \(M1\) until the output count \(M3\) of the ADC is equal to the zero balance value \(M3_{BAL}\). Initially electrode 1 is selected as a source electrode and all of the remaining electrodes are set as detector electrodes. Each detector circuit is selected in turn by the multiplexers and DACa is adjusted to restore the ADC output to the reference zero value \(M3_{BAL}\). The counts \(M1_{ij}(LOW)\) for DACa are recorded, as are the actual values of the ADC outputs following balance \(M3_{ij}(LOW)\).

The measured capacitance \(C_{ijm}\) is calculated using equation 6.6.1 and the values of \(M1\) to \(M3\) to achieve circuit balance.

6.7.4 Calculation of Absolute Capacitance Values

The true inter-electrode capacitance values are calculated by subtracting the appropriate channel charge injection capacitances \(C0(n)\) from the inter-electrode capacitance measurements. That is:

\[
C_{xij} = C_{ijm} - C0(n)
\]  

(6.7.1)

where \(C_{xij}\) is the true capacitance between electrodes \(i\) and \(j\), \(C_{ijm}\) is the measured inter-electrode capacitance and \(C0(n)\) is the measured charge injection capacitance for the measuring channel \(n=j\).
The CMU contains an embedded PC which interfaces to the remote control PC via a 10/100 MB/S ethernet link. Figure 6.8.1 shows the CMU connected to the control PC.

![Diagram showing control interfaces](image)

**Figure 6.8.1: ECT system showing control interfaces**

The embedded PC is in an industry-standard (PC104+/+) format. This is a modular standard, based on small circuit boards measuring 96 x 90 mm, which are interconnected by stacking them one above the other on standard connectors without the use of a motherboard.

The PC104 standard uses an ISA bus to interconnect the individual circuit boards which make up the embedded PC. The ISA bus is a 16-bit data bus which is clocked at a maximum speed of 8MHz. There is also an enhanced version of PC104, designated PC104+. This uses a 32-bit parallel data bus which is clocked at 33MHz or 66MHz and is therefore capable of operating at considerably higher speeds than the ISA bus if designed correctly. However, at the time of writing, most PC104+ digital I/O boards use the same (8255) digital I/O circuit which is used in similar ISA bus boards. This limits the speed of the board to that of an ISA bus device and so this potential speed advantage cannot be achieved in practice at present.

The embedded PC uses a PC104+ TP400 processor board made by DSP Design, together with an Onyx 48-way PC104 digital I/O board. The processor board, which can be used in both PCI and ISA modes, uses a 300 MHz Geode MMX enhanced processor and includes an ethernet port as well as a Compact Flash (CF) memory port, which allows the local control software to be stored on a CF memory card and updated via the remote ethernet link. The DSP unit has an interface which allows the embedded PC to be connected to an external PC monitor, keyboard and mouse for development and testing purposes. However, in normal use, these items are not used and the only external connection is the ethernet link to the remote control PC.

A custom interface board interconnects the digital I/O board to the digital measurement boards via 2 ribbon cables. A further ribbon cable goes to a remote circuit board containing isolated triggering circuits and LED indicator drive circuitry.
6.9 CONTROL SOFTWARE

6.9.1 Operating systems

The user-interface software on the host control PC is a new version of PTL's previous ECT32 control software, which runs under the Windows operating system.

The operating system on the embedded computer is Linux. One interesting feature of the Linux configuration adopted is that to overcome the limited write cycle life of Compact Flash (CF) memory, all parts of the file system that need to be writable are imaged to RAM at start-up. This has two further advantages: firstly the system can be returned to a known state by power cycling and also, it overcomes any risk of file system corruption at power-off. Moreover, the embedded software can be updated via the ethernet link which interconnects the CMU and the Control PC.

The new control system interface splits into a number of components.

6.9.2 Host (Remote Control) Computer

The Control PC is an Intel-compatible personal computer. The control software is a new version of PTL's ECT32 control software which communicates with the hardware through a Capture Sub-System DLL (CSD), which is chosen and loaded by the user at runtime. The ECT32 software can be run under all versions of Windows from Windows 95 onwards.

6.9.3 Communications Link Protocol

The use of an Ethernet link has many advantages, including a wide choice of media, speeds, and infrastructure components. It allows operation with long distances between the CMU and the host computer and the use of optical communications media in high noise environments and can even be used with an existing network infrastructure for control purposes.

The communications transport protocol is TCP/IP, which uses a mature efficient protocol and libraries to deliver an error-free data stream. Two TCP data streams are used, one for control and the other for data streaming, simplifying code design and enabling the addition of further slave data streaming channels. For improved performance, a proprietary binary frame data file protocol is being used.

6.9.4 Embedded Computer software

The embedded computer software has two elements. A ‘user space’ server application manages the network connection, builds and decodes network frames and makes all required floating point calculations. A ‘kernel space’ driver controls the hardware and in the current configuration, all the hardware sequencing.
Section 6.7 explained how the inter-electrode capacitances can be measured. Although an ECT system can be operated on the basis of absolute capacitance measurements, most practical ECT systems use normalised capacitances. These are derived from the absolute capacitances by carrying out a series of measurements under controlled conditions and generating a calibration data file.

### 7.1 CALIBRATION PRINCIPLE

In the normal method of operation, an ECT system is calibrated by filling the sensor with the two reference materials in turn and measuring the resultant inter-electrode capacitance values at these two extreme values of relative permittivity.

Figure 7.1.1  Relationship between capacitances and permittivity

This situation is shown diagramatically in figure 7.1.1, which illustrates how the measured inter-electrode capacitances change between the higher and lower values of permittivity used for calibration, for two materials of relative permittivity $K_L$ and $K_H$. For simplicity, it has been assumed that the variation is linear.

This method of calibration defines the two end points of the measurement range for most types of ECT measurement.

The data generated during the calibration process is held in a calibration file. A valid calibration file must be available before the ECT system can be used to capture valid data.
7.2 CALIBRATION FILE GENERATION

Calibration involves carrying out a sequence of measurements to determine the common measurement channel output balance count $M_{3\text{BAL}}$, measuring the capacitance to voltage converter circuit charge injection capacitances $C_0(n)$, and the capacitances between each combination of electrodes $i$ and $j$ ($C_{ij}$) for the cases when the sensor is filled with dielectric materials at the lower ($C_{ij}(\text{LOW})$) and upper ($C_{ij}(\text{HIGH})$) ends of the range to be measured.

Once these parameters have been measured and stored in a calibration file, this data can be used to set the parameters in the common analogue measurement channel to measure the inter-electrode capacitances when the sensor contains an arbitrary distribution of the two materials used to calibrate the sensor.

The calibration process is carried out as follows:

7.2.1 System balance count measurement $M_{3\text{BAL}}$

The first step in the calibration process is to measure the system balance count, as described in paragraph 6.7.1.

7.2.2 Charge Injection Capacitances measurement

The next step is to measure the so-called charge injection capacitances. This is done by operating the ECT system with no source electrode excited as described in paragraph 6.7.2. The parameters $M_1$, $M_2$ and $M_3$ are recorded for each capacitance to voltage measurement channel.

7.2.3 Lower Permittivity Capacitances measurement

Once these initial parameters have been measured, the next step is to measure the set of inter-electrode capacitances $C_L$ when the sensor is filled with the lower permittivity material. This is carried out as follows:

The sensor is filled with the lower permittivity material and the values of inter-electrode capacitances are measured as described in paragraph 6.7.3. The corresponding $M_1$, $M_2$ and $M_3$ values are again recorded. The true value of the inter-electrode capacitances are then calculated by subtracting the appropriate charge injection capacitances $C_0(n)$ from the measured values $C_{ij}(\text{LOW})$ as described in paragraph 6.7.4.

That is:

$$C_{x(\text{LOW})} = C_L - C_0(n) \quad (7.2.1)$$

where: $C_{x(\text{LOW})}$ is the true inter-electrode capacitance  
$C_L$ is the measured inter-electrode capacitance  
$C_0(n)$ is the charge injection capacitance for channel $n = j$
7.2.4 Higher Permittivity Capacitances measurement

The sensor is next filled with the higher permittivity material and the new inter-electrode capacitances \( C_{ij}(\text{HIGH}) \) are measured, again as described in paragraph 6.7.4.

In detail, for each inter-electrode measurement, DACa is set to the count measured for the low-level permittivity material (= \( M_{1ij}(\text{LOW}) \)). The digital attenuator (DACb) is set to its maximum gain of \( (1023/1024) \) (\( M_2 = 1023 \)) and the new circuit output is measured as an ADC count \( M_{3ij}(\text{HIGH}) \). If this operation causes \( M_3 \) to exceed a count of 3200, the gain of DACb is reduced by reducing \( M_2 \) to a new value \( M_2(\text{HIGH}) \) until the ADC count \( M_{3ij}(\text{HIGH}) \) is restored to a value around 3280. The \( M_1.M_2 \) and \( M_3 \) values are then recorded.

In practice, for many materials of low permittivity, it is often only necessary to set DACb to a gain of less than 1 in the case of capacitance measurements between adjacent electrodes. For all other combinations of electrodes, the gain of DACb is set to 1.

The true value of the inter-electrode capacitances are then calculated by subtracting the appropriate charge injection capacitances \( C_0(n) \) from the measured values \( C_{ij}(\text{HIGH}) \) as described in paragraph 6.7.4. That is:

\[
C_x(\text{HIGH}) = C_H - C_0(n) \quad (7.2.2)
\]

where: 
- \( C_x(\text{HIGH}) \) is the true inter-electrode capacitance
- \( C_H \) is the measured inter-electrode capacitance
- \( C_0(n) \) is the charge injection capacitance for channel \( n = j \)

7.2.5 calibration measurement timing

The way in which the ECT system is calibrated must be chosen with care to achieve accurate results. This is because, when the capacitance measurements are made at a high frame rate, the ADC readings will vary with timing. This is because it is necessary to read the ADC converters at a faster rate than the 100% settling time of the filters.

If a simple calibration method is used, the timings will be much slower than used in measurement mode because of the need to calculate the offsets for each capacitance measurement.

The strategy required is as follows:

1. Measure the M3BAL values with the gain set to zero.

2. Measure the offset \( M_{10} \), gain \( M_{20} \) and ADC values \( M_{30} \) with no source electrode selected (the offset capacitances). Then with \( M_{10} \) and \( M_{20} \) set, re-measure the \( M_{30} \) values at the normal operating speed and store these new M3 values.

3. Empty the sensor. With each electrode set as a source in turn and the gains set to maximum, measure the offsets \( M_{1L} \), and ADC values \( M_{30L} \) for the low-permittivity capacitances. Then with these \( M_{1L} \) and \( M_{2L} \) values set, re-measure the \( M_{3L} \) values at the normal operating speed and store these new M3 values.
4. Fill the sensor. With each electrode set as a source in turn and the gains set to maximum, set the offsets M1L measure the ADC values M3H for the the high-permittivity capacitances. If the ADC values exceed 3200, reduce the gai values M2H until M3H values are around 3200. Then with these M1L and M2H values set, re-measure the M3H values at the normal operating speed and store these new M3H values.

For a twin-plane system, read the ADCs for both planes as they would be read for a true high-speed scan.

### 7.2.6 Sample Calibration Data

A typical set of raw data held in the calibration data file is shown in Appendix 3 together with an explanation of the data format. The first set of data is the low-level permittivity calibration data, the second set is the high-level permittivity calibration data and the final set is the DC zero calibration data. For further information on the data format and information about interpretation of this data, please refer to Appendix 3.

### 7.2.7 Measurement of a range of calibration files.

True calibration can only be carried out when it is possible to fill the sensor with the lower and higher permittivity materials respectively. The ECT32 software allows partial recalibration, at either the lower or higher permittivity points only, and this facility is very useful for dealing with minor zero or full drift problems. However, it is a sensible precaution to measure a range of calibration files for a particular sensor under different conditions of room temperature etc before attempting to capture ECT data which will be used for subsequent analysis or processing. These calibration files can then be stored and the optimum file for the current measurement conditions can then be selected for use during data capture without the need for further full recalibration of the sensor.

### 7.3 CAPACITANCE MEASUREMENTS AND NORMALISATION

In PTL ECT systems, use is made of normalised parameters to represent both the inter-electrode capacitance measurements and also the displayed values of pixel permittivity.

Following the calibration process, the range of capacitance measurements for each electrode combination is known. Consequently the measurement system gains and offsets can be adjusted to normalise the capacitance measurements to lie between the values 0 and 1, where 0 corresponds to the values measured at the lower permittivity calibration point and 1 corresponds to the values measured at the upper permittivity calibration point, for each inter-electrode capacitance measurement.

When data capture starts, the capacitances between all unique pairs of sensor electrodes are measured continuously and these capacitance values are stored as normalised values for each frame of data in a binary data file. The normalised capacitance measurements can be displayed as vertical lines in the ECT32 software by displaying the appropriate capacitance windows.
7.3.1 Normalisation Of Inter-Electrode Capacitances

The absolute inter-electrode capacitances are normalised as follows: The values measured at the lower permittivity calibration point \( C_L \) are assigned values of 0 while the inter-electrode capacitances measured at the higher permittivity calibration point \( C_H \) are assigned values of 1. This relationship is shown in graphical format in figure 7.3.1 and is defined by the equation:

\[
C_N = \frac{(C - C_L)}{(C_H - C_L)} \quad (7.3.1)
\]

where \( C_n \) is the set of normalised inter-electrode capacitances and \( C \) are the set of absolute capacitances measured with the sensor containing a material of arbitrary permittivity, \( C_H \) are the set of absolute capacitances measured at the higher permittivity calibration point and \( C_L \) are the set of absolute capacitances measured at the lower permittivity calibration point.

![Figure 7.3.1 Normalisation of inter-electrode capacitances](image)

The absolute capacitances \( C_M \) can be calculated from the normalised capacitances as follows:

\[
C = C_N \cdot (C_H - C_L) + C_L \quad (7.3.2)
\]
### 7.4 NORMALISATION OF PIXEL PERMITTIVITY VALUES

The relative permittivity values of each pixel are calculated from the normalised capacitance values and are themselves normalised in a similar manner to the inter-electrode capacitances. Specifically:

The permittivity values for each pixel in the ECT image for the lower permittivity calibration point \(K_L\) are assigned values of 0, while the pixel permittivities in the image at the higher calibration point \(K_H\) are assigned values of 1. This relationship is shown in graphical format in figure 7.4.1 and is defined by the equation:

\[
K_n = \frac{K - K_L}{K_H - K_L}
\]  

(7.4.1)

where \(K_n\) is the set of normalised permittivities (pixel values) when the sensor is filled with a material of permittivity \(K\), \(K_H\) is the effective permittivity of the material used to calibrate the sensor at the higher permittivity calibration point and \(K_L\) is the permittivity of the material used to calibrate the sensor at the lower permittivity calibration point.

![Figure 7.4.1 Normalisation of pixel permittivity values](image)

**Figure 7.4.1** Normalisation of pixel permittivity values
SECTION 4

CALCULATION OF PERMIITTIVITY AND CONCENTRATION DISTRIBUTIONS

This section explains how permittivity and concentration images are obtained from the normalised capacitance measurements.
8 IMAGE RECONSTRUCTION OVERVIEW

8.1 OBJECTIVES OF ECT

ECT systems can be used to obtain images of the distribution of permittivity inside ECT sensors for any arbitrary mixture of different dielectric materials. However, the PTL300E ECT system is intended primarily for use with mixtures of two materials having different dielectric constants (permittivities). These are known as two-phase mixtures and for mixtures of this type, the ECT system can provide approximate information about the relative proportions (voidage) of the two materials inside the ECT sensor at any given time, as well as displaying their approximate distribution across the sensor plane. The main task in an ECT system is therefore to convert the measured capacitance values into a permittivity image. For a mixture of 2 dielectric materials, the concentration distribution is related to the permittivity distribution, so once the capacitance measurements have been made, the task reduces to calculating the permittivity distribution from these measurements.

8.2 ECT SYSTEM OPERATION

The basic method of operation of PTL ECT systems is as follows:

1. The properties of the sensor are measured or calculated to produce a sensitivity matrix of the sensor. This is a set of sub-matrices whose elements correspond to the individual pixels in a rectangular grid which is used to define the sensor cross-section. The sub-matrices are known as sensitivity maps.

2. The sensor is normally calibrated at each end of the range of permittivities to be measured by filling the sensor with the lower permittivity material initially and measuring all of the individual inter-electrode capacitances. This operation is then repeated using the higher permittivity material. The data obtained during the calibration procedure is used to set up the measurement parameters for each measuring channel and is stored in a calibration data file.

3. Once the system has been calibrated, the capacitances between all unique pairs of sensor electrodes are measured continuously at high speed, giving E(E-1)/2 unique values per measurement or image frame, where E is the number of sensor electrodes. These capacitance measurements are then converted to normalised values.

4. A capacitance sensor model, which defines the relationship between the permittivity distribution across the sensor and the resultant inter-electrode capacitance methods is chosen and the normalised capacitance measurements are modified according to this sensor model.

5. An image reconstruction algorithm is used to compute the cross sectional distribution of the permittivity of the material inside the pipe. Images can be constructed from the capacitance measurements either at the time of measurement (on-line) or from stored or captured data (off-line). The standard algorithm supplied with the PTL300E system is the so-called Linear Back-Projection (LBP) algorithm. This is a fast but approximate algorithm which uses the capacitance measurements, together with the sensitivity map to produce the image. Other alternative algorithms can be used with the stored data to produce more accurate images.
8.3 IMAGE RECONSTRUCTION PROBLEMS

There are several problems which make it difficult to calculate accurate permittivity distributions inside the sensor from the normalised measured inter-electrode capacitances. Some of these are listed below:

1. The **limited number of unique inter-electrode capacitance measurements** available severely limits the **image resolution** that can be achieved.

2. The **soft field effect**, which causes the **electric field lines** inside the sensor to be distorted by the **sensor contents**, means that simple image reconstruction algorithms may produce distorted images.

3. The relationship between the **measured capacitances** and the **permittivity distribution** inside the sensor depends on how the constituent materials are distributed inside the sensor. A suitable **sensor capacitance/permittivity/concentration model** must be chosen if accurate concentration figures are to be obtained.

4. Accurate information about the capacitance sensor (the sensor **sensitivity matrix**) must be known before permittivity images can be calculated.

8.4 LINEAR AND NON-LINEAR IMAGE RECONSTRUCTION METHODS

Most ECT sensors are inherently **non-linear devices**, partly because of the **soft field effect** and also because, in many cases, the **electrodes are located outside the walls of insulating vessels** so that the sensor can be **non-invasive**. In these cases, the electric field lines between the sensor electrodes are distorted by the vessel wall. Moreover, the capacitive coupling from the electrodes to the material inside the sensor will be weakened if the permittivity of the sensor contents is higher than that of the vessel wall.

Fortunately, in many cases, the permittivity contrasts between the materials in the mixture are relatively small (<3), resulting in correspondingly small distortions in the electric field. In these cases, linear methods, such as the LBP algorithm, already described briefly in paragraph 3.13, can be used with good effect to calculate the permittivity image. Improved accuracy can be achieved by using iterative versions of this algorithm. Further information about iterative algorithms is given in chapter 13 of this manual and also in **PTL Application Note AN4**. Even when the permittivity contrasts are higher, linear methods can still be used along with with iteration to obtain reasonable images.

However, when the permittivity contrasts are large (>10), **non-linear image reconstruction methods** must be used if accurate images are to be obtained. This is particularly the case when one of the dielectric materials is water, which has a very high relative permittivity (dielectric constant) of 80 (for pure distilled water). Non-linear image reconstruction methods are outside the scope of this manual at present.
A typical ECT permittivity image format uses a square grid of 32 x 32 pixels to display the distribution of the normalised composite permittivity of each pixel. For a circular sensor, 812 pixels are used to approximate the cross-section of the sensor. The values of each pixel represent the normalised value of the effective permittivity of that pixel. In the case of a mixture of two dielectric materials, these permittivity values are related to the fraction of the higher permittivity material present (the volume ratio (or voidage)) at that pixel location.

In principle, for an ideal ECT sensor with internal electrodes and containing a dielectric material of uniform permittivity, there will be a linear relationship between the normalised inter-electrode capacitances and the resulting normalised pixel permittivity values. For example, if the sensor contains a uniform material of normalised permittivity \( K_n = P \), the normalised inter-electrode capacitances will all have the value \( P \), resulting in an image where each pixel also has the value \( P \).

The overall volume ratio, which defines the ratio of the two materials present, averaged over the volume of the sensor, can also be obtained. The overall volume ratio of the materials inside the sensor at any moment in time is defined to be the percentage of the volume of the sensor occupied by the higher permittivity material. The volume of the sensor is the product of the cross-sectional area of the sensor and the length of the sensor measurement electrodes.

In all of the following we shall be referring to the relative permittivity (or dielectric constant) of materials. The relative permittivity of a material is its absolute permittivity divided by the permittivity of free space (or air). Hence the relative permittivity of air is 1 and typical values for other materials in solid or liquid format are polystyrene (2.5), glass (6.0) and mineral oil (2.3).

In this manual, we have used three different terms to describe the same concept, as they are all in common use. These are volume ratio, voidage and concentration, which we define to be the fraction of the higher permittivity material present in the mixture. These terms are inter-changeable in the following text.

Section 10 of this manual describes in detail the steps needed to obtain a permittivity image from the inter-electrode capacitances measured by the CMU, based on the use of the Linear Back Projection (LBP) algorithm and derivatives of this algorithm.
ECT is an example of what Mathematicians call an "Inverse Problem". Whereas we can measure the inter-electrode capacitances of an ECT sensor, what we actually want to know is the corresponding permittivity distribution inside the sensor, which can be considered to be the inverse of the actual measurement.

9.1 The Forward Problem

When the sensor inter-electrode capacitances are measured, the resulting values of capacitance are a direct result of the permittivity distribution inside the sensor. For a given sensor, containing \( E \) measurement electrodes in each measurement plane, there will be \( m \) unique inter-electrode capacitance measurements where:

\[
m = E \cdot \frac{(E-1)}{2}
\]

and \( E \) is the number of electrodes. For example, if \( E = 12 \) then there are \( m = 66 \) possible capacitance measurements.

We can represent the set of capacitance measurements corresponding to one image frame as an array (or matrix) \( C \) containing \( m \) measured normalised capacitance values.

If we similarly define the permittivity distribution as a set of \( n \) normalised square permittivity pixels, they can be represented as an \( n \) - element array or matrix \( K \). For example, if the permittivity distribution is based on a 32 x 32 pixel grid, then \( n = 32 \times 32 = 1024 \) pixels.

If we now assume that the relationship between the measured capacitances and the permittivity distribution inside the sensor is substantially linear (which may or may not be the case in practice), we can use the electrical superposition theorem to define the relationship between these two matrix parameters. Writing the superposition theorem in a form relevant to this situation, it states that the capacitance measured between any electrode pair for a given permittivity distribution \( K \) will be equal to the sum of the capacitances which would exist between the same electrode pair if each pixel in the permittivity distribution acted independently, with all other pixels set to zero normalised permittivity.

That is, we can find the capacitance between one pair of electrodes for a given permittivity distribution \( K \) by setting up a set of \( n \) pixel distributions, where successive pixels, starting with the first pixel, are set to their \( K \) value with all of the other pixels set to \( K = 0 \). We then measure the elemental inter-electrode capacitances for each case where one pixel is non-zero and add up all of these elemental capacitance values for each non-zero pixel distribution to obtain the value of capacitance \( C \) for the overall permittivity distribution \( K \).

This can be represented mathematically as a matrix equation:

\[
C = S \cdot K
\]

where: \( C \) is a matrix containing the set of \( m \) measured normalised inter-electrode capacitances

\( K \) is a matrix containing the set of \( n \) normalised permittivity values

\( S \) is a matrix which relates \( C \) and \( S \) and is known as the sensor sensitivity matrix (or forward transform) and has the dimensions (\( m \times n \)).

In practice, most ECT sensors containing low-permittivity materials are sufficiently linear for this approximation to be valid and equation 9.1 is substantially accurate in these cases.
So if we know the permittivity distribution $K$ inside the ECT sensor, we can calculate the capacitances that would be measured between each electrode-pair using equation 1, provided that we also know the values of the elements in the matrix $S$.

These values can be found by any of a variety of different methods and the process of obtaining these values (solving for the **sensitivity matrix** $S$) is known as solving the "**Forward Problem**" in Inverse Problem terminology.

### 9.2 The Inverse Problem

In principle, once the sensitivity matrix $S$ is known, it is a mathematically simple process to obtain the permittivity distribution $K$ from the capacitance measurements $C$ by inverting matrix equation 9.1. That is:

$$K = S^{-1}.C \quad (9.2)$$

The solution of this equation is known as solving the **Inverse Problem** by mathematicians and $S^{-1}$ is known as the **Inverse Transform**.

Unfortunately, it is only possible to obtain the inverse of a square matrix, where (in this case) the number of inter-electrode capacitance measurements $m$ equals the number of pixels $n$ in the permittivity distribution. However, we have already seen that for even a relatively low-resolution image, $n$ is typically 1024 whereas, for a 12-electrode sensor, there will only be $m=66$ capacitance measurements. Consequently it is not possible to use a true inverse of the sensitivity matrix to solve the inverse problem and some other suitable transform must be found.

In the LBP algorithm, the **transpose** of the sensitivity matrix (obtained by swapping the rows and columns of the sensitivity matrix) is used as the **inverse transform**. This $n \times m$ element matrix has the correct dimensions to satisfy equation 9.2 but is at best, a poor approximation to a true inverse transform. However, the use of this transform can be justified on physical grounds and as will be seen, although its use produces very blurred images, these can be improved by the subsequent use of more sophisticated algorithms.

So the **inverse problem** can now be defined as follows:

$$K = C.S^T \quad (9.3)$$

where:  
- $K$ is the permittivity distribution to be found  
- $C$ is the set of measured inter-electrode capacitances  
- $S^T$ is the transpose of the sensitivity matrix

The LBP algorithm is simple and fast. However, the images produced by this algorithm are blurred because, unlike the case of X-rays, where a single ray path between source and detector will pass through only one set of pixels, the electric field between two capacitance electrodes spreads out and intercepts many pixels. The effect of this is to give a spurious and unwanted level of background permittivity to each pixel. This can be removed by some form of filtering or thresholding if required. Alternatively, an iterative technique as described in chapter 13 X and PTL application note **AN4** can be used to improve the image accuracy. In the standard PTL PCECT operating software, no thresholding, filtering or iteration is used at present.

It is clear that the sensitivity matrix and its transpose are the keys to using the LBP algorithm and the next chapter discusses these matrices in further detail.
10 THE SENSITIVITY MATRIX

The **sensor sensitivity matrix** contains information about how the measured capacitance between any combination of electrodes changes when a change is made to the permittivity of a single pixel inside the sensor.

10.1 THE ELECTRIC FIELD DISTRIBUTION INSIDE THE SENSOR

The variation in sensitivity inside the sensor can be better understood by considering the case where one electrode of the sensor (at 3 o clock in the figure below), is connected to a positive potential $V$ and all of the other electrodes are connected to earth (or virtual earth).

![Equipotential lines inside ECT sensor](image1.png)

*Figure 10.1.1 Equipotential lines inside ECT sensor*

The electric field distribution for this situation is shown in figure 10.1.1 (the figure shows the equipotential lines) and is relatively uneven, the field being strongest near to the excited electrode (where the equipotential lines are closest together) and weakening with increasing distance from this electrode. The corresponding electric field lines are shown in the figure below.

![Electric field distribution inside ECT sensor](image2.png)

*Figure 10.1.2 Electric field distribution inside ECT sensor*
A second example, calculated and plotted using different software for an excited electrode located at 11 o clock is shown below.

![Diagram showing equipotentials for an electrode located around 11 o clock]

**Figure 10.1.3** Equipotentials for an electrode located around 11 o clock

The effect of these uneven electric field distributions is that the change in capacitance measured between any two electrodes caused by an object with a given permittivity will vary depending on the location of the object inside the sensor. For example, when used with a circular cross section sensor, the ECT system is most sensitive when an object is placed near the walls of the vessel and is least sensitive at the centre of the vessel.

Allowance is made for this effect in the LBP algorithm because the variation of sensitivity with position for each pixel is stored in the sensitivity map file. When the ECT system constructs images, it reads the sensitivity map and calculate the image pixels accordingly.

### 10.2 CALCULATION OF THE SENSITIVITY MATRIX

The sensitivity matrix must be calculated (or measured) for each individual sensor as a separate exercise prior to using the sensor with an ECT system. Two methods for doing this are described below. In general, the first method is preferred as experience has shown that it gives better results and is relatively fast due to easier computation.
10.2.1 Calculation directly from electric fields

The first method for calculating the sensitivity coefficient $S$ of a pixel for an electrode-pair $(i,j)$ is based on the use of equation 10.1.

$$S = \int_A E_i \cdot E_j \, dA \quad (10.1)$$

where $E_i$ is the electric field inside the sensor when one electrode of the pair $i$ is excited as a source electrode, $E_j$ is the electric field when electrode $j$ is excited as a source electrode and the dot product of the two electric field vectors $E_i$ and $E_j$ is integrated over the area $A$ of the pixel. The set of sensitivity coefficients for each electrode-pair is known as the sensitivity map for that pair. Hence the sensitivity matrix can be considered to be formed from m sensitivity maps, i.e., one map for each inter-electrode capacitance pair.

For circular sensors with either internal or external electrodes, it is possible to derive an analytical series expression for the electric fields and in this case, the sensitivity coefficients (and also the electrode capacitances) can be calculated accurately. For more complex geometries, numerical methods can be used to calculate the sensitivity coefficients. As circular ECT sensors have a high degree of symmetry, it is normally only necessary to calculate a few primary sensitivity maps for the set of unique geometrical electrode pairings, as all of the maps for the remaining electrode pairings can be derived from these primary maps by reflection or rotation (see paragraph 10.8 and Appendix 11 for further information about this).

10.2.2 Calculation from capacitances

A second method for calculating sensitivity matrices is based on calculating the inter-electrode capacitances when each pixel in turn contains the higher permittivity material, with all other pixel permittivities set to zero. That is:

$$S_{ij}(n) = \frac{C_{ij}(n) - C_{ij}(LOW)}{C_{ij}(HIGH) - C_{ij}(LOW)} \quad (10.2)$$

where: $S_{ij}(n)$ is the sensitivity coefficient for the $n$th pixel for the capacitance pair $i$-$j$

- $C_{ij}(n)$ is the capacitance measured between the $i$th and $j$th electrodes when pixel $n$ contains the higher permittivity material and all of the other pixels contain the lower permittivity material.
- $C_{ij}(LOW)$ is the capacitance measured between the $i$th and $j$th electrodes when the sensor contains the lower permittivity material only.
- $C_{ij}(HIGH)$ is the capacitance measured between the $i$th and $j$th electrodes when the sensor contains the higher permittivity material only.

Calculation of the inter-electrode capacitances requires knowledge of both the electric potential distribution $V(x,y)$ and the permittivity distribution $K(x,y)$ inside the sensor. The electric potential distribution $V_i(x,y)$ inside the sensor is calculated with electrode $i$ is the source electrode (at a potential +Vs) and all of the other electrodes set to be detector electrodes (at 0V potential). Finite element methods are normally used to calculate $V_i(x,y)$ for a given sensor geometry.

The permittivity distribution $K(x,y)$ can be defined quite simply as $K =$ the lower value of permittivity for all pixels except the $k$th pixel, for which the coefficients are to be calculated, in which case it is set to the high permittivity value.
Once the electric potential distribution $V_i(x,y)$ is known, the inter-electrode capacitances $C_{ij}(k)$ can be calculated using equation 10.3 below:

$$C_{ij}(k) = - \frac{1}{V_S} \int_{-R}^{R} \int_{-R}^{R} K(x,y) \nabla V_i(x,y) \, dx \, dy$$  \hspace{1cm} (10.3)$$

where $R$ is the internal radius of the circular vessel.

Having calculated each of the inter-electrode capacitances, the sensitivity coefficients may then be calculated using equation (10.2).

**10.3 NORMALISATION OF SENSITIVITY MATRICES**

Whichever method is used, the sensitivity coefficients have to be normalised so that when equations 9.1 and 9.3 are used, the pixel values have the value 1 when the normalised capacitances have the value 1 and vice-versa.

**10.4 TYPICAL SET OF PRIMARY SENSITIVITY MAPS**

A set of primary maps for an 8-electrode sensor operating under protocol 1 and calculated using the method described in paragraph 10.2.1 is shown in figure 10.4.1.

![Figure 10.4.1 Primary Sensitivity Maps for an 8-electrode sensor](image)

The maps show the relative pixel sensitivities on a compressed colour scale, where blue pixels represent areas of negative sensitivity, where the capacitance for the electrode pair will decrease when the permittivity of the pixel increases, green pixels represent areas of zero sensitivity and red pixels represents positive sensitivity regions, where the capacitance increases when the pixel permittivity increases.
10.5 SYMMETRY PROPERTIES OF SENSITIVITY MAPS

In principle, we need to calculate the sensitivity map for each electrode pair. Fortunately we only need to calculate the set of primary sensitivity maps, as shown, for example, in figure 10.4, because ECT sensors often have a high degree of symmetry. For example, of the 66 possible capacitance measurements for a 12 element sensor, there are only 6 unique inter-electrode-pair capacitances if the sensor is empty and is symmetrical. These are the capacitances C12, C13, C14, C15, C16, C17. That is the capacitances measured between adjacent electrodes, between next but one electrodes and so on, up to that between diametrically opposed electrodes. All of the other sensitivity maps may be deduced from the maps for these electrode pairs from the symmetry properties of the sensor.

The equivalence between the remaining capacitance measurements and the 6 values for which the sensitivity coefficients are actually calculated or measured is shown in table 10.1. This shows the 6 coefficients S12 - S17 calculated in the plane theta = 0 and the equivalent coefficients for the planes theta from 30 to 330 degrees.

### Table 10.5.1

**Equivalence Of Sensitivity Coefficients For A 12 Electrode Sensor**

<table>
<thead>
<tr>
<th>THETA Degrees</th>
<th>S1,2</th>
<th>S2,3</th>
<th>S3,4</th>
<th>S4,5</th>
<th>S5,6</th>
<th>S6,7</th>
<th>S7,8</th>
<th>S8,9</th>
<th>S9,10</th>
<th>S10,11</th>
<th>S11,12</th>
<th>S1,12</th>
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10.6 USE OF MODIFIED SENSITIVITY MATRICES FOR HIGH PERMITTIVITY MATERIALS

In certain cases (for example, when the sensor contains a high permittivity fluid such as water), it may be necessary to use a modified sensitivity matrix rather than the standard matrix. This will be necessary when sensors with electrodes outside the wall of the vessel are used to image high permittivity materials. This is because an undesirable effect occurs when the fluid to be imaged has a relative permittivity exceeding a value around 10. This occurs for example when water (permittivity = 80) is the fluid to be imaged. The effect is to cause the capacitance measured between adjacent electrodes to decrease rather than to increase when the higher permittivity material is present. This problem can also occur with lower permittivity materials for sensors with thick walls.

One solution to this problem is to ignore the capacitances measured between all pairs of adjacent electrodes. This can be achieved by modifying the sensitivity map so that the sensitivity coefficients for adjacent electrodes S[i-(i+1)] are set to zero.
10.7 PTL STANDARD GENERIC SENSITIVITY MAPS

In principle, a unique sensitivity map should be calculated for each individual ECT sensor. In practice, good results are obtained using standard generic maps for particular sensor geometries. Two sets of standard generic sensitivity map files for circular sensors are provided for use with the PTL ECT systems. The standard sensitivity maps are suitable for imaging most materials having a relative permittivity less than 10 (but not water). The Water sensitivity maps are modified versions of the standard maps with the coefficients for adjacent electrodes set to zero. These modified maps give improved images for high permittivity materials such as water.

10.8 CALCULATION OF CUSTOM SENSITIVITY MATRICES

Sensitivity matrices for specific circular sensors can be calculated using custom PTL Makemap software which is now supplied with each ECT system. Further information about the use of this software can be found in Appendix 11. All ECT sensors designed and supplied by PTL are now supplied with a custom sensitivity map.
11 CALCULATION OF PERMITTIVITY IMAGES

Once the sensitivity map of the sensor is known, sets of captured capacitance data can be converted into permittivity distribution images using a suitable image reconstruction algorithm. The simplest algorithm, the LBP algorithm, has already been described in chapter 9 and images are obtained directly using equation 9.3. Some sample ECT permittivity images are shown below.

11.1 SAMPLE ECT IMAGES

Figure 11.1.1  ECT Images for a fluidised bed

Figure 11.1.1 shows two image at closely-spaced measurement planes for a vertical fluidised bed. The first frame shows an area of low fluid concentration while the second image shows an area of high concentration.

Figure 11.1.2  ECT image of a cylindrical dielectric rod

Figure 11.1.2 shows a typical ECT image for a circular dielectric rod.
11.2 IMAGE RESOLUTION

The resolution of an ECT permittivity image is ultimately limited by the number of independent inter-electrode capacitance measurements that are available to the image reconstruction algorithm. The relationship between image resolution and the number of capacitance measurements can be considered to be an example of spatial filtering, as shown in figure 11.2.1 below.

![Resolution Limits Imposed by Spatial Filtering](image)

**Figure 11.2.1 Resolution limits imposed by spatial filtering.**

In this figure, the upper line represents relationship between the image resolution that would be achieved using a "perfect" image reconstruction algorithm for a given number of available capacitance measurements. The lower line shows the same relationship for a less-effective algorithm, as any real algorithm will be less effective than the hypothetical perfect algorithm.

The upper resolution limit for a perfect algorithm is difficult to define mathematically, but a simple engineering estimate can be made by assuming that the number of independent measurements $M$ corresponds to a similar number of discrete regions inside the sensor. If we assume that the angular resolution is equal to the number of electrodes $E$, then the radial resolution will equal $(M / E)$. For protocol 1 and a 12 electrode sensor, this gives a radial resolution limit of 5.5. For protocol 2 and 24 electrodes, this figure increases to 10.5.

The LBP algorithm is an example of an imperfect algorithm because, although the forward transform (the sensitivity matrix) can be reasonably accurate, the inverse transform used in this algorithm is relatively inaccurate. Consequently, the quality of image obtained using the LBP algorithm is relatively poor. Fortunately, these LBP images can be improved, either by further image processing or by the use of more sophisticated algorithms.
12 VOIDAGE CALCULATION

12.1 NOTE ON ABSOLUTE AND RELATIVE VOIDAGES

We define voidage to be the percentage of the higher permittivity material inside the sensor when the sensor contains a mixture of 2 dielectric materials. Other terms which have the same meaning as voidage in this context are "Concentration" and "Volume Ratio". Voidage can refer to the total contents of the sensor (the overall voidage), or to an individual pixel or groups of pixels.

All voidage values obtained from PTL ECT systems are based on the assumption that the voidage is 100% when the sensor is filled with the higher permittivity material and is zero when the sensor is filled with the lower permittivity material. Consequently, the voidage values obtained from an ECT system are Relative Voidages.

If the two materials used for calibration are liquids, then the voidages obtained from the ECT system will correspond nominally to the actual absolute voidages.

However, in many cases, one of the reference materials (the lower permittivity material) will be air. Air has a dielectric constant (relative permittivity) of 1, which is, by definition, the lowest possible value of dielectric constant which can exist for any real material. If the second reference material is in granular or powder form, the upper calibration point will be formed by a mixture of air and the granular material.

This will result in a lower permittivity for the upper calibration point than would be obtained by simply assuming the relative permittivity of the dielectric material in its solid form. For example for a mixture of glass beads and air, the measured permittivity of the mixture is around 3, whereas the permittivity of solid glass is approximately 6.

In this case, the absolute voidage for both the individual pixels and the sensor as a whole is obtained by multiplying the indicated relative voidage by the actual voidage at the upper calibration point.

For example, if the indicated relative voidage of a pixel is p and the absolute voidage when the sensor is full of the higher permittivity material is f, then the absolute voidage of the pixel, VR, will be given by:

\[ VR = p \cdot f \]  \hspace{1cm} (12.1)

It should be noted that the permittivity or volume ratio distribution can only be obtained from the inter-electrode capacitance measurements if:

1. There are no more than 2 materials present inside the sensor.
2. The sensor has been correctly calibrated using these two materials.
12.2 CALCULATION OF VOIDAGE OF SENSOR CONTENTS

Having obtained the permittivity distribution across the sensor, the next step is to derive the overall volume ratio (voidage), of the mixture of the two dielectric materials inside the sensor, and also the distribution of this voidage across the sensor. The overall voidage can be obtained either from the measurements of the normalised capacitances between the sensor electrodes or from the permittivity distribution of the mixture, derived from these measurements. The voidage distribution can only be obtained from the permittivity distribution.

12.2.1 CALCULATION OF OVERALL VOIDAGE

In principle, the overall voidage of the contents of the ECT sensor can be calculated from either the normalised pixel values in the reconstructed ECT image or from the normalised capacitance measurements directly.

In the case of calculation from image pixels, this is done by summing the values of the individual pixels in the ECT image for the required image frame and dividing this figure by the number of pixels.

Putting this in mathematical terms,

\[ VR = \frac{1}{N} \sum_{i=1}^{N} K(i) \]  

(12.2.1)

where \( VR \) is the voidage, \( N \) is the total number of pixels and \( K(i) \) is the normalised permittivity of the ith pixel.

In the case of calculation from the normalised inter-electrode capacitances, the voidage is obtained by summing all of the normalised capacitance values for one image frame and dividing these by the number of capacitance measurements. Again, putting this in mathematical terms,

\[ VR = \frac{1}{M} \sum_{m=1}^{M} C(m) \]  

(12.2.2)

where \( M \) is the total number of electrode-pair measurements and \( C_m \) are the individual electrode-pair normalised capacitances.

There are a number of possible methods which can be used to calculate the voidage and the choice of the optimum method depends on the electrical model used to describe the physical distribution of the two materials inside the sensor. For some applications, such as liquid or dense-phase mixtures, a simple parallel capacitance model can be used to obtain the voidage distribution directly from the permittivity distribution of the mixture. In this case, the voidage is numerically equal to the normalised pixel values. Other methods for calculating voidage are described in the following paragraphs and in PTL application note AN2.
12.3 CORRECTION FOR SENSOR CAPACITANCE/PERMITTIVITY MODELS

The equations in paragraph 12.2 are based on the assumption that the voidage is directly proportional to the normalised permittivity inside the sensor. This assumption may be valid under some circumstances and invalid in others. This is explored in detail in this chapter.

There are a number of possible methods which can be used to calculate the voidage of a 2-phase dielectric mixture and the choice of the optimum method depends on the electrical model used to describe the physical distribution of the two materials inside the sensor. For some applications, such as liquid or dense-phase mixtures, a simple parallel capacitance model can be used to obtain the voidage distribution directly from the permittivity distribution of the mixture. However, in other applications, such as fluidised beds with high levels of fluidisation, the use of a model based on capacitances in series produces better accuracy and sensitivity.

A further model which combines the parallel and series models and which was developed by Maxwell in the 19th century is a useful compromise in many practical applications. The need for these sensor models is discussed in this chapter. Further information can be found in PTL Application Note AN2.

The reason why these models are needed can be understood by considering the case of simple parallel plate capacitance cell containing a two different dielectric material as discussed in paragraph 12.4.

12.4 EFFECTIVE PERMITTIVITY OF A MIXTURE OF TWO DIELECTRIC MATERIALS

Permittivity images are calculated from the normalised capacitances using equation 9.3. However, before this is carried out, a sensor capacitance/permittivity model must be chosen and the normalised capacitances modified according to this model.

At first sight it is not obvious why different sensor models are needed. However a quick study of figure 12.4.1 gives an insight into the problem. We have shown a parallel plate capacitor (or capacitance cell) consisting of 2 horizontal electrodes 1 and 2. The first figure (a) shows the cell empty (filled with air, k= 1) and the second figure (b) shows the cell filled with a material of relative permittivity k.

Figures c and d show the cell half-filled with the dielectric material but with 2 very different distributions of the dielectric.

![Figure 12.4.1 Capacitance/permittivity distribution models](image-url)
If we assume that we can treat these cells as perfect parallel plate capacitors, we will measure the following values of relative capacitance for cells a to d:

a: (empty) 1
b: (full) k
c: (half-full horizontally) 2k/(k + 1),
d: (half-full vertically) 1/2(1 + k)

When the cell is filled with the dielectric material, the capacitance increases by a factor of k. However, when the cell is partially-full, the way the capacitance increases depends on the distribution of the dielectric material inside the sensor.

Where the distribution is layered vertically, as shown in figure d, the capacitance of the cell increases linearly with the proportion of dielectric material present. The effect is to create 2 elemental capacitances which are in parallel with each other. The capacitance of 2 parallel capacitors is found simply by adding up the 2 individual capacitances. That is:

\[ C = C_1 + C_2 \]  \hspace{1cm} (12.4.1)

However, if the distribution is layered horizontally, as shown in figure c, The capacitance increases in a non-linear manner. There are now effectively 2 capacitors in series formed by the air and dielectric regions. The capacitance of 2 capacitors in series is found by the reciprocal rule ie:

\[ \frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} \]  \hspace{1cm} (12.4.2)

Hence we have 2 fundamentally different methods of calculating how the capacitances will increase when the sensor is half-filled with a dielectric material. We refer to these 2 models as the parallel and series capacitance models.

It is worth noting that, at the end points (where the sensor is either empty or full, both methods give the same values (0 and 1) for the normalised capacitances. However, whereas the parallel model gives a straight line relationship between these 2 points, which means that in this case, the concentration is linearly related to the capacitances, the series model gives a series of non-linear curves, depending on the permittivity of the dielectric material in the sensor.

12.5 SERIES MODEL CORRECTION

Whereas for the parallel model, there is a straight-line relationship between the measured capacitances and the voidage, the results obtained using the series model are shown below for a range of permittivities K. The graph plots the indicated voidage (calculated from the measured capacitances) against the actual voidage (calculated on the basis of the proportion of dielectric material present inside the sensor). The deviation from a linear relationship increases with the permittivity of the material in the sensor.
The effect of this relationship is that the voidages calculated using the simple linear (parallel) model will always under-estimate the true voidage if the material distribution effectively forms parallel paths between pairs of electrodes.

This problem can be corrected by modifying the measured normalised capacitances by a correction factor defined in equation 11.2 below:

\[ C_{n2} = C_n \left( K_H / K_L \right) / \left( 1 + C_n \left( 1 - K_L / K_H \right) \right) \]  \hspace{1cm} (12.5.1)

Where \( C_{n2} \) is the corrected normalised capacitance, \( C_n \) is the measured normalised capacitance and \( K_L \) and \( K_H \) are the relative permittivities of the 2 materials in the sensor.

It should be noted that when \( K_L = K_H \), \( C_{n2} = C_{n1} \) and no correction is made to the measured capacitance values. Equation 11.2 can therefore be applied universally, corresponding to the parallel model when \( K = KH/KL = 1 \) and corresponding to the series model when \( K > 1 \).

The parallel capacitance model tends to be valid for densely packed materials, such as liquids, or powdered/granular materials in dense-phase processes. In this case, no modification of the measured capacitances is required and \( K \) is set to 1.

However, where the concentration values are low, as is the situation in lean-phase conveying or particles, the series model must be used to obtain accurate voidage values.
12.6. OTHER PERMITTIVITY MODELS

There are a number of other models which can be used to calculate the relationship between the voidage and the effective permittivity of the material inside the sensor.

12.6.1 Maxwell Model

This model is a compromise between the series and parallel models. It yields a slightly different correction factor which, in practice is applicable to mixtures of two materials where both the parallel and series models apply in different regions of the mixture.

\[ C_{n2} = K_{en_2}(2 + k)/(3 + C_{n_2}(k - 1) \] \hspace{1cm} (12.6.1)

where \( k = K_{H}/K_{L} \).

12.6.2 Yang/Szuster Model

A variation on the series model, which does not rely on knowing the ratio of the permittivities of the materials used at calibration, has been developed independently by Dr W. Yang of UMIST in the UK and K. Szuster in Poland. This method effectively deduces the permittivity ratio from the calibration data.

The correction factor which results from this model is given in equation 12.6.2.

\[ C_{n2} = C_{n_2} \cdot (C_H/C_m) \] \hspace{1cm} (12.6.2)

where:

- \( C_H \) is the absolute value of the capacitance measured during calibration for the higher permittivity material.
- \( C_m \) is the absolute value of the measured capacitance.
The iterative image reconstruction method is based on the use of equations 9.1 and 9.3. The idea is to use these two equations alternately to correct the sets of capacitance and pixel values in turn and hence produce a more accurate image from the capacitance measurements. The details are as follows:

1. Measure a set of (typically 66) normalised capacitances $C_1$ for one image frame.

2. Correct the set of normalised measured capacitances $C_1$ using the series model correction formula (or some other correction formula, see paragraphs 12.6/7).

3. Calculate the set of (typically 1024) pixel permittivities $K_1$ corresponding to $C_1$ using equation (9.3) ie.

   \[ K_1 = S^T C_1 \]  

   (13.1)

   Note that the matrix $S^T$ must be normalised as follows: As $K_1$ is a set of 1024 pixels and $C_1$ is a set of (eg 66) capacitance readings, then $S^T$ must be normalised by dividing each of the elements (permittivity coefficients) in $S$ which contribute to each specific pixel value in $K_1$ by the sum of all of the values of permittivity coefficients in $S^T$ which contribute to the specific pixel location (a sum of eg 66 permittivity coefficients).

4. Truncate the individual pixel values $k$ so that they lie within the range $0 < k < 1$ and save and display the image.

5. Use these new values of permittivity to back-calculate a new set of inter-electrode capacitances $C_2$ using equation (1) ie:

   \[ C_2 = S \cdot K_1 \]  

   (13.2)

   Note that in this case, the matrix $S$ must be normalised as follows: As $C_2$ is a set of eg 66 inter-electrode capacitance measurements and $K_1$ is a set of 1024 pixel values, then $S$ must be normalised by dividing each of the elements (capacitance coefficients) in $S$ which contribute to each specific inter-electrode capacitance measurement by the sum of all of the capacitance coefficients in $S$ which contribute to this capacitance measurement (a sum of 1024 capacitance coefficients).

6. Calculate a set of error capacitances $\Delta C$ where:

   \[ \Delta C = (C_2 - C_1) \]  

   (13.3)

7. Truncate $\Delta C$ to limit the maximum values of $\Delta C$ so that they lie within the range $(-0.05 < \Delta C < 0.05)$ or some other pre-defined limits. This is necessary to prevent the feedback loop from becoming unstable.

8. Multiply $\Delta C$ by a gain factor (typically 1.5) which is determined by empirical means.
9. Use equation (13.1) and the error capacitances $\Delta C$ to calculate a set of error pixel values $\Delta K$. ie:

$$\Delta K = S^T \cdot \Delta C$$  \hspace{1cm} (13.4)

10. Use the set of error pixels to generate a new set of pixel values $K_2$ where:

$$K_2 = (K_1 - \Delta K)$$  \hspace{1cm} (13.5)

11. Truncate these pixel values to lie within the range $0 < k < 1$ and save and display the image.

12. Repeat steps 5 to 11 using the new set of $K$ values $K_2$ (instead of $K_1$) in equation (13.2). In equation 13.3, generate the error capacitances by subtracting the original measured capacitances from the current set.

11. Repeat step 12 as many times as necessary to obtain an accurate image.

An illustration of the image improvement which can be obtained is shown in the following figure 13.1.1. The image data is for a 60mm OD plexiglass tube with 5mm walls, placed approximately centrally inside an 8 electrode ECT sensor having an internal diameter of 100mm. The figure shows the improvements in the image as the number of iterations is steadily increased.
Figure 13.1.1

TUBE IMAGE SHOWING IMPROVEMENTS WITH INCREASING NUMBER OF ITERATIONS
14. IMAGE RECONSTRUCTION ACCURACY TESTS

Tests were carried out using a 12-electrode sensor with internal electrodes to determine the accuracy of image reconstruction based on the calculation of voidage. Tests were carried out using sensitivity matrices calculated using the PTL Makemap software, the iterative algorithm and a range of permittivity models. The detailed results are shown in this chapter but can be summarised as follows:

For the case of a dielectric rod in air (i.e., a higher permittivity object inside a lower permittivity space) the series permittivity model gives the most accurate values of voidage when the permittivity ratio of the materials used for sensor calibration is used.

For the case of a cylindrical void containing air inside a sensor filled with glass beads (i.e., a lower permittivity object inside a higher permittivity space) the Maxwell permittivity model gives the most accurate values of voidage when the permittivity ratio of the materials used for sensor calibration is used.

Details of the individual tests are given in paragraphs 14.1 and 14.2.

14.1 PLASTIC ROD CONTAINING GLASS BEADS IN AIR

The following results were obtained by calibrating a 12-electrode sensor, of internal diameter 128mm, with air and glass beads (effective K = 3). A thin plastic tube of external diameter 40mm filled with glass beads was then introduced into the sensor. The true voidage is \((40/128)^2 = 9.8\%\).

Figure 14.1.1  Parallel model, \((K = 1)\), \(N=100\), \(VR = 4.4\%\)

Figure 14.1.1 shows the image obtained using the parallel permittivity model for 100 iterations and a permittivity ratio of 1. The voidage (VR) obtained is 4.8%, which is less than the known value (9.8%).
Figure 14.1.2  Series model, K = 2, N=100, VR = 8.0%

Figure 14.1.2 shows the same data but this time using the series model for a permittivity ratio of 2. The voidage (VR) has increased but is still less than the known value.

Figure 14.1.3  Series model, K = 3, N=100, VR = 10.9%

Figure 14.1.3 shows the same data but this time for the correct permittivity ratio of 3. The calculated voidage (VR) is 10.9% and now exceeds the known value. If the Maxwell model is used to construct the image, the VR is found to be 7.05% using the same data as used in figure 14.1.3.
14.2 CYLINDRICAL AIR VOID INSIDE GLASS BEADS

For a second set of tests, the sensor was filled with glass beads and the same plastic tube, this time empty, was inserted inside the sensor. The known voidage is 90.2%.

Figure 14.2.1 Parallel model, (K = 1), N=100, VR = 86.4%

Figure 14.2.1 shows the image constructed using the parallel permittivity model (K = 1). The calculated voidage (86.4%) is lower than the known voidage (90.2%).

Figure 14.2.2 Series model, K = 2, N=100, VR = 92.2%

Figure 14.2.2 shows the same data calculated using the series model and a permittivity ratio of 2. The calculated voidage now exceeds the known voidage.
Figure 14.2.3  Series model, $K = 3$, $N=100$, $VR = 94.6\%$

Figure 14.2.3 shows the results recalculated for the correct permittivity ratio of 3. The results show an even higher voidage (94.6%).

Figure 14.2.4  Maxwell model, $K = 3$, $N=100$, $VR = 91.1\%$

For comparison, figure 14.2.4 shows the same data recalculated using the Maxwell permittivity model. The results are now close to the true voidage.
It is possible to calculate enhanced inverse transforms (transformation matrices) which give better quality images than those produced by LBP, (which uses the simple transpose of the sensitivity matrix as the inverse transform).

A number of different transformation matrices can be used, but two methods which give useful improvements over back-projection are based on methods originally described by Tikhonov and Landweber. In principle, the Landweber method should give similar results to the iterative algorithm when pixel truncation is disabled. Both the Landweber and Tikhonov transformation matrices can be obtained from the sensitivity matrix for the sensor. This process is termed regularisation by Mathematicians.

### 15.1 The Tikhonov Transform

We are indebted to Dr Andrew Reader of UMIST (DIAS) for the following explanation of the Tikhonov transform:

In the LBP method, the forward and inverse transforms are defined by the two matrix equations:

\[ C = S.K \]  
\[ K = S^T.C \]

where:

- \( S \) is the sensor sensitivity matrix, \( S^T \) is the transpose sensitivity matrix and the forward transform (equation 15.1) is assumed to be accurate, but the inverse transform (equation 15.2) is known to be inaccurate.

Let \( K \) be the actual (physical) permittivity distribution and \( K_{BP} \) be the (erroneous) distribution calculated from the capacitance measurements \( C \) using equation (15.2).

Then

\[ K_{BP} = S^T.C \]  

Substituting for \( C \) using equation 15.2 we obtain:

\[ K_{BP} = S^T.S.K \]  

Hence

\[ K = K_{BP}.(S^T.S)^{-1} \]

and substituting for \( K_{BP} \) from equation (10.1.4) we obtain:

\[ K = S^T.C . (S^T.S)^{-1} \]

\[ K = \frac{S^T.C}{S^T.S} \]

That is, the true permittivity distribution \( K \) is obtained by using the inverse transform \( \frac{S^T}{S^T.S} \) instead of the simple transpose matrix \( S^T \).
However, the matrix $S^T S$ has squared sensitivity coefficients along its primary diagonal and if these coefficients are small, their squared values will be very small. There is a clear danger that dividing the matrix $S^T$ by this denominator matrix $S^T S$ will result in some divisions by very small numbers or even by zero. Consequently, the primary diagonal elements of the denominator matrix are padded out with constants to prevent this happening by adding a scaled identity matrix $I$ to the denominator.

That is equation (15.7) becomes:

$$K = \frac{S^T C}{S^T S + tI} \quad (15.8)$$

where $t$ is a scalar constant (the Tikhonov constant) and $I$ is the identity matrix (a matrix with ones along the primary diagonal and zeroes elsewhere).

As can be seen, equation 15.8 is similar to the LBP inverse transform except that the transpose matrix $S^T$ is replaced by the new transform $Q^T$ where:

$$Q^T = \frac{S^T C}{S^T S + tI} \quad (15.9)$$

This transform is readily computed from the sensor sensitivity matrix.

The Tikhonov transform can also be written in the alternative form shown in equation 15.10 below:

$$Q_T = S^T \cdot (S \cdot S^T + t \cdot I)^{-1} \quad (15.10)$$

In physical terms, what the Tikhonov transform does is correct the effect of the erroneous matrix $S^T$ (which causes low-pass spatial filtering of the permittivity distribution, removing all of the fine detail) by the use of a complementary transform (which has the effect of passing the data through an amplified high-pass filter). However, there is a limit to how much gain can be used without simply amplifying the noise in the low-pass-filtered capacitance measurements. The identity matrix and scaling factor effectively limit the gain which is applied to the correcting transform. Larger values of $t$ will have a large moderating effect while small values of $t$ will have minimal effect. The choice of $t$ is therefore critical to avoid spurious artefacts in the reconstructed image. Typical safe values for $T$ are in the range 0.1 to 100. Low values of $T$ yield very noisy higher-definition images while higher values of $T$ produce images similar to those produced by LBP.

To use the Tikhonov transform, all that is required is to replace the inverse transform used in the inverse problem equation (the transpose sensitivity matrix) by the Tikhonov transform.
15.2 The Landweber Transform

The transformation matrix $Q_L$ used in Landweber’s method can be derived from the sensor sensitivity matrix $S$ by defining a transform parameter $L$ and an iteration parameter $N$ (which defines the number of iterations).

$Q_L$ is defined in equation 7.1 as follows:

$$Q_L = V \cdot F (W, t, N) \cdot U'$$

(15.13)

where:

$V$, $W$ and $U$ are the matrices obtained by applying the Single Value Decomposition (SVD) process to the sensitivity matrix $S$. This operation produces a diagonal matrix $W$ of the same dimensions as $S$, and unitary matrices $U$ and $V$, so that $S = U \cdot W \cdot V$.

$F$ is the SVD filter function matrix defined in equation A1.2.

$$f = \frac{(1 - (1 - t \cdot w)^N)}{w}$$

(15.14)

where:

$f$ is one element of the filter matrix $F$

$w$ is one element of the diagonal matrix $W$

$t$ is a relaxation parameter (referred to in the main text as the Landweber transform parameter $L$).

$N$ is the number of iterations.

Typical safe values for $L$ are in the range 0.01 to 0.0001. Experience shows that high values of $L$ (0.01) can give rise to spurious artefacts around the edges of the image, while low values of $L$ appear to give results similar to those obtained using the simple LBP algorithm. Typical practical values for the number of iterations $N$ are in the range 10 to 100.

To use the Landweber transform, all that is required is to replace the inverse transform used in the inverse problem equation (the transpose sensitivity matrix) by the Landweber transform.
SECTION 5

OPERATING INSTRUCTIONS

The basic method of operation of the ECT system has already been described briefly in section 2, using one of the unguarded single-plane demonstration sensors supplied with the ECT system. This section gives more detailed information about the operation of the PTL300E ECT system using the ECT32v2 control software.

Firmware Licence Statement

The DAM200E is controlled by an internal embedded PC running the Linux operating system and proprietary PTL embedded software, which is stored on a compact flash memory card. We refer to this software on the embedded PC as "Firmware".

The DAM200E firmware consists of two elements.

1) The underlying operating system and associated software. This is GNU/linux which is distributed under the terms of this General Public Licence (GPL) which can be found at http://www.fsf.org/licenses/licenses.html. It is based on the Gentoo distribution (http://www.gentoo.org). The source code for this element has not been modified and can be acquired from the referenced url or from PTL on request.

2) The DAM200E specific software. This has been authored entirely by PTL and due to its linkage (to glib C and the Linux kernel) is bound by the Lesser General Public Licence (LGPL) (also at http://www.fsf.org/licenses/licenses.html). As the DAM200E driver uses the exported kernel interface, it is covered by the LGPL, which does not require the distribution of source code.
16. OPERATING PRECAUTIONS

16.1 *** STATIC CHARGE WARNING ***

The use of an ECT sensor with moving dielectric fluids in an insulating pipe can give rise to the development of high electrostatic potentials on the sensor and pipe which could create a safety hazard for both the operator and the plant. Any implications for the safety of the plant being monitored should be carefully considered before using the ECT system. In particular, the sensor metalwork should be solidly grounded and connected electrically to any adjacent metallic pipework to protect the operator. If installation of the sensor causes an insulated break in a run of metallic pipework, the two sections of pipe should be bonded together using a substantial electrical link which must also be connected electrically to the outer shield of the sensor.

The input channels of the DAM200E Capacitance Measurement Unit (CMU) contain CMOS circuitry. Because of the nature of the measurement of very small values of capacitance used in the system, it is not possible to fully protect these inputs. It is therefore very important that any sensors connected to the inputs of this unit are fully discharged before connections are made. All sensors used with the DAM200E unit should include built-in discharge resistors of no more than 1 Mohm in value, connected between the individual sensor electrodes and the screens of the coaxial connecting leads, to ensure that static charge cannot build up on the sensor electrodes.

16.2 ELECTROMAGNETIC COMPATIBILITY

The PTL300E ECT system is a sensitive scientific instrument. Under normal operating conditions, the system will not cause problems to other electronic equipment provided that the ECT sensor used with the system is adequately screened and grounded.

However, the PTL300E system may be adversely affected by high levels of electrical interference because of its high measuring sensitivity. If these problems persist, please contact PTL for advice on solutions to these problems.

16.3 INTRINSIC SAFETY DISCLAIMER

The PTL300E ECT system has not been certified for use in applications which require intrinsic safety certification and must not be used in applications where intrinically-safe equipment is mandatory.

17. SYSTEM SET UP AND SOFTWARE INITIALISATION

The PTL300E ECT system can be used with [either] a single [or twin] - plane ECT sensor, which may or may not contain driven guard electrodes.

1. Connect up the ECT system as described in paragraph 2.2 (Quickstart Instructions).

2. Connect a suitable single or twin-plane ECT sensor to the DAM200E Capacitance Measurement Unit (CMU) as follows:

Observing the static warning and precautions mentioned in paragraph 16.1, connect the Plane 1 sensor electrode leads of the appropriate capacitance sensor (labelled S1A etc) to the Plane 1 input.
channels of the CMU (labelled M1 to M12). Note that the channel numbers start at 2 on the right hand end of the front panel and that channel 1 is next to channel 12 on the DAM200E unit.

If the sensor is a twin-plane unit, similarly connect the Plane 2 sensor electrode leads of the capacitance sensor (labelled S1B etc) to the Plane 2 input channels of the CMU.

If the sensor contains guard electrodes, these should be connected to the plane 1 guard channels on the CMU. If there are two single-plane sensors or a twin-plane sensor with two sets of guard electrodes, connect these to the plane 1 and plane 2 guard channels on the CMU.

3. Power up the system as described in paragraph 2.3.

4. Double-click on the ECT32v2 icon to start the ECT32v2 software.
18. OVERVIEW OF ECT SYSTEM OPERATION USING THE ECT32v2 SOFTWARE

18.1 SUMMARY OF CONTROL SOFTWARE

The PTL300E ECT system is controlled by proprietary ECT32v2 software in either single or twin-plane mode. This software runs under all current versions of the Windows operating system.

![ECT32v2 Desktop window]

Figure 18.1.1 ECT32v2 Desktop window

The main control screen is the ECT32v2 Desktop window shown in figure 18.1.1. Other important windows are the ECT32v2 Configuration and Calibration Windows (figures 18.2 and 18.3).

The ECT32v2 software allows one or two ECT sensor planes to be controlled either independently or simultaneously, using one or more of a number of control tools, including an initial configuration window, control menus on the menu bar at the top of the ECT32v2 desktop, control icons on two further toolbars and control buttons on a separate Control panel window.

Facilities included in the software allow Permittivity Images to be constructed using a number of different physical sensor models. Capacitance data can be captured and played back at different frame rates, and displayed as permittivity images, normalised capacitances or any combination of these.

Image pixels can be truncated or inverted. The image gain can be set by the user and a permittivity offset can also be applied to the image to allow small variations about a preset value of permittivity to be displayed.

Measured capacitance or image data can be saved in either binary or ASCII format and sequential data files can be generated automatically. Calibration of twin plane systems can be carried out for each plane individually and a composite calibration file can be generated from the individual files.
A set of data can be stored in a **reference frame** and subtracted from all subsequent data frames to allow enhanced viewing of **changes in experimental conditions**. Simple on-line correlation of data from a **twin-plane system** can be implemented to measure the velocity of materials under relatively steady-state flow regimes.

Data from a **number of frames** can be **averaged** on a **rolling or fixed basis** to reduce the effect of noise for slowly-changing images and the **averaged data** can be used to produce the **Reference frame**.

Data capture can be triggered by or synchronised with other instruments. **Advanced facilities** are provided which allow the **fundamental measurement time constants** to be optimised to allow increased data capture speeds at the expense of increased system noise levels. This may be advantageous in some specific applications.

**Capacitance data can be exported on-line** via a fast ethernet link to a **remote PC**.

The **Configuration process** and **operating modes** are described briefly in the following paragraphs of this overview chapter. More detailed information is given in subsequent chapters of this manual, where we have tried to identify the **relevant software menu headings and options** which are **relevant to the topics under discussion** and have indicated these items in *italics* where appropriate.

### 18.2 SYSTEM CONFIGURATION WINDOW (**Mode menu, Configure system**)  

The **ECT32v2 software** has three main modes of operation, **Data Capture**, **Playback** and **Record** modes, together with an additional **Idle mode**, all of which are initiated following an initial **Configuration** process.

![ECT32 Configuration Window](image)

**Figure 18.2.1 ECT32v2 Configuration window**
The ECT system is set up initially by entering a set of appropriate control parameters in the Configuration window. This window (shown in figure 18.2.1) contains a number of sets of parameter groups titled Data sources, System calibration, Display format, Imaging control, Capture control and Session Description. The individual control parameters within these groups are described briefly below and in detail in chapter 19. The Configuration Window appears each time the ECT32v2 software is started up and provides a short-cut method for initialising the software control parameters and/or for setting them to their last known operating state at the start of each new session. The aim of this is to allow users to continue working where they left off without the complication of re-initialising each aspect of the system individually. It is also the quickest way to initialise and configure the ECT32v2 system software from scratch.

The Configuration window can also be accessed after the software has been started, either by clicking on icon 1 on the toolbar of the ECT32v2 Desktop or by selecting the Configure System option from the Mode menu. In this case, the function of the Configuration window is slightly different from that at start-up, as explained in paragraph 19.8.

Details of some of the parameters in the Configuration window are as follows:

1. Data Sources

Sensor hardware: If this source is selected, data is captured live using the Capacitance Measurement unit (DAM200E) for the enabled measurement planes.

Data File: If this source is selected, data is replayed from the captured capacitance data file selected.

2. System calibration from:

On-line: Calibration is carried out on-line immediately following system configuration.
File: Calibration data is read from the specified calibration data file.

3. Display: A valid Sensor information file (set of sensitivity maps) for the number of electrodes on the sensor must be selected before data capture can commence and a permittivity image displayed.

Two sets of generic sensitivity maps for circular sensors are supplied for use with the PTL300E ECT system. For most materials with relative permittivities less than 10, the standard maps should be used. For higher permittivity materials (particularly water) for use with sensors where the electrodes are external to the tube wall, the water maps should be used.

The water sensitivity maps omit capacitance measurements made between adjacent electrodes. When images are displayed using the water sensitivity maps, the pixels corresponding to measurements between adjacent electrodes will display zero values of permittivity and should be ignored.
4. Imaging Control

Permittivity offset: If a value other than zero is set here, the normalised permittivity image display will be offset by the value entered in the range 0 - 1.

Image gain: The normalised permittivity is multiplied by the value entered. The normal value is 1.

Truncate: If selected, the displayed image pixel values are truncated to lie between the nominal values of 0 and 1. This facility can be used to alleviate the effect of severe field distortion.

Capture Control:

Frame Rate: The data capture rate in frames per second

Buffer time: The size of the circular buffer file buffer.bcp in seconds

Auto Stop: If selected, data capture will cease once the buffer file has been filled. If this parameter is switched OFF, the buffer is continuously cycled and data capture and display are continuous. Suggested initial setting is OFF.

Buffer file name: The name of the circular buffer file

Record file name: The name of the data file used to capture data in Record mode.
18.3 OPERATING MODES (Mode menu)

The Operating modes may be selected in a number of ways, including selection as options on the Mode menu as follows:

18.3.1 Capture mode (Mode menu, Capture mode)

In Capture mode, data is displayed on-line from a single or twin-plane ECT sensor connected to the DAM200E unit. The displayed data is stored to a circular memory buffer continuously. When Capture mode is exited, the buffer memory is saved to the specified buffer data file automatically.

18.3.2 Record mode (Mode menu, Record mode)

In Record mode, the ECT32v2 software allows capacitance data from an ECT sensor to be recorded directly into a capacitance data file for subsequent replay and analysis. The main difference between Capture mode and Record mode is that data is automatically captured by over-writing a common buffer file in Capture mode whereas in Record mode, data is captured directly to a specified unique data file.

18.3.3 Playback mode (Mode menu, Playback mode)

In Playback mode, the ECT32v2 software displays data from a previously captured or recorded capacitance data file.

18.3.4 Idle mode (Mode menu, Idle Mode)

In Idle mode, the ECT system enters a quiescent state in which it is possible to set some of the control parameters for the Capture and Record modes.
The first step in using the ECT system is normally to calibrate the system. This is done by setting the capacitance measurement hardware control parameters at the nominal extremes of the permittivity range to be measured. In practice, this involves filling the ECT sensor with the lower and higher permittivity materials to be imaged before the ECT system can be used to display images. The system can be calibrated for either single or twin-plane sensor operation and the calibration process is controlled by a set of Calibration windows shown in figure 18.4.1. Further more detailed information about the calibration process is given in chapter 21.

Figure 18.4.1 Calibration Windows
18.5 THE ECTv32 DESKTOP WINDOW

Once the ECT system has been configured and calibrated, the ECT32 Desktop window is displayed, which allows capacitance data to be captured and permittivity images to be displayed.

![ECTv32 Desktop window](image)

**Figure 18.5.1 ECTv2 Desktop window**

The ECT32v2 Desktop (shown in figure 18.5.1), consists of a title bar (at the top of the window), a menu bar (immediately below the title bar), a toolbar (immediately below the menu bar), a display area containing a control panel, below which is a status bar with indicators (at the bottom of the window). The control panel is shown separately and at a larger scale in figure 18.5.2.

![Control Panel window](image)

**Figure 18.5.2 Control Panel window**

The menus on the menu bar control the major functionality of the ECT32v2 software, but most of this functionality is duplicated by control buttons, represented by icons on the toolbar and by function buttons on the control panel. Detailed information about the toolbar icons is given in paragraph 20.2.
18.6 DATA CAPTURE AND DISPLAY (Mode menu, Capture mode)

Following sensor calibration, the ECT system defaults automatically to Capture mode, displaying a live image of the normalised permittivity distribution of the sensor contents in a capture window.

The central circular area of the window displays the live permittivity image using a colour scale from blue (normalised pixel value = 0, corresponding to the permittivity of the material used to calibrate the sensor at the lower level) via green (0.5) to Red (normalised pixel value = 1, corresponding to the permittivity of the material used to calibrate the sensor at the higher level). The image immediately following calibration will normally be that for a full sensor and will therefore be displayed in red. The image shape is determined by the sensor information file.

The far left vertical bar shows the normalised permittivity scale.

The right hand vertical gauge is the volume fraction of the image expressed in % in a scale from 0 to 100%, where 0% corresponds to the sensor full of the lower permittivity material and 100% corresponds to the sensor full of the higher permittivity material. The volume fraction is calculated from the image pixels.

For the situation where there is a mixture of two materials inside the sensor, the normalised permittivity can be interpreted as the voidage or volume ratio of the materials with which the sensor was calibrated. The volume ratio is shown on a scale at the right hand side of the image window. The volume ratio scale has a nominal range from 0 to 100%, with the facility for displaying values 30% more or less than this nominal range.

Note that an indicated volume ratio of 100% corresponds to the situation where the sensor is full of the higher permittivity material and 0% corresponds to the situation where the sensor is full of the lower permittivity material. If, as is often the case in practice, the higher permittivity material is a mixture of air and solids, and the lower permittivity material is air, the actual volume ratio must be obtained by multiplying the indicated volume ratio by the absolute volume ratio at the higher permittivity point (typically 50 to 60% absolute volume ratio).

The normalised permittivity value of any pixel can be found by clicking the mouse pointer inside the image at the required location. The selected pixel is highlighted and its value is displayed at the bottom of the image, as shown in figure 18.4, in the form probe = X, where X is the voidage or normalised permittivity. This option is turned off by clicking the mouse cursor outside the image.

The permittivity image can be modified by changing the image gain, introducing a permittivity offset, truncating the image pixels and by the use of a number of different voidage models.

If icons 18 or 19 are selected on the toolbar, an additional window appears which displays the normalised values of capacitance. The capacitances are displayed in the order C12, C13, ’... C1E (where E is the number of electrodes), C23, etc. with gaps between the C1E, C2E, C3E,... sets of readings. This facility is also operative in Playback mode. The normalised capacitances window for a single plane sensor is shown at the RHS of figure 18.4. [A similar window with two sets of capacitances is displayed in twin plane mode].
18.7 EXAMPLE OF CAPTURING AND REPLAYING DATA

As an example of how 10 seconds of data can be collected, carry out the following instructions:

In the Control Panel window, select Idle mode and Autostop.

Set the Buffer time to 10 seconds.

Calibrate the system by clicking on the Calibrate icon (6) on the toolbar and follow the on-screen instructions.

Select Capture mode. Data will now be collected for 10 seconds, after which the system will revert to Playback mode.

Click the forward play button (2nd on right after Stop button). The capacitance data will now be replayed in the form of a permittivity image.

18.8 DATA FILES (File menu, Generate ASCII Data files)

Capacitance and image data can be saved and retrieved in a number of different formats. The primary measurement data can be saved in binary format as normalised inter-electrode capacitances. Normalised and absolute capacitances, image files and voidage files can also be saved in ASCII format.

This completes the brief overview of the ECT32v2 software. The detailed functionality of the software is described in the following chapters.
Before any of the operating modes can be used, the ECT32v2 software must be initialised and configured. The simplest way to do this is to use the Configuration window which appears when the program starts up. The basic method for doing this has already been described in outline in the Quickstart section 2. The following chapters explain the use of this window in more detail.

The text order follows the groupings of the controls and settings contained in the various parameter groups in the Configuration window (figure 19.1.1).
19.1 DATA SOURCES GROUP

The two basic options in this group are either to display data from an **On-line sensor**, or from a **Captured capacitance data file**.

19.1.1 On-line data

To **display data on-line** from an **ECT sensor**, the following parameters in the **Data Sources** group must be set:

**Sensor Hardware**: DAM200E selected and checked.

**Enabled Planes**: Check planes to be viewed.

**Note that** the ECT32v2 software can work with **1 or 2 sensor planes** simultaneously. On a DAM200E unit, these planes are numbered 1 and 2. The **Enabled planes** check boxes allow the **planes** to be used to be selected. **Planes** may be **selected** and **de-selected** while the software is running, **as long as one plane always remains active**.

19.1.2 Off-line data

To **display data off-line** from a **measured data file**, check the **Data File** box and select the required **measured data file** using the **Browse** button.

It should be noted that settings in different groups of the **Configuration** window are inter-dependent. For example, **replaying data** from a file does not require any sensor to be calibrated. Hence, if a **recorded data file** is selected as the **Data source**, the **calibration** option is **de-activated**. This restricts the user to initialising the ECT system in a reasonable configuration to allow it to be used straight away.

19.2 SYSTEM CALIBRATION DATA GROUP

The options selected in this group determine whether the ECT sensor is calibrated **on-line** on exiting the **configuration** window or whether data from a **an existing stored calibration file** is to be used as the **calibration data source**.

To set up the system for **on-line sensor calibration**, check the **Online** option.

To choose to calibrate the system using **data from a previous calibration**, select the **From File** option and select the required **calibration data file** from the **Working** folder using the **Browse** button.

19.3 DISPLAY GROUP PARAMETERS

A suitable **sensor information file** (sensitivity map) must be selected using the **Browse** button before data capture can commence or data replayed. In the the **normal mode of operation**, **permittivity images** are displayed by default but the **normalised capacitances** can also be displayed on request. However, **permittivity images** can only be produced if a **valid sensor information file** has been selected.
The sensor information file contains a number of pieces of information controlling the operation of the ECT32v2 software, including the number of electrodes, order of measurements, and the geometry and back-projection imaging parameters for each specific image format.

As set of generic sensor information files is supplied with each ECT system, together with specific .sif files for any custom sensors supplied with the system and these are stored in the Configuration folder.

The standard sensor information files are in the form: SSMA_B.sif where A is the number of electrodes and B is the display resolutions in pixels per line. These sensor information files can be used for most normal applications.

For example, SSM12_30.sif is the standard sensor information file for a 12 electrode sensor to display an image at a resolution of 32 X 32 pixels.

A second set of generic sensor information files have the form: WSMA_B.sif. These .sif files are for use with sensors having external electrodes and which are to be used for imaging water. In these files, the coefficients corresponding to adjacent electrode measurements have been set to zero.

Note that the number of electrodes on the sensor in use is defined by the sensor information file in the Display group. Permittivity images will be displayed as long as a valid .sif file is selected.

19.4 IMAGING CONTROL GROUP PARAMETERS

The parameters in this group allow the displayed permittivity image to be modified as follows:

Permittivity Offset: Inserting a non-zero value in this box allows the lower value of the normalised permittivity scale to be offset from the normal value of zero. When used with the Image gain control this allows small variations in permittivity around a fixed value to be seen. The default value is zero.

Image Gain: The pixel values in the permittivity image are multiplied by this parameter. The default value is 1.

Truncate: If this option is checked, the displayed image pixel permittivity values K are truncated to lie within the range 0 < K < 1.

Further information on the imaging control parameters is given in chapter 23.

19.5 CAPTURE CONTROL GROUP PARAMETERS

The parameters in this group define how the captured data is handled.

Frame rate: This parameter determines the rate (in frames per second) at which the ECT system attempts to capture data in both Capture and Record modes. The default value is 50 fps.

Buffer time: This parameter sets the length of the cyclic memory buffer to which data is temporarily stored in Capture mode. The default value is 10 seconds.

Buffer file name: This defines the name of the temporary buffer file. The default setting is Buffer.bcp

Recording File name: This sets the name of the file to hold recorded data in Record mode. The default setting is record.bcp.
19.6 SESSION DESCRIPTION GROUP PARAMETERS

This group contains a single text box to hold descriptive data. This data is stored with the capacitance data file and can be used to describe the experimental conditions details eg date, time, test number etc.

19.7 FUNCTION BUTTONS

The three buttons at the bottom of the Configuration window have the following functions:

**Restore Defaults:** The default values for the Configuration screen parameters are used to replace all existing settings.

**Dismiss:** The Configuration screen is exited without implementing the settings in the screen.

**Setup System:** The Configuration screen settings are used to set up the ECT system.

Hence to start the software with the same settings as were last in use, simply click the Setup System button at the bottom of the window. Alternatively, to start the software with the default parameters, click on the Restore Defaults button at the bottom of the Configuration window then click on the Setup System button.

At this point, either the Calibration window or the ECT32v2 Desktop window will appear and the system is now ready for calibration or data capture/playback etc by selecting one of the mode controls in the control panel.

19.8 CONFIGURATION WINDOW ACCESSED DURING PROGRAM EXECUTION

The Configuration window functions as described in paragraphs 19.1 to 19.7 when the Configuration window is used to set up the ECT system when the ECT32v2 software is started. However, the Configuration window can also be called-up during execution of the ECT32v2 software by clicking on the Display Configuration Window tool (icon 1) on the left hand end of the toolbar. When the Configuration window is accessed from within the software, it functions in a slightly different manner from that in which it operates when the software is started.

When the Configuration window is selected using the Display Configuration Window tool (icon 1), the window displays the state of the ECT system and software at the end of the session just prior to selecting the Configuration window. In practice, this means that a number of parameters in the parameter groups in the Configuration window act in a slightly different manner from that at start-up. The details are as follows:

**19.8.1 Data Sources Group.**

If at least one plane of the ECT system was enabled and calibrated before selecting the Configuration window, the DAM200E Online option will be checked.

If any sensor planes are enabled, these will be checked.

If any data has been captured or recorded during the previous session, the current data file name will be displayed and enabled.
If both the DAM200E Online and Current data file options are selected, the DAM200E Online option will take precedence and the ECT system will revert to On-line capture mode when the Setup system button is clicked.

19.8.2 System calibration group
Neither of the parameters in this group will be checked on entering the Configuration window from within the ECT32v2 software.
In this situation, the calibration data file which was last in use will be used when the Setup system button is clicked (even if the file has not been saved).
Alternatively, calibration on-line or from a different calibration file can be selected by checking the appropriate parameter in the System calibration group.

19.8.3 Display group
The parameters checked here will correspond to the last state of the ECT system before entering the Configuration window.

19.8.4 Imaging control group
The parameters values here will correspond to the last state of the ECT system before entering the Configuration window.

19.8.5 Capture control group
The parameters values here will correspond to the last state of the ECT system before entering the Configuration window.

19.8.6 ECT32v2 Program abnormalities.
Under some circumstances, selecting the Configuration window from within the ECT32v2 software can cause indeterminate operation of the software. If this occurs, the simplest solution is to quit the ECT software and restart it.
THE ECT32v2 DESKTOP

The ECT32v2 Desktop window is the main control and display window for the ECT32v2 software and allows capacitance data to be captured and permittivity images to be displayed.

Figure 20.1.1 Empty Desktop window

The ECT32v2 Desktop is shown in figure 20.1.1 with no images displayed and consists of a title bar (at the top of the window), a menu bar (immediately below the title bar), a toolbar (immediately below the menu bar), a display area containing a control panel, below which is a status bar with indicators (at the bottom of the window). The control panel is shown separately and at a larger scale in figure 20.4.1

Although the Configuration window offers a convenient way to set up the ECT system, the continuous operation of the software is carried out by the use of the control panel, the menus on the menu bar or the tool buttons on the toolbar of the ECT32v2 Desktop.

The parameters which must be set up differ for each operating mode and the required mode button only becomes operational when the necessary parameters relevant to that mode have been set up. For example, Capture mode will not function until a valid calibration data file is available and a valid sensor information file has been selected. Similarly, the Record mode will not operate until a file name for storing the recorded data has been selected.

N.B. The ECT32 Desktop window must be maximised to display the Status bar.
20.1 THE MENU BAR

The menu headings on the menu bar control the major functionality of the ECT32v2 software. Most of the Control menu functions can be implemented by alternative means, either by the use of tool buttons, represented by icons on the toolbar, or by function buttons on the control panel, or by parameters set in the Configuration window.

Section 20.1.1 lists the menu and sub-menu headings and gives details of any alternative means of implementing these menu functions by the use of the Toolbar, Control panel or Configuration window.

Details of those menu functions which have alternative means of implementation are given in subsequent chapters of this manual under the appropriate headings for the alternative controls.

Details of the non-duplicated menu functions are also given in subsequent chapters.
### 20.1.1 Main Control menu functions and alternative implementation.

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<td>![icon]</td>
</tr>
<tr>
<td>Sensor Information File details</td>
<td>None</td>
<td>![icon]</td>
</tr>
<tr>
<td>Image Display Parameters</td>
<td>Configuration window</td>
<td></td>
</tr>
<tr>
<td>Normal Image Display</td>
<td>None</td>
<td>![icon]</td>
</tr>
<tr>
<td>Quadrant Image Display</td>
<td>None</td>
<td>![icon]</td>
</tr>
<tr>
<td>Enable Continuous Averaging</td>
<td>20</td>
<td>![icon]</td>
</tr>
<tr>
<td>Continuous Averaging Controls</td>
<td>21</td>
<td>![icon]</td>
</tr>
<tr>
<td><strong>Correlation</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Enable/Disable Correlation</td>
<td>24</td>
<td>![icon]</td>
</tr>
<tr>
<td>Sensor Spacing</td>
<td>None</td>
<td>![icon]</td>
</tr>
<tr>
<td>Correlation Controls</td>
<td>25</td>
<td>![icon]</td>
</tr>
<tr>
<td>Enable Reference Frame</td>
<td>22</td>
<td>![icon]</td>
</tr>
<tr>
<td>Reference Frame Controls</td>
<td>23</td>
<td>![icon]</td>
</tr>
<tr>
<td>Main Menu</td>
<td>Sub-menu</td>
<td>Alternative implementation</td>
</tr>
<tr>
<td>-----------</td>
<td>----------------------------------------------</td>
<td>----------------------------</td>
</tr>
<tr>
<td>Windows</td>
<td>Display Plane 1 Permittivity Image</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>Display Plane 2 Permittivity Image</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>Display Plane 1 Capacitances</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>Display Plane 2 Capacitances</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>Tile Windows</td>
<td>None</td>
</tr>
<tr>
<td>Help</td>
<td>About ECT32v2 for Windows</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>List of active windows</td>
<td></td>
</tr>
</tbody>
</table>

### 20.2 THE TOOL BAR

The functionality of the control buttons on the toolbar is shown in the tool bar icon function list (paragraph 20.3). The toolbar button functionality can also be displayed on the PC screen by positioning the mouse pointer over a toolbar button for a second or so. In this case, information about the functionality of the button is displayed next to the button and also in more detail at the left hand side of the status bar at the bottom of the ECT32v2 Desktop window.
20.3 TOOL BAR ICON FUNCTION LIST

<table>
<thead>
<tr>
<th>Icon</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Displays the Configuration Window</td>
</tr>
<tr>
<td>2.</td>
<td>Loads recorded data file</td>
</tr>
<tr>
<td>3.</td>
<td>Sets recorded data file name</td>
</tr>
<tr>
<td>4.</td>
<td>Selects data capture subsystem hardware DLL</td>
</tr>
<tr>
<td>5.</td>
<td>Resets Baseline and measurement frequency</td>
</tr>
<tr>
<td>6.</td>
<td>Calibrates sensor (selected planes)</td>
</tr>
<tr>
<td>7.</td>
<td>Calibrates sensor (plane 1 only)</td>
</tr>
<tr>
<td>8.</td>
<td>Calibrates sensor (plane 2 only)</td>
</tr>
<tr>
<td>9.</td>
<td>Saves calibration data to file</td>
</tr>
<tr>
<td>10.</td>
<td>Selects parallel permittivity model (default setting)</td>
</tr>
<tr>
<td>11.</td>
<td>Selects series permittivity model 1 (requires permittivity ratio)</td>
</tr>
<tr>
<td>12.</td>
<td>Selects series permittivity model 2 (no permittivity ratio required)</td>
</tr>
<tr>
<td>13.</td>
<td>Selects Maxwell permittivity model</td>
</tr>
<tr>
<td>13(a)</td>
<td>Enable/disable iterative image reconstruction</td>
</tr>
<tr>
<td>14.</td>
<td>Loads sensor information file (sensitivity map etc.)</td>
</tr>
<tr>
<td>15.</td>
<td>Modifies image display parameters (Gain, offset, truncation, inversion, iteration)</td>
</tr>
<tr>
<td>16.</td>
<td>Selects and displays plane 1 permittivity image</td>
</tr>
<tr>
<td>17.</td>
<td>Selects and displays plane 2 permittivity image</td>
</tr>
<tr>
<td>18.</td>
<td>Selects and displays plane 1 normalised capacitances</td>
</tr>
<tr>
<td>19.</td>
<td>Selects and displays plane 2 normalised capacitances</td>
</tr>
<tr>
<td>20.</td>
<td>Enables Continuous Averaging</td>
</tr>
<tr>
<td>21.</td>
<td>Accesses Averaging Controls</td>
</tr>
</tbody>
</table>
22. Enables Reference Frame Option
23. Accesses Reference Frame Controls
24. Enables/Disables Cross-Correlation
25. Accesses Correlation Controls
26. Sets up Network Connection
20.4 THE CONTROL PANEL

The control panel is shown in figure 20.4.1 and the functions of the controls are as follows:

**Capture mode button.** (Alternative implementation, Mode menu, Capture mode)
This button captures live data to the rolling buffer memory. On exiting Capture mode, the buffer memory contents are automatically saved to the buffer file name specified in the Configuration screen.

**Record Mode Button.** (Alternative implementation, Mode menu, Record mode)
This sets up the system to allow data to be recorded to a pre-defined data file. Recording starts when the Record button (red button next to Stop button) is clicked.

**Playback mode button.** (Alternative implementation, Mode menu, Playback mode)
The contents of the buffer file or a selected recorded data file are replayed.

**Idle mode button.** (Alternative implementation, Mode menu, Idle mode)
This sets the ECT system into an idle state which allows the Capture mode and Record mode frame rates to be set (see frame rate).

**Freeze button.** This freezes the displayed image, while data capture continues.

**Autostop option:** If this option is selected, data capture ceases once the buffer memory has been filled and the system reverts automatically to Playback mode.

**Frame rate.** This sets the nominal frame rate in frames per second. The actual frame rate achieved is displayed next to this parameter. The interval between frames, corresponding to the set frame rate, is displayed as Interval (msec). As the interval resolution is integer milliseconds, this determines the actual frame rate achievable. It is therefore preferable to select a frame rate whose period corresponds to an integer number of milliseconds.
The **Frame rate** may also be set by inputting an integer directly into the **Interval data box**.

The **frame rate** set in **Idle mode** sets the **Capture** and **Record frame rates**. The **frame rate** set in **Playback mode** sets the **playback mode frame rate** only.

**File length**. This parameter sets the length of the **rolling circular buffer file**. The file length in image frames is defined to be equal to the selected **time** (seconds) multiplied by the selected **frame rate** (frames per second).

**Load button**. *(Alternative implementation, File menu, Load Recorded data)*
This button loads a pre-recorded data file for viewing.

**Save button**. *(Alternative implementation, File menu, Save As...)*
This button saves the current buffer memory contents to a new file name.

**[<]** button. Moves to the start of the data file.
**[>]** button. Moves to the end of the data file.
**[<]** button. Reverse play button.
**[>]** button. Forward play button.
**[Δ>>>]** button. Increment one frame
**[<Δ]<** button. Decrement one frame.

The **STOP** button halts the display without remembering direction.

At the top of the **control panel**, the **slider** control allows the **frame position** in the **file** to be forced with the **mouse**. The range of this **slider** is the **size of the file**. By holding the left mouse button down, the position of the slider indicator can be relocated by dragging it with the mouse.

### 20.5 THE STATUS BAR

As well as giving detailed information about the tool button functionality on the left-hand end of the bar, the **status bar** also contains **indicators** which appear on the right hand side of the bar and show the current status of the following parameters:

**System status**: Enabled or disabled. The ECT system must be enabled to allow data capture to proceed.

**Calibration status**: Shows which sensor planes are currently calibrated.

**Frame information**: Shows current frame number, time stamp and frame capture rate

**NB. The ECT32 Desktop window must be maximised to display the Status bar.**
20.6 THE IMAGE WINDOWS

The Desktop can display up to **four image windows** comprising, **two permittivity images** and **two sets of normalised capacitances**. The **images displayed** will depend on the **number of sensor planes in use**, the **settings** in the **Configuration window** and whether or not the **capacitance display icons** on the **toolbar** have been enabled. A typical single-plane image display for both **permittivity** and **capacitance images** is shown in **figure 20.6.1**.

![Figure 20.6.1 Single plane image](image)

**Figure 20.6.1 Single plane image.**
21. ECT SYSTEM CALIBRATION (Calibration Menu)

Before any capacitance data can be captured, a valid calibration data file must be available. This can either be created by calibrating the sensor on-line or by loading a previously stored calibration file. The ECT32v2 software implements the 2-point calibration technique as used in previous PTL ECT software (eg PCEPT, TransECT, ECT1 etc.).

On-line Calibration can be initiated either by checking the Online option in the System Calibration Data parameter group in the Configuration window or by the use of the Calibration menu on the Menu bar, or by the use of the calibration tool buttons on the tool bar.

The following instructions assume the use of the Menu/toolbar method.

21.1 SYSTEM CALIBRATION ON-LINE

21.1.1 Calibrate On-line (Calibration menu, Calibrate on-line)

Selecting this option calibrates all available sensor planes as follows.

1. Select the calibrate sensor button (icon 6 on the toolbar. Alternatively, select the Calibrate Online option from the Calibration menu. This will cause the Calibration window to be displayed as shown in figure 21.1.1.

![Figure 21.1.1 Initial Calibration window (low permittivity)](image)

2. Select the planes to be calibrated by clicking on Stream 1 (= Plane1), Stream 2 (= Plane 2) or both (appropriate to the connected sensor(s)), in the Calibration window.
3. With the PC displaying the calibration window shown in figure 21.1, fill the sensor with the lower permittivity material and click the Next button. After a short pause, followed by a beep, the screen changes to that shown in figure 21.1.2.

![Figure 21.1.2 Second Calibration window (high permittivity)](image)

4. Fill the sensor with the higher permittivity material and again click the Next button. After a short pause, followed by a beep, the screen changes to that shown in figure 21.1.3.

![Figure 21.1.3 Final Calibration Window (Save calibration data)](image)

5. Click on the Save file button. The Save Calibration Data window will appear.

6. Enter a suitable file name (such as demo1) in the File name box and click on the Save button. The calibration data will now be saved and a calibration window similar to that shown in figure 21.3 will be displayed. Note that the file extension .cal is added automatically to saved data file names.

7. Left click the Done button in the Calibration window to complete the calibration process. The ECT32v2 Desktop window will now appear and a live image of the contents of the sensor will be displayed as shown in figure 20.6.1 at the default frame rate (50 fps). This data is being captured on a continuous basis, to a circular buffer file in memory. The normalised capacitances can also be displayed by selecting icon 18.
21.1.2 Calibrate Plane 1 (Calibration menu, Calibrate Plane 2)

This option calibrates only Plane 1 of the sensor. Any previous calibration data for Plane 2 will remain unaffected.

It is implemented either using icon 7 (Calibrate sensor plane 1) or by selecting the Calibrate Plane 1 option from the calibration menu.

21.1.3 Calibrate Plane 2 (Calibration menu, Calibrate Plane 2)

This option calibrates only Plane 2 of the sensor. Any previous calibration data for Plane 1 will remain unaffected.

It is implemented either using icon 8 (Calibrate sensor plane 2) or by selecting the Calibrate Plane 2 option from the calibration menu.

21.2 SYSTEM CALIBRATION FROM A DATA FILE

As an alternative to calibrating the system on-line, a previous calibration file can be used as follows:

21.2.1 Load Calibration File (Calibration menu, Load Calibration file)

To load a data file generated during a previous system calibration:

1. Select the Load calibration file option from the Calibration menu, then select the required calibration file in the file window and click the Open button. Alternatively, select one of the calibration tool buttons (eg icon 6) and select the option Load Calibration file from the Calibration window. Select the required calibration file using the Brows button then click on the Load file button.

2. The system is now capable of being operated in Capture mode.

21.3 SAVING CALIBRATION DATA

Calibration data can be saved either at the time of calibration as above, or at some later time as follows:

21.3.1 Save Calibration File (Calibration menu, Save Calibration file)

If the calibration data is not saved at the time of calibration, it can be saved subsequently using the ‘Save Calibration’ option on the ‘Calibration’ menu on the menu bar. This will prompt for a filename for the calibration data file. Use a suitable name such as caldat1.cal. Alternatively the save calibration tool (icon no 9 on the toolbar) can be used.
21.4 CALIBRATION FILE TYPES

The type of Calibration data file generated during the calibration procedure depends on the number of measurement planes enabled.

If a single measurement plane is enabled during calibration, then the calibration file will contain data for that measurement plane only.

If both measurement planes are enabled, the calibration file will be a composite twin-plane data file.

21.5 GENERATION OF A TWIN-PLANE CALIBRATION FILE FROM TWO SINGLE-PLANE FILES

A composite, twin-plane calibration file can be generated from two separate single-plane files as follows:

Either:

1. Calibrate the two planes separately and save the calibration data files.

or

2. Load two separate calibration files using the Calibrate plane 1 and Calibrate plane 2 tool buttons.

Then:

Click the Save Calibration button, enter a file name for the composite twin-plane calibration file, then save this file.

The saved file will contain calibration data for both of the sensor planes.
21.6 RECALIBRATING AT THE LOW OR HIGH PERMITTIVITY POINTS ONLY

Once the ECT system has been calibrated, it can be recalibrated at any time. In particular, it is possible to recalibrate the system at either the low or high permittivity points only, as described in the following two paragraphs:

21.6.1 Recalibration at Low Permittivity Level Only

1. Select the appropriate calibrate sensor button depending on which planes have been calibrated (icons 6 to 8) on the toolbar. Alternatively, select the appropriate Calibrate Online option from the Calibration menu. This will cause the Calibration window shown in figure 21.6.1 to be displayed. Note that four extra buttons are now enabled, allowing calibration at the higher or lower permittivities only.

![Figure 21.6.1 High/low level re-calibration window](image)

2. With the PC displaying the calibration window shown in figure 21.6.1, fill the sensor with the lower permittivity material and click either the fix low or the Low Permittivity Only button. After a short pause, followed by a beep, the screen changes to that shown in figure 21.6.2.

![Figure 21.6.2 Final calibration window](image)
3. Proceed directly to step 5 if you do not want to save the new calibration data but simply want to use it on a temporary basis (it can be saved later).

4. To save the new calibration data, click on the Save file button. Enter a suitable file name (such as demo2) in the File name box and click on the Save button. The calibration data will now be saved and a calibration window similar to that shown in figure 21.6.2 will re-appear. Note that the file extension .cal is added automatically to saved data file names.

5. Left click the Done button in the Calibration window to complete the calibration process. Live data capture will resume at the default frame rate (50 fps).

When the fix low button is used, the system simply adjusts the M3 low permittivity ADC counts in the calibration file. When the Low permittivity only button is selected, the system carries out a full recalibration process at the low permittivity point, adjusting offsets and charge injection data as appropriate. For normal use, the fix low option should be used to correct small changes in the low permittivity calibration point.

21.6.2 Recalibration at High Permittivity Level Only

1. Select the appropriate calibrate sensor button depending on which planes have been calibrated (icons 6 to 8) on the toolbar. Alternatively, select the appropriate Calibrate Online option from the Calibration menu. This will cause the Calibration window shown in figure 21.4 to be displayed. Note that four extra buttons are now enabled, allowing calibration at the higher or lower permittivities only.

2. With the PC displaying the calibration window shown in figure 21.6.1, fill the sensor with the higher permittivity material and click either the fix high or the High Permittivity Only button. After a short pause, followed by a beep, the window changes to that shown in figure 21.6.2.

3. Proceed directly to step 5 if you do not want to save the new calibration data but simply want to use it on a temporary basis (it can be saved later).

4. To save the new calibration data, click on the Save file button. The Save Calibration Data window will appear. Enter a suitable file name (such as demo2) in the File name box and click on the Save button. The calibration data will now be saved and a calibration window similar to that shown in figure 21.6.2 will re-appear. Note that the file extension .cal is added automatically to saved data file names.

5. Left click the Done button in the Calibration window to complete the calibration process. Live data capture will resume at the default frame rate (50 fps).

When the fix high button is used, the system simply adjusts the M3 high permittivity ADC counts in the calibration file. When the High permittivity only button is selected, the system carries out a full recalibration process at the high permittivity point, adjusting gains and ADC counts as appropriate. For normal use, the fix high option should be used to correct small changes in the high permittivity calibration point.
21.7 ADVANCED CALIBRATION TECHNIQUES

The calibration method described so far has been based on calibrating the ECT system at two values of permittivity and operating the ECT system between these known calibration points. However, a number of alternative options are available using additional calibration software (Recal) supplied with the ECT system. The Recal software allows a sensor permittivity file to be generated for the ECT system by carrying out measurements with the sensor filled with test samples of known permittivity. Once this file has been generated it is possible to carry out subsequent sensor calibration at a single permittivity value only (eg with the sensor containing air). This technique is known as single point calibration. It is also possible to adjust the measurement range, so that the ECT system operates between two values of permittivity which may not be the same as those used for the original system calibration. Detailed instructions for the use of the Recal software are given in Appendix 8.

21.8 RESETTING THE MEASUREMENT BASELINE

The main cause of drift in the CMU is the charge injection capacitances. These can be set to be remeasured at regular periods determined by values set in the Acquisition menu. Further information about this is given in chapter 29.

21.8.1 Reset Baseline

It is possible to turn off the automatic frequency resetting and drift compensation in the Acquisition menu (see paragraph 29.1). When this has been done, it is possible to apply manual resetting of these parameters using the Reset Baseline option in the Calibration menu.
22. CAPTURE MODE

Capture mode is the default operating mode of the ECT32v2 software and is established automatically following system configuration.

In Capture mode, data is stored continuously to a data memory buffer and is simultaneously displayed live on the screen in a Display window. The following instructions demonstrate the operation of Capture mode and assume that the ECT system has been configured and calibrated as described in paragraphs 19 and 21 to allow the ECT32v2 Desktop window to show a permittivity image.

22.1 CAPTURE MODE OPERATION (Mode menu, Capture mode)

Figure 22.1.1 ECT Desktop in Capture Mode

1. Click the Capture button on the control panel. The Capture button will appear depressed and the ECT system will now be in Capture mode, displaying a live image of the sensor contents on the screen in either one or two display windows (corresponding to each active sensor plane) as shown in figure 22.1.1 for a twin-plane image). Data capture and display starts immediately following activation of the Capture button and the captured data is stored to a circular memory buffer continuously. The default file name for the stored buffer data file is buffer.cap. The frame capture rate is set by the Frames/Sec control in the control panel.

Click on icons 18 and 19 on the toolbar to display the Normalised capacitances.
2. Move the sensor so that the image changes for a few seconds. Data is now being continuously captured to a **rolling memory buffer**, whose size is determined by the figures set in the **Frames** and **Time** boxes in the **control panel**. The buffer is continuously overwritten as it is filled.

3. Click the **Freeze button** on the **Control panel**. This temporarily suspends the display, but continues data capture while freezing the screen image.

4. Click the **Freeze button** again. The on-line image display resumes.

5. Click the **Stop button** in the control panel. Data collection will cease and the system will automatically revert to **Playback mode**. (Note that the **Playback button** is now depressed, and that the number of frames captured and the **Time** in seconds are displayed in the **control panel**.)

6. The data in the **memory buffer** is automatically saved to the **hard disk** each time that the system changes from **Capture mode** to **Playback mode**. The default file name is **buffer.cap**.

7. Note that the **Record button** has not been active so far. The function of this button is described fully in chapter 25.

Please refer to chapter 26 for further information on **playing back captured and recorded data**.

### 22.2 SETTING THE CAPTURE BUFFER FILE PARAMETERS

#### 22.2.1 Buffer File name (**File menu, Set Capture mode file name**)

The **buffer file name** is set initially in the **Configuration window** and has the default name **buffer.bcp**. This file name can be changed, either by changing it in the **Capture control parameter group** in the **Configuration screen**, or by selecting the **Set Capture Mode Buffer file name** option in the **File menu**. The buffer file is saved automatically at the end of data capture to the default file name. It can also be saved at any other time by the use of the **Save button** on the **Control panel** or by the use of the **Save as..** option on the **File menu**. Saving the buffer file in this manner will generate data files with sequential numbers appended to the end of the file name, eg **Buffer_1.bcp** etc.

#### 22.2.2 Buffer file length

The **buffer file size** is also set initially in the **Configuration window** and has a default length of 10 seconds of data. The number of captured frames will depend on the selected **frame capture rate** (see paragraph 22.3). The file length can be changed, either by changing it in the **Capture control parameter group** in the **Configuration screen**, or by changing the **Buffer length (Time)** setting in the **Control panel** when the system is in **Idle Mode**.
22.3 SETTING THE FRAME RATE IN CAPTURE MODE

The frame rate in Capture mode is set initially in the Configuration window and has a default value of 50 frames per second (fps). The frame rate can be changed, either by changing it in the Capture control parameter group in the Configuration screen, or by changing the Frame rate setting in the Control panel when the system is in Idle Mode. The Capture mode framerate also determines the capture rate in Record Mode.

Note that the default frame rate in Playback mode is also 50 fps and the framerate set in Playback mode is not affected by the settings in Capture and Record modes.

The achievable frame rate depends on a number of parameters. The first of these is determined by the fact that the frame rate timer has a resolution of 1 mSec. It is therefore preferable to set frame capture rates which correspond to an integer number of millisecond periods, eg 20 fps (50), 25 fps (40), 40 fps (25), 50 fps (20) etc. The second limitation is the maximum data capture rate, which depends on the number of electrodes selected. If the set frame rate exceeds the maximum possible rate, data will be captured as fast as possible.

The actual frame rate achieved is displayed in the Control panel next to the set Framerate box as Actual framerate.

22.4 EFFECTS OF DRIFT

The circuitry used in the data acquisition module is highly sensitive and some short-term drift will occur after switch-on. The system should therefore be allowed to stabilise for approximately 15 minutes before final calibration and the commencement of measurements.

Similarly, the capacitance sensor will be sensitive to small changes in temperature of the sensor and the temperature of the sensor must be stable before making measurements.

If drift becomes a problem, the ECT system should be recalibrated just before measurements are made. Alternatively, a number of calibration files should be generated prior to an experimental programme, under different conditions of ambient temperature and time from switch on. The calibration file which gives the best results (for eg the low permittivity calibration point) can then be selected for subsequent measurements. A further option is to recalibrate the sensor either full or empty only, just before commencing measurements.
23. PERMITTIVITY IMAGE AND CAPACITANCE DISPLAY FORMATS

23.1 PERMITTIVITY IMAGE DISPLAY FORMATS

ECT images are displayed in a rectangular grid format (normally 32 X 32 pixels, depending on the sensor information file), using a colour scale from blue to red. Blue corresponds to low value pixels (0) and red corresponds to high-value pixels (1). The pixel colour scale is indicated by a vertical bar on the LHS of the image. The volume ratio of the image is displayed on a gauge on the RHS of the image in the range 0 to 100%, where 0 corresponds to the case where the sensor is filled with the lower permittivity material used for calibration and 1 corresponds to sensor filled with the higher permittivity material. A pixel probe controlled by the mouse cursor allows the values of individual pixels to be measured. Its operation is described in paragraph 18.6.

Any Image display window can be removed by clicking the X box in the top RHS of the window. It can be retrieved by either selecting the Plane 1 or Plane 2 image option in the Windows menu or alternatively by using the Plane 1 or Plane 2 image buttons (icons 16 and 17) near the right-hand end of the toolbar.

It is also possible to display normalised capacitances by selecting the Plane 1 or Plane 2 capacitance buttons (icons 18 and 19) on the toolbar.

The normalised capacitance data display is in the form of a histogram of inter-electrode capacitance measurements in the nominal range (0.0 to 1.0).

The capacitances are displayed as sets of vertical lines (with a gap between each set) where each line represents the normalised capacitance on a nominal scale from 0 to 100%, with facilities for 30% over and under-range values. The first set of lines are the capacitances $C_{12}$ to $C_{1E}$ in order (where $E$ is the total number of electrodes), the second set is $C_{23}$ to $C_{2E}$ and so on.

Capacitance display windows can be closed in the normal way by clicking on the X symbol in the top RHS of the title bar.

23.2 IMAGE DISPLAY PARAMETERS (Data Display menu)

The format of the displayed image can be modified using options available from the Data Display drop-down menu. The following options are currently available:

23.2.1 Load Sensor Information File (Data Display menu, Load Sensor Information file)

This option allows the current sensor information file to be replaced with a new file and can also be implemented using icon 14 on the toolbar.
23.2.2 Sensor Information file details (Data Display menu, Sensor Information file details)
This option displays a window giving details of the current sensor information file. An example is shown in figure 23.2.1.

Figure 23.2.1 Open sensor information file window

23.2.3 Image Display Parameters (Data Display menu, Image Display Parameters)

Figure 23.2.2 Image Display Controls window
This option (icon 15) opens the Image Display Controls window (figure 23.2.2) which allows a number of parameters in the image reconstruction algorithm to be modified. The original capacitance measurements, and capacitance data files are not affected in any way. The control parameters, which affect only the displayed image, are as follows:
Permittivity offset: The Permittivity offset parameter OS is normally set to zero, in which case the displayed image covers the normalised permittivity range from 0 to 1. If an offset value other than zero is entered (eg OS), in the range 0 to 1, the permittivity range displayed will be from OS to 1 + OS. The effect of this is to offset the measurement range. This facility can be used, for example, to display permittivity values which exceed the nominal maximum value of 1.

Imaging Gain: The Image gain parameter G normally has the value 1. However, if a value of G other than 1 is entered, the permittivity value of each pixel is multiplied by the Image gain factor G. The effect is to change the overall gain of the image. Note that the colour scale bar changes to reflect the effect of the new gain setting.

If both Image gain (G) and Permittivity offset parameters (OS) are in use, the permittivity scale will be modified to run from OS to OS + 1/G. This facility can be very useful for monitoring small permittivity changes.

Iterative Reconstruction settings
The 3 parameters in this group allow images to be reconstructed using iterative techniques in all operating modes.

The Iterations parameter sets the number of iterations to be performed for the construction of each image. If a large number of iterations are set, the image display rate may fall. Note that iteration can be enabled and disabled using the Iteration button on the Toolbar (icon 13a).

The Feedback gain parameter sets the feedback gain in the iterative algorithm. A value = 1 will result in a safe but slow convergence process. Values exceeding 1.5 may cause the iterative process to diverge rather than converge.

Image truncation parameters. If the Truncate option is selected, the normalised image pixel values are truncated at each image iteration to lie within the set range. The first figure is the low permittivity truncation level and the second figure is the high permittivity level.

Pixel inversion: If the Invert option is selected, the value of each pixel is multiplied by -1. This facility can be used for viewing the contents of sensors where the capacitances decrease below the calibration values. This often occurs when an earthed or partially-earthed sample is introduced inside the sensor following calibration.

23.2.4 Normal Image Display (Data Display menu, Normal Image Display)
This option, displays the permittivity image in its normal format as described in paragraph 23.1.
23.2.5 Quadrant image display (Data Display menu, Quadrant image display)
This option displays the image as four isolated quadrants as shown in figure 23.2.3. In this mode, the volume ratios of each quadrant are displayed separately.

![Figure 23.2.3 Quadrant image display window](image)

23.2.6 Enable Continuous Averaging (Data Display menu, Enable Continuous Averaging)
This option enables the continuous averaging of the measured data and can also be implemented using icon 20 on the toolbar. Details of the averaging facility are given in paragraph 23.2.7.

23.2.7 Continuous Averaging Controls (Data Display menu, Continuous Averaging controls)

![Continuous Averaging](image)

This option (which can also be implemented using icon 21 on the toolbar) displays the Continuous Averaging Window shown in figure 23.2.4. If this option is enabled, the displayed images show the data averaged over the number of frames selected in the Size boxes on a rolling basis. The parameters for plane 1 and plane 2 can be set independently. If no averaging is required on one of the planes only, the enable selection option for this plane should be disabled. The example in figure 23.2.4 shows data for plane 1 averaged over 20 frames with that for plane 2 averaged over 10 frames. This technique is very useful for reducing noise levels in images for slowly-changing concentration distributions.
An example of the image display when frame averaging is enabled is shown in figure 23.2.5.

Note that the standard text “frame”, followed by the current frame number, located at the top of the image display window (eg as shown in figure 22.1.1) is replaced by the text “Avg[X]”, where X is the number of frames selected in the size box, followed by the current frame number.

As a general rule, optimum operation of the ECT system will occur when the frame rate is set to its fastest possible value (eg 200 fps for an 8-electrode sensor) and averaging as above is used to reduce the overall measured noise level.

23.3 ADDITIONAL IMAGE RECONSTRUCTION AND DISPLAY SOFTWARE

The ECT32 software allows basic ECT images to be displayed both during data capture (on-line) and also during the replay of captured data (off-line). Two further sets of off-line image reconstruction and display software are also supplied with the ECT system. The IU2000 software allows 2-D ECT images to be reconstructed and displayed and the Plot3D software allows 2 and 3-D images to be reconstructed and displayed. Details of these two sets of software are given in Appendices 9 and 10 respectively.
24. PERMITTIVITY MODELS

Having captured the normalised capacitances, it is necessary to decide how to convert these measurements into a permittivity or voidage image.

This will depend on the physical model chosen to represent the relationship between the permittivity distribution inside the sensor and the measured capacitances.

Selection of the permittivity model to be used is carried out either by the use of the Permittivity Model drop-down menu or alternatively, by the use of icons 10 to 13.

Detailed information about this topic is given in PTL Application Note 1.

24.1 PARALLEL PERMITTIVITY MODEL (Permittivity Model menu, Parallel Model)

This is the default option and assumes a linear relationship between the elementary capacitances inside the sensor and the capacitance measured between any pair of electrodes. This is known as the parallel permittivity model as it combines the elementary capacitances inside the sensor as if they were connected in parallel.

This simple model is useful for imaging fluids such as vertical columns of immiscible liquids where there may be true parallel paths across the sensor through the different dielectric materials. This option is selected by clicking on icon 10 on the tool bar or by selecting the Parallel model option from the Permittivity model menu.

24.2 SERIES PERMITTIVITY MODEL (Permittivity Model menu, Series model)

The Series option assumes that the elementary capacitances inside the sensor contribute to the overall capacitance measured between any pair of electrodes as though they were connected in series.

The Series model is useful for imaging fluids such as powders or granules in fluidised beds where there will normally not be a continuous path between electrodes through the higher permittivity material.

The first series model option is selected by clicking on icon 11 on the tool bar or by selecting the Series 1 model option from the Permittivity model menu. For this version of the Series model it is necessary for the user to know the approximate ratio ($K$) of the dielectric constants of the two materials used for calibrating the sensor. This value of $K$ must be entered by selecting the Set Permittivity Ratio ($K$) option in the Permittivity model drop-down menu (see paragraph 24.5). A typical image display using the series model (1) is shown in figure 24.2.1.

![Figure 24.2.1 Permittivity image display window using series 1 model](image)
24.3 SERIES 2 MODEL  (Permitivity Model menu, Series 2 model)
The second series model option is selected by clicking on icon 12 on the tool bar or by selecting the Series 2 Model option from the Permitivity model menu. This version of the series model, deduces the permittivity ratio from the calibration data and there is therefore no need to enter a value for K.

NB This option is currently inoperative in the PTL300E ECT system.

24.4 THE MAXWELL MODEL  (Permitivity Model menu, Maxwell model)
This is effectively a composite parallel/series capacitance model developed by Maxwell in the 19th century. It is a good compromise for most practical ECT applications. This option is selected by clicking on icon 13 on the tool bar or by selecting the Maxwell model option from the Permitivity model menu.

24.5 SET PERMITTIVITY RATIO (K) (Permitivity Model menu, Set Permittivity Ratio (K))
This option displays the Set Permittivity Model Window (figure 24.5.1) and allows the Permittivity ratio (K) to be set or changed directly by the user.

![Set Permittivity Model Window](image)

Figure 24.5.1 Set Permittivity Model window
25. RECORD MODE (Mode Menu, Record mode)

In Record mode, data is captured directly to a disk file for subsequent viewing and/or post-processing.

25.1 RECORD MODE FILE NAME  (File menu, Set Recorded data file name)

The ECT system is configured and enabled in a similar manner to that used for the Capture mode, but with the additional requirement that a file name for the captured data must be set. A default record file name (Record.bcp) is set in the Configuration window but this can changed as required. The record file name can be changed, either by changing it in the Capture control parameter group in the Configuration screen, by selecting the Set Recorded data file name option in the File menu or by the use of icon 3 (Set recorded data file name) on the toolbar. Once a record filename has been set, the Record mode button on the control panel will be enabled.

25.2 RECORD MODE OPERATION (Mode menu, Record mode)

When the Record mode button is clicked, (or Record mode is selected from the Mode menu) the Record button (Red dot) and STOP button on the control panel become active, indicating that the system is ready to start recording. It is possible to adjust the frame rate in the same way as in Capture mode.

To start recording, press the Record button marked by the red dot. This will start the data capture process and data will be stored in the file name set previously. Capacitance data will be recorded continuously until recording is stopped. To stop the recording, press the stop button. This will make the file which has just been recorded available for immediate Playback, and will also initialise the system to record a new data file using a follow-on filename. Each recording session will generate data files with sequential numbers appended to the end of the file name, eg Record_1.bcp etc.

25.3 RECORD MODE FILE LENGTH

In Record mode, the length of the recorded data file is potentially unlimited. Consequently, the PC hard disk will soon be filled with unwanted data if care is not exercised in the use of this option.

However, if the Stop after buffer filled option is checked on the Control panel, the recorded file length will match that of the buffer file. To set the length of the buffer file, please refer to paragraph 22.2.2.

25.4 SETTING THE FRAME RATE IN RECORD MODE

The frame rate in Record mode is the same as that set in Capture mode. Please refer to paragraph 22.3 for details. The limitations on achievable data capture rates are the same as for Capture mode.
26. PLAYBACK MODE (Mode Menu, Playback mode)

In Playback mode, captured data can be replayed to allow detailed analysis.

26.1 PLAYBACK MODE OPERATION FOLLOWING DATA CAPTURE

If data has just been captured, the data can be played back immediately as follows:

1. Click the Playback mode button and then click the forward play [>] button on the control panel (second button from the right). The image data will be replayed and the current image number and the time from the start of data collection are displayed on the right hand end of the status bar at the bottom of the window.

2. Click the reverse play [<] button (to left of stop button) on the control panel. The captured data will be replayed in reverse order.

3. Click the Go to last frame [>] and Go to first frame [<] buttons on the control panel in turn. Note that these set the displayed image to the last and first captured frames respectively.

4. Click the increment one frame button [Δt]. The image will advance to the next frame. Similarly, click the decrement one frame button [Δt]<. The image will change to the previous frame.

26.2 PLAYBACK OF PREVIOUSLY RECORDED DATA

Data can be played back from a previously recorded data file once the required data file has been loaded.

1. To load a recorded data file, select the Load Recorded Data option on the File menu, or the Load recorded data file button (icon 2) on the toolbar or the Load button on the Control Panel and enter the required file name.

2. If image display is required, then a sensor information file compatible with the captured data file must be loaded. This can be done by using the Load sensor information file option on the Image Reconstruction menu, or by using the Load sensor information file button (icon 20) on the toolbar or by selecting the required file name in the Configuration menu.

3. Once these files have been loaded, data can be played back using the Playback button on the control panel. At this point, all of the control buttons and the file position pointer will become active.

4. Detailed information about the remaining Control panel buttons is given in paragraph 20.4.
27. CORRELATION AND REFERENCE FRAME OPTIONS

27.1 CORRELATION (Correlation menu)

The ECT32v2 software contains a simple on-line correlation facility which can be used to determine the velocity of slowly-moving fluids. This facility can only be used in on-line mode and functions as follows:

The ECT system must be operated in twin-plane mode. If the correlation option is enabled, an image is displayed of the permittivity distribution for the first plane. A second image is also displayed of the difference between the permittivity distributions for plane 1 (measured for frame N) and that for plane 2 (measured for frame N + M where M can be set to any positive integer value). For a steady state flow, the user can adjust the frame-rate (or delay time between frames N and N+1) using the Framerate interval (msec) control on the Control Panel to attempt to minimise the difference image. If this can be done, it is possible to deduce the flow velocity from knowledge of the spacing between the two sensor measurement planes and the time delay between frames N and (N+M) (or planes 1 and 2).

This technique can be implemented using either the standard or quadrant image formats and hence some spatial measurement of velocity is possible. Moreover, the frame averaging facility can also be used to allow averaging of the difference image to facilitate the setting of the optimum delay time to achieve a minimised difference image.

The correlation controls are accessed from the Correlation drop-down menu or alternatively using icons 24 and 25 on the toolbar. Details of the correlation controls and windows are given below.

27.1.1 Enable/Disable Correlation (Correlation menu, Enable/Disable Correlation)

This option toggles the correlation option on and off alternately. It can also be implemented by clicking on icon 24 on the toolbar. When correlation is enabled, the Plane 2 image is replaced by a Difference image.

27.1.2 Sensor Spacing (Correlation menu, Sensor Spacing)

When this option is selected, the Set inter-plane spacing window (shown in figure 27.1.1) is opened. This allows the user to set the spacing between the centres of the two measurement planes and also to set the order of the sensor planes relative to the direction of flow. This allows the software to calculate the apparent flow velocity from the frame time interval.

![Image of Set inter-plane spacing window]

Figure 27.1.1 Set inter-plane spacing window
27.1.3 Correlation Controls (*Correlation menu, Correlation controls*)

When this option is selected, the **Correlation Controls window** (shown in figure 27.1.2) is opened.

![Correlation Controls](image)

**Figure 27.1.2 Correlation control window**

The **Frame interval** parameter is the time between successive frames and is the value set in the **Framerate interval box** in the **Control Panel**.

The **Interval frames** parameter determines the value of $M$ defined in the second paragraph of paragraph 27.1. Together with the **frame interval**, it determines the **time delay** between the measurement planes used for correlation.

The **Difference Image Gain** control allows the **difference image** to be displayed at a **higher gain** setting than the standard image, to **facilitate viewing** of the **difference image**.

The **apparent velocity**, calculated from the **set time delay** between the planes and the **sensor spacing**, is shown at the bottom of this window.

A typical set of images displayed when correlation is enabled is shown in figure 27.1.3. Note that the second image is now the **difference** between the two images being correlated.

![Image Display](image)

**Figure 27.1.3 Image Display with correlation and averaging enabled**
27.2 REFERENCE FRAME OPTION

The Reference frame option allows a set of measured capacitance data to be defined as a reference set. If the Reference Frame option is enabled, this data is then subtracted from all subsequent data frames. This facility can be useful in a number of circumstances:

For example, it can be used to remove the effects of low-level calibration drift from the displayed images, or it can be used to view changes from a fixed point in an experiment.

The Reference frame can be derived from current or previous measurement data and can be derived from either a single data frame or the average of a number of data frames.

The operation of the Reference Frame facility is described below.

27.2.1 Enable Reference Frame (Correlation menu, Enable Reference Frame)

The Reference Frame facility is enabled either by selecting option 4 on the Correlation drop-down menu or by clicking on icon 22 on the toolbar.

27.2.2 Reference Frame Controls (Correlation menu, Reference Frame controls)

Click on the Reference Frame Controls option or icon 23 on the toolbar to access the Reference Frame Controls window, shown in figure 27.2.1

![Reference Frame Control](image)

Figure 27.2.1 Reference frame control window

The Reference frame can be defined in two ways, either from a set of previously-captured capacitance data or from on-line data.

To define the Reference frame from previously-captured data, click on the Load/Compute button in the Reference Frame Control window. A second Load/Compute Reference Frame window will appear as shown in figure 27.2.2.
Define the Data file to be used in the Source File box and the range of frames to be averaged in the Start and End Frame boxes. Insert the same frame number in both boxes to use a single frame of data for the Reference Frame. Then click on the Apply button.

To derive the Reference frame from live data in Capture mode, click on the Reset button in the Reference Frame Control window to delete any previous reference frame data. Then click on the Start button in the Accumulate Reference Data group. The Start button changes to a Stop button. Click the Stop button when the required number of frames have been captured. These frames will then be averaged and will become the Reference Frame.

Click on the Enable button to implement the Reference Frame option, then close the Reference Frame Control window.

A typical image display with the Reference frame option enabled is shown in figure 27.2.3.

Note that when the capacitances are displayed when the reference frame is active, “ghost values” of the capacitances of the reference frame are shown as short horizontal lines in the capacitance window.
28. DATA FILES

28.1 FILE FOLDERS

The ECT32v2 software maintains a Configure folder, Installation folder and a Working folder. Users will usually only be concerned with the Working and Configure folders. The Working folder is used to store calibration files and capacitance data files and is also the target folder for any recording operation. The Configure folder holds the sensor information files. The current folders are retained between subsequent uses of the ECT32v2 software.

28.2 GENERATING ASCII FILES (*File menu, Generate ASCII files*)

When capacitance data is captured to file, it is stored as binary data to minimise the size of the stored data files. The ECT32v2 software allows capacitance data files in binary format (.bcp files) to be converted into a number of different data types which can then be saved in ASCII (text) format.

Binary capacitance data files (.bcp files) can be converted into ASCII data files in the following formats:

- Normalised capacitance files (.anc files)
- Absolute capacitance files (.aac files)
- Image files (.aim files)
- Volume ratio files (.avr files)

The format of the data in these files is described in Appendix 3.

The method for generating these data files is decribed in the following actions. In each case, it is assumed that data has been captured and stored to a suitable disk file and that, where appropriate, a calibration data file has also been saved.

The method for generating the data files is common to all data file types and is initiated by selecting the Generate ASCII data files option from the File menu. This brings up the ASCII file generation window shown in figure 28.2.1

![Figure 28.2.1 ASCII output file creation window](image)

Figure 28.2.1 ASCII output file creation window
28.2.1 Normalised capacitance data files

1. In the Data source parameter group, select the name of the stored capacitance data file in the Capacitances box using the Browse button.

2. In the Output file parameter group, set the output file name (without a file extension) in the Output File box and select the range of capacitance frames to be converted in the From and to boxes.

3. In the Output file type box, select Normalised Capacitance.

4. When all of the above parameters are correct, click on the Save button. The data will be converted and written to the output file which will be given the file extension .anc (ASCII Normalised Capacitance) and a finished message will appear. To exit this window, click on the Finished button.

5. The data file will be saved in the ECT32v2 Working folder and can be viewed with a suitable word-processor such as Microsoft Word. A typical converted data file is shown in appendix 3.

28.2.2 Absolute capacitance data files

1. In the Data source parameter group, set the name of the stored capacitance data file in the Capacitances box using the Browse button and set the name of the calibration file used to produce this data in the Calibration file box. If necessary set the frequency option to the setting used to generate the original capacitance data.

2. In the Output file parameter group, set the output file name (without a file extension) in the Output File box using the Browse button and select the range of capacitance frames to be converted in the From and to boxes.

3. In the Output file type box, select Absolute Capacitance.

4. When all of the above parameters are correct, click on the Save button. The data will be converted and written to the output file which will be given the file extension .aac (ASCII Absolute Capacitance) and a finished message will appear. To exit this window, click on the Finished button.

5. The data file will be saved in the ECT32v2 Working folder and can be viewed with a suitable word-processor such as Microsoft Word. A typical converted data file is shown in appendix 3.

28.2.3 Image data files

1. In the Data source parameter group, set the name of the stored capacitance data file in the Capacitances box.

2. In the Output file parameter group, set the output file name (without a file extension) in the Output File box and select the range of capacitance frames to be converted in the From and to boxes.

3. In the Output file type box, select Image.

4. Select the permittivity model to be used and the permittivity ratio K if appropriate.

5. When all of the above parameters are correct, click on the Write button. The data will be converted and written to the output file which will be given the file extension .aim (ASCII Image) and a finished message will appear. To exit this window, click on the Finished button.
6. The data file will be saved in the ECT32v2 Working folder and can be viewed with a suitable word-processor such as Microsoft Word. A typical converted data file is shown in appendix 3.

28.2.4 Volume Ratio data files
1. In the Data source parameter group, set the name of the stored capacitance data file in the Capacitances box.
2. In the Output file parameter group, set the output file name (without a file extension) in the Output File box and select the range of capacitance frames to be converted in the From and to boxes.
3. In the Output file type box, select Volume Ratio.
4. Select the permittivity model to be used and the permittivity ratio K if appropriate.
5. When all of the above parameters are correct, click on the Save button. The data will be converted and written to the output file which will be given the file extension .avr (ASCII Volume Ratio) and a finished message will appear. To exit this window, click on the Finished button.
6. The data file will be saved in the ECT32v2 Working folder and can be viewed with a suitable word-processor such as Microsoft Word. A typical converted data file is shown in appendix 3.
29. ADVANCED FEATURES

29.1 DAM200E TIMING PARAMETERS
The timing parameters used in the DAM200E unit during capacitance capture can be changed using the Timing Parameters option on the Acquisition menu. These parameters should not be changed without reference to PTL.

Selecting this option displays the window shown in figure 29.1.1

![DAM200E Hardware Settings](image)

**Figure 29.1.1** DAM200E timing parameters window

The parameters in this window are as follows:

**29.1.1 Dynamic Baseline period**
This is the period between baseline autozero and measurement frequency reset operations (default is 60 seconds). The control parameters are automatically updated at these intervals to compensate for any drift in the measurement system zero reference point and the measurement frequency is reset to the chosen value. This last operation is normally unnecessary but is included as a useful precaution for situations where high electrical noise levels exist which can cause the selected measurement frequency to be corrupted.

Notes: A value of 0.0 in the baseline period turns off the dynamic baseline reset option.

The measurement frequency should normally be set to the High option (1.25MHz).

Note that this operation can be carried out manually any time by clicking on icon 10 (Reset Baseline and Measurement frequency) on the toolbar.

**29.1.2 Long setup delay**
This is the delay time between changing the source electrode and changing the measurement channel. (default = 380 uS)

**29.1.3 Short setup delay**
This is the delay time between changing the measurement channel and reading the ADC value. (default = 20 uS).

These parameters collectively determine the maximum frame capture rate. Lowering them from the default values will increases the system noise levels.
29.2 THE SENSOR INFORMATION FILES

These files contain information, including the sensor sensitivity maps, which determines how the image is to be calculated and are stored in the Configure folder. Details of the standard generic files are given in paragraph 19.3 and detailed information about each file can be displayed by selecting the Sensor Information File details option from the Data Display menu. This will display the window shown in figure 29.2.1.

![Figure 29.2.1 Sensor information file details window](image)

Additional sensor information files, for example files for square or rectangular sensors or unique, more accurate files for individual sensors may be added to the Configure folder.

29.3 TRIGGER MODE OPERATION

The normal operation of the PTL300E ECT system is via the control PC. However, options are available which allow data capture to be controlled by an external trigger signal as follows:

The trigger mode is set by selecting the Trigger Control option in the Acquisition menu, which displays the following window:

![Figure 29.3.1 Trigger Control window](image)

The trigger I/O connector is located on the rear panel of the CMU. Details of this connector and information about signal levels is given in Appendix 5.
There are 3 options for Trigger mode and the effect on the system operation depends on whether the ECT32v2 software is set to Capture mode or Record mode.

29.3.1 Capture Mode

In the default trigger mode (none) the system operates as determined by the user directly.

In Start mode, data capture will not start until a valid signal is applied to the trigger input terminal on the trigger I/O connector on the rear panel of the CMU. Data capture will cease when terminated by the software controls. The system will revert to Playback mode and the trigger input signal plays no further part until Capture mode is re-selected.

In Start Stop mode, data capture will commence when a valid trigger input occurs and will stop when this input ceases, when the system will revert to Playback mode.

29.3.2 Record Mode

In the default trigger mode (none) the system operates as determined by the user directly.

In Start mode, data capture will not start until a valid signal is applied to the trigger input terminal on the trigger I/O connector on the rear panel of the CMU. Data capture will cease when terminated by the software controls. The system will remain in Record mode and recording (to a new file name) will restart on the next valid trigger signal.

In Start Stop mode, data capture will commence when a valid trigger input occurs and will stop when this input ceases. The system will remain in Record mode and data capture will restart to a new file name when the trigger input signal becomes valid again.

29.3.3 Trigger output signal.

When the system is capturing or recording data, a trigger output signal (logic 0) is present on the trigger output pin on the trigger I/O connector. When no data capture is in progress, the trigger output level will be a logic 1 (+5V).
30. DATA EXPORT

The PTL300E ECT system can export live capacitance data to a remote PC using a fast ethernet link.

This facility is initiated by clicking on Icon 26 on the toolbar, which sets up the Network Connection.

Note that the PC which is connected to the DAM200E unit will be referred to as the "Host PC" and the PC receiving the exported capacitance data will be referred to as the “Remote PC”.

Note also that both PC's will need to be connected to a fast (10/100MB) ethernet link for this facility to work.

The exported data is intended for incorporation into the customer’s own software. However, two demonstration programs are included with the software to allow exported data to be displayed in graphical or text format on the remote PC. These programs should be installed on the remote PC as described in Appendix 7.

30.1 SETTING UP THE NETWORK CONNECTION

To establish the network connection software and start to export data, proceed as follows:

1. With the Host (Control) PC running ECT32v2, select Idle mode from the Control Panel.
2. Click on icon 26 (Set up Network Connection). The Network Connection Window, shown in figure 30.1.1 will appear.
3. Enter the TCP/IP address and port number of the Remote (target) PC in the Target Network Address box as shown in figure 30.1. In this case, the port number is 2000.
   Note that the TCP/IP address of a PC running under the Windows XP operating system can be found by typing “ipconfig” in a command window as shown in figure 30.1.2.
4. Set the Protocol to TCP/IP.
5. To send every data frame, ensure that the Reduced Frame Rate box is unticked.
6. To send data at a reduced rate, tick the Reduced Frame Rate box and select the frame rate in the Select Every nth Frame box.
7. Switch on the Remote PC and double click on either the Rem32G icon for capacitance data display in graphical format or the Rem32T icon for capacitance data display in text format.
8. For instructions for the use of the graphical mode display mode, proceed to step 1 in paragraph 30.2. To use the text display mode, proceed directly to step 1 in paragraph 30.1.3.
Figure 30.1.1. Network Connection windows on Host PC

(a) Before connection

(b) After connection

Figure 30.1.2  Command window showing network address of PC.
(a) Window at start-up

(b) Window following connect request

(c) Window displaying live twin-plane capacitance data

Figure 30.1.3. Network connection windows on remote (target) PC in graphics mode
30.2 Graphical display of capacitance data

1. When the **Rem32G icon** is selected on the **remote (target) PC**, the window shown in **figure 30.1.2(a)** will appear. Set the **port number** to match that selected on the **host PC** (this is the last 4 digits of the **Target network address** (2000 in the example shown in **figure 30.1.1**).

2. Click on the **Connect button** in the window on the **remote PC**. The window will change to that shown in **figure 30.1** and the **status message** “Waiting for connection” will be displayed.

3. Click on the **Connect button** on the **Host PC**. The **Connect button** will change to a **Disconnect button** and the message at the bottom of the window will change to "**Connection successfully created**" as shown in **figure 30.1.1(b)**.

4. Click on the **Finish button**. The **Remote PC** will display the message "**Connected**".

5. Click on the **Capture mode button** on the **Host PC**. Data **capture** will start and **data will be exported to the remote PC** and displayed in the format shown in **figure 30.1.3(c)**, which shows the normalised capacitance data for an 8-electrode, twin-plane sensor.

6. Click on the **Stop button** in the **Control Panel of the host PC**. Data export will cease. It can be restarted by clicking again on the **Capture button**.

7. Click on the **Idle Button**, then click on **icon 26**. The **Network Connection Window** will re-appear.

8. Click on the **Disconnect button**. The network connection will terminate and the remote PC will display the message "**Connection closed by remote client**".

30.3 Text display of capacitance data

1. When the **Rem32T icon** is selected on the **remote PC**, a DOS window displaying the message "*Waiting for connection*" will appear.

2. Click on the **Connect button** on the **Host PC**. The **Connect button** will change to a **Disconnect button** and the message at the bottom of the window will change to "**Connection successfully created**" as shown in **figure 30.1.1(b)**.

3. Click on the **Finish button**. The **Remote PC** will display the message "**Connected**".

4. Click on the **Capture mode button** on the **Host PC**. **Data capture** will start and **data will be exported to the remote PC** in the format shown in **figure 30.1.4**.

5. Click on the **Stop button** in the **Control Panel**. Data export will cease. It can be restarted by clicking again on the **Capture button**.

6. Click on the **Idle Button**, then click on **icon 26**. The **Network Connection Window** will re-appear.

7. Click on the **Disconnect button**. The network connection will terminate and the remote PC will display the message "**Connection closed by remote client**".
Figure 30.1.4 Network Connection DOS window output on remote PC in text mode

Waiting for connection

Connect

Electrodes 8
Measurements 28
PlaneVector 3
Desc string Replaying data from file 'Buffer.bcp'
Frame 1
Timestamp 0
Plane 1
VolumeRatio 1.00
1.00 1.00 1.00 1.00 0.99 1.00 1.00
1.00 1.00 1.00 0.99 1.00 1.00
1.00 1.00 1.00 1.00 1.00
1.00 1.00 1.00 1.00
1.00 1.00
1.00
Frame 1
Timestamp 0
Plane 2
VolumeRatio 1.00
1.01 1.00 1.00 0.99 0.99 1.00 1.00
1.00 1.00 1.00 0.99 1.00 1.00
1.00 1.00 1.00 1.00
1.00 1.00 1.00
1.00 1.00
1.00
Frame 101
Timestamp 4000
Plane 1
VolumeRatio 1.00
1.00 1.00 1.00 1.00 0.99 1.00 1.00
1.00 1.00 0.99 1.00 1.00 1.00
1.00 1.00 1.00 0.99 1.00
1.00 1.00 1.00 1.00
1.00 1.00
1.00
Frame 101
Timestamp 4000
Plane 2
VolumeRatio 1.00
1.01 1.00 1.00 1.00 1.00 0.99 1.00
1.00 1.00 0.99 1.00 0.98 1.00
1.00 1.00 0.99 1.00
1.00 1.00 0.99 1.00
1.00 1.00
1.00
1.00

Finish

Connection closed by remote client
SECTION 6

FILE CONVERSION SOFTWARE

This brief section describes two sets of file conversion software.

The first program (BCPconvert) converts standard captured capacitance data files into a range of alternative data files.

The second program (ECT16con) allows data files produced by previous version of PTL ECT software to be converted so that the data can be read by the ECT32 software.
31.1 FILE CONVERSION SOFTWARE BCPCONVERT FOR CAPTURED ECT DATA

The BCPCONVERT software converts a measured normalised capacitance data file into a range of alternative files, including image and absolute capacitance files. A reference file can also be used to compensate for the effects of any residual offsets in the original measured data file. The BCPCONVERT software is supplied as a stand-alone executable program file.

When the BCPconvert program is run the following data input window appears:

![BCPconvert Window at Start-Up](image)

**Figure 31.1 The BCPconvert window at start-up**

The various data, scroll and tick boxes are used to enter the input and output data. Note that the data to be entered depends on the form of output data required. The data input parameters are as follows:

**Capacitance file:** The captured .bcp normalised capacitance data file to be converted. Select the required file using the adjacent Browse button.

**Start frame:** The number of the first frame in the data file to be converted.

**Number:** The number of consecutive frames to be converted,

**All:** If this box is ticked, all of the frames in the input data file will be converted.

**Calibration file:** The calibration file used to generate the recorded data (only required to generate absolute capacitance files). Select using the adjacent Browse button.
View button: Displays the contents of the **selected calibration file** as **absolute** capacitances in fF.

**Coup cap file:** The coupling capacitance file for the DAM200E unit used to generate the recorded data (only required to generate **absolute capacitance files**). Select using the adjacent Browse button. This file can be **generated or copied** to the control PC from the **embedded PC** inside the DAM200E unit using the ECT Toolkit software.

**View button:** Displays the contents of the selected **calibration file** as **absolute** capacitances in fF.

**Map file:** The **sensitivity matrix file** used to convert the .bcp data into **image data**. Only required to produce image data files. Select the required file using the adjacentBrowse button.

**Model/Perm:** The **capacitance/permittivity model** and **permittivity ratio** used to generate the output image data. Only required to produce **image data files**. Select the required model (**parallel/series/Maxwell**) using the scroll box.

**Image trunc:** The **upper and lower normalised permittivity pixel limits** used to generate the image file.

**Cap trunc:** The **upper and lower normalised capacitance limits** used to generate the image file.

**Iter/Gain:** The **number of iterations** and the **feedback gain** to be used for iterative image reconstruction. For LBP reconstruction, set Iter = 0.

**Reference frame:** If this box is ticked, capacitance data from a reference frame (see below) is **subtracted from all of the frames in the data file before they are converted**. This facility is useful for removing residual offset errors from captured data files.

**Reference file:** The file name of the file containing the reference data. Select using the Browse button. The data used for the reference frame is the average of all of the frames selected below:

**Start frame:** The number of the **first frame** to be used to calculate the reference frame data.

**Number:** The **number of consecutive frames** to be averaged to produce the reference frame data.

**Output file:** The name of the file to hold the **converted output data**. Select the file type (norm cap, absolute cap, image, bcp file) using the adjacent scroll box.

**Generate button:** This button generates the output file.

**View file button:** Views the converted output data file.
31.2. FILE CONVERSION UTILITY ECTCON16

This file conversion utility converts earlier PTL ECT file formats to the ECT32v2 file format and vice-versa.

31.2.1 TO CONVERT A PCECT DATA FILE TO ECT32v2 FORMAT

1. Quit the ECT32v2 software if this is in use.
2. Double click on the ECT16CON icon in the ECT Program group. The file conversion window shown in figure 31.2.2 will appear.

![ECT16 File conversion window](image)

3. Enter the name of the file to be converted in the Source filename box (eg 8tube.mes).
4. Enter the name of the file to hold the converted data in the Destination filename box (eg 8tube.bcp).
5. Select the ECT Standard format option in the Destination file group box.
6. Click on the Convert button. The file will be converted and the converted file will be in the same folder as the source file.
7. Exit the file conversion window.

Note: To convert from another file format to PCECT format, select the PCECT option in the Destination file group box.
SECTION 7

THE ECT TOOLKIT

This section describes a set of diagnostic and maintenance software options for the PTL300E ECT system contained within the ECT Toolkit program.
32. THE ECT TOOLKIT

The ECT Toolkit program is a set of software which runs on the embedded PC within the DAM200 unit and which can be accessed using a web browser interface (eg Internet Explorer) on the Control PC.

The Toolkit software contains a number of utility program options for testing and maintaining the software and hardware in the DAM200E CMU. The Toolkit software is run by clicking on the ECT Toolkit icon in the ECT program group window.

When the software is run, the software defaults to the About ECT Toolkit screen shown in figure 32.1.1.

![ECT Toolkit software opening window](image)

**Figure 32.1.1 ECT Toolkit software opening window**

The opening screen is formed from 2 separate windows, a Left Hand Window, which contains 7 program options for the DAM200E CMU and a Right hand window, which displays the results of running these programs. The required program is selected by double-clicking on the appropriate selection in the Left hand window.
32.1 THE ABOUT WINDOW

The about window lists the current hardware and software status as follows:

**Mode:** The Capacitance Measurement Unit (CMU) hardware in use.

**Firmware:** The version number of the compiled (C) software installed on the flash memory card in the embedded PC inside the CMU.

**OS:** The operating system installed on the flash memory card in the embedded PC in the CMU.

**HTTP:** The web server program on the embedded PC in the CMU.

**CGI:** The Common Gateway Interface software library version

This information may be requested by PTL for diagnostic purposes.

32.2 THE DAMCONTROL PROGRAM OPTION

The DAMcontrol program allows the CMU to be controlled in a semi-manual mode from the control PC. It provides facilities for measuring selected inter-electrode capacitances and displays the intermediate measurement parameters. This facility is useful for carrying out experiments on prototype sensors and also for fault finding if problems occur in the ECT measurement system.

The program can operate in either single-plane or twin-plane mode and allows the user to determine which (if any) electrode is to be the source electrode and also allows one or all of the electrodes to be set to be detector electrodes. The measurement parameters M1, M2 and M3 are set automatically by a measurement bridge balancing algorithm and the program calculates the absolute value of capacitance between the source electrode and the selected detector electrodes.

The charge injection capacitances for each measuring channel are also measured and updated at a refresh rate determined specified by the user.

The following notes make reference to the terms used in the capacitance measurement chapter 6 which should be read before using this software.
32.2.1 THE DAMCONTROL PROGRAM WINDOW

When the DAMControl program is run the screen shown in figure 32.2.1 appears.

The column headings and operating buttons have the following functions:

Browse buttons:

**PLANE**
- The measurement plane to be displayed (1, 2, All = both)

**SOURCE**
- The electrode which is to be the source electrode (1 - 11)

**DETECTOR**
- The electrodes which are to be detectors. (2-12 or All)

**OFFSET CONTROL**
- Selects auto or manual measurement bridge balancing.

**CHARGE INJECTION**
- Selects manual or automatic charge injection measurement (Cinj)

**AVERAGING**
- Sets number of measurement frames Nf to be averaged for noise measurement.

**REFRESH**
- Sets screen refresh rate.

**CLOCK FREQ**
- Sets the system measurement frequency (norm = high).
**Function Buttons:**

- **APPLY** Applies changes set by Browse buttons
- **RESET Cref** Sets Cref = current measured values of Cx.
- **RESET OFFSETS** Rebalances the measurement bridge in manual mode.

**Column Headings**

- **PLANE** Displays the current measurement plane(s).
- **DETECTOR ELECTRODE** Displays the selected detector electrodes.
- **OFFSET (M1):** The offset voltage applied to balance the measuring circuit, expressed as a count M1 (in the range 0-1023) applied to DACa.
- **GAIN (M2):** The gain of the programmable attenuator DACb expressed as a count M2 (in the range 0-1023). The actual gain (attenuation) = M2/1023.
- **OUTPUT (M3):** The output count M3 from the A/D converter (in the range 0-4095).
- **CNOISE fF:** The rms value of the capacitance Cx averaged over the number of frames Nf set in the AVERAGING box.
- **Cinj fF:** The charge injection capacitance of the measuring channel in femtoFarads.
- **Ccoup** The internal inter-channel coupling capacitances within the CMU in fF.
- **Cx fF:** The measured capacitances in femtoFarads between the selected source electrode and the electrode connected to the measuring channel.

**Cx - Cref**

When valid figures are entered in the Ccoup boxes, the values of Cx are corrected for the measured values of **internal cross-channel coupling capacitance** (caused by spurious coupling between measurement channels inside the DAM200E unit), using the set of capacitances measured with no sensor connected to the CMU. The coupling capacitances are measured as described in paragraph 32.4.

* The method used to calculate the rms noise level in the CNOISE column is described below:

The capacitance Cav, averaged over the number of frames Nf set in the averaging box, is calculated using the formula:

\[
Cav = \frac{1}{Nf} \sum_{1}^{Nf} C_n
\]  

(32.2.1)

where Cn is the measured inter-electrode capacitance for the nth frame.
The rms noise is equal to the standard deviation of the set of capacitance measurements and is calculated using the formula:

\[
C_{\text{noise}} = \left[ \sum_{1}^{N_f} (C_n - C_{\text{av}})^2 \right]^{1/2}
\] (32.2.2)

32.2.2 OPERATING INSTRUCTIONS FOR DAMCONTROL PROGRAM

1. Set the measurement plane and then select the electrode which is to be the source electrode. If there is to be no source electrode, click on the None option.

2. Select All of the electrodes to be Detector electrodes in the Detector box.

3. Click the Apply button. All of the Gain values M2 in column 4 will be set to 1023 (maximum) and the Offsets M1 in column 3 will be automatically set to give Output values M3 in column 5 around the system balance count (1000).

4. The capacitances between the selected source electrode and the remaining electrodes are displayed in columns 6, 7 and 8.

5. Column 6 displays the charge injection capacitance \(C_{\text{inj}}\) for each measuring channel. If the Auto Cinj option is selected these are measured at the interval selected in the refresh box. If the manual option is selected, they are remeasured when the Reset Offsets button is clicked.

6. Column 7 displays the absolute values of the inter-electrode capacitances \(C_x\).

7. Column 6 displays the rms noise level of the capacitances in column 7 averaged over the number of frames set in the Averaging box.

8. Column 8 displays the difference between the measured capacitances \(C_x\) and a set of reference capacitances \(C_{\text{ref}}\). The reference capacitances can be set to the current measured values \(C_x\) by clicking the Reset Cref button. This column allows changes in capacitance to be viewed easily.
32.3 THE DIAGNOSTICS PROGRAM OPTION

When this option is selected, the window shown below appears.

32.3.1 DIAGNOSTICS

The first 3 lines of output indicate that the common measurement channels are working correctly.

FIRMWARE: Embedded CMU firmware 1.37c 15/04/04

Plane 1 acquisition appears operational (967)

Plane 2 acquisition appears operational (959)

Figure 32.3.1 The diagnostics window (1)

32.3.2 INTER-ELECTRODE CAPACITANCES

The next block of data is the set of inter-electrode capacitances for each measurement plane. These are the absolute capacitances, measured between the source and detector electrodes, for each possible electrode measurement combination which the CMU can carry out. They are updated each time the Diagnostics option is selected by the mouse. These capacitances exclude the correction for the internal coupling capacitances within the CMU.

Capacitances (fF) Note: does not include coupling component.

**Plane 1**

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<tr>
<th>Src/Det</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
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<td>47.80</td>
<td>22.42</td>
<td>15.98</td>
<td>12.32</td>
<td>8.48</td>
<td>7.24</td>
<td>10.05</td>
<td>18.49</td>
<td>52.84</td>
<td>496.91</td>
</tr>
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<td>469.03</td>
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<td>12.59</td>
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<td>10.24</td>
<td>10.70</td>
<td>19.02</td>
<td>45.42</td>
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<tr>
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<td>11.64</td>
<td>8.91</td>
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<td>9.20</td>
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**Plane 2**

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<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
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<td>47.72</td>
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</table>

Figure 32.3.2 The diagnostics window (2) inter-electrode capacitances
32.3.3 RMS NOISE LEVELS

The next blocks of data are the rms noise levels (in femtofarads) for each capacitance-pair measurement.

Noise Plane 1

<table>
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<tr>
<th>Src/Det 2</th>
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<th>4</th>
<th>5</th>
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Noise Plane 2

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Figure 32.3.3 The diagnostics window (2) rms noise levels
### 32.3.4 SYMMETRY CHECK

The final part of the diagnostics window checks for symmetry by measuring (where possible) the reciprocal capacitances $C_{ab}$ and $C_{ba}$ etc., compares these values and displays the differences in femtofarads.

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**Figure 32.3.4 Diagnostics window (3), Symmetry check**

**Note:** These are the results obtained by subtracting the $C_{ba}$ values from the $C_{ab}$ values. If the measurement system is perfect, all of these values will be zero. Small discrepancies as shown above are normal for the DAM200E CMU.
32.4 THE CAPACITANCES PROGRAM OPTION

When this option is selected, the inter-electrode capacitances, corrected for the internal measurement system coupling, are displayed as shown below.

**Capacitances (fF)**

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**Cinj**


|     | 12.77 | 28.20 | 9.03 | 17.05 | 15.55 | 16.96 | 21.49 | 16.03 | 23.89 | 11.95 | -129.44 |

A text file of measured capacitances can be accessed [here](#).

---

**Figure 32.4.1 The capacitances window**

A control window is displayed after the capacitances and this allows the capacitance measurement unit internal coupling capacitances to be measured. These are small values of stray capacitance between the individual measurement channels in the CMU and are used to correct the capacitance values displayed when the Capacitances option is selected.

The ECT system is delivered with a default set of measured capacitance coupling data and this data set can normally be used for most applications. The default coupling capacitance data file can be viewed by clicking on the [here](#) link on the first line of the Coupling Capacitances window shown in figure 34.4.2.
Coupling Capacitances

The current coupling capacitance file can be viewed here. Note: you may have to hit refresh on your browser to get the latest file if it has changed recently.

To measure, remove sensor leaving leads connected if possible, then hit Measure.

To make the changes permanent hit Save.

To upload a file, select a file here and hit Upload.

Figure 32.4.2 Coupling capacitances window

This window is used to measure any stray coupling capacitances within the CMU. As these capacitances are affected by the coaxial cable capacitances, these should, if possible, be measured with unterminated lengths of RG174 coaxal cable connected to each SMB connector for the measurement channels on the CMU. If suitable cable lengths are not available, the SMB connectors on the CMU should be left unterminated.

To measure a new set of data, either leave the CMU unconnected to any sensors or (preferably) connect 24 unterminated coaxial leads to the SMB connectors for the plane 1 and 2 measurement channels. Then click on the Measure button. A new set of coupling data will be measured and stored in temporary memory in the CMU.

To overwrite the existing default data file with the new coupling data, click on the Save button. This will save a new file of data to the permanent (flash) memory in the embedded PC in the CMU. This file can also be saved to the Control PC by Right-clicking the mouse on the here link and selecting the "Save Target as" option. The default file name is ect_coupcap.cap.

To upload a new coupling capacitances file from the Control PC to the CMU, click on the Upload button and follow the instructions.
When the ECT32 software creates a calibration file on-line or loads a stored calibration file, this file is stored in temporary memory (RAM) in the embedded PC inside the CMU. When the CMU is switched off, this file is lost from its memory. The Calibration program option checks to see if there is a current valid calibration file stored in the embedded PC RAM. If a valid file is found, the data is read and processed to produce an output of the low and high-level calibration capacitances in fF for each measurement plane (data stream). A typical output for a twin-plane file is shown below.

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### Protocol

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<td>1197.46 55.07 28.75 21.29 17.43 14.40 16.91 22.14</td>
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Stream 1 (Plane 2)
Protocol
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(11,12)

C low
1197.42 59.52 29.33 20.55 15.15 13.65 16.46 20.52 24.36 59.13 1306.49
1102.62 60.23 33.72 18.42 18.69 19.77 21.29 19.61 33.97 65.95
1163.93 61.76 26.28 20.86 20.60 20.69 16.79 26.25 33.47
1248.53 53.93 28.74 21.88 20.23 15.53 21.61 23.89
1230.47 62.56 30.58 22.44 16.29 20.25 20.73
1234.56 58.93 30.52 17.55 21.44 19.95
1226.04 59.21 23.78 20.00 17.71
1243.75 53.16 31.09 24.09
1247.00 65.47 33.40
1275.36 58.08
1286.38

Cinj low
9.37 36.27 18.85 13.74 41.50 34.48 30.12 23.41 38.40 22.65 -81.56

C high
1324.66 93.04 45.06 30.42 22.95 20.78 24.22 30.52 40.04 92.81 1436.86
1252.09 94.81 49.32 28.46 26.33 27.17 29.28 29.58 49.42 100.64
1271.46 94.83 41.70 30.67 28.21 27.60 24.23 35.74 48.94
1370.32 87.93 44.50 31.89 27.87 22.55 29.46 33.98
1371.63 96.34 46.18 32.24 23.73 27.51 28.57
1369.83 92.53 45.91 27.32 29.20 27.09
1363.34 93.30 39.77 30.33 25.86
1378.10 87.15 46.65 33.94
1387.08 99.44 48.94
1416.16 92.12
1433.37

Cinj high
10.95 38.19 19.86 14.87 43.58 36.48 32.05 24.95 39.60 24.57 -78.32

C high/C low
1.106 1.563 1.536 1.481 1.515 1.522 1.471 1.487 1.643 1.570 1.100
1.136 1.574 1.463 1.545 1.409 1.374 1.375 1.509 1.455 1.526
1.092 1.535 1.587 1.470 1.369 1.334 1.443 1.362 1.462
1.029 1.630 1.549 1.458 1.377 1.452 1.363 1.423
1.115 1.540 1.510 1.437 1.457 1.359 1.378
1.110 1.570 1.504 1.556 1.362 1.358
1.112 1.576 1.673 1.517 1.460
1.108 1.639 1.500 1.409
1.132 1.519 1.465
1.110 1.586
1.114

Figure 32.5.1 Calibration file window

One use of the calibration program option is to check that a valid low-level calibration has been achieved before the high point is taken. This can be useful if calibration conditions mean that a large time interval will pass between calibrating at the low and high permittivity points. This check can be carried out by running the ECT32 software in a small window. Once the low value permittivity calibration has been completed, the Toolkit software can be run and the calibration program mode used to check that sensible capacitance values have been measured at the low calibration point. Any problems eg with connecting leads etc. will become clear at this point and can then be corrected before the sensor is filled with the higher permittivity fluid.
This window allows the **network address** of the **CMU** to be set up for use on a **local network**. Please contact PTL for information about changing the default addresses supplied with the ECT system.

### Network

<table>
<thead>
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<th>Boot Protocol</th>
<th>Static</th>
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<tr>
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<tr>
<td>Net Mask</td>
<td>255.255.255.0</td>
</tr>
<tr>
<td>Gateway</td>
<td>192.168.0.1</td>
</tr>
</tbody>
</table>

Remember to point your browser at the new address.
32.7 UPGRADE PROGRAM OPTION

This option allows the embedded software in the CMU to be updated or upgraded. The Upgrade window is shown below:

**Upgrade**

Current version: Embedded CMU firmware 1.37c 15/04/04

File Upload:

(Select A Local File)

Pressing Upgrade Now will initiate the upgrade process.

Warning: Do not turn the unit off until it has rebooted, otherwise the unit is likely to become nonfunctional.

![Upgrade Now button]

**Figure 32.6.1 Upgrade window**

If a new embedded software upgrade is available, it should be installed using this program. The BROWSE button should be used to locate the required upgrade file (eg from a floppy disk or internet download location).

It is very important not to disturb or switch off the PC or CMU while the upgrade is in progress as this may lead to an unrecoverable situation which will involve a complex software re-installation procedure via the Diagnostic serial port. Once the upgrade has been completed, the CMU will reboot and an "upgrade completed" message will appear.
SECTION 8.

FREQUENTLY ASKED QUESTIONS ABOUT ECT

In this section, we have listed some of the most commonly-asked questions about ECT together with the answers.
Q1 What is ECT?

Electrical Capacitance Tomography (ECT) is a measurement technique which allows information about the spatial distribution of a mixture of dielectric materials inside a vessel to be obtained by measuring the electrical capacitances between sets of electrodes placed around its periphery and converting these measurements into an image showing the distribution of permittivity.

Q2 What materials can be imaged?

ECT can be used with non-conducting materials such as plastics, hydrocarbons, sand or glass and is often used with mixtures of two different dielectric materials, as the permittivity distribution corresponds to the concentration distribution in this case.

We are often asked whether it is possible to use ECT with water. There are two basic difficulties when using water. The first arises because although pure water is an insulator, only small amounts of impurities present in the water cause it to become conducting. The second problem results from the very high relative permittivity (80) of water, which causes major distortion of the electric field, lines inside the capacitance sensor. To summarise, special precautions must be observed if ECT is to be used successfully with water.

Q3 What other information can be obtained using ECT?

Where the mixture is flowing along the vessel, measurements of the concentration distributions at two separate axial planes allow the velocity profile and the overall flow rate of the fluid to be found.
Q4 Where can I find out more information about ECT?

Background information on ECT can be found in papers by Huang (1989), Reinecke (1996), Loser (2001) and Byars (2001). Full details of these papers are given below.


Reinecke N. and Mewes D., (1996), Recent Developments and industrial/research applications of capacitance tomography, Meas. Sci. Technol. 7 pp 233-246


You can view a copy of this last paper by clicking here.

A list of further papers on ECT technology can be viewed by clicking here.

Q5 What equipment is needed to carry out an ECT measurement?

An ECT system consists of a capacitance sensor, capacitance measurement circuitry and a control computer, together with some suitable control software.

Q6 How is the measurement equipment connected to the sensor?

For imaging a single vessel type with a fixed cross-section and with a fixed electrode configuration, the measurement circuitry can be integrated into the sensor and the measurement circuits can be connected directly to the sensor electrodes. This simplifies the measurement of inter-electrode capacitances and is potentially a good design solution for standardised industrial sensors. However, most current applications for ECT are in the research sector, where it is preferable to have a standard capacitance measuring unit which can be used with a wide range of sensors. In this case, screened cables connect the sensor to the measurement circuitry.

Q7 Can ECT be used with vessels of any cross-section?

Yes, but most work to-date has used circular geometries.
Q8 What image resolution is achievable?

The image resolution achievable depends on the number of independent capacitance measurements, but is generally low. To a first approximation, the angular resolution is equal to the number of electrodes located around the sensor periphery and the radial resolution is equal to the number of independent measurements divided by the angular resolution.

For example, for a 12-electrode sensor, the angular resolution will be around 30 degrees. As there are 66 possible independent capacitance measurements, the radial resolution will be around 20% of the sensor radius, or 10% of its diameter.

Q9 What image frame rates can be achieved?

Images can be generated at high frame rates depending on the number of electrodes on the sensor. For example 100fps is achievable using a 12-electrode sensor, increasing to approximately 200 fps for an 8-electrode sensor.
FAQ2 APPLICATIONS

Q1 What are some typical applications of ECT?
Q2 Where can I view information about these?

Q1 What are some typical applications of ECT?

Successful applications of ECT include imaging 2-phase liquid/gas mixtures in oil pipelines and solids/gas mixtures in fluidised beds and pneumatic conveying systems.

Q2 Where can I view information about these applications?

Details of some applications are given on our Applications page which can be accessed by clicking here.
Q1 *What is special about the capacitance measurement circuitry needed for ECT?*

The capacitance measuring system must be able to measure very small inter-electrode capacitances, of the order of $10^{-15}$ Farads (1 fF), in the presence of much larger capacitances to earth of the order of 200,000 fF (mainly due to the screened connecting cables).

The capacitance measurement technique used in PTL equipment is based on the use of an excitation signal in the form of a 1.25MHz square waveform. The excitation signal is applied to one electrode (the SOURCE electrode) and the currents which flow into the remaining (DETECTOR) electrodes (which are held at virtual ground potential) are measured using a synchronous demodulator. These measured currents are proportional to the capacitance between the SOURCE electrode and the DETECTOR electrodes.

Q2 *What are the limits on capacitance measurement?*

With the current state of capacitance measurement technology, it is possible to measure capacitance changes between 2 unearthed electrodes of 0.2 fF in the presence of stray capacitance to earth of 200pF at a rate of 2000 measurements per second. This sets a practical lower design limit on the smallest capacitance between any pair of electrodes of around 10fF. Sensors with inter-electrode capacitances lower than 10fF will usually produce very noisy and unstable images.

Q3 *What are typical inter-electrode capacitance values?*

The capacitance values when the sensor contains air are referred to as "standing capacitances". Sequential electrodes (adjacent electrodes), have the largest standing capacitances (values for a typical sensor are around 200-500fF), while diagonally opposing electrodes (opposite electrodes) have the smallest capacitances (typically 10-20 fF).
Q4 What determines the sequence of capacitance measurements?

Many different ECT measurement protocols are possible (see e.g. Reinecke, 1994), as capacitances can be measured between many combinations of groups of electrodes (which effectively become new "virtual electrodes").

Q5 Are the capacitance measurements made simultaneously?

No. The measurements for a single frame of data are made sequentially. Consequently, the capacitance data within the frame will be collected at different times and there will be some skewing of the data. Interpolation techniques can be used to de-skew this data if this effect is likely to produce significant errors.

Q6 What is the simplest capacitance measurement protocol?

Most work to-date with circular vessels has used the simplest arrangement (which we refer to as protocol 1) where capacitances are measured between single pairs of electrodes. The measurement sequence for protocol 1 involves applying an alternating voltage from a low-impedance supply to one (source) electrode. The remaining (detector) electrodes are all held at zero (virtual ground) potential and the currents which flow into these detector electrodes (and which are proportional to the inter-electrode capacitances) are measured. A second electrode is then selected as the source electrode and the sequence is repeated until all possible electrode pair capacitances have been measured. This generates M independent inter-electrode capacitance measurements, where:

\[ M = E(E - 1)/2 \]

and E is the number of electrodes located around the circumference. For example for E = 12, M = 66.

Q7 What other capacitance measurement protocols are possible?

Other possible protocols involve grouping electrodes and exciting them in pairs (protocol 2) and triplets (protocol 3) etc. The formula for the number of independent measurements for grouped electrodes is:

\[ M = (E)(E - (2P - 1)) / 2 \]

where P (the protocol number) is the number of electrodes which are grouped together.

Q8 What are the advantages in using more complex capacitance measurement protocols?

In principle, the use of more complex protocols can generate a larger number of independent measurements for a given electrode size and capacitance measurement sensitivity than the simple single-pair protocol 1. Improved image resolution is therefore achievable, although at the expense of the maximum image frame rate, which falls as the protocol number or number of electrodes increases.
**Q9 Is there a linear relationship between the permittivity of the contents of the sensor and the measured capacitances?**

For a sensor with internal electrodes, the components of capacitance due to the electric field inside the sensor will always increase in proportion to the material permittivity when the sensor is filled uniformly with higher permittivity material. However for sensors with external electrodes, the permittivity of the wall causes non-linear changes in capacitance, which may increase or decrease depending on the wall thickness and the permittivities of the sensor wall and contents.
FAQ4 - CAPACITANCE SENSORS FOR ECT

Q1 Where are the electrodes located?
If the vessel wall is non-conducting, the electrodes can be located inside the vessel wall, embedded within the wall or located external to the wall. However, if the tube wall is a conductor, the electrodes must be located inside the conducting wall and insulated from it.

Q2 What determines the choice of electrode location?
If the vessel wall is non-conducting, internal, embedded or external electrodes can be used. In general, ECT sensors with external electrodes are easier to design and fabricate than sensors with internal electrode sensors and they are also non-invasive, which gives ECT an important advantage over many other imaging techniques. However, if the tube wall is electrically-conducting (usually metallic), the electrodes must be located inside the wall.

Q3 How many electrodes are needed?
The number of sensor electrodes that can be used depends on the range of values of inter-electrode capacitances and the upper and lower measurement limits of the capacitance measurement circuit. Practical ECT sensors tend to have between 6 and 16 electrodes located around the periphery of the sensor.

Q4 How are the electrodes identified?
The convention we use to identify electrodes is to number them anticlockwise, starting at the electrode at or just before 3 o'clock, when viewing the sensor from the connector end, or the end from which the coaxial leads emerge.
Q5 What limits the number and size of electrodes?

As the number of electrodes increases, the electrode surface area per unit axial length decreases and the inter-electrode capacitances also decrease. When the smallest of these capacitances (for opposite electrodes), reaches the lowest value that can be measured reliably by the capacitance circuitry, the number of electrodes, and hence the image resolution, can only be increased further by increasing the axial lengths of the electrodes. However, these lengths cannot be increased indefinitely because the standing capacitances between pairs of adjacent electrodes will also increase and the measurement circuitry will saturate or overload once the highest capacitance measurement threshold is exceeded. See also Q7.

Q6 Why are driven guard electrodes often needed?

Axial resolution and overall measurement sensitivity can be improved by the use of driven axial guard electrodes, located either side of the measurement electrodes, as shown in the flexible laminate design illustrated in the figure below. These driven guard electrodes are excited at the same electrical potentials as the associated measurement electrodes and prevent the electric field from being diverted to earth at the ends of the measurement electrodes. For large diameter vessels, axial guard electrodes are normally an essential requirement to ensure that the capacitances between opposing electrodes are measurable.

Q7 What determines the minimum required total electrode lengths?

Simple electric field simulations show that the sum of the lengths of the axial guard and the measurement electrodes must equal or exceed the diameter of the sensor to ensure that the electric field across the sensor is reasonably constant and is not diverted to earth in the measurement region and that the capacitances between opposite electrodes remain measurable. Sensor sensitivity can be further improved by increasing the electrode lengths up to twice the sensor diameter, although the axial resolution of the sensor will decrease.

Q8 What are the smallest practical sizes for ECT electrodes?

The capacitance measurement limit equates to measurement electrodes of minimum axial length around 3.5cm for an 8 electrode sensor or 5 cm for a 12 electrode sensor. These dimensions assume that effective driven axial guards are used, as described in the response to Q7.

Q9 How are the electrodes and sensors fabricated?

The easiest method for constructing ECT electrodes is to use CAD drawing software to produce a master drawing and to use this to fabricate the electrode array from a flexible copper-coated laminate using photolithographic and copper-etching techniques. The electrode foil is then wrapped around the outside of an insulating tube to form the required sensor electrode array.
Q10 What does a typical ECT sensor electrode design look like?

Part of a design for an 8-electrode single plane sensor with driven axial guards is illustrated in figure X. This shows earthed screening tracks between the sets of electrodes (to reduce the adjacent electrode capacitances) together with earthed areas at the ends of the sensor (to allow the screens of the connecting cables to be terminated).

Q11 How are the electrodes connected to the capacitance measurement circuitry?

The usual method is to use coaxial leads (with a maximum length of 2m to minimise capacitance to ground) to connect the capacitance measurement circuitry to the electrodes. Each electrode must be screened individually, which means that one coaxial lead must be used for each electrode.

Q12 What sensor screening arrangements are required?

An earthed screen must be located around the sensor to exclude any external signals and to prevent the signals applied to the source electrodes from interfering with other electronic equipment in the vicinity.

Q13 What are discharge resistors and why are they needed?

Discharge resistors (typically 1 MOhm) must be connected between each electrode and the cable screen to ensure that no static charge can build up on the electrodes and connecting leads, otherwise damage may occur when the sensor is connected to the capacitance measurement circuit. The discharge resistors do not affect the capacitance measurement and must be connected permanently to the sensor electrodes.

Q14 What types of sensors can be constructed using these techniques?

These basic techniques can be used to construct either static or sliding sensors with either internal or external electrodes. More complex fabrication techniques must be used to construct sensors suitable for operation at elevated temperatures and pressures.
Q1 Why are the capacitance measurements and pixel values converted to normalised values?
Q2 How are ECT sensors calibrated?
Q3 How are the capacitances normalised?
Q4 How are the pixel permittivity values normalised?

Q1 Why are the capacitance measurements and pixel values converted to normalised values?

For most practical ECT sensors, there is not a simple linear relationship between the capacitances measured between the electrodes and the permittivity of the material inside the sensor. The relatively large number of different measurements required and the fact that the relationship between capacitance and permittivity may be different for each of these measurements, creates potential calibration and operating problems for ECT systems.

The method which is commonly used to overcome these problems is to restrict the use of ECT to the case where the sensor contains mixtures of two materials of differing permittivities and to operate the ECT system between the range of permittivities of these two materials.

This is done by calibrating the sensor before any measurements are commenced and involves first filling the sensor with the lower permittivity material and measuring all of the inter-electrode capacitances and then repeating this operation with the higher permittivity material. All subsequent capacitance measurements are then referenced (or normalised) to the values measured at calibration. For example, all of the capacitances have normalised values zero when the sensor contains the lower permittivity material and one when the sensor is filled with the higher permittivity material. For all other conditions, the capacitances will have values which nominally lie between these two measurement limits. The image pixel values are also normalised in a similar manner so that they have the values zero and one when the sensor contains the lower and higher permittivity materials respectively. Further details about normalisation and calibration are given in subsequent FAQs (see below).

Q2 How are ECT sensors calibrated?

When a mixture of two dielectric materials is to be imaged, ECT systems are normally calibrated by measuring two reference sets of inter-electrode capacitances, CL and CH with the sensor filled with the lower and higher permittivity materials in turn. These values are then used to normalise the subsequent capacitance measurements as described in the following FAQ.

Q3 How are the capacitances normalised?

Once the sensor has been calibrated, all subsequent capacitance values CM are normalised to have values CN between zero (when the sensor is filled with the lower permittivity material) and 1 (when filled with the higher permittivity material) by applying the formula:

\[ CN = \frac{(CM - CL)}{(CH - CL)} \]
Q4 How are the pixel permittivity values normalised?

The pixel values in the permittivity image are normalised in a similar way to the capacitances, so that they have the value 0 when the sensor is filled with the lower permittivity material and 1 when the sensor is filled with the higher permittivity material.
FAQ6 CONCENTRATION MODELS

Q1 How is the permittivity of a mixture of two materials related to the concentration of one of the components of the mixture?

The relationship between the permittivity distribution and the capacitance measured between a pair of electrodes must be considered carefully if accurate permittivity/concentration images are to be obtained. There are a number of models which can be used to improve the accuracy of the concentration measurement. It is very important to use the correct permittivity model (parallel/series/Maxwell etc) if accurate concentration values are to be obtained from the permittivity image. Further information on capacitance/permittivity models (including Maxwell's method) is given in the paper by Yang and Byars (1999).

Q2 What is the parallel capacitance model?

If the two dielectric materials exist as discrete stratified permittivity layers between the two electrodes, then two component capacitances, each due to one of the dielectric materials, and effectively connected in parallel, will exist between the electrodes. The sum of these capacitances will therefore accurately reflect the relative proportions (or concentration) of the 2 materials present. In this case, the mixture concentration is found by assuming that the dielectric materials combine to form two capacitances in parallel.

Q3 What is the series capacitor model?

If the materials exist as alternating bands of permittivity between the electrodes, the capacitances measured between the electrodes will be constituted from component capacitances which are effectively connected in series. In this case, the reciprocal rule for adding up capacitances in series must be used to obtain the component permittivities and concentration from the measured capacitances.

Q4 What is the composite (Maxwell) capacitance model?

If there is a combination of the two basic parallel and series material distributions, more complex relationships, such as the method described by Maxwell, must be used to define the permittivity/concentration/capacitance relationships.
FAQ7 ECT IMAGE FORMAT

Q1 What is the format of an ECT permittivity image?

The permittivity distribution of a mixture of two fluids is often displayed as a series of normalised pixels located on either a (32 x 32) or (64 x 64) square pixel grid, using an appropriate colour scale to indicate the normalised pixel permittivity as shown, for example, in the figure below. This uses a graduated blue/green/red colour scale, where pixel values corresponding to the lower permittivity material used for calibration have the value zero and are shown in blue, while pixels corresponding to the higher permittivity material have the value 1 and are shown in red. The normalised permittivity distribution corresponds to the fractional concentration distribution of the higher permittivity material.

Q2 How is a square grid used to represent a circular cross-section?

If the sensor cross-section is circular, this circular contour must be projected onto the square grid containing typically 1024 pixels. Some of the pixels will lie outside the vessel circumference and the image is therefore formed from those pixels that lie inside the vessel. A typical arrangement which is commonly used constructs the image using 812 of the available 1024 pixels.

Q3 What image resolution can be achieved using ECT?

The resolution of an ECT permittivity image is limited by the number of independent measurements that can be made and this relationship can be considered to be an example of spatial filtering, as shown in the figure below. The resolution limit is difficult to define mathematically, but a simple engineering estimate can be made by assuming that the number of independent measurements M corresponds to a similar number of discrete regions inside the sensor. If we assume that the angular resolution is equal to the number of electrodes E, then the radial resolution will equal M/E. For protocol 1 and a 12 electrode sensor, this gives a radial resolution limit of 5.5. For protocol 2 and 24 electrodes, this figure increases to 10.5.

Q4 What errors are present in ECT permittivity images?

It is not possible to obtain a unique solution for each image pixel when the number of pixels in the image exceeds the number of capacitance measurements. Furthermore, image distortion can occur because ECT is an inherently soft-field imaging method (the electric field is distorted by the material distribution inside the sensor).
Q1 What are the main problems in obtaining a permittivity image from the capacitance measurements?

The number of pixels in the image usually exceeds the number of capacitance measurements by several orders of magnitude. Unfortunately, it is not possible to obtain a unique solution for each image pixel when the number of pixels in the image exceeds the number of capacitance measurements. Furthermore, image distortion can occur because ECT is an inherently soft-field imaging method (the electric field is distorted by the material distribution inside the sensor).

Q2 How are ECT images calculated in view of the limited number of available measurements and the soft field problem?

In many cases, the contrast between the permittivities of the materials inside the sensor is small, resulting in only limited field distortion. This allows approximate linear algorithms to be used to relate the capacitance measurements to the pixel values in the image and vice-versa. However, if the field distortion is severe, more accurate non-linear algorithms must be used.

Q3 What is the most commonly used image reconstruction method?

The method which has been used with greatest success to-date is known as Linear Back Projection (LBP), and is based on the solution of a set of forward and reverse (or inverse) transforms.
**Q4 What is the forward transform?**

The forward transform is a matrix equation which relates the set of inter-electrode capacitance measurements \( C \) to the set of pixel permittivity values \( K \). This transform assumes that the measured inter-electrode capacitances resulting from any arbitrary permittivity distribution \( K \) inside the sensor will be identical to those obtained by summing the component capacitance increases which occur when each pixel has its defined permittivity, with all other pixels values set to zero. This forward transform is defined in the equation below, where bold characters represent matrices:

\[
C = S.K
\]

\( C \) is an \((M \times 1)\) dimensioned matrix containing the set of \( M \) inter-electrode pair capacitances (where \( M \) is typically 66 for a 12-electrode sensor or 28 for an 8-electrode sensor for protocol 1).

\( K \) is an \((N \times 1)\) dimensioned matrix (where \( N \) is 1024 for a 32 x 32 grid) containing the set of \( N \) pixel permittivity values which describe the permittivity distribution inside the sensor (the permittivity image).

\( S \) is the forward transform, usually known as the sensor Sensitivity Matrix. \( S \) has dimensions \((M \times N)\) and consists of \( M \) sets (or maps) of \( N \) (typically 1024) coefficients, (1 map for for each of the \( M \) capacitance-pairs), where the coefficients represent the relative change in capacitance of each capacitance pair when an identical change is made to the permittivity of each of the \( N \) (1024) pixels in turn.

**Q5 What is the inverse transform?**

In principle, once the set of inter-electrode capacitances \( C \) have been measured, the permittivity distribution \( K \) can be obtained from these measurements using an inverse transform \( Q \) as follows:

\[
K = Q.C
\]

\( Q \) is a matrix with dimensions \((N \times M)\) and, in principle, is simply the inverse of the matrix \( S \).

**Q6 So what is the problem in finding a suitable inverse transform?**

It is only possible to find the true inverse of a square matrix (where \( M = N \)). In physical terms, this is confirmation that it is not possible to obtain the individual values of a large number of pixels (eg 1024) from a smaller number of capacitance measurements (eg 66). As an exact inverse matrix does not exist, an approximate matrix must be used. The LBP algorithm uses the transpose of the sensitivity matrix, \( S' \) which has the required dimensions \((N \times M)\).
Q7 What is the justification for using the transpose of the sensitivity matrix as the inverse transform in the LBP algorithm?

Although we have no means of knowing which pixels have contributed to the capacitance measured between any specific electrode-pair, we know from the sensitivity matrix $S$ that certain pixels have more effect than others on this capacitance. Consequently, we allocate component values to each pixel proportional to the product of the electrode-pair capacitance and the pixel sensitivity coefficient for this electrode-pair. This process is repeated for each electrode-pair capacitance in turn and the component values obtained for each pixel are summed for the complete range of electrode-pairs.

Q8 What are the characteristics of the LBP algorithm?

The LBP algorithm produces approximate, but very blurred permittivity images. The LBP algorithm acts as a spatial filter with a lower cut-off frequency than that of the fundamental filter and consequently produces sub-optimal images from a given set of input data.

Q9 How is the sensor sensitivity matrix obtained?

The forward transform (sensitivity matrix) must be calculated (or measured) for each individual sensor as a separate exercise prior to using the sensor with an ECT system. One method for calculating the sensitivity coefficient $S$ of a pixel for an electrode-pair $(i,j)$ is based on the use of the equation below.

$$S = E_i \cdot E_j \cdot dA$$

where $E_i$ is the electric field inside the sensor when one electrode of the pair $i$ is excited as a source electrode, $E_j$ is the electric field when electrode $j$ is excited as a source electrode and the dot product of the two electric field vectors $E_i$ and $E_j$ is integrated over the area $A$ of the pixel.

For a sensor with internal electrodes, the components of capacitance due to the electric field inside the sensor will always increase in proportion to the material permittivity when the sensor is filled uniformly with higher permittivity material. However for sensors with external electrodes, the permittivity of the wall causes non-linear changes in capacitance, which may increase or decrease depending on the wall thickness and the permittivities of the sensor wall and contents.
FAQ9 ADVANCED IMAGE RECONSTRUCTION METHODS

Q1 Is it possible to obtain better images than those obtained using the LBP algorithm?

It is possible to improve the image resolution and accuracy to values much closer to the theoretical limit by the use of iterative techniques. The idea is to use the forward and inverse transforms alternately to progressively correct the pixel values, and is based on the assumption that the forward transform is reasonably accurate if the field distortion is low but that the inverse transform may be very inaccurate. This technique is conceptually similar to the practice of correcting the distortion of an imperfect amplifier by the use of negative feedback.

Q2 How does the iterative method work?

The iterative method operates as follows:

The set of capacitances C1 for one image frame are measured and a set of initial pixel values K1 are calculated using (the inaccurate) forward transform. These approximate permittivity values K1 are then used to back-calculate a set of capacitances C2 using the (relatively accurate) inverse transform. A set of error capacitances dC = (C2 - C1) are calculated and used to generate a set of error permittivities dK using equation the inverse transform. These error permittivities are then used to correct the previous set of permittivities to generate a new set of pixel values K2, where K2 = (K1 - dK). These new permittivities K2 are then used to calculate a new set of capacitances C2 and the sequence is iterated until the permittivity values converge to the correct solution.

A number of additional steps are possible, including truncating the image pixels to lie within the known calibration range at each iteration and applying gain and truncation factors to the error capacitances. However, it is important to check that the permittivity values converge in order to ensure a valid solution. Experience shows that this method can produce images of good resolution, close to the theoretical maximum achievable with a given measurement protocol and number of electrodes.

Q3 Can improved images be obtained without resorting to iterative methods?

Although the iterative method produces good images, it cannot be used on-line because of the time taken to carry out the relatively large number of iterations required to produce the image. It is possible to develop better inverse transforms for Q by using more advanced mathematical concepts for deriving approximate inverses of matrices. Two examples are methods developed by Landweber and Tikhonov.
Q4 What is Landweber's method?

In Landweber's method, the inverse transform $Q$ is given by the equation:

$$QL = V \cdot F(W, t, R) \cdot U'$$

where: $V$, $W$ and $U$ are the matrices obtained by applying the Single Value Decomposition (SVD) process to the sensitivity matrix $S$, $F$ is the SVD filter function matrix, $U'$ is the transpose of $U$ and

$$f = \frac{(1 - (1 - w)R)}{w}$$

where: $f$ is one element of the filter matrix $F$, $w$ is one element of the diagonal matrix $W$, $L$ is the Landweber transform parameter and $R$ is the number of iterations.

Q5 What is Tikhonov's method?

In Tikhonov's method, the inverse transform $Q$ is given by the equation:

$$QT = S' \cdot (S \cdot S' + t \cdot I)^{-1}$$

where: $S$ is the sensitivity matrix, $S'$ is the transpose sensitivity matrix, $t$ is the Tikhonov transform factor, and $I$ is the identity matrix.

Q6 What is the effect of using Landweber's method?

Some insight into the mechanism of operation can be seen from the figure below which shows the Landweber transform plotted as an equivalent set of primary sensitivity maps. By comparing these transforms with the figure shown in response to FAQ8 Q11 it is clear that the Landweber transforms have far more structure. Consequently, they produce more detailed images from the same capacitance data, as shown in the second figure below. However, they also produce some spurious artefacts in the image. These can be reduced, while further improving the image, by carrying out a small number of iterations using the appropriate inverse transform in place of the transpose sensitivity matrix, as the third figure below, obtained after only 5 iterations, illustrates. The attraction of these techniques is that they are fast enough for use on-line.

Q10 What are sensitivity maps?

The set of sensitivity coefficients for each electrode-pair is known as the sensitivity map for that pair.
Q11 How are sensitivity maps calculated?

For circular sensors with either internal or external electrodes, it is possible to derive an analytical expression for the electric fields and in this case, the sensitivity coefficients (and also the electrode capacitances) can be calculated accurately. For more complex geometries, numerical methods can be used to calculate the sensitivity coefficients. It is normally only necessary to calculate a few primary sensitivity maps for the unique geometrical electrode pairings, as all of the other maps can be derived from these by reflection or rotation.