PROCESS TOMOGRAPHY Ltd.

ELECTRICAL CAPACITANCE TOMOGRAPHY SYSTEM

TYPE PTL300E

OPERATING MANUAL

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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.

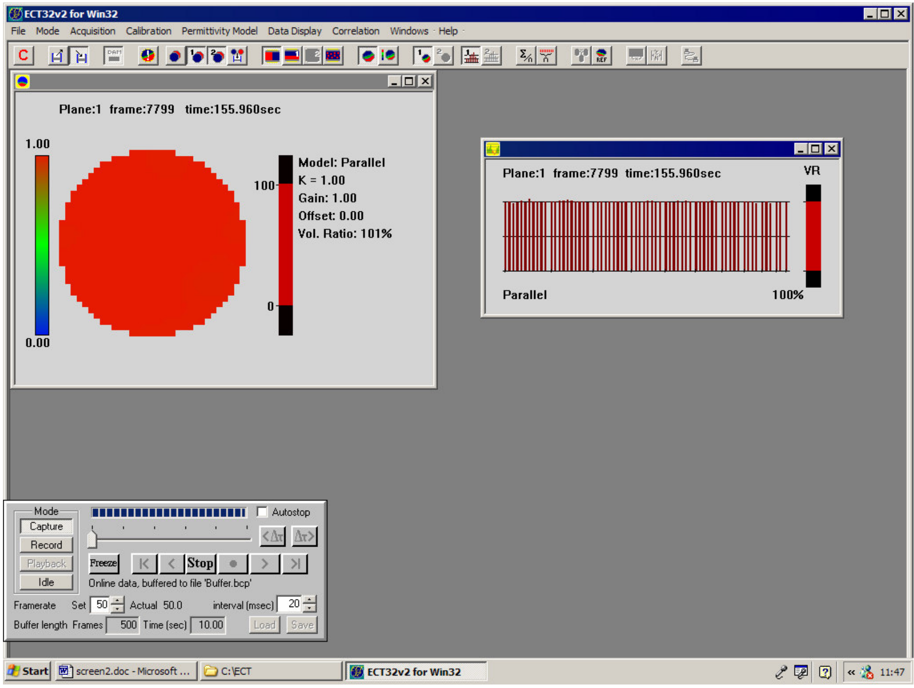


Figure 18.1.1 ECT32v2 Desktop window

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 c**ontrol 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 con**structed using a number of different **physical sensor models. Capacitance d**ata 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.

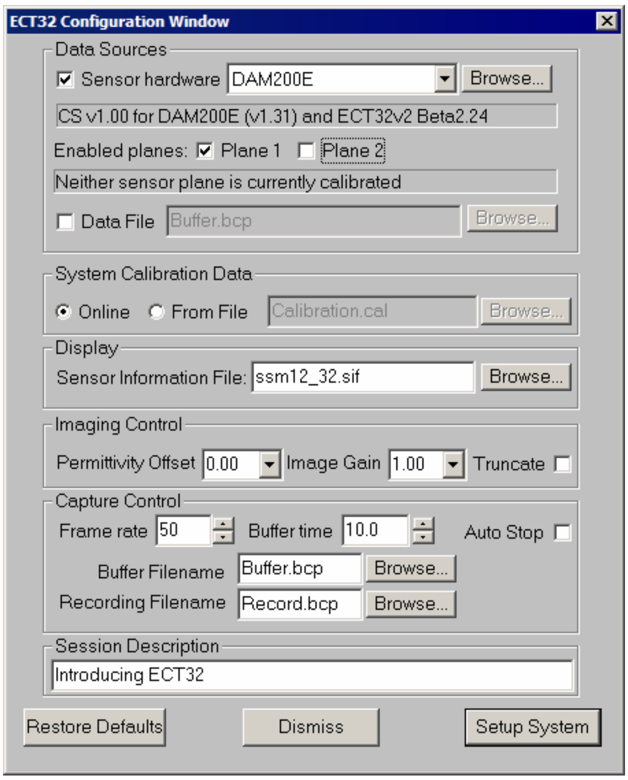


Figure 18.2.1 ECT32v2 Configuration window

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 configuratio**n.
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.

18.4 SYSTEM CALIBRATION (*Calibration menu*)

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**.

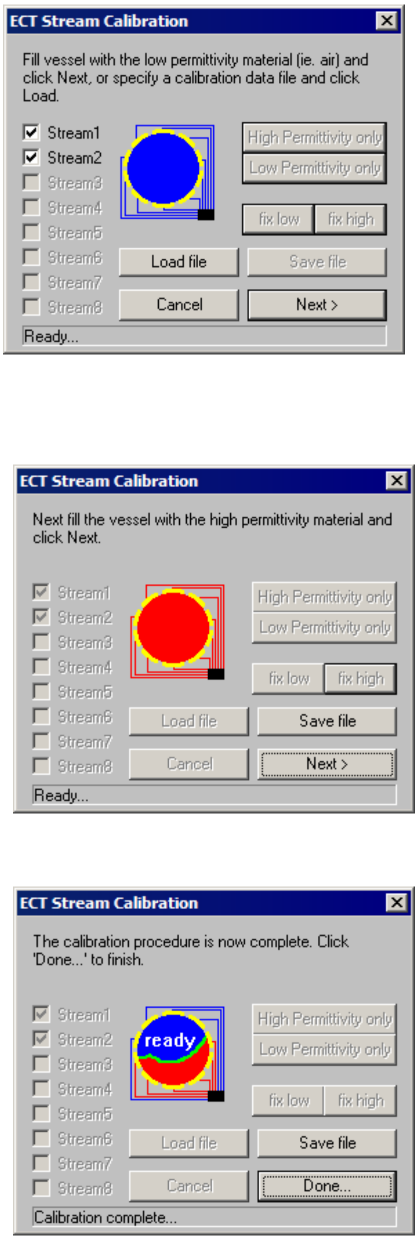


Figure 18.4.1 Calibration Windows

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**.**

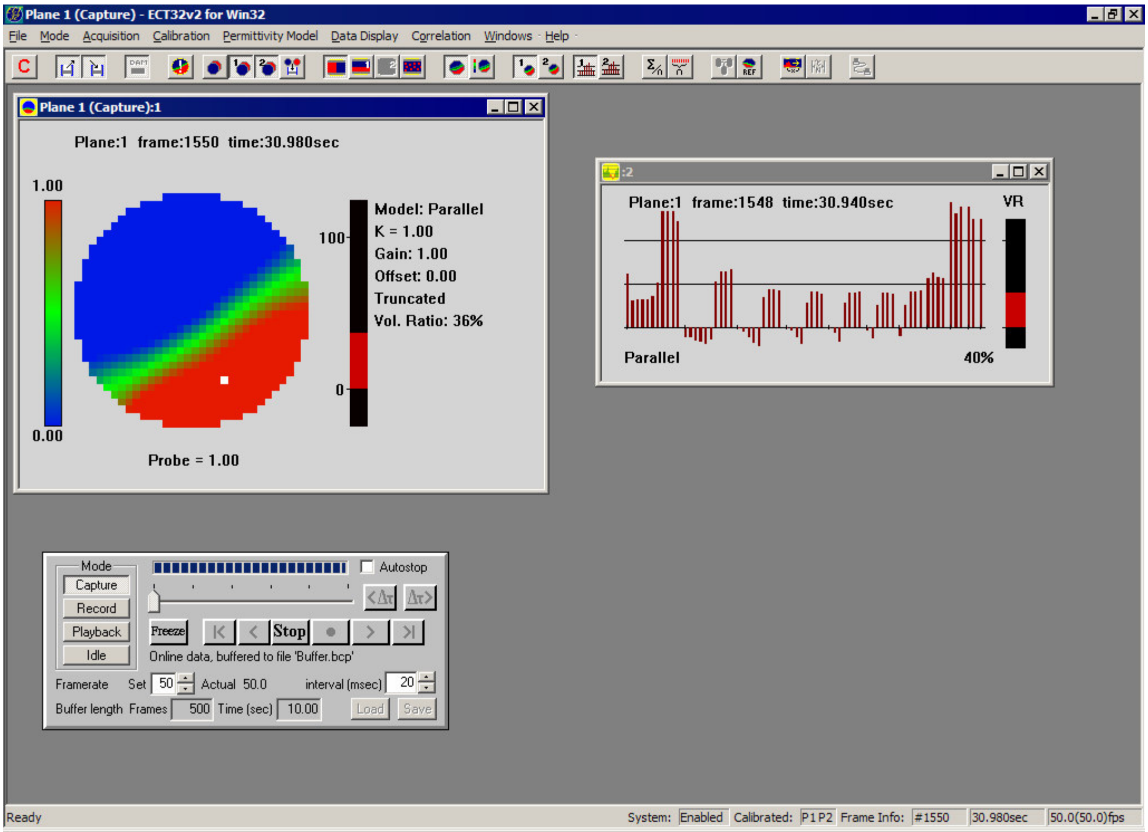


Figure 18.5.1 ECTv2 Desktop window

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

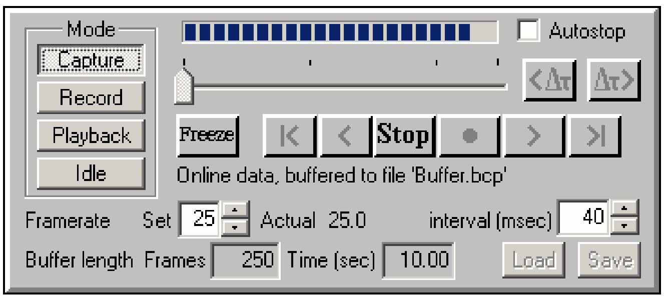


Figure 18.5.2 Control Panel window

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 diferent 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.

18.9 DETAILED FUNCTIONALITY

This completes the **brief overview of the ECT32v2 software**. The detailed functionality of the component parts of the software is described in the following chapters.

19. Configuration window
20. ECT32v2 Desktop window
21. System calibration
22. Operation in capture mode
23. Permittivity image and display formats
24. Permittivity models
25. Operation in Record mode
26. Operation in Playback mode
27. Correlation and Reference frame options
28. Data file conversion
29. Advanced features, including triggered operation
30. Data Export on-line
31. File conversion utility.

The use of the **ECT32v2 software in Playback mode** only is also described in detail in the separate **ECT32v2 Software User Guide** supplied.

19. THE CONFIGURATION WINDOW

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**).

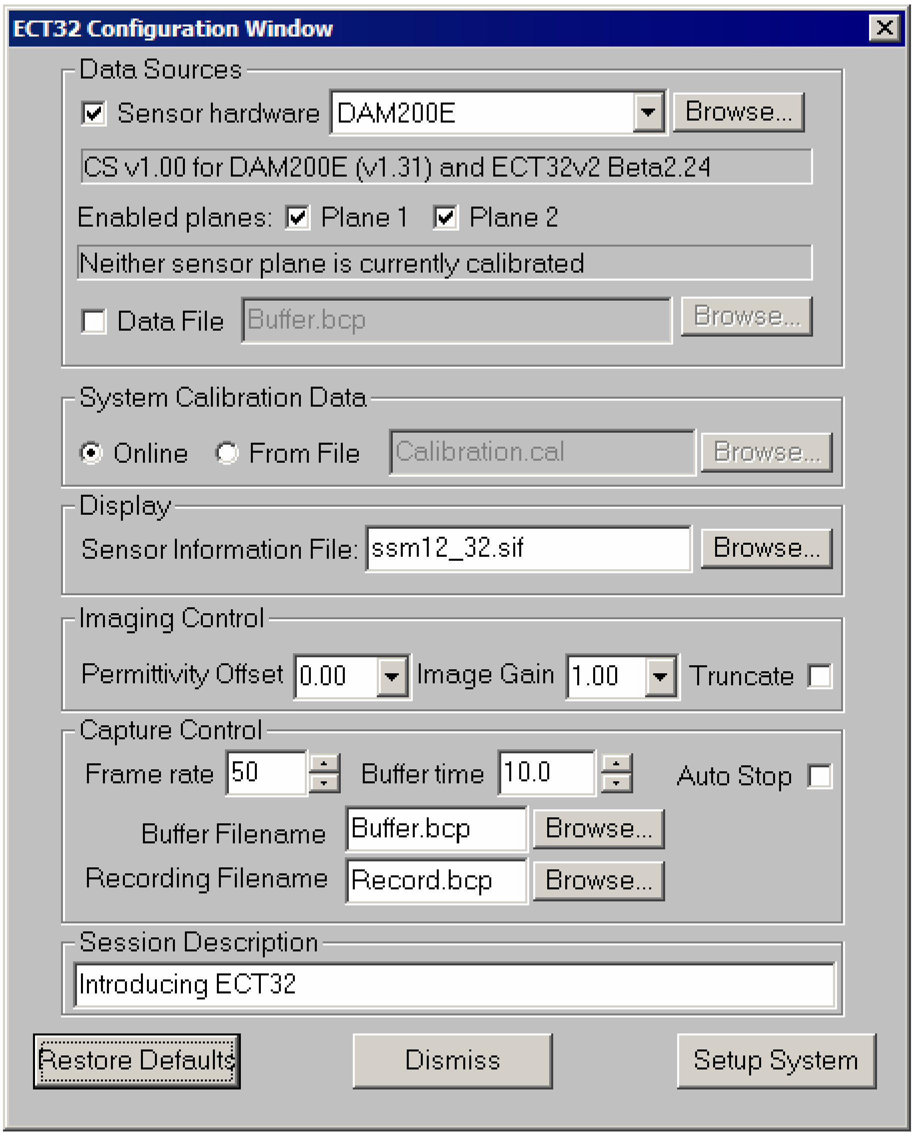


Figure 19.1.1 Configuration Window

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 **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_32.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**.

20. 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**.**

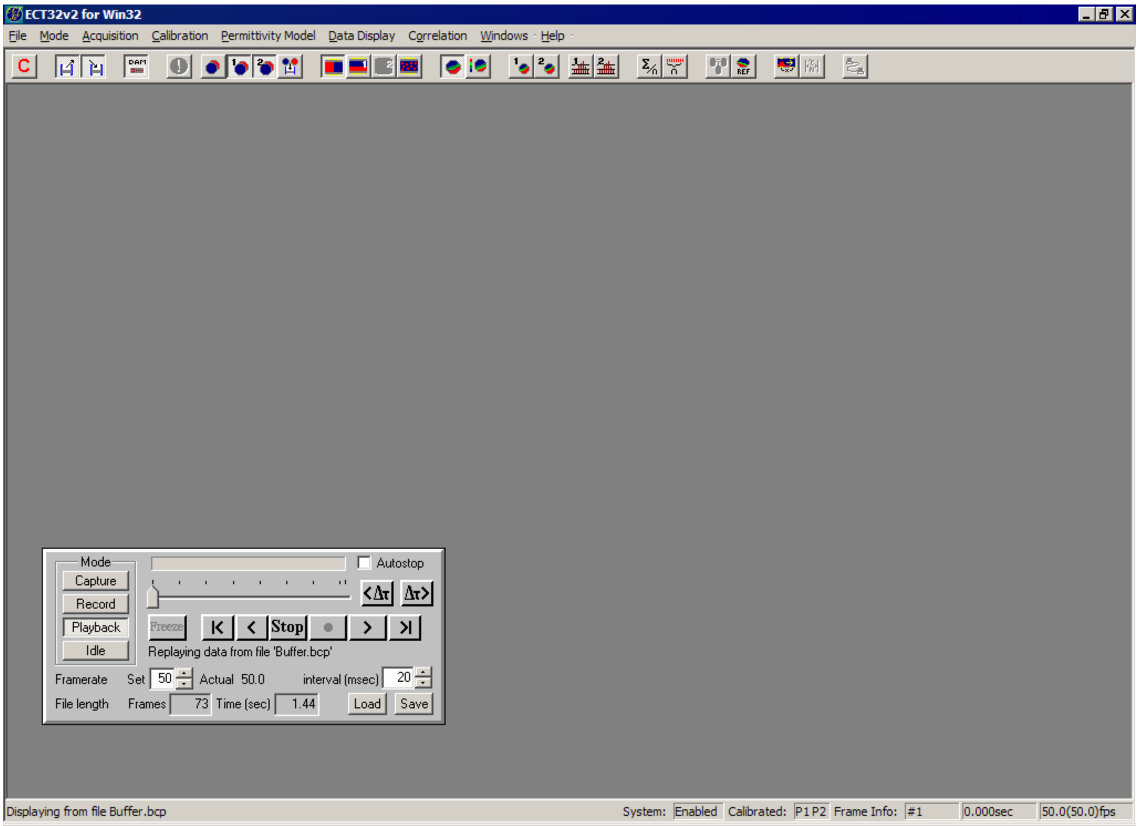


Figure 20.1.1 Empty Desktop window

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

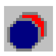
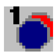
The **menu headings** on the **menu bar** control the major functionality of the **ECT32v2** software Most of the **Control menu** functions can be implemented by alternative means, either by the use of **tool buttons,** represented by **icons on** the **toolbar**, or by **function** buttons on the **control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

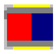
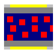
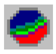
Section 20.1.1 lists the **menu** and **sub-menu headings** and gives details of any **alternative means** of implementing these menu functions by the use of the **Toolbar**, **Control panel** or **Configuration** window.

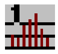
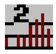
Details of those menu functions which have **alternative means of implementation** are given in subsequent chapters of this manual under the appropriate headings for the alternative controls.

Details of the non-duplicated menu functions are also given in subsequent chapters.

20.1.1 Main Control menu functions and alternative implementation.

Main Menu	**Sub-menu**	**Alternative implementation** (Numbers refer to toolbar **icons**)
File	Load Recorded Data	2 
	Set Recorded Data filename	3 
	Set Capture Mode Buffer Filename	Configuration window
	Save As...	Control Panel save button
	Set Session Description	Configuration window
	Generate Ascii Data Files...	None
	Data streaming Network Connection	26 
	Exit	None
Mode	Configure System	1 
	Capture Mode	Control Panel Capture button
	Record Mode	Control Panel Record button
	Playback Mode	Control Panel Playback button
	Idle Mode	Control Panel Idle button
Acquisition	Enable/Disable Measurement System	4 
	Select Sensor Planes	None
	DAM200E Timing Parameters	None
Calibration		
	Reset Baseline and Measurement freq.	5 
	Calibrate Online (selected planes)	6 
	Calibrate Plane 1 only	7 
	Calibrate Plane 2 only	8 
	Load Calibration File	Calibration window Load File
	Save Calibration File	Calibration window Save File

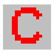
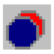
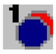
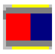
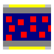
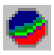
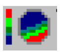
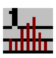
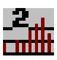
Main Menu	Sub-menu	Alternative implementation (Numbers refer to toolbar **icon**s)
Permittivity Model		
	Parallel model	10 
	Series Model	11 
	Series 2 Model	12  (Not in use)
	Maxwell Model	13 
	Set Permittivity Ratio (K)	None
Data Display		
	Enable iterative image reconstruction	13(a) 
	Load Sensor Information File	14 
	Sensor Information File details	None
	Image Display Parameters	Configuration window
	Normal Image Display	None
	Quadrant Image Display	None
	Enable Continuous Averaging	20 
	Continuous Averaging Controls	21 
Correlation		
	Enable/Disable Correlation	24 
	Sensor Spacing	None
	Correlation Controls	25 
	Enable Reference Frame	22 
	Reference Frame Controls	23 

Main Menu	Sub-menu	Alternative implementation (Numbers refer to toolbar **icon**s)	
Windows	Display Plane 1 Permittivity Image	16	
	Display Plane 2 Permittivity Image	17	
	Display Plane 1 Capacitances	18	
	Display Plane 2 Capacitances	19	
	Tile Windows	None	
Help	About ECT32v2 for Windows List of active windows	None	

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

	Icon	**Function**
1.		Displays the Configuration Window
2.		Loads recorded data file
3.		Sets recorded data file name
4.		Seects data capture subsystem hardware DLL
5.		Resets Baseline and measurement frequency
6.		Calibrates sensor (selected planes)
7.		Calibrates sensor (plane 1 only)
8.		Calibrates sensor (plane 2 only
9.		Saves calibration data to file
10.		Selects parallel permittivity model (default setting)
11.		Selects series permittivity model 1 (requires permittivity ratio)
12.		Selects series permittivity model 2 (no permittivity ratio required)
13.		Selects Maxwell permittivity model
13(a)		Enable/disable iterative image reconstruction
14.		Loads sensor information file (sensitivity map etc.)
15.		Modifies image display parameters (Gain, offset, truncation, inversion, iteration)
16.		Selects and displays plane 1 permittivity image
17.		Selects and displays plane 2 permittivity image
18.		Selects and displays plane 1 normalised capacitances
19.		Selects and displays plane 2 normalised capacitances
20.		Enables Continuous Averaging
21.		Accesses Averaging Controls

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

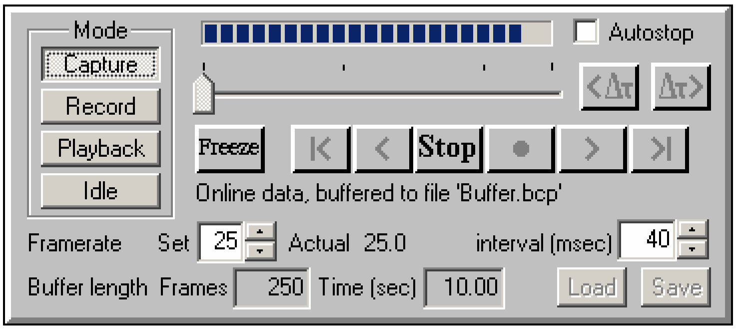


Figure 20.4.1 Control Panel window

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 thefore 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.
[Δτ>]	**button**.	Increment one frame
[<Δτ]	**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.**

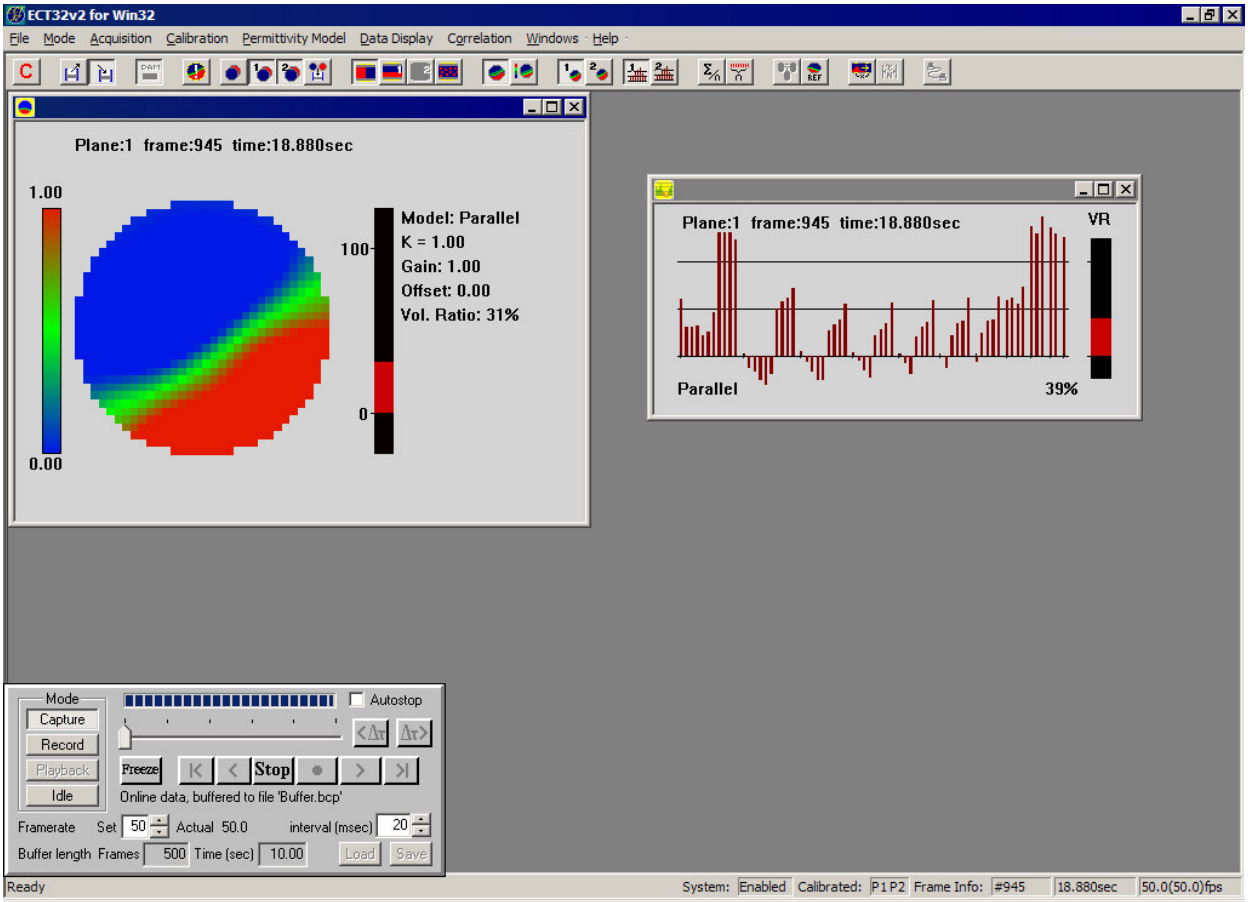


Figure 20.6.1 Single plane image .

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 PCECT, 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.**

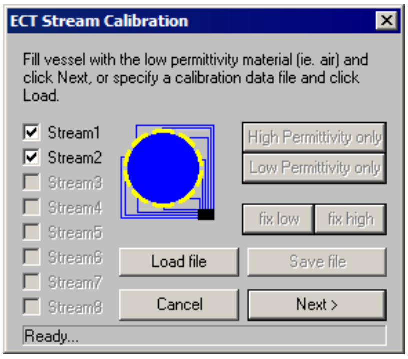


Figure 21.1.1 Initial Calibration window (low permittivity)

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.**

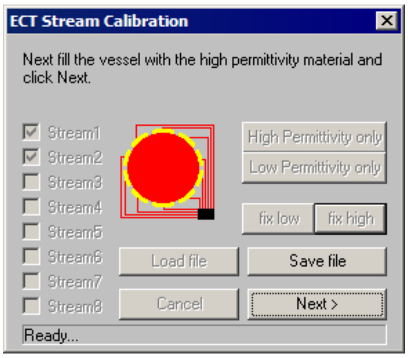


Figure 21.1.2 Second Calibration window (high permittivity)

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.**

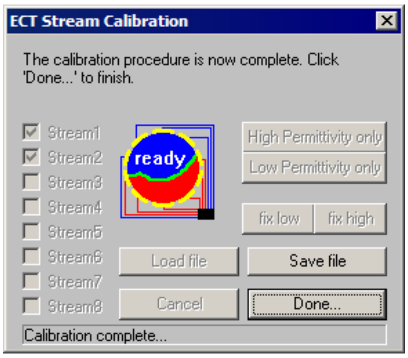


Figure 21.1.3 Final Calibration Window (Save calibration data)

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** (**icon**s **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.

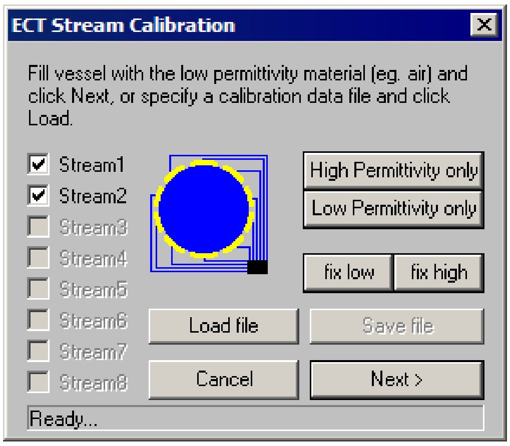


Figure 21.6.1 High/low level re-calibration window

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 the **Low Permittivity Only** button. After a short pause, followed by a beep, the screen changes to that shown in **figure 21.6.2.**

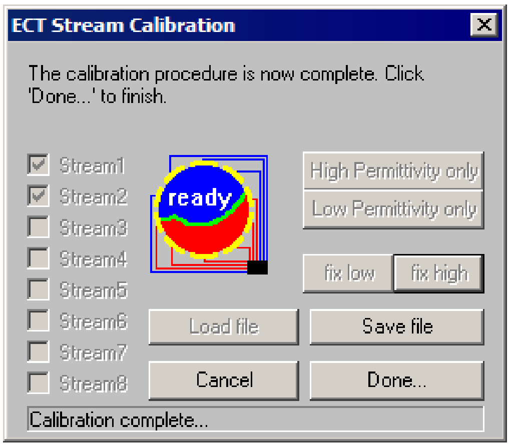


Figure 21.6.2 Final calibration window

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 caries 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** (**icon**s **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 caries 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 reseting 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 **chapters 19 and 21** to allow the **ECT32v2 Desktop** window to show a **permittivity image**.

22.1 CAPTURE MODE OPERATION (*Mode menu, Capture mode*)

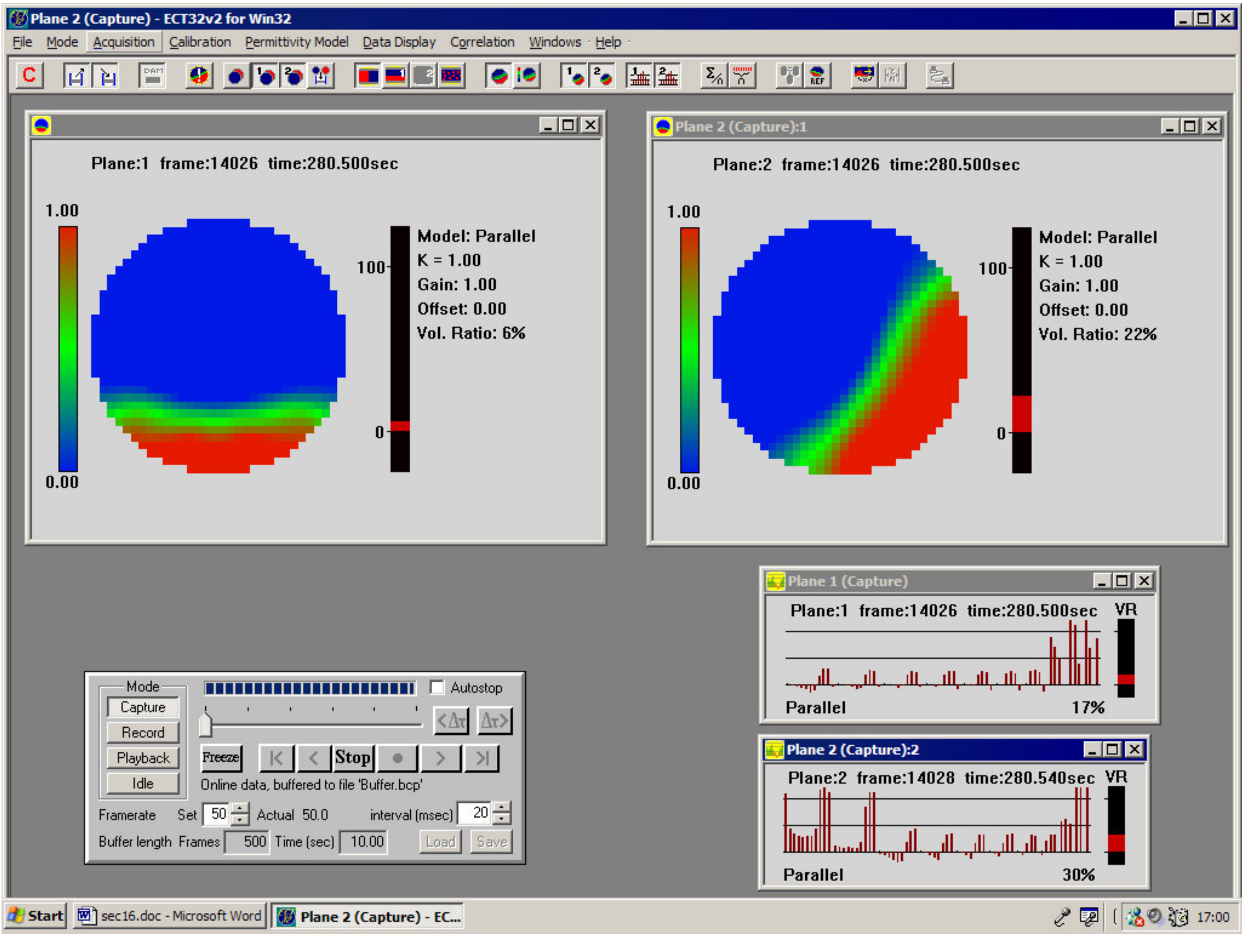


Figure 22.1.1 ECT Desktop in Capture Mode

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 mannner 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 avaliable:

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.**

.

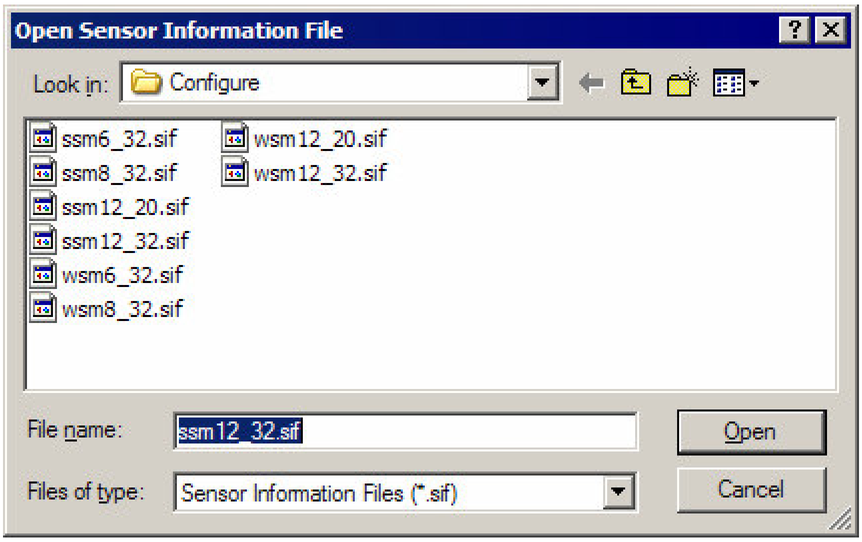


Figure 23.2.1 Open sensor information file window

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

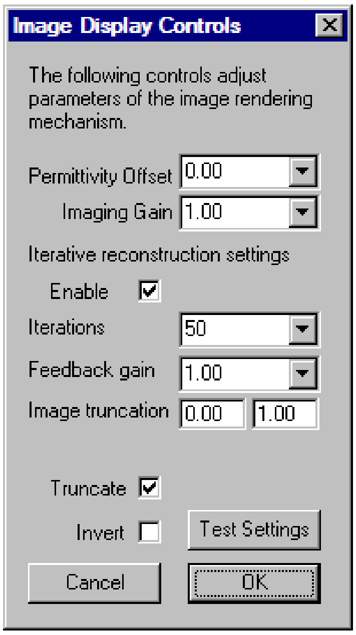


Figure 23.2.2 Image Display Controls window

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.

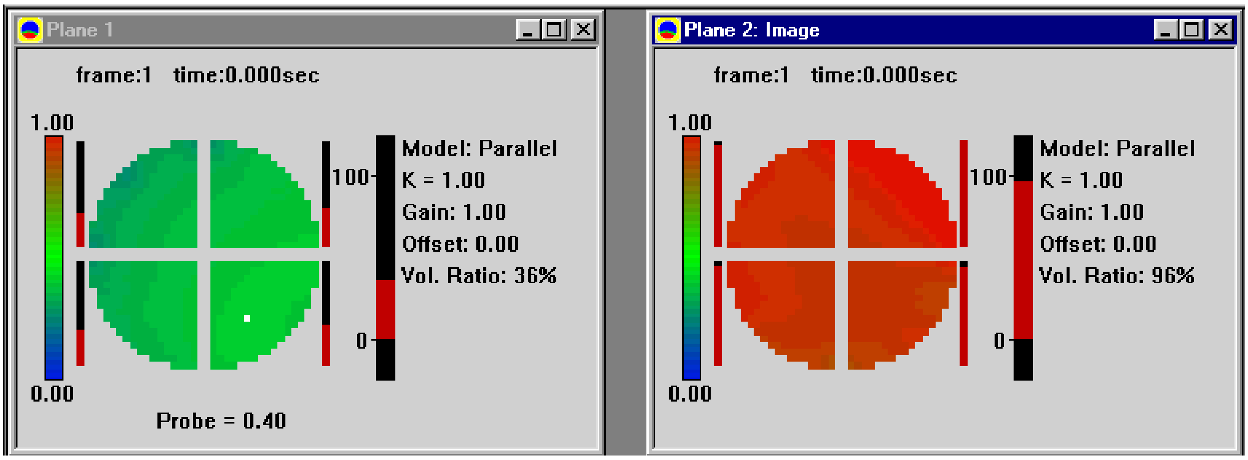


Figure 23.2.3 Quadrant image display window

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)*

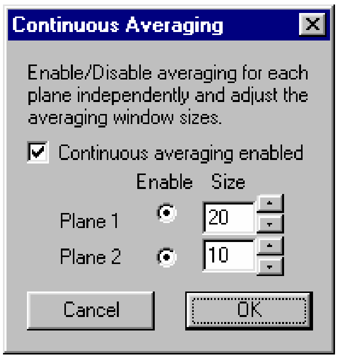


Figure 23.2.4 Continuous Averaging window

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.

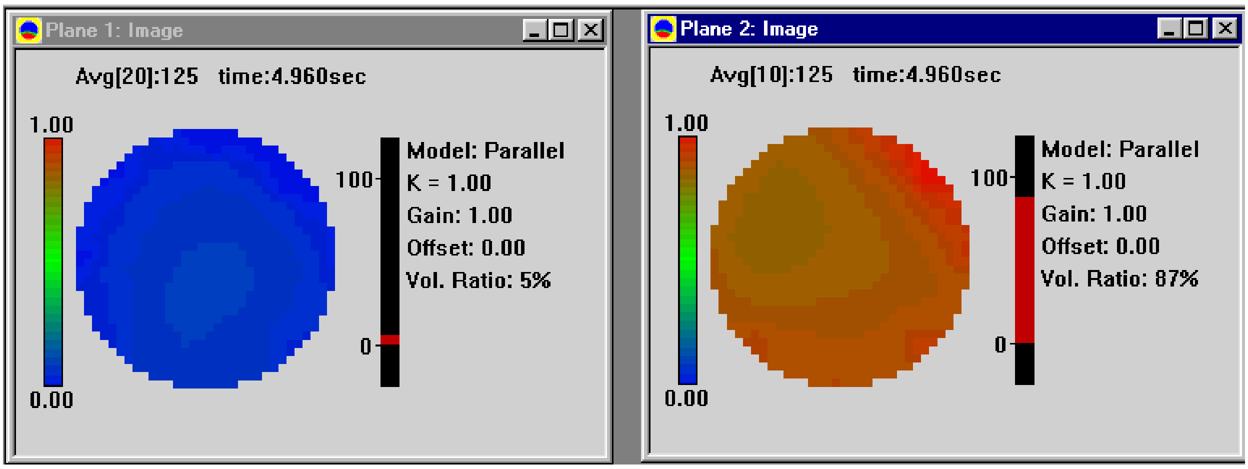


Figure 23.2.5 Permittivity Images in continuous averaging mode

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 **icon**s **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.**

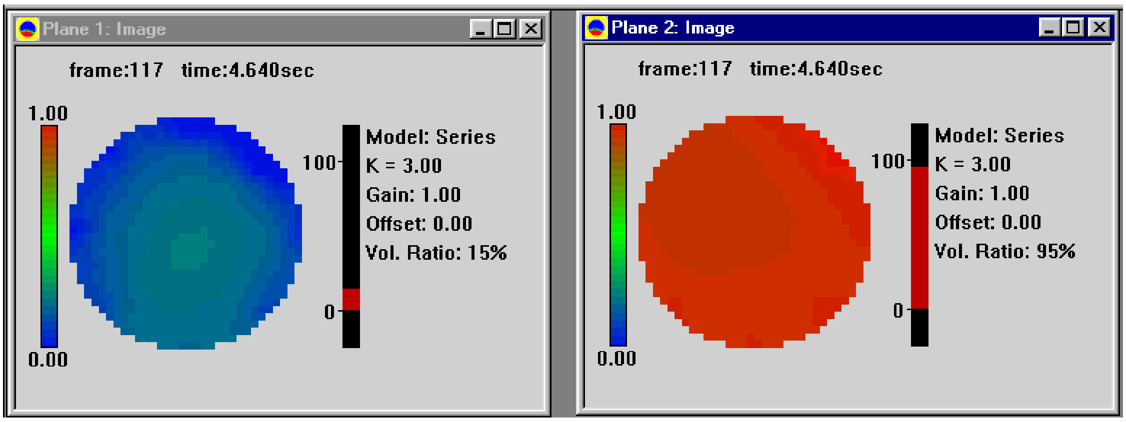


Figure 24.2.1 Permittivity image display window using series 1 model

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 **Permittivity 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 (*Permittivity 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 **Permittivity model** menu.

24.5 SET PERMITTIVITY RATIO (K) (*Permittivity 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.

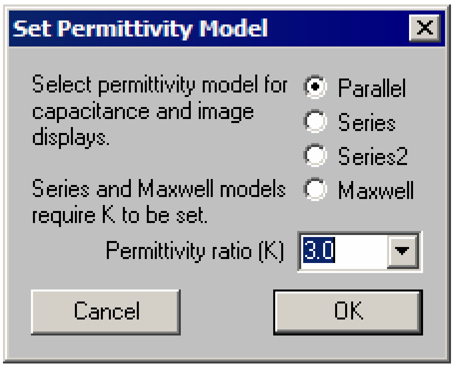


Figure 24.5.1 Set Permittivity Model window

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 **t**hese set the **displayed image** to the **last** and **first** captured **frames** respectively.

4. Click the **increment one frame** button [**Δτ>**]. The image will advance to the next frame. Similarly, click the **decrement one frame** button [**<Δτ**]. The image will change to the previous frame.

26.2 PLAYBACK OF PREVIOUSLY RECORDED DATA

Data can be played back from a previously recored 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 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**.

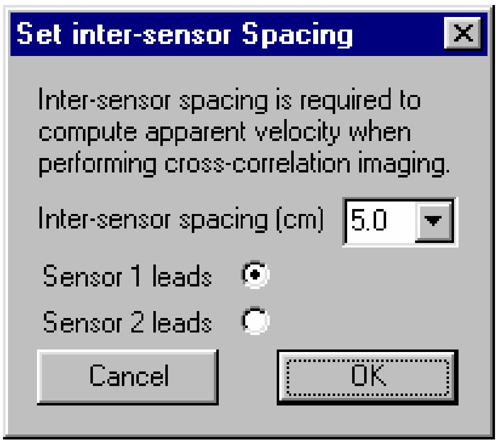


Figure 27.1.1 Set inter-plane spacing window

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.

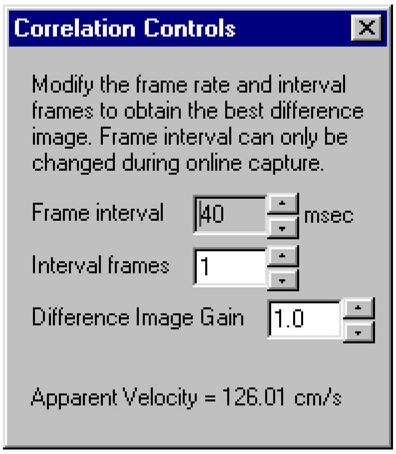


Figure 27.1.2 Correlation control window

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 diplayed 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.

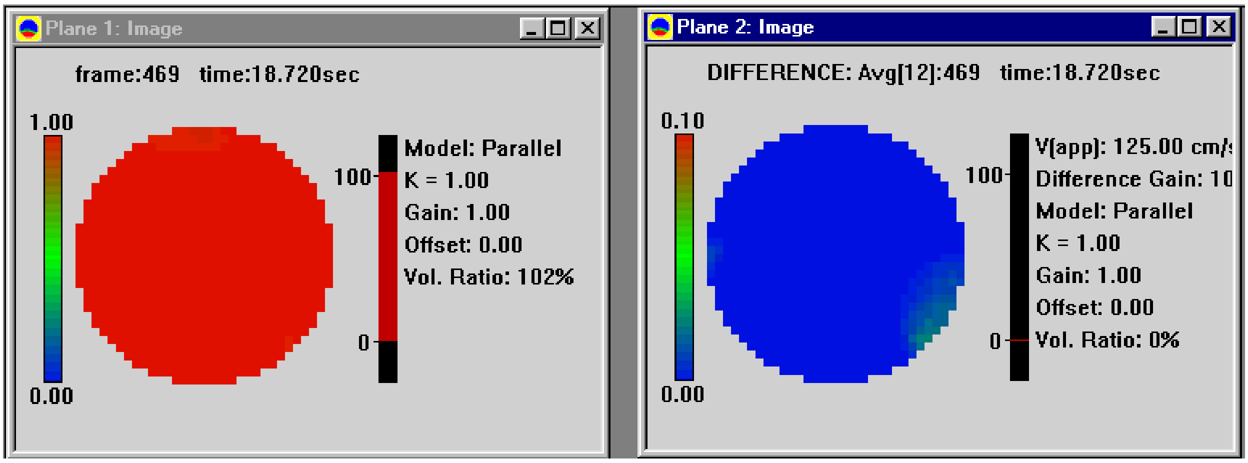


Figure 27.1.3 Image Display with correlation and averaging enabled

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**

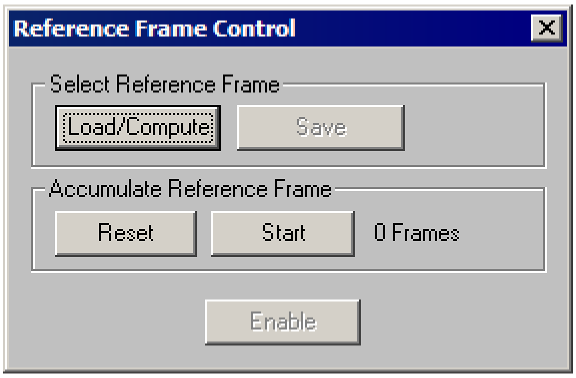


Figure 27.2.1 Reference frame control window

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**.

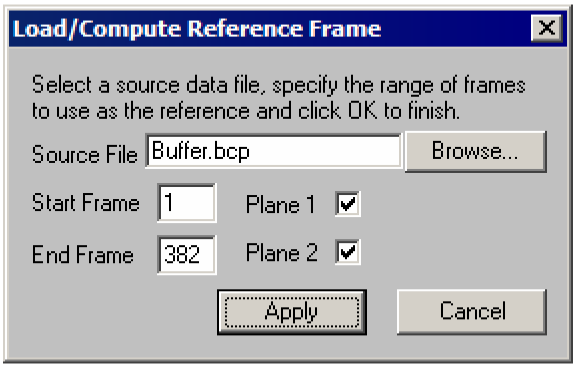


Figure 27.2.2 Load/compute reference frame window

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.

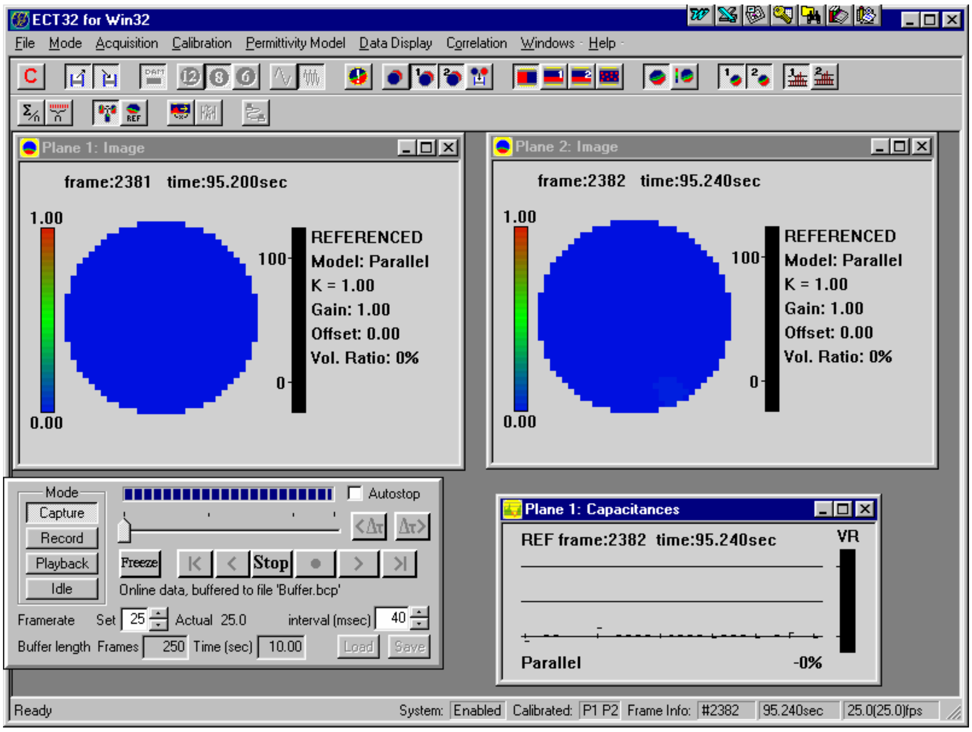


Figure 27.2.3 Image display with Reference Frame enabled

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*)

Capacitance and **image** data can be saved and retrieved in a number of diferent formats.

When primary capacitance measurement data is captured to file, it is stored by default in **binary** format as **normalised inter-electrode capacitances.** This format is used to minimise the size of the stored data files.

However, facilties are provided to convert these **capacitance data files in binary format** (**.bcp files**) into a number of **different data types** (including **normalised** and **absolute capacitances**, **image files** and **voidage files)** 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 1**.

The method for generating these data files is decribed in the following sections. In each case, it is assumed that data has been captured and stored to a suitable 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.**

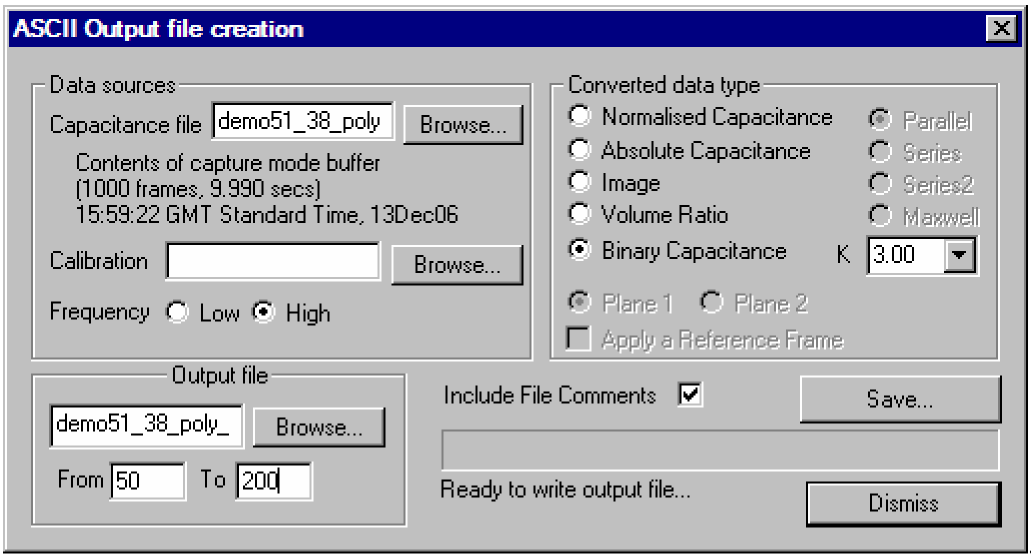


Figure 28.2.1. ASCII output file creation window

28.2.1 Normalised capacitance data files

1. In the **Data sources** parameter group, locate the required **capacitance data file** to be converted in the **Capacitance File** box using the **Browse** button.

2. In the **Output file** parameter group, use the **Browse button** to select a folder for the **output file** which is to contain the **normalised capacitance** data and then click on **Save** without entering a file name. An output file with the same name as the input data file, but with a new file extension will be generated automatically. Also select the **range of capacitance frames to be converted** in the **From** and **to boxes.**

3. In the **Converted data type** list, select **Normalised Capacitance** and also select the **measurement plane(s)** for which the data is to be converted.

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 **Dismiss** button.

5. The data file will be saved in the specified 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 sources** parameter group, locate the required **capacitance data file** to be converted in the **Capacitance File** box using the **Browse** button and also 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, use the **Browse button** to select a folder for the **output file** which is to contain the **absolute capacitance** data and then click on **Save** without entering a file name. An output file with the same name as the input data file, but with a new file extension will be generated automatically. Also select the **range of capacitance frames to be converted** in the **From** and **to boxes.**

3. In the **Converted data type** list, select **Absolute Capacitance** and also select the **measurement plane(s)** for which the data is to be converted.

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 **Dismiss** button.

5. The data file will be saved in the specified 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 sources** parameter group, locate the required **capacitance data file** to be converted in the **Capacitance File** box using the **Browse** button.

2. In the **Output file** parameter group, use the **Browse button** to select a folder for the **output file** which is to contain the **image** data and then click on **Save** without entering a file name. An output file with the same name as the input data file, but with a new file extension will be generated automatically. Also select the **range of capacitance frames to be converted** in the **From** and **to boxes.**

3. In the **Converted data type** list, select **Image** and also select the **measurement plane(s)** for which the data is to be converted.

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 **Dismiss** button.

6. The data file will be saved in the specified 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 sources** parameter group, locate the required **capacitance data file** to be converted in the **Capacitance File** box using the **Browse** button.

2. In the **Output file** parameter group, use the **Browse button** to select a folder for the **output file** which is to contain the **Volume Ratio** data and then click on **Save** without entering a file name. An output file with the same name as the input data file, but with a new file extension will be generated automatically. Also select the **range of capacitance frames to be converted** in the **From** and **to boxes.**

3.In the **Converted data type** list, select **Volume Ratio** and also select the **measurement plane(s)** for which the data is to be converted.

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 specified folder and can be viewed with a suitable word-processor such as Microsoft Word. A typical converted data file is shown in **Appendix 3.**

28.2.5 Modified Binary Capacitance Files

By selecting the **Binary Capacitance file** option and the **range of frame numbers** required in the **output file**, a new smaller data file can be generated. This option allows part of a large data file to be saved to a new file name.

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**

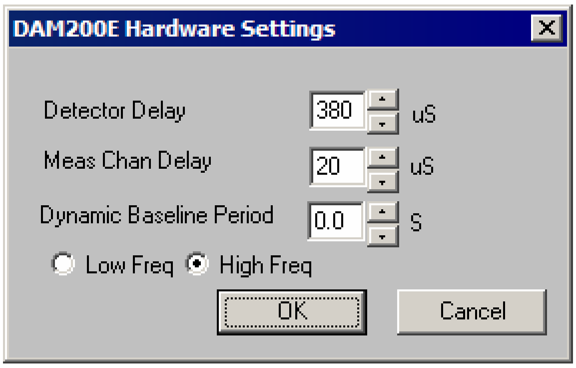


Figure 29.1.1 DAM200E timing parameters window

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.**

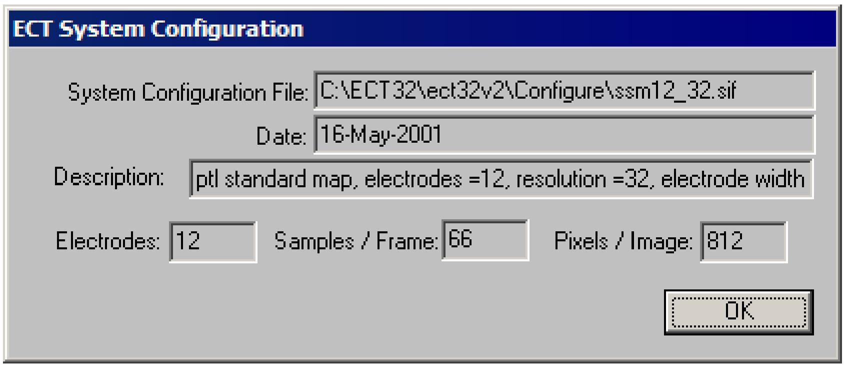


Figure 29.2.1 Sensor information file details window

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:

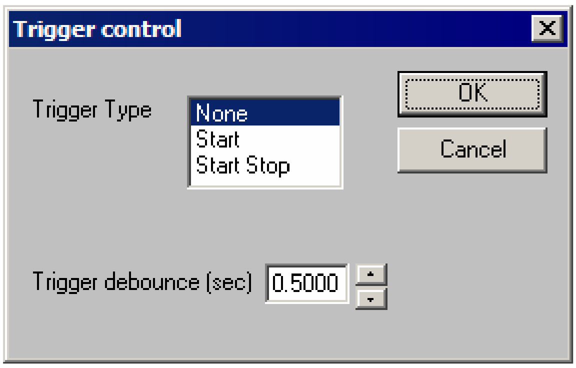


Figure 29.3.1 Trigger Control window

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.

In both cases, the **Stop button** on the **Control Panel** must be clicked at the **end of each triggered data capture operation**, otherwise the **control software** will latch up and cease to function in **trigger mode**. If this occurs, select the default **(none**) trigger mode in the **Trigger Control window** and carry out **data capture** in this mode. The normal triggering functionality will then be reactivated.

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 restrt 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 whern 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).

29.4 SENSOR C/K CORRECTION OPTION

29.4.1 Overview

A new option has been added to the **Permittivity Model sub-menu** which allows any **non-linearities** in the relationship between the **sensor inter-electrode capacitances (C)** and the **permittivity (K)** of the material inside the sensor to be corrected. A **valid correction (.ckp) file** for the sensor must be available to implement this option. A sample correction file, suitable for use with PTL demonstration ECT sensors, has been included with the **sample data files** supplied with the **ECT32 software**.

C/K linearity correction (.ckp) files can be generated using the **Recal** software (version 1.13 and later), as described in **Appendix 8 (volume 3)** of the **PTL300E Operation Manual**.

The use of linearity correction is illustrated in **figures 29.4.1** And **2** below. Figure 2 shows the image of a 12-electrode demonstration sensor filled with polypropylene beads (K=1.6) using a sensor calibration file for a sensor filled with glass beads (K=3). Note that the permittivity image is not uniform because of the non-linearity in the sensor **capacitance/permittivity** characteristics.

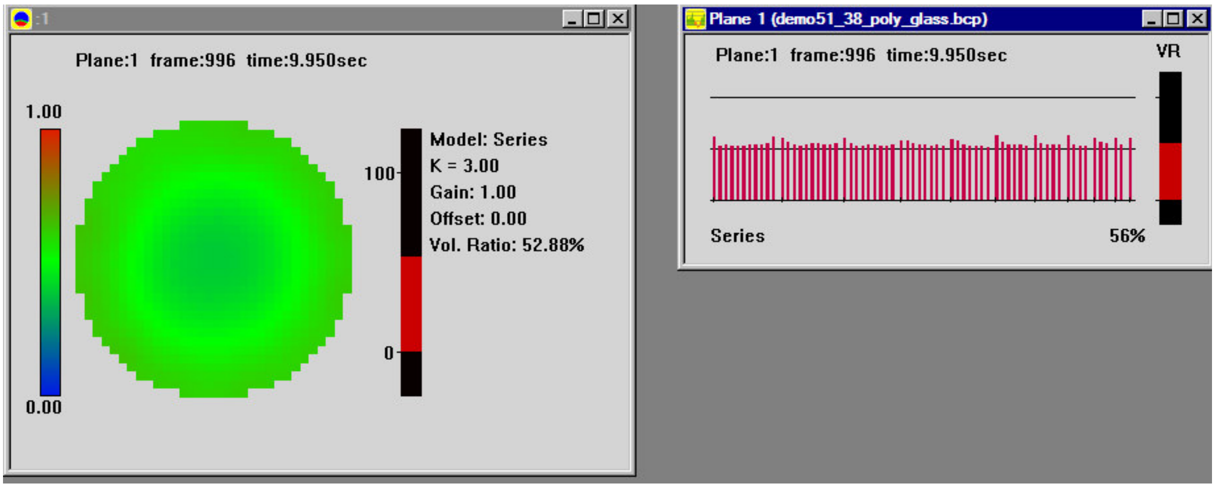


Figure 29.4.1. Without linearisation

Figure 3 shows the same data but this time with the sensor linearised using the C/K file. As well as producing a more uniform image, the calculated overall concentration (vol. ratio) has increased by almost 1%.

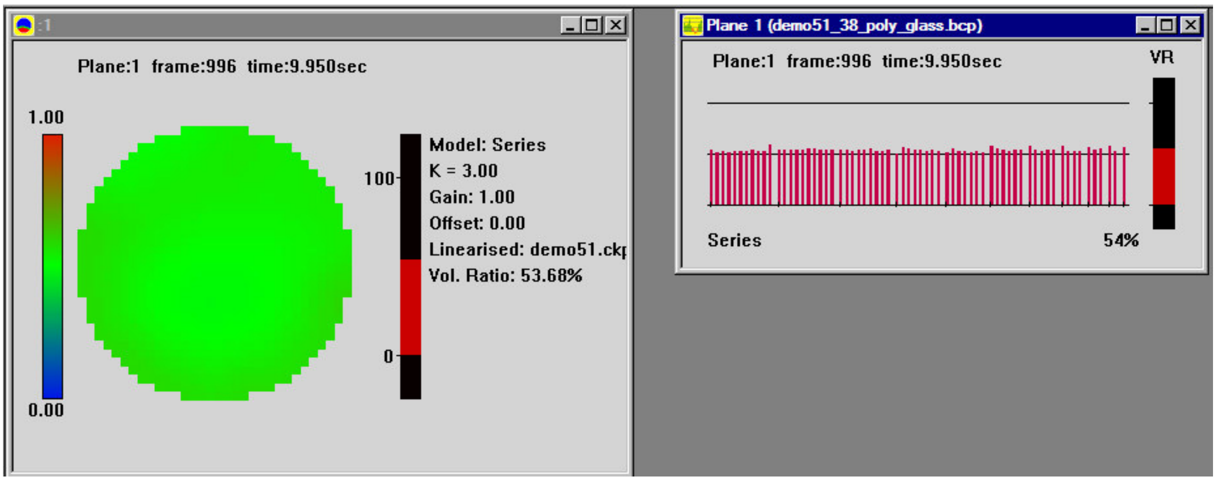


Figure 29.4.2. With linearisation

29.4.2 To implement linearisation

The linearisation process is implemented as follows:

1. Select ***Permittivity Model > Load Linearisation file*** and select the required file. The sample file **demo51.ckp**, for use with PTL demonstration ECT sensors. is located in the **c:\ect32v2\datafiles\examples\calibration files** folder.

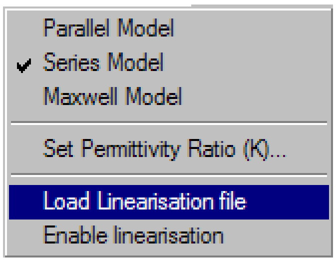


Figure 4. Permittivity model sub-menu

2. Select the appropriate **Concentration model** (parallel/series/Maxwell) and then **enable linearisation**, either by using the option in the drop-down menu or by clicking on the

enable linearisation button  located on the **Toolbar.**

30. DATA EXPORT

The PTL300E ECT system can export live capacitance data to a **remote PC** using a **fast ethernet link**.

This facility is intiated 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, a **demonstration program (ECTRemote)** is included with the software to allow exported data to be displayed in **graphical** or **text** format on the **remote PC**. The data export software 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:

30.1.1 HARDWARE SET-UP DETAILS

The **PTL300E unit** and the **2 PCs** are connected to an ethernet switch using standard ethernet cables as shown below.

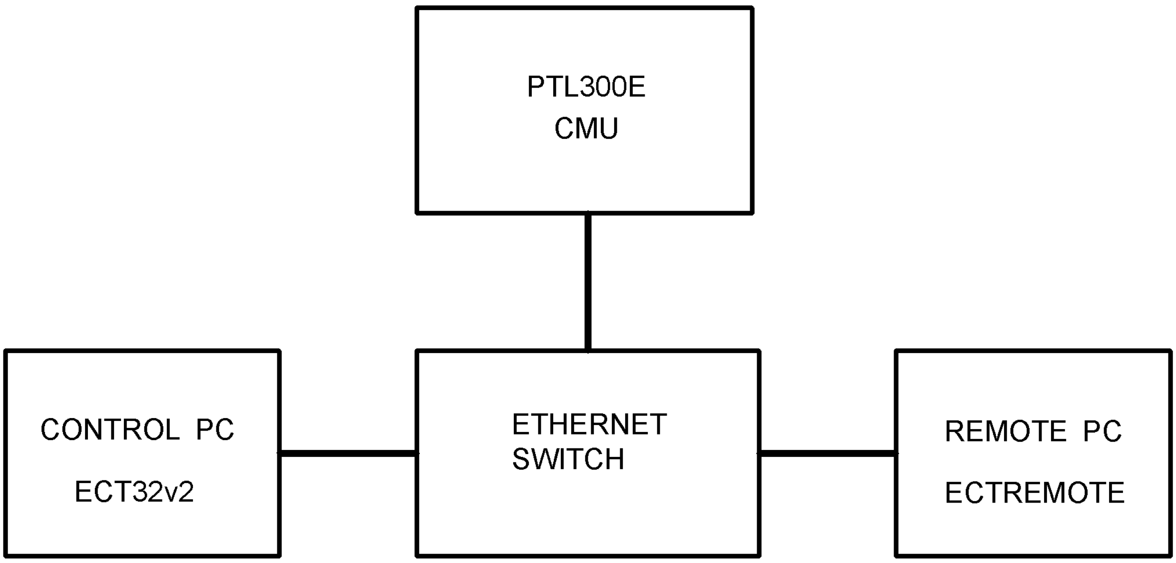


Figure 1. Data export hardware configuration

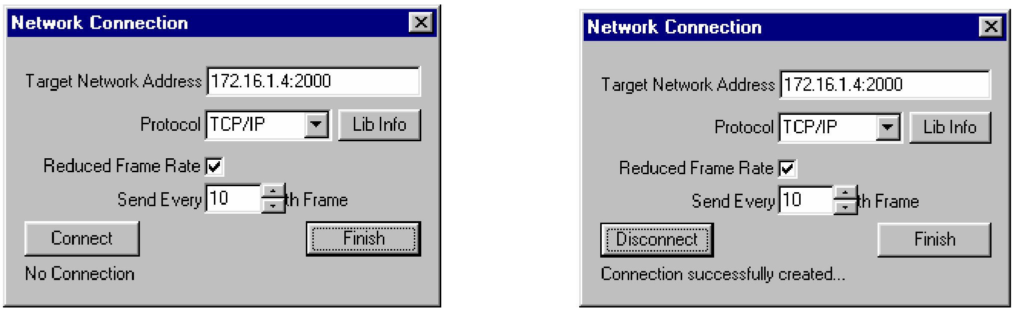
Note that a unique fixed **TCIP(v4)** internet address must be allocated to each **PC** and the **PTL300E CMU.** Any **Windows Firewalls** should be turned off.

30.1.2 SOFTWARE SET UP DETAILS

The **Control PC** runs the normal **ECT32v3** ECT software and a **Network Connection** window is used to set up the data transfer to the **Remote PC**.

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(a)** will appear.



(a) Before connection **(b) After connection**

Figure 30.1.1. Network Connection windows on Host PC

3. Enter the **TCP/IP address** and port number of the **Remote (target) PC** in the **Target Network Address box** as shown in figure 30.1.1(a) In this case, the port number is **2000.** Note the **colon (:)** before the **port number.**

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.**

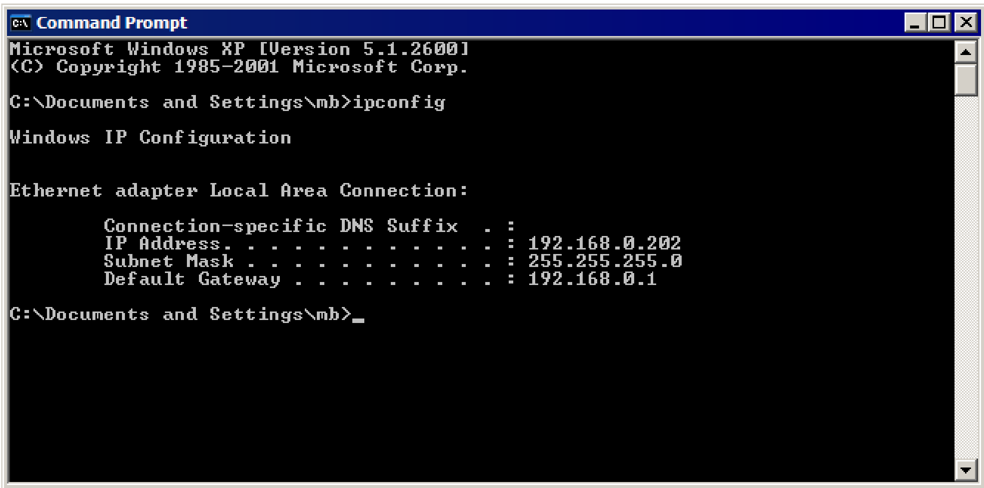


Figure 30.1.2 Command window showing network address of PC.

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 **ECTRemote icon.** This program will display **capacitance data** in **graphical format.**

8. Instructions for the use of the **ECTRemote** program **are given in in paragraph 30.2.**

30.2 Graphical display of capacitance data using ECTRemote program

1. When the **ECTRemote** icon is selected on the **remote (target) PC**, the window shown in **figure 30.1.3(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).**

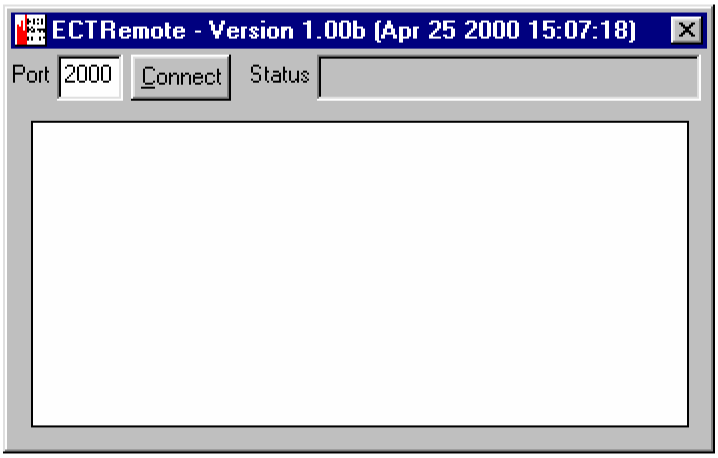


Figure 30.1.3(a). Network connection Window at start-up

2. Click on the **Connect button** in the **ECTRemote** window on the **remote PC**. The window will change to that shown in **figure 30.1.3(b)** and the **status message** "**Waiting for connection**" will be displayed.

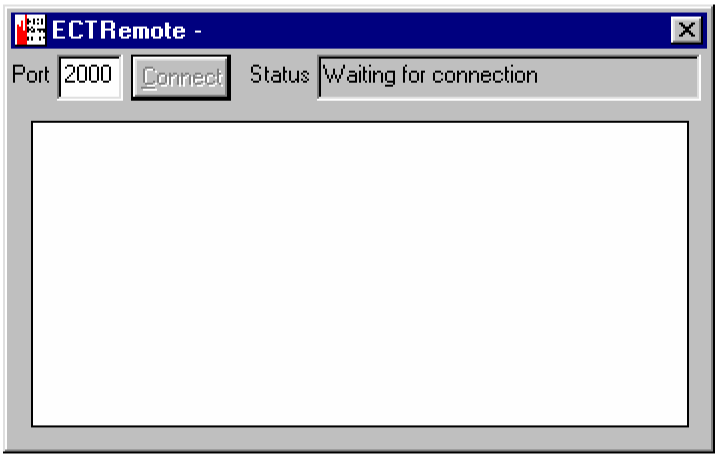


Figure 30.1.3(b). Network connection Window following connect request

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 **ECTRemote** window will display the message "**Connection established**".

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.

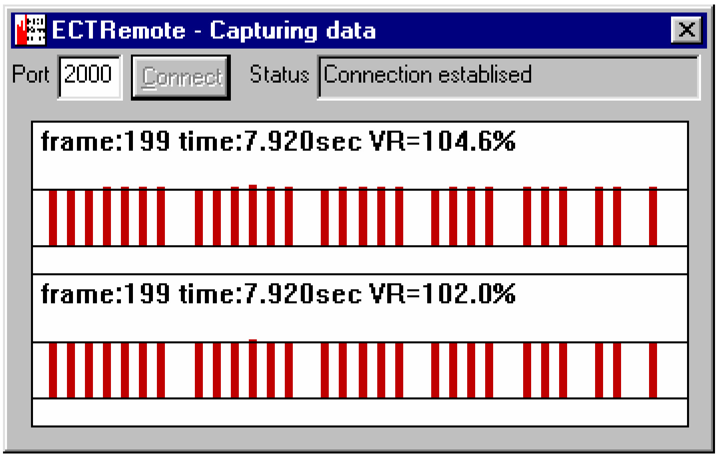


Figure 30.1.3(c). Network connection Window displaying live twin-plane capacitance data

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**".

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:

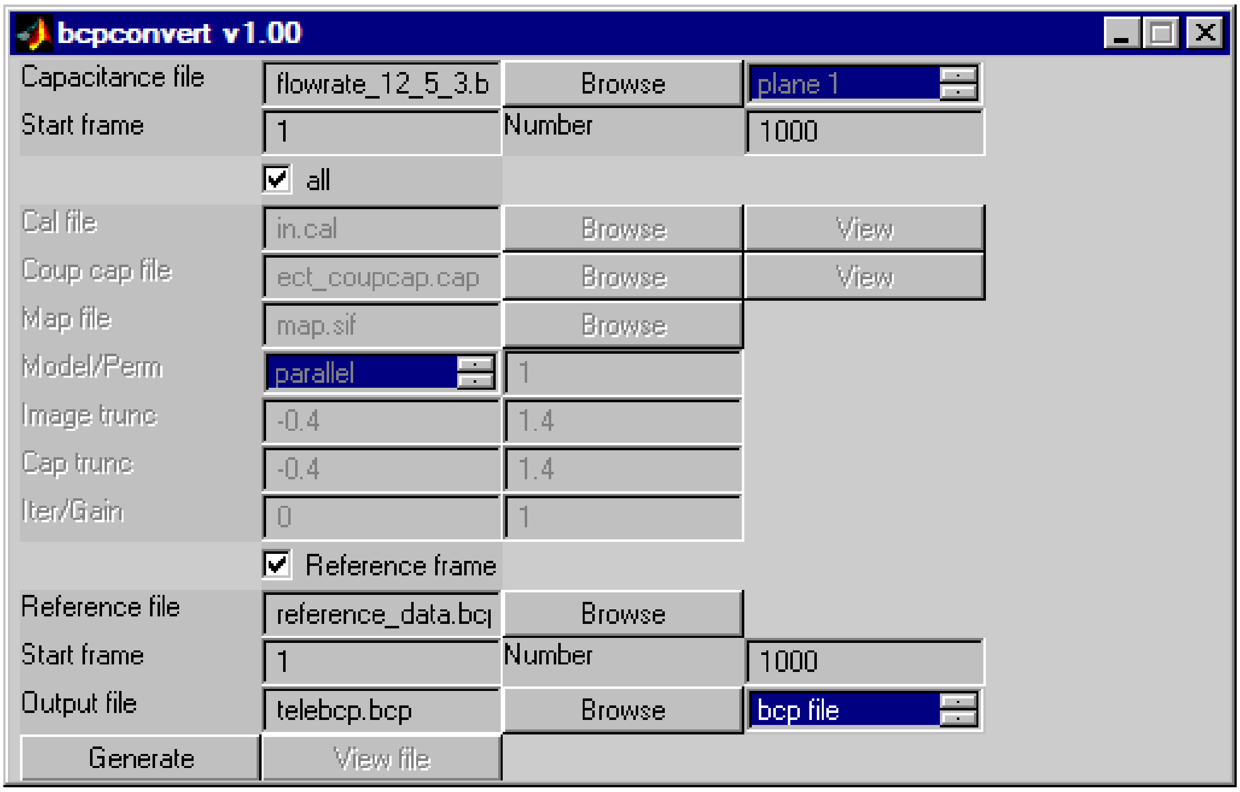


Figure 31.1 The BCPconvert window at start-up

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.

Coupcap 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 coupling capacitance 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 adjacent **Browse** 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 limit**s 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, absloute 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.

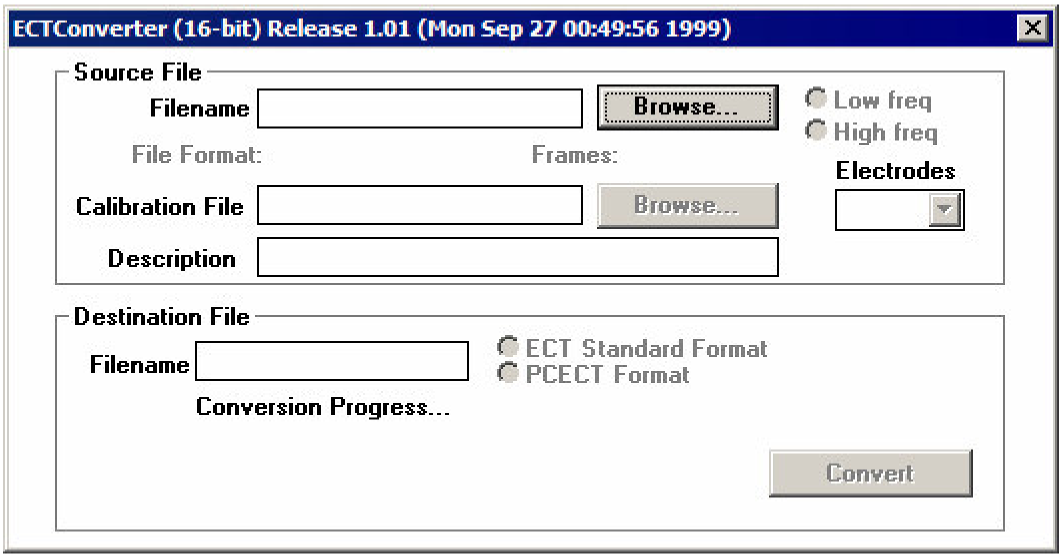


Figure 31.2 ECT16 File conversion window

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 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**.

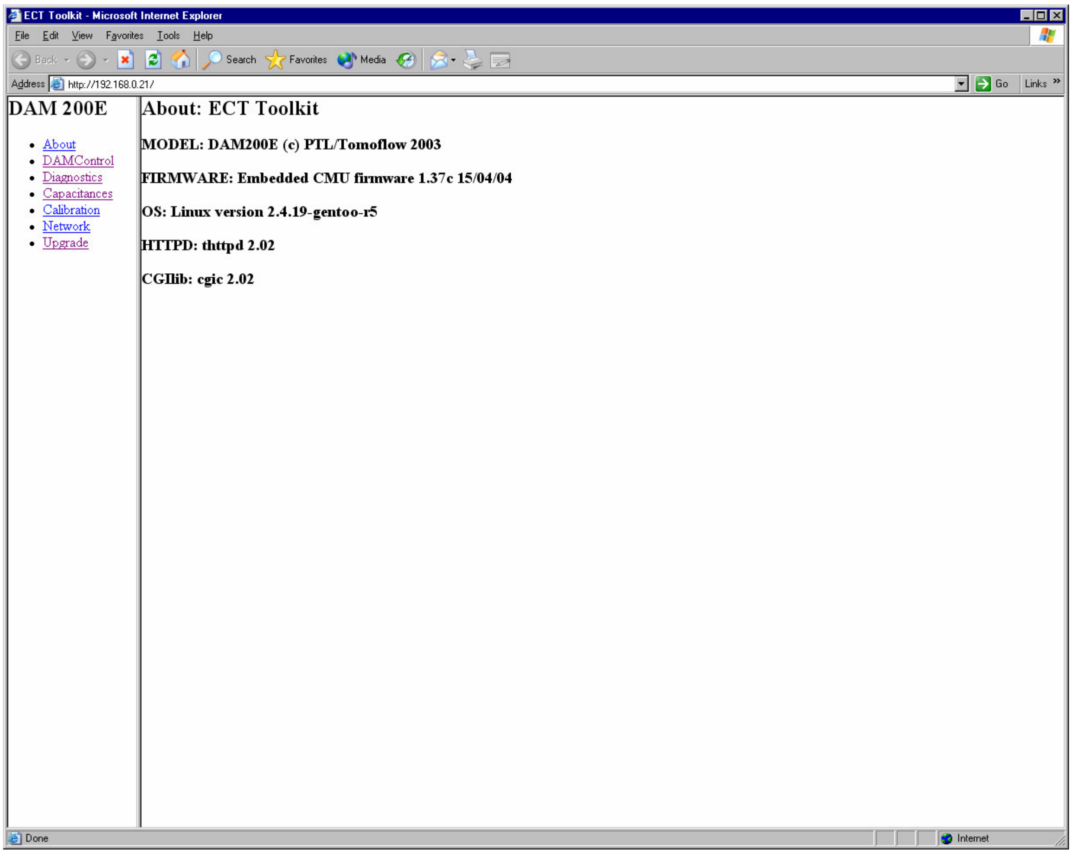


Figure 32.1.1 ECT Toolkit software opening window

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

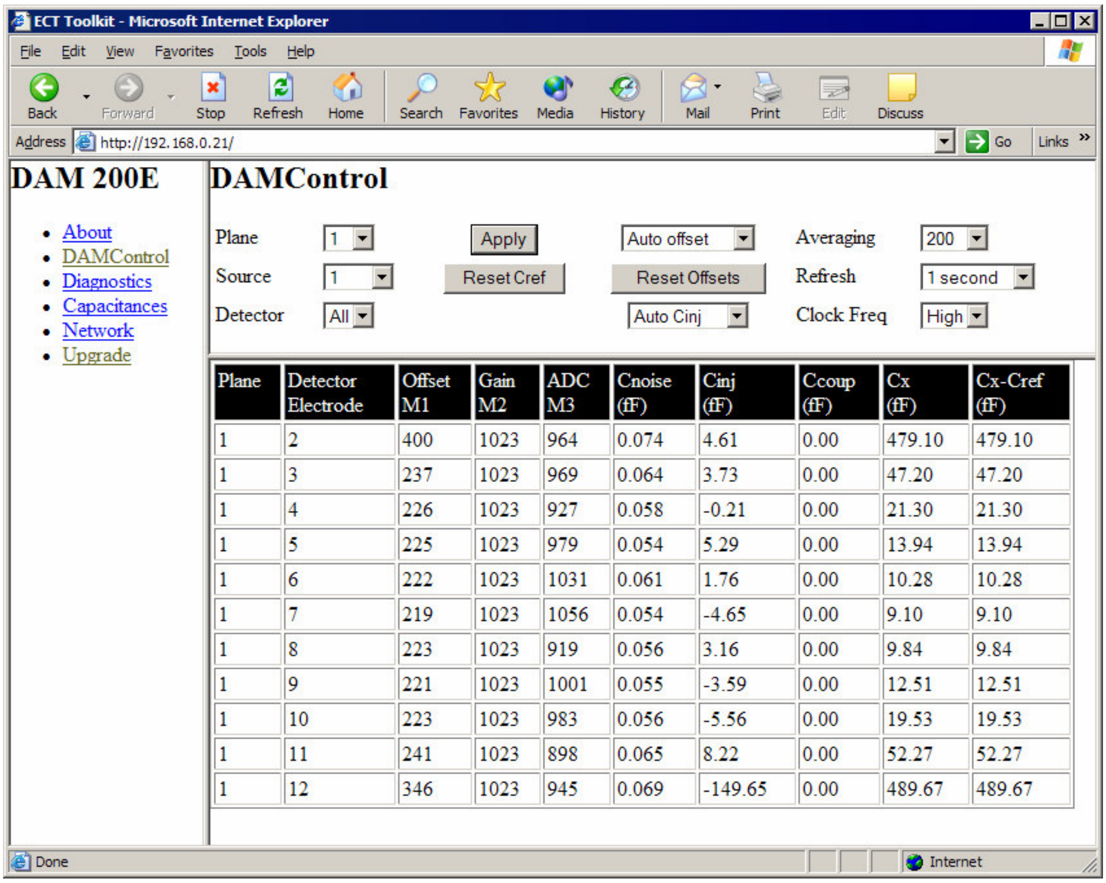
The **DAMcontrol** program allows the CMU to be controlled in a semi-manual mode from the control PC. It provides facilities for measuring selected inter-electrode capacitances and displays the intermediate measurement parameters.This facility is useful for carrying out experiments on prototype sensors 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



Plane	Detector Electrode	Offset M1	Gain M2	ADC M3	Cnoise (fF)	Cinj (fF)	Ccoup (fF)	Cx (fF)	Cx-Cref (fF)
1	2	400	1023	964	0.074	4.61	0.00	479.10	479.10
1	3	237	1023	969	0.064	3.73	0.00	47.20	47.20
1	4	226	1023	927	0.058	-0.21	0.00	21.30	21.30
1	5	225	1023	979	0.054	5.29	0.00	13.94	13.94
1	6	222	1023	1031	0.061	1.76	0.00	10.28	10.28
1	7	219	1023	1056	0.054	-4.65	0.00	9.10	9.10
1	8	223	1023	919	0.056	3.16	0.00	9.84	9.84
1	9	221	1023	1001	0.055	-3.59	0.00	12.51	12.51
1	10	223	1023	983	0.056	-5.56	0.00	19.53	19.53
1	11	241	1023	898	0.065	8.22	0.00	52.27	52.27
1	12	346	1023	945	0.069	-149.65	0.00	489.67	489.67

Figure 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 (Cinj) — Selects manual or automatic charge injection measurement

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	Cx - C ref

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:

$$Cav = (1/Nf).\sum_{1}^{Nf} Cn \qquad (32.2.1)$$

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:

$$Cnoise = \left[\sum_{1}^{Nf} (Cn - Cav)^2\right]^{1/2} \qquad (32.2.2)$$

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 ch**arge injection capacitance Cinj** 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 a**bsolute values** of the **inter-electrode capacitances Cx**.

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 **Cx** and a set of reference capacitances **Cref.** The reference capacitances can be set to the current measured values Cx 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

Src/Det	2	3	4	5	6	7	8	9	10	11	12
1	485.50	47.80	22.42	15.98	12.32	8.48	7.24	10.05	18.49	52.84	496.91
2	---.--	491.50	45.14	16.53	12.88	12.47	12.92	13.82	15.07	20.39	45.45
3	492.55	---.--	466.81	45.90	20.72	13.99	12.11	11.79	11.73	13.35	20.40
4	44.61	467.41	---.--	469.03	48.10	20.46	12.59	10.23	10.07	11.24	12.35
5	16.59	45.54	469.47	---.--	473.75	46.54	18.94	11.03	9.32	10.62	8.85
6	12.62	20.76	48.46	474.56	---.--	495.35	45.96	19.20	10.98	9.90	7.88
7	12.89	14.40	20.88	46.62	499.02	---.--	482.30	46.06	20.02	11.66	9.49
8	13.68	12.74	12.45	18.52	45.68	481.28	---.--	480.75	45.77	17.90	12.94
9	14.25	12.43	10.24	10.70	19.02	45.42	479.51	---.--	475.28	42.76	20.70
10	15.18	12.05	10.32	9.50	10.58	19.45	45.36	476.04	---.--	473.53	46.62
11	20.22	13.08	11.12	10.69	9.49	11.44	18.22	42.98	474.52	---.--	486.33
Cinj	13.55	11.64	8.91	13.23	9.20	12.68	22.29	19.49	11.25	26.01	-129.70

Plane 2

Src/Det	2	3	4	5	6	7	8	9	10	11	12
1	513.64	47.80	22.23	15.21	11.81	9.61	6.84	8.57	15.79	48.15	408.47
2	---.--	504.93	43.94	16.67	11.32	11.43	13.43	14.20	15.36	20.37	48.16
3	503.62	---.--	508.22	45.45	21.00	13.95	12.17	12.11	12.20	13.99	21.80
4	43.11	506.86	---.--	472.57	47.72	21.58	12.30	10.14	10.46	12.23	13.03
5	16.49	45.08	478.17	---.--	547.46	47.80	19.20	11.10	9.74	11.98	9.36
6	10.89	20.78	47.54	541.51	---.--	504.53	46.02	18.99	11.28	11.43	8.23
7	11.70	14.42	21.87	47.37	506.88	---.--	528.92	46.93	19.74	12.89	9.60
8	13.58	12.77	12.75	19.50	45.99	529.27	---.--	496.83	46.48	18.25	12.93
9	14.39	12.72	10.41	11.70	19.27	46.74	496.64	---.--	505.18	43.13	20.73
10	15.36	12.58	10.71	10.31	11.56	19.88	46.44	508.00	---.--	483.42	46.55
11	20.91	13.95	11.89	11.23	10.57	12.81	18.77	43.70	484.59	---.--	509.47
Cinj	12.78	28.20	9.05	17.07	15.58	16.96	21.49	16.03	23.89	11.97	-129.44

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

Src/Det	2	3	4	5	6	7	8	9	10	11	12
1	0.056	0.060	0.052	0.051	0.052	0.051	0.046	0.050	0.057	0.046	0.053
2	--.---	0.056	0.051	0.057	0.053	0.053	0.049	0.049	0.057	0.050	0.056
3	0.060	--.---	0.048	0.052	0.057	0.052	0.050	0.050	0.053	0.052	0.055
4	0.054	0.057	--.---	0.054	0.051	0.055	0.050	0.050	0.059	0.050	0.053
5	0.057	0.055	0.055	--.---	0.055	0.054	0.050	0.050	0.055	0.051	0.061
6	0.058	0.053	0.057	0.059	--.---	0.051	0.046	0.044	0.059	0.048	0.055
7	0.057	0.057	0.054	0.051	0.056	--.---	0.049	0.050	0.057	0.057	0.055
8	0.053	0.052	0.052	0.058	0.052	0.052	--.---	0.051	0.051	0.055	0.062
9	0.054	0.055	0.052	0.056	0.052	0.049	0.051	--.---	0.055	0.054	0.056
10	0.058	0.053	0.049	0.054	0.060	0.048	0.050	0.048	--.---	0.049	0.057
11	0.054	0.056	0.060	0.053	0.059	0.049	0.049	0.046	0.055	--.---	0.052

Noise Plane 2

Src/Det	2	3	4	5	6	7	8	9	10	11	12
1	0.048	0.057	0.059	0.053	0.054	0.054	0.054	0.049	0.047	0.053	0.046
2	--.---	0.051	0.056	0.054	0.058	0.053	0.050	0.046	0.045	0.049	0.048
3	0.051	--.---	0.063	0.054	0.063	0.058	0.057	0.050	0.049	0.050	0.047
4	0.050	0.050	--.---	0.058	0.058	0.055	0.058	0.048	0.047	0.047	0.047
5	0.051	0.053	0.055	--.---	0.059	0.053	0.058	0.045	0.050	0.051	0.047
6	0.049	0.053	0.058	0.057	--.---	0.058	0.050	0.050	0.049	0.049	0.049
7	0.052	0.056	0.055	0.053	0.062	--.---	0.049	0.048	0.050	0.051	0.048
8	0.052	0.057	0.063	0.061	0.056	0.057	--.---	0.050	0.047	0.054	0.048
9	0.051	0.049	0.061	0.057	0.053	0.057	0.053	--.---	0.043	0.051	0.050
10	0.053	0.054	0.058	0.056	0.061	0.051	0.058	0.049	--.---	0.054	0.050
11	0.054	0.059	0.060	0.052	0.055	0.056	0.056	0.049	0.046	--.---	0.045

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 Cab and Cba etc., compares these values and displays the differences in femtofarads.

Symmetry check Plane 1

Src											
1	---.--	---.--	---.--	---.--	---.--	---.--	---.--	---.--	---.--	---.--	---.--
2	-1.04	0.53	-0.06	0.26	-0.42	-0.76	-0.43	-0.11	0.17	---.--	
3	-0.60	0.37	-0.04	-0.41	-0.63	-0.64	-0.32	0.27	---.--		
4	-0.45	-0.36	-0.43	0.14	-0.01	-0.25	0.12	---.--			
5	-0.81	-0.08	0.43	0.34	-0.18	-0.07	---.--				
6	-3.68	0.28	0.18	0.40	0.41	---.--					
7	1.02	0.64	0.56	0.23	---.--						
8	1.23	0.41	-0.31	---.--							
9	-0.75	-0.22	---.--								
10	-0.99	---.--									
11	---.--										

Symmetry check Plane 2

Src											
1	---.--	---.--	---.--	---.--	---.--	---.--	---.--	---.--	---.--	---.--	---.--
2	1.31	0.83	0.18	0.43	-0.27	-0.15	-0.19	0.00	-0.54	---.--	
3	1.37	0.36	0.22	-0.47	-0.59	-0.62	-0.39	0.04	---.--		
4	-5.60	0.19	-0.29	-0.45	-0.27	-0.25	0.34	---.--			
5	5.94	0.43	-0.30	-0.59	-0.57	0.74	---.--				
6	-2.35	0.02	-0.28	-0.29	0.86	---.--					
7	-0.36	0.19	-0.13	0.09	---.--						
8	0.19	0.04	-0.51	---.--							
9	-2.83	-0.57	---.--								
10	-1.16	---.--									
11	---.--										

Figure 32.3.4 Diagnostics window (3), Symmetry check

Note: These are the results obtained by subtracting the Cba values from the Cab 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)

Plane 1

Src											
1	486.72	48.15	21.75	14.46	11.71	11.00	12.21	15.45	23.33	50.23	470.52
2	489.49	48.25	21.73	13.51	11.08	10.57	11.05	13.55	20.16	44.30	
3	466.52	47.61	21.21	14.00	11.00	9.99	10.48	12.88	19.89		
4	465.60	48.17	21.82	13.15	10.30	9.36	10.12	12.77			
5	473.36	47.02	20.68	13.07	10.01	9.29	9.80				
6	493.40	47.90	21.55	13.81	10.54	9.71					
7	481.38	48.45	21.66	13.82	11.29						
8	479.06	47.47	21.30	13.19							
9	474.94	47.96	21.64								
10	476.54	47.99									
11	488.06										
Cinj	13.58	11.67	8.93	13.22	9.20	12.71	22.28	19.49	11.25	25.99	-129.70

Plane 2

Src											
1	514.83	48.66	21.34	13.71	10.87	10.10	11.17	13.70	21.14	46.32	385.37
2	504.41	47.76	21.23	13.52	10.86	9.80	10.70	13.50	20.38	47.41	
3	508.97	47.96	21.76	13.77	10.87	9.90	10.52	13.58	21.40		
4	470.12	47.18	21.78	13.47	10.66	9.62	10.54	13.56			
5	545.87	48.06	21.14	13.50	10.22	9.90	10.99				
6	503.72	48.22	22.00	14.20	11.10	10.26					
7	528.29	49.21	22.24	14.34	11.31						
8	495.90	47.75	21.66	14.18							
9	505.14	48.26	21.45								
10	486.93	48.03									
11	511.56										
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.

32.5 THE CALIBRATION PROGRAM OPTION

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.

Calibration (fF)   Stream 0 (Plane 1)

Protocol

(1,2)	(1,3)	(1,4)	(1,5)	(1,6)	(1,7)	(1,8)	(1,9)	(1,10)	(1,11)	(1,12)
(2,3)	(2,4)	(2,5)	(2,6)	(2,7)	(2,8)	(2,9)	(2,10)	(2,11)	(2,12)	
(3,4)	(3,5)	(3,6)	(3,7)	(3,8)	(3,9)	(3,10)	(3,11)	(3,12)		
(4,5)	(4,6)	(4,7)	(4,8)	(4,9)	(4,10)	(4,11)	(4,12)			
(5,6)	(5,7)	(5,8)	(5,9)	(5,10)	(5,11)	(5,12)				
(6,7)	(6,8)	(6,9)	(6,10)	(6,11)	(6,12)					
(7,8)	(7,9)	(7,10)	(7,11)	(7,12)						
(8,9)	(8,10)	(8,11)	(8,12)							
(9,10)	(9,11)	(9,12)								
(10,11)	(10,12)									
(11,12)										

C low

1214.07	59.34	27.33	21.29	17.13	15.79	15.93	19.40	25.97	58.02	1277.39
1209.24	57.32	28.43	20.56	18.45	18.21	17.41	17.05	29.88	61.90	
1208.25	58.98	28.31	21.48	19.95	17.84	16.03	21.93	31.18		
1197.46	55.07	28.75	21.29	17.43	14.40	16.91	22.14			
1234.52	61.04	30.08	21.17	15.22	15.91	19.40				
1260.48	59.29	27.95	16.72	16.43	19.04					
1247.90	57.31	22.75	16.44	16.30						
1271.61	53.49	27.62	22.88							
1291.76	60.55	31.16								
1311.42	56.46									
1281.69										

Cinj low

30.03	21.67	31.14	24.77	23.83	13.60	34.76	33.94	27.95	43.07	-86.72

C high

1346.41	93.59	43.44	31.77	25.13	23.28	23.74	29.57	42.00	92.18	1410.02
1350.44	91.88	44.45	30.63	26.65	25.69	25.63	27.61	45.76	96.67	
1340.71	93.18	44.06	31.63	27.55	24.94	24.14	31.95	47.14		
1327.57	89.56	44.70	31.14	25.09	21.88	25.13	32.52			
1365.62	95.22	45.53	30.97	23.26	23.61	27.58				
1398.49	92.89	43.51	27.16	24.62	26.50					
1392.69	91.83	39.12	27.18	24.79						
1414.49	87.97	43.62	33.22							
1440.46	95.02	47.17								
1464.83	91.14									
1438.33										

Cinj high

32.49	23.85	33.08	27.60	26.46	15.25	37.53	36.06	30.03	44.76	-83.51

C high/C low

1.109	1.577	1.589	1.493	1.467	1.474	1.490	1.524	1.617	1.589	1.104
1.117	1.603	1.564	1.490	1.444	1.410	1.472	1.619	1.532	1.562	
1.110	1.580	1.556	1.473	1.381	1.398	1.506	1.457	1.512		
1.109	1.626	1.555	1.463	1.440	1.519	1.486	1.469			
1.106	1.560	1.514	1.463	1.527	1.484	1.422				
1.109	1.567	1.557	1.624	1.499	1.392					
1.116	1.602	1.720	1.653	1.521						
1.112	1.645	1.579	1.452							
1.115	1.569	1.514								
1.117	1.614									
1.122										

Stream 1 (Plane 2)

Protocol

(1,2)	(1,3)	(1,4)	(1,5)	(1,6)	(1,7)	(1,8)	(1,9)	(1,10)	(1,11)	(1,12)
(2,3)	(2,4)	(2,5)	(2,6)	(2,7)	(2,8)	(2,9)	(2,10)	(2,11)	(2,12)	
(3,4)	(3,5)	(3,6)	(3,7)	(3,8)	(3,9)	(3,10)	(3,11)	(3,12)		
(4,5)	(4,6)	(4,7)	(4,8)	(4,9)	(4,10)	(4,11)	(4,12)			
(5,6)	(5,7)	(5,8)	(5,9)	(5,10)	(5,11)	(5,12)				
(6,7)	(6,8)	(6,9)	(6,10)	(6,11)	(6,12)					
(7,8)	(7,9)	(7,10)	(7,11)	(7,12)						
(8,9)	(8,10)	(8,11)	(8,12)							
(9,10)	(9,11)	(9,12)								
(10,11)	(10,12)									
(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		
1.098	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							
1.112	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.

32.6 NETWORK WINDOW OPTION

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

Boot Protocol	Static
IP Address	192.168.0.21
Net Mask	255.255.255.0
Gateway	192.168.0.1

Set

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

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.

FAQ1 ECT TECHNOLOGY

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.

Huang S.M. et al., (1989), Tomographic imaging of two-component flow using capacitance sensors, J. Phys. E: Sci. Instrum. 22, pp 173-177.

Reinecke N. and Mewes D., (1996), Recent Developments and industrial/research applications of capacitance tomography, Meas. Sci. Technol. 7 pp 233-246

Loser T., Wajman R. and Mewes D., (2001), New Reconstruction Algorithm for Electrical Capacitance Tomography, Proceedings of the 2nd World Congress on Industrial Process Tomography, Hannover, Germany, pp 20-28.

Byars M., (2001), Developments in Electrical Capacitance Tomography, Proceedings of the 2nd World Congress on Industrial Process Tomography, Hannover, Germany, pp 542-549.

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.

FAQ3 CAPACITANCE MEASUREMENT

Q1 What is special about the capacitance measurement circuitry needed for ECT?
Q2 What are the limits on capacitance measurement?
Q3 What are typical inter-electrode capacitance values?
Q4 What determines the sequence of capacitance measurements?
Q5 Are the capacitance measuremements made simultaneously?
Q6 What is the simplest capacitance measurement protocol?
Q7 What other capacitance measurement protocols are possible?
Q8 What are the advantages in using more complex capacitance measurement protocols?
Q9 Is there a linear relationship between the permittivity of the contents of the sensor and the measured capacitances?

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 0.1 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 smllest 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 eg 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 us 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 sceened 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 constuct sensors suitable for operation at elevated temperatures and pressures..

FAQ5 CALIBRATION AND NORMALISATION

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 subesequent capacitance measurents 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 sabout normalisation and calibration are given in subsequent FAQs (see below).

Q2 How are ECT sensors calibrated?

When a mixture of 2 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 subequent 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:

$$CN = (CM - CL) / (CH - CL)$$

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?
Q2 What is the parallel capacitance model?
Q3 What is the series capacitor model?
Q4 What is the composite (Maxwell) capacitance model?

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?
Q2 How is a square grid used to represent a circular cross-section?
Q3 What image resolution can be achieved using ECT?
Q4 What errors are present in ECT permittivity images?

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).

FAQ8 OBTAINING A PERMITTIVITY IMAGE FROM THE CAPACITANCE MEASUREMENTS (Basic Image Reconstruction)

Q1 What are the main problems in obtaining a permittivity image from the capacitance measurements?
Q2 How are ECT images calculated in view of the limited number of available measurements and the soft field?
Q3 What is the most commonly used image recontruction method?
Q4 What is the forward transform?
Q5 What is the inverse transform?
Q6 So what is the problem in finding a suitable inverse transform?
Q7 What is the justification for using the transpose of the sensitivity matrix as the inverse transform in the LBP algorithm?
What are the characteristics of the LBP algorithm?
Q9 How is the sensor sensitivity matrix obtained?
Q10 What are sensitivity maps?
Q11How are sensitivity maps calculated?

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 recontruction 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 x 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 x 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 x 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 x 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 x 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.

$S = Ei . Ej . dA$

where Ei is the electric field inside the sensor when one electrode of the pair i is excited as a source electrode, Ej is the electric field when electrode j is excited as a source electrode and the dot product of the two electric field vectors Ei and Ej 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 . F (W, t, R) . 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 = ((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' . (S . S' + t . 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?

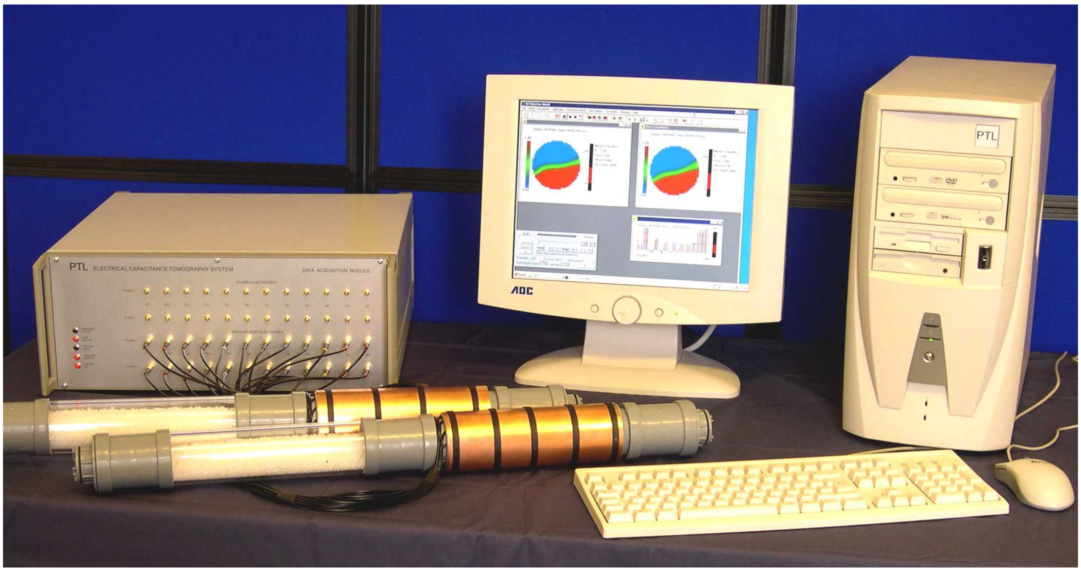
The set of sensitivity coefficients for each electrode-pair is known as the sensitivity map for that pair.

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.

APPENDIX 1

DETAILED SPECIFICATION FOR PTL300E ECT SYSTEM



The PTL300E is an enhanced Electrical Capacitance Tomography (ECT) system controlled by Windows-based software running on a Pentium PC. Image data can be captured at a rate in excess of 100 frames per second in twin-plane mode for a 12-electrode sensor and at correspondingly higher rates for sensors with smaller numbers of electrodes (either 6 or 8). The ECT system can display, capture and replay images based on the variation in the permittivity of the material inside the sensor, which, in the case of a mixture of 2 dielectric materials, corresponds to the concentration of the higher permittivity material in the mixture. The images displayed are approximate and of relatively low resolution, but can nevertheless give a good insight into the distribution and concentartion of the materials inside the sensor.

Two versions of the ECT system are available, suitable for use with sensors containing either one or two planes of measuring electrodes and a set of driven guard electrodes. The single plane system (type PTL300E-SP-G) consists of an industry-standard PC together with a Data Acquisition Module type DAM200E-SP-G and a demonstration 12 element ECT sensor. Capacitance sensors containing sets of between 2 and 12 measurement electrodes, together with a set of driven axial guard electrodes can be used with the system.

A further version of the system (type PTL300E-TP-G), suitable for imaging in two axial planes, is also available. This is similar to the single plane system but uses a dual-plane Data Acquisition Module type DAM200E-TP-G. The twin-plane version has the potential for measuring the velocity profile of the sensor contents under suitable flow conditions, by correlating the permittivity data between the two image planes.

Although the DAM200E capacitance measurement unit must be located close to the capacitance sensor, the control PC can be located remotel from the sensor as it communicates with the DAM200E via an ethernet link. In principle, operation of the ECT system can be carried out and controlled over an internet connection.

Applications of the PTL300E ECT system include the imaging of fluidised beds, combustion, dense and medium phase pneumatic conveying, mixed oil and gas flows and the measurement of moisture profiles.

Model Options

PTL300E-SP-G	Single plane ECT system with driven guard drive circuitry.
PTL300E-TP-G	Twin-plane ECT system with driven guard drive circuitry.

PTL300E-SP/TP-G SYSTEM SPECIFICATION

Number of capacitance sensor measurement electrodes: 6, 8 or 12.

Number of driven guard electrodes: 12 maximum

Number of measurement electrode planes: 1 (SP version) or 2 (TP version)

Data capture rates can be set by the user up to the following maximum values for twin-plane systems:

- 300 image frames per second with 6 electrode sensor
- 190 image frames per second with 8 electrode sensor
- 100 image frames per second with12 electrode sensor

The captured images can be replayed at the same rate as captured, or in slow motion.

External trigger signals can be used to synchronise the start of data capture with other equipment.

Image details:

Images are displayed in colour on a 32 X 32 pixel grid, or any other suitable grid, depending on the format of the sensor sensitivity map. A screen probe allows the value of any pixel to be displayed. Image resolution (the minimum size of phase boundary/particles which can be resolved) is approximately 1 in 10 of the diameter or 1 in 100 of the cross sectional area of the process vessel. For phase variations or particles below this minimum size, the ratio of phases can be estimated although individual particles can not be resolved.

Measurement Sensitivity:

This depends on the design of the sensor and the permittivities of the materials to be imaged. The capacitance measurement noise level is typically 0.07fF rms and the effective measurement resolution is 0.1fF. Typically, sample concentrations down to 3% of the upper calibration value (corresponding to the case where the sensor is filled with the higher permittivity material) can be measured.

Capacitance Sensor Characteristics

The maximum sensor inter-electrode capacitance should not exceed approximately 1.5 pF with the higher permittivity material inside the sensor (the measuring system saturates at 2pF). The maximum electrode-to-screen capacitance (including connecting leads) must not exceed 200 pF and the recommended maximum length for the sensor connecting leads is 1.5m. The recommended minimum lengths for measurement electrodes are 3.5cm for 8-electrode and 5cm for 12-electrode sensors, subject to the provision of effective driven guard electrodes in the sensor design.

System Software

The ECT system is supplied with a comprehensive set of pre-installed data capture (ECT32E) and post-processing image reconstruction software (IU2000 and MatPTL) for use with 6, 8 and 12 electrode sensors. Additional flow measurement software is available from our associate company, Tomoflow Ltd.

APPENDIX 2

DETAILS OF THE DEMONSTRATION 12 ELEMENT SENSOR

A2.1 ASSEMBLY INSTRUCTIONS

On delivery, the demonstration sensor is supplied in two sections, together with a bag of plastic beads, and it must be assembled before use. This is carried out as follows:

1. Hold the end of the sensor containing the electrode assembly vertical, with the open end upwards.

2. Carefully fill this section with beads from the bag. Use all of the beads.

3. Assemble the second section, containing the clear tube, onto the first section as follows: hold the bottom section by the coupling at the open end, insert the open end of the clear section and carefully twist and push the two sections together. The clear section is fragile at the coupling ends where its diameter has been machined to fit the PVC coupler. Care should therefore be exercised when fitting the sections together. Try to avoid holding the electrode assembly during this process as this may damage the sensor. The demonstration sensor is now ready for use.

Note: a second length of PVC tubing is also supplied which can be ased as an alternative to the length of clear tube if required.

A2.2 SENSOR DETAILS

The demonstration sensor is constructed from 2 inch (50mm) polythene tubing and fittings. The electrode assembly is fabricated from a flexible copper-clad laminate using standard photo-lithographic and etching techniques.

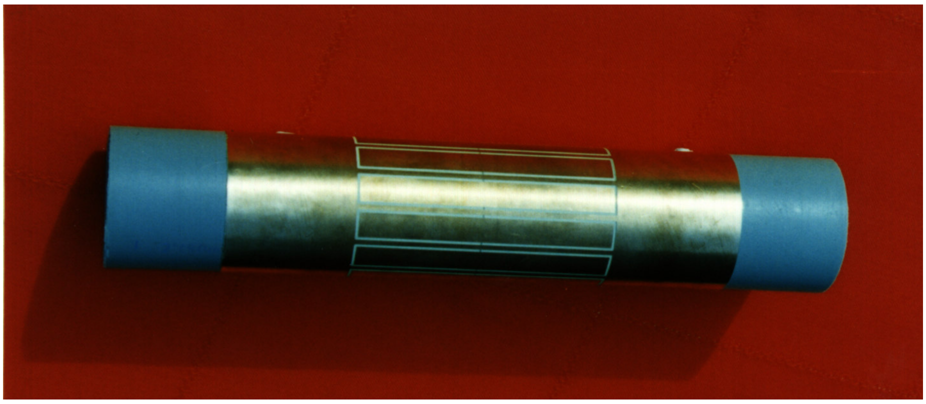
Figure A2.1 shows a series of photographs of the sensor electrode assembly at various stages of construction: The top figure shows the sensor electrode laminate wrapped around the outside of the 2 inch tube.

The middle figure shows the addition of four radial spacers adapted from 2 inch push fit couplings.

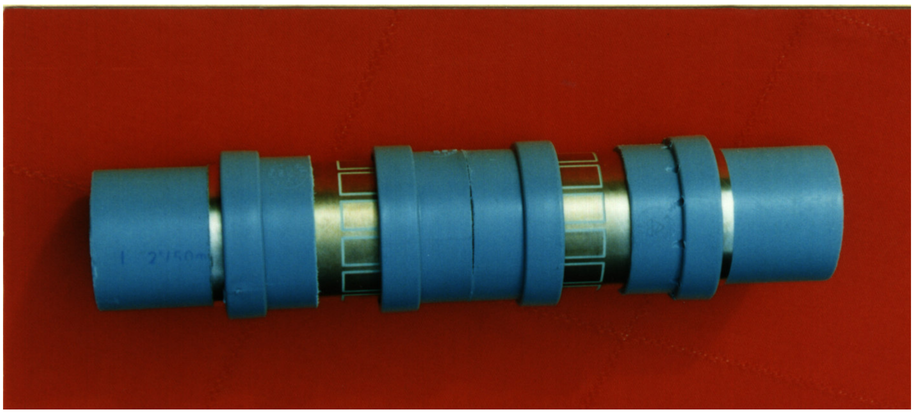
The bottom figure shows the addition of the screen, formed from a copper sheet which is wrapped around the radial spacers and held in place by releasable plastic cable ties.

Figure A2.2 shows a negative image of the copper laminate which forms the sensor electrodes. The electrodes are 100 mm in length and are separated by axial screening tracks of width 0.1 inches (2.54 mm). A 2 inch (50mm) length of screen extends axially beyond the sensor electrodes at each end of the electrode assembly and 1 M ohm discharge resistors are connected between each sensor electrode and the screen.

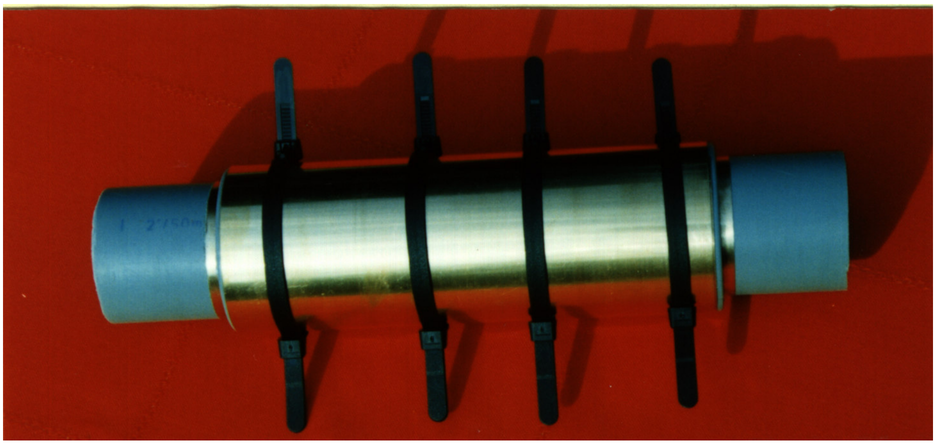
Figure A2.3 shows an axial cross section of the sensor electrode assembly showing the radial spacers and the outer copper screen. Figure A2.4 shows the complete demonstration sensor.



Pipe with sensor electrodes



Addition of radial spacers



Addition of outer screen

Figure A2.1 Views showing construction of Demonstration ECT sensor

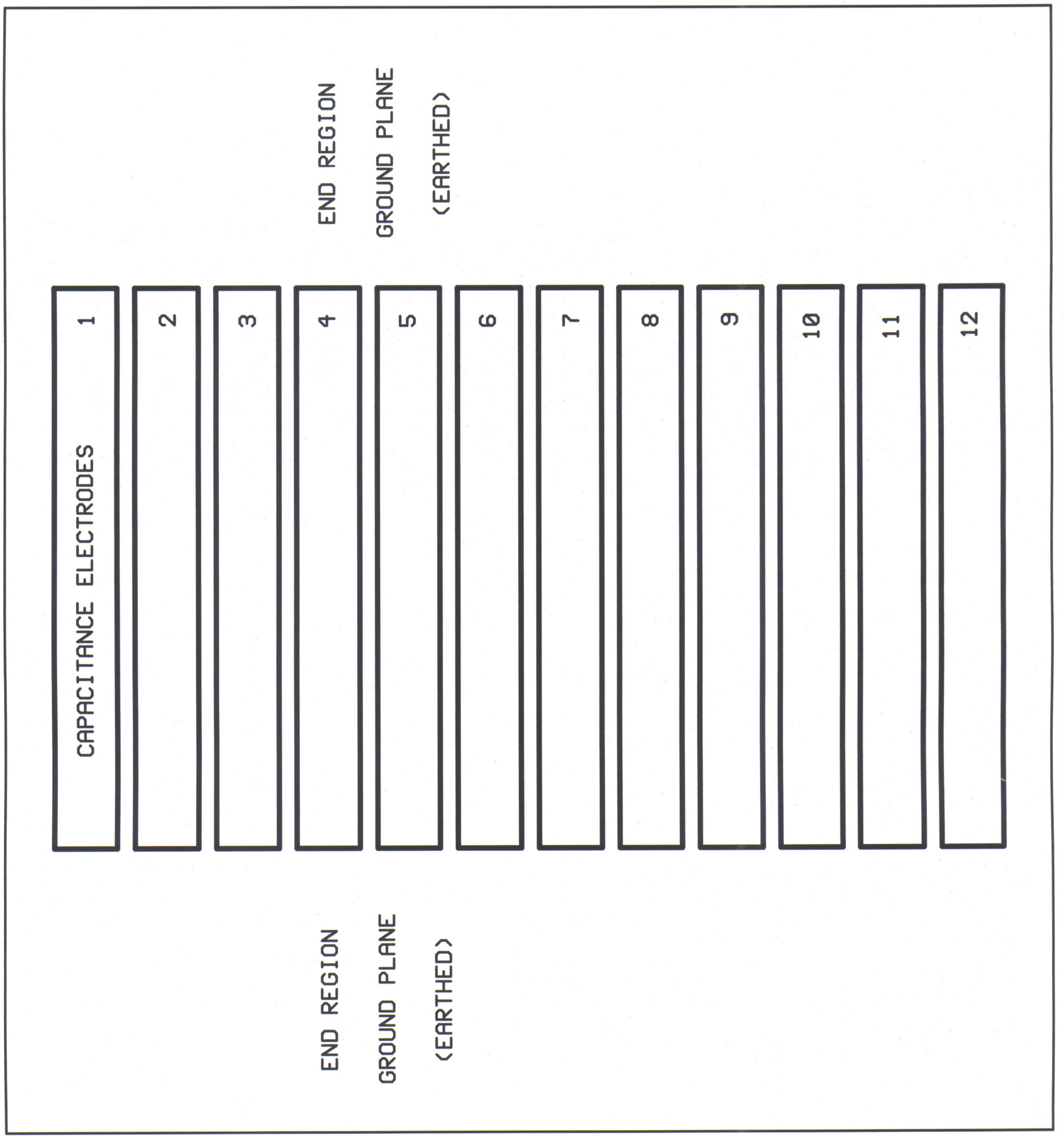


Figure A2.2 12-element capacitance sensor electrode foil artwork (negative)

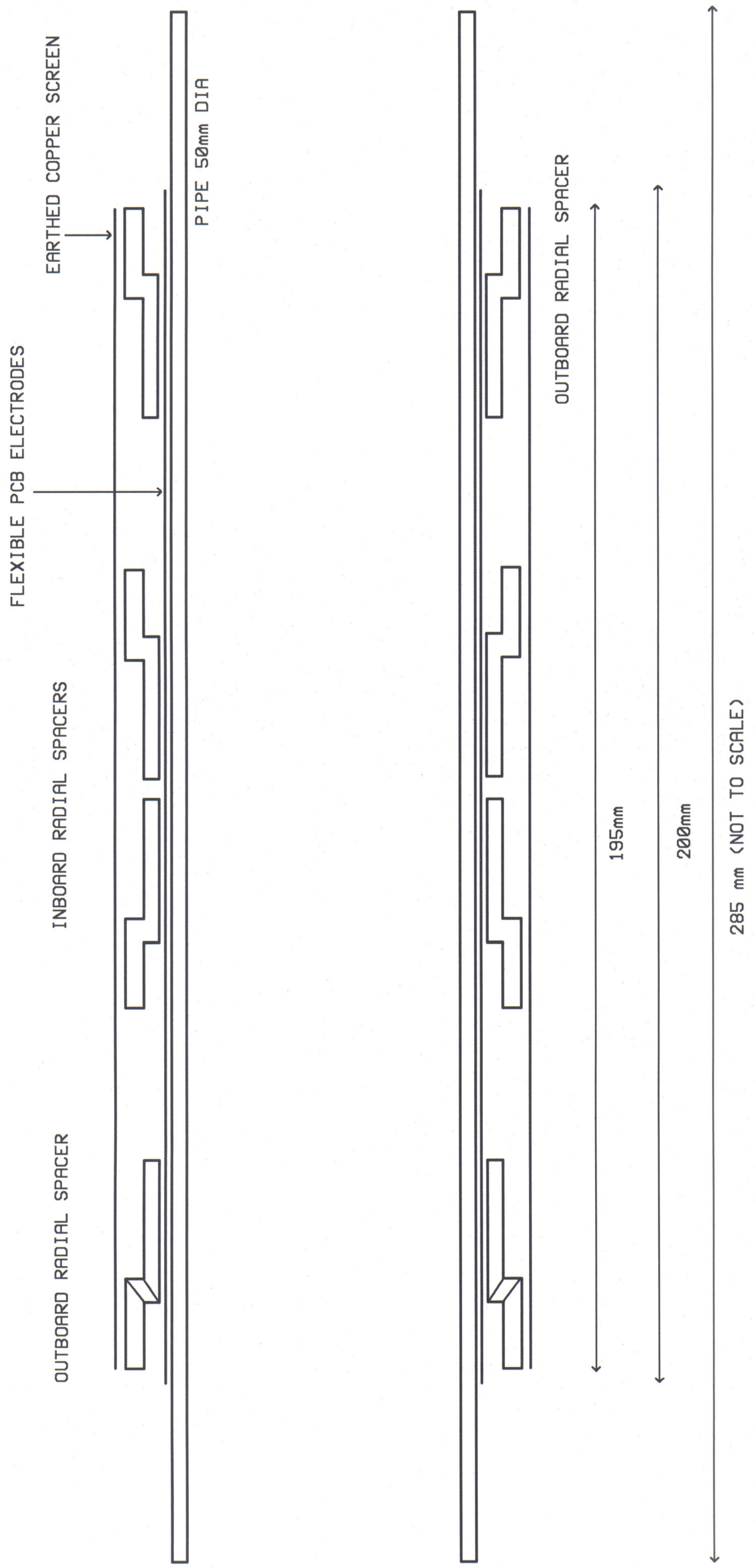


Figure A2.3 Cross-section of demonstration 12-electrode capacitance sensor

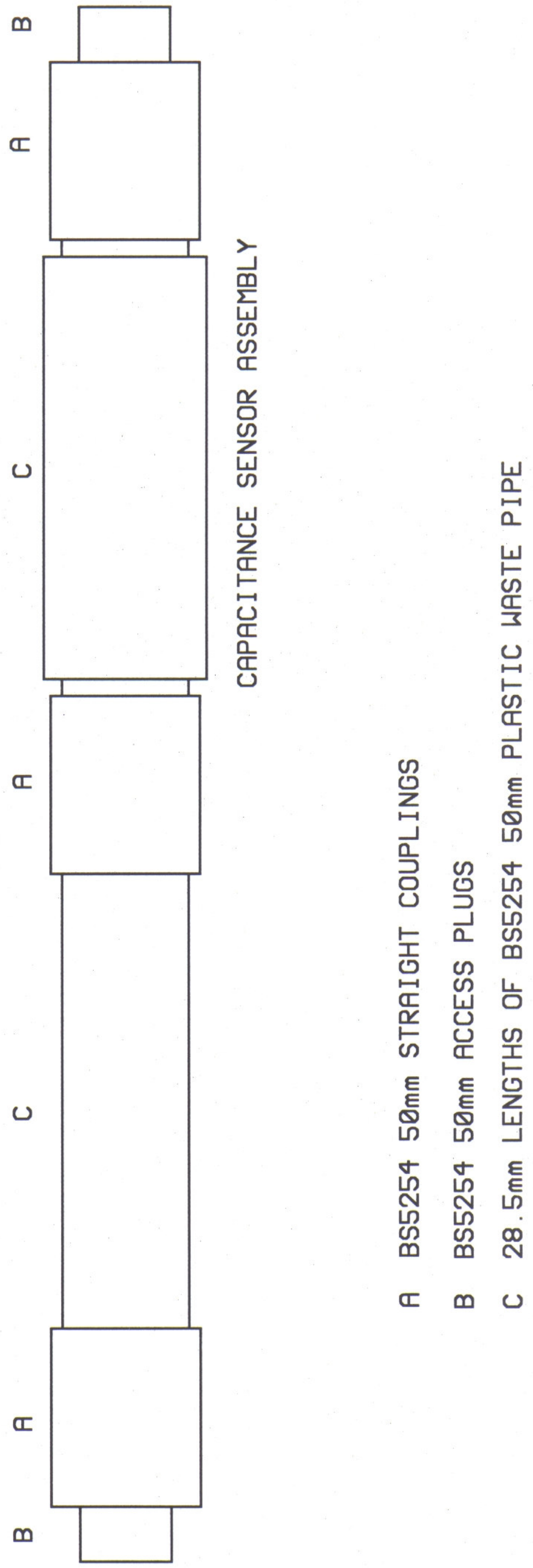


Figure A2.4 View of completed demonstration ECT sensor

A2.3 SAMPLE MEASURED CAPACITANCES FOR DEMONSTRATION SENSORS

A2.3.1. EMPTY SENSOR

Capacitances (fF)

Src											
1	478.49	47.33	21.62	14.13	10.28	9.21	9.91	12.31	19.52	52.52	489.56
2	501.66	46.16	20.40	13.71	11.04	10.89	12.44	14.70	20.46	45.90	
3	481.49	46.53	21.23	14.22	11.46	10.64	10.80	12.97	20.24		
4	477.22	47.48	21.56	13.69	10.26	9.01	10.32	11.82			
5	479.03	46.99	20.13	12.61	9.79	9.78	8.21				
6	491.95	45.50	20.12	13.09	10.29	7.27					
7	471.26	46.90	19.91	12.22	9.09						
8	512.05	45.98	18.58	13.37							
9	526.90	45.87	21.71								
10	493.64	47.35									
11	490.57										
Cinj	5.59	4.94	0.35	5.82	1.11	−5.27	3.05	−3.81	−6.31	7.95	−146.64

A2.3.2. SENSOR FILLED WITH POLYPROPYLENE BEADS

Capacitances (fF)

Src											
1	561.48	75.96	34.96	22.82	17.23	15.83	17.17	21.56	33.67	82.16	569.09
2	578.40	73.44	33.45	22.07	17.92	17.33	19.39	23.44	33.70	72.55	
3	560.00	74.10	34.09	22.96	18.32	16.90	17.51	21.44	32.71		
4	556.63	74.67	34.91	22.24	16.94	15.14	16.83	19.78			
5	557.08	74.94	33.26	21.05	16.34	15.81	14.52				
6	570.10	72.26	32.66	21.29	16.68	13.07					
7	550.33	74.08	32.99	20.73	15.65						
8	582.36	73.65	32.02	21.83							
9	591.18	73.74	34.78								
10	566.55	74.90									
11	566.00										
Cinj	5.67	5.03	0.43	5.88	1.20	−5.20	3.12	−3.75	−6.21	8.04	−146.80

APPENDIX 3 DATA FILE FORMATS

A3.1 INTRODUCTION

The following sections describe the general format of **calibration data** files, **sensitivity map** files, **captured data** files **image files** format and **capacitance** files, together with other more detailed information about the data in some of these files.

A3.2 MEASUREMENT SEQUENCE AND REPRESENTATION

When a set of inter-electrode capacitance measurements is taken, a notional inter-electrode capacitance matrix C can be formed from these measurements. For protocol 1, where measurements are made between single electrode-pairs only, this sequence reduces to:

Inter-electrode capacitance matrix **C:**

C11	C12	C13	...	C1e
C21	C22	C23	...	C2e
C31	C32	C33	...	C3e
.	.	.		.
Ce1	Ce2	Ce3		Cee

Where *Cxy* is the capacitance between electrodes ‘x’ and ‘y’ and e is the number of measurement electrodes.

Due to the symmetry in the matrix and the redundancy of the diagonal elements, only the upper or lower triangle of measurements need be measured and recorded. The elements where x = y have no physical meaning as capacitances and hence, choosing the "upper set" where y > x the sequence of actual measurements reduces to:

C12 C13 ... C1e C23 ... C2e C34 ... C(e-1)e

In ASCII file formats, a newline sequence is inserted at the end of each ‘row’, i.e. after element Cxe. Measurements in these files therefore appear in the following triangular form when displayed on a monitor or when printed:

C12	C13			...	C1e
C23	C24		...	C2e	
C34	C35	...	C3e		
.	.	.			
C(e-2)(e-1)	C(e-2)e				
C(e-1)e					

This matrix is known as the "measurement order" matrix.

Detailed information about the file formats used for each type of data file are given in a separate document. Examples of data formats for each data type are given in the following sections.

A3.3 CALIBRATION DATA FILE

The calibration data file stores information necessary for the accurate operation of the DAM200E CMU using the two-point calibration technique.

A3.3.1 Data File Format

The default extension of a calibration file **.CAL** and the data is stored in **ASCII** format.The sequence of data stored in the calibration file for a 12-electrode sensor is as follows and follows the numbers in brackets to the right of each set of data in the sample data file shown on the next page.

1. Calibration file identifier code (D2CA). (1 parameter in total)

2. Number of measurement planes, number of electrodes, number of independent measurements. (3 parameters in total)

3. System zero balance count **M3BAL**. The value of the ADC count when the system gain is set to zero. (1 in total)

4. Zero (charge injection) offset counts **M10** (DAC values 0-1023). These are the readings in all measurement channels (2 to 11) with no excitation, i.e. no source electrode. (11 parameters in total)

5. Zero (charge injection) balance counts **M30** (ADC values 0-4095). (11 in total)

6. Low permittivity offset counts **M1L** (DAC values 0-1023). These integers are displayed in triangular measurement sequence (see above) with newline sequences separating rows. (66 in total).

7. Low permittivity ADC balance counts **M3** (ADC values 0-4095). These are values read from the DAM200 ADC while the sensor is filled with the low permitivity component for calibration. (66 in total)

8. High permittivity gain counts **M2H** (DAC values 0-1023). The system gain values set when the sensor is filled with the higher permittivity material. (66 in total)

9. High permittivity ADC counts **M3H** (ADC values 0-4095) when the sensor is filled with the higher permittivity material. (66 in total).

A sample single-plane 12-electrode calibration file is shown below.

CALIBRATION DATA FILE

Data type: ASCII

File extension: .CAL

Sample file: Single plane calibration file.

```
D2CA                                                                                          (1)
1      12      66                                                                             (2)
954                                                                                           (3)
216    219    217    227    229    225    227    217    216    217    176                     (4)
965    954    954    976    1048   1064   986    963    988    982    996                     (5)
 422  237  225  234  233  229  230  221  224  237  324                                        (6)
 406  234  235  234  230  230  221  222  226  193
 409  244  238  231  231  220  220  223  184
 414  248  235  232  221  220  221  181
 413  246  234  222  220  220  180
 417  245  225  221  220  180
 427  234  224  221  180
 401  233  224  181
 401  234  184
 400  194
 362

 978  997  968  778 1000 1008 1011 1025  974  993 1017                                        (7)
1025 1027  965 1033  984 1016  962  983  993  991
 990 1010  973 1032  968 1018 1037  976  979
 975 1000 1006 1016  960  982 1005 1016
1027  959 1127  981  979 1002 1019
 968 1007  967  965  956  990
1010 1026  958  971 1029
 998  985  982 1029
1000  981 1005
 981  980
1040

 512 1023 1023 1023 1023 1023 1023 1023 1023 1023  480                                        (8)
 480 1023 1023 1023 1023 1023 1023 1023 1023 1023
 496 1023 1023 1023 1023 1023 1023 1023 1023
 512 1023 1023 1023 1023 1023 1023 1023
 480 1023 1023 1023 1023 1023 1023
 512 1023 1023 1023 1023 1023
 544 1023 1023 1023 1023
 464 1023 1023 1023
 424 1023 1023
 448 1023
 464

3303 2821 1833 1168 1496 1484 1519 1653 1835 2759 3296                                        (9)
3314 2919 1861 1689 1475 1502 1413 1558 1859 2721
3262 2903 1875 1683 1432 1483 1550 1523 1798
3292 2842 1922 1631 1395 1404 1469 1595
3285 2778 2159 1556 1437 1446 1506
3270 2846 1826 1520 1390 1421
3283 2897 1827 1551 1541
3289 2878 1898 1663
3278 2870 1919
3251 2809
3280
```

A3.3.2 Representation of Calibration file contents

The set of inter-electrode pair coefficients in data sets 6 to 9 form a triangular measurement sequence (the measurement order) as displayed in the table below, in which 1-2 means the measurement which corresponds to the capacitance measured between electrodes 1 and 2 etc.

Electrode-pair combinations

1-2, 1-3, 1-4, 1-5, 1-6, 1-7, 1-8, 1-9, 1-10, 1-11, 1-12,
2-3, 2-4, 2-5, 2-6, 2-7, 2-8, 2-9, 2-10, 2-11, 2-12,
3-4, 3-5, 3-6, 3-7, 3-8, 3-9, 3-10, 3-11, 3-12,
4-5, 4-6, 4-7, 4-8, 4-9, 4-10, 4-11, 4-12,
5-6, 5-7, 5-8, 5-9, 5-10, 5-11, 5-12,
6-7, 6-8, 6-9, 6-10, 6-11, 6-12,
7-8, 7-9, 7-10, 7-11, 7-12,
8-9, 8-10, 8-11, 8-12,
9-10, 9-11, 9-12,
10-11, 10-12,
11-12

A3.3.3 Calibration file characteristics

In the case of the low-level permittivity balance coefficients, all of the data should be approximately equal to the the nominal ADC count for 1V (around 1000).

The low-permittivity offset coefficients required to achieve a nominal 1V output form a pattern. Each vertical column should contain approximately equal value coefficients, but these nominal values will differ for each column.

The high-level permittivity balance coefficients should ideally all be around the nominal value for 4V output. However, it will not be possible to achieve this output voltage for all combinations of electrodes because of the finite gain available.

The high level permittivity gain coefficients should again form a pattern, with similar nominal values in each vertical column. If all of the coefficients are 1023, this indicates that the system is working at maximum gain and that the nominal 4V level is not achievable.

The 11 zero balance coefficients should all be around the nominal value for 1V.

The 11 zero offset coefficients should have broadly similar values, but these will depend on the uniformity of the capacitance sensing electronic circuitry.

Large deviations from the expected values may be an indication of wrong connections of cables to electrodes, or of improper/unreliable connections, etc. Faulty electrodes can be identified by marking coefficients which deviate from the expected values and by using table 1 to identify the problem electrodes or channels. Alternatively, the Diagnostic test program can be used to rapidly identify faulty electrodes or measurement channels.

A3.4 SENSITIVITY MATRIX FILES

The **sensitivity matrix file**, which is created by external software, forms the basis of most linear image reconstruction methods. The sensitivity matrices are binary files with the generic names SSME-P.SIF where E is the number of electrodes in the sensor and P is the number of pixels in one line of the square pixel grid. At present, there are two sets of these files, one for normal use and one for use when imaging pure water. Sets of sensor sensitivity maps are held in the Configure folder of the ECT32 software.

A3.4.1 Data file format

The **sensitivity matrix** consists of **m** sets of **sensitivity maps**, each containing **n** pixels, where **m** is the **number of unique inter-electrode capacitance pairs** and **n** is **the number of pixels in each ECT image frame**.

Each sensitivity map corresponds to one pair of electrodes. Elements in a sensitivity map correspond to individual pixels in the image area including the 'corners' outside the imagein the case of circular vessels. In this case, only elements inside the circle (non-zero entries) are used, the others are ignored by the software.

Sensitivity maps for individual electrode pairs are stored in **measurement order** in the **sensitivity matrix**.

We use the following convention for naming sensitivity matrices:

(NAME)E_P.SIF

where:

Name is a suitable descriptor,

E is the number of measurement electrodes

P is the number of pixels along one row odf the image (= $N^{0.5}$ where N is the number of pixels in the image)

A3.4.2 Viewing sensitivity map files

Sensitivity matrix files can be viewed as sets of sensitivity maps, using a binary file editor such as "Norton Commander" or by using the ect_smapplot utility in the supplied MATECT software which runs under Matlab.

When the files are viewed on the screen in hex format, each coefficient is a group of 4 hex number pairs. The coefficients are listed in the order of pixels:

S1-2(k) (k =1 to 1024)
S1-3(k) (k =1 to 1024)
.
.
S11-12(k) (k = 1 to 1024)

The pixel number k refers to the pixel in the 32 X 32 grid shown in figure 17 in the following way:

Pixel 1 is at row 1, column 1
Pixel 2 is at row 1, column 2
.
.
Pixel 32 is at row 1, column 32
Pixel 33 is at row 2, column 1
.
.
Pixel 1024 is at row 32, column 32.

A3.5 CAPTURED DATA FILE

A3.5.1 Introduction

These files contain frames of normalised inter-electrode capacitance data and have the default extension .BCP. The data is stored in **binary format** as a series of ‘data frames’ preceded by a file header. The header contains sufficient information to permit the correct interpretation of the remaining data as frames and to replay them in the application’s ‘Playback’ mode. Frames are stored as normalised capacitances rather than images, so that the original measurement data are saved. This allows images to be reconstructed retrospectively, using any desired image reconstruction algorithm and with arbitrary resolution. Capacitance values are normalised to the range 0-0xFFF. Negative values can occur in the file as well as values higher than 0xFFF.

As well as the stored capacitance values, the data files contain other information, including the number of electrodes, number of measurements in each frame, number of frames stored in the file, and the time between frames. Provision has also been made for storing the upper and lower calibration values of permittivity, although this feature is not functional at present.

The data is stored in binary format as a sequence of 8 bit bytes. As it is not easy to view these binary files directly, a file conversion facility is included in the ECT32 software to convert these files to ASCII format, which allows them to be viewed using a simple text editor.

A3.6 IMAGE DATA FILE

The image file is an **ASCII** file containing the numeric values of all pixels of a single frame or a series of frames. These files are produced by selecting **image** in the **converted data typ**e selection box which appears when the **Generate ASCII data files** option is selected in the **File** menu of the ECT32 software. The image file contains data for one or more images. The default extension of an image file name is .**AIM** (Ascii IMage) .

The format of the files is a set of **P X P** numbers corresponding to the numeric value of each pixel in the image, where **P** is the set resolution (eg 32 pixels). The numbers are formatted in a square table (number of columns and rows are equal), and separated within rows by **TAB** characters. The pixels are in row order, with the top left hand pixel at the start of the data file and the bottom right pixel at the end of the data file. For circular vessels, regions outside the sensor (with zero entries in the sensitivity map file) are filled with zeros. The numbers are stored with a precision of three digits after the decimal point.

The pixel data is normalised and lies nominally in the range 0 (lower permittivity limit) to 1 (higher permittivity limit). However, this situation will only apply if the sensor is full or empty when the simple linear back-projection image reconstruction algorithm supplied with the software is used. For partially-filled sensors, the electric field distribution will be distorted, causing errors in the images. In these circumstances, pixel values outside the range 0 - 1 will occur. Note, that negative values can occur in this file as well as values higher than 1. This is a result of the field distortion in the sensor which is highlighted by the backprojection reconstruction technique.

Each image frame is preceded by a pair of integer numbers, the frame number and a time stamp which shows the frame time in milliseconds from the start of data collection.

If the image file contains more than one image, subsequent data sets follow immediately without any delimiters.

A typical image file is shown on the following page.

Data type: ASCII

File extension: .AIM

The data in this file is the **normalised image pixel permittivity values** in the nominal range 0 to 1. Each frame starts with a time stamp giving the elapsed time in milliseconds from the first frame.

Sample file: (2 frames)

```
## Image (normalised permittivity) data file
## Created by: ECT32 for Windows95 Beta 1.05(Sep 14 1998 04:23:37)
## Source: demo1.cap
##    Description:
##    Date: 12:16:17 , 12Oct98
## Electrodes = 12, Measurements = 66, pixels = 820
## Data for Plane 1

## frame 0, 0 msec
0 0 0 0 0 0 0 0 0 0 0 0.998 0.999 1.005 1.007 1.012 1.012 1.010 1.006 1.000 0.991 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0.998 0.999 1.001 1.002 1.002 1.005 1.008 1.011 1.008 1.006 1.003 1.001 0.998 0.997 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 1.002 1.005 1.004 1.002 1.001 0.999 1.002 1.006 1.008 1.009 1.008 1.006 1.001 1.000 1.001 1.003 1.008 0.995 0 0 0 0 0 0 0
0 0 0 0 0 0 1.005 1.007 1.007 1.003 1.002 1.000 1.001 1.001 1.000 1.003 1.005 1.004 1.002 1.002 0.998 0.999 0.994 0.995 0.999 0.998 0 0 0 0 0 0
0 0 0 0 0 1.001 1.003 1.005 1.008 1.003 1.007 0.999 0.999 0.996 0.999 1.000 1.000 0.999 0.993 0.992 0.989 0.991 0.993 0.998 0.981 0.968 0.949 0 0 0 0 0
0 0 0 0 0.999 0.997 1.003 1.002 1.008 1.001 1.007 0.998 0.999 0.993 0.992 0.987 0.988 0.986 0.983 0.982 0.979 0.982 0.967 0.968 0.959 0.951 0.933 0.921 0 0 0 0
0 0 0 0.996 0.996 0.998 0.998 1.000 1.003 0.996 1.000 0.994 0.990 0.986 0.982 0.978 0.976 0.967 0.963 0.961 0.956 0.951 0.937 0.933 0.928 0.925 0.905 0.904 0.895 0 0 0
0 0 0.997 0.997 0.996 0.993 0.995 1.000 0.996 0.997 0.993 0.989 0.983 0.975 0.969 0.961 0.954 0.942 0.932 0.929 0.921 0.919 0.900 0.903 0.886 0.891 0.872 0.883 0.861 0.854 0 0
0 0 1.000 0.997 0.995 0.994 0.992 0.993 0.989 0.991 0.983 0.985 0.971 0.960 0.949 0.937 0.927 0.914 0.905 0.893 0.883 0.868 0.850 0.855 0.836 0.849 0.824 0.842 0.833 0.862 0 0
0 1.000 1.001 0.997 0.994 0.990 0.987 0.986 0.985 0.981 0.979 0.970 0.959 0.946 0.930 0.909 0.899 0.866 0.867 0.836 0.819 0.826 0.841 0.813 0.814 0.825 0.818 0.850 0.853 0.858 0.866 0
0 1.001 1.000 0.997 0.992 0.989 0.985 0.980 0.977 0.973 0.967 0.955 0.944 0.924 0.908 0.877 0.863 0.847 0.840 0.825 0.789 0.760 0.786 0.782 0.805 0.795 0.803 0.806 0.855 0.865 0.900 0
0.989 1.000 0.998 0.993 0.988 0.984 0.979 0.975 0.971 0.966 0.955 0.937 0.926 0.909 0.884 0.874 0.838 0.828 0.792 0.769 0.768 0.749 0.766 0.739 0.781 0.781 0.833 0.847 0.893 0.906 0.920 0.938
0.997 0.997 0.994 0.991 0.984 0.981 0.972 0.969 0.960 0.956 0.944 0.936 0.907 0.896 0.860 0.846 0.800 0.788 0.769 0.755 0.745 0.728 0.754 0.752 0.801 0.816 0.837 0.865 0.908 0.927 0.951 0.952
0.994 0.993 0.990 0.985 0.979 0.974 0.967 0.966 0.953 0.948 0.927 0.919 0.891 0.878 0.847 0.825 0.801 0.775 0.739 0.729 0.737 0.734 0.754 0.764 0.783 0.835 0.885 0.908 0.939 0.956 0.968 0.982
0.991 0.989 0.986 0.981 0.976 0.970 0.961 0.956 0.943 0.939 0.926 0.908 0.900 0.864 0.826 0.800 0.785 0.748 0.747 0.749 0.746 0.756 0.768 0.803 0.841 0.884 0.911 0.939 0.957 0.985 0.987 0.991
0.990 0.989 0.984 0.978 0.971 0.970 0.962 0.953 0.950 0.931 0.928 0.896 0.889 0.848 0.837 0.787 0.822 0.772 0.744 0.755 0.764 0.787 0.805 0.842 0.868 0.915 0.935 0.974 0.983 1.005 1.005 1.014
0.990 0.988 0.982 0.982 0.975 0.965 0.959 0.943 0.942 0.921 0.920 0.896 0.891 0.842 0.847 0.831 0.774 0.781 0.770 0.789 0.805 0.824 0.849 0.887 0.916 0.948 0.971 0.996 1.001 1.013 1.011 1.013
0.994 0.993 0.987 0.978 0.970 0.967 0.963 0.951 0.941 0.928 0.918 0.892 0.890 0.866 0.845 0.826 0.808 0.793 0.802 0.813 0.832 0.858 0.880 0.912 0.948 0.971 0.997 1.015 1.014 1.013 1.010 1.010
0.996 0.995 0.994 0.988 0.978 0.973 0.959 0.946 0.935 0.933 0.916 0.908 0.886 0.881 0.858 0.851 0.828 0.830 0.836 0.848 0.867 0.888 0.921 0.942 0.979 0.999 1.015 1.016 1.019 1.013 1.008 1.006
0.996 0.998 0.992 0.988 0.975 0.969 0.964 0.961 0.943 0.944 0.920 0.922 0.897 0.893 0.872 0.865 0.858 0.855 0.856 0.866 0.892 0.915 0.951 0.973 1.004 1.015 1.031 1.026 1.022 1.013 1.005 1.004
0.998 0.998 0.995 0.990 0.980 0.976 0.964 0.961 0.943 0.947 0.935 0.928 0.908 0.906 0.894 0.886 0.879 0.873 0.889 0.902 0.921 0.942 0.971 0.996 1.017 1.028 1.038 1.030 1.023 1.012 1.004 1.022
0 0.996 0.993 0.989 0.980 0.976 0.971 0.969 0.963 0.954 0.944 0.934 0.927 0.924 0.910 0.902 0.896 0.901 0.912 0.917 0.939 0.959 0.989 1.011 1.026 1.040 1.045 1.034 1.025 1.014 1.008 0
0 0.993 0.995 0.990 0.988 0.980 0.978 0.971 0.967 0.963 0.955 0.941 0.938 0.933 0.918 0.924 0.915 0.919 0.927 0.944 0.958 0.984 1.003 1.024 1.034 1.043 1.041 1.039 1.029 1.019 1.012 0
0 0 0.995 0.992 0.990 0.982 0.983 0.975 0.975 0.963 0.963 0.957 0.955 0.947 0.942 0.938 0.932 0.939 0.936 0.955 0.967 0.990 1.010 1.027 1.040 1.052 1.047 1.044 1.033 1.026 0 0
0 0 0.992 0.994 0.995 0.991 0.990 0.982 0.983 0.974 0.973 0.965 0.961 0.958 0.954 0.956 0.948 0.953 0.953 0.971 0.983 1.003 1.020 1.034 1.049 1.049 1.047 1.045 1.038 1.024 0 0
0 0 0 0.996 0.997 0.995 0.994 0.989 0.981 0.980 0.977 0.977 0.974 0.970 0.968 0.966 0.961 0.965 0.966 0.977 0.987 1.004 1.018 1.039 1.048 1.051 1.054 1.047 1.040 0 0 0
0 0 0 0 0.998 0.997 0.996 0.992 0.987 0.986 0.980 0.980 0.977 0.976 0.977 0.977 0.972 0.972 0.975 0.978 0.996 1.015 1.019 1.042 1.047 1.054 1.048 1.053 0 0 0 0
0 0 0 0 0 0.999 0.997 0.997 0.990 0.988 0.986 0.987 0.986 0.986 0.986 0.981 0.981 0.976 0.983 0.983 0.997 1.014 1.022 1.045 1.049 1.054 1.053 0 0 0 0 0
0 0 0 0 0 0 0.995 0.995 0.992 0.991 0.988 0.990 0.990 0.992 0.994 0.990 0.989 0.984 0.990 0.992 1.001 1.012 1.019 1.039 1.047 1.053 0 0 0 0 0 0
0 0 0 0 0 0 0 0.996 0.992 0.991 0.990 0.994 0.996 0.998 0.999 0.998 0.992 0.991 0.994 0.996 1.001 1.014 1.026 1.036 1.030 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0.989 0.994 0.996 0.998 1.003 1.002 1.002 0.997 0.996 0.996 0.999 1.004 1.005 1.005 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 1.000 1.000 1.003 1.004 1.004 1.002 0.999 0.997 0.997 0.998 0 0 0 0 0 0 0 0 0 0 0

## frame 1, 33 msec
0 0 0 0 0 0 0 0 0 0 0 0.997 1.000 1.007 1.010 1.016 1.015 1.012 1.007 1.001 0.991 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0.994 0.996 1.000 1.002 1.003 1.007 1.011 1.014 1.010 1.007 1.003 1.001 0.998 0.996 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0.998 1.002 1.001 0.999 0.999 0.998 1.003 1.007 1.010 1.011 1.010 1.007 1.001 1.000 1.001 1.002 1.008 0.995 0 0 0 0 0 0 0
0 0 0 0 0 0 1.003 1.004 1.003 0.999 0.998 0.997 0.999 1.000 1.000 1.004 1.006 1.005 1.002 1.002 0.998 0.998 0.993 0.995 0.999 0.999 0 0 0 0 0 0
0 0 0 0 0 1.000 1.001 1.003 1.005 0.999 1.001 0.995 0.995 0.994 0.998 1.000 1.001 1.001 0.993 0.992 0.988 0.990 0.993 0.999 0.981 0.968 0.949 0 0 0 0 0
0 0 0 0 0.999 0.996 1.002 1.000 1.005 0.997 1.001 0.993 0.994 0.990 0.990 0.986 0.988 0.986 0.983 0.982 0.978 0.982 0.967 0.968 0.958 0.951 0.933 0.920 0 0 0 0
0 0 0 0.997 0.997 0.998 0.998 0.999 1.000 0.993 0.995 0.989 0.985 0.982 0.979 0.976 0.975 0.966 0.962 0.960 0.955 0.950 0.935 0.932 0.927 0.924 0.904 0.903 0.894 0 0 0
0 0 0.997 0.997 0.996 0.993 0.994 1.000 0.994 0.994 0.989 0.985 0.979 0.971 0.966 0.959 0.952 0.941 0.931 0.928 0.919 0.917 0.898 0.902 0.885 0.889 0.870 0.881 0.859 0.851 0 0
0 0 1.000 0.997 0.996 0.994 0.993 0.993 0.988 0.989 0.980 0.982 0.968 0.957 0.946 0.935 0.925 0.913 0.904 0.892 0.881 0.865 0.847 0.853 0.833 0.846 0.821 0.839 0.830 0.859 0 0
0 1.000 1.001 0.997 0.995 0.991 0.988 0.987 0.986 0.981 0.978 0.969 0.957 0.944 0.929 0.909 0.899 0.865 0.866 0.835 0.817 0.823 0.838 0.810 0.810 0.822 0.814 0.847 0.851 0.855 0.864 0
0 1.000 1.000 0.997 0.993 0.991 0.987 0.982 0.979 0.974 0.969 0.955 0.944 0.923 0.908 0.878 0.864 0.847 0.840 0.824 0.787 0.756 0.783 0.778 0.802 0.792 0.800 0.802 0.853 0.863 0.898 0
0.989 1.000 0.998 0.994 0.989 0.986 0.981 0.978 0.974 0.969 0.957 0.939 0.927 0.911 0.886 0.875 0.839 0.828 0.792 0.768 0.766 0.746 0.763 0.736 0.777 0.776 0.830 0.845 0.891 0.905 0.919 0.938
0.997 0.997 0.994 0.992 0.985 0.982 0.974 0.972 0.963 0.959 0.948 0.940 0.911 0.899 0.863 0.848 0.802 0.789 0.770 0.755 0.744 0.726 0.751 0.748 0.798 0.813 0.834 0.862 0.907 0.927 0.951 0.952
0.994 0.993 0.991 0.986 0.980 0.976 0.970 0.969 0.957 0.952 0.932 0.923 0.895 0.882 0.850 0.828 0.804 0.777 0.741 0.729 0.736 0.731 0.751 0.760 0.780 0.832 0.883 0.906 0.938 0.956 0.969 0.982
0.992 0.990 0.987 0.982 0.977 0.971 0.964 0.959 0.946 0.943 0.930 0.913 0.905 0.869 0.830 0.804 0.788 0.751 0.748 0.749 0.746 0.754 0.765 0.800 0.838 0.882 0.909 0.938 0.956 0.985 0.988 0.992
0.991 0.990 0.984 0.979 0.972 0.971 0.963 0.955 0.953 0.935 0.933 0.901 0.894 0.854 0.841 0.792 0.824 0.774 0.746 0.755 0.763 0.786 0.803 0.839 0.864 0.913 0.933 0.973 0.983 1.006 1.006 1.016
0.991 0.989 0.982 0.982 0.975 0.966 0.960 0.946 0.945 0.926 0.925 0.901 0.896 0.847 0.851 0.834 0.777 0.783 0.772 0.789 0.804 0.821 0.846 0.884 0.914 0.946 0.970 0.996 1.001 1.014 1.012 1.014
0.995 0.994 0.987 0.979 0.971 0.968 0.965 0.953 0.944 0.932 0.922 0.897 0.894 0.870 0.849 0.828 0.810 0.794 0.802 0.812 0.830 0.856 0.877 0.909 0.946 0.969 0.995 1.015 1.015 1.013 1.011 1.011
0.996 0.995 0.994 0.988 0.979 0.974 0.961 0.950 0.940 0.937 0.921 0.913 0.890 0.884 0.860 0.852 0.828 0.830 0.836 0.848 0.866 0.886 0.919 0.940 0.976 0.997 1.014 1.015 1.019 1.013 1.009 1.006
0.996 0.998 0.992 0.988 0.976 0.971 0.966 0.964 0.948 0.948 0.926 0.927 0.901 0.895 0.873 0.864 0.857 0.853 0.855 0.863 0.889 0.913 0.949 0.971 1.002 1.013 1.029 1.025 1.022 1.013 1.005 1.004
0.998 0.998 0.995 0.991 0.982 0.978 0.968 0.966 0.949 0.952 0.940 0.933 0.911 0.908 0.894 0.883 0.876 0.869 0.885 0.899 0.919 0.939 0.969 0.993 1.016 1.027 1.037 1.029 1.023 1.012 1.004 1.023
0 0.997 0.994 0.990 0.982 0.979 0.975 0.973 0.968 0.960 0.950 0.939 0.929 0.924 0.907 0.898 0.890 0.895 0.907 0.911 0.936 0.956 0.987 1.009 1.024 1.039 1.045 1.034 1.025 1.013 1.008 0
0 0.994 0.995 0.992 0.989 0.983 0.982 0.976 0.973 0.969 0.961 0.945 0.940 0.931 0.913 0.918 0.908 0.912 0.921 0.940 0.954 0.981 1.001 1.023 1.033 1.042 1.040 1.039 1.028 1.019 1.011 0
0 0 0.995 0.993 0.991 0.986 0.986 0.981 0.980 0.970 0.968 0.961 0.956 0.945 0.937 0.930 0.922 0.931 0.929 0.949 0.962 0.988 1.007 1.026 1.039 1.051 1.046 1.044 1.032 1.026 0 0
0 0 0.994 0.995 0.995 0.994 0.993 0.987 0.987 0.980 0.977 0.968 0.960 0.954 0.948 0.949 0.938 0.944 0.946 0.965 0.979 1.000 1.018 1.032 1.049 1.048 1.047 1.045 1.037 1.023 0 0
0 0 0 0.997 0.997 0.996 0.995 0.992 0.986 0.984 0.980 0.979 0.974 0.967 0.962 0.958 0.952 0.957 0.958 0.972 0.983 1.001 1.017 1.038 1.047 1.051 1.054 1.046 1.039 0 0 0
0 0 0 0 0.999 0.998 0.998 0.994 0.990 0.989 0.982 0.981 0.976 0.972 0.971 0.971 0.965 0.964 0.969 0.972 0.993 1.013 1.018 1.042 1.047 1.054 1.048 1.053 0 0 0 0
0 0 0 0 0 0.999 0.998 0.998 0.991 0.989 0.987 0.987 0.985 0.983 0.981 0.975 0.975 0.969 0.978 0.978 0.994 1.012 1.022 1.045 1.050 1.054 1.053 0 0 0 0 0
0 0 0 0 0 0 0.995 0.994 0.992 0.991 0.988 0.990 0.989 0.990 0.992 0.986 0.985 0.980 0.987 0.990 0.999 1.012 1.019 1.039 1.048 1.053 0 0 0 0 0 0
0 0 0 0 0 0 0 0.996 0.992 0.991 0.990 0.993 0.995 0.997 0.997 0.995 0.988 0.989 0.993 0.994 1.000 1.014 1.027 1.036 1.030 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0.988 0.994 0.996 0.998 1.002 1.001 1.001 0.995 0.995 0.995 0.998 1.004 1.005 1.005 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 1.001 1.000 1.001 1.001 1.000 0.999 0.997 0.995 0.996 0.998 0 0 0 0 0 0 0 0 0 0 0

##EOF
```

A3.7. NORMALISED CAPACITANCE DATA FILE

These files are produced by selecting **normalised capacitance** in the **converted data typ**e selection box which appears when the **Generate ASCII data files** option is selected in the **File** menu of the ECT32 software. The file cntains **ASCII** data for all normalised capacitances of a single frame or series of frames and the default file name extension is **.ANC** (Ascii Normalised Capacitance).

The capacitance values are normalised in the nominal range [0,1]. When the sensor is filled with the medium used for the low-permitivity calibration, the resulting capacitances are set to be equal to zero. The capacitance values are set to 1 when the sensor is filled the with high-permitivity medium used for calibration. The numbers are stored in measurement order in the file with rows separated by newline sequences. The precision of the numbers is 3 digits after the decimal point. If more than one frame of data is stored, subsequent frame records follow.

For a 12 electrode system, there will be 66 values of capacitance, stored in the order:

C12, C13, ...C1N
C23...C2N
C34... etc.

Each capacitance data frame is preceded by an integer number which is a time stamp which shows the frame time in milliseconds from the start of data collection. A sample data file containing 2 frames of data, is shown below.

Data type: ASCII

File extension: .ANC

The data in this file is the **normalised inter-electrode capacitance values** in the nominal range 0 to 1. Each frame starts with a time stamp giving the elapsed time in milliseconds from the first frame.

Sample file: (2 frames)

```
## Normalised capacitance data file
## Created by: ECT32 for Windows95 Beta 1.05(Sep 14 1998 04:23:37)
## Source: demo1.cap
##    Description:
##    Date: 12:16:17 , 12Oct98
## Electrodes = 12, Measurements = 66
## Data for Plane 1


## frame 0 (0 msec)
1.000 1.085 0.981 0.987 0.939 0.970 0.984 1.022 0.969 0.974 0.946
1.055 0.990 0.987 0.977 0.966 1.000 1.023 1.035 1.020 0.939
1.000 0.970 0.979 0.979 1.022 1.015 1.012 1.000 0.833
0.999 0.998 1.001 1.031 1.086 1.020 1.005 0.723
1.000 0.983 1.010 1.047 1.005 0.956 0.630
1.000 0.987 1.002 1.002 0.963 0.608
1.000 0.987 0.978 0.969 0.628
1.000 0.995 0.974 0.705
1.000 0.977 0.830
1.001 0.933
0.942

## frame 1 (33 msec)
1.000 1.086 0.980 0.975 0.939 0.972 0.995 1.016 0.973 0.975 0.946
1.055 0.986 0.980 0.988 0.980 1.005 1.002 1.037 1.022 0.935
1.000 0.964 0.980 0.966 1.027 1.019 1.035 1.002 0.822
0.999 1.005 1.001 1.022 1.067 1.012 0.991 0.715
1.000 0.986 1.012 1.051 1.021 0.963 0.642
1.000 0.985 1.005 0.998 0.970 0.603
1.000 0.987 0.987 0.971 0.619
1.000 0.993 0.973 0.711
1.000 0.971 0.813
1.001 0.932
0.942

##EOF
```

A3.8 ABSOLUTE CAPACITANCE DATA FILE

These files contain **absolute inter-electrode capacitance values** in **femtofarads** in ASCII format for one or more frames and are produced by selecting **absolute capacitance** in the **converted data typ**e selection box which appears when the **Generate ASCII data files** option is selected in the **File** menu of the ECT32 software. The file format is similar to the normalised capacitance file. The only difference is that the numbers are now absolute capacitances in femtofarads. The default file name extension is **.AAC**.

As for the normalised capacitance files, each capacitance data frame is preceded by an integer number which is a time stamp which shows the frame time in milliseconds from the start of data collection.

Data type: ASCII **File extension: .AAC**

A sample data file containing 2 frames of data, is shown below.

Sample file: (2 frames)

```
## Absolute capacitance data file
## Created by: ECT32 for Windows95 Beta 1.05(Sep 14 1998 04:23:37)
## Source: demo1.cap
##   Description:
##   Date: 12:16:17 , 12Oct98
## Electrodes = 12, Measurements = 66
## Data for Plane 1

## frame 0 (0 msec)
386.02 36.65 16.60 11.08 7.53 6.96 8.06 11.08 17.30 40.66 407.26
267.80 37.24 17.20 9.69 7.73 7.79 8.77 11.19 17.48 34.74
467.01 36.97 16.32 10.42 8.38 7.82 8.62 11.39 15.27
270.47 37.22 17.17 10.93 8.37 7.79 9.01 9.35
309.01 37.53 17.08 10.55 8.04 7.95 6.91
320.94 37.60 17.15 10.61 8.17 6.35
263.83 37.40 16.87 10.40 7.01
320.96 36.66 16.43 9.24
282.44 36.88 15.70
270.47 36.52
469.66

## frame 1 (33 msec)
386.02 36.67 16.59 11.04 7.53 6.96 8.10 11.06 17.33 40.68 407.26
267.80 37.18 17.15 9.73 7.78 7.80 8.71 11.20 17.49 34.69
467.01 36.88 16.32 10.37 8.40 7.83 8.70 11.40 15.20
270.47 37.32 17.17 10.89 8.31 7.76 8.96 9.32
309.01 37.57 17.09 10.57 8.10 7.98 6.95
320.94 37.57 17.16 10.60 8.19 6.33
263.83 37.40 16.93 10.40 6.98
320.96 36.64 16.42 9.26
282.44 36.80 15.60
270.47 36.50
469.66
```

A3.9 VOLUME RATIO DATA FILE

This file contains the volume ratio in % for each frame.
This file contains the volume ratio in % for each frame.

Data type: ASCII

File extension: .AVR

The data in this file is the **volume ratio (concentration)** for each frame of data. and these files are produced by selecting **volume ratio** in the **converted data typ**e selection box which appears when the **Generate ASCII data files** option is selected in the **File** menu of the ECT32 software.

The data is listed in groups of 3 numbers. The **first** number is the **elapased time** in milliseconds from the first frame, the **second** number is the **volume ratio % calulated from the normalised capacitances** and the **third** number is the **volume ratio % calculated from the image pixels**.

Sample file: (10 frames)

```
## Volume ratio data file
## Created by: ECT32 for Windows95 Beta 1.05(Sep 14 1998 04:23:37)
## Source: demo1.cap
##    Description:
##    Date: 12:16:17 , 12Oct98
## Electrodes = 12, Measurements = 66
## Data for Plane 1
## Time        CVR    IVR
0       96      95
33      96      95
66      96      94
99      96      94
132     96      95
165     96      957
198     96      95
231     96      94
264     96      94
297     96      95
330     96      95

##EOF
```

APPENDIX 4

THE DAM200E CAPACITANCE MEASUREMENT UNIT

A4.1 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.

A4.2 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 A4.2.1.

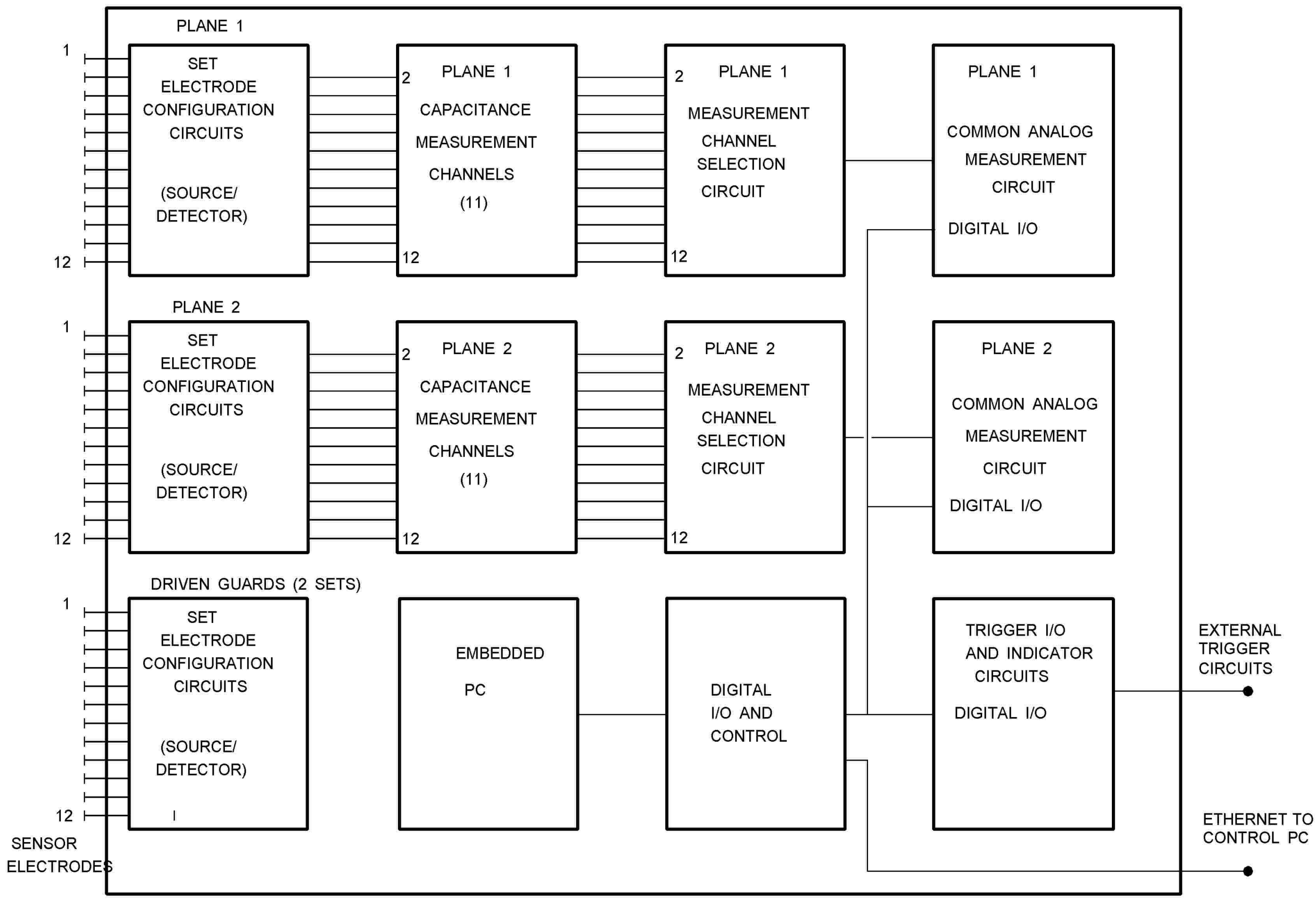


Figure A4.2.1 Component parts of the DAM200E-TP-G Capacitance Measurement Unit

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.

A4.3. CAPACITANCE MEASUREMENT INPUT CIRCUITS

A4.3.1 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 A4.3.1.

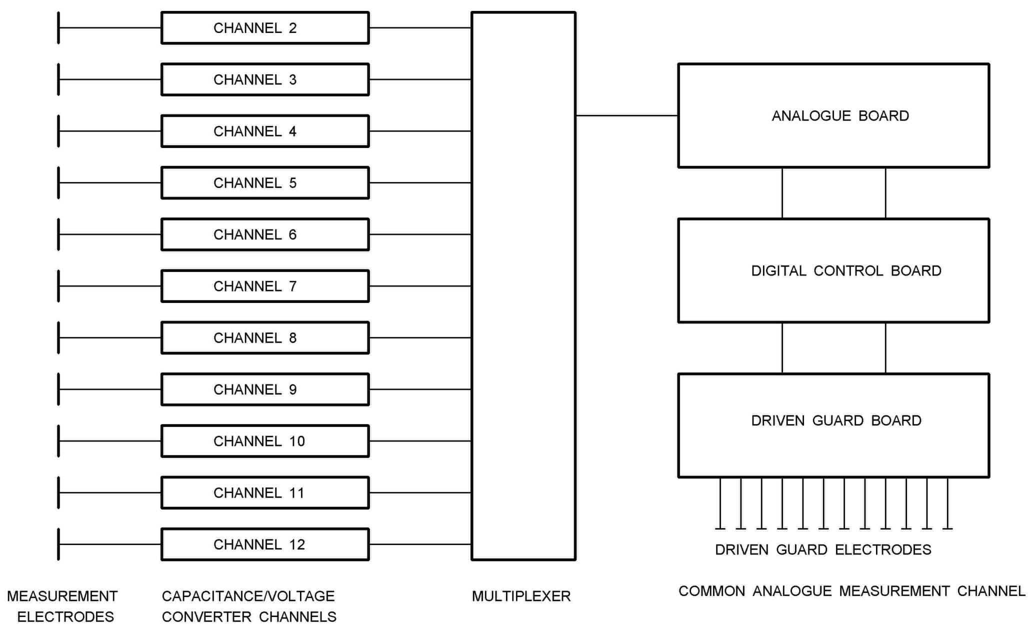


Figure A4.3.1 Capacitance measurement circuitry for a single plane of electrodes

A4.3.2 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 A4.3.2 and works on the **charge transfer principle**, with one electrode of the pair (the **SOURCE** electrode) connected to a high frequency square wave source of amplitude Vs (15V) and frequency f (1.25 MHz), while the other electrode (the **DETECTOR** electrode) is held at virtual ground potential (0V). The current which flows into the second (**DETECTOR)** electrode of Cx (which is held at virtual ground potential) is measured using a synchronous demodulator. This measured current is proportional to the capacitance between the **SOURCE** electrode and the **DETECTOR** electrode of **Cx**.

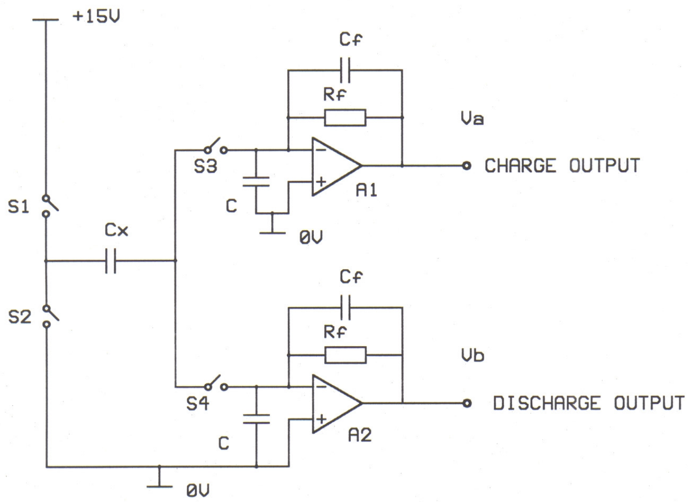


Figure A4.3.2 Basic capacitance to voltage converter circuit

Referring to figure A4.3.2, S1 and S2 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 of the unknown capacitance Cx.

Switches S3 and S4 also operate alternately at the same frequency f but the phasing of the switching waveforms applied to S3 and S4 is in quadrature with the switching waveforms controlling S1 and S2. Consequently, the charging currents for the charging and discharging cycles of Cx 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 ouputs of each amplifier to increase to provide a current through the feedback resistors Rf 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).

The basic operation of the circuit can be understood by considering one half of the circuit, A1 which processes the current pulses which occur during the charging cycle of C_x. As will be demonstrated, the voltage across C, which is made to be much larger than C_x, remains substantially zero.

When C_x is charged by V_s, the stored charge in C_x is simply $V_s.C_x$ Coulombs. Moreover, the same amount of charge will be stored in the capacitance C as both C_x and C are effectively in series.

In one second, there will be f charging cycles (where f is the source excitation frequency), so the total charge stored in C will be $f.V_s.C_x$ Coulombs per second, corresponding to an average charging current of $f.V_s.C_x$ amps.

This accumulation of charge charge causes the voltage across C to rise, causing in turn, an immediate much larger increase in the output voltage of A1 (Vo), which will be of the opposite plarity to that of the voltage across C. This output voltage causes a current $I = V_o/R_f$ to flow into C until the voltage across C has been reduced to zero again.

For equilibrium, the 2 sets of current flowing into C must be equal and of opposite polarity.

Hence we can write:

$$f.Vs.Cx = -Vo/Rf \qquad \text{(A4.1)}$$

giving

$$\mathbf{Vo = -f.Vs.Rf.Cx} \qquad \textbf{(A4.2)}$$

In practice, there will also be a small offset voltage e in addition to the main output voltage. As there are two separate outputs from this circuit, V_a and V_b corresponding to the **CHARGING** and **DISCHARGING** cycles of the circuit, we can write:

$$V_a = -f.V_s.R_f.C_x + e_1 \qquad \text{(A4.3)}$$

$$V_b = f.V_s.R_f.C_x + e_2 \qquad \text{(A4.4)}$$

R_f is the feedback resistance value used in the current detector circuits (figure A4.3.2), 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:

$$V_o = 2.f.V_s.R_f.C_x + e_2 - e_1 \qquad \text{(A4.5)}$$

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

$$V_o = 2.f.V_s.R_f.C_x \qquad \text{(A4.6)}$$

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 electrodse and up to 11 detector electrodes to be measured simultaneously. This relatively simple measuring circuit has most of the desirable properties outlined in paragraph A4.3.1.

A4.4 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 A4.4.1.

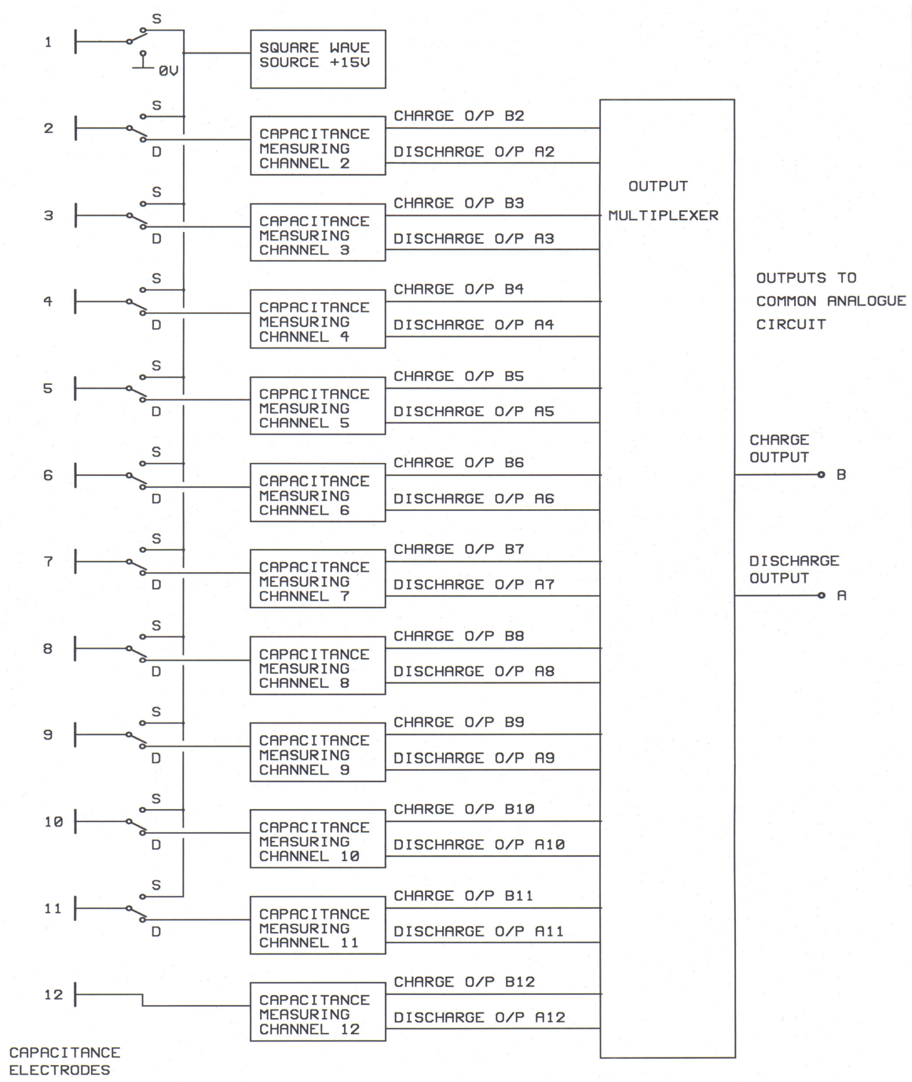


Figure A4.4.1 Electrode control and output multiplexer circuits

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 A4.4.1, 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 A4.4.1.

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 A4.4.1. The multiplexer operates under software control to select the outputs from one measuring channel at a time to the common analogue measurement circuit.

A4.5 CAPACITANCE MEASUREMENT SEQUENCE

A4.5.1 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:

	Source channel
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},	1
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}	2
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}	3
C_{4-5}, C_{4-6}, C_{4-7}, C_{4-8}, C_{4-9}, C_{4-10}, C_{4-11}, C_{4-12}	4
C_{5-6}, C_{5-7}, C_{5-8}, C_{5-9}, C_{5-10}, C_{5-11}, C_{5-12}	5
C_{6-7}, C_{6-8}, C_{6-9}, C_{6-10}, C_{6-11}, C_{6-12}	6
C_{7-8}, C_{7-9}, C_{7-10}, C_{7-11}, C_{7-12}	7
C_{8-9}, C_{8-10}, C_{8-11}, C_{8-12}	8
C_{9-10}, C_{9-11}, C_{9-12}	9
C_{10-11}, C_{10-12}	10
C_{11-12}	11

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 betweeen selecting the output of each successive capacitance measurement channel to the common measurement channel via the multiplexer.

A4.5.2 Capacitance Measurement Control Sequence

The table in paragraph A4.5.1 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 apture 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.

A4.6 THE COMMON ANALOGUE MEASURING CIRCUIT

A4.6.1 OVERVIEW

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 10fF 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.

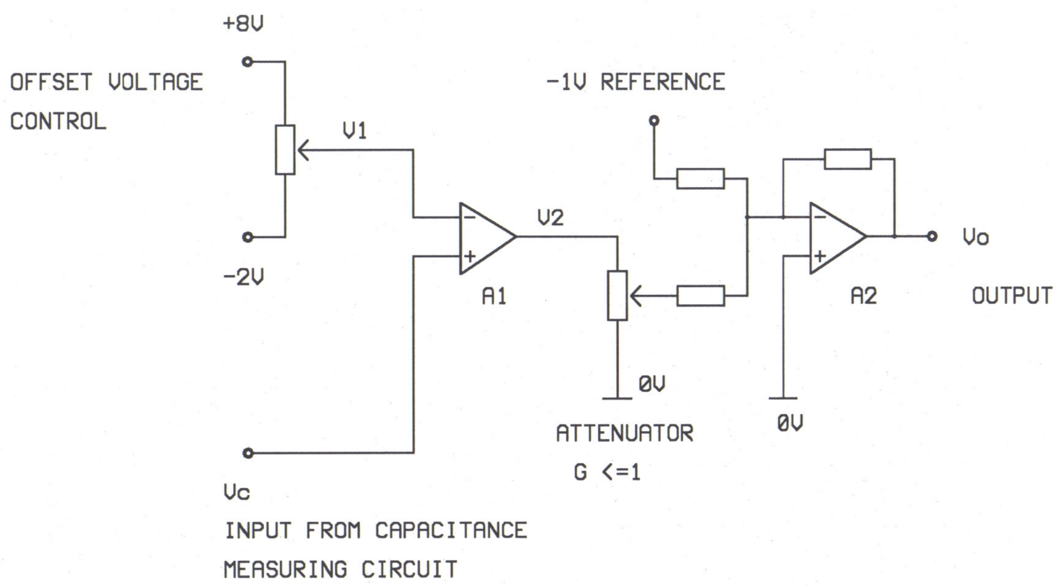


Figure A4.6.1 Simplified common analogue measurement channel

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 A4.6.1.

The circuit operates in the following manner:

1. The measurement circuit takes the form of a DC bridge, shown in simplified form in figure A4.6.1, 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.

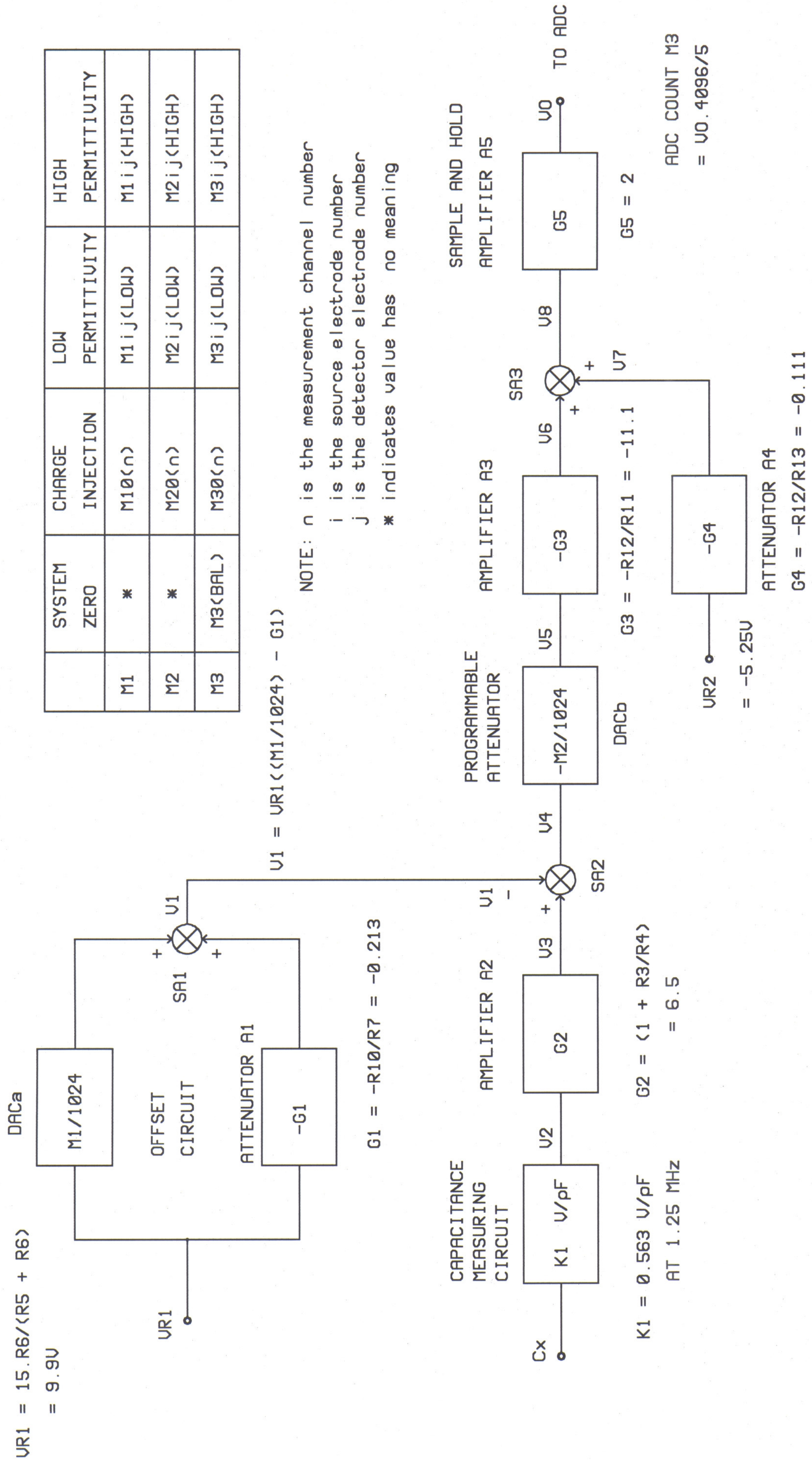
3. The measurement circuit operates by adjusting the programmable attenuator and programmable offset voltage so that, as far as is possible, the ADC output counts are the same for all of the electrode-pair capacitances, whatever their actual values. The programmable offsets and attenuation figures are 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 A4.6.2 and a description is given in section A4.6.3, which derives the measurement system equation which has been repeated below.

$$C_{meas} = (1/(K_1.G_1)).[(1024/ (M_2.G_3)).(5.M_3/(4096.G_5) - VR_2.G_4) + VR_1.(M_1/1024 -G_1)] \qquad (A4.7)$$

The parameters in equation A4.7 are defined in figure A4.6.2.

In practice the common analogue circuit is more complicated than the simplified circuit shown in figure A4.6.1 and the actual circuit is summarised in figure A4.6.2. The next few sections describe the operation of this circuit in more detail.



	SYSTEM ZERO	CHARGE INJECTION	LOW PERMITTIVITY	HIGH PERMITTIVITY
M1	✱	M10(n)	M1ij(LOW)	M1ij(HIGH)
M2	✱	M20(n)	M2ij(LOW)	M2ij(HIGH)
M3	M3(BAL)	M30(n)	M3ij(LOW)	M3ij(HIGH)

Figure A4.6.2 Common analogue measurement circuit (2)

A4.6.2 CIRCUIT CONSTANTS

The values of the individual electronic components referred to in figure A4.6.2 are given below

Vs:	15V
Rf:	15kohm
f:	0.625 MHz (LOW)
	1.25 MHz (HIGH)
R3:	10kohm
R4:	1.82kohm
R5:	5.1kohm
R6:	10kohm
R7:	47kohm
R8:	10kohm
R10:	10kohm
R11:	1.8kohm
R12:	20kohm
R13:	180kohm

VR1:	Vs.(R6/(R5 + R6))
VR2:	5.25V

G1:	R10/R7
G2:	(1 + (R3/R4))
G3:	R12/R11
G4:	R12/R13
G5:	2
K1:	2.Vs.f.Rf

A4.6.3 PRINCIPLE OF OPERATION

The pair of output voltages from the capacitance to voltage converters are selected by the output multiplexer and subtracted in a differential amplifier to give an output voltage Vc where

$$Vc = Vb - Va = 2.f.Vs.Rf.Cx + e2 - e1 \qquad \text{(A4.8)}$$

This output voltage Vc is proportional to the unknown capacitance Cx and becomes the input to the common analogue measurement circuit.

If the two error voltages e1 and e2 are similar, they will partially cancel and the unwanted output due to charge injection will be minimised. However, the residual charge injection output may still be comparable in magnitude with the output due to the unknown capacitance and the method used to measure the unknown capacitance must therefore separate out these two voltages.

The common analogue measurement circuit operates as a computer-controlled bridge which converts the outputs from each capacitance converter circuit into a set of digital integer values, from which the unknown capacitance value can be calculated. The 3 digital values are M1, an offset value in the range 0-1023, M2, an attenuation value in the range 0-1023 and M3, the ADC count, in the range 0-4095. The offset and attenuator circuits are controlled by a 10 bit data bus, which is one of several data buses within the DAM200E unit.

The summed output voltage from the capacitance to voltage measuring circuit Vc, forms one input to a difference amplifier A1. The second input to this amplifier is a variable offset voltage V_1 in the range -2 to +8V obtained from a 10-bit digitally-controlled offset voltage circuit. V_C is measured by balancing it against the voltage V_1 set by a count M1 applied to the offset circuit. When the system is balanced, the output (V_2) from amplifier A1 is zero.

The output of A1 is attenuated by a count M2 applied to a digitally-controlled 10-bit programmable attenuator and the attenuator output becomes one input of the unity gain summing amplifier A2. The second input of A2 is a fixed reference voltage (approximately -1V). These two voltages are summed by amplifier A2.

At balance, the output of the inverting amplifier A2 (V_O) will be approximately +1V (-1 X the reference voltage + any residual circuit offsets) and this voltage is termed the circuit zero balance voltage V_{BAL}. It is measured (using a 12-bit ADC) at the beginning of the calibration procedure and the corresponding ADC count ($M3_{BAL}$) is then used as a reference point for all further measurements.

A4.6.3.1 Capacitance to Voltage circuit output

Referring to figure A1.2, the summed output from the selected capacitance measuring channel Vc = V2 is given by equation 8.2.3 which is repeated here in a modified format:

$$V2 = K1.Cx + e \qquad \text{(A4.9)}$$

where K1 = 2.Vs.f.Rx and e is the residual charge injection offset voltage.

A4.6.3.2 Summing Amplifier SA2

The output voltage V2 is amplified with a gain G2 and the output voltage V3 becomes one input to a summing amplifier SA2.

The second input to SA2 is an offset voltage -V1 derived from a 10-bit digital to analogue converter (DAC) circuit DACa. The offset voltage is set in the range -2 to 8V by the count M1 sent to the 10 bit data bus and is given by the equation:

$$V1 = VR1.((R10/R8).(M1/1024) - R10/R7) \qquad \text{(A4.10)}$$

where VR1 is a reference voltage (approximately 10V) whose actual value is given by the following equation:

$$VR1 = 15.(R6/(R5+R6)) \qquad \text{(A4.11)}$$

and where M1 is the count applied to DACa and R5,R6,R7,R8 and R10 are circuit constants.

A4.6.3.3 Programmable attenuator DACb

The output of SA2, V4, passes to the input of a 10 bit digital attenuator formed by DACb. The output voltage of this attenuator is given by:

$$V5 = -V4.(M2/1024) \qquad (A4.12)$$

where M2 is the count applied to DACb via the 10 bit data bus C. Note that when M2 = 0, the output voltage V5 is zero.

A4.6.3.4 Summing Amplifier SA3

The digital attenuator output V5 is amplified with gain -G3 and forms one input to a summing amplifier SA3.

The second input to SA3 is a voltage, V7 derived from a stable reference voltage VR2 (-5.25V).

$$V7 = -VR2.G5 \qquad (A4.13)$$

A4.6.3.5 Sample and Hold Amplifier A5

The output voltage of SA3, V8 is the sum of V6 and V7 and this passes to a sample and hold (S/H) circuit which has a gain G5 (=2).

A4.6.3.6 ADC

The output of the sample and hold circuit becomes the input of a 12 bit analogue to digital converter (ADC). The output count of this ADC is M3.

A4.6.3.7 System Measurement Equation

It can be readily shown that the output voltage from the common analogue measuring circuit equates to an apparent measured capacitance C_{meas} where:

$$C_{meas} = (1/(K_1.G_1)).[(1024/ (M_2.G_3)).(5.M_3/(4096.G_5) - VR_2.G_4) + VR_1.(M_l/1024 -G_1)]$$

(A4.14)

which is the system measurement equation for the CMU.

A4.7. 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 convereter 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:

A4.7.1 System Zero Balance count M3BAL

The first task is to measure the balance point for the DC bridge circuit in the common anaolgue measurement channel with no input to the bridge ciruit. This is the system zero balance voltage V_{BAL} and is measured as as an equivalent ADC count $M3_{BAL.}$

M3BAL is measured by setting the gain of DACb in figure A4.6.2 to zero (M2 = 0) and by measuring the output voltage V_{BAL} as an equivalent ADC count $M3_{BAL}$. This value of M3 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.

A4.7.2 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 (M2=1023) and electrodes 2 to 12 are set to be 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 V1 is adjusted by varying the count M1 applied to DACa until the ADC count M3 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 C0(n) are then calculated using equation 6.6.1 and the values of M1, M2 and M3 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.

A4.7.3 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 Cmij, 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 M3BAL. The counts M1ij(LOW) for DACa are recorded, as are the actual values of the ADC outputs following balance M3ij(LOW).

The measured capacitance Cijm is calculated using equation 6.6.1 and the values of M1 to M3 to achieve circuit balance.

A4.7.4 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:

$$Cxij = Cijm - C0(n) \qquad \text{(A4.131)}$$

where Cxij is the true capacitance between electrodes i and j, Cijm is the measured inter-electrode capacitance and C0(n) is the measured charge injection capacitance for the measuring channel n = j.

A4.7.5 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 as 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 M10, gain M20 and ADC values M30 with no source electrode selected (the offset capacitances). Then with M10 and M20 set, re-measure the M30 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 M1L, and ADC values M30L for the low-permittivity capacitances. Then with these M1L and M2L values set, re-measure the M3L 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.

A4.8 COMPUTER INTERFACES

The CMU contains an embedded PC which interfaces to the remote control PC via a 10/100 MB/S ethernet link. Figure A4.8.1 shows the CMU connected to the control PC.

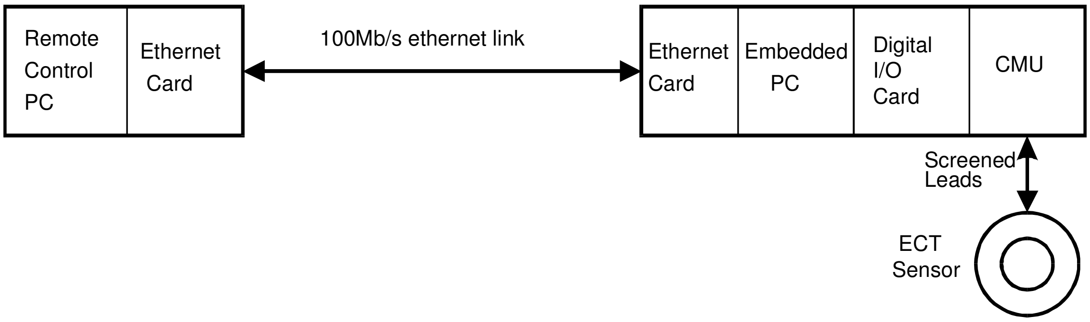


Figure A4.8.1: ECT system showing control interfaces

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.

A4.9 CONTROL SOFTWARE

A4.9.1 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.

A4.9.2 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.

A4.9.3 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.

A4.9.4 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.

APPENDIX 5

TRIGGER INPUT/OUTPUT CIRCUIT AND CONNECTOR

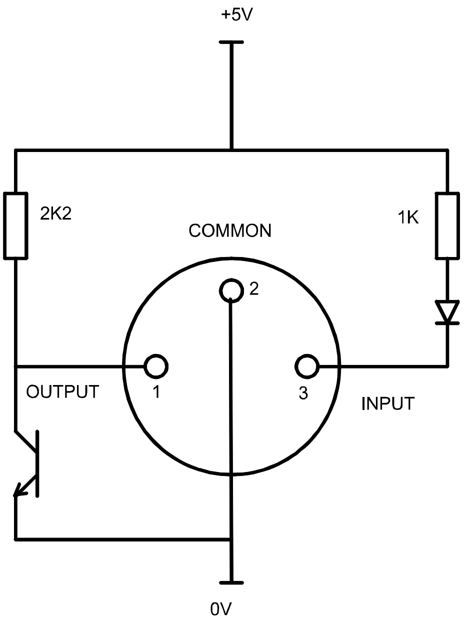


Figure A5.1 Trigger input/output circuit

The trigger input output circuit is shown above and is accessed via a 3-pin DIN connector. The pin-out as shown above is as viewed from the rear of the unit.

Both input and output circuits are opto-isolated from the internal measurement electronics to minimise the chance of interfering signals entering the DAM200E unit.

A trigger input signal is generated by shorting pin 3 to the common pin 2. This can be done using either a mechanical switch or a suitable electronic device. Please contact PTL for further information.

The trigger output signal is generated between pins 1 and 2. When the system is in data capture mode, the trigger output level is low (0v). When the system is not capturing data, the trigger output signal is high (+5V).

Note that the common pin 2 is not connected to the system chassis (earth) and should be kept isolated if possible to minimise the risk of interference entering the system.

APPENDIX 6

CALCULATION OF ABSOLUTE CAPACITANCES FROM NORMALISED VALUES

A6.1 INTRODUCTION

This appendix explains how normalised inter-electrode capacitances stored in, for example **.bcp** data files can be converted into absolute capacitance values.

For conversion to be possible, both the **.bcp** file and the associated **.cal** file must be available.

The conversion may be carried out automatically using the **ECT32 software** by loading the **.bcp** file in the **FILE** menu, selecting the **Generate ASCII Data files** option and then selecting the **absolute capacitance** option in the **ASCII Output File Generation** window. The data is stored on a frame-by frame basis with the readings given in **femtoFarads.** Note that the **calibration file** used to generate the data must be available and must be selected in **the ASCII Output File Generation** window.

A6.2 DETAILS OF CONVERSION PROCEDURE

The following information is given to allow programmers to understand how this conversion procedure is carried out. Sample data files are given in figures A2.1 to A2.3.

For each electrode pair Cij:

1. Calculate the ADC count M3 corresponding to Cij using

$$M3 = Cnorm * (M3H - M3L) + M3L$$

where:

Cnorm is the normalised capacitance between electrodes i and j, obtained from the **.ncp** file (ASCII format) or the **.mes** file (binary format).

M3H is the ADC count for each Cij when the sensor is full of the higher permittivity material (obtained from calibration file).

M3L is the ADC count for each Cij when the sensor is full of the lower permittivity material (obtained from calibration file).

2. Calculate the offset parameter M1 (which corresponds to the output voltage from the capacitance measuring circuit) for each Cij using

$$M1 = (M3 - M3(0))/(GAIN * ATTEN) + OFFSET$$

where:

M3(0) is the ADC zero balance count (obtained from the calibration file).

GAIN is the overall circuit gain from the offset DAC input to the ADC output (excluding the DAC attenuator). This value (around 0.17) is taken from the calibration file.

ATTEN is the attenuation set by the DAC stage (= M2/1023), where M2 is obtained from the calibration file.

OFFSET is the offset count M1L obtained from the calibration file.

3. Calculate the input capacitance for each Cij in fF using

$$Cij = (M1 - M1(0)) * VR1/(1023 * CONV)$$

where:

M1(0) is the charge injection offset value for measuring channel i. This data is obtained from the calibration file.

VR1 is the circuit reference voltage (9.9338 V).

CONV is the capacitance/voltage conversion factor = 0.00365316 V/fF at 1.25 MHz.

A simple **Basic** programme for calculating absolute capacitances from normalised values is given in the following section.

A6.3 EXAMPLE QBASIC PROGRAM FOR CALCULATING ABSOLUTE CAPACITANCE FROM NORMALISED VALUE

```
REM CALCULATION OF ABSOLUTE CAPACITANCE FROM NORMALISED
VALUE
CLS
M30 = 965
GAIN = .173321
CONV = .00365316#
VR1 = 9.9338
M10 = 220.679
ATTEN = 463
M1L = 406
CNORM = .0198
M3H = 3278
M3L = 909
M3 = CNORM * (M3H - M3L) + M3L
PRINT CNORM, M3H, M3L, M3
M1 = (M3 - M30) / (GAIN * ATTEN) + M1L
C = (M1 - M10) / CONV * VR1 / 1023
PRINT M1, C
```

The parameters used in the above equation are defined in appendix A3.3.

APPENDIX 7

SOFTWARE INSTALLATION

PTL ECT systems are **normally supplied with software pre-installed on the control PC**. The software installation files are also included on a CDROM supplied with the ECT system. If users wish to install the software on an additional PC, the following instructions should be followed:

1. Insert the **PTL ECT CDROM** in the CD drive. Note that the CD has **not** been set up to auto run when inserted in the CD drive.

2. Use Windows Explorer to access the individual program setup files on the CDROM.

3. The programs must be installed separately as described in the instructions listed below for each utility. Note that the **ECT32v2** (and **Flowan** where supplied) software is protected by a software key which must be obtained from PTL (see A7.1.4 below) before the program can be used.

A7.1 ECT32v2 SOFTWARE INSTALLATION

1. Insert the **PTL program CDROM** in the PC and locate the file **Setup_ECT32v*.exe.**

2. Run this file by double clicking on it. The installation wizard will then run.

3. Either accept the default folder (C:\ECT32\ECT32v2) or choose a suitable folder in which the program is to be installed when requested by the wizard.

4. The ECT software will be installed and an **ECT software program group window** containing a number of icon short cuts will be set up. The **ECT32v2** software will attempt to run and at this stage, a **Registration window** containing a user ID code will appear as shown below.

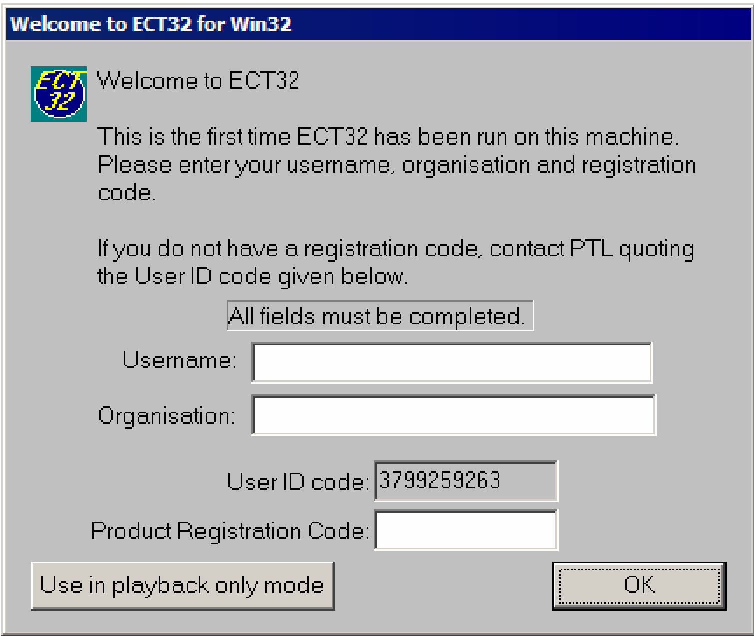


Figure A7.1 Software Registration window

5. Note the **User ID code** which appears and **email this code to:**

enquiries@tomography.com.

A return **Product Registration Code** will be emailed to you within 24 hours. Click on the **Cancel button** to exit the program.

6. Once the **Product Registration Code** has been received, rerun the **ECT32v2** software, by clicking on the **ECT32v2** icon in the ECT software window, when the **Registration window** will again appear. Enter your **name** and **organisation** in the window and then carefully enter the **Product Registration code** which has been sent to you.

NB. In view of the mix of lower and upper case characters in the product registration code, it is safest to cut and paste this code directly from the return email to the registration window (using CTRL C to copy and /CTRL V to paste).

8. Once the code has been entered, click **OK**. The **ECT32 software** will start and the **Configuration window** will appear.

9. If the correct code is not entered, the ECT32 software will not start. The registration window will then appear again next time the ECT32 software is run.

A7.1.1 Notes on the Security Code

The **ECT32v2** software is **protected** by a **security code system** in the form of a **Product Registration code** (which is unique for each PC on which the software is to be used). A software **User ID code** is generated during the software installation and **this code must be sent to PTL by email** to obtain the **security code** before the software can be run for the first time on each new PC. PTL will supply **up to 3 unique User ID codes** to **each registered purchaser of the software**, allowing it to be used on **up to 3 PCs simultaneously**.

If a **User ID code** is not available, the **ECT32** program can be used in a restricted **Playback only** mode. In this case, the **Registration window** appears each time the **ECT32 software** is started and the program can be used in **Playback only** mode by clicking on the **Use in playback only mode** button. This facility allows unrestricted use of the **ECT32 software** with either the **example data files** provided, or with data files generated by users. It therefore allows the use of the software as an ECT teaching aid by engineering and physics students.

A7.1.2 The ECT software group window

Following installation of the ECT32v2 software, the ECT software group window will contain the following icon short cuts.

ECT32v2 **ECTcon** **ECT Toolkit** **ECTremote** **Websites**

Uninstall **Documentation**

Further icons will be added to this window as additional programs are installed.

A7.2 IU200 IMAGE RECONSTRUCTION SOFTWARE INSTALLATION

1. Locate the file **Setup_IU2000v*.exe** on the **PTL ECT program CDROM**.

2. Run this file by double clicking on it. The installation wizard will then run.

3. Either accept the default folder (**C:\IU2000**) or choose a suitable folder in which the program is to be installed when requested by the wizard.

4. The **IU2000** software will be installed and an **IU2000** icon button, will appear in the **ECT software program group window.**

This completes the **IU2000** software installation.

A7.3 RECAL ADVANCED CALIBRATION SOFTWARE INSTALLATION

1. Locate the file **Setup_Recalv*.exe.** on the **PTL ECT program CDROM.**

2. Run this file by double clicking on it. The installation wizard will then run.

3. Either accept the default folder (**C:\Recal**) or choose a suitable folder in which the program is to be installed when requested by the wizard.

4. The **Recal** software will be installed and a **Recal** icon button will appear in the **ECT software program group window.**

This completes the **Recal** software installation.

A7.4 PLOT3D IMAGE RECONSTRUCTION SOFTWARE INSTALLATION

1. Locate the file **Setup_Plot3dv*.exe** on the **PTL ECT program CDROM.**

2. Run this file by double clicking on it. The installation wizard will then run.

3. Either accept the default folder (**C:\Plot3d**) or choose a suitable folder in which the program is to be installed when requested by the wizard.

4. The **Plot3d** software will be installed and a **Plot3d** icon button, will appear in the **ECT software program group window.**

This completes the **Plot3d** software installation.

A7.5 MAKEMAP SENSITIVITY MAP GENERATION SOFTWARE INSTALLATION

1. Locate the file **Setup_Makemapv*.exe** on the **PTL ECT program CDROM** .

2. Run this file by double clicking on it. The installation wizard will then run.

3. Either accept the default folder (**C:\Makemap**) or choose a suitable folder in which the program is to be installed when requested by the wizard.

4. The **Makemap** software will be installed and a **Makemap** icon button will appear in the **ECT software program group window.**

This completes the **Makemap** software installation.

A7.6 BCPCONVERT FILE CONVERSION SOFTWARE INSTALLATION

1. Locate the file **Setup_Bcpconvertv*.exe** on the **PTL ECT program CDROM.**

2. Run this file by double clicking on it. The installation wizard will then run.

3. Either accept the default folder (**C:\Bcpconvert**) or choose a suitable folder in which the program is to be installed when requested by the wizard.

4. The **Bcpconvert** software will be installed and a **Bcpconvert** icon button will appear in the **ECT software program group window.**

This completes the **Bcpconvert** software installation.

A7.7. MATECT MATLAB UTILITIES SOFTWARE INSTALLATION

1. Locate the file **Setup_MatECT*.exe** on the **PTL ECT program CDROM.**

2. Run this file by double clicking on it. The installation wizard will then run.

3. Either accept the default folder (**C:\MatECT**) or choose a suitable folder in which the program is to be installed when requested by the wizard.

4. The **MatECT** software will be installed and a **MatECT** icon button will appear in the **ECT software program group window.**

This completes the **MatECT** software installation.

A7.8 FLOWAN SOFTWARE INSTALLATION (Purchase option)

1. Locate the file **Setup_Flowan*.exe** on the **PTL ECT program CDROM.**

2. Run this file by double clicking on it. The installation wizard will then run.

3. Either accept the default folder (**C:\Flowan**) or choose a suitable folder in which the program is to be installed when requested by the wizard.

4. The **Flowan** software will be installed and a **Flowan** icon button will appear in the **ECT software program group window.**

This completes the **Flowan** software installation.

Note that the **Flowan** software is protected by a **security code** and a procedure similar to that used for the **ECT32v2** software must be followed following installation to obtain a software key.

A7.9 DATA EXPORT SOFTWARE INSTALLATION (ONLY IF REQUIRED)

Some **additional software** must be loaded to both the **Control** and **Remote PCs** to send and receive the exported capacitance data and this is also contained on the software installation CDROM.

The software should be installed on the **Control PC** as follows:

1. Insert The **PTL software CD** rom in the **Control PC**.

2. **Right click** on the **CD drive** and select the **Explore** option. The list of folders on the PC will be displayed.

3. Open the **Data export** folder and copy the **Netstream.dll** file to the **C:\ECT32v2** folder on the **Control PC**.

The sofware on the **Remote PC** should be installed as follows:

1. Insert The **PTL software CD** rom in the **Control PC**.

2. **Right click** on the **CD drive** and select the **Explore** option. The list of folders on the PC will be displayed.

3. Open the **Data export** folder and copy the **ECTRemote.exe** file to a new folder (**REM32**) on the **Remote PC**.

4. Create a **shortcut** to the file **ECTRemote.EXE** in the **rem32 folder** and **drag this shortcut** to the **Windows desktop**.

5. Re-name the shortcut **icon ECTRemote.**

The demonstration data export display software is now installed and ready for use.

A7.10 ECT SOFTWARE WINDOW AFTER SOFTWARE INSTALLATION

Following the software installation, the **ECT Software** group window should appear in a similar format to that shown below. Note that a full set of documentation for the programs can be found in the **Document files** folder.

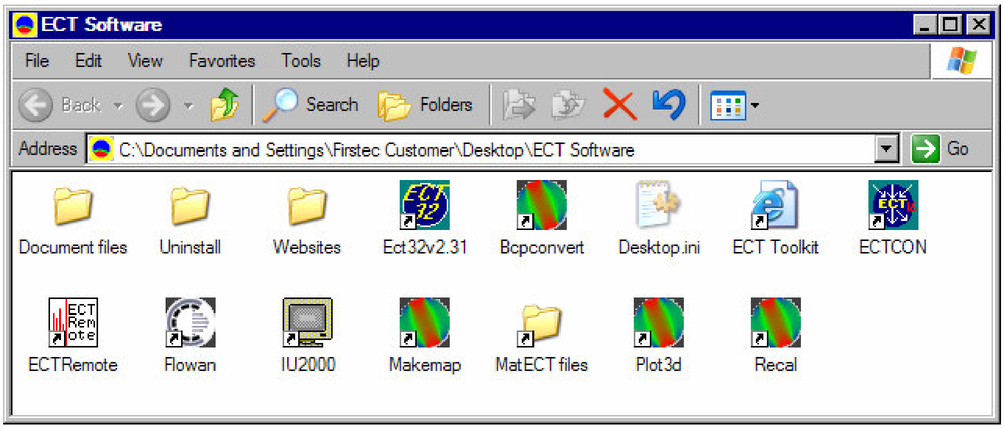


Figure A7.2 ECT Program group window

A7.11 SOFTWARE INITIALISATION

Once all of the software has been installed, **the PC must be re-booted** by exiting Windows and restarting the PC. This initialises some of the programs which use Matlab DLL files.

A7.12 SETTING UP THE PC FOR NETWORKING

Before the **ECT32v2, Toolkit** and **Flowan** software can be used to control the ECT system, the **Control PC** must be set up to allow **basic networking** via the **ethernet port**. The following instructions allow the PC to be used to control the ECT system using a **crossover ethernet lead,** as described in the **Quick Start Instructions** (chapter 2.2 of this manual).

Open the ***Control panel*** on the PC and double-click on the ***Network Connection*** icon.

Right click on ***Local area connection***, and click on the ***Properties*** button.

Select ***Internet Protocol (TCP/IP)*** from the ***menu list*** and click on the ***Properties button.***

Uncheck ***Obtain an IP address automatically*** and instead check ***Use the following address.***

Insert the following address in the upper part of the ***Internet Properties (TC/IP) Properties*** window.

IP address:	192.168.0.X
Subnet mask:	255.255.255.0
Default gateway:	192.168.0.1

where X is a unique address for the PC.

Each **DAM200E** unit has a unique **network (IP) address**, which is determined by its serial number. This can be found on the **identification plate** on the **rear panel** of the **DAM200E** unit. The PTL convention is to set X to the value 100 + the serial number of the **DAM200E unit**. So, for example, if the serial number is 038 then X becomes 138.

The DNS server address section of this window can be left blank.

Click on the ***OK buttons*** to exit the network setup software.

A7.13 TO SET UP THE EMBEDDED PC NETWORK ADDRESSES

The final step is to set up the **EctToolkit software** to point to the correct address for the **DAM200E** unit connected to the **Control PC**.

Right click on the ***ECT Toolkit shortcut*** in the ***ECT32 program group window*** and click on the ***Properties*** button. The ***ECT Toolkit Properties*** window will appear as shown below:

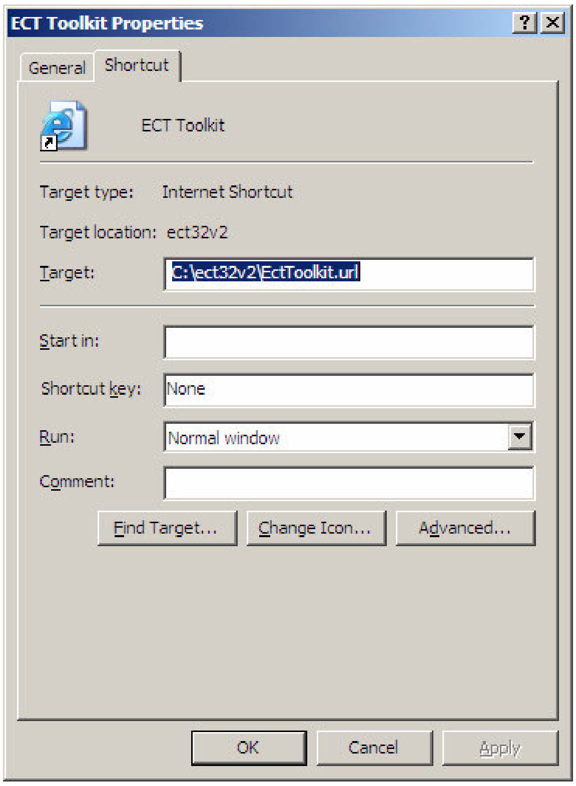


Figure A7.3. ECT Toolkit Properties window

Click on the ***Find Target*** button. This will browse to the ***target file*** for the ***shortcut*** as shown in the next figure.

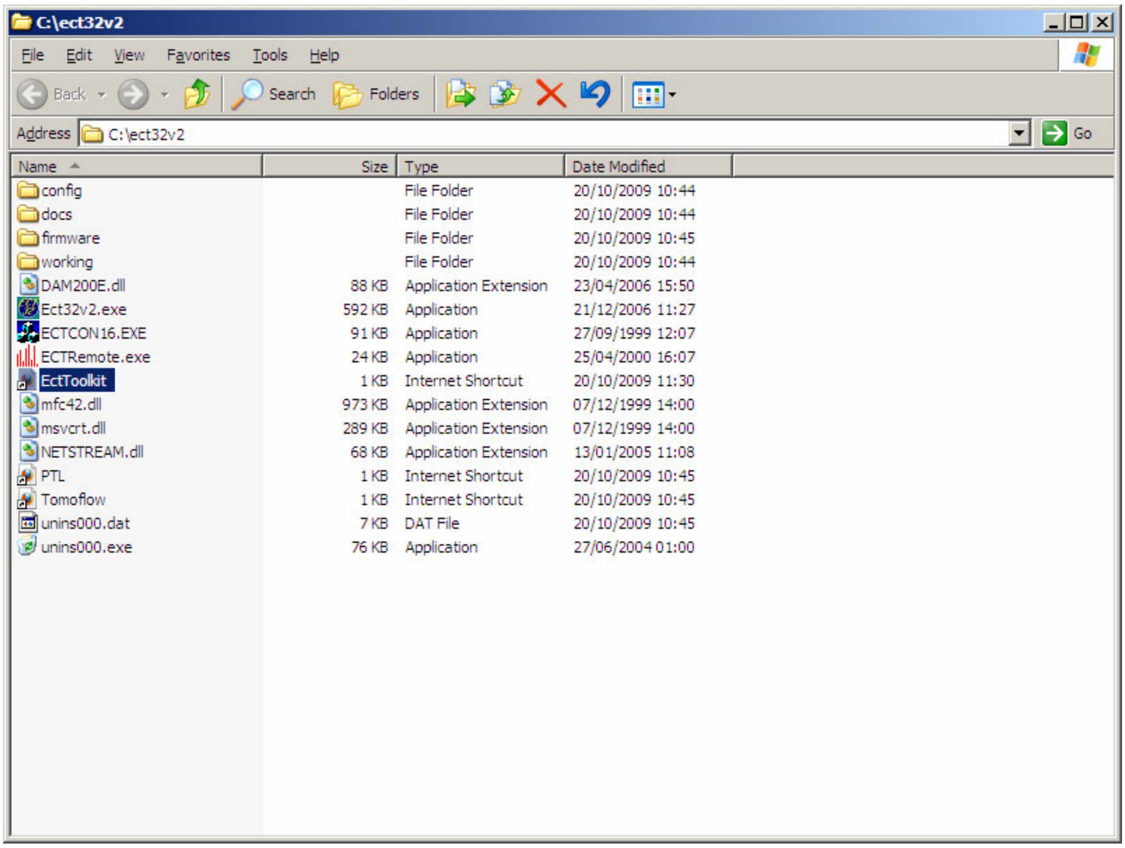


Figure A7.4 . Shortcut target file

Right click on the highlighted target file (***EctToolkit***). The ***Ect Toolkit Properties window*** appears as shown in the next figure.

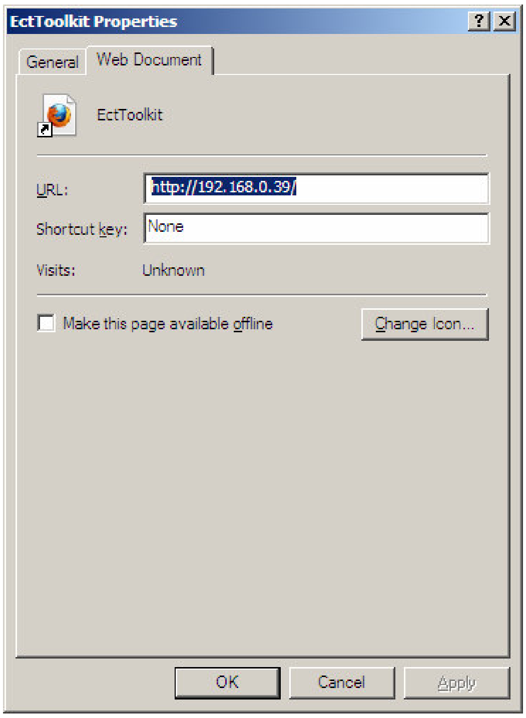


Figure A7.5. EctToolkit Properties Window

Change the ***last 2 digits*** *in the* ***URL address*** to match the ***serial number*** on the rear panel of the ***DAM200E*** unit. In the above example, this has been set to 39.

Click the ***Apply button*** and then click on the ***OK*** button to exit this window.

Now click on the ***ECT Toolkit*** icon in the ***ECT software group window*** on the ***PC desktop***. This should open the ***ECT Toolkit software***, indicating that an ethernet connection has been successfully established between the **control PC** and the **DAM200E** unit.