OPERATION MANUAL FOR
Grad601 MAGNETIC GRADIOMETER

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All dimensions are in mm unless stated
1 GENERAL DESCRIPTION

The Grad601 magnetic gradiometer is supplied in two versions, the dual sensor Grad601-2 (Figure 1) and the single sensor Grad601-1 (Figure 2). The instrument is used for detailed archaeological site surveys and for the location of pipes, cables, drums or unexploded ordnance.

The Grad-01-1000 sensor used in the Grad601 is a high-stability fluxgate gradient sensor with a 1m separation between the sensing elements, giving a strong response to deep anomalies. The resolution is 0.1nT/m when used on the 100nT/m range, and 1nT/m when used on the 1000nT/m range. The exceptional temperature stability of this sensor ensures minimal drift during surveys and reduces the need for adjustment. Adjustments to remove the small residual errors are made automatically, requiring the operator only to rotate the gradiometer in response to instructions from the data logger.

The Grad601-2, with two gradiometer sensors, records two lines of data during each traverse and reduces the survey time and distance walked to one half compared to using a single gradiometer. Both versions can operate as either a survey tool, where data are logged while covering the site in parallel or zigzag paths, or in a scanning mode where it is used as a search tool with an audible output for locating and tracing pipes, cables etc. without data logging. When used as a survey tool, data are saved in grids of 10 x 10, 20 x 20 or 30 x 30m. The magnetic gradient is measured along a series of lines spaced at 0.25, 0.5 or 1m depending on the resolution required. (Prior to data logger software V5.7 and Datalog downloading software V3.13, only the single sensor Grad601-1 could be used for 0.25 or 0.5m line spacing.) Measurements are taken at intervals of 0.125 to 1m along each traverse. A non-volatile 256kB flash memory is used to maintain data security. The memory will hold the equivalent of 30 grids of 30 x 30m with a 1m line separation and a resolution of 4 readings per metre. Grids may be downloaded as individual files so different size grids may be recorded during a survey, giving added flexibility.

The data logger has a simple six-key control panel with menu-selected operations and a 20 character, two-line liquid crystal display (Figure 3). External push buttons are provided for use during survey operations. The gradiometer operates from a 12V rechargeable battery giving more than 24 hours operation and offers a wide selection of operating parameters.

Software is provided for downloading data from the data logger to a PC via a serial RS232 interface and saving it in one of three formats for subsequent data processing. Downloading a full memory takes 6.5 minutes.

The Grad601 system includes the following components:
Grad-01-1000 sensor(s)
DL601 Data Logger
BC601 Battery cassette and charger
Single or dual-sensor carrying bar and associated cables
Carrying Harness (Grad601-2 only)
Grad-601 DATALOG downloading software and USB to RS232 converter
Carrying case
In the following text, references to keys and displayed characters are shown in italic text. The output of the Grad601 represents a differential measurement. As the separation of the sensing elements in each gradient sensor is 1m, all measurements reported in nT also correspond to gradients in units of nT/m.

2 BATTERY CASSETTE AND CHARGER

The gradiometer battery is a sealed Lithium Ion type and is housed in a sealed, separate cassette (Figure 4) which also contains the charging circuitry. To charge the battery, connect the mains adapter supplied, or any isolated 9-18V DC supply (at 1.2A minimum), to the 2.1mm input socket for 6-8 hours. One charge will operate the system for up to 27 hours with two gradient sensors or 36 hours with one gradient sensor.

The case may become warm during charging and this is perfectly normal. The red LED will be illuminated while the battery is being charged. At the end of the charging period the charging current will be switched off automatically and the red LED will be extinguished. The data logger may be switched ON when the battery is being charged, but the red LED will then not indicate the end of the charging period. The protective cover provided for the connector should always be used when not charging.

The battery has a press-to-view indicator showing the charge remaining in the battery in the form of four green LEDs. The battery should be recharged at the end of each surveying session. The battery contains electronic protection against short circuit which, if activated, will reset after a delay of 10 minutes.

3 ASSEMBLY

The gradiometer system is supplied as a carrying bar with battery and data logger attached and one or two gradient sensors as appropriate (See Figures 11 & 12). The data logger, battery cassette and connecting cables will normally be left attached to the carrying bar. For the dual sensor version, the gradient sensors are spaced at a fixed 1m apart. The gradient sensors are attached at the ends of the carrying bar. To attach a sensor, loosen the plastic knobs to release the clamp, and insert the sensor at the desired working height with the connector at the top (see Figure 5). Rotate the gradiometer(s) so that the heading arrow on the connector junction block label (see Figure 10) of each gradiometer is pointing away from the operator, in the direction of survey. Re-tighten the plastic knobs, but do not over-tighten.

The data logger unit has a pair of fixing holes on the underside (Figure 6) for securing the unit to the carrying bar. The Grad601-1 single gradiometer has the sensor and data logger mounted in front of the operator and the battery box located at the end of the bar to give a balanced assembly as shown in Figure 11.

The Grad601-2 dual sensor gradiometer is carried with the beam across the front of the operator with one sensor on each side as shown in Figure 1. The data logger is located with the controls facing the operator and the battery mounted directly below it and attached to the data logger through the support bar with two knurled captive screws.
Green and red push buttons are provided on the support bar as alternatives to the keypad ENTER and ESC keys respectively. The auxiliary push buttons, which are easily replaced, are conveniently located near the operator’s hand and reduce excessive wear of the most frequently used keys. They provide control of the data collection and interruption during surveys and setting up without moving the hand from the carrying bar.

4 CONNECTIONS

Connect the gradient sensors to the relevant connectors on the data logger. If only one sensor is used it should be connected to socket 1 and the protective cover should be fitted to socket 2. If two sensors are used, the gradiometer sensor to the left of the operator should be connected to socket 1 and the one to the right to socket 2. Ensure the battery lead to the data logger is connected. The 9-way socket on the datalogger is fitted with a replaceable gender changer to greatly extend the operating life, and a protective cover, which must be fitted at all times except when downloading data. Protective caps are provided for the data logger cables and sensor connectors and should always be fitted when the connectors are not in use to minimise dirt ingress.

5 Grad601-2 CARRYING HARNESS

The harness supplied with the dual gradiometer is shown in figure 1. This completely relieves the operator’s arms of the weight of the gradiometer system allowing easy operation of the controls.

The harness comprises a lightweight, soft, padded shoulder harness, with a bag to contain a balance weight (sand or water), attached to an abdominal spacer by adjustable webbing straps through two replaceable plastic links.

The gradiometer can be quickly attached and detached from the harness using two simple sprung hooks. This makes it possible to use more than one harness (and operator) with one gradiometer.

The sprung cradles on the abdominal spacer are clipped onto the bearings located on the carrying bar. The webbing straps allow the height of the carrying bar to be adjusted to suit the user. To remove the gradiometer from the harness, use a thumb on each hand to spring open the cradle. All parts may be separated for repair or replacement and may be cleaned in water.

6 INSTRUMENT STANDS

The gradiometers each have an integral prop attached to the carrying bar for parking the gradiometer when not in use.
7 SETTING UP

In order to remove alignment errors and scaling differences between the sensing elements forming the gradient sensor, it is necessary to set up the instrument using an automated procedure. This procedure, which takes only a few minutes, must also be repeated whenever the gradiometer sensors are adjusted for height relative to the support bar. The procedure will remove any offset error generated by changes in the position of the battery and other magnetic components relative to the sensor elements. It is recommended that, after assembly, the Grad601 should be switched on for a period of at least 15 minutes before carrying out the setting up procedure detailed in section 13. The alignment should be checked at intervals over the course of a day, and the setting up procedure repeated as necessary. Setting up a single sensor unit is carried out with the operator holding the unit in the normal way. Setting up a dual sensor unit may be carried out with or without the harness.

8 KEYPAD OPERATION AND DISPLAY

The Grad601 Data logger DL601 (See Figure 3) has 6 keys to set parameters and control the operation. A two-line, 20-character display shows the menus, results etc. The functions of the keys are as follows:

**ON/OFF** controls the power to the unit and gradiometers. Press the button to alternately apply and remove power. When the display is blank, the power is off, and when the display is active, the power is on. A short delay is incorporated, and to prevent power being removed during boot-up, the unit cannot be switched on or off for four seconds after the last operation.

**ENTER** starts the operation of the menu item displayed on the top line against the >cursor. It is also used to progress to the next operation if requested by a displayed message when static information is shown, or to confirm the user’s selection. If in doubt, press **ENTER** to continue and **ESC** to go back.

**ESC** (Escape) is used to exit a procedure and return to the previous menu or operation.

**↑↓ (UP/DOWN ARROWS)** are used to scroll through the menus to set the required option to the top cursor line before starting the operation with the **ENTER** key.

**STEP** is used to step through the available options for each of the operating parameters.

With the exception of the **ON/OFF** key, the required action occurs only when a key is released after being pressed.

External push buttons are provided for use as optional **ENTER** (green) and **ESC** (red) keys. These are particularly useful in the survey mode and during setting up.

A menu may offer an action which is not valid at that time, for example moving back one line when at the start of the first line. If a non-valid menu selection is made then the data logger will bleep and take no action.
Connect the data logger to the gradient sensors and battery and then press and hold the ON/OFF switch until the display is activated. At switch-on the display will show the title screen with the program version for a few seconds before switching to the Main Menu. The items in the menu are as follows:

- Start survey
- Start scan
- Output data
- Delete data
- Set parameters
- Adjust gradiometer
- System reset

The two-line display will show only the first two items as:
>Start survey
Start scan

The > prompt in the top line shows the menu item to be activated when the ENTER key is pressed. The second line shows the next item in the list. Pressing the down arrow will cause the items to scroll up by one position which brings the lower item to prompt and also shows the next lower item in the display as:
>Start scan
Output data

Pressing the up arrow will cause the menu items to scroll down one position. In this way the up and down arrows are used to select an item from the menu by positioning it adjacent to the prompt. When the ENTER key is pressed the indicated action is taken.

After completing each task the program returns to this Main Menu. The user should always return to this menu before pressing the ON/OFF switch to turn off the power.

Before selecting Start Survey or Start Scan the user should select Set parameters and set the number of sensors being used and all other variables to ensure correct operation. When set to the appropriate values, the ENTER key will cause parameters to be saved for use during subsequent operations. The user may then wish to select Delete data to clear the memory.

When using the instrument for the first time, if the Set Parameters menu shows invalid values or is incomplete, return to the main menu and select System Reset. This sets default values into the operating parameters, deletes the memory and resets the memory pointers. The parameters can then be set to the values required by the user.
10 SETTING PARAMETERS

From the Main Menu select Set parameters and press ENTER. This will give a further menu as follows:

Pace : 1.8m/s
Gridsize : 30 x 30
Start : North
Pattern : ZigZag
Lines/m : 1
Samples/m : 4
Range : 100nT
Audio : On
Volume : High
Threshold : 1 nT
Sensors : 2
Reject : 50 Hz
Save

Use the arrow ↑↓ keys to set each item in turn adjacent to the prompt on the top line, and then press the STEP key to step through the available options for that parameter. The individual parameters and available settings are explained below:

Pace: select the walking pace of the operator - 0.5 to 2m/s or Single shot
Gridsize: select the size of grid for surveying - 10 x 10m, 20 x 20m or 30 x 30m
Start: select the starting direction of the grid, N, NE, E, SE, S, SW, W or NW
Pattern: select the traverse pattern to be followed - Parallel or Zigzag
Lines/m: select the required number of data lines per metre - 1, 2 or 4

Note: for a dual sensor system the spacing is fixed at 1 metre so the operator will walk (traverse) at 2m intervals to record data at 1 line/m. For 2 or 4 lines/m a special traverse pattern is required with a 2m repeat. See sections 15 and 19 for details.

Samples/m: select the number of samples per metre along each line - 1, 2, 4 or 8
Range: select the full scale range of 100nT (resolution 0.1nT) or 1000nT (resolution 1nT)
Audio: select the audio output for scanning and survey operations - off or on
Volume: select volume - high or low
Threshold: select the deviation in nT at which the alarm is required to operate during a scan operation - increments in units, tens and hundreds and thousands of nT. When the field deviates by the level selected, the ALARM message will be shown in the display for the appropriate sensor, and the audio output rate will start to increase. The audio tone varies from the value set to about ten times this value.

Sensors: select the number of sensors to be used - 1 or 2
Reject: select the local mains frequency of 50 or 60Hz to minimise pick-up
Save: pressing ENTER will cause the parameter settings shown in the display to be saved
When all parameters have been set to the required option, select Save as an item and press ENTER or simply press ENTER at any point. The display will indicate that the parameters have been saved before reverting to the Main Menu.

To leave the Set parameters menu without saving the changes, simply press ESC at any time and the display will indicate that the parameters have been reset to the previous settings.

The parameter settings can be reviewed at any time and are saved in memory, until changed by the user. However, if System reset is selected from the menu or if a run-time error causes a system reset then the settings will revert to the initial default values and will need to be reselected.

11 GRADIOMETER RANGE AND RESOLUTION

The Grad-01-1000 sensor has two linear operating ranges ±100nT and ±1000nT, with a resolution of 0.1nT and 1nT respectively. Each range has a compressed over-range scale from the linear full-scale value to 30 times full scale, allowing the unit to be used in applications requiring high gradient measurement such as pipe and cable location. For the 100nT range, the maximum value will be 3,000.0nT. In survey mode, the result is displayed with a resolution of 1nT regardless of the range selected but the result is saved to memory with the resolution appropriate for the range selected.

Each measured value is the average of many samples. In survey mode the sampling time is adjusted to produce an average value over the sampling distance at the pace selected. The measurement time is further modified to integrate the signal over a discrete number of mains cycles. This enhances the high 50/60Hz rejection of the gradiometer sensors. The background noise can be further reduced by integration when walking more slowly or using fewer samples per metre.

Integrating the readings over the measurement interval reduces the noise level, but also effectively limits the bandwidth. If the sampling interval is set at e.g. 4 samples/m, the minimum spatial resolution will be 0.25m and any anomaly smaller than this will be diluted by the averaging process. The sampling interval should therefore be set to allow the smallest anomaly expected to be recognised, with 4 samples/m being a good compromise.

Under optimum ground conditions the best survey results are obtained with the lower sensor around 20cm above the surface. This produces the highest sensitivity to buried features whilst minimising surface noise. The height of the gradient sensors can easily be adjusted to avoid vegetation.

NOTE: each time the height settings are adjusted the system must be set up again using the Adjust Gradiometer menu item before use.
12  OPERATOR MAGNETIC HYGIENE

The Grad601 gradiometer is a very sensitive instrument, and any magnetic objects placed near the sensors will affect the measurements. The operator must ensure that there are no magnetic items on their person or in their clothing. Common objects causing errors include spectacles, watches, keys, belt buckles, zips, magnetic parts of shoes etc. If the gradiometer is carried close to the ground, the operator’s shoes are particularly important. To check the operator for magnetic items, set the gradiometer to the 100nT range with the appropriate setting for the number of sensors and run in Scan mode. Hold the gradiometer stationary and check the readings when the operator approaches the gradiometer sensor. The operator should check all parts against the end of a gradiometer sensor until a change of less than 0.1nT is seen.

13  CHECKING AND ADJUSTING THE GRADIOMETERS

Introduction
Each Grad-01-1000 gradiometer sensor contains two single axis fluxgate sensing elements, which must be precisely matched to obtain accurate gradient measurements. To avoid large variations when rotating the gradiometer, it is necessary to match the gain, offset and exact alignment of the two sensing elements. The sensors are extremely stable but over time and with changes in temperature it is inevitable that some change will occur in the matching of the sensors. A setting up procedure is provided to apply corrections to restore the precise matching required. The procedure requires the operator to point the arrows marked on the sensors in the appropriate direction, press either the ENTER key or the green external push button and hold the instrument still until the instrument beeps and issues the next instruction. This routine, which automatically applies corrections, must be carried out in a previously selected low gradient area.

The setting up procedure takes only a few minutes and should be carried out after the instrument has been assembled and left switched on for about 20 minutes. The rotational errors should be checked occasionally, at the original set-up position, and the setting up procedure repeated as necessary.

Selecting a site for error measurement and adjustment
Before attempting to set up the instrument or make any measurements, ensure the operator is completely free of magnetic materials - see the section entitled Operator Magnetic Hygiene. In order to check the sensor errors and apply corrections, the sensor must be positioned in a low magnetic gradient environment. To locate a suitable low gradient environment, proceed as follows.

Select a site away from roads, drains and any possible magnetic objects.

Switch on the power using the ON/OFF switch, select the appropriate settings from the Set Parameters menu and then leave the sensor to warm up for a few minutes. Select Start scan and, holding the instrument vertically and pointing in a constant direction, scan the operating area and search for an area where the reading of the meter does not vary by more than about 1 or 2nT over about 1m in any direction. When a convenient spot has been found, ensure that the reading from either sensor does not change by more
than about 2nT when raising the sensors vertically from about 30 to 60cm above the surface. Check the area with the sensors pointing either east/west or north/south. Mark this reference area for future use. The instrument set-up will only be as good as the area used for the set-up, so the area should be selected with care.

**Error measurement**
In order to measure and correct the errors in the sensors, it is necessary to know the directions of magnetic North/South and East/West with a reasonable accuracy. Use a compass to determine easily identified features in the landscape on the North/South and East/West directions from the magnetically clean area selected above.

Each Grad-01-1000 sensor has a label on the connector junction block showing an arrow for the heading direction (see Figure 10). Operate the instrument in the Scan mode on the 100nT range and, keeping the sensors over the magnetically clean reference point, measure the errors as follows:

**North/South Error**
This error is due to misalignment of the sensors in the direction of the heading direction arrow and has a maximum value when the arrow points north / south.

**East/West Error**
This error is due to misalignment of the sensors at right angles to the direction of the arrow, and has a maximum value when the arrow points east / west.

**Vertical Error**
This error arises from imbalance between the top (reference) sensor and the lower (measuring) sensor and has a maximum value when the gradiometer is inverted.

**Offset Error**
This is a fixed zero offset error regardless of the orientation of the gradiometer. For optimum results, the difference in the gradiometer readings should vary by no more than about ±0.2nT for any of the above tests, and the offset error should also be less than 0.2nT. If any error exceeds this value, the gradiometer should be adjusted to reduce the variation as indicated below. When operating with two gradiometers both units can be checked independently over the same reference point as necessary.

**Adjusting the gradiometers**
The following is written assuming a dual gradiometer system is used. The procedure is the same for a single system but read sensor and arrow instead of sensors and arrows.

This procedure must be carried out with the gradiometer over the low gradient site selected earlier. The operator is required to rotate the complete gradiometer assembly to align the sensors as required by the program, but must keep the assembly static, and the gradiometer tubes as vertical as possible, while the instrument carries out the necessary adjustments. If only one gradiometer sensor is used, the sensor should be maintained over the same point while the assembly is rotated. If two gradiometer sensors are used, the routine sets both gradiometer sensors at the same time, and the operator should keep the centre of the assembly over a fixed point. This is most easily achieved using the harness.
It is good practice to always assemble the gradiometer such that the arrows marked on
the sensors are carefully aligned to point in the direction in which the operator will
walk. This will assist the operator in pointing the arrows in the required direction
during the set up procedure. For a single sensor the arrow should be aligned with the
carrying bar. The carrying bar can then be pointed in the appropriate direction during
set up. Dual sensors should be mounted with the arrows carefully aligned parallel and at
right angles to the carrying bar, so the bar can be set to east/west when the arrows are
required to be set north/south etc.

When the display requests that the sensors be moved to the opposite direction, the
gradiometer should be rotated through a true 180 degrees for the best result. Find N, S,
E & W to within a few degrees using a compass, which should then be removed to a
safe distance.

From the Main Menu select Adjust gradiometer. At each stage in the sequence of
operations, the instrument will bleep, and the display will prompt the operator when a
change in the position of the gradiometer is required. After setting the required
direction, the operator should press the green button - equivalent to the ENTER key and
wait for the adjustment to be made. It is advisable to hold the instrument as far above
the ground as is reasonable, so any ground effect is minimised. **It is essential that, at
each position, the sensor is kept stationary and vertical while the adjustment is
being carried out, after which the unit gives an audible bleep.**

The initial display will prompt the operator to Point arrows North and Then Press
Enter/PB. Align the assembly so the sensor arrows point north and the sensors are
vertical then press the green push button. When the button is pressed, the instrument
will take readings from the gradiometer sensors and then bleep and prompt the operator
with the message Point arrows South and Then Press Enter/PB. The gradiometer
should be rotated to point the arrows south and the green button pressed when stable.
The gradiometer will then take a series of measurements and make corrections to the
sensors in turn.

The display will then prompt the operator to point the sensor arrows east and west and
make corrections as before.

The operator will then be prompted to invert the sensor with the arrows west. The
operator should face west and then rotate the carrying bar so that the tops of the sensors
are now pointing vertically downward and press the green button. The next prompt will
be to restore the sensors to the normal position with the arrows pointing west. At this
point, both the vertical error and offset are adjusted.

The operator will then be prompted to face east, south and north again while further
corrections are made.

If all is well the display will show Set up finished and prompt the operator to press the
ENTER key or push button.
The above set-up procedure is carried out with the full-scale range set to 100nT by the program and the results displayed with a resolution of 0.1nT. If, at any stage, the program detects that the controls are too far out of adjustment, the controls will be re-set automatically and the procedure will be re-started with the full-scale range set to 1000nT and the fields displayed with a resolution of 1nT. After completing the procedure with the range set to 1000nT, the instrument should be within the normal starting range for the set-up procedure and the program will set the range back to 100nT and re-start the procedure from the beginning.

If the program resets the controls and sets the range to 1000nT for a coarse adjustment, the operator will see a Please Wait message in the upper line of the display and a series of dots appearing in the lower line of the display. During this short time, no measurements are made and the orientation of the gradiometer is unimportant. The operator will be aware that the fields are displayed to a resolution of 1nT during the coarse setting. The coarse adjustment will end with the operator facing north and the new fine adjustment sequence will begin with the operator facing north again.

A coarse adjustment may be required after attempting to set-up the instrument in a high gradient area, or indoors. If the coarse adjustment is called a second time, a fault is indicated and the set-up routine will end with the message Coarse Error Sensor followed by the sensor number 1 or 2.

If the set-up is attempted in a relatively high gradient or when some magnetic interference is present, possibly from a poor set-up area or an operator with magnetic material, the fine control may reach the end of its adjustment. The set-up will continue and the result may be acceptable but a warning message Fine control limit together with the relevant sensor number, will be displayed at the end of the set-up.

The set up should always be checked by selecting the Scan mode and noting the field readings as the gradiometer is rotated so the arrows on the sensors point north, south, east and west over the set up area. The results should all be zero within the range ±1nT. However, the result will depend on the gradients within the setting up area.

Each gradiometer holds the adjustment settings in internal non-volatile memory and adjustments made during the above operations will be maintained until the next set up operation.

14 SCAN MODE

In the Scan mode, the gradiometer readings are continuously displayed but not saved to memory. The operation is determined from the values shown in the Set Parameters menu. If the Audio option has been set to ON, the audio output will vary with changes in magnetic gradient. The audio Volume can be set to high or low. The Threshold function selects the field gradient at which the frequency of the audio output will increase. When the gradient reaches the selected level, the ALARM message will also be shown in the display for the relevant sensor. The audio tone increases from the alarm point to about ten times this value with increasing gradient levels. The Scan mode is terminated using the ESC key.
15  SURVEY MODE

Survey parameters
The Data Logger is programmed to record surveys based on a series of areas, termed Grids. Each grid will cover an area of 10m x 10m, 20m x 20m or 30m x 30m. Each Grid is numbered sequentially, starting at Grid 1 and is surveyed using a pattern of traverses, starting at Traverse 1. In the display 'Traverse' is abbreviated to 'Trav'. The user should record carefully the relative position of each grid, the order in which grids are measured, and ensure that the starting direction is set in the parameters for future reference. The number of Lines of data recorded will be determined by the size of the Grid and the line spacing selected as Lines/m. For the Grad601-1 single gradiometer, one line of data will be recorded for each traverse. For the Grad601-2 dual gradiometer, two lines of data will be recorded for each traverse. The traverse number is displayed during the survey. Values of the magnetic gradient will be recorded at a series of Positions along each Traverse. The number of samples per metre, selected in the Set Parameters menu, determines the number of Positions and is set by the user at 1, 2, 4 or 8 samples per metre. The readings will start at Position 1.

Grids are surveyed in a series of traverses which are walked in either parallel (Figure 7) where each traverse starts at the same side of the grid, or zigzag pattern (Figure 8), where traverses start at alternate sides of the grid. A zigzag pattern is normally used to minimise the distance walked.

Multiple gradiometers
When using the Grad601-2 dual gradiometer, the sensors are arranged to the left and right of the operator with a fixed separation of 1m. The operator therefore walks between two data lines recorded during each traverse. A line corresponds to a line of data. When using a single sensor gradiometer, the Trav (traverse) number shown in the display will correspond to the data line number. When using the dual gradiometer, the Trav (traverse) number will correspond to two lines of data recorded simultaneously.

The number of data lines per metre required should be set into the Set Parameters menu. Therefore if data is required at a density of one line per metre with a dual gradiometer then the operator will select 1Line/m but will traverse the grid at 2m intervals. For a 10x10m grid then only five traverses will be walked but ten lines of data will appear in the results at the appropriate positions after downloading. Results from each gradiometer are logged at each position with the gradiometer to the left of the operator being referred to as Gradiometer 1 and the one to the right as Gradiometer 2. Either parallel or zigzag traverse patterns can be used. Provided the parameters have been set correctly, the software will automatically allocate the correct spatial position to the data when downloading the data to a PC.

Setting Parameters
Before starting a survey, all details must be entered using the Set Parameters menu to enable the data to be interpreted correctly. The number of sensors (gradiometers) is entered to allow the data to be subsequently arranged correctly in the Grid. A spacing of 1m is assumed between sensors when using two sensors. Grids with different sizes may be recorded during a survey but may cause complications in the plotting software.
Data are collected at the distance intervals set by the user assuming a fixed walking pace. The pace can be set as one of the survey parameters between 0.5 and 2m/S. The operator should find a comfortable walking pace but a good starting pace would be about 1.6m/s. Lines are often laid along the traverse markers at 1m intervals. If Audio is set to ON, the logger will emit an audible bleep once per metre to allow the operator to match their walking pace with the data recording rate.

The parameters are saved as part of the data for each grid in the form of a header to enable correct processing of the data when downloading. The parameters of the current grid cannot be changed once a grid has been started, but an incomplete grid may be deleted and restarted at any time. Grids are saved to memory in numerical order. When downloaded using the software provided, the data for each grid will form a separate file with a header containing the details of the parameters with which the grid was measured.

**Survey conventions**

In order to maintain compatibility with existing practices, it is assumed that each grid will be surveyed starting in a clockwise direction from one corner (Figure 14). The display of the first line of data can be imagined as being a line printed horizontally from left to right at the top of the page (Figure 15). The next line is measured parallel to the first and one line space away. Grids may be surveyed using parallel traverses (Figure 7) or zigzag (Figure 8). The Set parameters option allows the initial starting direction to be saved as part of the header information.

**Lines and Positions**

In order to interface the data of one grid with others to form a larger area map, the lines are spaced symmetrically in one direction and the values are measured at positions spaced symmetrically along the lines. The first line should therefore be measured at a distance of one half line space from the edge of the grid. The first measurement will be centred on a point one half of the reading interval from the start line.

If we consider a 30m x 30m grid with a line spacing of 1m, then the first line is positioned 0.5m from the top edge of the grid and the remaining lines are then spaced at 1m intervals down the grid, with the last line at 29.5m from the top of the grid. Similarly, if measurements are taken along the line at intervals of 0.5m then the first measurement will be taken at 0.25m from the start of the line and the last at 0.25m from the end of the line. The results from each grid will then interface seamlessly with adjacent grids without the need for a reference edge (Figure 16).

The four corners of the grid should be determined using standard survey practice, and marked out with non-magnetic flags. The traverse starting and finishing lines can be marked with suitable ropes. It is also convenient to lay a rope along each traverse with 1m rope markers on it to allow the operator to keep pace with the data logging.

**Surveying at 1 Line/m**

A line spacing of 1m (Lines/m set to 1 in Survey Parameters) is normally used and is sufficient to locate most archaeological features. A “trapeze” comprising of two ropes spaced 1m apart with marks at 1m intervals along the ropes, will allow the operator to keep pace with the time bleeps. For a single sensor, the operator should walk with the
sensor over one trapeze line and return with it over the other, as in figure 17. For a dual sensor, the right hand sensor is held over the trapeze lines as in figure 18. The centre of the trapeze and the ropes along the start and end of the traverses should be marked appropriately to allow the trapeze to be positioned correctly. If the centre of the trapeze is marked, then for a single gradiometer the start and end traverse ropes should be marked at intervals of 2m with the first mark 1m from the edge of the grid. For a dual gradiometer the intervals should be 4m with the first mark 2m from the edge of the grid.

Surveying at 2 or 4 Lines/m

The Grad601 Datalogger software Version 5.7 and later, allows data to be collected with a line spacing of 1, 2 or 4 lines/m for both single and dual gradiometers. The line spacing is therefore 1, 0.5 or 0.25m. Using a Grad601-1 single gradiometer, the situation is straightforward with the first line being recorded at half the line space from the edge of the grid and subsequent lines separated by one line space. The pattern may be parallel or zigzag as selected in the Set Parameters menu and the marking of ropes at the ends of traverse is straightforward. If using a 1m wide trapeze as described above, the width of the trapeze should correspond to the line space selected when using a Grad601-1 single gradiometer.

When using the Grad601-2 dual gradiometer for collecting data at 2 or 4 lines/m, the situation is more complex due to the overlap of the data from the two gradient sensors. The operator must follow the traverse pattern described in the paragraphs below in order that the downloading software can re-arrange the data into the correct positions in the grid. As the surveys can be made in parallel or zigzag the following description uses the centre of the support bar, or the position of the operator relative to the edge of the grid as the reference point for measurements regardless of direction.

When using the Grad601-2 dual gradiometer for surveying at 2 lines/m with a parallel or zigzag traverse pattern, the operator must follow exactly the appropriate pattern shown in Figures 19 and 20. The first traverse is made with the left-hand sensor at 0.25m and therefore the centre of the support bar at 0.75m from the edge of the grid. The second traverse is made with the centre of the support bar 1.25m from the edge of the grid. The third traverse is made with the centre of the support bar 2.75m from the edge of the grid and the fourth traverse with the centre of the bar at 3.25m from the edge of the grid. This alternating pattern of 1.5m and 0.5m increments is repeated for the complete grid.

When using the Grad601-2 dual gradiometer for surveying at 4 lines/m with a parallel or zigzag traverse pattern, the operator must follow exactly the appropriate pattern shown in Figures 21 and 22. The first traverse is made with the left-hand sensor at 0.125m and therefore the centre of the support bar at 0.625m from the edge of the grid. The second traverse is made with the centre of the support bar 0.875m from the edge of the grid. The third traverse is made with the centre of the support bar 1.125m from the edge of the grid and the fourth traverse with the centre of the bar at 1.375m from the edge of the grid. The fifth traverse is made with an increment of 1.25m placing the centre of the bar at 1.625m from the edge of the grid and the next three increments are 0.25m. This pattern of increments of 1.25m, 0.25m, 0.25m, 0.25m is repeated for the remainder of the grid.
For a Grad601-2 dual gradiometer it is recommended that a trapeze be used with 1m between the two ropes. The ropes defining the start and end of each traverse should be marked such that placing the centre marks of the trapeze over the marks on the edge ropes guides the operator along the traverse with one sensor over each of the trapeze lines. Figure 23 shows the rope marking, trapeze position and sensor position for obtaining data at 1, 2 or 4 lines/m with a dual gradiometer. This diagram should be used to prepare different ropes for each case. It has been found that walking between ropes as shown requires two operators to move the ropes but avoids the operator carrying the sensors walking along a line on the ground with the possibility of tripping.

With practice the trapeze guide may be abandoned and the operation simplified by using canes to walk to at each end of the traverse as described later.

Surveying a grid at 2 or 4 lines/m requires proportionally more memory than a grid surveyed at 1 line/m and the number of grids which can be saved will be reduced accordingly.

16 SURVEY OPERATION

When Start Survey is selected from the menu, the data logger indicates the Grid number and waits for the operator to confirm this by pressing the ENTER key.

The display will then show that the instrument is ready to start the first traverse. It is good practice for the operator to stand away from the line marking the start of the traverse and press and hold the external green push button, start walking and release the push button when passing the start line. If Audio on has been selected, the data logger will bleep as the operator releases the key, and then at 1m intervals along the traverse. The operator should regulate the pace so that the bleeps coincide with the sensor passing the metre markers. A double bleep will sound as the operator reaches the end of the traverse. During a traverse the data logger will display the current gradiometer readings, Grid, Traverse and Position numbers. The gradiometer readings will be displayed with only 1nT resolution but will be saved with 0.1nT resolution when operating with a range of 100nT.

In order to ensure good alignment of the data, it is most important that the operator starts the traverse well outside the grid and reaches the normal pace before crossing the start line. It is also most important to release the Enter key or green push button exactly as the gradiometer sensors reach the start line. For example, with a pace of 1.8m/s and 4 readings per metre, a delay of only 140ms will cause an apparent shift in the data by 0.25m. When this is repeated in the other direction for zigzag traverses, a total stagger of 0.5m will be seen. When walking at a fast pace therefore, the operator should aim to release the key a little early to allow for the reaction time.

The data logger prompts the operator to start each new traverse. When the last line is completed, the operator will be prompted to save the grid or go back one line. If the save option is selected the display will then show the maximum, minimum and mean values for Sensor 1. A series of asterisks will be seen if the numbers are too large to fit the display. The ENTER key clears the display and returns to the main menu.
During traverses the sensors should be maintained in a vertical position to minimise rotational errors. If the instrument is tilted in the traverse direction the data will be biased in that direction and when a zigzag pattern is used a significant stagger may appear between traverses.

**Interrupting a survey**
Pressing the *ESC* key at any time during a traverse will halt the data collection process, and a menu will offer the following choice:

> Finish and Mirror
Finish grid
Finish traverse
Change Pace
Back one trav
Back one posn
Enter dummy at
Delete this grid
Esc/PB to continue

Dummy values outside the normal range are used to fill the data pattern over inaccessible areas. When operating in a zigzag pattern an obstruction may prevent the end of the current traverse and the start of the next traverse being completed.

*Finish and Mirror* will fill the remainder of the current traverse with the dummy value (32702) and will cause an equal number of dummy values to be inserted at the start of the next traverse. Data can then be collected normally for the remainder of the traverse. If the selected pattern is parallel rather than zigzag, then the instrument will simply give an audible bleep to indicate an invalid command.

If *Finish grid* is selected, the remainder of the grid is filled with dummy values. The operator will then be prompted to save the grid or return to the start of the last line.

If *Finish traverse* is selected the *ENTER* key will insert dummy values up to the end of the current traverse, and the operator will be prompted to start the next traverse. This is used to complete a line where an obstruction prevents a line being completed.

If *Change Pace* is selected the current pace is displayed and the operator is prompted to use the *Arrow* keys and *Enter* to set the pace required.

If *Back one trav* is selected during a traverse, the first *Enter* key operation will cause the displayed Position number to return to 1 ready to start the traverse again. Further operations of the *Enter* key will cause the Traverse number to be decremented. If the option is selected before starting a line, the Traverse number will be decremented each time *Enter* is pressed. When the required number of traverses have been deleted, pressing *Esc* will return the unit to the survey mode ready to continue from the start of the selected traverse. This option allows the survey to be restarted from the beginning of any previous traverse. If Traverse 1 is reached, the unit will bleep and prompt the operator to start the line.
If Back one Position is selected, the Position number shown with the menu item is decremented for each operation of the Enter key. When the required position has been reached, pressing Esc will allow the survey to continue from that position. When Position 1 is reached, the unit will bleep and prompt the operator to start the traverse. If Enter dummy at is selected, the ENTER key will insert a single dummy value each time it is pressed and the Position number shown will be incremented accordingly. It is important to remember that if data is being recorded at 0.25m intervals then four dummy values are required for each metre of traverse. If a dummy is entered at the last position of a traverse, the unit will bleep and prompt the start of the next traverse.

If Delete this grid is selected, the ENTER key will cause the current grid to be deleted after confirmation and the display will return to the Main Menu.

If the ESC key is pressed, the display will always show the next position to be measured and prompt the operator to press ENTER to start. If possible the operator should follow the same procedure as at the start of the traverse, as the recording will continue at the same pace when the ENTER key is released.

By using dummy values in a grid and using different sized grids, it will be possible to carry out surveys with irregular boundaries or obstructions. Dummy values can be transposed to any other value when downloading to a PC.

**Data logging and control**
Data is collected at a fixed rate and is automatically saved to the flash memory at the end of each traverse. If a survey is interrupted by loss of power, the data logger should continue from the start of the interrupted traverse when power is restored. However, it is not recommended that power be deliberately removed during a survey.

Data values are stored as two-byte signed integers to minimise both the memory requirements and the time taken to download data. The 256kByte memory is sufficient to hold the data for 36 grids of 30x30m with a line separation of 1m and 4 readings per metre. This corresponds to 36 grids, each with 3,600 data points. If smaller grids are used or measurements are made at less frequent intervals the capacity of the memory will increase proportionally up to the limit of 99 grids. Dummy values take up the same memory space as real values and finishing a grid with dummies utilises the same memory space as a normal grid.

In order to place the data into a larger matrix after downloading, the operator must record separately the relative position of each recorded grid.

**Single Shot operation**
If Single Shot is selected as Pace in the Set Parameters menu (between 2 and 0.5m/s), then the survey operates as normal except that only one reading will be recorded each time the operator presses and releases the Enter, or green, button rather than data being recorded at a fixed rate. The gradiometer can then be moved between individual readings.
17 DOWNLOADING SURVEY DATA TO A PC

The Grad601 gradiometer is supplied with Grad601 Datalog software on a CDROM to enable the user to download the contents of the memory to a PC and save each grid to a file with one of three formats. All data recorded in a zigzag pattern or with interlacing as for 2 or 4 lines/in using a dual gradiometer, will automatically be re-arranged to appear as it would if recorded in a parallel pattern with the correct line order.

Other proprietary data processing software such as ArcheoSurveyor from DW Consulting, allows direct download from the gradiometer into the program ready for processing.

Installing the Grad601 Datalog software
Place the CDROM in the CDROM reader and the program installation should start automatically. If it does not, use My Computer or File Manager to locate the program setup.exe on the CDROM drive and double click on it to start. Follow the instructions given.

If a previous version of the software is installed the CDROM will uninstall it. The CDROM should then be restarted to install the new version. A copy of the Grad601 Datalog icon can be copied from the shortcut tool bar into the desktop display for future use using copy and paste.

Starting the program
Connect the Grad601 data logger to an RS232 communications port on the PC using the 9-way cable provided. Alternatively, use the USB to serial converter provided along with appropriate installation software.
Switch on the data logger; it does not need to be connected to any sensors.
On the PC, start the program Grad601 Datalog.

The Downloading Screen
Select the Com Port to correspond to the port on the PC to which the gradiometer is connected. If the USB to RS232 converter is used, the operator should go to My Computer/Control Panel/System/Hardware/Device Manager/Ports(Com & LPT) to determine the number of the port allocated by the computer to the converter.
In the Dummy Data window, set the number required to represent dummy data. The default value in the incoming data stream is 32702.
From the main menu of the Grad-601 data logger select Output data and press ENTER. The message Waiting for PC will appear.
On the PC select START, and after a few seconds the data download will begin.
The PC screen will indicate the number of the Grid being transferred and the total number of bytes received. Each value consists of two bytes and the total number of bytes will be somewhat larger than twice the total number of readings.

The Grad-601 data logger display will also show the number of the Grid being sent. When all data has been sent, a checksum is sent to validate the data. If the checksums do not match, an error occurred and the user will be prompted to repeat the download operation or proceed with the data as received.
If the data is received without error, the screen will change to the Save Screen to allow the data to be saved as individual Grid files.

**The Save Screen**
The screen will show both the total number of grids and the next grid to be saved. The header information for the first grid, giving the survey parameters, will also be shown. The options of saving or skipping the current grid, saving all grids or abandoning all data are given.

Before selecting **SAVE**, the format, number of files and data delimiter must be set as required. The data for each grid can be saved as two files, one for the header information and the other for data, or as a composite with the header and data in one file. The files can be formatted as a Spreadsheet with tab or comma delimiters, as XYZ files with tab or comma delimiters or as a Z stream with <CR><LF> delimiters. All data is in ASCII format. X and Y represent the position in the grid and Z represents the amplitude of the gradient recorded at that point.

Select either one or two files, the data delimiter as a tab or comma, and the file format required. The tab delimiter should be used in countries where a comma is used for the decimal separator. The single file with Spreadsheet format and tab delimiter is recommended for initial use. This gives an ASCII file that can be subsequently transferred directly into Excel or various mapping programs. Other data processing programs may require the Z string or XYZ file format, with a separate header file. When all parameters are correct, select **SAVE** or **SAVE ALL**.

If **SAVE** is selected, a separate **SAVE AS** window will appear and allow the user to select a folder and file name. When the data has been saved, the information for the next Grid will be presented and the process can be repeated.

If **SAVE ALL** is selected, a Choose a Filename Prefix window will appear. The user should select a folder and then enter a name to be used for all the files. The data will then be saved with filenames comprising the chosen prefix and the grid number. If the user selects the prefix *mygrid*, the grids will be saved in files called mygrid1.dat, mygrid2.dat etc.

If the **SKIP** or **SAVE** operations are used followed by the **SAVE ALL** operation, the correct grid number will be allocated to filenames of the remaining grids.

At the end of the saving process the screen reverts to the initial download screen. Press **EXIT** to close the program.

After downloading it is recommended that the saved data is checked and backed up before deleting the data in the *Grad*601 data logger. After downloading and saving, the data cannot be re-formatted by the downloading program. However, the download process can be repeated with data being saved in different formats whilst the data remains in the *Grad*601 data logger.

The provision of three file formats allows the user to select a type compatible with export to the preferred data processing software. All results are shown in nT/m. A
decimal point will be shown if the 100nT range had been selected when collecting the data.

**Spreadsheet format**

If the data has been downloaded in spreadsheet format as one file and opened as tab or comma delimited data in Excel, the header and first section of data will appear as follows:

**Time** = 18:19:39  
**Date** = 08/05/2002  
**Grid Number** = 3  
**Number of Sensors** = 2  
**Grid Size** = 30 x 30  
**Method of collection** = ZigZag  
**Starting Direction** = North  
**Data Range** = 100 nT  
**Line Spacing** = 1.00 m  
**Sampling** = 4 samples / m  
**Sensor Spacing** = 1.0 m  

**Mean** = 0.0  
**Max** = 3.6  
**Min** = -3.7

The time and date is recorded from the computer clock when the file is saved. The remainder of the header information corresponds to the parameter settings when the data was recorded during the survey. If the two-file format had been selected during downloading, the header and data would appear in separate files, the data file being given the .dat extension and the header file the .hdr extension.

The data will have been re-arranged by the downloading software to remove the effects of zigzag data collection and the dual sensor arrangement so that it represents the results as would be seen if the data had been collected by a single sensor working in a parallel traverse mode. The data is therefore organised into a grid, which represents the plan of the site with the top left position being the start of the data collection and the top row corresponds to the first traverse.
**Z string format**

In the single-file Z string format the start of the same data will appear as follows:

```
Time = 18:19:39
Date = 08/05/2002
Grid Number = 3
Number of Sensors = 2
Grid Size = 30 x 30
Method of collection = ZigZag
Starting Direction = North
Data Range = 100 nT
Line Spacing = 1.00 m
Sampling = 4 samples / m
Sensor Spacing = 1.0 m

Mean = 0.0
Max = 3.6
Min = -3.7
-0.6
-0.3
-0.3
0.9
1.5
0.9
0
0.4
1.5
```

The data represents a continuous stream of gradiometer readings, re-formatted as though they had been collected using a single sensor working in parallel traverses. Each reading is followed by a `<CR><LF>` delimiter. If the two-file format had been selected, the header and data would appear in separate files with different filename extensions.
XYZ format
In XYZ format using a single file, the data will appear as follows:

Time = 18:19:39
Date = 08/05/2002
Grid Number = 3
Number of Sensors = 2
Grid Size = 30 x 30
Method of collection = ZigZag
Starting Direction = North
Data Range = 100 nT
Line Spacing = 1.00 m
Sampling = 4 samples / m
Sensor Spacing = 1.0 m

Mean = 0.0
Max = 3.6
Min = -3.7

0.125  0.5  1.3
0.375  0.5  1.2
0.625  0.5  1.1
0.875  0.5  0.9
1.125  0.5  0.9
1.375  0.5  0.8
1.675  0.5  0.8
1.875  0.5  0.8
2.125  0.5  0.4

The data is arranged in comma delimited columns with the first column representing the position in the X direction in metres, the second column representing the position in the Y direction in metres, and the last column representing Z, the gradient measured in nT at that point.

The X direction corresponds to the direction of the traverse lines, and the minimum value of X corresponds to the start of the first traverse with the values shown in metres. The Y direction represents the spacing between traverses, with the values in metres. In order that the plotted values correspond with the spreadsheet view, the first traverse represents the maximum value of Y and the last traverse corresponds to the minimum value of Y. Assuming the first traverse starts at the top left of the grid, X=min, Y=min therefore represents the bottom left of the grid and X=min, Y=max represents the top left, X=max, Y=max represents the top right.

18 SERIAL OUTPUT

The Grad601 data logger outputs the data from memory via a 3-line RS232 interface (TX, RX and Gnd). When Output Data is selected from the main menu, the data logger will turn on the RS232 interface and wait until the character S is received from the PC before starting transmission. The gradiometer will then transmit 32 signed integers as 64 bytes and wait for the next character S from the PC.
The baud rate is set to 9600 baud with 8 data bits, no parity, 1 stop bit and no handshaking. The last transmission may be less than 64 bytes.

**Data Format**
The data represents a number of grids. The data file for each grid comprises a header, the gradiometer readings and summary information. An End of Transmission integer and a final checksum follows the data for the final grid. All data is saved in the gradiometer and subsequently output in binary (signed integer) format, 2 bytes per integer, MSB first. All data are translated into ASCII characters in the PC after receipt. The gradiometer has two ranges, one is linear over ±100nT with a non-linear extension to ±3,000nT and the other is linear over ±1000nT with a non-linear extension to ±30,000nT. The measured magnetic data will therefore have signed integer values of up to ±32,000, representing values of ±30,000nT for the 1000nT range and ±3,000.0nT for the 100nT range. The range is given as part of the header information and decimal points are added when the range is ±100nT. Integers above 32000 are used for markers in the data stream.

**Markers**
The following specific integers are reserved for markers.

- 32700 = Start of Header
- 32701 = End of Header
- 32702 = Dummy data
- 32703 = End of Data
- 32704 = End of File
- 32705 = End of Transmission (this will be followed by a two-byte checksum)

**Transmission Format**
Each grid has a 10-integer header containing the conditions under which the data was collected. The gradiometer readings are transmitted in the order in which they were recorded. Therefore for a dual gradiometer system the data for the left hand and right hand gradiometers will appear alternately. Similarly, if the grid was covered using zigzag traverses the data will represent this traverse pattern. The downloading program uses the header information to re-organise the data as if it was collected with a single using parallel traverses. The Datalog software allows the header and data to be saved together or as two separate files.
**Header**

The format of each header is as follows:

<table>
<thead>
<tr>
<th>Integer Number</th>
<th>Value</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>32700</td>
<td>Start of Header</td>
</tr>
<tr>
<td>2</td>
<td>1,2,3 etc</td>
<td>Grid number</td>
</tr>
<tr>
<td>3</td>
<td>1 or 2</td>
<td>Number of sensors</td>
</tr>
<tr>
<td>4</td>
<td>10, 20 or 30</td>
<td>Grid size 10x10, 20x20 or 30x30</td>
</tr>
<tr>
<td>5</td>
<td>0 or 1</td>
<td>Zigzag or parallel</td>
</tr>
<tr>
<td>6</td>
<td>100 or 1000</td>
<td>Range</td>
</tr>
<tr>
<td>7</td>
<td>1,2 or 4</td>
<td>Lines/m (number of data lines /m)</td>
</tr>
<tr>
<td>8</td>
<td>1,2,4 or 8</td>
<td>Samples per metre along traverse line</td>
</tr>
<tr>
<td>9</td>
<td>10</td>
<td>Sensor spacing 1m</td>
</tr>
<tr>
<td>10</td>
<td>0 to 7</td>
<td>Starting direction, N, NE, E, SE, S, SW, W, NW</td>
</tr>
<tr>
<td>11</td>
<td>32701</td>
<td>End of Header</td>
</tr>
</tbody>
</table>

**Gradiometer Data**

The header is followed by the data as recorded in zigzag or parallel form. If a dual gradiometer is used then the first integer represents the left-hand gradiometer reading and the second integer represents the right-hand gradiometer reading. The data is structured as:

One zero value for a single gradiometer and two zero readings if two sensors were used.

The gradiometer data. For a 30x30 grid with 4 Samples/m, 2 Sensors and traverse interval of 2m there will be 3600 signed integers in the range ±30000. Values of 32702 in the data are dummy values, which can be changed by the user as required.

One zero value for a single gradiometer and two zero readings if two sensors were used.

The End of Data integer, 32703.

Three signed integers representing the summary data of mean gradient, maximum gradient and minimum gradient. For a dual gradiometer system, the values are those recorded for the left-hand sensor.

One zero value.

The End of File integer, 32704.

Other similar files will follow for further grids.

The End of Transmission integer, 32705.

A two-byte integer representing a simple checksum formed by exclusive-or of the current integer with the previous checksum.
19  RUN-TIME ERRORS

The program for the Grad601 is held in one non-volatile flash memory whilst details of the operating parameters, memory locations and data are held in a separate flash memory. In the unlikely event that the data concerning the operating parameters becomes corrupt or some other fault occurs causing a run-time error, the display will show “Warning! – Error xxx / Enter to continue”, where xxx is an error code. Pressing ENTER will start a system reset, allowing the processor to restart but causing the data memory to be cleared and the parameters set in the Set Parameters menu to be changed to the initial default values. Please report the occurrence of any error messages to support@bartington.com together with the error code for analysis. A list of possible errors is shown in the following table.

<table>
<thead>
<tr>
<th>Ranges of Error codes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Code</td>
</tr>
<tr>
<td>-----------</td>
</tr>
<tr>
<td>0-99</td>
</tr>
<tr>
<td>100-127</td>
</tr>
<tr>
<td>128-227</td>
</tr>
<tr>
<td>228-255</td>
</tr>
</tbody>
</table>

**System fatal errors**

<table>
<thead>
<tr>
<th>Code</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>228</td>
<td>Pointer store out of bounds</td>
</tr>
<tr>
<td>229</td>
<td>Array index out of bounds</td>
</tr>
<tr>
<td>230</td>
<td>Stack corrupted</td>
</tr>
<tr>
<td>231</td>
<td>Stack overflow</td>
</tr>
<tr>
<td>232</td>
<td>Aux stack overflow</td>
</tr>
<tr>
<td>233</td>
<td>Not used</td>
</tr>
<tr>
<td>234</td>
<td>Domain error (e.g., acos (2))</td>
</tr>
<tr>
<td>235</td>
<td>Range error (e.g., tan(pi/2))</td>
</tr>
<tr>
<td>236</td>
<td>Floating point overflow</td>
</tr>
<tr>
<td>237</td>
<td>Long divide by zero</td>
</tr>
<tr>
<td>238</td>
<td>Long modulus, modulus zero</td>
</tr>
<tr>
<td>239</td>
<td>Subtraction overflow</td>
</tr>
<tr>
<td>240</td>
<td>Integer divide by zero</td>
</tr>
<tr>
<td>241</td>
<td>Unexpected interrupt</td>
</tr>
<tr>
<td>242</td>
<td>Execute outside program bounds (RST38)</td>
</tr>
</tbody>
</table>

20  PRACTICAL ASPECTS OF SURVEYING

This section describes practical aspects of setting up and using the Grad601 single and dual gradiometers for geological surveys for archaeological prospecting and detailed mapping of archaeological features. Some points, which have been covered in the earlier text, are repeated where it may be appropriate. For recommendations on managing archaeological projects see www.eng-h.gov.uk/welcome.htm.
**Conventions**

For compatibility with existing plotting software and current practice, certain conventions apply. The site to be surveyed will be divided into areas (grids) of 10 x 10, 20 x 20 or 30 x 30m over which data is collected for subsequent assembly into a matrix. The gradiometer is carried along a series of traverses across each grid. The first traverse may start at any corner of the grid but the operator must set off in a clockwise direction as shown in Figure 14. This enables the data to be plotted with the correct orientation, using only the starting direction from the list of parameters saved as a header file. Plotting software will normally show a single grid with the first traverse starting from the top left corner as shown in Figure 15. Traverses may be done with a parallel or zigzag pattern as shown in Figures 7 and 8, respectively.

If a 10 x 10m grid is constructed from 1m squares and measurements are to be made at 1m intervals along 1m traverse intervals, then measurements should be made at the centre of each grid square as shown in Figure 16. This allows the data from adjacent grids to be seamlessly joined, and no convention is required about which edges are used for reference. The same principle applies when the sampling interval is less than 1m.

**Planning the survey**

It is important to remember the position of each grid and any reference points in order to be able to assemble the individual grids later into a matrix showing the complete site. Careful notes should be kept when planning the site survey. It is helpful if the site is divided into rows of regular grids. Grids of 30 x 30m are normal but difficult areas may be surveyed using 10 x 10m or 20 x 20m grids. The grids will be recorded in the order in which they are measured and given numbers starting at grid 1. Different grid sizes may be recorded in any order by changing the grid size parameter in the data logger.

The starting point for the survey depends on the shape of the area to be covered. If the area has a major axis in a north/south direction then the first grid can conveniently be the most northerly with the first traverse starting in the north west corner and walking east. Traversing is normally done with a zigzag pattern to minimise the walking distance. The traverses may carried out in either parallel or zigzag fashion but it is important to set the pattern parameter correctly in the data logger as the downloading software provided will always re-organise any zigzag data to parallel format before saving it to a file. The second traverse is made one interval to the south of the first. Traverses along east west lines then continue from the north to the south end of the grid. The adjacent grid to the south of the completed grid can then be surveyed and the pattern repeated until a complete column of grids has been measured. The survey can then move to the next column of grids.

Provided each grid starts with a clockwise traverse, surveys may be run in any direction but it will be most convenient and most easily recorded if successive grids progress in one direction, i.e. west to east, north to south or vice versa.

**Gridding Data**

The Grad601 gradiometer provides gridded data by sampling at regular intervals and emitting an audible bleep corresponding to each metre of traverse. A line with one-
metre marks can be laid on the ground along the traverse enabling the operator to maintain synchronism with the data sampling by ensuring that the instrument passes over a mark in time with the bleep. A suitable pace can be set as a survey parameter in the Grad601 data logger and modified during the course of a survey to suit the operator. A pace of about 1.6m/s is suggested as a starting point.

**Grids, Lines and Positions**
Each grid is normally surveyed with a line interval of 1m and a sample interval of 0.25m along the line of the traverse. This is a good compromise between the sampling rate and walking distance and provides good resolution of archaeological features. The Grad601 may be set for line intervals of 0.25m, 0.5m or 1m and sampling intervals of 0.125m, 0.25m, 0.5m or 1m.

The Grad601 saves grids in numerical order starting with grid 1. The memory has sufficient capacity to store the equivalent of 30 grids of 30 x 30m with 1m line spacing and 4 readings per metre, a total of 108,000 readings.

For the Grad601-1 single sensor gradiometer, the traverse lines correspond to the data lines. For the Grad601-2 dual gradiometer, the number of traverses will be half the number of data lines. The data logger allocates numbers to the traverse lines starting with 1.

The positions at which samples are taken along each traverse line are also numbered, starting at position 1. The current position is displayed during the survey.

**Survey methods**
The survey method will depend on the purpose of the survey. For archaeological prospecting prior to land development, the operation may need to be carried out quickly and with the minimum number of personnel. Detailed surveys of archaeological sites may require more precise measurements and additional personnel may be available. The following suggestions assume data is required at 1m traverse intervals over a 30 x 30m grid with a zigzag pattern, and is recommended for most purposes as a starting point. For line spacing of 0.5m or 0.25m refer to Figures 19 to 23 to prepare the survey equipment.

**Equipment required**
It is important that the operator and all equipment used must be non-magnetic. Mark about 12 bamboo canes of about 1m in length with fluorescent markers so they are easily seen from a distance.

Assuming a survey of a 30x30m grid at 1 line/m, prepare a trapeze with two rigid bars just over 1m wide joined by two 30m ropes spaced exactly 1m apart. The trapeze ropes should be marked at 1m intervals with the first mark at 1m from the end bar. The supports should be marked at the centre between the two ropes.

To mark the start and finish of the traverses, prepare two 30m ropes with loops at the ends to fit over canes when pushed into the ground 30m apart. These ropes should be marked with fluorescent sleeves or tape to show the start and end of each traverse. For a single sensor gradiometer the first mark should be at 1m from the end and subsequent
marks at 2m intervals. This corresponds to the arrangement in Figure 17. For a dual sensor gradiometer the first mark should be at 2m, and subsequent marks at intervals of 4m as in Figure 18. These are to be used at the edges of the grid to show the traverse limits and align the trapeze when the centres of the ends of the trapeze are placed on the marks on the start and finish ropes.

**Setting out the area**
Before setting out the area, switch on the gradiometer to allow the maximum warm up time before setting up the instrument.

The site should be set out using standard survey techniques such as a total station at some national grid reference point. The positions of the corners of the grids should be established and marked with the bamboo canes. Select the first grid to be surveyed and loop the edge lines over the canes at opposite sides of the grid to mark the start and finish of the traverses.

**Setting up the Gradiometer**
Ensure that instrument has been switched on for at least 20 minutes prior to setting up. Before setting up always check the operator for magnetic materials. Run the instrument in Scan mode fixed in one position and check that the readings do not change when the operator moves close to the upper and lower sensors.

As rotational and tilt errors are likely to be present prior to setting up, it is essential to hold the sensor in one orientation whilst searching the ground for a low gradient area over which to set up. When running the automatic set up procedure the gradiometer should be set as high above the ground as possible to avoid gradients near the ground.

**Logging data**
At the edge of the grid where the survey will start, stretch the trapeze across the grid with the centre marks of the trapeze bars over the first marks of the ropes as in Figure 17 for a single gradiometer or Figure 18 for a dual unit.

The trapeze lines then mark the position of the first two traverses, 0.5 and 1.5m from one end of the grid. Remember that the first traverse will start in a clockwise direction. When using a single-sensor gradiometer, the operator will carry the gradiometer sensor over the first traverse line and back along the second traverse line. A dual gradiometer will be carried with one sensor at 0.5m and the other at 1.5m for the first traverse.

In either case, the operator will select Start Survey on the data logger and Enter when accepting the Next Grid Number, press and hold the green button when ready and start walking from outside the grid towards the traverse line. When the sensor is over the edge of the grid at the start of the traverse, the operator will release the green button and the data collection will begin. The operator should adjust the pace so that the sensor passes each metre mark in time with the bleep of the data logger and the double bleep should correspond with passing the end of the traverse. It is important to pass the start and end of the traverse at the normal walking pace if staggering of the data is to be avoided.
When the first two traverses have been recorded, the trapeze is moved to the next mark on the edge lines and the next two traverses are recorded. This process is repeated until the grid has been completed. Using a dual gradiometer with a trapeze, as described above, the last traverse for a 10 or 30m grid will be completed with the centre of the trapeze in line with the edge of the grid.

The edge lines are then moved to the adjacent grid and the next grid is surveyed in the same manner. In this way a complete row of grids can be quickly covered.

**Other methods**

The equipment described above is suitable for single or dual sensor operation. For the highest spatial accuracy the operator should walk relatively slowly and ensure the sensor is held upright at all times and the movement should be smooth and well synchronised with the bleeps from the data logger. With experience, and where the spatial accuracy is less critical, it is possible to walk at a constant pace without the aid of the 1m marks on the trapeze lines and the trapeze may then be abandoned. The operator may then mark only the end of the traverse lines with canes, count the bleeps during each traverse and aim to reach the end of the traverse at the last double bleep. This procedure minimises the number of operators required.
21 SPECIFICATIONS

**Grad-01-1000 Fluxgate Gradiometer Sensor Specification**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor element spacing</td>
<td>1m</td>
</tr>
<tr>
<td>Gradient range (linear)</td>
<td>±100nT/m or ±1000nT/m full scale</td>
</tr>
<tr>
<td>Extended range</td>
<td>±3000nT/m or ±30000nT/m</td>
</tr>
<tr>
<td>Output</td>
<td>±4V full scale, output impedance 1kΩ</td>
</tr>
<tr>
<td>Accuracy</td>
<td>±2%</td>
</tr>
<tr>
<td>Maximum ambient field</td>
<td>±100μT</td>
</tr>
<tr>
<td>Noise</td>
<td>100pT pk-pk max.</td>
</tr>
<tr>
<td>Drift</td>
<td>&lt;1nT in 24 hours</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>d.c. to 14Hz with -40dB 50Hz/60Hz rejection</td>
</tr>
<tr>
<td>Power supply current</td>
<td>60mA</td>
</tr>
<tr>
<td>Connector</td>
<td>12 pole Tajimi R04-R12M</td>
</tr>
<tr>
<td>Environmental</td>
<td>IP65</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>-20°C to +70°C</td>
</tr>
<tr>
<td>Size</td>
<td>38mm diameter x 1050mm in length</td>
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<tr>
<td>Weight</td>
<td>0.825kg</td>
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**Grad-01 DL601 Data Logger Specification**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensors</td>
<td>1 or 2 Grad-01-1000 gradiometers</td>
</tr>
<tr>
<td>Gradient ranges</td>
<td>±100nT and ±1000nT linear with compression at higher values</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.1nT on ±100nT range</td>
</tr>
<tr>
<td></td>
<td>1nT on ±1000nT range</td>
</tr>
<tr>
<td>Attenuation</td>
<td>-20dB 50Hz/60Hz rejection</td>
</tr>
<tr>
<td>Controls</td>
<td>ON/OFF switch and keypad and external switch</td>
</tr>
<tr>
<td>Display</td>
<td>liquid crystal 2 rows x 20 characters</td>
</tr>
<tr>
<td>Display update rate</td>
<td>operation dependent</td>
</tr>
<tr>
<td>Connectors</td>
<td></td>
</tr>
<tr>
<td>Grad-01-1000</td>
<td>2 off 12 way Tajimi R04-R12F</td>
</tr>
<tr>
<td>RS232 output</td>
<td>9 way D type</td>
</tr>
<tr>
<td>External switch</td>
<td>3 way series 712 sub miniature</td>
</tr>
<tr>
<td>Battery</td>
<td>2 way 62GB type</td>
</tr>
<tr>
<td>Gradiometer adjustment</td>
<td>automatic via keypad</td>
</tr>
<tr>
<td>Data logging memory</td>
<td>256 Kbytes flash non-volatile</td>
</tr>
<tr>
<td>Data logging output</td>
<td>RS232 interface using Grad601 Datalog software</td>
</tr>
<tr>
<td>Audio output</td>
<td>Variable rate bleeper</td>
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<tr>
<td>Power supply</td>
<td>9-18V DC</td>
</tr>
<tr>
<td>Supply current</td>
<td>&lt;45mA</td>
</tr>
<tr>
<td>Environmental rating</td>
<td>IP65</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>-20°C to +70°C</td>
</tr>
<tr>
<td>Dimensions</td>
<td>160 x 80 x 60mm</td>
</tr>
<tr>
<td>Weight</td>
<td>0.485kg</td>
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BC601 Battery Cassette Specification

<table>
<thead>
<tr>
<th>Battery</th>
<th>1 off 12V 4Ah Lithium Ion</th>
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</thead>
<tbody>
<tr>
<td>Charge Indicator</td>
<td>Red LED lit when charging, off when finished&lt;br&gt;Push button charge level indicators</td>
</tr>
<tr>
<td>Connectors</td>
<td>2.1mm socket&lt;br&gt;2-way 62GB type on a 250mm cable</td>
</tr>
<tr>
<td>Battery charging</td>
<td>6-8 hours with mains adapter supplied (automatic termination)</td>
</tr>
<tr>
<td>Protection</td>
<td>Short circuit protection - 10 minutes recovery time&lt;br&gt;Fuse – 2A 20mm anti-surge internal</td>
</tr>
<tr>
<td>Environmental rating</td>
<td>IP65</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>-20°C to +70°C</td>
</tr>
<tr>
<td>Dimensions</td>
<td>210x120x25mm</td>
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<tr>
<td>Weight</td>
<td>0.91kg including battery</td>
</tr>
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</table>

Dimensions and Weights

<table>
<thead>
<tr>
<th>Gradiometer</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grad601-1 Single</td>
<td>2.9kg</td>
</tr>
<tr>
<td>Grad601-2 Dual</td>
<td>4.3kg + Harness 1.6kg</td>
</tr>
<tr>
<td>Carrying Case for either system</td>
<td>1160 x 270 x 230mm</td>
</tr>
</tbody>
</table>

The specification of this product is liable to change without prior notice
FIGURE 1  Grad601-2 DUAL GRADIOMETER ARRANGEMENT WITH HARNESS

FIGURE 2  Grad601-1 SINGLE GRADIOMETER ARRANGEMENT
FIGURE 3 Grad-01 DATA LOGGER DL601 CONTROL PANEL

FIGURE 4 BC601 BATTERY CASSETTE
FIGURE 5  GRADIOMETER CLAMP SHOWING Grad-01-1000L CABLE

FIGURE 6 Grad601 DATA LOGGER DL601 UNDERSIDE
FIGURE 7  PARALLEL TRAVERSE PATTERN

FIGURE 8  ZIGZAG TRAVERSE PATTERN
FIGURE 9  Grad-01-1000L IDENTIFICATION LABEL

FIGURE 10  HEADING DIRECTION LABEL ON Grad-01-1000L CONNECTOR JUNCTION BLOCK
Dimensions in mm

FIGURE 11  Grad601-1 SINGLE GRADIOMETER
FIGURE 12 - Grad601-2 DUAL GRADIOMETER
FIGURE 13 – Grad601-2 DUAL GRADIOMETER CARRYING HARNESS

FIGURE 14 - POSSIBLE STARTING POINTS FOR FIRST TRAVERSE

FIGURE 15 - FIRST TRAVERSE DIRECTION WHEN PLOTTED
FIGURE 16 - MEASUREMENT POINTS ON A SERIES OF GRIDS
FIGURE 17 - SINGLE SENSOR OPERATION WITH TRAPEZE (1m TRAVERSES)

FIGURE 18 - DUAL SENSOR OPERATION WITH TRAPEZE (1m TRAVERSES)
FIGURE 19 - DUAL SENSOR
PARALLEL SURVEY AT 2 LINES / m
Dimension in metres

FIGURE 20 - DUAL SENSOR
ZIG ZAG SURVEY AT 2 LINES / m
Dimensions in metres
FIGURE 21 - DUAL SENSOR
PARALLEL SURVEY AT 4 LINES / m
Dimensions in metres

FIGURE 22 - DUAL SENSOR
ZIG ZAG SURVEY AT 4 LINES / m
Dimensions in metres
Figure 23 - DUAL SENSOR TAPE MARKINGS FOR 1, 2 & 4 LINES / m