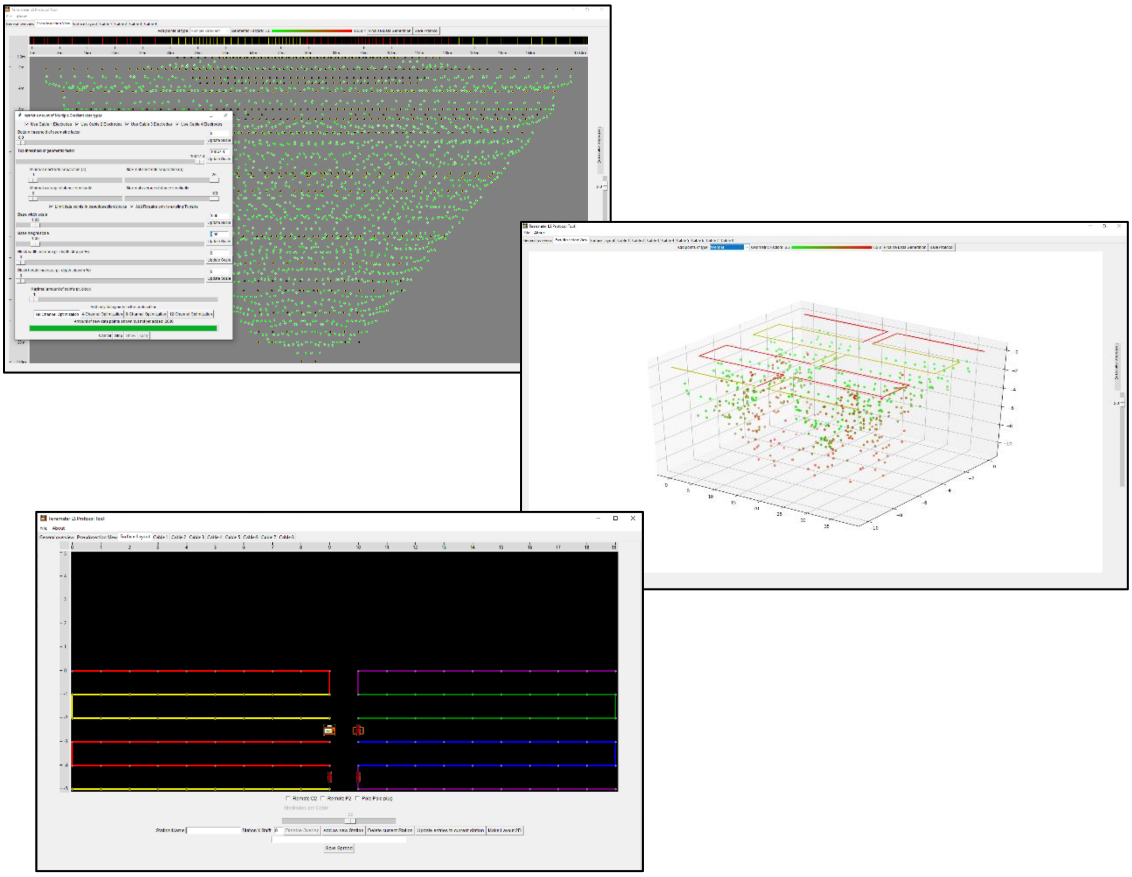
ABEM

User Manual



Terrameter LS Protocol Tool

ABEM Product Number 19-33320095

ABEM 2019-08-09, based on release 1.0 of Terrameter LS Protocol Tool

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1 Background

The cable configuration and measuring sequence of the ABEM Terrameter LS instruments are controlled by two types of .xml files; spread files and protocol files. While these .xml files provide a clean way of interacting with the instruments, the multitude of configurations that goes into setting up a specific geophysical survey makes it a cumbersome task to do manually. The Terrameter LS Protocol Tool described here is a visual package that overlays these two types of .xml files, enabling creation from scratch of both spreads and protocols. Additionally, the software handles the core computations needed for producing an optimized protocol (one which makes best use of the available measurement channels on a particular instrument).

2 Overview

The Terrameter LS Protocol Tool is built around tabs. When the software is started only three tabs are shown, as can be seen in field 2 of Figure 1, but as spread and protocols are built more tabs will be added. The tabs can be navigated freely throughout the process.

Figure 1 shows an annotated view of the first screen presented in the program. The highlighted elements are as follows:

1. The File menu is the main path to access and manipulate files on the disk.
2. The tab bar shows the currently active tab as General Overview.
3. The main controls for initiating either work on a protocol or a spread. While it is possible to navigate via the File menu and tab bar, these buttons perform the initial steps for each action.
4. The names and descriptions of the currently active spread and protocol; if a file is loaded, these are filled in automatically, otherwise they should be filled in before saving a new spread or protocol. The program will prompt if the fields are empty prior to saving.
5. Measurement statistics of the current protocol; once a protocol and spread are active these lines present computations of the specified characteristics for that measurement sequence.
6. Specific settings of the Terrameter LS, matching the key attributes on the *Receiver Settings* menu in the Terrameter LS user interface. These can be kept blank throughout the process, but values can be entered to calculate *Estimated execution time of protocol in RES Measure Mode* and *Estimated execution time of protocol in IP Measure Mode* shown in field 5 of the same figure.
7. Protocols can be optimized for 4-, 8- and 12-channel instruments. The controls given in the General Overview tab allow for selecting which type of instrument to optimize for. The controls are also available where the actual optimization is made, see Chapter 5 *Adding measurement points to a protocol*. Selecting an option in this tab sets the default type of Terrameter LS to optimize against and, if a protocol is open, it will affect the computations of *Amount of current injections in protocol* and *Average amount of data points pr. current injection* in field 5 of the same figure.

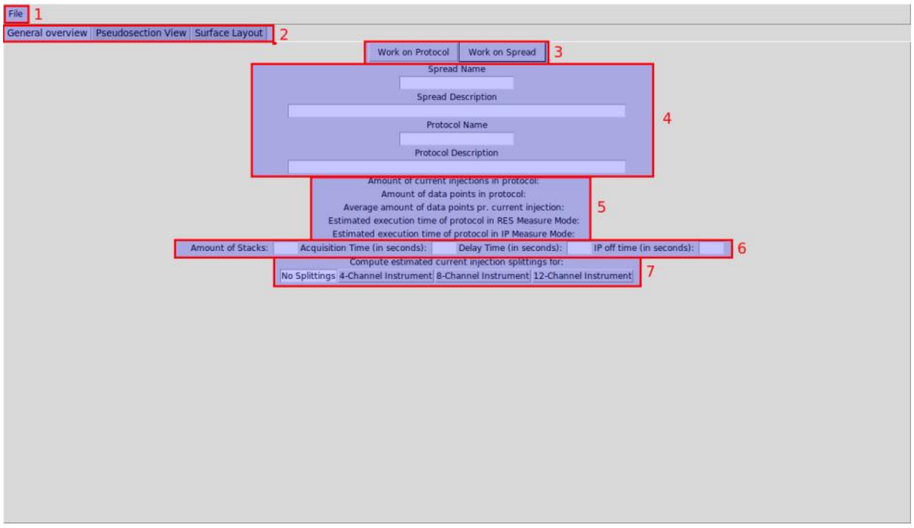

Figure 1 - Start-up view of the program; highlighted and numbered red boxes refer to the main elements of the screen discussed in the text

3 Spread files

A spread file is a cable configuration file for the Terrameter LS. It is the base for electrode coordinate handling and will define necessary information such as the number of cables to be used, number of electrodes per cable, whether cables are placed in a straight line (2D survey) or in a pattern (3D survey), whether external electrode selectors are required and the station and roll-along presets.

Note that spread files are made generic to be used with any electrode spacing. The 'true' electrode spacing will be defined in the Terrameter LS user interface when creating a task.

3.1 Surface Layout tab

Via a click on the *Work on Spread* button of field 3 in Figure 1, the view shifts to the *Surface Layout* tab, which is used to create a new spread or modify existing spread files. Clicking directly on the *Surface Layout* tab (field 2, Figure 1) will also open this screen. The view consists of six parts, as shown in Figure 2, and are described as:

1. Overview of the surface layout. This is an idealized view, seen from above, of how the cable spread is set up; in other words, how the Terrameter LS is connected with cables, electrodes, cable joints, external electrode selectors (ES10-64C) and boreholes. In this initial view, where no spread is available, only the Terrameter LS is visible. Chapter 3.2 *How to build a spread* gives details on how to create a new system layout.
2. The checkboxes specify internal Terrameter LS settings for the spread. The first two indicate whether a remote current (C2) or remote potential (P2) connection is in use – enabling Pole-Dipole and Pole-Pole points in protocols. The final check box specifies whether a Pole-Pole plug is used. If a Pole-Pole plug is used, current injections can handle up to 12 Pole-Pole measuring points; but only Pole-Pole points are possible for the protocol. If a Pole-Pole plug is not used, the instrument can use a maximum of two Pole-Pole measuring points per current injection, but it will allow additional data points from other electrode configurations.

3. The *Electrodes per cable* slider specifies how many take-outs on each cable are used. It is only possible to adjust this slider prior to building the spread, as the number of electrodes per cable is a fixed number.
4. The *Station Name* and *Station X Shift* are explained in Chapter 3.3 *Setting up stations*, along with the buttons *Add as new station*, *Deleted current Station* and *Update entries to current station*.
   The *Enable/Disable overlap* button toggles whether adjacent cables in the spread should have their first and last take-outs overlap, making them function as a single electrode position.
   The *Make Layout 3D* button converts the spread to a 3D configuration, enabling the cables and measurements to run in more than a single straight line. This is explained in Chapter 9 *3D spreads and protocols*.
5. The station list is empty in the initial view, but its function is explained in depth in Chapter 3.3 *Setting up stations*.
6. The *Save Spread* button is greyed out – and without function – until there is an active spread to save at which point it automatically becomes active.

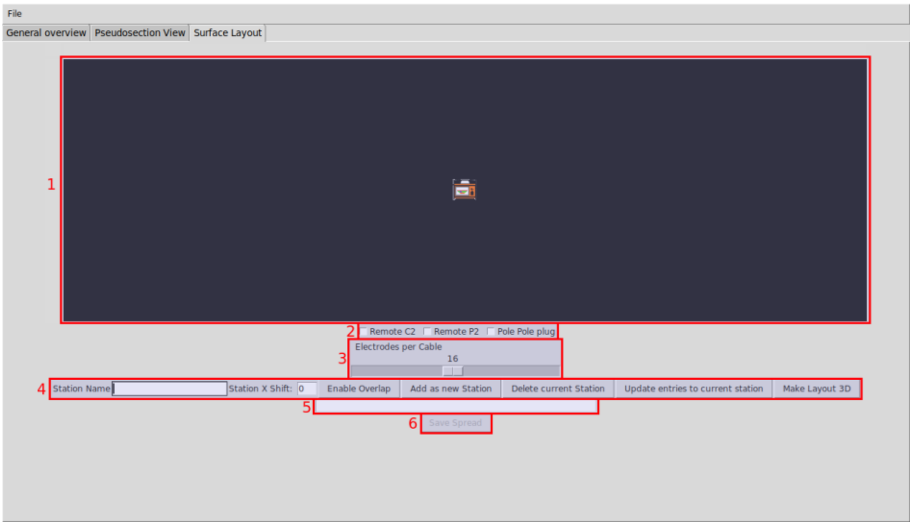

Figure 2 - The elements of the Surface Layout tab

3.2 How to build a spread

Existing .xml spread files can be loaded from the File menu and either used ‘as is’ or modified if needed. This chapter focuses on the creation of a new spread file. Altering an existing spread file utilizes the same functionality as described here.

Figure 3 shows the Surface layout tab, and the highlighted *Electrodes per cable* slider has been moved to 21 electrodes per cable. To initiate building a spread, left click on the central Terrameter LS icon as shown in Figure 3.

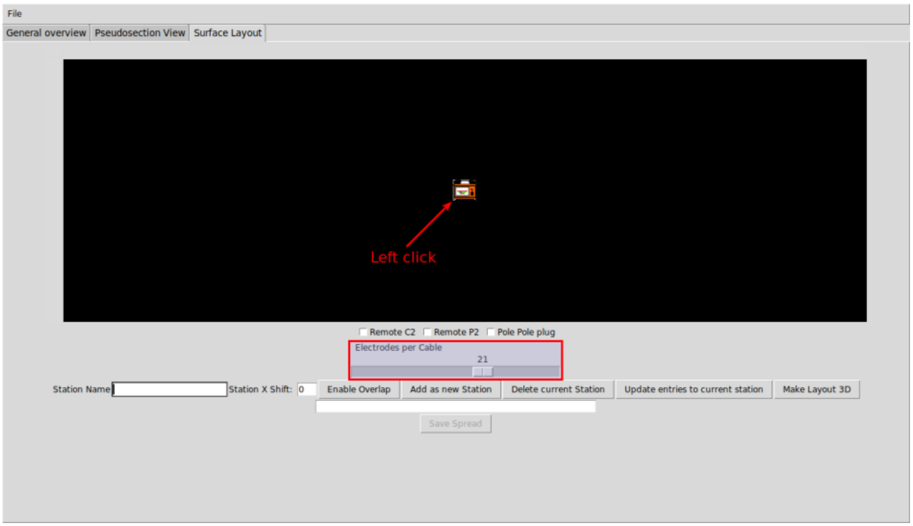

Figure 3 - Initiating a spread from the central Terrameter LS icon

The left click provides a menu as in Figure 4. At this initial stage in the spread creation the only options are positioning a cable either to the left or the right of the Terrameter LS.

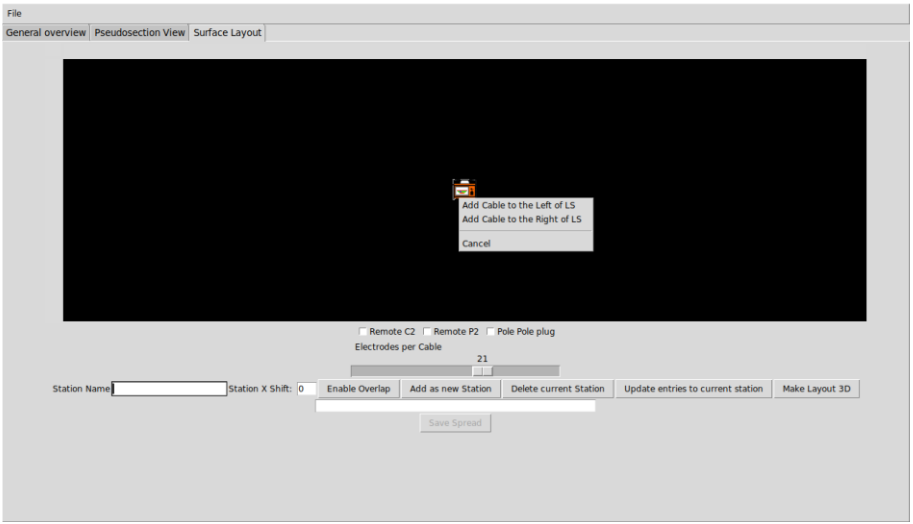

Figure 4 - Initial cable selection

In Figure 5, a cable to the left of the Terrameter LS has been added. There are several things to take note of in this figure, besides the new red cable with 21 grey electrodes attached to it:

- Above the black surface layout window, within the red highlighted box, an x-axis has appeared. The units of this axis are steps between the electrodes – starting with 0 at the left side of the general setup – and thus is independent of 'real world' electrode spacing.
- The *Electrodes per Cable* slider, altered in Figure 4, has been greyed out, barring further changes to the number of electrodes per cable. This slider only becomes active again if no cables are present in the spread.
- A new tab entitled "Cable 1" has appeared next to the present *Surface Layout* tab. The additional cable tab(s) provide a more advanced method for customizing individual cables which is covered in Chapter 3.4 *Individual Cable tabs*.

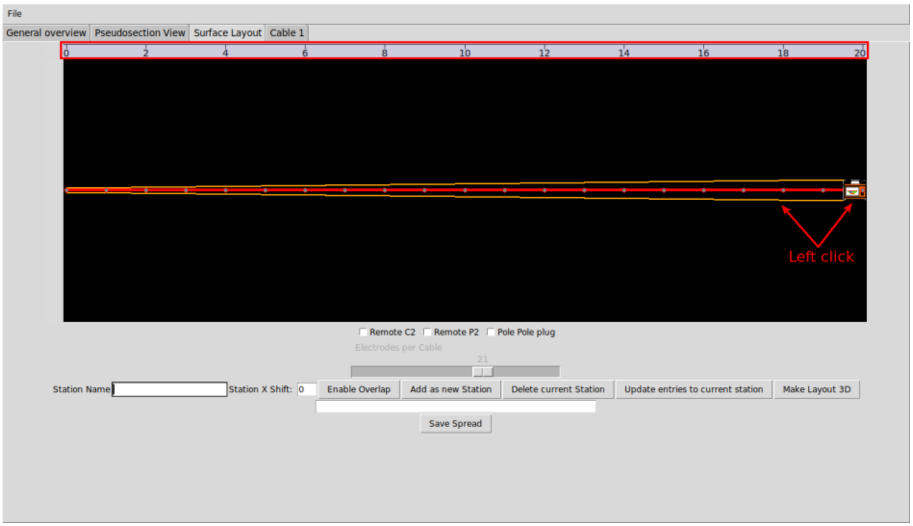

Figure 5 - Both the new cable and the Terrameter LS icons

With a new cable added, there are now two options available for adding to the surface layout:

- A cable to the right of the Terrameter LS can be added – which is obtained by a left click on the Terrameter LS.
- Or a cable/device can be added to the left of the newly created cable – which is achieved via a left click on the red cable.

A Terrameter LS has 64 unique addressable electrodes, which means that the selected number of "*Electrodes per Cable"* will influence the available options for adding new cables. In turn, this influences the options available for positioning new cables and devices. It is not possible to use more than 32 active electrodes on each side of the Terrameter LS, unless an external electrode selector (ES10-64C) is added.

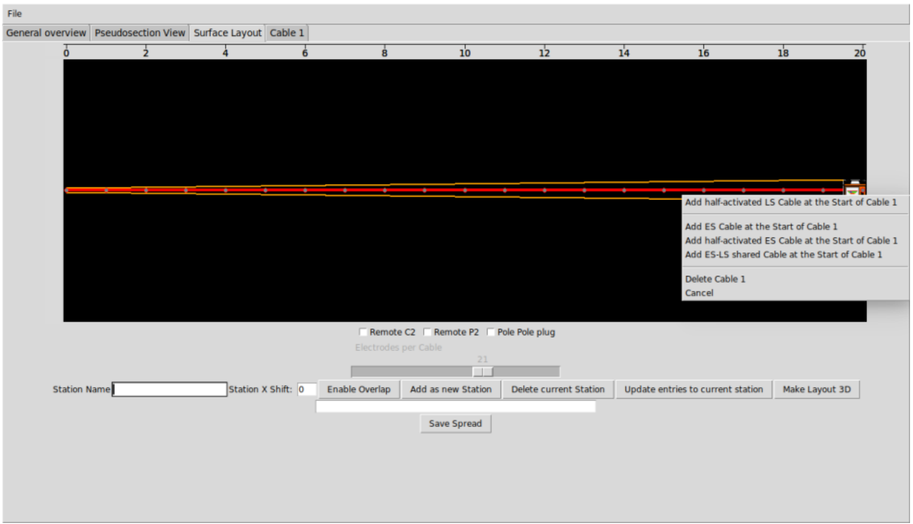

Figure 6 - The menu from a left click on the cable

In Figure 6, a left click is made on the newly created cable. Since the spreads created in the software evenly distribute the 64 available electrodes on the Terrameter LS to the left and right of the instrument, and there are 21 electrodes per cable in this spread, there are 11 electrodes (64/2 -

21) available for the left side of the Terrameter LS. The fact that there are only 11 electrodes available influences the options offered in the menu:

- One option is to add a half-activated cable, meaning that only every other of the 21 electrode take-outs on the cable (uneven numbers) will be activated, thus matching the 11 electrodes that can be accessed on the left side of the Terrameter LS.
  Note: This option is only available for setups selecting 21 Electrodes per cable.
- For the case that an ES10-64C is to be attached, there is an option to add either a half-activated or full cable to the left of the current setup. These are both the same as described for the Terrameter LS cable options.
- The option of an ES-LS shared cable gives the possibility of utilizing the 11(uneven numbered) electrodes available on the left side of the Terrameter LS with new electrodes (even numbered take-outs) connected to an ES10-64C, meaning that all electrodes on the 21 take-out cable are utilized.
  Note: A special cable joint is required to be able to use this setup.
- Finally, there is the option to delete the currently selected cable. Deleting cables will not always be an option – since the integrity of the spread setup needs to remain – however, the left-most/right-most cables in the surface layout can always be deleted.

Continuing as above, adding successively more objects to the surface layout, a configuration such as the 7-cable setup shown in Figure 7 could be obtained.

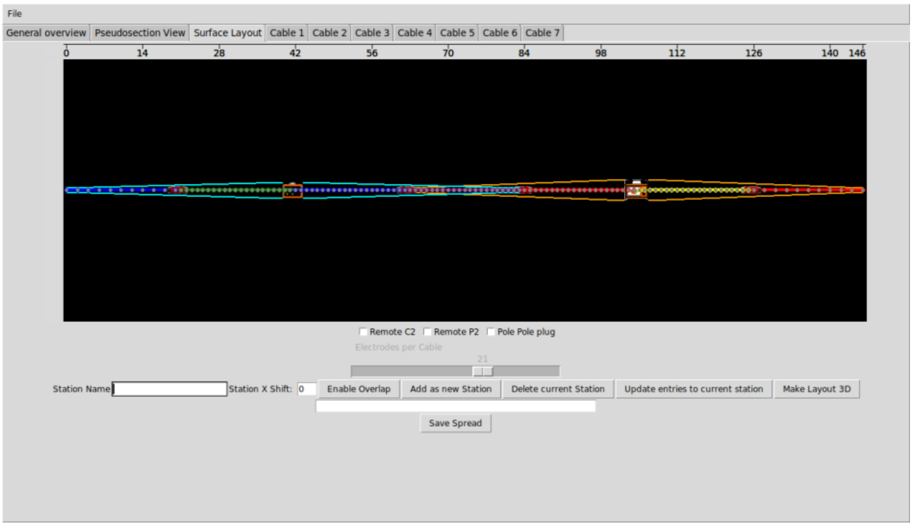

Figure 7 - Setup consisting of 7 21-take-out cables, using one ES10-64C and one Terrameter LS

The cables attached to the Terrameter LS via cable joints alternate between red and yellow – and they are enclosed by orange lines. Cables attached to the ES10-64C alternate between blue and green and are enclosed by cyan lines. Note the overlap of orange and cyan lines at the centre of Figure 7, as cable number 4 is connected to both the ES10-64C and Terrameter LS.

In Figure 8, the highlighted *Enable/Disable Overlap* button has been pressed. This means that the final take-out of each cable is made to overlap with the initial take-out on the next cable. There are 6 overlaps along the 7 cables and this is reflected in the highlighted x-axis altering from a maximum of 146 electrodes spaces to a maximum of 140.

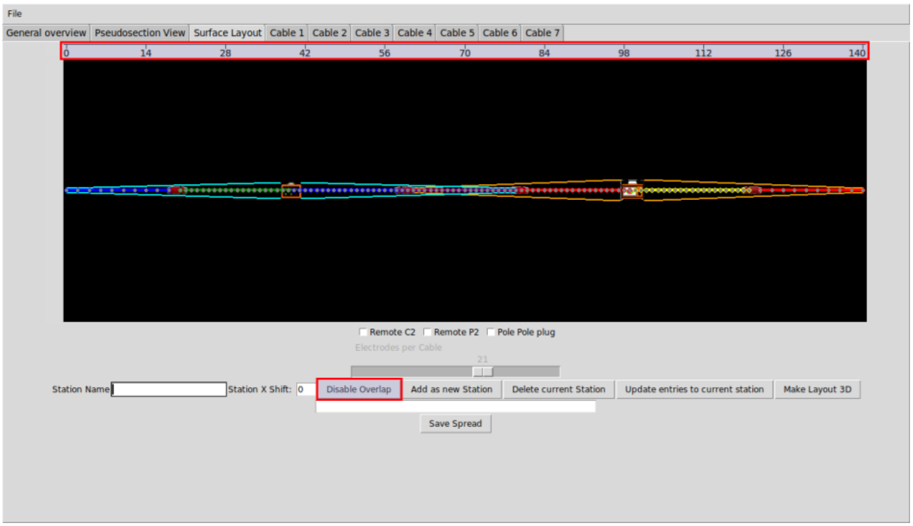

Figure 8 - Toggling the overlap makes the end electrodes of the

The checkboxes *Remote C2* and *Remote P2* controls the <C2 Current> and <P2 Current> tags of the .xml file, reserving internal electrodes of the Terrameter LS to enable Pole-Dipole and Pole-Pole protocols. These are both enabled in Figure 9.

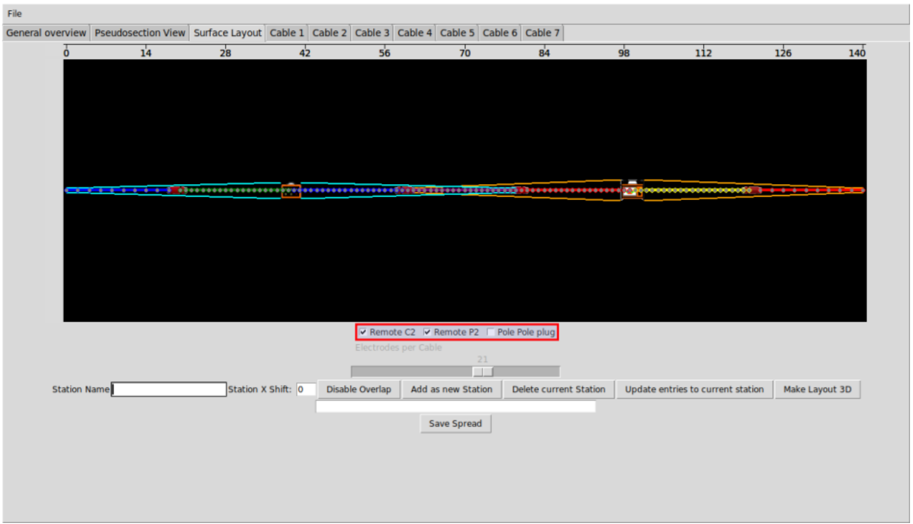

Figure 9 - Remote C2 and Remote P2 checkboxes have been ticked to allow for protocols with Pole-Dipole and Pole-Pole configurations

3.3 Setting up stations

In the Terrameter LS user interface, stations are presets that will set the instrument position to a pre-defined value and can also automatically exclude unnecessary cables. To show how to work with stations, the 7-cable spread from the previous chapter will be used.

In Figure 10 the desired name of the station is written in the field *Station Name* (this is what will be displayed in the Terrameter LS “Create new station” menu). Pressing *Add as new station* updates the list of stations to include this new entry.

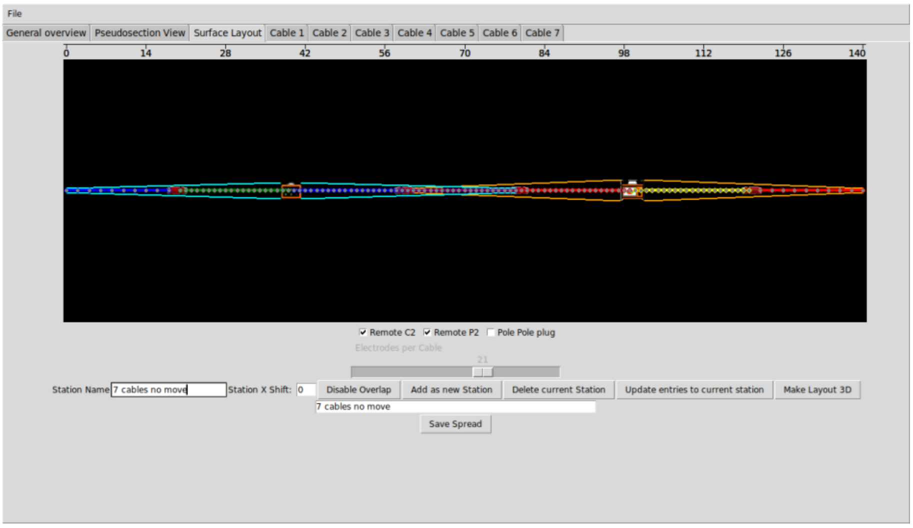

Figure 10 - A station called "7 cables no move" has been added to the list of stations

In this way stations can be added successively. The *Station X Shift* indicates movement of the cable spread, and the entered value represents the number of electrode positions that the first electrode of the first cable will move. The value zero indicates no movement, hence the cable spread at this station will start at metre zero on the profile, regardless of 'real-world' electrode spacing. A positive *Station X Shift* value indicates a move in the forward direction (increasing electrode positions, a shift from left-to-right on Figure 10), and a negative number indicates a move in the backward direction (decreasing electrode positions, shifting right-to-left on Figure 10).

In Figure 11 the *Station X Shift* entry is set to 20, the amount of electrodes on one cable minus the overlap, and a new station called *1 cable forward* has been created. Notice that the X-axis is altered again, reflecting that when performing a roll-along the left-most cable has been moved to the right side of the cable spread and that the electrode position numbers above the black surface layout have changed.

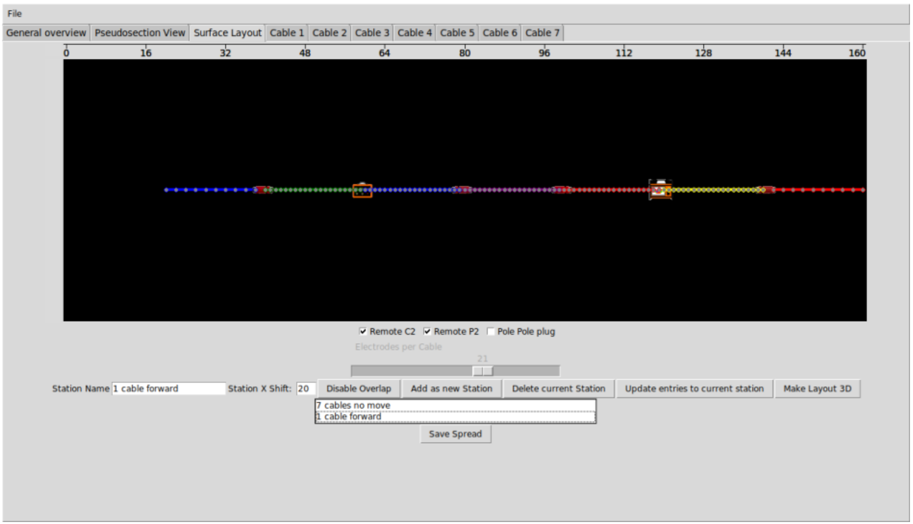

Figure 11 - "1 cable forward" station have been added

When using 21 take-out cable systems it can be useful to have stations that exclude some of the cables, for instance for the start and end station. In Figure 12 a new station with one cable backwards (Station X Shift -20) has been made, plus an exclusion of the first cable. This is done via the menus that appear when left clicking on the individual cables, as shown in Figure 12, and selecting “Deactivate Cable 1 from Station”.

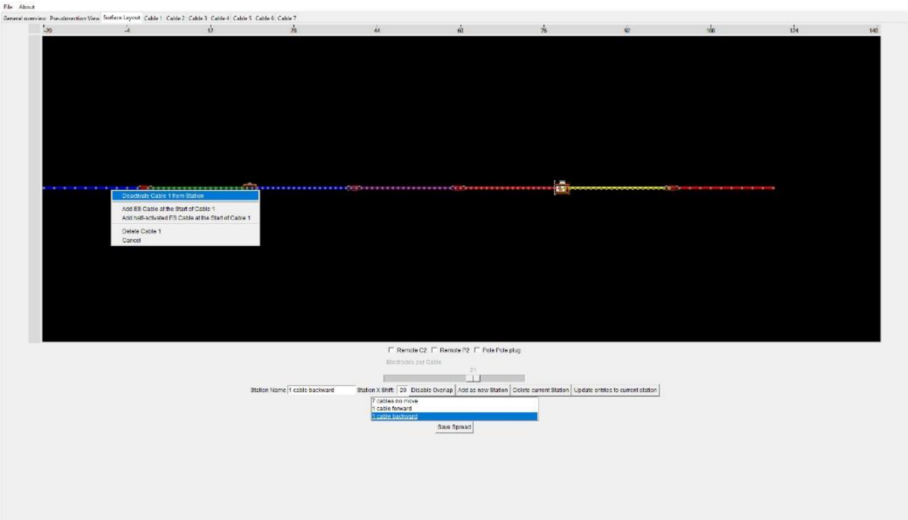

Figure 12 - The left-most cable (Cable 1) has been clicked, and we select "Deactivate Cable 1 from Station".

In Figure 13 the excluded cable is colored grey in the surface layout.

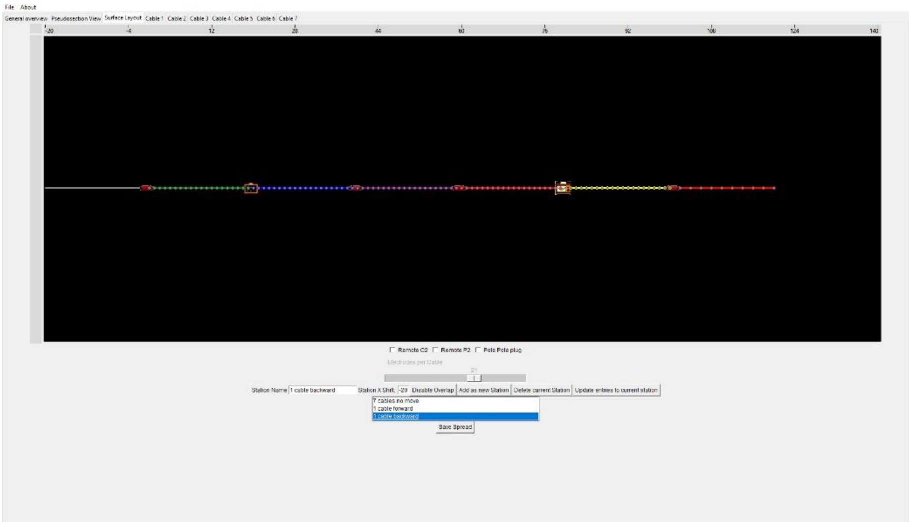

Figure 13 - The excluded Cable 1 is colored grey

To change a name of a station select the station from the list, then change the station name in the *Station Name* field, and press the button *Update entries to current station.*

Stations are added in this way until all desired stations are available in the list. The order of the stations shown is the order that they appear on the Terrameter LS *Create New Station* window. In Figure 14 the order of the stations is altered, by dragging individual stations to the desired place. When ready to save the completed spread, click on the highlighted *Save Spread* button.

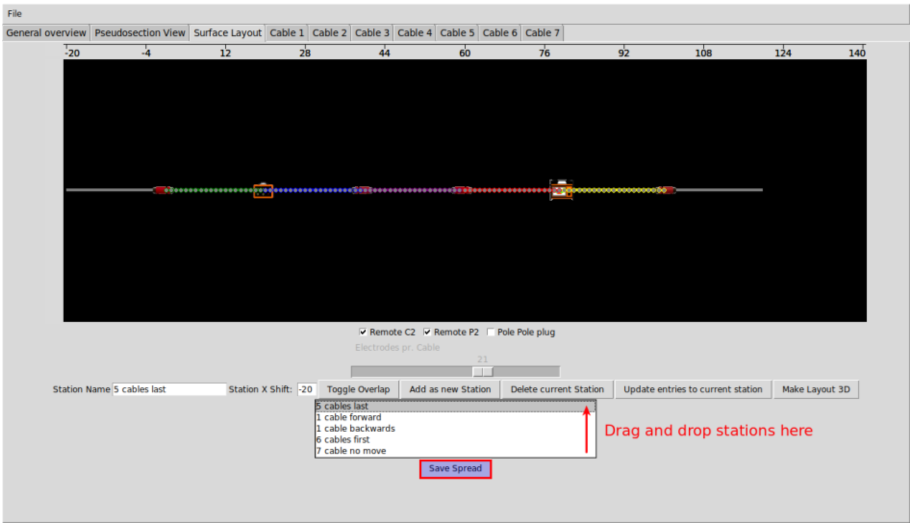

Figure 14 - The spread is done now that we have created the stations and ordered them in a convenient way

Upon pressing *Save Spread* the spread will be saved to file and a dialog box will allow a destination folder and file name to be chosen. If the fields *Spread Name* and *Spread Description* - marked as 4 in Figure 1 - have not been entered, a window appears (Figure 15) prior to the save file dialog box allowing for naming and describing the new (or edited) spread file.

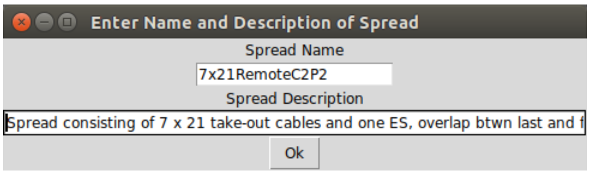

Figure 15 - Spread Name and Description entered before it is saved.

Once a Spread file has been saved, it can be loaded from the File drop-down menu, marked as 1 in Figure 1.

3.4 Individual Cable tabs

When a spread file with cables added is open, each of the spread's cables will have its own tab. The cable tab holds specific information for that cable and allows for modifying certain properties of the cable. For standard usage of the Terrameter LS it is not necessary to edit cables individually. All standard usage can be done from the Surface Layout tab.

Nonetheless, full access to the entries of the spread .xml file are available via the Cable tabs. In Figure 16, an activated cable tab is shown.

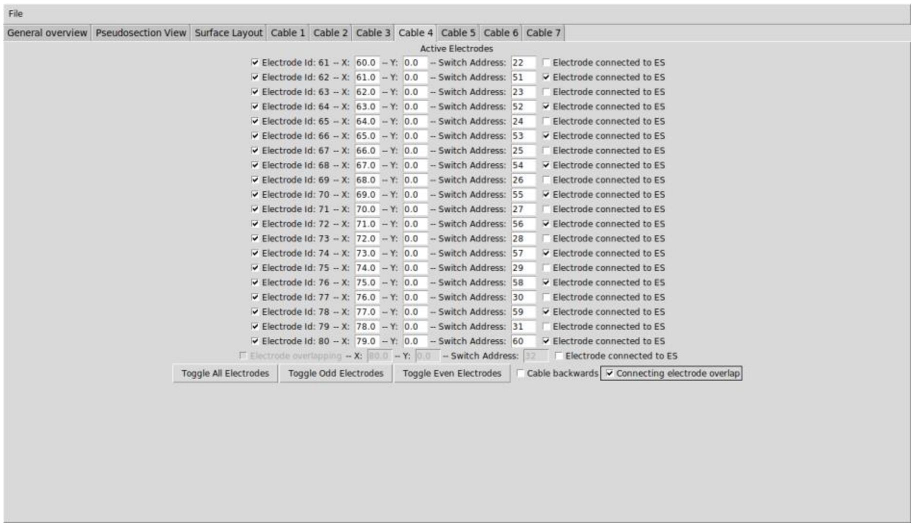

Figure 16 - The ES-LS shared Cable 4 of the 7 cable spread from Figure 9, with overlapping electrodes activated.

For each electrode on the cable there is a row that describes its name (Id), physical position (X / Y) and electrical connection to the instrument circuits (address). There follows a summary of the individual controls:

- In the source .xml file each of these rows is associated with a block of information identified by an "Id"; this identifier is listed as the number *n* in "Electrode Id: *n*". Changing any values in the rows on a Cable tab will affect the block of electrode information in the .xml file associated with that Id.
- The check-button to the left of "Electrode Id" determines whether an electrode is activated or not. Deactivated electrodes will not be part of any protocols, and thus not used by the Terrameter LS or ES10-64C. Deactivating an electrode removes the drawn grey dots from the surface layout tab as well.
- To the right of "Electrode Id" are the entry boxes for X and Y. These values determine the (X,Y)-coordinates in the Surface Layout, with respect to the axes shown there. If a spread is 2D, in other words a single straight line of electrodes, Y will always be 0.
- The *Switch Address* shows the internal switch matrix address of the given electrode (which in turn, correlates to a specific pin on the instrument connectors). These are computed to fit with standard cable layouts for the Terrameter LS but may need to be changed if special custom cables are used. The Terrameter LS internal switch addresses range from 1 to 64.
- The right-most *Electrode connected to ES* checkbox determines whether the electrode is on an ES10-64C cable or not. For the cable shown in Figure 16, an ES-LS shared cable is used, so every other electrode is attached to the Terrameter LS (uneven numbers) and every other to the ES10-64C (even numbers). The ES10-64C switch matrix has 64 addresses. If using multiple ES10-64C units the switch addresses will increment by 64 for each ES10-64C added. E.g. the first ES10-64C uses switch address 1-64 (remember that the .xml file has an entry to flag that these are "1-64" on an ES unit and not "1-64" on the LS), the second ES10-64C uses switch address 64-128, the third 129-192, etc.
- The final row, which is greyed out and labelled *Electrode overlapping,* indicates that the final take-out of the cable is overlapping with the first take-out of the next cable – so these particular electrode properties are controlled by the first entry on the next cable (Cable 5). All the controls of this particular row are therefore irrelevant.
- The buttons *Toggle All Electrodes*, *Toggle Odd Electrodes* and *Toggle Even Electrodes* are shortcuts for changing the status of the check-boxes left of the *Electrode Id*. Turning them all on/off or just turning the odd/even numbered electrodes on/off.

- The check-button *Cable backwards* ensures that when the final .xml spread file is saved, the switch addresses are saved in the reverse order of what is shown in the entry boxes. So, the first electrode Id is assigned the switch address of the bottom row.
  Note that checking this box does not affect what is shown in the entry boxes, only how the .xml file is saved.
- The *Connecting electrode overlap* sets whether there is a take-out overlap between the given cable and the next cable in the spread. When looking at the final cable in a spread, the overlap would be with the previous cable; if there is a mismatch between the overlap options on the penultimate cable and the last cable, the selection on the final cable tab takes priority. This option only greys out the overlapping electrode on the selected cable, thus overlaps can be made on individual cables rather than all of them.

4 Protocols

A protocol file defines the measuring sequence for the Terrameter LS. It will instruct the Terrameter LS which electrodes are to be used for current injection and which electrodes are to be used for potential measurement for a given reading or set of readings.

With the Protocol Tool it is possible to create new protocols from scratch or open existing protocols and modify them.

4.1 Initiating a protocol

Clicking on *Work on Protocol* in Figure 1 initiates work on a protocol. Before work on a protocol can be started, a compatible spread file needs to be selected. If a spread file has not already been selected, a dialog will prompt to load a spread file as in Figure 17. For the purpose of the examples in the following chapters, the 4x21RemoteC2P2.xml standard spread will be used. It is shipped along with the Terrameter LS and is also installed along with the Terrameter LS Toolbox.

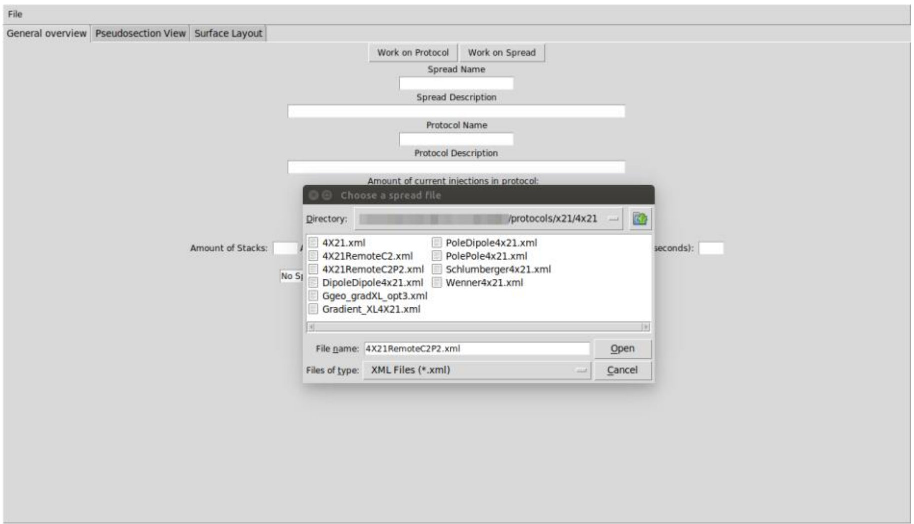

Figure 17 - The program prompts to load a spread file - the 4x21RemoteC2P2 spread is loaded

Once a spread file is selected the *Pseudosection View* tab appears, shown in Figure 18. Clicking the *Make Protocol From Scratch* button will start the creation of new protocol.

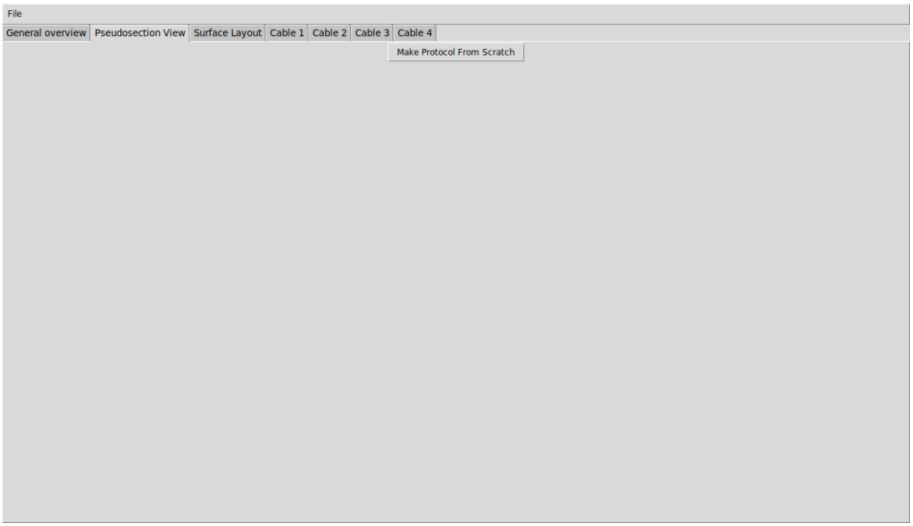

Figure 18 - Initial Pseudosection View tab.

4.2 Working with an existing protocol

The Terrameter LS comes preinstalled with a number of standard protocols, but they are made to be generic and, in some situations, there might be advantages to modifying them by adding extra data points, for example.

After selecting an appropriate spread file, the protocol file can be opened from the main File menu by selecting *Open Protocol File* as shown in Figure 19.

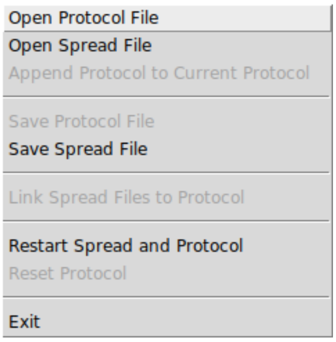

Figure 19 - Opening an existing .xml protocol file

For illustration purposes of the features of the Pseudosection view, a Multiple Gradient protocol, as shown in Figure 20, is loaded.

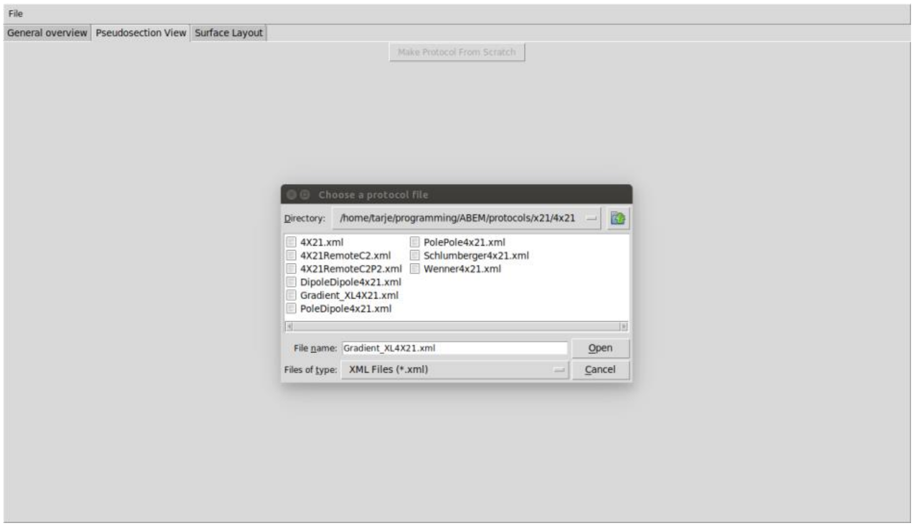

Figure 20 - Selecting a Multiple Gradient protocol

Upon loading the protocol, a pseudoplot of all the measuring points listed within it appears. The features of this tab are described through a series of figures in this section.

Since it is a 4x21 format spread that was loaded, the two outer cables are only half-activated and the two inner cables are regular ‘full’ cables. This is illustrated in Figure 21, by the highlighted bar above the measuring points view, by yellow and red bars. Each bar represents an electrode, and the bar’s color will alternate between every cable. On the right side of the window, the internal C2 and P2 electrodes are also highlighted.

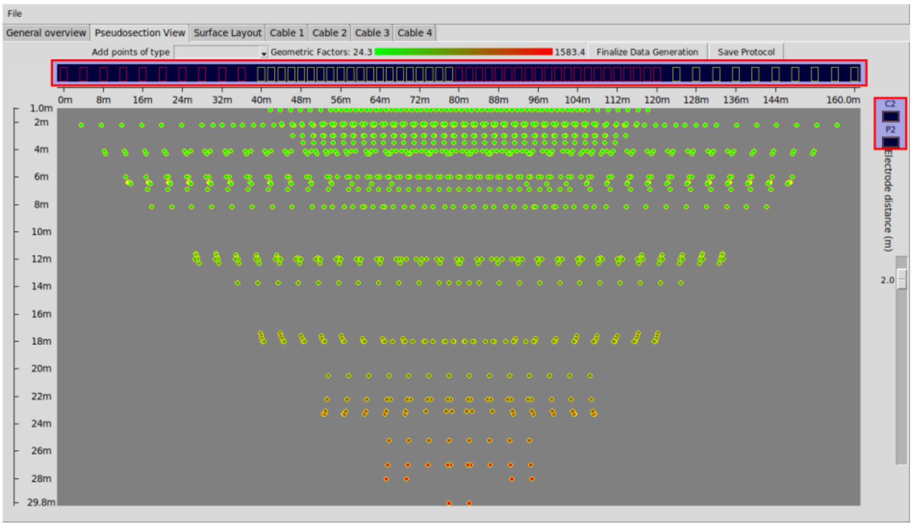

Figure 21 - The Multiple Gradient protocol

There is an x-axis as well as a z-axis in the downwards direction. In Figure 22 the highlighted ”Electrode distance” slider has been moved from 2 m to 5 m. Note that this slider has no influence on the .xml file itself; at the time of measurement any physical electrode distance will work regardless of how this slider has been set. However, compared to Figure 21, the x- and z-axis have changed to run from 0m-400m and 2.5m-74.5m, respectively. This slider hence gives us a reference to where pseudo-positions are for a given electrode distance.

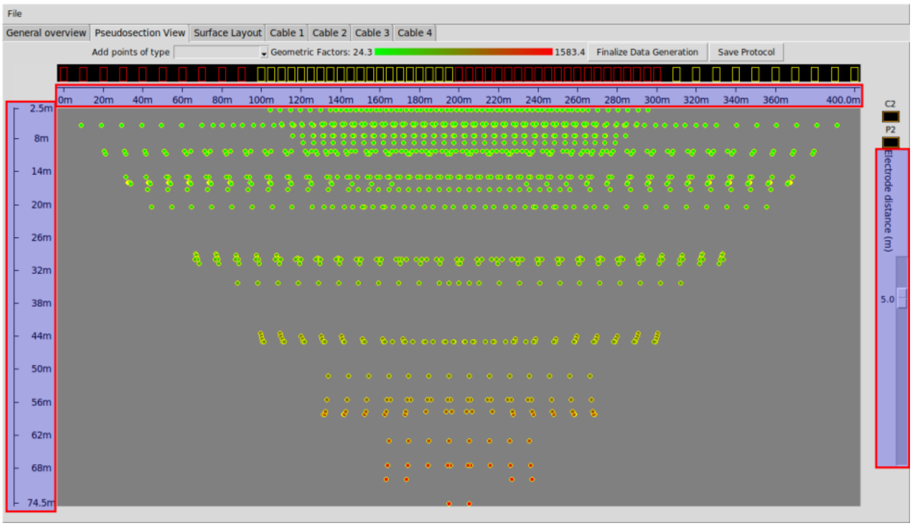

Figure 22 - Changing the electrode distance to 5m.

Specific points can be examined by clicking on them. In Figure 23 a left click has been made on a point that is now colored cyan. In the upper bar, illustrating the cables and electrodes, certain electrode bars are now filled:

- The current electrodes are colored blue – in the figure marked as A and B.
- The potential electrodes are colored green – in the figure marked as M and N.
- Some electrodes have been colored in brown/red. These represent electrodes being used as other MN measurement pairs (and so are responsible for other measurement points in the diagram) during the same current injection (between AB) as the active point. Remember that the LS is a multi-channel instrument and thus it is possible to take more than one measurement per current injection when using compatible electrode arrays.

In the lower part of the main window, as highlighted in Figure 23, a text field will show information about the selected data point. This text field will generally contain useful information throughout the usage of the program.

We can read off the position of the A and B electrodes (Tx positions) and the M and N electrodes (Rx positions), as well as the data pseudo-position in the coordinate system describing the pseudosection. Finally, the computed geometric factor of the measuring point is present as well. Notice that in Figure 23 there is also a highlighted color-bar called *Geometric Factors* which, for this protocol, runs from 24.3 to 1583.4. If a point is not active, its color is represented by a color on this scale corresponding to its geometric factor. Note that in order to get an appropriate distribution of colors, the color-scale is logarithmic – so, for an accurate reading of the geometric factor, it is best to click on the measuring point in question and read the value from the text field.

There are two additional controls in the Pseudosection View:

- The button “Finalize Data Generation” - which stops any new points from being added, and is explained more fully in Chapter 8 *Finalize Data generation*
- The button “Save Protocol”, which prompts the user to save the protocol as an .xml file.

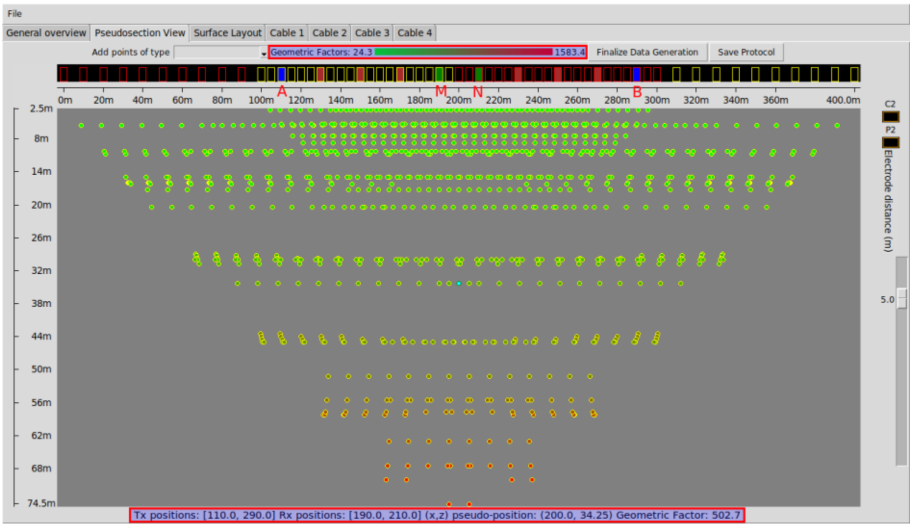

Figure 23 - A single point in the protocol has been clicked upon. The current (A,B) and potential electrodes (M,N) are shown on the cables

More information is available by clicking on the same data point for a second time, as shown in Figure 24. The selected point is still colored cyan but there are now six other points highlighted, colored in blue. These are points that have the same current electrodes as the selected point. The extra Rx electrodes will always have the same Tx electrodes as the initial point, but they may not be measured in one single current injection, as this depends on the number of channels and possible channel utilization. More information can be found in Chapter 7 *A note on the switch matrix*.

At the third click on the same data point, all measuring points with the same geometric factor are colored blue.

On the fourth click, all the points that were blue and cyan in Figure 24 remain but, in addition, all the points where the same electrode pattern (say A,M,N,B) is repeated along the spread are highlighted. In other words, these are data points where the pattern of electrodes has just been shifted by a fixed amount “x” (A+x,M+x,N+x,B+x).

Clicking once more returns to the initial view (Figure 23). At all stages, a description of the present view is given in the same highlighted field as we see in Figure 24.

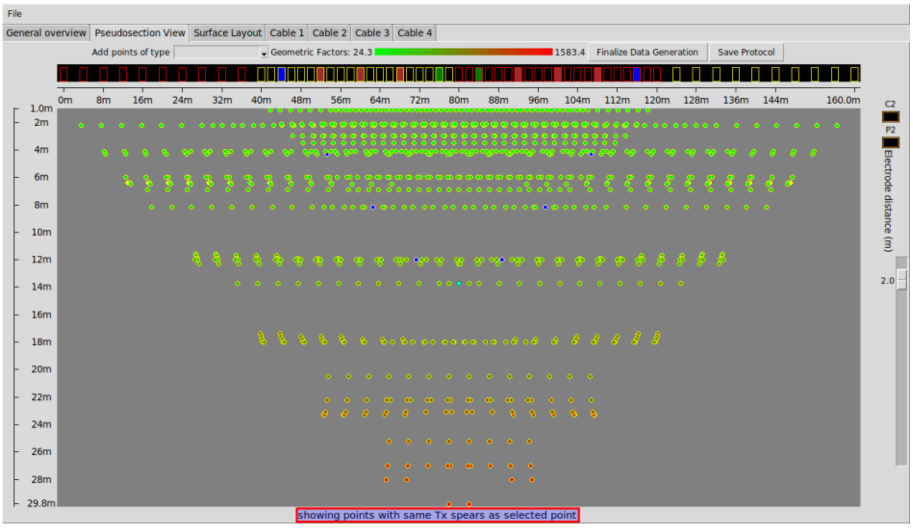

Figure 24 - Clicking on a selected point for a second time shows all points from the entire current injection(s) using that TX pair

4.3 Altering measuring points of a protocol

Making protocols that suit special needs in field surveys is a main motivation behind the Guideline Geo Protocol Tool. To this end, making new protocols, as well as altering existing protocols, is the focus of this section.

The buttons “Finalize Data Generation” and “Save Protocol” are for when all required measuring points have been added to the protocol. See Chapter 8 *Finalize Data generation*.

4.3.1 Deleting selected points

Individual data points can be removed by first selecting a data point by left clicking on it, and then right clicking on it and selecting *Remove selection.* Related groups of data points can also be removed by left clicking multiple times on a single data point, as illustrated in Figure 23 and Figure 24, and then right clicking on it and selecting *Remove selection*

Another option is to select all data points within a certain region. By pressing and holding the left mouse button and then moving the mouse a black rectangle will indicate the size and position of the region to be selected (Figure 25).

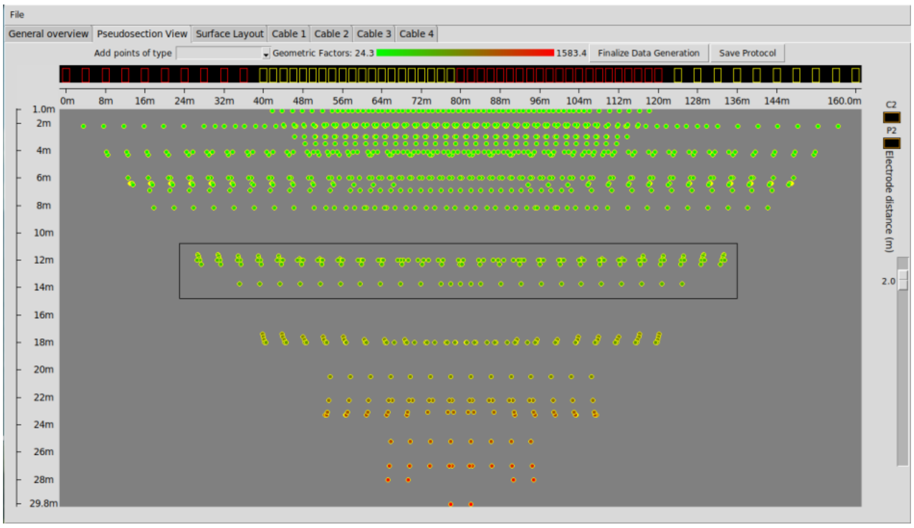

Figure 25 - Selecting all points in a rectangle

Once these points have been selected, a menu will appear, prompting for the deletion of the points as shown in Figure 26.

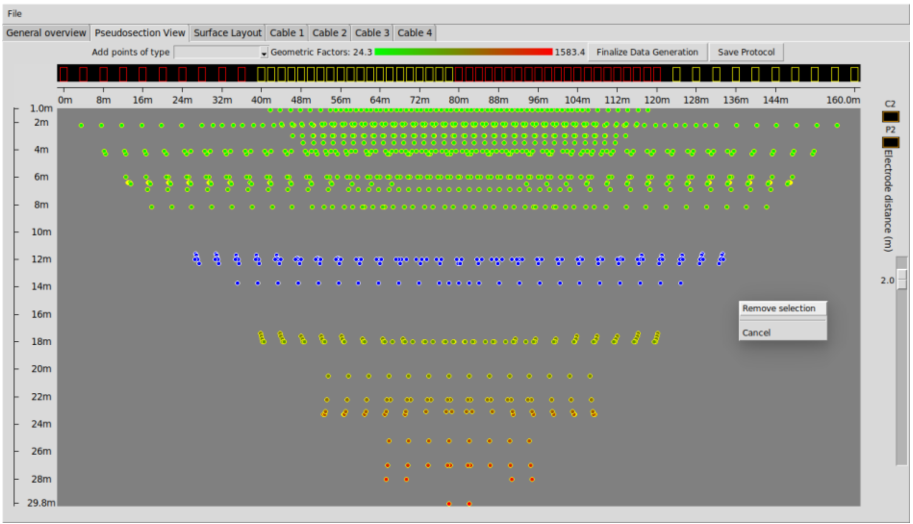

Figure 26 - Menu asking whether selection should be deleted

In Figure 27, the selected points are removed from the protocol.

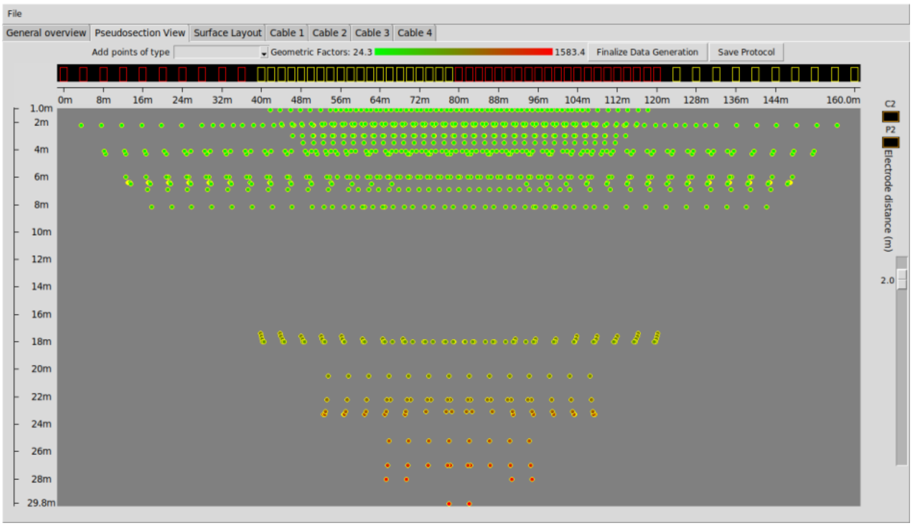

Figure 27 - The protocol without the selected rectangle

4.3.2 Link Spread Files to Protocols

Some protocols will work across a range of different spread files. These can be specified in the *Link Spread Files to Protocol* item of the File Menu, as shown in Figure 28.

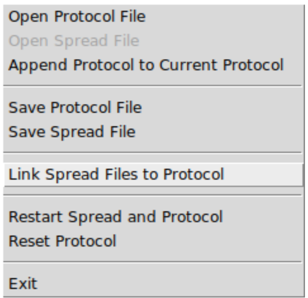

Figure 28 - Selecting "Link Spread Files to Protocol"

This opens a pop-up window as shown in Figure 29. The list of filenames are the spread files that are currently linked to the protocol. If the current spread file is not linked to the active protocol, but the protocol could successfully be loaded with it, then the filename is automatically added to the list as well.

The button *Add New Spread File* prompts for a compatible spread filename.

Remove Selected Spread Link removes a selected spread filename from the list.

Pressing *Close* closes the pop-up window. The list is saved to the protocol .xml once the protocol is saved using the main controls of the program.

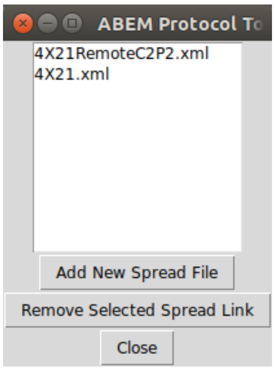

Figure 29 - The pop-up window displaying spreads linked to the current protocol

5 Adding measurement points to a protocol

While points can be added to any active protocol, this illustration utilizes the *Make Protocol From Scratch* option of Figure 18 to initiate a blank protocol. From here the dropdown menu highlighted in Figure 30 is used to select the type of measuring points to add.

Figure 30 - New points can be added to a protocol using the highlighted drop-down menu

The content of this drop-down menu is reflected in the section headings below. Note that protocols can mix measurement points of different electrode array types. If only a single type of point is used, the protocol will be marked as being of that array type. If multiple types of points are used it will be marked as a mixed/general type protocol.

In the sections below, many options are similar for the different array types. In Figure 31 a pop-up window for selecting Wenner data points is shown. With the exception of *Custom patterns* (see Chapter 5.1.7 *Custom Patterns*), these controls are mostly the same for all types of data point – and without changing any settings in the pop-up window all measuring points of the given type will be included. This is generally not very practical, and therefore there are controls for restricting the number of measurement points to add:

1. Cable controls; selecting which cables are to be activated. If a cable is deselected, any point requiring an electrode on that cable is excluded from the added points. See Chapter 5.2.1 *Cable Controls*.
2. Thresholds for geometric factor. These sliders specify a range, from the *Bottom threshold of geometric factor* to the *Top threshold of geometric factor*. If a point doesn't have a geometric factor within this range, then it is excluded. See Chapter 5.2.2 *Geometric factors*.
3. Array specific factors. While the other controls are generic, these sliders are specific to the individual array type and are described in the relevant chapters below.
4. The checkbox *Limit data points in pseudosection blocks* enables a selection of measuring points based on their pseudo-position. See Chapter 5.2.4 *Limit data points in pseudosection blocks.*
5. The checkbox *Add Rx pairs to existing Tx pairs only* ensures that no points are added that involves a new pair of current electrodes. This is particularly useful for channel optimization purposes. See Chapter 7.1.1 *Creating an optimized protocol*.
6. The controls for the pseudosection blocks are activated if the checkbox *Limit data points in pseudosection blocks* is checked. The first four sliders set the block size and how the size increases with depth. The final slider sets the maximum number of measure points that are allowed per block. See Chapter 5.2.4 *Limit data points in pseudosection blocks*.
7. If either of the checkboxes in point 4 or point 5 are enabled, the *Add only data points to the protocol for* radio buttons becomes active, and it is then possible to limit data pints based on the number of available measurement channels on the Terrameter LS. Doing so will ensure that the list of measurement points created do not cause a Tx pair to be split into two or more current injections.
   Note that this will drastically increase computation time; see Chapter 5.2.3 *Adding only to existing Tx pairs* and Chapter 5.2.4 *Limit data points in pseudosection blocks* as well as Chapter 7.1.1 *Creating an optimized protocol.*
8. The *Cancel* button cancels the addition of new points to the protocol and closes the window without adding any new points. The *Stop* button is active if computations are ongoing and makes it possible to halt the computations if a very large dataset is inadvertently chosen.
9. Pressing the *Show* button will start the measurement point generation based on the parameters listed in points 1-7. The status bar will update as the computation proceeds and, when finished, a pseudosection will visualize the new measurement points. Note that at this stage no measurement points have been added to the protocol, and it is possible to change parameters to add or remove points. Pressing the *Apply* button will add the new measurement points to the protocol.

Note that wherever a 'slider' bar is present, there are two ways to use it: firstly, left-click on the marker and drag it left or right without letting go of the mouse button; secondly, left-click on the bar to the left or the right of the marker to move it one step up or down. Some slider options have a window at the right-hand side where it is possible to enter a discrete value – to apply the change it is necessary to either hit "Enter" on the keyboard or left-click on the *Update Scale* button beneath the number.

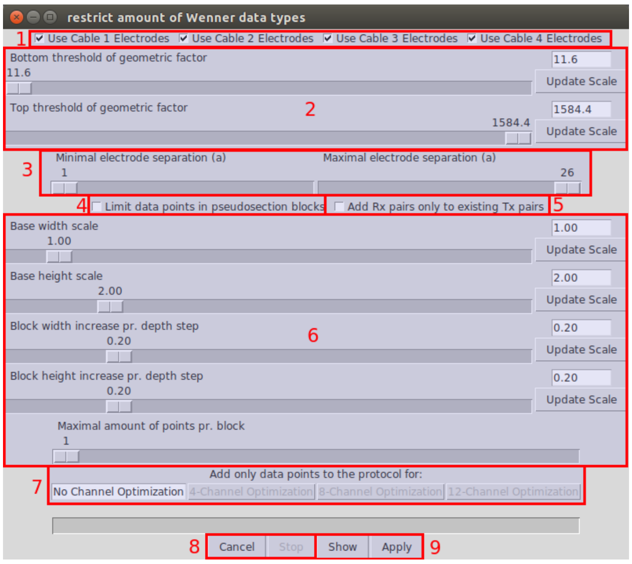

Figure 31 - The controls in the pop-up for adding new points to a protocol.

When new data points are added to the pseudosection view they will be colored according to the *Geometric factors* scale with a white outline. If any previous measuring points exist in the protocol prior to pressing *Show,* the old points will be colored black with a yellow outline to clearly visualize which are the new and old measurement points. An example can be seen in Figure 37.

In Figure 32 a count of the calculated points to be added to the protocol is highlighted. Notice that until any controls are modified in the pop-up window the button *Show* has been greyed out. At this stage it is possible to either choose to alter the way measuring points are restricted, or they can be accepted by pressing *Apply*.

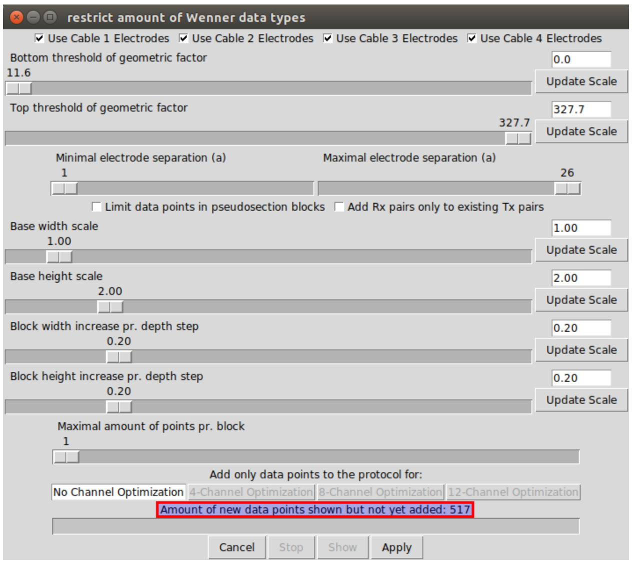

Figure 32 - After pressing "Show" a count of how many data points are to be included is displayed

5.1 Array types

5.1.1 Wenner

A Wenner measuring point is defined by electrode placements having:
A<M<N<B
and:
B-N = N-M = M-A
We call this common inter-electrode spacing "a".

Due to the geometry of the electrode placement, Wenner is defined as a single channel protocol because there is only one possible location to measure voltage from for a particular current pair.

Selecting "Wenner" in the dropdown menu of Figure 30 opens a pop-up as shown in Figure 31. The result of pressing "Show" immediately, is given in Figure 33; a pseudosection filled with all possible Wenner points.

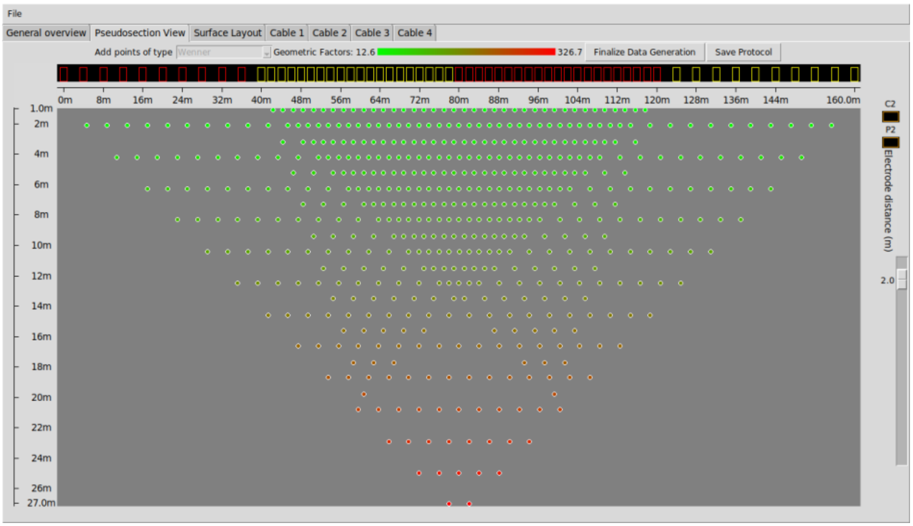

Figure 33 - The result of pressing "Show" in Screenshot 31. Notice that the outlines of the points are all white - indicating that they are not yet part of the protocol

The distance between electrodes in Wenner protocols is denoted “a”. By setting minimal and maximal cut-offs on the sliders, the range of accepted values of “a” can be limited as shown in Figure 34.

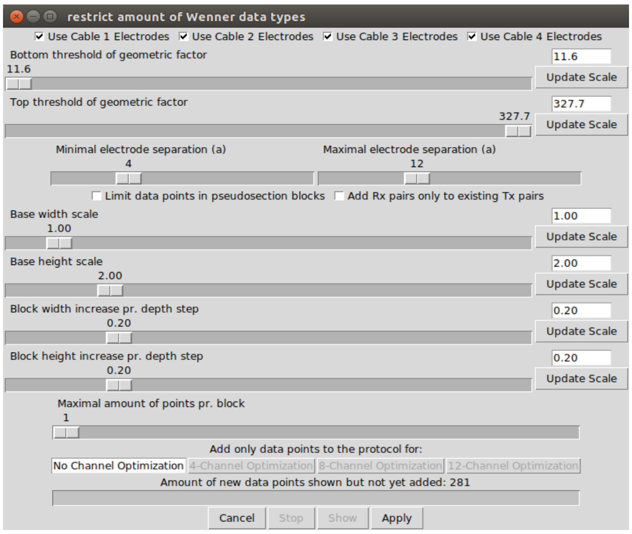

Figure 34 - restricting the electrode distance to the range [4,12]

In Figure 35, the result of pressing “Show” in Figure 34 is given. The z-axis has automatically been restricted to reflect the extreme low and high values of “a” not being part of the protocol.

Figure 35 - The restriction on "a" in data points

5.1.2 Schlumberger

For a configuration A,M,N,B, a Schlumberger measuring point is defined by having:

A<M<N<B

and:

M-N = a

and:

A-N = B-N = a*n

In the program, "a" designates the potential electrode separation and "n" the current electrode distance factor. In the creating of a Schlumberger measuring point, fractional values of "n" that make a*n an integer (whole number) are also incorporated.

Clicking on Schlumberger in "Add points of type" provides a similar pop-up window to Wenner, except the electrode spacing controls are different as we can now also limit "n". In Figure 36 the sliders have been moved so "n" can only be the values 1 or 2 and, additionally, only cables 2 and 3 are utilized in the Cable Controls at the top of the window.

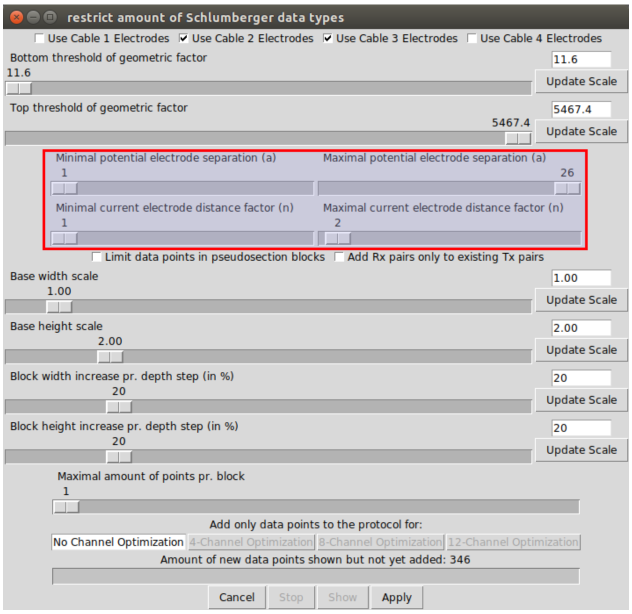

Figure 36 - "n" is in the range [1,2] – resulting in only a slight deviation from a Wenner protocol

In Figure 37 the Schlumberger points are shown on top of some Wenner measurement points. The original Wenner measurement points in the protocol are colored black, and the additional Schlumberger points are colored green to aid visualization of the new points. Rows of Schlumberger points that sit directly above rows arising from the Wenner protocol appear and are a result of using n=2 at those locations. This illustrates that these Schlumberger settings only deviate slightly from a Wenner protocol. Once *Apply* is pressed all points will be colored according to their geometric factor again.

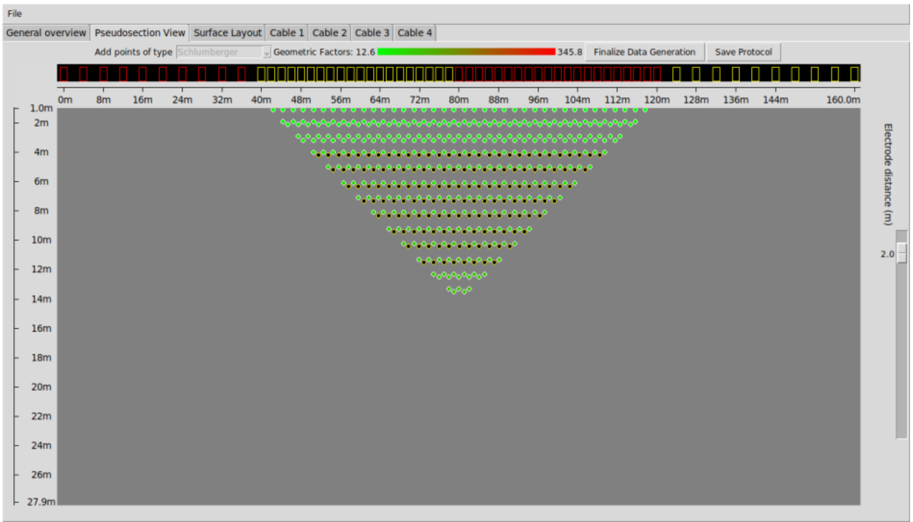

Figure 37 - Having pressed "Show" for the Schlumberger points defined by settings in Figure 36, the extra rows coming from n=2 appear directly above the Wenner lines (taken from Figure 57). The points currently active in the protocol are colored black.

5.1.3 Dipole-Dipole

For a Dipole-Dipole measuring point the electrodes are grouped in dipoles with one for current and a minimum of one for potential electrodes. For a generic configuration A,B,M,N a Dipole-Dipole measuring point is defined as having:

N<M<A<B

or:

B<A<M<N

and:

|A-B| = |M-N|.

The structure of Dipole-Dipole settings allows for more control over what points are included. As can be seen in Figure 38, there are four settings that alter the type of points included:

- The *dipole length* is the initial distance between both the current electrodes and the potential electrodes; this value is called “a” (= |A-B| = |M-N|).
  Note that the value set for minimal dipole length will affect what the maximal dipole separation will be on the slider.
- The *dipole separation* is the value “n” that scales the distance between the current dipole and the potential dipole(s). The factor “n” is determined by the formula:
  A-M = n*a, if B<A<M<N
  or:
  M-A = n*a, if N<M<A<B.
- The *Maximal dipole shift deviance* imposes a shift that allows the points described in the first two bullet points to deviate from the specified “a” and “n” values. Changing the slider provides value “s” that lies from 0 to the value of the slider. This “s” value readjusts the formula in the second bullet point to:
  A-M= n*a-s, if B<A<M<N
  or:
  M-A = n*a-s, if N<M<A<B
  This ensures that the lower geometric factors occur when “s” is small, and that all possible values of dipole separation are obtained.
- The *maximal dipole distance deviance* changes the distances between the potential electrodes, or between the current electrodes; deviating further from the above three bullet points. Calling the value “t” – which lies in the interval from 0 to the value of the slider – the additional data points achieved are given by either having:
  |M-N| = a-t
  or:
  |A-B| = a-t

Note that lower values of “s” and “t” will produce points with minimal deviation from a symmetric layout, and hence provide points with lower geometric factors. Increasing “s” and “t” will allow for points with higher geometric factors.

Setting “t” and “s” to their maximum values will allow all possible Dipole-Dipole configurations; i.e. only the fundamental dipole-dipole restrictions N<M<A<B or B<A<M<N are applicable.

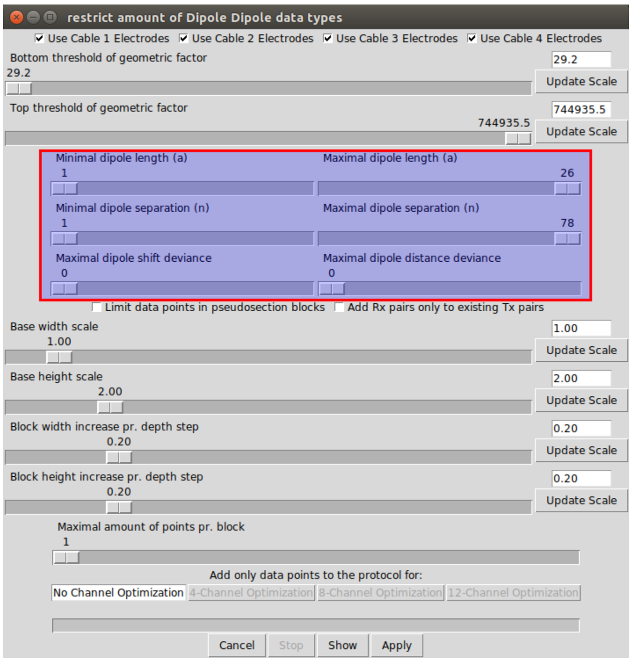

Figure 38 - The six highlighted sliders control the types of Dipole-Dipole measurements

Setting *Maximal dipole shift deviance* and *Maximal dipole distance deviance* to their maximum values, as shown in Figure 39, can generate very large datasets. Depending upon computer processing power, such a dataset can take very long time to generate. Obviously, it may also take a considerable amount of time for the instrument to measure all points of such a protocol.

At times it can be sensible to consider large datasets, primarily in the case of a search for candidates that fit the final slots in the switch matrix. An example of that can be seen in Figure 73 from Chapter 7.1.1 *Creating an optimized protocol*, where the purpose is to maximize the number of measuring points per current injection. However, for building initial datasets, it can be impractical to use very flexible Dipole-Dipole parameters. If the point generation takes too long, the *"Stop"* button is active while the progress bar moves and can be used to terminate the ongoing calculations.

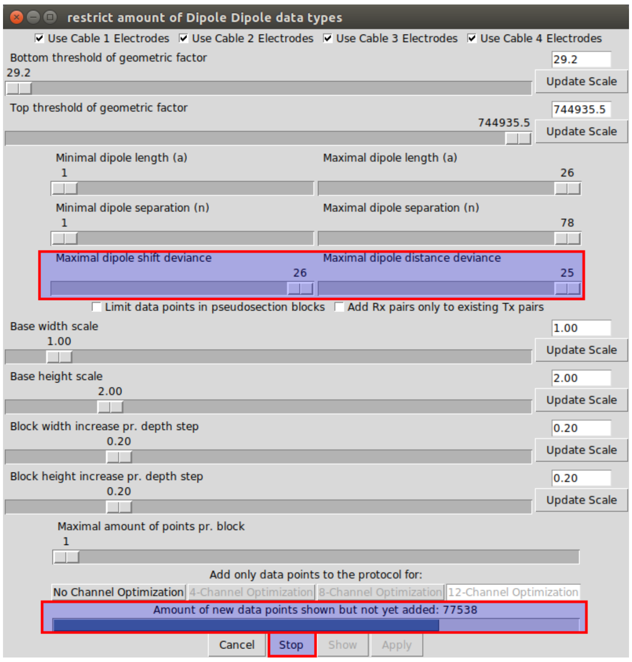

Figure 39 - A very large dataset is obtained by adding all data points - and the computation will be lengthy. The process can be stopped by pressing the highlighted "Stop" button

Letting the progress bar run to the end using the settings in Figure 39, results in all possible Dipole-Dipole points, as shown in Figure 40. This illustrates the need for imposing further restrictions on the generation of data points such as Chapter 5.2.1 *Cable Controls*, Chapter 5.2.2 *Geometric factors* or Chapter 5.2.4 *Limit data points in pseudosection blocks*.

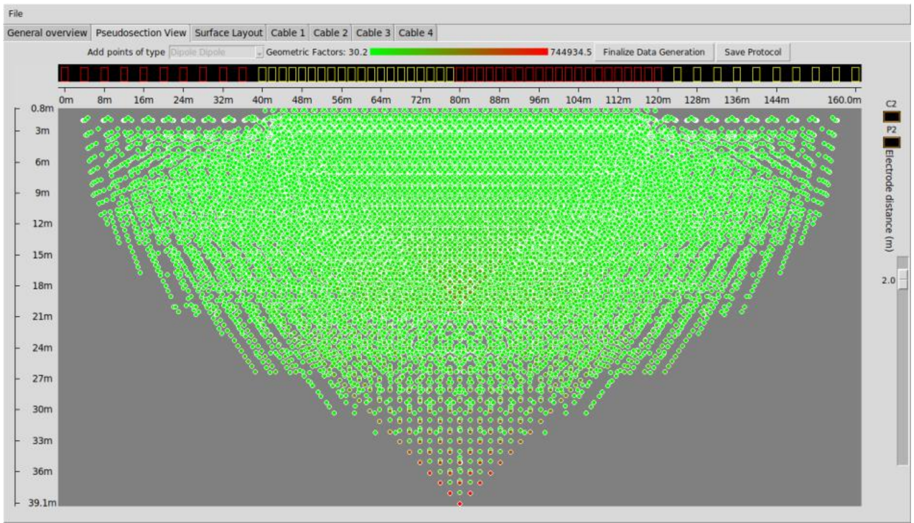

Figure 40 - A highly impractical set of measuring points with all Dipole-Dipole configurations for a 4x21 spread

5.1.4 Restricted Gradient

Restricted Gradient measuring points are an expansion of the Schlumberger array, but are limited in scope compared to Multiple Gradient points (Chapter 5.1.5 *Multiple Gradient*). The name is most likely not used anywhere else except for in the Terrameter LS Protocol Tool but it serves as a hybrid protocol in between the Schlumberger and Multiple Gradient measurement arrays.

Compared to the Schlumberger array, the Restricted Gradient adds an extra parameter called *Midpoint maximal shift,* which is defined as "*m*" and can be seen in Figure 41. The shift defines a range of values [-s,s] that the variable "*m*" can obtain. The conditions for Restricted Gradient are that:

$A<M<N<B$

and:

$M-N = a$

and:

$A-N = a*n-m$

and:

$B-N = a*n+m.$

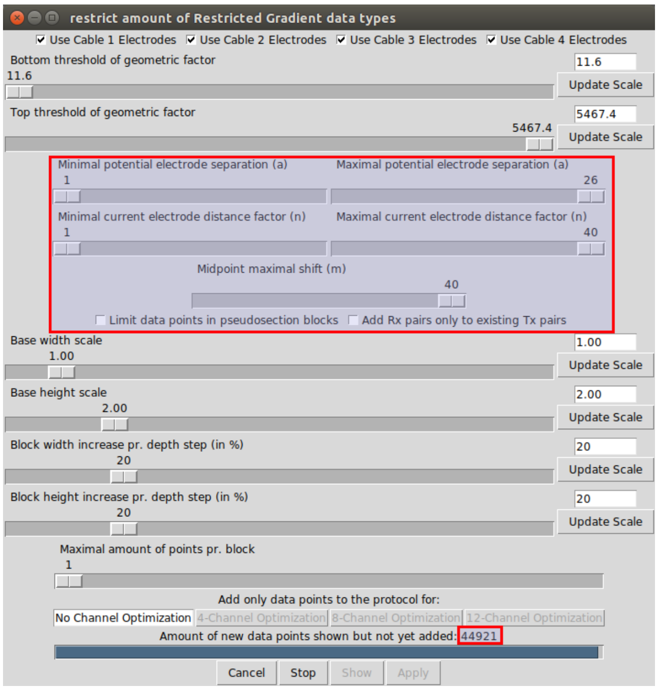

Figure 41 - Adding Restricted Gradient points with maximum values, resulting in 44921 points

Note that, just as with Dipole-Dipole, the Restricted Gradient can generate a lot of measuring points, and options may therefore be needed to restrict the number of data points to get a more practical protocol.

5.1.5 Multiple Gradient

Multiple Gradient points are defined only by the condition that:

$A<M<N<B$

In Figure 42 there are two sets of sliders. To describe these, let:

$A-M = x$

$M-N = y$

$N-B = z$

Calling the values from the sliders *Minimal/Maximal electrode separation* "a_min" and "a_max",

respectively, the produced points will have:
min(x,y,z) ≥ a_min
and:
max(x,y,z) ≤ a_max.
To describe the *Minimal/Maximal distance similarity*, call the values from the sliders "d_min" and "d_max", respectively, such that the additional condition for adding Multiple Gradient points is:

$$d_{min} \leq \frac{|x-y|+|y-z|+|x-z|}{3} \leq d_{max}$$

In other words, the average of the difference between the electrode distances are restricted by the range [d_min,d_max]. This ensures that for low values of "d" in [d_min,d_max] Multiple Gradient points will only be allowed to deviate slightly from a symmetrical positioning of the electrodes – meaning lower values of "d" will, as a rule of thumb, give low geometric factors.

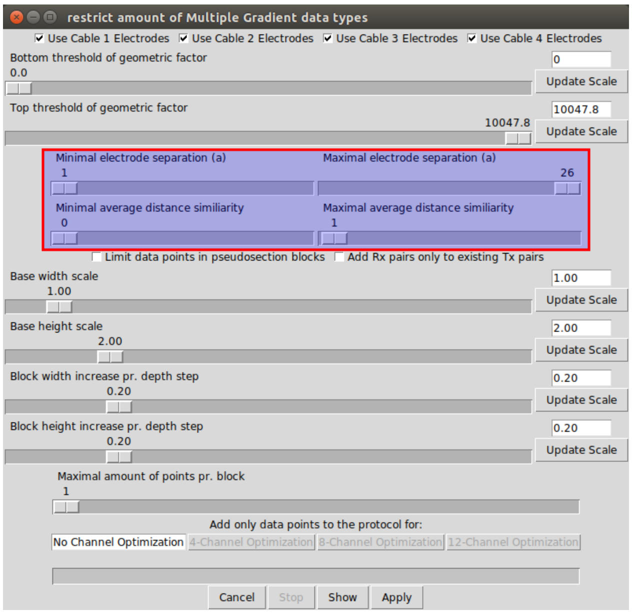

Figure 42 - The initial controls for Multiple Gradient

In Multiple Gradient protocols, those data points where the sliders set to obtain maximal values and where |A-M| > |M-N| ≥ |N-B| could be described as Restricted Gradient measurements. Conversely, *all* Restricted Gradient data points can be described as Multiple Gradient data points, but it is easier to control specifically what Restricted Gradient points are included using the controls described in Chapter 5.1.4 Restricted Gradient.

5.1.6 All Combinations

All Combinations data points can be described as combining Multiple Gradient measurements (with controls set to maximize the number of data points) along with Dipole-Dipole measurements (again with maximal data points). There are no sliders to control these settings, as these are only intended to be used to initiate long computations to ensure that all possible data points are found. This would be primarily to maximize the amount of data points per current injection as is done in Chapter 7.1.1 *Creating an optimized protocol*.

5.1.7 Custom Patterns

Custom Pattern does not provide a pop-up window when clicked upon. Instead it enables the creation of completely user-defined protocols by applying shifts to specified electrode configuration patterns across the spread.

When *Add data points of type* is set to *Custom Pattern*, the creation process is initiated by left-clicking on the line of red and yellow electrodes in the spread schematic at the top of the screen. The first left-click selects the left-most current electrode (A) in the pattern. This is shown in Figure 43; notice that a brief text in the bottom of the window (highlighted) indicates the current step of the custom pattern and guides the user to the next one.

Figure 43 - The left-most electrode is selected as first Tx electrode

The second Tx (current) electrode (B) is selected by left-clicking on the desired electrode in the spread schematic, as shown in Figure 44.

Figure 44 - The second Tx electrode (in blue) is selected by a left-click

As indicated in the text below the pseudosection area, the next step is to add the first Rx (potential electrode) pair to the Tx pair. As shown in the two images of Figure 45, left-clicking on the two desired Rx electrodes provides a single data point, with its color determined by the geometric factor colorscale. Previously added data points are colored black – as in Figure 37 – to better distinguish the new pattern from the rest of the existing protocol.

Note: If, at any stage in this process, an invalid click is made on one of the electrodes – for instance, if one of the blue Tx electrodes is clicked – the entire pattern is reset. This is a way to reset the process if an unwanted click is made.

Figure 45 - The first Rx pair of the pattern

Additional Rx pairs can now be added by left clicking on the electrodes to be used. This process is continued until the desired pattern of Rx pairs belonging to that Tx pair have been selected. In Figure 46 five data points have been created but as many, or few, Rx pairs as wanted can be associated with a single Tx pair.

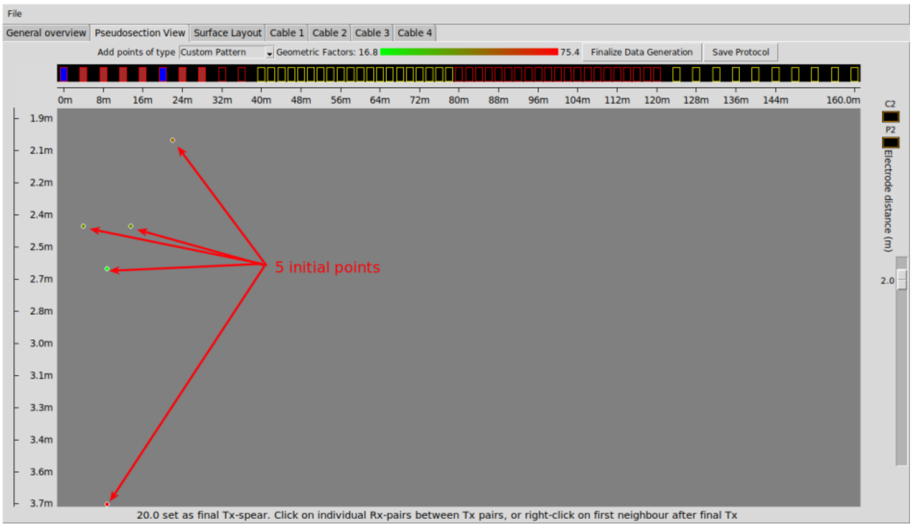

Figure 46 - A pattern of 5 data points is created - one of them is a dipole-dipole point

Having defined the layout of Rx pairs, the next step is to set-up the shift pattern. This is done in two steps:

1. Select the electrode shift size; this is how many electrode steps each movement of the measurement pattern will be. The shift size is defined by right clicking on an electrode to the right of the right-most current electrode (B).
   If the selected electrode is next to the B electrode, as seen in Figure 47, then each move will be one electrode step. If the selected electrode is three electrodes away from the B electrode, then each move will be three electrode steps.
2. Define the end position of the pattern movement. This is done by clicking on the intended final electrode position for the B current electrode. The pattern that has been defined in Figure 46 will then be moved, as described by these two steps, across the spread to the end position, and the resulting measurement points displayed in the pseudosection view. For the example pattern defined in the above figures, the end result can be seen in Figure 48.

*Figure 47 - A right click selects the first shift - there are now 2*5 data points displayed*

Figure 48 - The completed pattern; here obtained by left- or right-clicking on the right-most electrode of the spread

Once a pattern and shift are complete, the measurement points will be automatically added to the protocol. More custom patterns can be added by repeating the selection and shift process over again, or the protocol can be manipulated in any other way described in this manual, to obtain a suitable protocol to use in the field.

Note: Many of the protocols bundled in the Terrameter LS and LS Toolbox software can be recreated via custom patterns as described here. However, these are generally created using overlays of several patterns. To obtain protocols of this type, a recommended approach is to save individual patterns as.xml protocol files and then merge the patterns into a single protocol via the *Append Protocol to Current Protocol* option in the File menu, which joins two compatible protocols together. This ensures that specific patterns can be reused for other purposes – they could be considered as building blocks from which to create more complex protocols.

5.1.8 Pole-Dipole

If the spread underlying the protocol has Remote C2 enabled, see Figure 9, an option to add Pole-Dipole points becomes available. These are characterized as having one distant current electrode (B) connected to the C2 electrode connector on the end panel of the LS (geophysically mimicking a point at infinity) and the other current electrode (A) as any of the active standard electrodes along the cable spread. The potential electrodes (M,N) can be at any two standard electrodes that are not A.

This means that there are two variable distances between the electrodes:

- |M-N| = a, called the dipole length
- min(|A-M|,|A-N|) = n, called the dipole separation (distance from A to the nearest potential electrode)

In the dialog box shown in Figure 49 the limits specifying the minimum/maximum of “a” and “n” respectively, are controlled via the highlighted sliders.

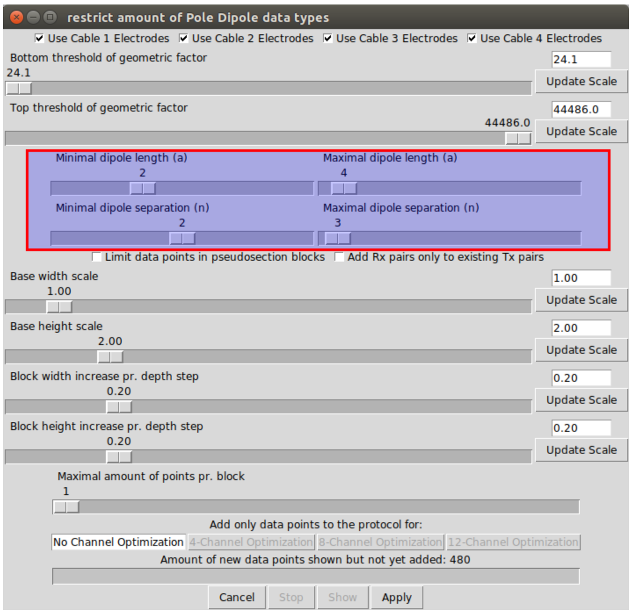

Figure 49 - Pole-Dipole pop-up with the relevant sliders moved to limit the amount of added points

As an illustration of how Pole-Dipole points are displayed, Figure 50 shows the C2 electrode flag is highlighted on the right side of the window for a selected Pole-Dipole point. In the text string at the bottom of the pseudosection view, remote electrodes are represented as *inf* (for infinity).

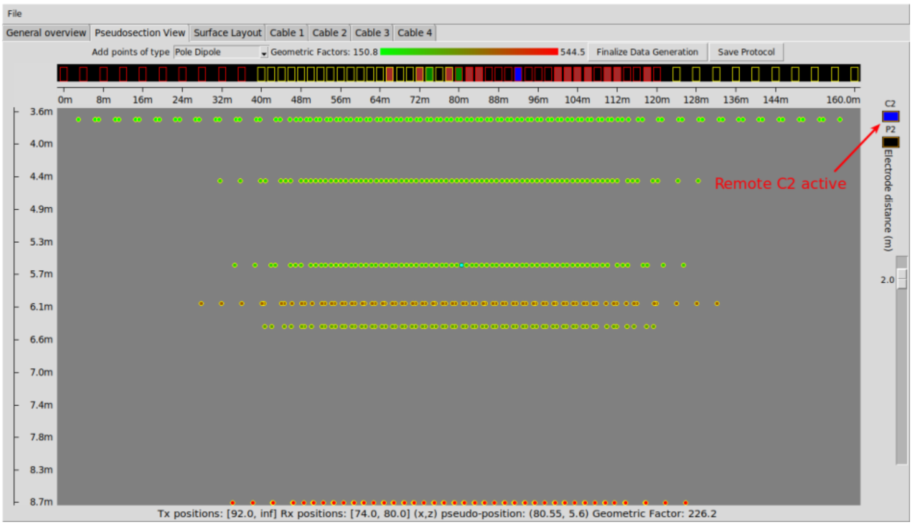

Figure 50 - The protocol resulting from parameters in Figure 49 with a Pole-Dipole point selected.

5.1.9 Pole-Pole

If both remote electrodes (C2 and P2) are activated, see Figure 9, Pole-Pole configurations can be added as data points. Pole-Pole measurement points are defined by having “infinitely” distant current (B) and potential (N) electrodes connected to the C2 and P2 terminals on the end panel of the LS. The only limitation upon the position of the remaining current (A) and potential (M) electrodes is that they need to be different electrodes along the main spread. As a result, the dialog box for adding Pole-Pole points only has one slider for electrode separation, the distance between A and M.

In Figure 51 an example protocol is shown. In the protocol the selected measurement point uses both the remote C2 and P2 electrodes, thus both flags are highlighted at the side of the window.

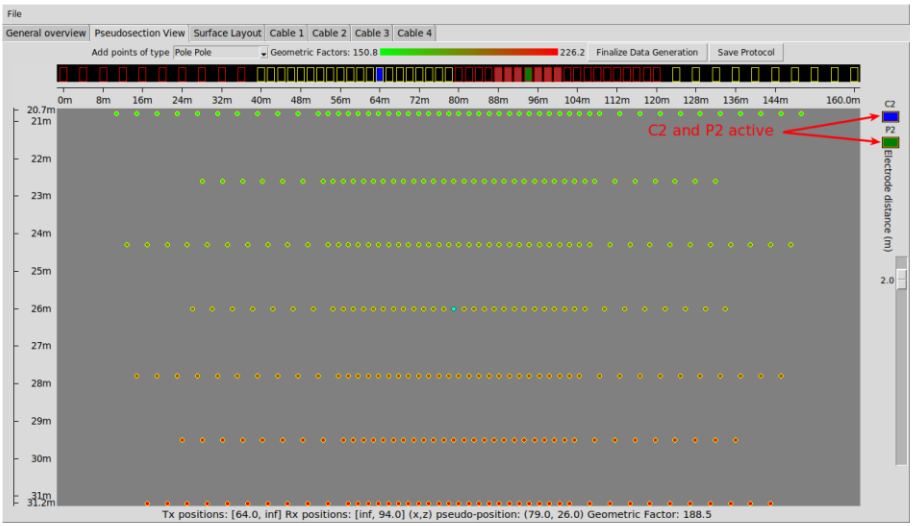

Figure 51 - An example Pole-Pole protocol with a single measuring point selected.

5.2 Restricting data points

If maximum settings are used when creating protocols, there is a high chance of generating tens of thousands of data points. Although data coverage may be excellent, field measurements using such a long protocol may take many hours, or even days, to finish. For that reason, it can be time efficient to restrict how measuring points are generated and the following chapters describe some of the different controls to achieve this.

5.2.1 Cable Controls

One way of restricting the number of measurement points generated is to deactivate one or more cables. In Figure 52 measuring points will only occur on the two central cables as the checkboxes for Cable 1 and Cable 4 are deselected.

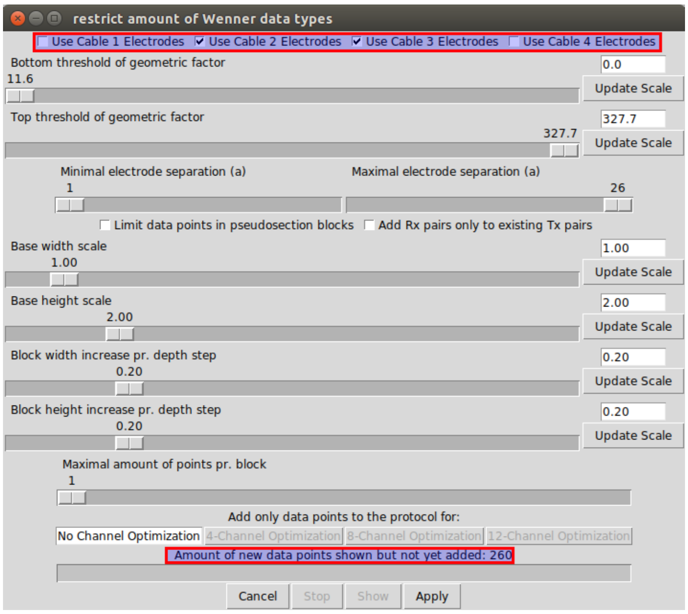

Figure 52 - Cable 1 and Cable 4 are excluded from use for this particular set of new data points.

In Figure 53 only data points that are associated with Cable 2 and Cable 3 are created. Note that deselecting cables – as well as using any other controls in the pop-up – only affects the generation of new measurement points; points already in the protocol (yellow outline) are unaffected.

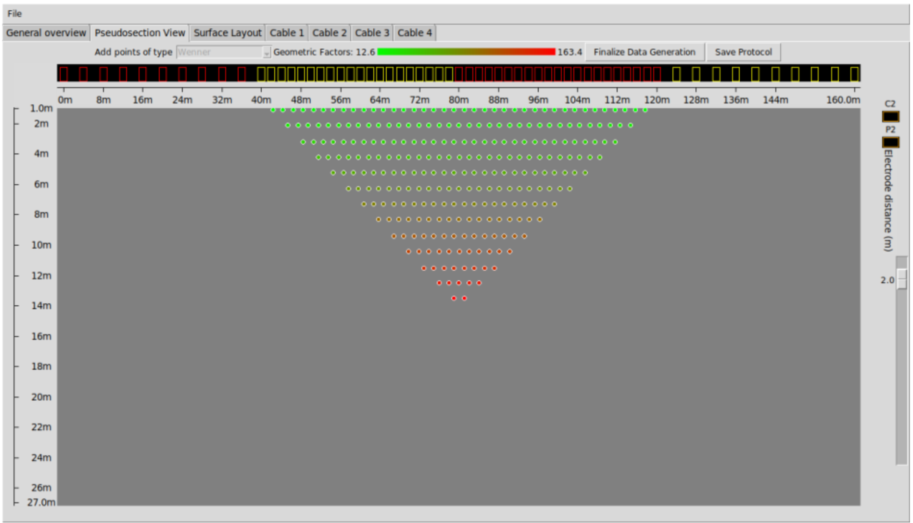

Figure 53 - The result of excluding cable 1 and 4 from a new Wenner protocol

5.2.2 Geometric factors

As highlighted in Figure 54, controls can be set to limit the geometric factors to a specified minimum and maximum value. As with most of the slider controls, values can be controlled either by moving the marker, or by entering an appropriate value in the text field. Remember, if values are entered as text it is necessary to press “Enter”, or click on the *Update Scale* button, to confirm the value. In the figure, the maximum value is set to 150 and the minimum to 50.

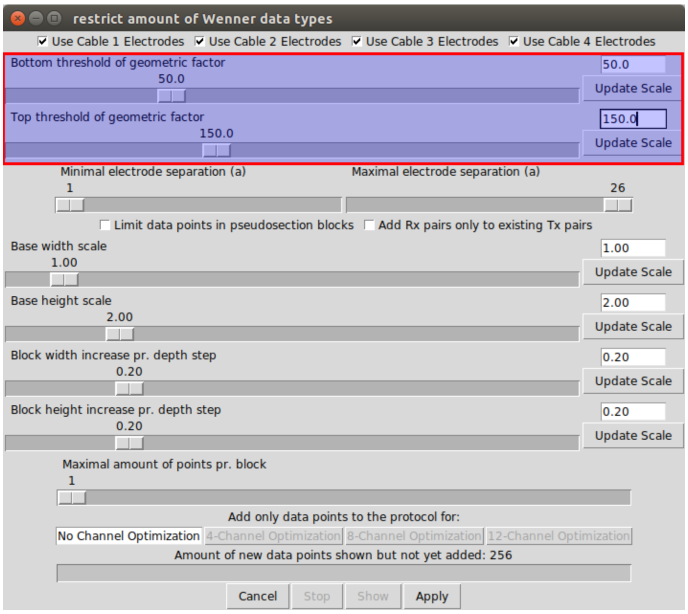

Figure 54 - Setting the limit of geometric factors to the range [50,150]

The result of pressing *Show* on the restricted geometric factors is shown in Figure 55.

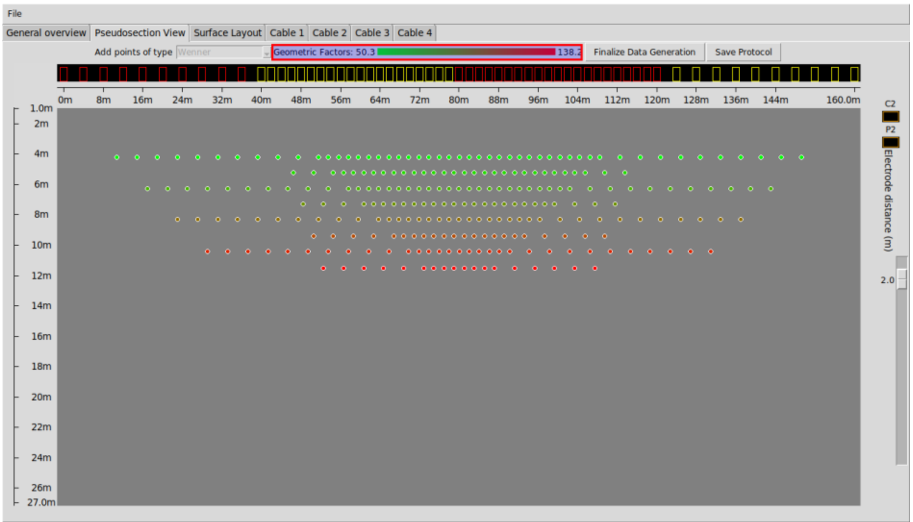

Figure 55 – Restrictions by geometric factor for a Wenner protocol. The highlighted geometric factor bar shows that the lowest value in that range is 50.3 and the upper value 138.2

It is possible to combine different restriction controls. Figure 56 shows an example where a combination of restrictions has been made by deselecting cables 1 and 4, limiting the geometric factor and also limiting the electrode separation.

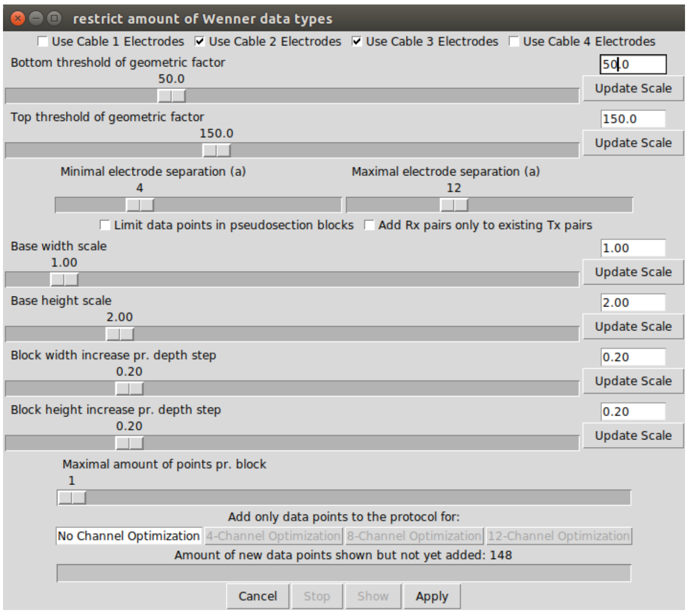

Figure 56 – Protocol generation with combined restrictions

Pressing *Apply* generates the measurement points shown in Figure 57. Note that for a Wenner protocol, restricting the geometric factor, and narrowing the range for electrode separation, has more or less the same effect; a smaller/larger electrode separation respectively leads to a lower/higher geometric factor. In Figure 57 the final range of geometric factors will have its two endpoints given by a combination of both the restrictions on geometric factor and electrode separation.

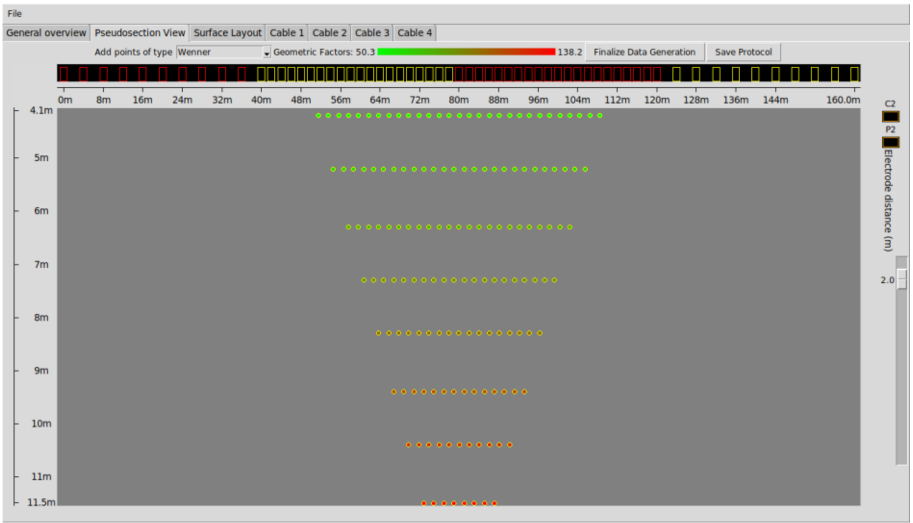

Figure 57 – A Wenner protocol resulting from combined restrictions

5.2.3 Adding only to existing Tx pairs

When adding additional measurement points to a protocol there is a high chance that extra current injections will also be added. In some cases this is acceptable but sometimes it is undesirable as it will increase the time taken to complete a protocol in the field. It is possible to restrict the generation of new measurement points only to existing Tx (current) pairs, which can be convenient when trying to achieve a high channel utilization.

In Figure 58, additional Schlumberger measurement points are added to a protocol. The checkbox *Add Rx pairs only to existing Tx pairs* has been clicked (remember Rx are potential (M,N) electrodes and Tx are current (A,B) electrodes). This means that only Schlumberger points that can re-use Tx electrodes already existing in the protocol will be added.

Even though new current electrodes are not introduced to the protocol, it is possible that the Terrameter LS instrument could split the measurements from a Tx pair into two or more current injections, thereby lengthening the required measurement time. This can happen if the set of potential electrode pairs does not 'fit' the switch matrix of the Terrameter LS (see Chapter 7 *A note on the switch matrix*) or if the number of potential pairs are higher than the number of measurement channels on the instrument. For this reason, a channel optimization option is available. By clicking one of the buttons within the *Add data points to the protocol for* section, new measurement points will be added for either 4-, 8- or 12-channel instruments. If *No Channel Optimization* is selected, there is no limit on the number of RX pairs, but they will still only be added to existing Tx pairs.

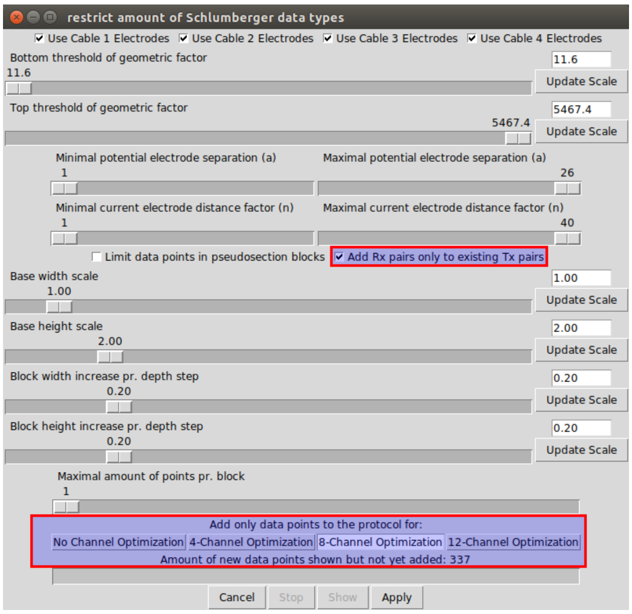

Figure 58 – By checking the "Add Rx pairs only to existing Tx pairs", significantly fewer data points are added

5.2.4 Limit data points in pseudosection blocks

The option *Limit data points in pseudosection blocks* offers a method for distributing newly added points more evenly across a protocol. In Figure 59 this option has been activated and, as in Figure 58, the option for choosing 4-, 8- or 12-channel optimization becomes available. As above, by selecting one of these instrument types, points are only added if they do not split an existing current injection into two or more measurement cycles. In this example, a 12-channel instrument is selected.

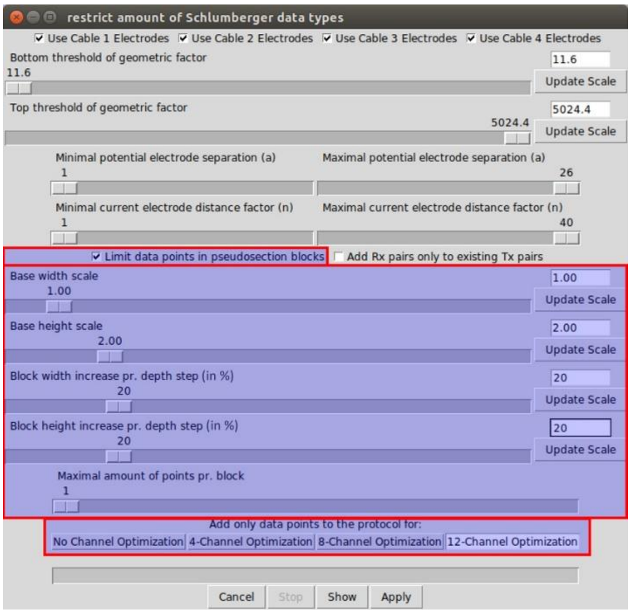

Figure 59 - Initial settings for limiting data in pseudosection blocks

To explain the five sliders associated with pseudosection blocks, Figure 60 shows how the main pseudosection view would look after adjusting sliders in the pseudosection block controls and pressing *Show*. This superimposes a grid of pseudosection blocks over the main window and can be explained as follows:

- There is, at most, one measurement point in each block, which is controlled by the last slider, *Maximal amount of points per Block*. It limits the number of points in the block to the value set on the slider and discards the points with the highest geometric factor. If a block has fewer points than the slider value, all those points are added (unless other limiting controls are in place).
- The *Base width scale* and *Base height scale* sets the height and width of blocks at depth zero of the pseudosection; that is, at the top of the pseudosection, there is 1 block per lateral meter, each with a height of 2m, as specified by the slider controls.
- The *Block width increase per step (in %)* and *Block height increase per step (in %)* specifies how much bigger the blocks should be in each new row down the pseudosection. In this case, both the width and the height are increased by 20% compared to the previous row of blocks.

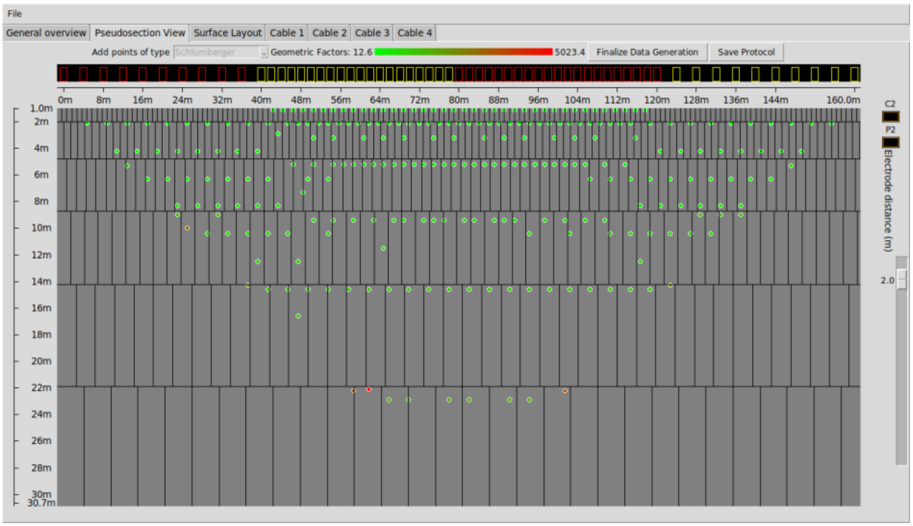

Figure 60 - Pseudosection blocks from initial settings, displayed by pressing "Show"

6 Boreholes

Provision for boreholes has been made in the spreads and protocols. Boreholes are initiated in the surface layout, via the menu obtained by clicking at the left- or right-most part of the layout. For a 16-electrode cable setup, Figure 61 shows the drop-down menu originating from a left-click on the left-most cable. This gives the option to add a borehole to the left of the cable.

6.1 Example: Spread with 2x16 Cables and two Boreholes

The option of adding a borehole is available in the dropdown menu, when clicking on the left-most or right-most cable of a spread, provided there are sufficient spare electrodes on the ES/LS available for the boreholes.

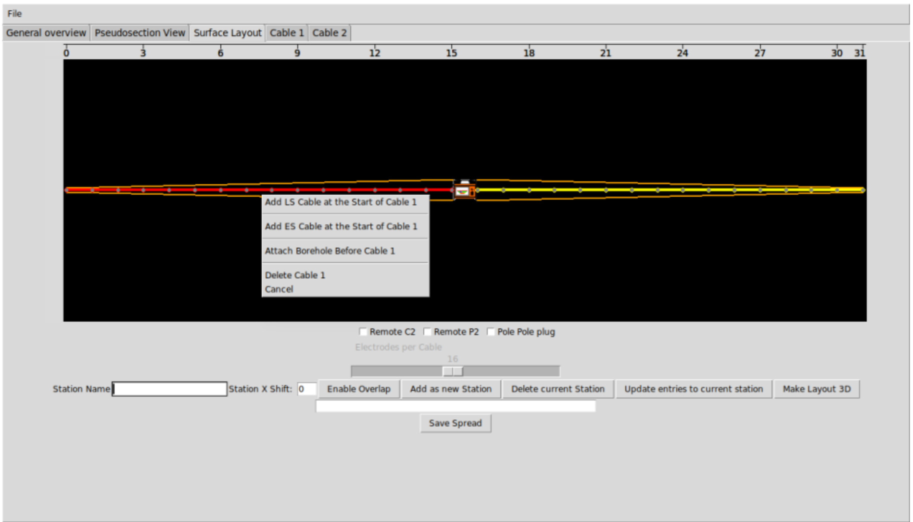

Figure 61 - In a 2x16 spread the option of adding a borehole is available

Boreholes are shown on the spread as crossed circles; Figure 62 shows the result of adding a borehole to the left of Cable 1 and then activating the drop-down menu on Cable 2 to attach a borehole to the right of this cable. The result is a spread with two surface cables and two boreholes.

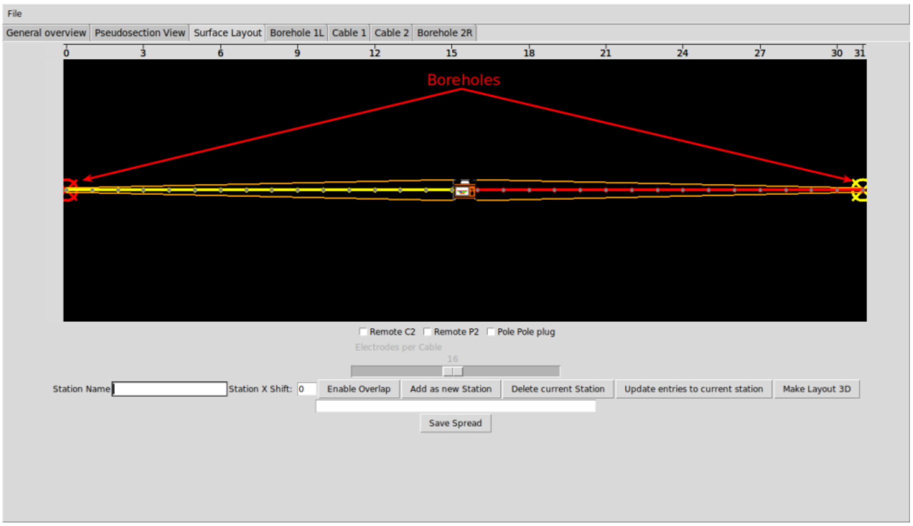

Figure 62 - A 2x16 take-out cable spread with boreholes at the left and right side

Along the top of the window, the two surface cables and the two boreholes are each available as separate tabs. The name of the borehole tab indicates to which cable, and which side of that cable, the borehole is connected. The particulars for borehole cables are similar to surface cables (as described in Figure 16) however, as shown in Figure 63, there is now an entry for depth (Z) and an extra option to alter the number of electrodes in the borehole. The latter is done by sliding the *Amount of Electrodes on borehole cable* marker. If a non-standard setup is chosen, the user should enter the specific switch addresses that are associated with each borehole electrode in the *Switch Address* field.

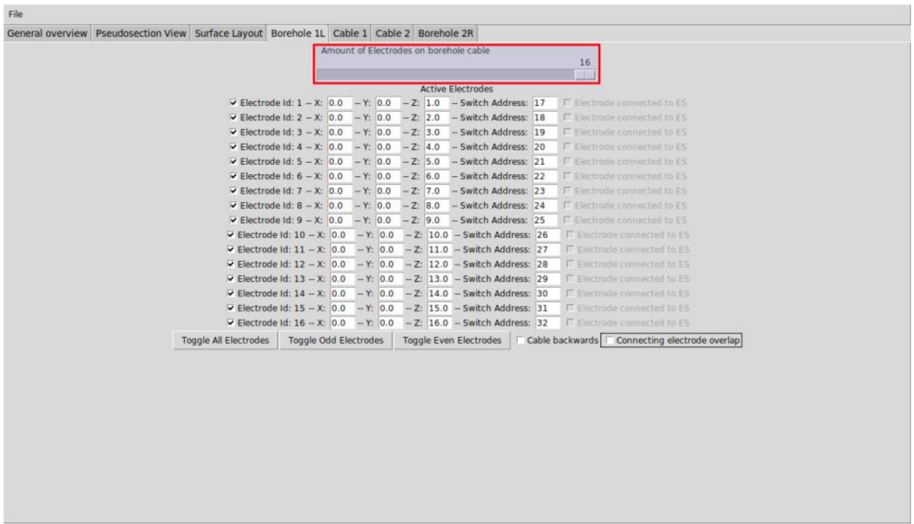

Figure 63 - The tab for a borehole cable; initial configuration for boreholes is similar to regular surface cables.

6.2 Example: Building a Protocol with Boreholes

Adding measurement points using just the part of the spread that lies on the surface, follows the standard procedure as described in Chapter 5 *Adding measurement points* . Measuring points can also be added to individual boreholes or, by utilizing electrodes in both boreholes, cross-borehole measurements can be created.

In Figure 64, the previous example spread has been used, and a 12-channel optimized protocol has been made for the surface cables. The highlighted dropdown menu is used to switch views between the boreholes and surface cables. This menu is only available when there are boreholes present in the spread.

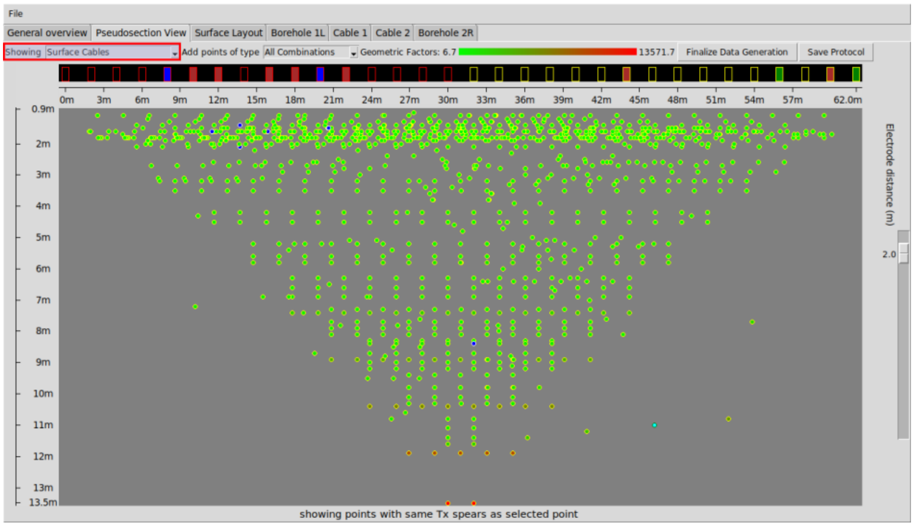

Figure 64 - The standard view of surface cable protocol. Note the additional top-left "Showing" menu, highlighted red

To access and work on the individual boreholes, select the relevant menu item, given by “<Borehole Name> Single Cable”, where <Borehole Name> is that shown on the cable tabs, described in Figure 63. The “Single Cable” menu item treats the boreholes as individual cables, with only that cable shown. It is always displayed down the right-hand side of the screen with the associated measuring points shown to the left of the cable; Figure 65 shows an example where all possible Wenner points have been added. The controls for adding points to single borehole cables is the same as described in Chapter 5 *Adding measurement points* .

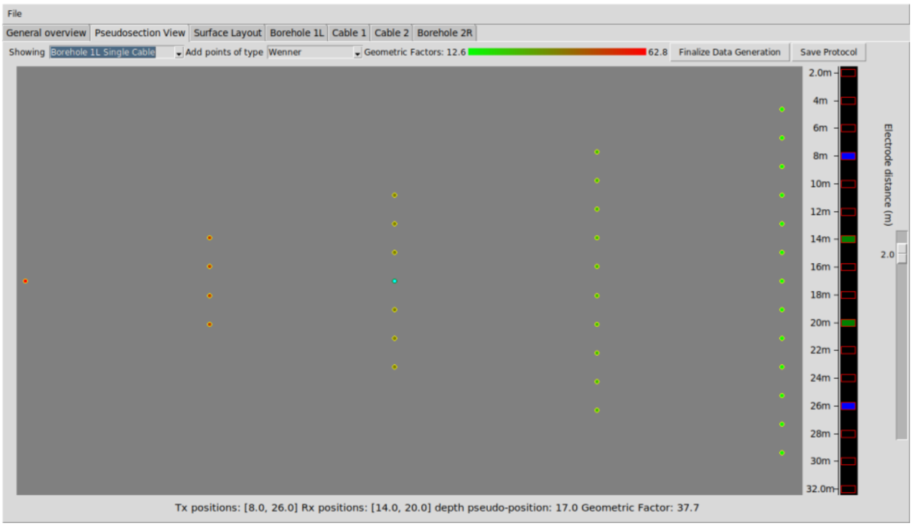

Figure 65 - A "Single Cable" view is activated in the "Showing" menu.

The geometry of measuring in a borehole is different from surface cables, where the pseudosection can be assumed to represent the half-plane directly below the electrodes. For a borehole, current is flowing in a cylindrical fashion around the borehole – the representation given in Figure 65 can be considered as a projection of this cylinder onto a half-plane. This representation should only be considered as a visual handle to the measuring; not a representation of where the current is "centered" in the ground.

Measurements can be made between the two boreholes by selecting "Borehole 1L vs. Borehole 2R". For these cross-borehole measurements, the only available option for *Add data points of type* is *Custom Pattern*. Measurements are constructed using a similar technique as the one described in Chapter 5.1.7 *Custom Patterns*, with the main difference being that measurement points require active electrodes on both cables and shifting the patterns is done downwards along the cables.

A sequence constructing a custom pattern of data points is shown in Figure 66 to Figure 68.

Figure 66 - Current electrodes are selected first (as in Figure 43). From here, potential electrodes can be selected (as in Figure 45 and Figure 46).

Figure 67 - Three Rx pairs have been selected, by right-clicking (as in Figure 47) the first shift of the current electrodes are defined

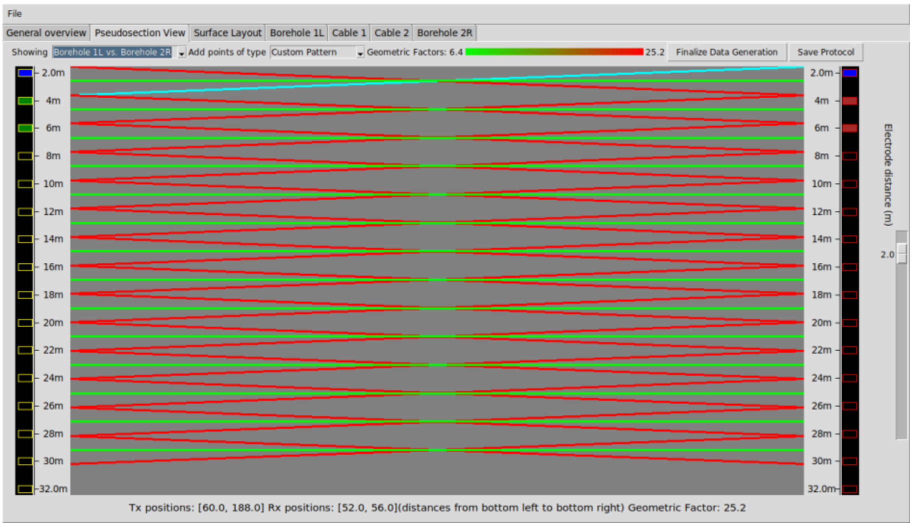

Figure 68 - The pattern is completed by clicking on the bottom electrode of borehole 1L, and the measurements are shown as lines from one borehole to the other

In Figure 68, measurements in a cross-borehole protocol are shown. Instead of points, these measurements are illustrated as lines connecting the average position of the electrodes on one cable to the average position of electrodes on the other cable.

Whilst the diagram gives an idea about the coverage of the protocol, this method of depiction only serves as an illustration of what measurements are available in the protocol. It also provides a neat way to interact with the protocol by clicking on individual measurement lines.

7 A note on the switch matrix

In order to connect the current transmitter and measurement channels to different take-outs on the multi-electrode cables, an electrode selector is needed. On the Terrameter LS the electrode selector is built-in and consists of a switch matrix made of relays. If many electrodes are needed, it may be necessary to use external electrode selectors as well.

The switch matrix of the Terrameter LS consists of 10 rows, to which the current transmitter and measurement channels are connected, and 64 columns, to which the electrode connectors on the instrument's end panel are connected. Rows and columns can be connected freely and multiple rows can be connected to one column, i.e. multiple measurement channels can share the same electrode.

The design of the switch matrix allows for up to 12 simultaneous measurement channels to be used, but due to the technical design used there are some limitations that the spread and protocol need to handle. In order to create a protocol with high channel utilization it may be necessary to mix measure points of different array types, e.g. Gradient and Dipole-Dipole. More tips on achieving a high channel utilization can be found in Chapter 7.1.1 *Creating an optimized protocol*.

A more thorough description of the switch matrix is given in Chapter 4.5 / 4.6 of the Terrameter LS / LS2 user manuals, respectively.

7.1.1 Creating an optimized protocol

Returning to field 5 in Figure 1, the *Average amount of data points pr. current injection* indicates how efficiently a protocol is using the Terrameter LS measurement architecture. The following example uses the features available in the Protocol Tool to optimize a protocol with the aim of maximizing the *Average amount of data points pr. current injection*. This requires additional measuring points to be added without increasing the execution time of the protocol.

The first step in protocol optimization is to create a core of measurement points. From the perspective of a 'real world' measurement, which type of points are selected will depend upon the main interest of the field survey.

As an example of core data points, the Wenner protocol constructed in Figure 35 are used. To then extend the protocol from this core, measuring points are added with the *Add Rx pairs only to existing Tx pairs* checkbox activated. In Figure 69 Schlumberger points have been added to the protocol.

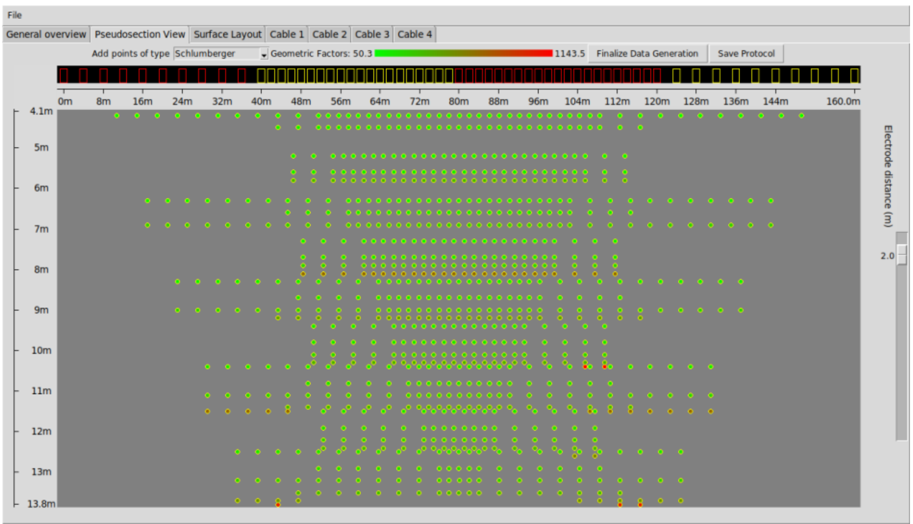

Figure 69 - The protocol is extended with all Schlumberger points available from the existing Tx points

Clicking on the *General Overview* tab, allows a review of the key information for channel optimization, in particular the *Average Amount of data points per current injection*, which is highlighted in Figure 70. The computed number of "3.2" is higher than the initial Wenner protocol when it was "1". It can be seen in the figure that optimization calculations have been made for a 12-channel instrument. Due to geometrical limitations and compromises inherent to the design of the switch matrix, it can be difficult to consistently use all 12 measurement channels, but 3.2 is still not close to the theoretical upper bound of 12, for such an instrument.

Figure 70 - The General Overview tab shows that, on average, there are still only 3.2 points per current injection.

It is sensible to control what types of points are added to the protocol. In Figure 71 an additional set of restricted gradient points have been added to the protocol, with the "m" factor (see Chapter 5.1.4 *Restricted Gradient*) limited to between -4 and 4. This shows a more densely filled protocol with extra measurements around the original core points. In other words, a lot of extra data points will be added in the field for the same number of current injections.

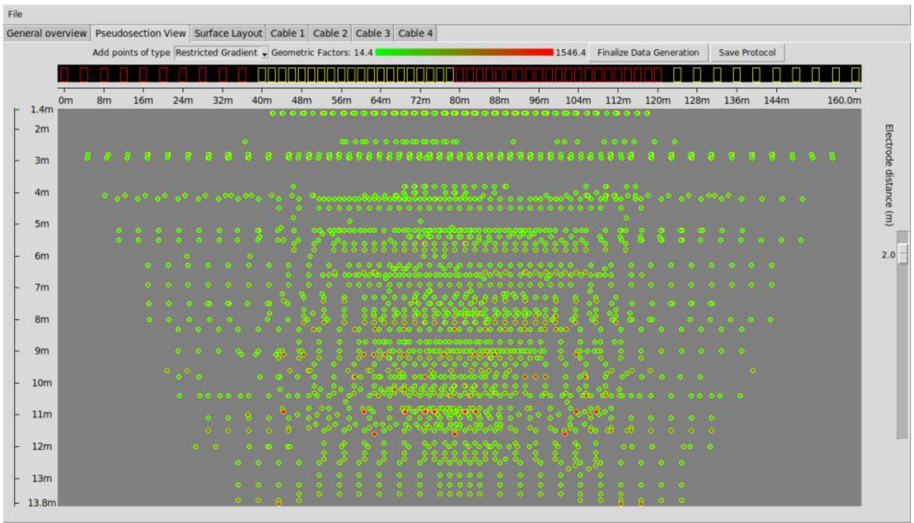

Figure 71 – A selection of Restricted Gradient points are added to the protocol

As shown in Figure 72, the *Average amount of data points per current injection* is now "6.92".

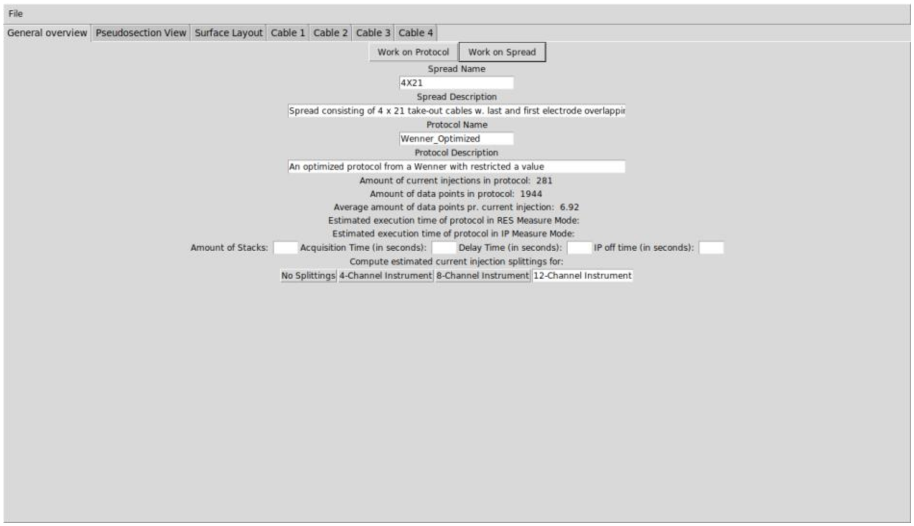

Figure 72 - With the addition of Restricted Gradient points the number points per injection goes from 3.2 to 6.92

Although this would be fine to use as an optimized protocol, it can be further extended by working through some large datasets to find additional points for the existing TX pairs. Note however that computing which data points fit the protocol can take a very long time. Depending on the computer used, it may take several hours to complete such a task so, in some cases, it might be recommended to make the final calculations overnight.

Figure 73 shows the *General overview* tab after adding *All Combinations* to the existing Tx pairs of the protocol in Figure 71. The current injection utilization has now increased to 9.43, which is very close to the practical limit of what one can expect to obtain from the Terrameter LS, with reasonable efforts and no extreme geometric factors.

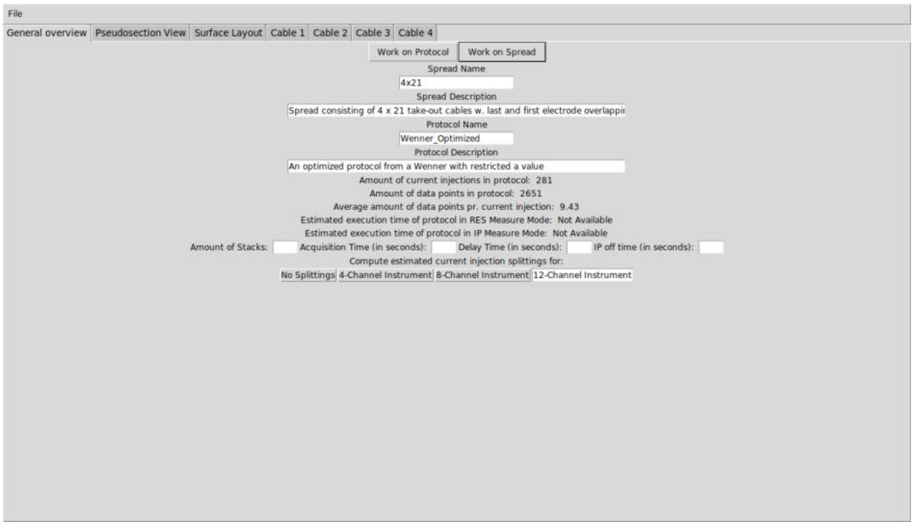

Figure 73 - Data points have been added via "All Combinations", providing a good utilization of the a 12-channel switch matrix

Looking at the pseudosection view (Figure 74) the pseudo points are primarily spread around the original core points, with some positioned further down the section. These will generally be points that, after a long sequence of attempts, could be ‘squeezed’ into the switch matrix. However, when working with large sets of measuring points, such as *All Combinations*, there are fewer controls on the type of points added.

Because everything that can be added to the switch matrix has been added, in the resulting protocol at least two points seem to have very little practical geophysical value; these are marked with red arrows in Figure 74. Indeed, their geometric factors are so high that they have skewed the colorscale to such an extent that it is hard to distinguish the geometric factors in the main cluster of measuring points from each other. It is sensible to delete these two extreme points, as described in Chapter 4.3.1 *Deleting selected points*.

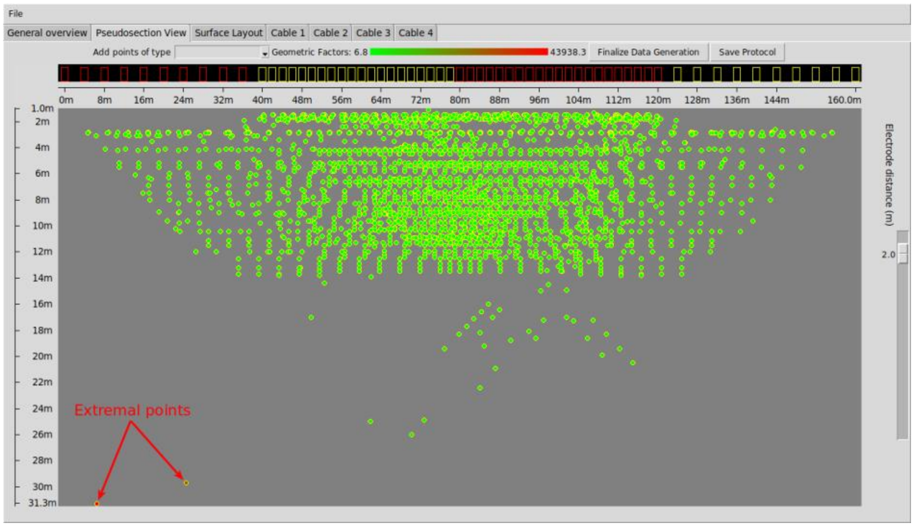

Figure 74 - The pseudosection view of the optimized protocol

Deleting these outliers results in the protocol shown in Figure 75, where it is now easier to distinguish the geometric factors of the remaining measurement points. While the available points are of significantly better quality than the two deleted points, further refinements could be made, as deemed necessary.

Whilst two more points, highlighted by arrows in Figure 75, could be considered extreme and removed, the rest of this optimization chapter is a walkthrough of further ‘fine grained’ tweaking of the switch matrix utilization that can be performed. In short, it is possible to backtrack on the selection of points – the complex nature of the switch matrix means that sometimes it can be possible to squeeze an extra measurement in, if different choices are made when filling the available current injections up.

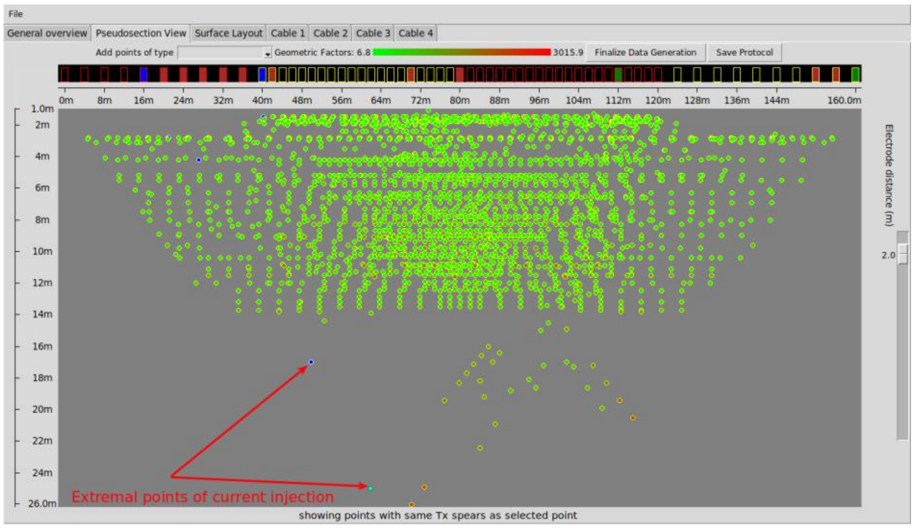

Figure 75 - In the optimized protocol, a current injection with two extreme points selected

First, the two extreme points identified in Figure 75 are deleted. Next, one of the remaining measurement points from that current injection is chosen and clicked on twice, to highlight all of the other points associated with that current injection. From this, the point can be right-clicked, and a menu appears, as in Figure 76.

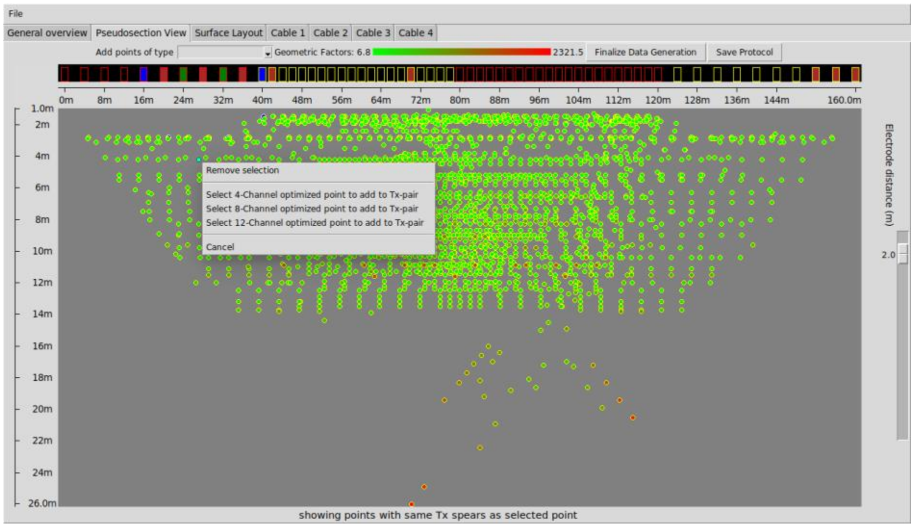

Figure 76 - Right clicking on a point in a current injection provides a menu with additional choices for adding channel optimized points

From this menu, the option *Select 12-Channel optimized point to add to Tx-pair* is selected. The program will perform some computations regarding the available paths through the switch matrix – the progress is shown as text in the lower part of the window. After the computations are done, a cloud of white points is shown on top of the present view (Figure 77). These white points are the available new measurements for that current injection, now that two points have been deleted, creating "room" in the switch matrix. To help decide which of the white points to select, the mouse can be moved over them to analyze their individual parameters. The geometric factor of the point beneath the cursor is shown in the text box at the bottom of the screen, whilst the potential electrodes of the new points are colored in the spread schematic at the top of the screen. Once a suitable point is found, it can be left-clicked to add it to the protocol.

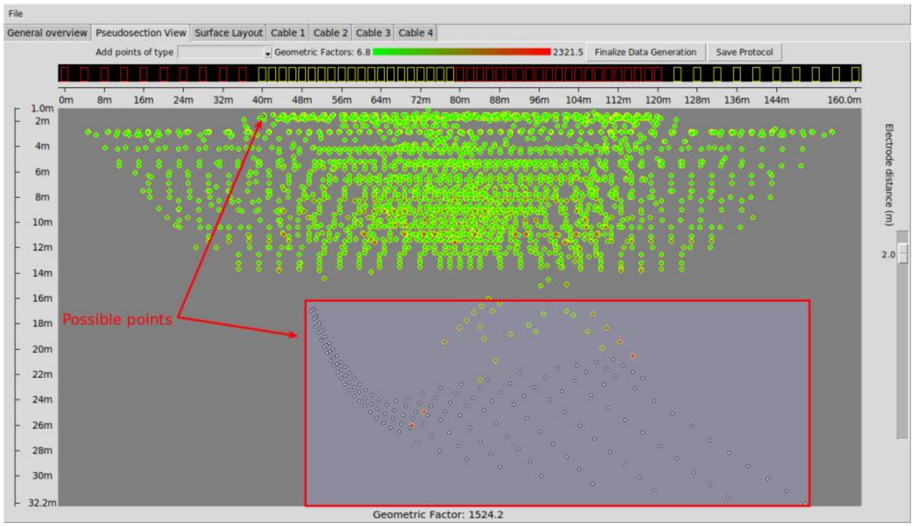

Figure 77 - The "possible points" are shown in white on top of the existing measuring points of the protocol

In Figure 78 the new point has been chosen. This point has a geometric factor between the two points that were shown in Figure 75 and deleted. The procedure is now repeated, the new point is double-clicked and a right click then provides the menu from which a 12-channel optimization is chosen. The result is a new point cloud shown in Figure 78.

Having added a new point, in principle there should now be less space on the switch matrix. However, the upper isolated white point shown in Figure 77 has now expanded to a small cloud of white points; this shows some of the complexities of the switch matrix. A new pair of potential electrodes can mean that it is possible to link more potential electrodes together through the maze of relays forming the switch matrix, hence providing new options for measurement pairs. Beneficially, the resulting point cloud contains electrodes with lower geometric factors than the two points that were deleted.

Figure 78 - Compared to Screenshot 77 there are fewer possible points in the lower half of the section, but more points appear above

In Figure 79 a point is chosen from the upper cloud of white points in Figure 78, filling a small gap; that is, in a position where a sub-optimal coverage of the subsurface existed. Repeating the process for the same current injection, double-clicking on a new point and right-clicking to choose 12-

channel optimization, another white point cloud appears. This time the point cloud all have geometric factors higher than any other points in the protocol and the point with the lowest geometric factor is one of the points deleted in order to start this “fine-grained” optimization of the individual current injection. Effectively, this represents the end point of optimizing this particular current injection. The result is three measuring points instead of two with, overall, an improved geometric factor, and sitting more closely around the core of the protocol, potentially giving better data quality in the region of interest.

An optimization of current injections, such as this, is something that can only be achieved in rare cases; most of the time it is not possible to improve upon the choices made by the automated algorithm.

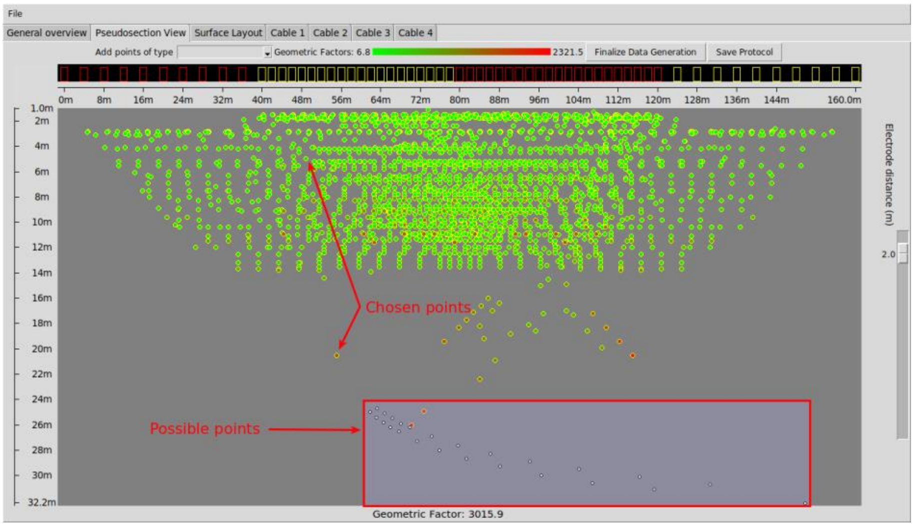

Figure 79 - A point cloud appears for the third time for the current injection

The final optimized protocol is shown in Figure 80. When the current injection is selected again (by double clicking one of its points) the highlighted text shows that, in this instance, it is impossible to add more points to the selected Tx pair without splitting it into multiple current injections.

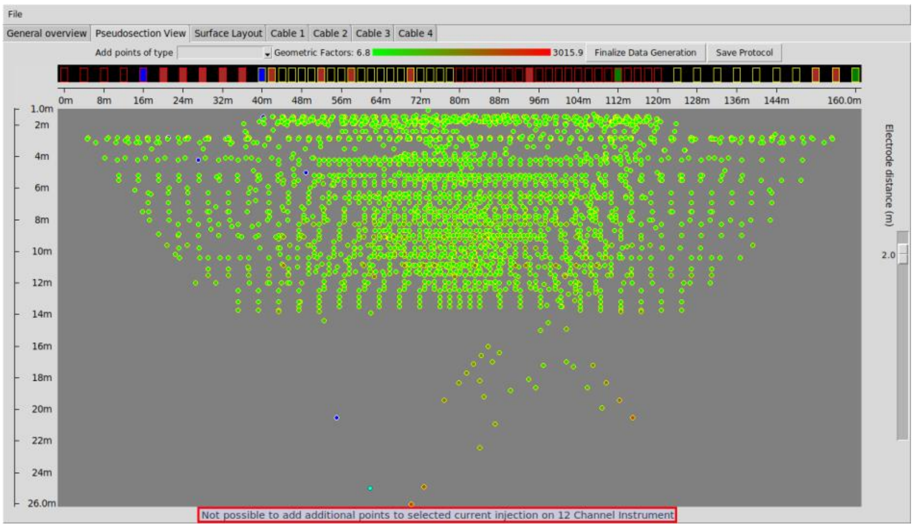

Figure 80 - The final optimized current injection is selected

8 Finalize Data generation

Using the example protocol from Chapter 7.1.1 *Creating an optimized protocol*, the button *Finalize Data Generation* has been pressed in Figure 81. This action indicates that the protocol has all the desired measuring points, and a new set of options appear for analyzing the final protocol. Returning to the option of adding new points to a protocol is done by saving the active protocol and reloading it.

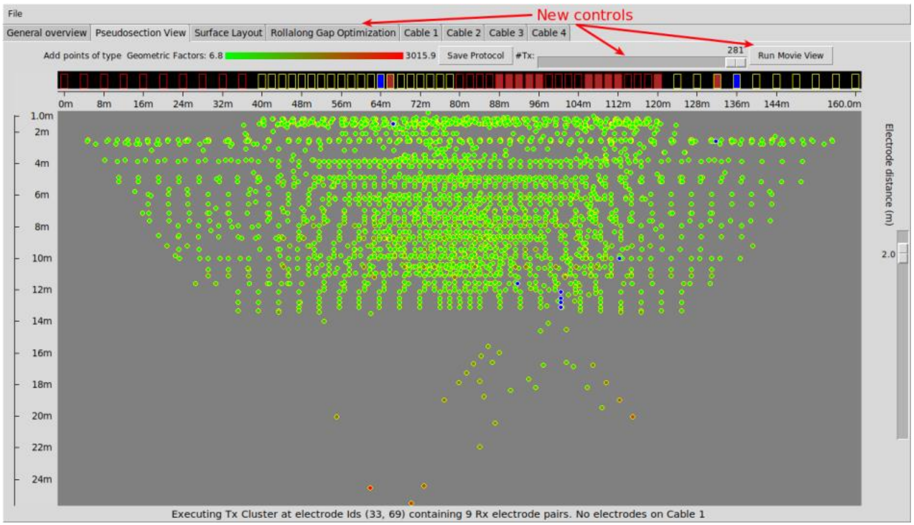

Figure 81 - The view of the protocol after "Finalize Data Generation" has been pressed

The three new controls are a new tab for *Roll-along Gap Optimization* described in Chapter 8.1 *Roll-along Gap Optimization*, a slider that can be moved to view the execution order of the protocol, and the *Run Movie View* button which can be used to see the execution order from start to end without interaction. This is described in Chapter 8.2 *Sequential view of protocol*.

8.1 Roll-along Gap Optimization

The Terrameter LS will execute the measurement of data points sequentially as specified by the protocol .xml file. If current has been sent through an electrode, then that electrode will be polarized but that polarization will decay over time. If an electrode that is still polarized is used as a potential electrode, it can have a negative influence on data quality. It is therefore desirable to schedule the sequence of measurements so that the resting time after an electrode has been used for current injection, and before that electrode is used in a different measurement cycle to measure potential, is as long as possible.

For a current injection with Tx electrodes A and B, the “Gap” referred to is the amount of current injections that occur on other electrodes before A or B are used as potential poles in a new current injection. Scheduling the current injections in a fashion that makes the “gap” between current and potential usage as long as possible is a task that is impossible by hand, and costly in processing power for a computer. The Protocol Tool has implemented an algorithm that reorders the current injections to optimize the gap length; the algorithm also ensures that gaps are optimized in a roll-along setting.

When *Finalize Data Generation* in the *Pseudosection View* is pressed, an additional tab labelled *Roll-along Gap Optimization* will be made available, as shown in Figure 82. From this tab it is possible to run the algorithm described above.

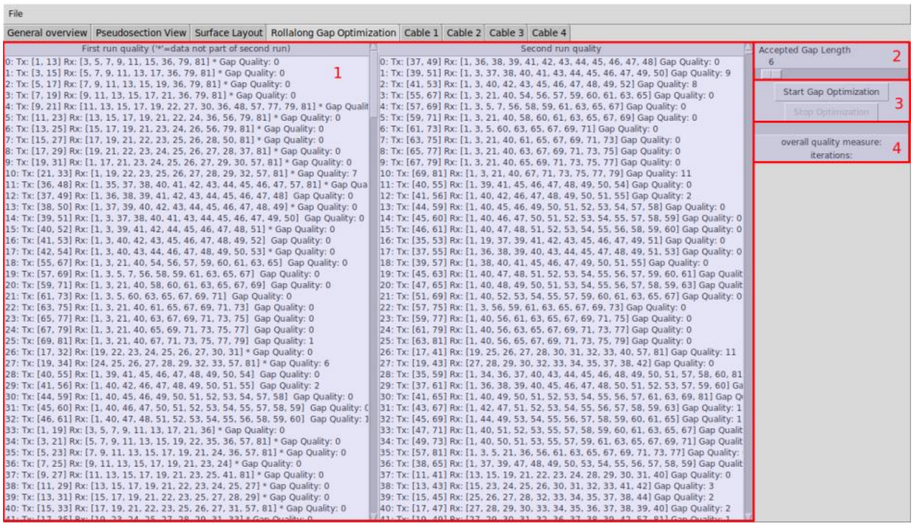

Figure 82 - The elements of the Roll-along Gap Optimization tab

The elements of the *Roll-along Gap Optimization* tab are described as follows:

1. The lists labelled *First run quality* and *Second run quality* show the execution order of the protocol's current injections. That is, in a roll-along setup, the *First run quality* list are the current injections of the first station that is set up in the field; here all measurements are utilized. The *Second run quality* list is the subsequent stations where the Terrameter LS has been moved one step forward – and some measurements are excluded as they have already been collected in previous stations.

   The individual rows contain the entries *Tx* (the Electrode Id's of the current electrodes), *Rx* (the set of Electrode Id's of the potential electrodes) and *Gap Quality* which, importantly, is the number of steps from the current row until one of the Tx electrodes is utilized as an Rx pole.

   In the left-most *First run quality* list of current injections, some rows are marked with a star (*). These are measurements that are excluded in the *Second run quality* list.

   Right-clicking on one of the lines gives a menu that allows for a manual swap of the individual current injections. However, as stated above, manually swapping current injections to optimize the gaps is an impossible task. It can be useful to swap them manually only if an electrode is desired in a special position in the measurement sequence, for some reason.

2. The slider *Accepted Gap Length* specifies to the algorithm above what limit the gap lengths are not considered worth moving; by default this is set to 6. The definition of an "acceptable" value highly depends on the measurement parameters used during field acquisition, but the algorithm will generally work fine with a large range of values.

3. The button *Start Optimization* initiates the algorithm, which will run for both *First run quality* and *Second run quality* columns at the same time.

Even for a standard protocol, the algorithm can run for a very long time. It is therefore possible to stop the process manually by pressing the *Stop Optimization* button, if an acceptable quality has been achieved.

The algorithm initially orders the cables so that all measuring points that use an electrode on cable 1 are executed first (in the field, this allows Cable 1 to be moved to the next roll-along position before the full measurement sequence is complete). This ordering is kept that way throughout the optimization process.

Once the user saves a protocol, it will be saved with the sequence order from the latest gap optimization.

4. When running gap optimization, the process can be monitored via the field labeled 4. In Figure 83 an example of a satisfactory gap optimization is shown. The *overall quality measure* indicates how well-optimized the protocol is with respect to all gaps and will decrease as the algorithm progresses. The number will depend on the value set in *Accepted Gap Length* and also takes into account the number of current injections. Lower gap qualities contribute significantly more to this overall measure than higher gap qualities, still below the accepted gap length. A number in a range of 20 to 40 will indicate a pretty well-optimized protocol where there are a few, but not many, gaps of length 2. Such overall values should be obtainable for most protocols.

   The *Iterations* count increases as the optimization progresses. An increase by one indicates that a current injection has gone through a process of testing for a new position, and successfully or unsuccessfully moved; that the *Iterations* is increasing is a way to see that the algorithm is running.

   The final element is a progress bar that will start moving once most standard options for the algorithm have been exploited and it attempts more randomized moves. This means that the algorithm is in a position where it is hard, but often not impossible, to move current injections to a better position.

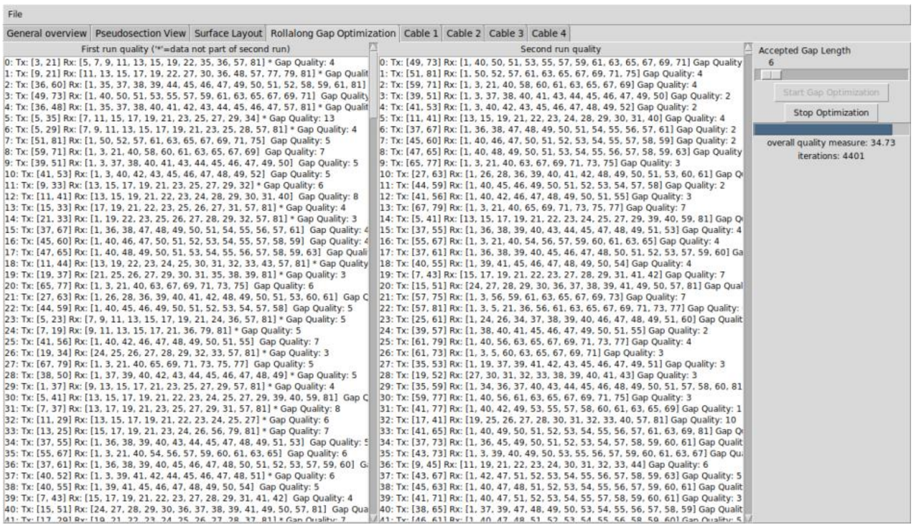

Figure 83 – Roll-along Gap optimization in progress; at this stage new optimizations are sparse

In Figure 83 the *Roll-along Gap Optimization* has been run on a laptop with a 2.7 GHz CPU for some hours on the protocol given in Figure 80. This protocol has been made with quite heavy switch matrix optimization. This means that there are many potential electrodes used in each current injection, which makes it harder to position a measurement cycle so that none of the potential electrodes coincide with a current electrode from the steps immediately above it. As it is also a rather large protocol, there are many possibilities for moving measurements, further slowing down the optimization process

In Figure 82 with no *Roll-along Gap Optimization*, there are a lot of rows with *Gap Quality* at 0, indicating that an electrode is used as a potential electrode directly after it has been functioning as a current electrode. In Figure 83, the protocol has the *Gap Quality* for most rows at 2 or higher, and those measurements with *Gap Quality* 2 are rare, which constitutes a significant improvement in the execution order.

On smaller protocols, a satisfactory optimization could be achieved relatively quickly, but this is a task that could easily be run overnight, requiring no input from the user once the process is started; the algorithm will continue finding optimizations, albeit at a slower and slower pace. Getting rid of Gap quality 0 measurements is something that is generally done within a minute or two on a standard computer.

8.2 Sequential view of protocol

As a visual aid to understanding how the protocol is executed in the field, it is possible to see the progress of the protocol sequentially.

With *Finalize Data Generation* pressed, the new slider shown in Figure 81 determines the position of the sequential view. Setting the slider to a specific value makes all current injections indexed up until the given value visible in the pseudo-plot. Measuring points that are indexed higher in the protocol are not shown until the slider is moved further right.

The highlighted text in Figure 84 shows information on the Tx pair at the stage of the slider. The information shown is the electrode Ids of the current electrodes and the amount of Rx pairs associated to this Tx pair.

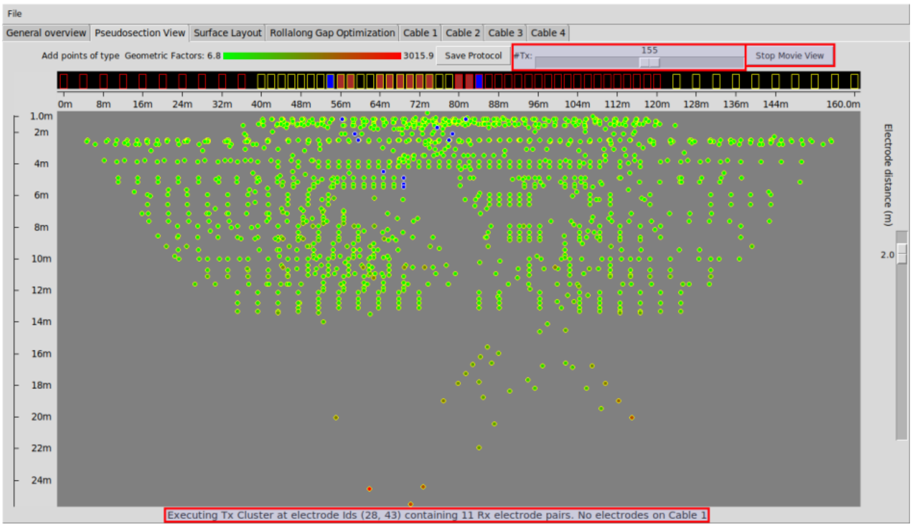

Figure 84 - The sequential view of the protocol. Here the slider has moved to Tx execution number 155 - a Tx-pair with electrodes not on Cable 1. This screenshot is taken in movie mode – the button now reads "Stop Movie View"

In Figure 84 the slider has been moved far enough to the right, that the highlighted text reads that there are no electrodes on Cable 1. If the protocol has been optimized, as in Chapter 8.1 *Roll-along Gap Optimization,* this indicates that at this stage Cable 1 could now be moved forwards in a roll-along while the remaining measurements are ongoing.

The button *Run Movie View* starts the slider from position 0 and runs it until the end, giving an animated view of the measurement sequence.

9 3D spreads and protocols

3D spreads are enabled from the *Surface Layout* tab and in Figure 85 the highlighted button has been pressed. In, for instance, Figure 2 this button read *Make Layout 3D*, whereas it now reads *Make Layout 2D*, indicating that the Surface Layout screen is now in 3D mode, even though the cables still lie in a straight line.

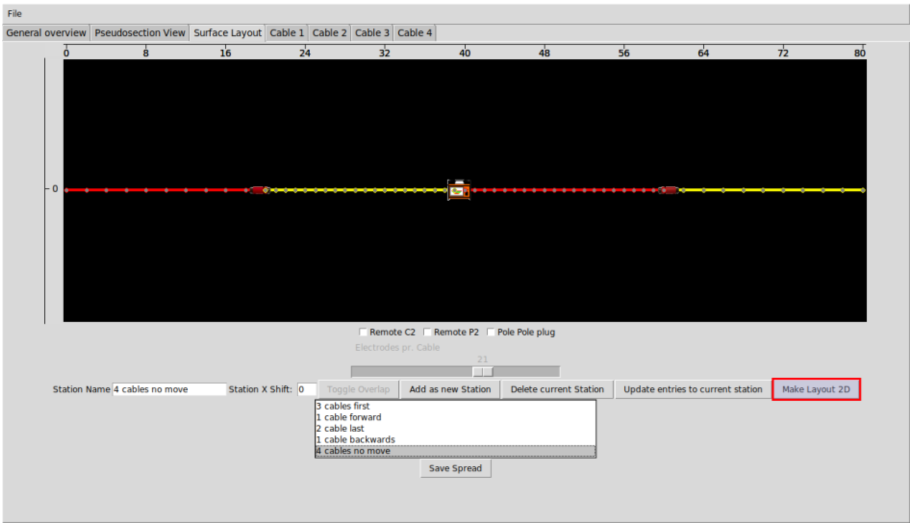

Figure 85 - In a 4x21 spread, the "Make Layout 3D" has been pressed and now reads "Make Layout 2D"

There are two general ways to move the cables out of the straight layout: ‘folding’ cables in a zig-zag pattern or by positioning the straight cables at increasing offsets. These are covered in the three examples below.

9.1 Example: single click zig-zag

A zig-zag pattern can be created by clicking on any of the electrodes. In Figure 86, a left-click on electrode 27 has resulted in a menu with 3D options. The two lower options (excluding *Cancel*) will initiate a zig-zag pattern in upward or downward directions, as selected.

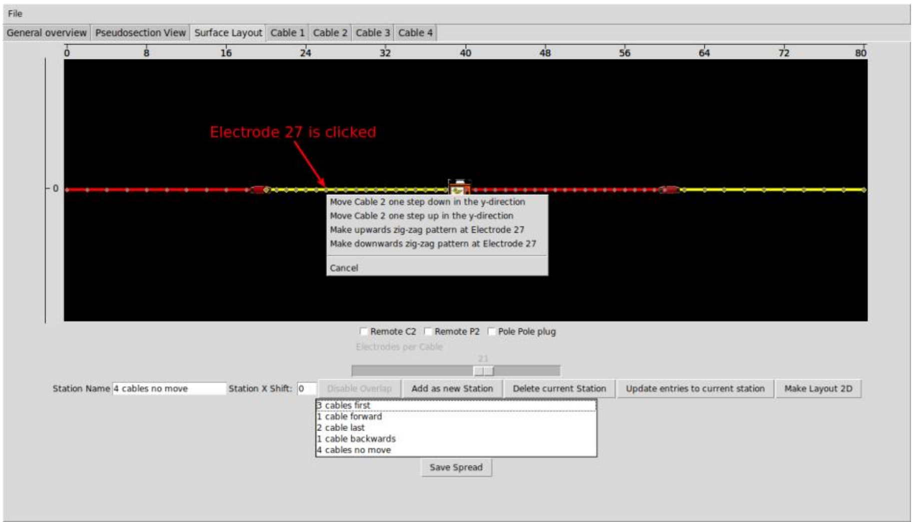

Figure 86 - The menu appearing when left-clicking an electrode

Pressing *Make upwards zig-zag pattern at Electrode 27* results in the spread shown in Figure 87.

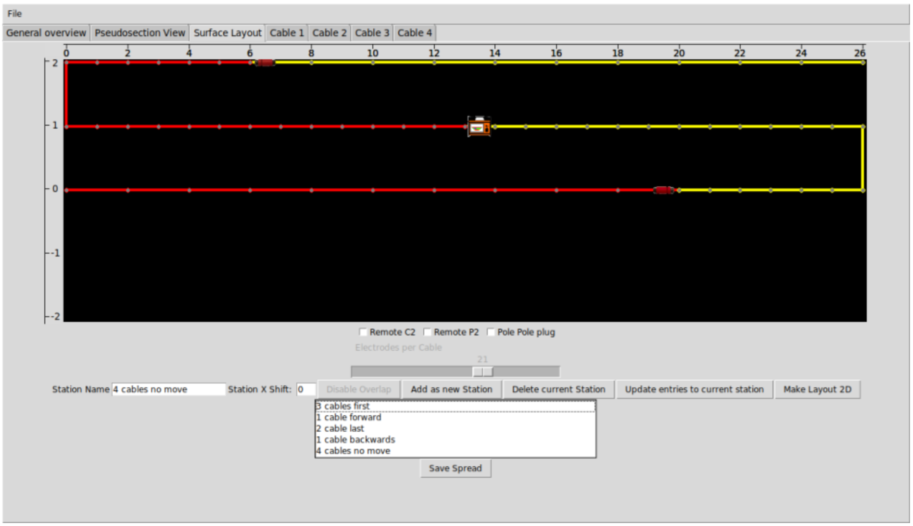

Figure 87 - Three parallel lines of the same length run in a zig-zag initiated at electrode 27

After this modification, the spread can be used as the basis for a 3D protocol. In Figure 88 the *Pseudosection View* tab has been selected, followed by *Make Protocol From Scratch*. In this example, a full Wenner protocol has been made, followed by a Schlumberger protocol with *Add only Rx pairs to existing Tx pairs* activated. By pressing and holding the left mouse button it is possible to move the 3D volume to get a different view of the pseudo-plot.

In general, protocols can be made much the same as in the 2D case, using the *Add points of type* drop-down menu. However, *Custom pattern* is made unavailable in 3D view, as is the possibility to manipulate individual points via manual selection within the pseudosection view.

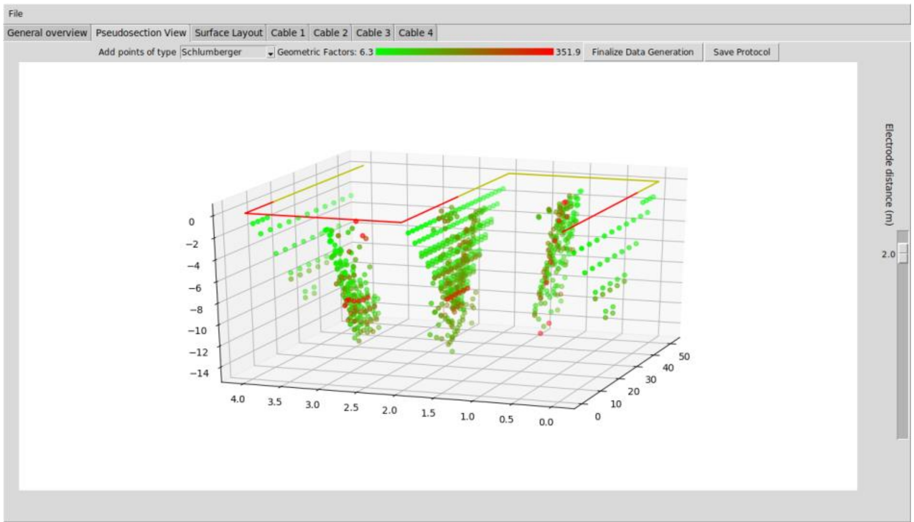

Figure 88 - A 3D view of the protocol; the view can be clicked and dragged with the cursor to change the viewpoint

In Figure 86 an electrode was selected that immediately gave a zig-zag with three lines of equal length; i.e. there are 81 electrodes from 0 to 80, and three lines of 27 electrodes, giving 3*27 = 81. The following chapter provides a way of dealing with zig-zags starting at less ‘idealized’ positions.

9.2 Example: Readjusting a zig-zag

In the previous example Example: single click zig-zag) an electrode was selected that generated an even zig-zag pattern. If a different starting point for the zig-zag is chosen, additional menu items can be used to obtain a more regular setup of the surface layout. In Figure 89 a spread with four 16 electrode cables is made into a 3D spread. Similar to Figure 86, a zig-zag pattern is initiated, now by clicking electrode 19 and making a downwards zig-zag. In Figure 89, a left-click on a cable has brought up a new menu.

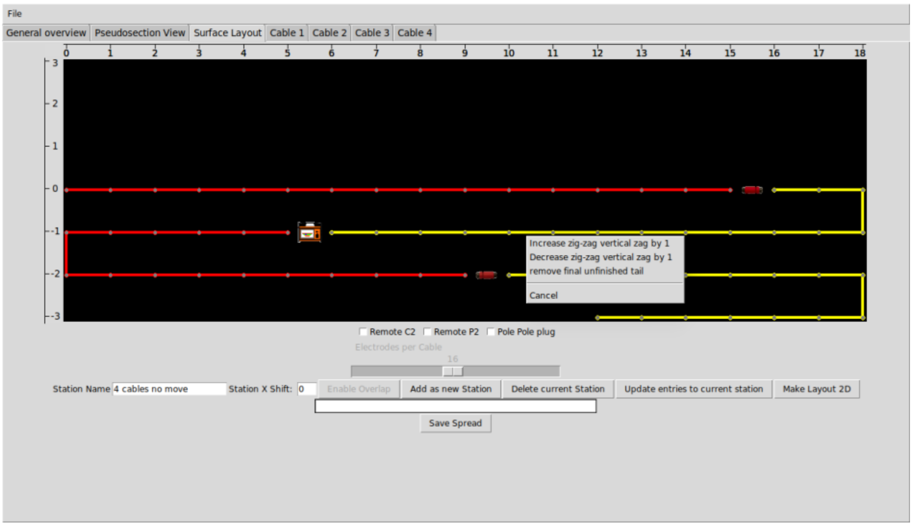

Figure 89 - From a standard 4x16 spread, a 3D spread is initiated, with a downward zig-zag at electrode 19

Increasing/Decreasing the vertical "zag" means that the cables are shifted by moving electrodes, one at a time, from the horizontal part of the layout to the vertical part of the layout. Pressing *Increase zig-zag vertical zag by 1* at electrode 19 would move the horizontal part of the zig-zag upwards 1 electrode spacing, thus making all cables lie in a straight line again.

In Figure 90 a layout with no horizontal component on the lower part of the layout is achieved by twice applying *Decrease zig-zag vertical zag by 1* to the layout in Figure 89. As indicated in the figure, along each vertical section of the layout there are now two electrodes. This increases the 3D interplay on associated protocols, and has moved the lower "unfinished" section of the cable away from its horizontal position.

In the menu shown in Figure 90, activated by clicking on a cable of the layout, there is an option to *Remove final unfinished tail*. This results in the last three electrodes, forming the vertical tail, to be disabled (Figure 91). If the option were to be initiated in Figure 89, the 7 electrodes forming the lower horizontal tail of the layout would be disabled.

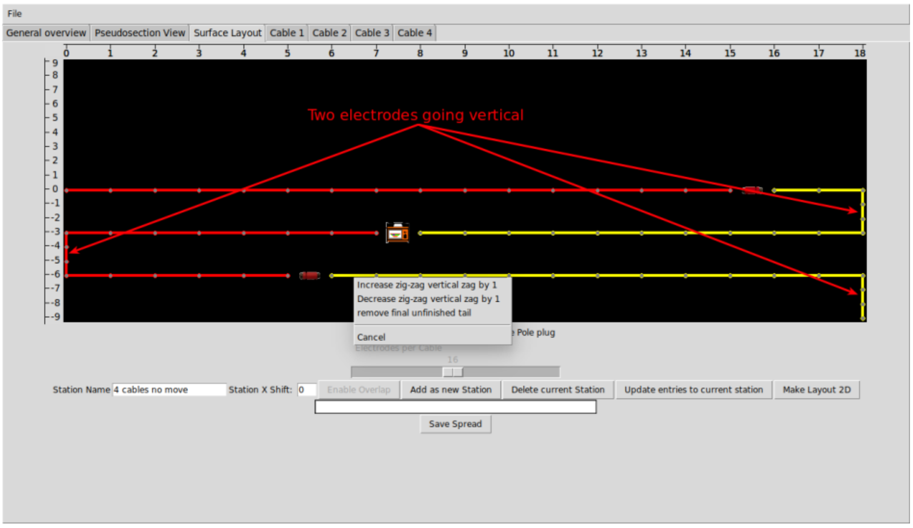

Figure 90 - Two additional vertical "zag" decreases have been made to obtain a layout as shown

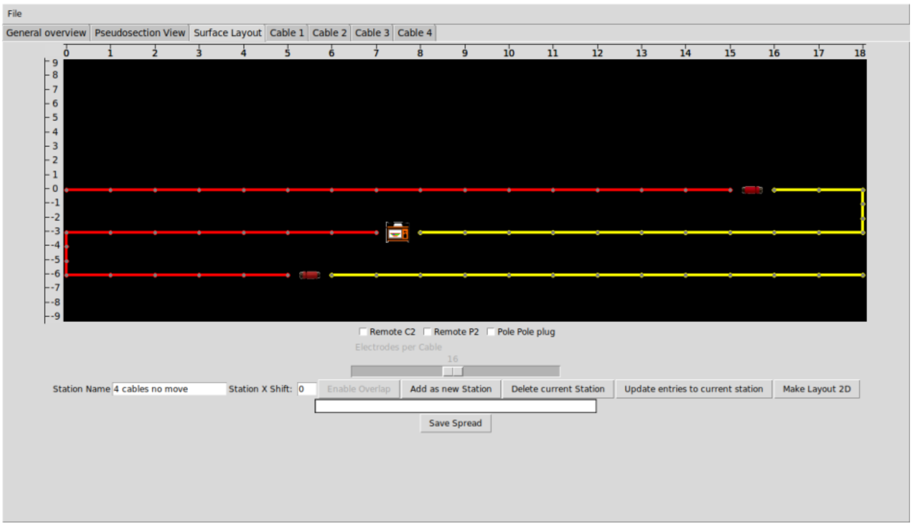

Figure 91 - The result of applying "remove unfinished tail" to the layout from Figure 90

9.3 Example: Moving cables individually

Cables can be moved individually via the options *Move Cable [nr] one step [up/down] in the [x/y]-direction*. In Figure 92, the option *Move Cable 2 one step down in the y-direction* is selected, resulting in the shown rearrangement of the cables. If cable 2 is clicked again, the extra options *Move Cable 2 one cable-length [right/left] in the x-direction* are available. These options are only available when no other cables are sitting in the target direction.

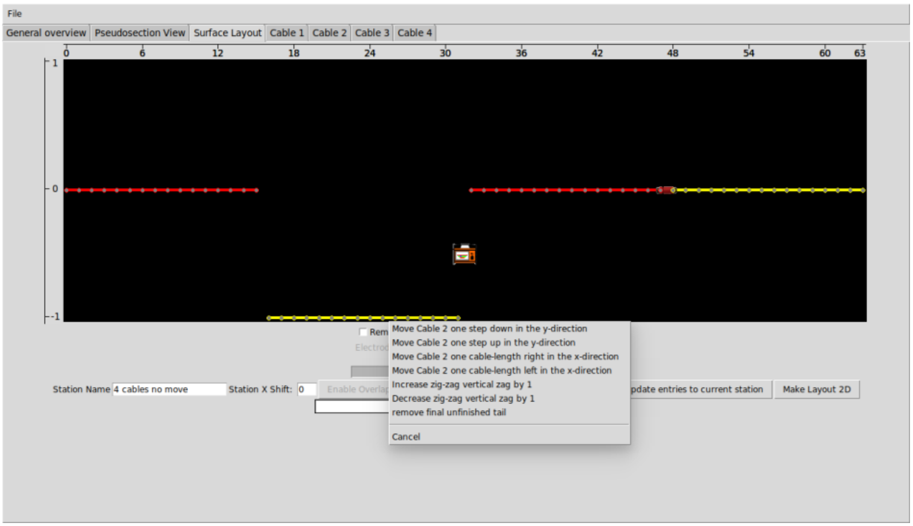

Figure 92 - Cable 2 is moved one step down

Clicking *Move Cable 2 one cable-length left in the x-direction* positions cable 2 directly below Cable 1. This process can be continued, moving Cable 3 two steps down and two cable-lengths left, and Cable 4 three steps down and three cable-lengths left, until all cables sit directly under each other, as shown in Figure 93.

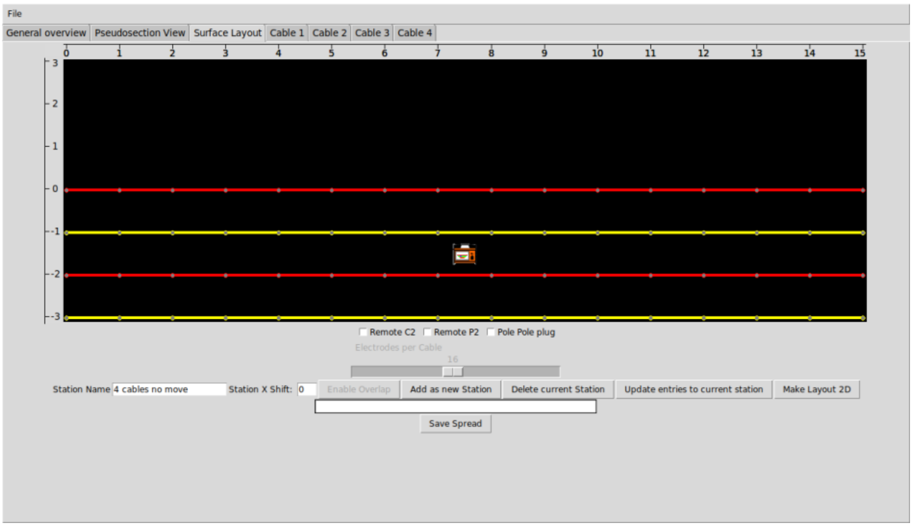

Figure 93 - A layered spread where all cables are positioned below Cable 1