Manual for Program "EM1DTM"

Version 1.0

Developed under the consortium research project

TIME DOMAIN INVERSION AND MODELLING OF
ELECTROMAGNETIC DATA

UBC – Geophysical Inversion Facility,
Department of Earth & Ocean Sciences,
University of British Columbia,
Vancouver, CANADA.

September 2007

Contents

Acknowledgments

This project was made possible by funding from the “TIME” consortium, of which the following companies were participants: Anglo American Corp., ENI Exploration & Production Division, Falconbridge Ltd. (Exploration), INCO Exploration & Technical Services Inc., M.I.M. Exploration Pty. Ltd., Newmont Exploration Ltd., Placer Dome Inc., Teck-Cominco Ltd., and from the Natural Sciences and Engineering Research Council of Canada.

Contact Information

UBC–GIF Director:	Doug Oldenburg,
Author:	Colin Farquharson,
Outreach Coordinator:	Francis Jones,

UBC – Geophysical Inversion Facility,
Department of Earth & Ocean Sciences,
University of British Columbia,
6339 Stores Road,
Vancouver, B.C., V6T 1Z4,
CANADA.

`http://www.eos.ubc.ca/research/ubcgif`

`ubcgif@eos.ubc.ca`

1. Overview

The name: EM1DTM – electromagnetics ("EM"), one-dimensional models ("1D"), time-domain observations ("T"), and magnetic sources and receivers ("M").

The observations are values of voltage (i.e., dB/dt) or magnetic field. Receiver coils can be oriented in the x-, y- or z-directions, and they can be at any position relative to the transmitter loop. The transmitter loop can have any number of sides (greater than 2), and can be at any height above the ground surface. It is assumed to be horizontal. The transmitter current waveform can be a step off, a linear ramp turn-off, or a general waveform that is provided in discretized form. Observations can be for any time after the step or ramp turn off, or any time after or during a discretized waveform. All the observations (in any combination) that are provided for a particular transmitter loop constitute a "sounding", and are used to construct the one-dimensional model for that sounding. Measurement uncertainties can be in the same units as the observations or as relative uncertainties in percent.

The product: an electrical conductivity model. The Earth models are composed of layers of uniform conductivity with fixed interface depths. The value of the conductivity in each layer is sought by the inversion. Multiple soundings can be handled in a single run of the program. Each sounding is inverted independently for a one-dimensional model under the sounding location, with the sequence of one-dimensional models written out. These can be viewed directly as a composite two-dimensional image using the graphical user interface, or converted to a format which is suitable for viewing as a three-dimensional image using MeshTools3D.

General measures for both the measure of data misfit and the measure of the amount of model structure:
- Huber M-measure for data misfit, and
- Ekblom p-measure for model structure, allow for a whole suite of variations, from the traditional sum-of-squares measures, to more robust measures which can ignore outliers in the observations and which can generate piecewise-constant models.

Four possible methods for determining the degree of regularization:
- the trade-off parameter is specified by the user, either as a single constant value, or with a cooling schedule to some final value, or
- the trade-off parameter is automatically chosen to achieve a user-supplied target misfit, or
- the trade-off parameter is automatically chosen using the GCV criterion, or
- the trade-off parameter is automatically chosen using the L-curve criterion.

Documentation is provided in two parts:
- this document containing detailed descriptions of the inputs to and outputs from program EM1DTM (and description of the related independent forward-modelling program), and
- the document "Background for Program EM1DTM" describing the forward modelling and inversion algorithms used by program EM1DTM.

2. Input & Output Files

2.1 Input files

2.1.1 Main input file (Required, and called "`em1dtm.in`")

This is the main input file containing the parameters specifying the names of the file containing the observations and the files containing the starting and reference models, the type of the inversion algorithm, and the various parameters for the inversion and for the forward modelling.

The structure of the file "`em1dtm.in`" is:

rootname	← line 1: root for names of output files;
obsfname	← line 2: name of file containing the observations;
stconfname	← line 3: starting conductivity model file, or layer thicknesses file;
rsconfname	← line 4: reference (smallest) conductivity model file;
rzconfname	← line 5: reference (flattest) conductivity model file;
`NONE`	← line 6: information about additional model weights;
hc eps ees epz eez	← line 7: parameters for Huber & Ekblom measures;
acs acz	← line 8: coefficients of model norm components;
iatype	← line 9: type of inversion algorithm;
iapara(s)	← line 10: additional inversion algorithm parameter(s);
maxniters	← line 11: maximum number of iterations in an inversion;
`DEFAULT`	← line 12: small number for convergence tests;
`DEFAULT`	← line 13: number of explicit evaluations of Hankel transform kernels;
`DEFAULT`	← line 14: information for explicit evaluations of Fourier transform kernels;
outflg	← line 15: flag indicating amount of output;

where, on . . .

line 1, *rootname* is the root for the names of all output files (character string of length less than or equal to 20 characters);

line 2, *obsfname* is the name of the file containing the observations (see Section 2.1.2) (character string of length less that or equal to 99 characters);

line 3, *stconfname* is the name of the file containing the starting conductivity model, or the name of the file containing the layer thicknesses if best-fitting halfspaces are to be used as the starting models (see Section 2.1.4 for the format of this file), required (character string of length less than or equal to 99 characters);

line 4, *rsconfname* is the name of the file containing the reference conductivity model for the smallest component of the model norm (see Section 2.1.5), required if $asc > 0$ (if $asc = 0$, "`NONE`" can be entered on this line) (character string of length less than or equal to 99 characters), or "`DEFAULT`" if the best-fitting homogeneous halfspace is to be used, or the conductivity of the homogeneous halfspace to use;

line 5, *rzconfname* is the name of the file containing the reference conductivity model for the flattest component of the model norm (see Section 2.1.6), completely optional – if such a model is supplied in a file whose name is given here then it will be used in the inversion, otherwise, if "`NONE`" is given on this line of the input file, there will be no reference conductivity model in the flattest component of the model norm (character string of length less than or equal to 99 characters if a file name is being given, or the string "`NONE`" if no reference model is being supplied), or "`DEFAULT`" if the best-fitting homogeneous halfspace is to be used, or the value of the halfspace to be used;

line 6, either "`NONE`" is specified to indicate that no additional user-supplied weights are to be provided for use in the model norm, or the name of the file containing the additional weighting (see Section 2.1.7 for the format of this file) (character string of length less than or equal to 99 characters);

line 7, the parameters *hc*, *eps*, *ees*, *epz* and *eez*, where *hc* is the parameter c in the Huber measure for the misfit:

$$\rho(x_j) \;=\; \begin{cases} x_j^2 & |x_j| \le c, \\ 2c|x_j| - c^2 & |x_j| > c, \end{cases}$$

and *eps* and *ees* are the parameters p and ε in Ekblom's measure for the smallest component of the model norm:

$$\rho(x_j) \;=\; \left(x_j^2 + \varepsilon^2\right)^{p/2},$$

and *epz* and *eez* are the parameters p and ε in Ekblom's measure for the flattest component of the model norm;

line 8, the two parameters *acs* and *acz*, where the value of *acs* is α_s in the expression for the model norm below, and the value of *acz* is α_z:

$$\phi_m \;=\; \alpha_s\, M_m^s\big(\underline{\mathbf{W}}_s(\mathbf{m} - \mathbf{m}_s^{\mathrm{ref}})\big) + \alpha_z\, M_m^z\big(\underline{\mathbf{W}}_z(\mathbf{m} - \mathbf{m}_z^{\mathrm{ref}})\big)$$

(the two parameters that are read in are real numbers greater than or equal to zero);

line 9, *iatype* indicates the type of inversion algorithm to be used, *iatype* = 1 implies a fixed, user-supplied value for the trade-off parameter or a user-supplied cooling schedule, *iatype* = 2 implies that the trade-off parameter will be chosen by means of a line search so that a target misfit is achieved (or, if this is not possible, then the smallest misfit), *iatype* = 3 implies the trade-off parameter will be chosen using the GCV criterion, and *iatype* = 4 implies that the trade-off parameter will be chosen using the L-curve criterion;

line 10, if *iatype* = 1, the value of the trade-off parameter is expected (and optionally the starting value of the trade-off parameter, and the factor by which the trade-off parameter is to be decreased at each iteration, down to the specified value), or if *iatype* = 2, the target misfit (in terms of the factor *chifac* where the target misfit is *chifac* times the total number of observations for the sounding) and the greatest allowed decrease in the misfit (in terms of *decr* where $\phi_d^{n+1,\mathrm{tar}} = \max(\mathit{chifac} \times N, \mathit{decr} \times \phi_d^n)$) at any one iteration (and optionally the starting value of the trade-off parameter) are expected , or if *iatype* =3 or 4, the greatest allowed decrease in the trade-off parameter at any one iteration (in terms of *decr* where $\min(\beta^{n+1}) = \mathit{decr} \times \beta^n$) (and optionally the starting value of the trade-off parameter);

line 11, *maxniters* is the maximum number of iterations to be carried out in an inversion (a strictly positive integer);

line 12, either "`DEFAULT`" can be entered to indicate that the default value of 0.01 is to be used in the tests of convergence for an inversion, or, if another value is desired, it can be entered on this line (a strictly positive real number);

line 13, either "`DEFAULT`" can be entered to indicate the kernel of the Hankel transforms is to be explicitly evaluated the default number of times (=70), or, if there are concerns about the accuracy of the Hankel transform computations, a larger number can be entered on this line;

line 14, either "`DEFAULT`" to indicate the kernel of the Fourier transforms is to be explicitly evaluated at the default number of frequencies (=50), or, if there are concerns about the accuracy of the Fourier transform computations, a number greater than 50 can be entered on this line, or the number of frequencies and the minimum and maximum frequencies can be supplied;

line 15, *outflg* is the flag indicating the amount of output from the program (*outflg* = 1 implies the output of a brief convergence/termination report for each sounding plus the final two-dimensional composite model for all the soundings and the corresponding forward-modelled data, *outflg* = 2 implies the aforementioned output plus the values of the various components of the objective function at each iteration in the inversion for each sounding, and *outflg* = 3 implies the aforementioned output plus the one-dimensional model and corresponding forward-modelled data for each iteration in the inversion for each sounding, plus an additional diagnostics file which records the progress of the inversion for each sounding, *outflg* = 4 implies the aforementioned output plus misfit, GCV function or L-curve curvature versus trade-off parameter at each iteration for each sounding, plus the frequency-domain total and secondary H-fields for the model at each iteration for each soundings).

WARNINGS:

- Filenames cannot include spaces.
- *outflg* = 3 and 4 should only be used for inversions with a limited number of soundings because the amount of output with these options can be considerable.

Examples:

```
test1                         ! root for output file names
tV_WHfig4.4.obs               ! observations file
hspace2.con                   ! starting conductivity
0.001                         ! reference conductivity
NONE                          ! reference conductivity (flat.)
NONE                          ! additional model weights
1000.  2. 0.0001  2. 0.0001   ! Huber c parameter, Ekblom p & eps parameters
0.001 1.                      ! alpha_s & alpha_z
1                             ! inversion algorithm
20.  1000.  0.5               ! final beta, starting beta, decrease factor
15                            ! maximum number of iterations
DEFAULT                       ! small number for convergence tests
DEFAULT                       ! number of Hankel kernel evaluations
DEFAULT                       ! number of Fourier kernel evaluations
4                             ! amount of output
```

```
test2                         ! root for output file names
C:\GIF\EM1DTM\line1\obs       ! observations file
C:\GIF\EM1DTM\start\layers    ! starting conductivity
DEFAULT                       ! reference conductivity
NONE                          ! reference conductivity (flat.)
NONE                          ! additional model weights
2.  1. 0.0001  1. 0.0001      ! Huber c parameter, Ekblom p & eps parameters
0.001 1.                      ! alphas & alphaz
2                             ! inversion algorithm
0.8  0.5  1000.               ! chifac, max decrease, starting beta
15                            ! maximum number of iterations
0.001                         ! small number for convergence tests
100                           ! number of Hankel kernel evaluations
100  3.0E-01  3.0E+09         ! no. of Fourier kernel evals., min & max freq.
1                             ! amount of output
```

For the lines in `em1dtm.in` containing filenames, the whole line is read in, and everything up to the first space (ignoring any leading spaces) is taken as the filename. For the lines containing numbers, program EM1DTM knows how many numbers to expect. Hence, anything beyond the first space in lines containing filenames, or anything beyond the requisite number of numbers in lines containing numbers, is ignored and so can act as comments.

2.1.2 Observations file (Required)

The file that contains the observations and all the survey parameters (except those for the transmitter current waveform):

- the number of soundings;
- the (absolute) x- and y-coordinates and elevation of each sounding (and any other information that is to pass through EM1DTM to the output files, such as a fiducial and/or line number);
- the number of segments in each transmitter loop, the (relative) x- & y-coordinates of the start of each segment, the z-coordinate of the plane of the transmitter loop;
- the name of the file containing the transmitter current waveform information;
- the number of receivers, and units for all times;
- the dipole moment of each receiver, the (relative) x-, y- & (absolute) z-coordinates, and the orientation of the receiver, the number of measurement times, flag for units/normalization of data;
- time, sweep index, datum, flag for type of uncertainty, uncertainty.

The structure of the observations file is:

$$
\begin{array}{ll}
\textit{nsounds} & \leftarrow \text{line A;} \\
\textit{soundx\_a}(i_s) \quad \textit{soundy\_a}(i_s) \quad \textit{soundz\_a}(i_s) \quad \textit{blurb} & \leftarrow \text{line B;} \\
\textit{ntsegs\_a}(i_s) \quad (\ \textit{xt\_a}(j,i_s),\ \textit{yt\_a}(j,i_s),\ j=1,\ldots,\ \textit{ntsegs\_a}(i_s)\ ) \quad \textit{zt\_a}(i_s) & \leftarrow \text{line C;} \\
\textit{tcwfn\_a}(i_s) & \leftarrow \text{line D;} \\
\textit{nr\_a}(i_s) \quad \textit{tu\_a}(i_s) & \leftarrow \text{line E;} \\
\textit{momr\_a}(i_r,i_s) \quad \textit{xr\_a}(i_r,i_s) \quad \textit{yr\_a}(i_r,i_s) \quad \textit{zr\_a}(i_r,i_s) \quad \textit{or\_a}(i_r,i_s) \quad \textit{nt\_a}(i_r,i_s) \quad \ldots & \\
\quad \ldots \quad \textit{ontype\_a}(i_r,i_s) & \leftarrow \text{line F;} \\
\quad \textit{t\_a}(i_t,i_r,i_s) \quad \textit{tf\_a}(i_t,i_r,i_s) \quad \textit{obs\_a}(i_t,i_r,i_s) \quad \textit{utype\_a}(i_t,i_r,i_s) \quad \textit{uncert\_a}(i_t,i_r,i_s) & \leftarrow \text{line G.}
\end{array}
$$

where:

nsounds is the number of soundings;

soundx_a(i_s) is the x-coordinate (m) of the i_sth sounding;

soundy_a(i_s) is the y-coordinate (m) of the i_sth sounding;

soundz_a(i_s) is the elevation (m) above sea level (or some other datum) of the i_sth sounding;

blurb is any collection of numbers and/or words that is read in by EM1DTM and then written out in the equivalent location in the predicted data file (essentially anything on line B beyond the elevation of the sounding is read into a character string, and this string is written out to the predicted data file);

ntsegs_a(i_s) is the number of linear segments in the transmitter loop for the i_sth sounding (i.e., one transmitter per sounding, but can be different for different soundings);

xt_a(j,i_s) the (relative) x-coordinate (m) of the start of the jth segment of the i_sth transmitter loop (the end of the jth segment is assumed to be joined to the start of the $(j+1)$-th segment, with the end of the *ntsegs*-th segment joined to the start of the first segment);

yt_a(j,i_s) the (relative) y-coordinate (m) of the start of the jth segment of the transmitter loop for the i_sth sounding;

zt_a(i_s) the z-coordinate (m) of the plane (which is assumed to be horizontal) of the transmitter loop for the i_sth sounding (with z positive downwards, $z=0$ being at the Earth's surface, and *zt_a*≤ 0 for all soundings);

tcwfn_a(i_s) the name of the file with the transmitter current waveform information (either the code and required parameters for specific waveforms, or the current as a function of time – see Section 2.1.3) for the i_sth sounding;

nr_a(i_s) the number of receivers for the i_sth sounding, with each different component being considered to be from a distinct receiver;

tu_a(i_s) a flag to indicate the units of the measurement times for the i_sth sounding ($=1$ implies microseconds, $=2$ means milliseconds, $=3$ implies seconds);

momr_a(i_r,i_s) the dipole moment ($\mathrm{A\,m^2}$) of the i_rth receiver for the i_sth sounding;

xr_a(i_r,i_s) the (relative) x-coordinate (m) of the i_rth receiver for the i_sth sounding (relative to the same origin used to define the transmitter loop);

yr_a(i_r,i_s) the (relative) y-coordinate (m) of the i_rth receiver for the i_sth sounding;

zr_a(i_r,i_s) the (absolute) z-coordinate (m) of the i_rth receiver for the i_sth sounding (with z positive downwards, $z = 0$ being at the Earth's surface, and *zr_a*$\leq$ 0 for all receivers);

or_a(i_r,i_s) the orientation (`x`, `y`, or `z`) of the i_rth receiver for the i_sth sounding;

nt_a(i_r,i_s) the number of measurement times for the i_rth receiver for the i_sth sounding;

ontype_a(i_r,i_s) flag indicating the type and units of the observations for the i_r receiver for the i_s sounding (= 1 implies voltages in micro-Volts, = 2 implies voltages in milli-Volts, = 3 means voltages in Volts, = 4 implies B-field in nano-Tesla, = 5 implies B-field in micro-Tesla, = 6 implies B-field in milli-Tesla);

t_a(i_t,i_r,i_s) the i_tth measurement time (in the units indicated by *tu_a*(i_r,i_s)) for the i_rth receiver for the i_sth sounding;

tf_a(i_t,i_r,i_s) flag indicating to which sweep the i_tth time for the i_rth receiver for the i_sth sounding belongs (relevant to, e.g., Geonics measurement styles);

obs_a(i_t,i_r,i_s) the observed data at the i_tth measurement time for the i_rth receiver for the i_sth sounding in the units specified by *ontype_a*(i_r,i_s);

utype_a(i_t,i_r,i_s) flag indicating the form of the uncertainty (`p` for relative in % or `v` for absolute in the same units as the observations) in the i_tth observation for the i_rth receiver for the i_sth sounding;

uncert_a(i_t,i_r,i_s) the uncertainty in the i_tth observation for the i_rth receiver for the i_sth sounding.

This structure of the observations file is designed to be as general as possible, enabling the program to handle many survey configurations. The lines in the file form a series of nested loops. Repetition occurs over the indices: $i_t = 1, \ldots,$ *nt_a*(i_r,i_s); $i_r = 1, \ldots,$ *nr_a*(i_s); and $i_s = 1, \ldots,$ *nsounds*. In other words, line G is repeated for each time for each receiver for each particular sounding; line F and the associated line(s) G are repeated for each receiver for each sounding; lines B, C, D & E, and the associated line(s) F and line(s) G are repeated for each sounding. All the information for a particular measurement time is expected on the same single line in the file.

Examples:

```
1
0.  0.  0.   extra blurb, e.g., fiducial, line number, etc.
4  -4.43 -4.43  -4.43 4.43  4.43 4.43  4.43 -4.43  0.
tcw_step
1  2
 0.0127  100. 0. 0.  z  10  1
  4.1950  1  49170.  v  2458.5
  4.3910  1  29270.  v  1463.5
  4.6300  1  18495.  v  924.75
  4.9110  1  11690.  v  584.50
  5.2150  1  7729.0  v  386.45
  5.5410  1  5195.0  v  259.75
  5.9310  1  3488.0  v  174.40
  6.4090  1  2230.0  v  111.50
  6.9950  1  1356.0  v  67.800
  7.7330  1  810.00  v  60.000
```

```
2
549014.0 3495283.0 13.5  20050812 10001
4  10.8 0.   0. 10.8  -10.8 0.   0. -10.8  -120.0
tcw_Bzvst
1  2
 5.  120.0 0. -70.0  z  5  1
  4.1950  1  24008.  p  5.
  4.3910  1  14789.  p  5.
  4.6300  1  9614.0  p  5.
  4.9110  1  6204.0  p  5.
  5.2150  1  4168.0  p  5.
549019.0 3495284.0 11.0  20050812 10002
4  10.8 0.   0. 10.8  -10.8 0.   0. -10.8  -119.0
tcw_Bzvst
1  2
 5.  120.0 0. -69.0  z  5  1
  4.1950  1  24214.  p  5.
  4.3910  1  14899.  p  5.
  4.6300  1  9674.0  p  5.
  4.9110  1  6240.0  p  5.
  5.2150  1  4187.0  p  5.
```

2.1.3 Transmitter current waveform for each/all transmitters (Required)

The file containing the particulars of the transmitter current waveform for each sounding. There can be one file for each sounding (one transmitter per "sounding"), or one file for all soundings if they all have the same particulars, or any combination. The first line of a transmitter current waveform file contains either the code for a special waveform (followed by the necessary parameters), or the number of times in a discretized, user-supplied waveform. If it's a discretized waveform, the subsequent lines in the file contain the times (in the same units as the measurement times for the sounding: see *tu_a*) and values of current (in Ampères) at the discrete points at which the waveform is supplied. The waveform is assumed to vary linearly between the provided points.

If the special waveform is a *step*, the code on the first line of the file is "ste" (or "STE"). If the effects of previous negative & positive step-offs are to be taken into account, then the number of previous step-offs to take into account and the time (in the same units as for the observation times: see *tu_a*) are expected on this line. (If one previous step-off is asked for, it's the negative one (i.e., of opposite sense to the main, first one) at the specified time before. If two previous step-offs are asked for, it's the negative one at the specified time before, and the positive one at twice the specified time. Etc.)

If the special waveform is a *linear ramp turn-off*, the code on the first line of the file is "ram" (or "RAM"). Also on this first line of the file, the number of different ramp turn-off times (between 1 & 6 inclusive), and the values of the ramp turn-off times (in the same units as for the observations times: see *tu_a*) are expected. For this waveform, all observations times are measured from the end of the ramp. The flag *tf_a* in the observations file indicates to which sweep a particular observation corresponds.

2.1.4 Starting conductivity model file (Required)

The file containing the starting conductivity model for all soundings, or, if (crude) best-fitting halfspace(s) are to be used as the starting model(s), then this is the file containing the number of layers and the layer thicknesses. If this file is the starting model, the relevant quantities are the number of layers, and the thickness (m) and conductivity (S/m) of each layer. A dummy value for the thickness of the basement halfspace is required in this file, but nothing is ever done with it after it is read in. It is from this file that the program gets the number of layers and their thicknesses, which then must be the same for all other models read in by the program. This file is therefore required. The structure of this file is as follows (just as for all 1-D model files):

$$\begin{array}{ll} nlayers & \\ thicks\_a(1) & con\_a(1) \\ thicks\_a(2) & con\_a(2) \\ \vdots & \\ thicks\_a(nlayers-1) & con\_a(nlayers-1) \\ \texttt{0.} & con\_a(nlayers) \end{array}$$

where *nlayers* is the number of layers in the model, $thicks\_a(j)$ is the thickness in metres of the jth layer and $con\_a(j)$ is the conductivity in S/m of the jth layer, or:

$$\begin{array}{l} nlayers \\ thicks\_a(1) \\ thicks\_a(2) \\ \vdots \\ thicks\_a(nlayers-1) \\ \texttt{0.} \end{array}$$

if best-fitting halfspace(s) are to be used as the starting model(s).

2.1.5 File for reference conductivity model (for smallest model component) (Optional)

The file containing the reference conductivity model for the smallest component of the model norm if one is required for the inversion. This file is in the same format as the starting conductivity model file (see Section 2.1.4), and must have the same number of layers with exactly the same thicknesses as the starting model.

2.1.6 File for reference conductivity model (for flattest model component) (Optional)

The file containing the reference conductivity model for the flattest component of the model norm if one is required for the inversion. Whether or not this file is specified in "`em1dtm.in`" determines whether or not such a reference model plays a part in the inversion. This file is in the same format as the starting conductivity model file (see Section 2.1.4), and must have the same number of layers with exactly the same thicknesses as the starting model.

2.1.7 File for additional model-norm weights (Optional)

The file containing any additional weighting of the layers for one or both of the two components of the model norm. The first line of this file must contain the number of layers in the model. The order of the two possibilities must be the same as shown below, with any set of weights that is not needed by the program simply omitted.

```
smallFlag smoothFlag          ! 0/1 to turn off/on weights
nlayers                       ! number of layers
uswcs_a(j), j=1:nlayers       ! smallness weights
uswcz_a(j), j=1:nlayers-1     ! smoothness weights
```

where *nlayers* is the number of layers in the model, $uswcs\_a(j)$ is the weight for the jth layer in the smallest component of the model norm, and $uswcz\_a(j)$ is the weight for the difference between the jth and $(j+1)$th layers in the flattest component of the model norm. The supplied weights must be greater than zero. A weight greater than one increases the weight relative to the default setting, and a weight less than one decreases the weight relative to the default setting.

2.1.8 File for frequency-domain filter (Optional)

The file containing the frequency-domain filter, if one is to be applied. This file has to be called "`freqfilter`". If it exists, it will be read in: if not, then no frequency-domain filter will be applied. The first line contains the number of points in the filter (which must be greater than 4). The other lines in this file each contain the frequency in Hertz, and the real and imaginary values of the filter function at each point that it is specified.

$$
\begin{array}{lll}
\textit{nfltrpts} & & \\
\textit{freq\_a}(1) & \textit{rfltr\_a}(1) & \textit{ifltr\_a}(1) \\
\textit{freq\_a}(2) & \textit{rfltr\_a}(2) & \textit{ifltr\_a}(2) \\
\vdots & \vdots & \vdots \\
\textit{freq\_a}(\textit{nfltrpts}) & \textit{rfltr\_a}(\textit{nfltrpts}) & \textit{ifltr\_a}(\textit{nfltrpts})
\end{array}
$$

The filter is interpolated and extrapolated by cubic splines in the logarithmic frequency domain to frequencies which match those at which the frequency-domain H-field is known.

2.2 Output files

2.2.1 Standard output (i.e., the screen) (Always)

Reports on the progress of the inversion are written to the standard output (usually the screen). The amount of this output depends on the value of *outflg* (see Section 2.1.1) in the same way as the amount of output written to the main output file "`em1dtm.out`" (see Section 2.2.2). Any error messages generated by the program will be written to the standard output.

Example:

```
PROGRAM "EM1DTM" (v1.0).

Start at 15:50:11.897, 21/04/2006.

Sounding 1 (0.0,0.0).
Initial phid= 35174., beta= 1000.0, phim= 2.6293, Phi= 37804.
Iteration 1: phid= 12406., beta= 1000.0, phim= 1.1748, Phi= 13581.
Iteration 2: phid= 737.47, beta= 500.00, phim= 0.83563, Phi= 1155.3 (12994.).
Iteration 3: phid= 42.563, beta= 400.00, phim= 0.71192, Phi= 327.33 (1071.7).
Iteration 4: phid= 20.211, beta= 400.00, phim= 0.73238, Phi= 313.16 (327.33).
Iteration 5: phid= 19.027, beta= 400.00, phim= 0.73193, Phi= 311.80 (313.16).
Iteration 6: phid= 18.988, beta= 400.00, phim= 0.73201, Phi= 311.79 (311.80).
Convergence.

Final conductivity model written to "test.con".

The End! [15:51:35.029, 21/04/2006]
```

2.2.2 The main output file (Always, and called "`em1dtm.out`")

This file contains a summary of the inversion and model parameters for the particular run of the program, and either a two-line summary of the completion status (including values of the various components of the objective function) of the inversion of each sounding if *outflg* $= 1$, or an iteration-by-iteration account of the values of the various parts of the objective function for the inversion of each sounding if *outflg* $= 2$, 3 or 4. Any error messages generated by the program will also be echo-ed to this file.

Example:

```
PROGRAM "EM1DTM" (v1.0).

Run started at 15:50:11.901, 21/04/2006.

Reading inputs ...
Root for file names:           "test".
Number of soundings:           1.
Observations file:             "test.obs".
Number of special waveforms:   1.
Starting conductivity model:   best-fitting.
[Thicknesses-only file:        "../../../../start.layers".]
Ref. (small.) cond. model:     0.333E-03 S/m.
Ref. (flat.) cond. model:      NONE.
Additional model weights:      NONE.
Huber c:                       0.100E+04.
Ekblom p (small.):             2.00.
Ekblom epsilon (small.):       0.100E-03.
Ekblom p (flat.):              2.00.
Ekblom epsilon (flat.):        0.100E-03.
alpha_s:                       0.100E-02.
alpha_z:                       1.00.
Inversion algorithm:           1  (fixed trade-off parameter).
Final trade-off parameter:     400.0.
Starting trade-off parameter:  1000.0.
Decrease of trade-off param.:  0.500.
Max. number of iterations:     25.
Convergence parameter:         0.100E-01.
Number of lambdas:             100.
Number of frequencies:         100.
Minimum frequency:             1.00 Hz.
Maximum frequency:             0.100E+09 Hz.
Level of output:               3.

Sounding 1 (0.0,0.0).
Best-fitting conductivity:     0.548E-02 S/m.
Initial phid= 35174., beta= 1000.0, phim= 2.6293, Phi= 37804.
Iteration 1: phid= 12406., beta= 1000.0, phim= 1.1748, Phi= 13581.
  ⋮
```

```
  ⋮
Iteration 6: phid= 18.988, beta= 400.00, phim= 0.73201, Phi= 311.79 (311.80).
Convergence.

Conductivity model:          "test.con".

The End! [15:51:35.029, 21/04/2006]
```

2.2.3 The final model (Always)

If only a single sounding is being inverted, the final one-dimensional conductivity model will be written to the file "*rootname*`.con`", which has the same format as the input one-dimensional conductivity models (see Section 2.1.4).

If two or more soundings are being inverted, the final one-dimensional conductivity models for all soundings are written to the file "*rootname*`_con.mod`". The structure of this file is as follows:

`Number of layers:` *nlayers*
`Layer thicknesses (m):` *thicks_a*(1) ... *thicks_a*(*nlayers*–1)
`Number of soundings:` *ns*
`Sounding x- & y-coordinates (m), Conductivities (S/m) ...`
soundx_a(1) *soundy_a*(1) *soundz_a*(1) *con_a*(1,1) ... *con_a*(*nlayers*,1)
⋮
soundx_a(*ns*) *soundy_a*(*ns*) *soundz_a*(*ns*) *con_a*(1,*ns*) ... *con_a*(*nlayers*,*ns*)

where *nlayers* is the number of layers in the one-dimensional models for all soundings; *thicks_a*(j), $j = 1,\ldots,$*nlayers*–1, are the thicknesses of the layers in the one-dimensional models; *ns* is the number of soundings; *soundx_a*(i), *soundy_a*(i) and *soundz_a*(i), $i = 1,\ldots,$ *ns*, are the x- and y-coordinates and elevations of the soundings; and *con_a*(j,i) is the conductivity (in S/m) in the jth layer for the ith sounding.

In addition, if two or more soundings are being inverted, a second conductivity model file is written out. This is called "*rootname*`_con.mod2`". It is similar to the file described above, except that on each line for a sounding the conductivities of the layers are followed by the depths to the tops of all the layers, and then by the depths to the bottoms of all the layers. (*nlayers* depths to the bottoms of layers are supplied: the final depth is set at 1.1 times the depth to the top of the basement halfspace.) This file, with its column-dominant format, is designed to be more compatible with typical data management and interpretation software.

2.2.4 The forward-modelled data for the final model (Always)

The forward-modelled data for the final model is written to the file "*rootname*`.prd`". The format for this file is the same as that for the input observations file (see Section 2.1.2), but without the information about the uncertainties.

2.2.5 Iteration-by-iteration one-dimensional models for each sounding (If *outflg* $\geq$ 3)

If *outflg* $\geq$ 3, then the one-dimensional conductivity model obtained at each iteration in the inversion for each sounding is written out. The conductivity models are written to the files "*rootname*_*isound*_*iter*`.con`" where *isound* is the number of the sounding ($2 \leq$ *isound* ≤ 999) and *iter* is the number of the iteration ($0 \leq$ *iter* ≤ 99, *iter* $=0$ indicating the starting conductivity model). These files have the same format as the input conductivity files (see Section 2.1.4).

2.2.6 Iteration-by-iteration forward-modelled data for each sounding (If *outflg* $\geq$ 3)

If *outflg* $\geq$ 3, the forward-modelled data for each iteration for each sounding are written out to the files "*rootname_isound_iter*.dprd" where *isound* is the number of the sounding ($2 \leq isound \leq 999$) and *iter* is the number of the iteration ($0 \leq iter \leq 99$, $iter = 0$ indicating the forward-modelled data for the starting model). The data are written out as they are ordered in the input observations file, but with none of the survey parameters. The observations for each sounding are also written out in this format to the file "*rootname_isound*.dobs".

2.2.7 Full list of diagnostics for each iteration for each inversion (If *outflg* $\geq$ 3)

If *outflg* $\geq$ 3, the value of the gradient, data misfit, trade-off parameter, model norm, value of the whole objective function, value of the objective function for the previous iteration using the current value of the trade-off parameter, step length taken, norm of the update added to the model, and the norm of the new model for each iteration for each sounding are written to the file(s) "*rootname_isound*.dgns" where *isound* is the number of the sounding.

2.2.8 Misfit versus trade-off parameter during line search (If *outflg* = 4 and *iatype* = 2)

If *outflg* = 4, and *iatype* = 2 (i.e., a line search over the misfit is used at each iteration to choose the trade-off parameter), the values of the trade-off parameter and the corresponding values of the misfit during each line search at each iteration of each inversion are written out to the file "phidvsbeta". There is just a single such file for a whole run of the program with the information for each iteration separated from that for others. The pairs of values of the trade-off parameter and misfit are written out in the order in which they are computed during the line search: they are not re-ordered.

2.2.9 GCV function versus trade-off parameter during line search (If *outflg* = 4 and *iatype* = 3)

If *outflg* = 4, and *iatype* = 3 (i.e., a line search over the GCV function is used at each iteration to choose the trade-off parameter), the values of the trade-off parameter and the corresponding values of the GCV function during each line search at each iteration of each inversion are written out to the file "GCVvsbeta". There is just a single such file for a whole run of the program with the information for each iteration separated from that for others. The pairs of values of the trade-off parameter and GCV function are written out in the order in which they are computed during the line search: they are not re-ordered.

2.2.10 Total and secondary H-field for each iteration for each inversion (If *outflg* = 4)

If *outflg* = 4, the total and secondary frequency-domain H-fields for the model at each iteration for each sounding are written out to the files "*rootname_isound_iter*.Hvsf" and "*rootname_isound_iter*.Hsvsf" respectively, where *isound* is the number of the sounding ($2 \leq isound \leq 999$) and *iter* is the number of the iteration ($0 \leq iter \leq 99$, $iter = 0$ indicating the fields for the starting model).

3. Examples

3.1 Example 1: synthetic Geonics EM47-like example

The first example is for a single synthetic sounding. The transmitter is a square 50×50 m loop on the ground surface. The receiver is at the centre of the loop, and also on the ground surface. The transmitter current waveform is a linear ramp turn-off of duration 4 μs. Values of the voltage were computed for the three-layer conductivity model shown in Figure 1. Gaussian noise of standard deviation equal to 2.5% of the value of the noise-free data was added to produce the data-set which was inverted. These data are shown in Figure 2.

The inversion illustrated here used essentially an l_2 norm measure of misfit. To achieve this, the Huber c parameter was set to 1000. Ekblom measures with $p = 1$ were used for both the smallest and flattest components of the measure of model structure. This was to generate a blocky model. Algorithm 1, that is, the cooling schedule to a fixed, user-supplied trade-off parameter, was used. The starting value of the trade-off parameter was 1000, and the decrease in the trade-off parameter from one iteration to the next was 0.5. The final value of the trade-off parameter (= 100) was determined by trial-and-error. A reference model (for the smallest component) was included, specifically a homogeneous halfspace of 0.05 S/m. However, the coefficient of the smallest component of the model norm was 0.001, compared to 1 for the flattest component, meaning the reference model only has an effect at depths well below those to which the late time measurements are sensitive. The various input files are given below.

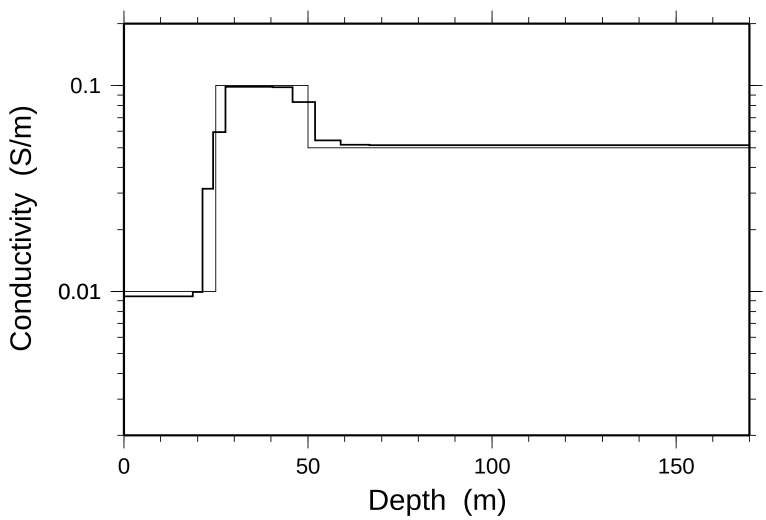

Figure 1. The three-layer conductivity model, shown by the grey line, from which the synthetic data-set in Example 1 was generated. The dark line is the final model produced by the inversion in Example 1.

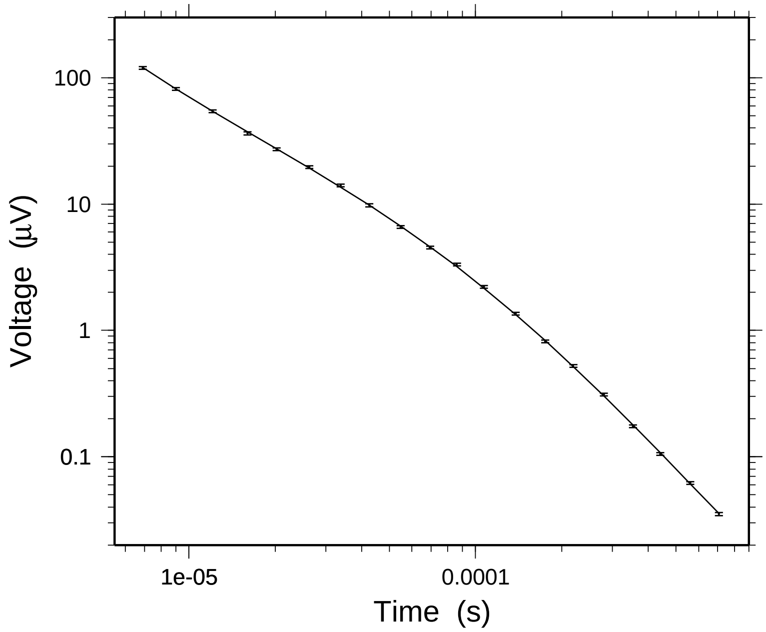

Figure 2. The synthetic data for Example 1, shown by the dots and error bars. The solid line indicates the forward-modelled data for the model produced by the inversion.

File "`em1dtm.in`":

```
test                          ! root for output file names
../tV_ramp.obs                ! observations file
../../../layerthicks.out      ! starting conductivity
0.05                          ! reference conductivity
NONE                          ! reference conductivity (flat.)
NONE                          ! additional model weights
1000.  1. 0.0001  1. 0.0001  ! Huber c parameter, Ekblom p & eps parameters
0.001 1.                      ! alpha_s & alpha_z
1                             ! inversion algorithm
100.  1000.  0.5              ! final beta, starting beta, decrease factor
30                            ! maximum number of iterations
0.001                         ! small number for convergence tests
100                           ! number of Hankel kernel evaluations
40  1.0E+02  1.0E+08          ! number of Fourier kernel evaluations
4                             ! amount of output
```

File "`../tV_ramp.obs`":

```
1
0. 0. 0.
4  -25.  -25.   25.  -25.   25.  25.   -25.  25.   0.
tcw_ramp
1  3
 1.   0.  0.  0.   z   20   1
  0.69000E-05  1  -119.26     v  2.9749
  0.90000E-05  1  -81.421     v  1.9954
  0.12100E-04  1  -54.142     v  1.3259
  0.16000E-04  1  -36.255     v  0.91785
  0.20200E-04  1  -27.178     v  0.67629
  0.26300E-04  1  -19.608     v  0.47779
  0.33800E-04  1  -14.014     v  0.33958
  0.42500E-04  1  -9.7746     v  0.24659
  0.54700E-04  1  -6.5926     v  0.16950
  0.69300E-04  1  -4.5196     v  0.11691
  0.86000E-04  1  -3.3181     v  0.81476E-01
  0.10700E-03  1  -2.2184     v  0.55127E-01
  0.13800E-03  1  -1.3601     v  0.34035E-01
  0.17500E-03  1 -0.81894     v  0.21110E-01
  0.21900E-03  1 -0.52244     v  0.13147E-01
  0.28000E-03  1 -0.31077     v  0.76645E-02
  0.35400E-03  1 -0.17438     v  0.45005E-02
  0.44100E-03  1 -0.10560     v  0.27051E-02
  0.56100E-03  1 -0.61912E-01 v  0.15334E-02
  0.70700E-03  1 -0.35239E-01 v  0.88967E-03
```

File "`tcw_ramp`":

```
ramp  1  0.4E-05
```

File "`../../../layerthicks.out`":

```
50
  .20000   .50000E-01
  .20000   .50000E-01
  .22600   .50000E-01
  .25538   .50000E-01
  .28858   .50000E-01
    ⋮
  43.299   .50000E-01
  48.928   .50000E-01
  55.289   .50000E-01
  62.477   .50000E-01
  70.598   .50000E-01
```

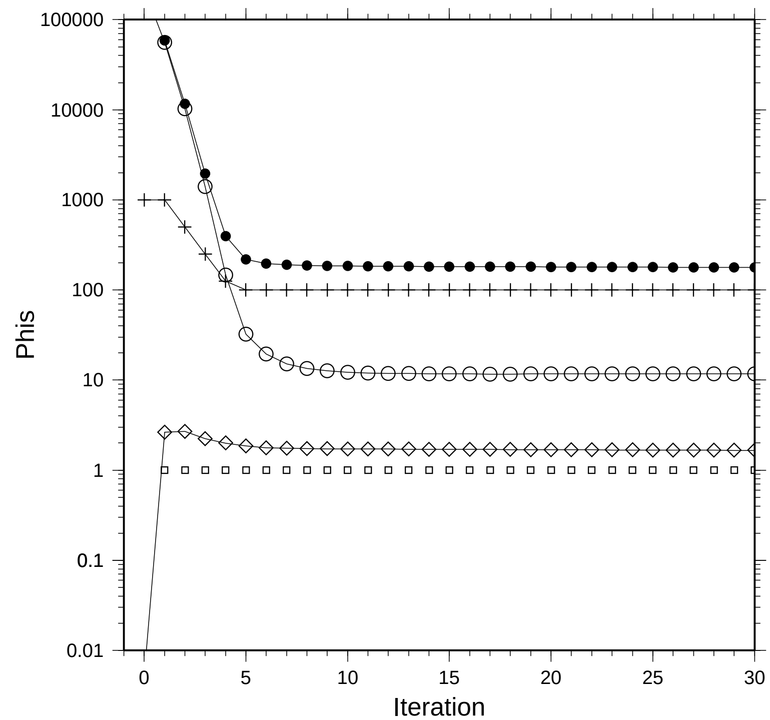

Figure 3. The variation with iteration of the components of the objective function for Example 1: closed circles – the objective function; open circles – the data misfit; diamonds – measure of model structure; and cross – value of the trade-off parameter. The squares indicate the step length at each iteration, which was 1 for all iterations in this inversion.

The final conductivity model is shown in Figure 1. The corresponding forward-modelled data are shown in Figure 2. The variation with iteration of the objective function, misfit, measure of model structure, and trade-off parameter are shown in Figure 3. The main output file and the predicted data file are shown below.

The main output file "`em1dtm.out`":

```
PROGRAM "EM1DTM" (v1.0).

Run started at 12:55:32.904, 30/03/2006.

Reading inputs ...
Root for file names:            "test".
Number of soundings:            1.
Observations file:              "../tV_ramp.obs".
Number of special waveforms:   1.
Starting conductivity model:   "../../../layerthicks.out".
```

```
Ref. (small.) cond. model:     0.500E-01 S/m.
Ref. (flat.) cond. model:      NONE.
Additional model weights:      NONE.
Huber c:                       0.100E+04.
Ekblom p (small.):             1.00.
Ekblom epsilon (small.):       0.100E-03.
Ekblom p (flat.):              1.00.
Ekblom epsilon (flat.):        0.100E-03.
alpha_s:                       0.100E-02.
alpha_z:                       1.00.
Inversion algorithm:           1  (fixed trade-off parameter).
Final trade-off parameter:     100.0.
Starting trade-off parameter:  1000.0.
Decrease of trade-off param.:  0.500.
Max. number of iterations:     30.
Convergence parameter:         0.100E-02.
Number of lambdas:             100.
Number of frequencies:         40.
Minimum frequency:             100. Hz.
Maximum frequency:             0.100E+09 Hz.
Level of output:               4.

Sounding 1 (0.0,0.0).
Initial phid= 0.21526E+06, beta= 1000.0, phim= 0.49050E-02, Phi= 0.21527E+06.
Iteration 1: phid= 56155., beta= 1000.0, phim= 2.6331, Phi= 58788.
Iteration 2: phid= 10253., beta= 500.00, phim= 2.6906, Phi= 11599. (57472.).
Iteration 3: phid= 1402.7, beta= 250.00, phim= 2.2280, Phi= 1959.7 (10926.).
Iteration 4: phid= 146.25, beta= 125.00, phim= 1.9960, Phi= 395.76 (1681.2).
Iteration 5: phid= 32.392, beta= 100.00, phim= 1.8507, Phi= 217.46 (345.85).
   ⋮
Iteration 27: phid= 11.739, beta= 100.00, phim= 1.6660, Phi= 178.34 (178.62).
Iteration 28: phid= 11.732, beta= 100.00, phim= 1.6633, Phi= 178.06 (178.34).
Iteration 29: phid= 11.722, beta= 100.00, phim= 1.6605, Phi= 177.77 (178.06).
Iteration 30: phid= 11.712, beta= 100.00, phim= 1.6577, Phi= 177.48 (177.77).
Max number of iterations (=30) done without convergence.

Conductivity model:           "test.con".

The End! [13:00:22.784, 30/03/2006]
```

The predicted data file “`test.prd`”:

```
1
0.0   0.0   0.0
4  -25.0  -25.0   25.0  -25.0   25.0  25.0   -25.0  25.0   0.0
tcw_ramp
1  3
1.0   0.0   0.0   0.0   z   20   1
  0.69000E-05  1  -120.74
  0.90000E-05  1  -81.772
  0.12100E-04  1  -54.322
  0.16000E-04  1  -37.382
  0.20200E-04  1  -27.411
  0.26300E-04  1  -19.234
  0.33800E-04  1  -13.597
  0.42500E-04  1  -9.8180
  0.54700E-04  1  -6.7136
  0.69300E-04  1  -4.6114
  0.86000E-04  1  -3.2050
  0.10700E-03  1  -2.1658
  0.13800E-03  1  -1.3367
  0.17500E-03  1 -0.82993
  0.21900E-03  1 -0.51782
  0.28000E-03  1 -0.30273
  0.35400E-03  1 -0.17835
  0.44100E-03  1 -0.10755
  0.56100E-03  1 -0.61206E-01
  0.70700E-03  1 -0.35637E-01
```

3.2 Example 2: a single synthetic GEOTEM-like sounding

This second example is for a transmitter and receiver arrangement typical of the GEOTEM airborne system. The transmitter current waveform is also typical of that for the GEOTEM system. The transmitter loop was a rhombus with four vertices: $(10.77, 0.)$, $(0., 10.77)$, $(-10.77, 0.)$, and $(0., -10.77)$. (The units of these distances are metres.) The transmitter loop was at a height of 120 m about the ground surface. The receiver was 130 m in the x-direction from the centre of the transmitter loop, and at a height of 70 m. (See the third and sixth lines of the observations file “`on+off.obs`” below.)

The transmitter current waveform for this example was a discretized half-sine waveform. It is shown in Figure 4. Values of the current in the transmitter at 96 times were specified in the file “`tcw_Geo_trunc`”. (The current is linearly interpolated between these values. The values are assumed to be in Ampères.)

The synthetic data-set for this example comprised values of the voltage induced in a z-directed receiver during both the on- and off-times of the transmitter current waveform. The data were generated for the four-layered model shown in Figure 5. Gaussian noise with standard deviation equal to 2.5% of the value of a datum, or 0.0005 μV, whichever was greater, was added to the computed voltages to form the data-set which was inverted. These data are shown in Figure 6.

As for Example 1, an l_2 measure of data misfit and an l_1-like measure of model structure were used in this example. This was achieved by setting the Huber c parameter to 1000, and the Ekblom p parameters to 1.

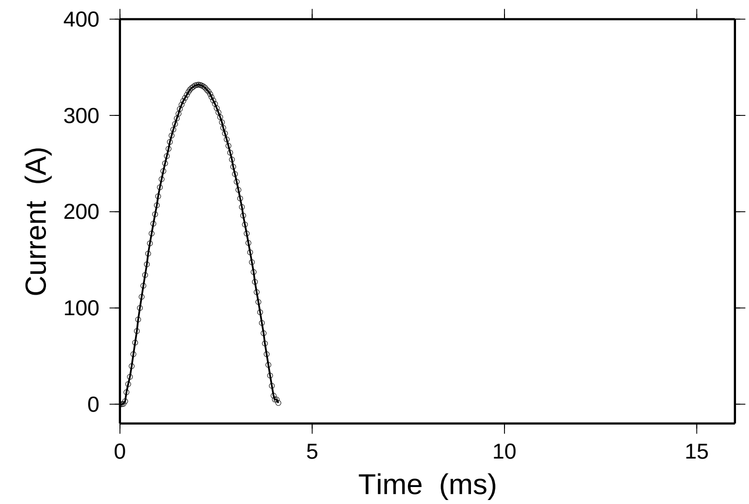

Figure 4. The discretized half-sine transmitter current waveform used in Example 2.

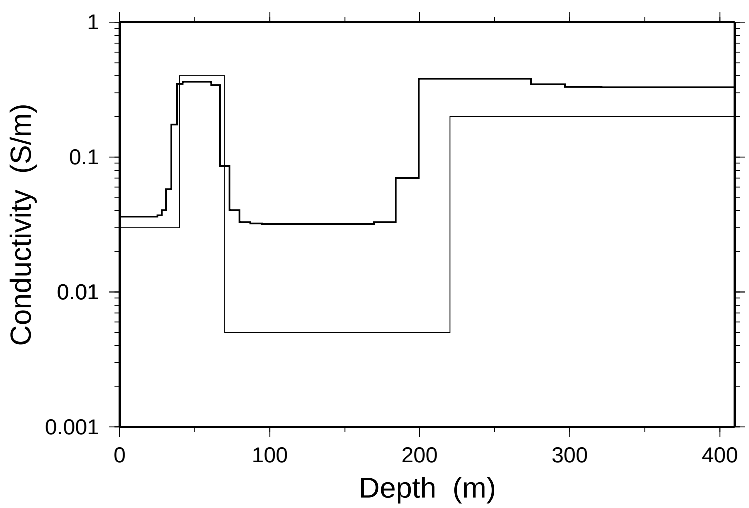

Figure 5. The four-layered model (grey line) from which the synthetic data-set in Example 2 were generated. The black line indicates the final model produced by the inversion.

The GCV criterion (inversion algorithm number 3) was chosen as the means of determining the trade-off parameter during the inversion. The starting value of the trade-off parameter was 1000. The maximum allowed decrease in the trade-off parameter from one iteration to the next was 0.5. A reference halfspace of 0.05 S/m was used for the smallest component. No reference model was used for the flattest component. The coefficients of the smallest and flattest components of the measure of model structure were $\alpha_s = 0.001$ and $\alpha_z = 1$ respectively. The various input files are given below.

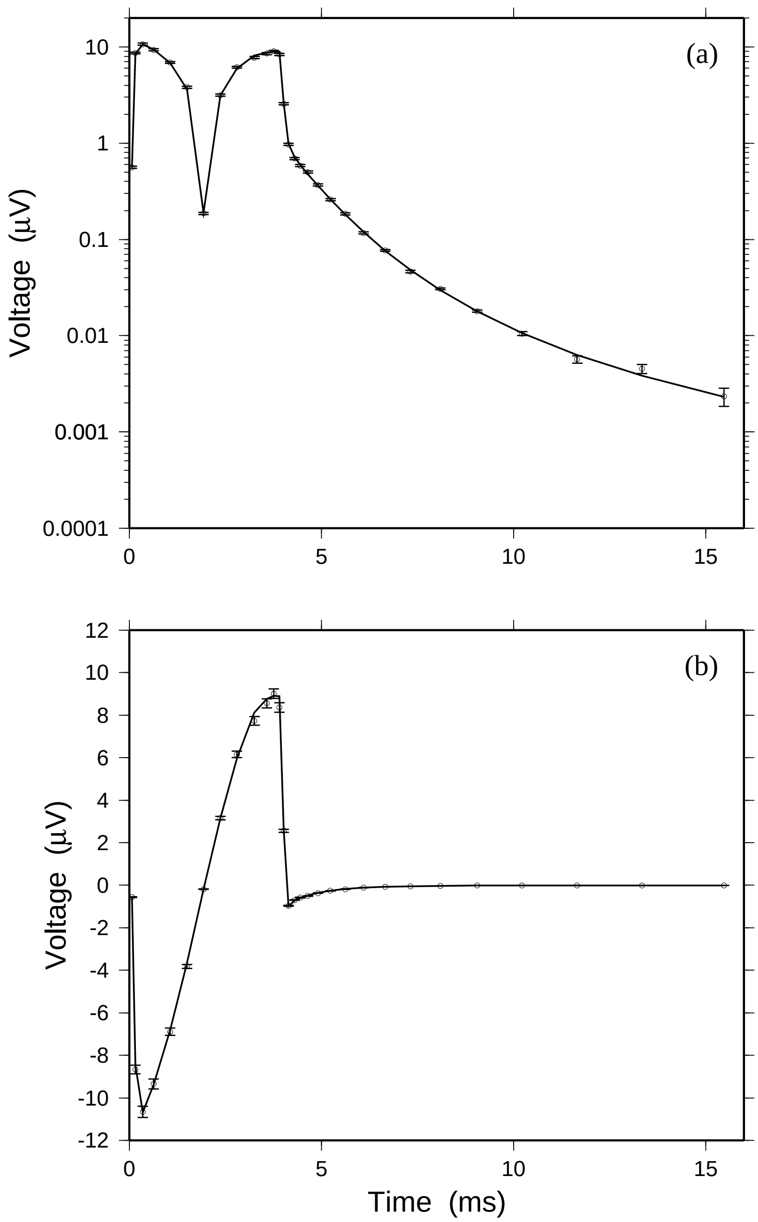

Figure 6. The synthetic data (circles and error bars) for Example 2. Panel (a) has a logarithmic vertical axis, panel (b) has a linear vertical axis. The solid lines show the forward-modelled data for the final model produced by the inversion in Example 2.

File "`em1dtm.in`":

```
test                          ! root name
../on+off.obs                 ! observations file
../../../layerthicks.out      ! starting conductivity model
0.05                          ! reference conductivity model
NONE                          ! reference conductivity model (flat)
NONE                          ! weights
1000.  1. 0.0001  1. 0.0001  ! hc, eps,ees, epz,eez
0.001 1.                      ! acs, acz
3                             ! inversion type
0.5  1000.                    ! beta info.
30                            ! max no. of iterations
0.001                         ! convergence test
100                           ! Hankel kernel evaluations
100  1.0E-00 1.0E+10          ! Fourier kernel evaluations
4                             ! amount of output
```

File "`../on+off.obs`":

```
1
0. 0. 0.
4  10.77 0.00  0.00 10.77  -10.77 0.00  0.00 -10.77  -120.00
tcw_Geo_trunc
1  2
 6.00  130.00 0.00 -70.00  z  30  1
  0.65104E-01  1 -0.56059     v   0.14094E-01
  0.15191      1  -8.6652     v   0.21019
  0.34800      1  -10.666     v   0.26486
  0.62934      1  -9.3437     v   0.23347
  1.0634      1  -6.8957     v   0.16968
  1.4974      1  -3.8130     v   0.90614E-01
  1.9314      1 -0.18615     v   0.47581E-02
  2.3655      1   3.1516     v   0.78361E-01
  2.7995      1   6.1553     v   0.14807
  3.2552      1   7.7348     v   0.20171
    ⋮
  5.6207      1 -0.18482     v   0.46246E-02
  6.0981      1 -0.11682     v   0.30649E-02
  6.6623      1 -0.76916E-01 v   0.19672E-02
  7.3134      1 -0.46391E-01 v   0.12407E-02
  8.0946      1 -0.30649E-01 v   0.75883E-03
  9.0495      1 -0.17991E-01 v   0.50000E-03
  10.221      1 -0.10517E-01 v   0.50000E-03
  11.654      1 -0.56886E-02 v   0.50000E-03
  13.346      1 -0.45468E-02 v   0.50000E-03
  15.473      1 -0.23394E-02 v   0.50000E-03
```

File “`tcw_Geo_trunc`”:

```
96
  0.000000       0.000000
  0.433854E-01   0.000000
  0.867708E-01   0.607759
  0.130156        3.26149
  0.173542        12.4418
  0.216927        20.8657
  0.260312        28.5697
  0.303698        39.6580
  0.347083        51.9037
  0.390469        64.1257
     ⋮
   3.73115        73.7866
   3.77453        62.9102
   3.81792        51.9382
   3.86130        40.9547
   3.90469        29.9454
   3.94807        18.9720
   3.99146        8.99713
   4.03484        4.77586
   4.07823        4.73994
   4.12161        1.12356
```

File “`../../../layerthicks.out`”:

```
50
  1.0000    0.2
  1.0000    0.2
  1.0790    0.2
  1.1642    0.2
  1.2562    0.2
     ⋮
  28.375    0.2
  30.617    0.2
  33.036    0.2
  35.646    0.2
  38.462    0.2
```

Figure 5 shows the final model for this example inversion. Figure 6 shows the corresponding forward-modelled data. The variation of the data-misfit, the measure of model structure, the trade-off parameter, the objective function, and the step length during the inversion is shown in Figure 7. The main output file and the predicted data file are given below.

The main output file "`em1dtm.out`":

```
PROGRAM "EM1DTM" (v1.0).

Run started at 21:04:36.481, 09/05/2006.

Reading inputs ...
Root for file names:           "test".
Number of soundings:           1.
Observations file:             "../on+off.obs".
No. of discretized waveforms:  1.
Starting conductivity model:   "../../../layerthicks.out".
Ref. (small.) cond. model:     0.500E-01 S/m.
Ref. (flat.) cond. model:      NONE.
Additional model weights:      NONE.
Huber c:                       0.100E+04.
Ekblom p (small.):             1.00.
Ekblom epsilon (small.):       0.100E-03.
Ekblom p (flat.):              1.00.
Ekblom epsilon (flat.):        0.100E-03.
alpha_s:                       0.100E-02.
alpha_z:                       1.00.
Inversion algorithm:           3  (GCV line search).
Max. decr. trade-off param.:   0.500.
Starting trade-off parameter:  1000.0.
Max. number of iterations:     30.
Convergence parameter:         0.100E-02.
Number of lambdas:             100.
Number of frequencies:         100.
Minimum frequency:             1.00 Hz.
Maximum frequency:             0.100E+11 Hz.
Level of output:               4.

Sounding 1 (0.0,0.0).
Initial phid= 2996.7, beta= 1000.0, phim= 0.20066.
Search bumping against minimum allowed beta, continuing anyway.
Iteration 1: phid= 497.62, beta= 500.00, phim= 2.5857, Phi= 1790.5 (3097.0).
Search bumping against minimum allowed beta, continuing anyway.
Iteration 2: phid= 279.13, beta= 250.00, phim= 1.4474, Phi= 640.97 (1144.0).
Search bumping against minimum allowed beta, continuing anyway.
Iteration 3: phid= 135.71, beta= 125.00, phim= 1.6683, Phi= 344.25 (460.05).
Search bumping against minimum allowed beta, continuing anyway.
Iteration 4: phid= 75.235, beta= 62.500, phim= 2.0431, Phi= 202.93 (239.98).
Search bumping against minimum allowed beta, continuing anyway.
Iteration 5: phid= 52.548, beta= 31.250, phim= 2.3480, Phi= 125.92 (139.08).
Search bumping against minimum allowed beta, continuing anyway.
Iteration 6: phid= 41.320, beta= 15.625, phim= 2.6574, Phi= 82.841 (89.235).
Search bumping against minimum allowed beta, continuing anyway.
Iteration 7: phid= 37.146, beta= 7.8125, phim= 2.8664, Phi= 59.540 (62.081).
Search bumping against minimum allowed beta, continuing anyway.
Iteration 8: phid= 35.194, beta= 3.9063, phim= 2.9799, Phi= 46.834 (48.343).
Search bumping against minimum allowed beta, continuing anyway.
```

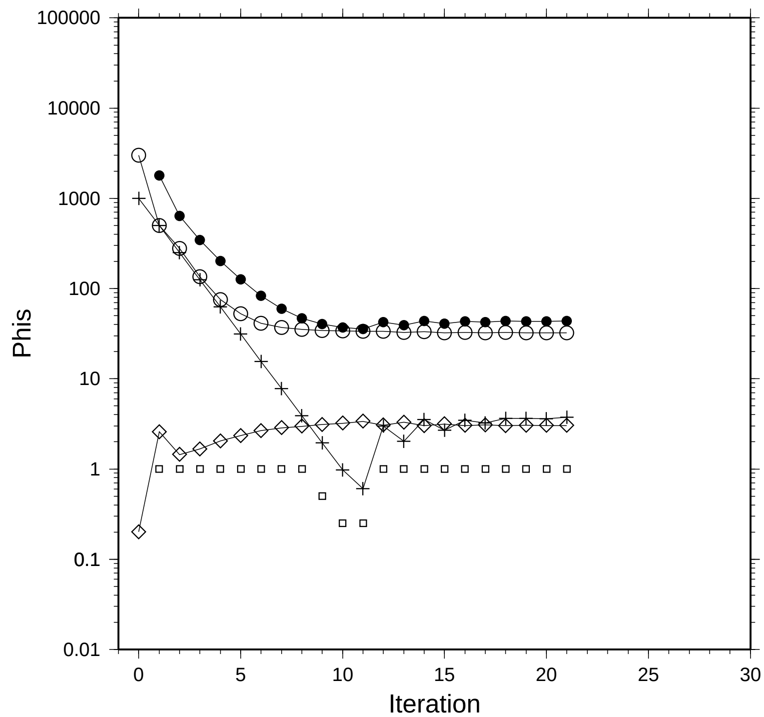

Figure 7. The variation with iteration of the components of the objective function for Example 2: closed circles – the objective function; open circles – the data misfit; diamonds – measure of model structure; and cross – value of the trade-off parameter. The squares indicate the step length at each iteration.

```
Iteration 9: phid= 34.356, beta= 1.9531, phim= 3.1082, Phi= 40.426 (41.014).
Search bumping against minimum allowed beta, continuing anyway.
Iteration 10: phid= 33.887, beta= 0.97656, phim= 3.2190, Phi= 37.030 (37.391).
Iteration 11: phid= 33.687, beta= 0.60592, phim= 3.3772, Phi= 35.733 (35.837).
Iteration 12: phid= 33.460, beta= 2.9910, phim= 3.0642, Phi= 42.625 (43.788).
Iteration 13: phid= 32.769, beta= 2.0249, phim= 3.2873, Phi= 39.425 (39.664).
Iteration 14: phid= 33.195, beta= 3.5225, phim= 3.0141, Phi= 43.813 (44.349).
Iteration 15: phid= 32.447, beta= 2.6984, phim= 3.1576, Phi= 40.968 (41.329).
Iteration 16: phid= 32.675, beta= 3.4611, phim= 3.0354, Phi= 43.181 (43.376).
Iteration 17: phid= 32.439, beta= 3.2417, phim= 3.0801, Phi= 42.424 (42.515).
Iteration 18: phid= 32.540, beta= 3.6284, phim= 3.0311, Phi= 43.538 (43.615).
Iteration 19: phid= 32.442, beta= 3.6284, phim= 3.0415, Phi= 43.477 (43.538).
Iteration 20: phid= 32.399, beta= 3.6216, phim= 3.0394, Phi= 43.407 (43.457).
Iteration 21: phid= 32.393, beta= 3.7443, phim= 3.0315, Phi= 43.744 (43.780).
Convergence.

Conductivity model:           "test.con".

The End! [21:11:46.373, 09/05/2006]
```

The predicted data file "`test.prd`":

```
1
0.0    0.0    0.0
4  10.77 0.00  0.00 10.77  -10.77 0.00  0.00 -10.77  -120.00
tcw_Geo_trunc
1  2
6.00  130.00 0.00 -70.00  z  30  1
  0.65104E-01  1 -0.56793
  0.15191      1  -8.4744
  0.34800      1  -10.673
  0.62934      1  -9.3880
   1.0634      1  -6.8185
   1.4974      1  -3.6396
   1.9314      1 -0.18829
   2.3655      1   3.1530
   2.7995      1   5.9554
   3.2552      1   8.1110
   3.5807      1   8.7736
   3.7543      1   8.9108
   3.9063      1   8.8928
   4.0148      1   2.5722
   4.1450      1 -0.98832
   4.2969      1 -0.71453
   4.4488      1 -0.59596
   4.6441      1 -0.47998
   4.9045      1 -0.36381
   5.2301      1 -0.26174
   5.6207      1 -0.18085
   6.0981      1 -0.11931
   6.6623      1 -0.76435E-01
   7.3134      1 -0.48305E-01
   8.0946      1 -0.29788E-01
   9.0495      1 -0.17931E-01
   10.221      1 -0.10640E-01
   11.654      1 -0.63081E-02
   13.346      1 -0.38276E-02
   15.473      1 -0.23073E-02
```

3.3 Example 3: a line of synthetic VTEM-like soundings

The final example presented in this manual is for a synthetic flight-line of soundings. The disposition of transmitter and receiver, and the transmitter current waveform, mimic that of the VTEM airborne system. The transmitter loop was a twelve-sided polygon with a diameter of 23 m. This loop was at a height of 20 m. The receiver was at the centre of the transmitter loop (and so also at a height of 20 m), and measured

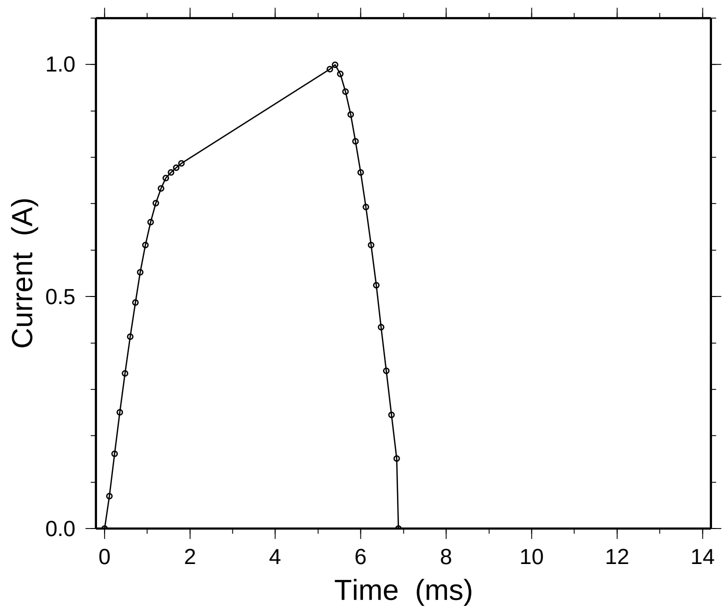

Figure 8. The discretized VTEM-like transmitter current waveform used in Example 3. The circles indicate the time–current pairs which were provided in the transmitter current waveform file.

the voltage for the rate of change of the vertical component of the magnetic field. (See the observations file "`../../VTEM_11locs-2.obs`" below.) Figure 8 shows the transmitter current waveform that was used.

The data-set comprised eleven soundings. The synthetic data for the soundings were computed from the eleven three-layer models shown in Figure 9. (The eleven models are displayed next to one another in a 2-D image.) The models all have a conductive layer beneath a resistive top layer and a resistive basement. The thickness of the conductive layer increases from sounding 1 to sounding 11. The synthetic VTEM-like data computed for each model are also shown in Figure 9. Gaussian noise of standard deviation equal to 2.5 % of the size of a datum was added to the computed data to give the data-set that was inverted. The resulting data for the first and last soundings are also shown in Figure 10.

The example presented here used l_2-measures for both the data misfit and the measure of model structure. The GCV criterion (inversion algorithm number 3) was used to estimate the trade-off parameter during the inversions for each sounding. The reference model was a homogeneous halfspace of 0.001 S/m. (There was no reference model for the flattest component.) The relative weighting of the smallest and flattest components of the measure of model structure was given by $\alpha_s = 0.001$ and $\alpha_z = 1$. The starting value of the trade-off parameter was 1000, and the maximum allowed decrease in the trade-off parameter from one iteration to the next was 0.5. The starting model was the best-fitting homogeneous halfspace. This option is specified by only giving layer thicknesses in the starting model file and no layer conductivities. The input files are illustrated below.

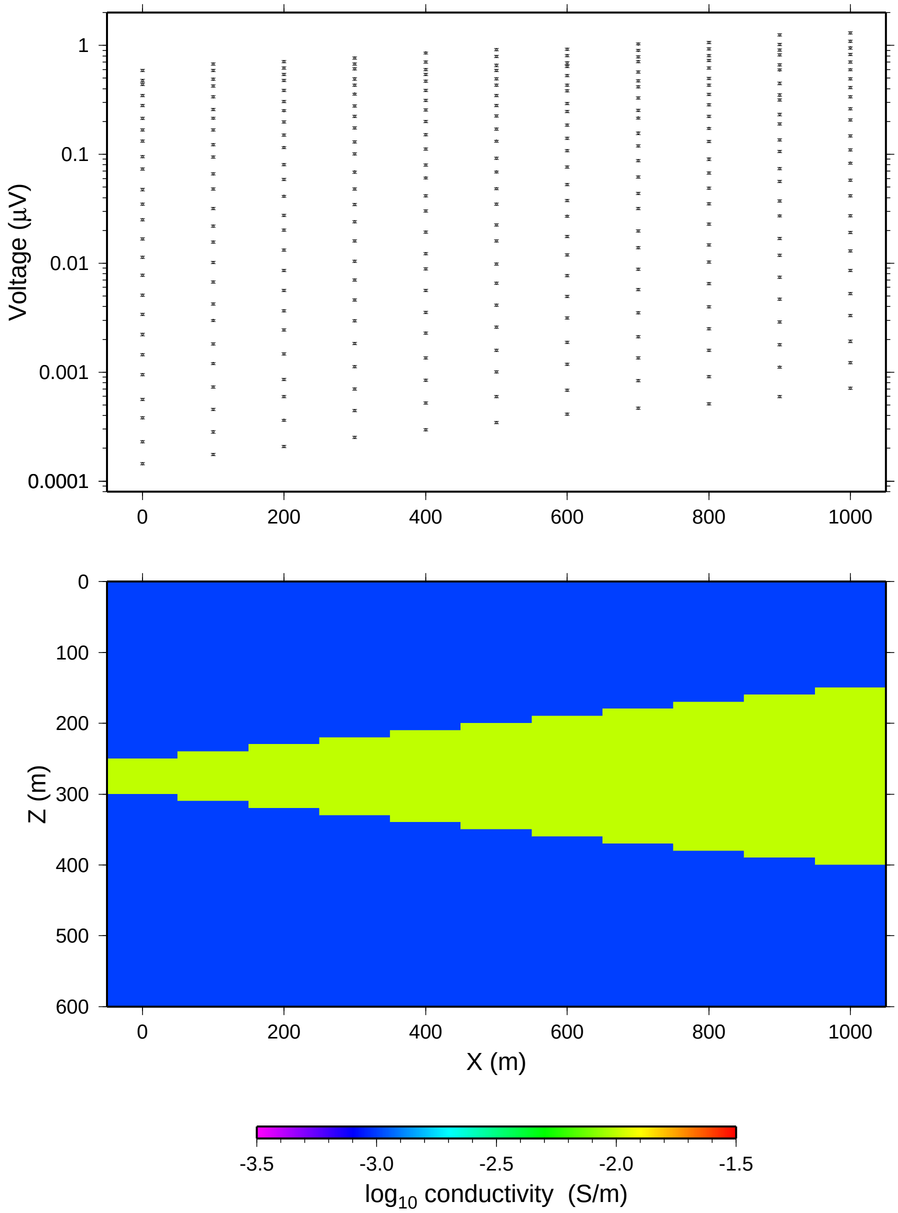

Figure 9. The sequence of eleven three-layered models used to generate the synthetic data for Example 3 are shown in the lower panel. The data for the resulting eleven synthetic soundings are shown in the upper panel.

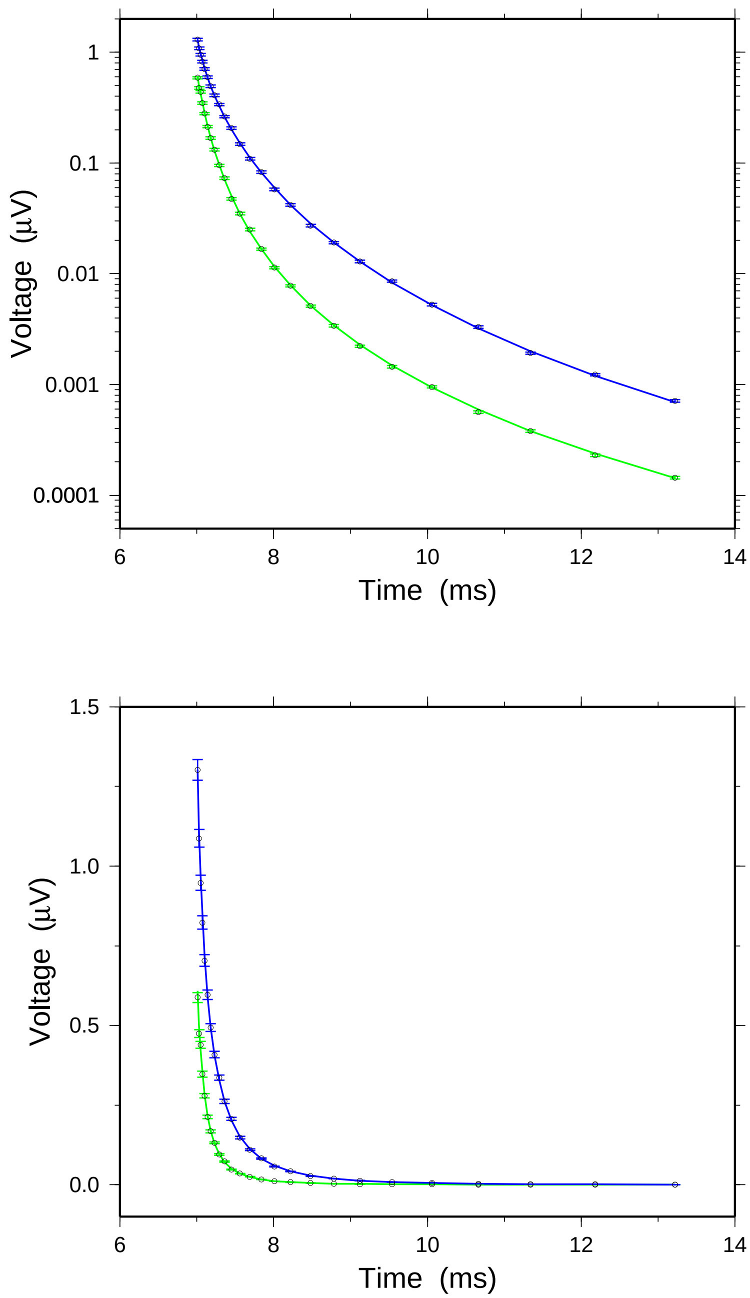

Figure 10. The synthetic data for the first and last synthetic soundings (that is, the left-most and right-most in Figure 9) in Example 3. The green lines and error bars are for the first sounding; the blue lines and error bars are for the last sounding. The error bars are the synthetic data which incorporate Gaussian noise (of standard deviation equal to 2.5% of the noise-free datum); the lines indicate the noise-free data. The upper panel shows the data on a logarithmic vertical axis. The lower panel shows the data on a linear vertical axis. The times are with respect to the zero time in Figure 8.

File "em1dtm.in":

```
test                          ! root name
../../VTEM_11locs-2.obs       ! observations file
../../start.layers            ! starting conductivity model
0.001                         ! reference conductivity model
NONE                          ! reference conductivity model (flat)
NONE                          ! weights
1000.  2. 0.0001  2. 0.0001  ! hc, eps,ees, epz,eez
0.001 1.                      ! acs, acz
3                             ! inversion type
0.5 1000.                     ! beta info.
30                            ! max no. of iterations
0.001                         ! convergence test
100                           ! Hankel kernel evaluations
60  1.0E-00 1.0E+08           ! Fourier kernel evaluations
2                             ! amount of output
```

File "../../VTEM_11locs-2.obs":

```
11
 0. 0. 0.
 12  0.0 13.0  6.5 11.258  11.258 6.5  13.0 0.0  11.258 -6.5  6.5 -11.258  →
 →  0.0 -13.0  -6.5 -11.258  -11.258 -6.5  -13.0 0.0  -11.258 6.5  →
 →  -6.5 11.258  -20.0
 tcw_VTEM_dec2
 1  2
  1884.0  0.0 0.0 -20.0  z  25  1
  7.0100      1  0.58752     v   0.15203E-01
  7.0300      1  0.47416     v   0.12533E-01
  7.0500      1  0.43918     v   0.10496E-01
  7.0700      1  0.34695     v   0.89039E-02
  7.1000      1  0.27933     v   0.70971E-02
    ⋮
  10.060      1  0.95103E-03 v   0.23414E-04
  10.660      1  0.56342E-03 v   0.14851E-04
  11.340      1  0.38012E-03 v   0.95241E-05
  12.180      1  0.23001E-03 v   0.59293E-05
  13.220      1  0.14407E-03 v   0.35791E-05
 100. 0. 0.
 12  0.0 13.0  6.5 11.258  11.258 6.5  13.0 0.0  11.258 -6.5  6.5 -11.258  →
 →  0.0 -13.0  -6.5 -11.258  -11.258 -6.5  -13.0 0.0  -11.258 6.5  →
 →  -6.5 11.258  -20.0
 tcw_VTEM_dec2
 1  2
  1884.0  0.0 0.0 -20.0  z  25  1
  7.0100      1  0.67419     v   0.16852E-01
  7.0300      1  0.58867     v   0.14180E-01
```

```
 7.0500     1  0.48982     v   0.12089E-01
 7.0700     1  0.42234     v   0.10415E-01
 7.1000     1  0.33690     v   0.84665E-02
   ⋮
 10.060     1  0.11969E-02 v   0.29593E-04
 10.660     1  0.72950E-03 v   0.18571E-04
 11.340     1  0.45448E-03 v   0.11781E-04
 12.180     1  0.28253E-03 v   0.72484E-05
 13.220     1  0.17495E-03 v   0.43237E-05
⋮
```

(The arrows indicate the continuation of the single line in the actual observations file.)

File “`tcw_VTEM_dec2`”:

```
31
0.000000   0.000000
0.120000   0.069489
0.240000   0.161502
0.360000   0.250246
0.480000   0.334679
   ⋮
6.480000   0.433886
6.600000   0.340249
6.720000   0.245104
6.840000   0.151106
6.88       0.
```

File “`../../start.layers`”:

```
50
 1.0000
 1.0000
 1.0900
 1.1881
 1.2950
   ⋮
 44.337
 48.327
 52.677
 57.418
 62.585
```

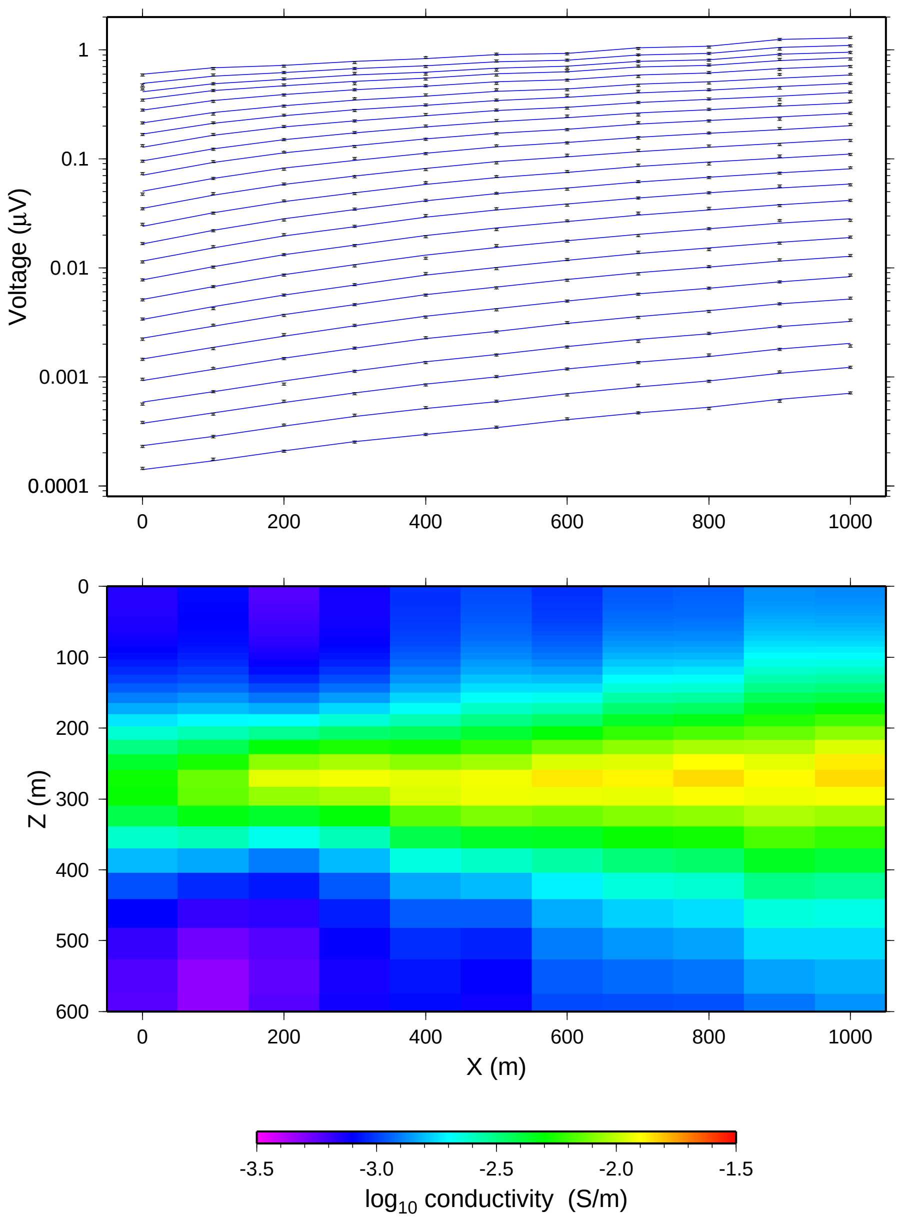

Figure 11. The sequence of eleven models (lower panel) and corresponding forward-modelled data (lines, upper panel) produced by the inversion in Example 3. This inversion used l_2-type measures for both the data misfit and the amount of model structure. The GCV criterion (inversion algorithm number 3) was used to estimate the trade-off parameter during the inversion.

The models resulting from the inversions of the eleven soundings are shown in Figure 11. The eleven models are stitched together to give a 2-D image of the subsurface. The forward-modelled data for the eleven models are also shown in Figure 11. Excerpts from the main output file "`em1dtm.out`" are shown below.

The main output file "`em1dtm.out`":

```
PROGRAM "EM1DTM" (v1.0).

Run started at 15:45:45.104, 15/06/2006.

Reading inputs ...
Root for file names:            "test".
Number of soundings:            11.
Observations file:              "../../VTEM_11locs-2.obs".
No. of discretized waveforms:  1.
Starting conductivity model:   best-fitting.
[Thicknesses-only file:         "../../start.layers".]
Ref. (small.) cond. model:     0.100E-02 S/m.
Ref. (flat.) cond. model:      NONE.
Additional model weights:      NONE.
Huber c:                        0.100E+04.
Ekblom p (small.):              2.00.
Ekblom epsilon (small.):        0.100E-03.
Ekblom p (flat.):               2.00.
Ekblom epsilon (flat.):         0.100E-03.
alpha_s:                        0.100E-02.
alpha_z:                        1.00.
Inversion algorithm:            3  (GCV line search).
Max. decr. trade-off param.:   0.500.
Starting trade-off parameter:  1000.0.
Max. number of iterations:     30.
Convergence parameter:          0.100E-02.
Number of lambdas:              100.
Number of frequencies:          60.
Minimum frequency:              1.00 Hz.
Maximum frequency:              0.100E+09 Hz.
Level of output:                2.

Sounding 1 (0.0,0.0).
Best-fitting conductivity:     0.158E-02 S/m.
Initial phid= 1020.4, beta= 1000.0, phim= 0.15429.
Iteration 1: phid= 869.07, beta= 500.00, phim= 0.33724, Phi= 1037.7 (1097.5).
Iteration 2: phid= 89.890, beta= 250.00, phim= 0.30903, Phi= 167.15 (953.38).
Iteration 3: phid= 40.431, beta= 125.00, phim= 0.35083, Phi= 84.285 (128.52).
   ⋮
Iteration 9: phid= 25.002, beta= 65.474, phim= 0.42421, Phi= 52.776 (52.780).
Iteration 10: phid= 24.987, beta= 65.427, phim= 0.42426, Phi= 52.745 (52.757).
Iteration 11: phid= 24.987, beta= 64.646, phim= 0.42426, Phi= 52.413 (52.414).
No suitable step found at iteration 12.

Sounding 2 (100.0,0.0).
Best-fitting conductivity:     0.158E-02 S/m.
Initial phid= 3447.2, beta= 1000.0, phim= 0.15429.
Iteration 1: phid= 492.51, beta= 500.00, phim= 0.35198, Phi= 668.51 (3524.4).
Iteration 2: phid= 144.62, beta= 250.00, phim= 0.40024, Phi= 244.68 (580.51).
```

```
Iteration 3: phid= 76.712, beta= 125.00, phim= 0.42795, Phi= 130.21 (194.65).
   ⋮
Iteration 13: phid= 15.957, beta= 41.837, phim= 0.61274, Phi= 41.592 (41.594).
Iteration 14: phid= 15.961, beta= 42.373, phim= 0.61250, Phi= 41.914 (41.920).
Iteration 15: phid= 15.946, beta= 41.061, phim= 0.61252, Phi= 41.096 (41.110).
No suitable step found at iteration 16.

Sounding 3 (200.0,0.0).
Best-fitting conductivity:     0.239E-02 S/m.
Initial phid= 2774.3, beta= 1000.0, phim= 0.56308.
Iteration 1: phid= 1500.0, beta= 500.00, phim= 0.56784, Phi= 1783.9 (3055.8).
Iteration 2: phid= 1328.7, beta= 250.00, phim= 0.64421, Phi= 1489.8 (1642.0).
Iteration 3: phid= 219.81, beta= 125.00, phim= 0.63485, Phi= 299.16 (1409.3).
   ⋮
Iteration 8: phid= 16.786, beta= 29.311, phim= 0.71709, Phi= 37.805 (37.808).
Iteration 9: phid= 16.780, beta= 30.248, phim= 0.71726, Phi= 38.476 (38.476).
Iteration 10: phid= 16.779, beta= 30.226, phim= 0.71727, Phi= 38.459 (38.460).
No suitable step found at iteration 11.

Sounding 4 (300.0,0.0).
 ⋮

Conductivity model:           "test_con.mod".

The End! [16:00:09.891, 15/06/2006]
```

The above example illustrates a situation in which the inversions have essentially converged, although not all of the criteria checked within the code have been met (see Theoretical Background). Specifically, the model and objective function are no longer changing appreciably from one iteration to the next, but the gradient is not as small as expected. The results produced by an inversion terminating with the “no suitable step found” message are probably perfectly adequate.

4. The stand-alone forward-modelling program "EM1DTMFWD"

The program EM1DTMFWD provides a means of forward-modelling a single-sounding data-set for a given layered conductivity model. It uses exactly the same algorithm as that used within program EM1DTM. The option of adding Gaussian random noise to the forward-modelled data is available. Four input files are required: a control file "`em1dtmfwd.in`", a file containing the transmitter loop dimensions, the receiver locations and orientations, and the observation times (in nearly the same format as an observations file for program EM1DTM); a transmitter current waveform file (in the same format as for EM1DTM), and the file containing the layered conductivity model (in the same format as for EM1DTM).

4.1 Main input file (Required, and called "`em1dtmfwd.in`")

The structure of the file "`em1dtmfwd.in`" is:

obstypefname	← line 1: name of file containing the survey parameters;
confname	← line 2: name of file containing the conductivity model;
`DEFAULT`	← line 3: number of explicit evaluations of Hankel transform kernels;
`DEFAULT`	← line 4: information for explicit evaluations of Fourier transform kernels;
noiseflag	← line 5: flag indicating whether noise is go be added;
perc thre seed	← line 6: percentage & threshold of noise, seed for random number generator;

where, on . . .

line 1, *obstypefname* is the name of the file containing the transmitter and receiver parameters, and observation times (see Section 4.2) (character string of length less than or equal to 99 characters);

line 2, *confname* is the name of the file containing the one-dimensional conductivity model (in the same format as the model files for program EM1DTM – see Section 2.1.4);

line 3, either "`DEFAULT`" can be entered to indicate the kernel of the Hankel transforms is to be explicitly evaluated the default number of times (=70), or, if there are concerns about the accuracy of the Hankel transform computations, a number greater than 70 can be entered on this line;

line 4, either "`DEFAULT`" to indicate the kernel of the Fourier transforms is to be explicitly evaluated at the default number of frequencies (=50), or, if there are concerns about the accuracy of the Fourier transform computations, a number greater than 50 can be entered on this line, or the number of frequencies and the minimum and maximum frequencies can be supplied;

line 5, *noiseflag* indicates whether noise is to be added to the computed data (*noiseflag*="`y`"), or no noise is to be added (*noiseflag*="`n`");

line 6, the standard deviation of the Gaussian noise to be added to a particular computed datum is either *perc*% of the absolute value of the datum, or *thre* (in the same units as the forward-modelled data), whichever is larger, and *seed* is a positive integer that is used as the seed of the random number generator (the same seed for two different runs of the program will give the same sequence of random numbers) .

Example:

```
tV_WHfig4.4.obstype     ! file with transmitter & receiver params, and times
../em1dtm/hspace2.con   ! conductivity model file
200                     ! number of Hankel kernel evaluations
100  1.  1.0E+10        ! no. of Fourier kernel evals., min & max freq.
NO                      ! Noise to be added?
```

4.2 Observations-style file (Required)

Program EM1DTMFWD expects all the survey parameters (the geometry of the transmitter loop, the locations and orientations of the receivers, the measurement times) to be in a file that is almost identical to the observations file for the inversion program (see Section 2.1.2). The only differences are that (*i*) there are no lines indicating the number of soundings nor the coordinates of the sounding, and (*ii*) observations and their uncertainties are not in this file. This means that lines in this file that are equivalent to lines A and B (see Section 2.1.2) in the observations file for EM1DTM do not appear, and the lines equivalent to line G only contain the measurement time and the flag indicating to which sweep the measurement time belongs. The information about the transmitter current waveform is expected in exactly the same form as for program EM1DTM: see Section 2.1.3.

Example:

```
4  -4.43 -4.43  -4.43 4.43  4.43 4.43  4.43 -4.43  0.
tcw_ramp
1  2
 0.0127  100. 0. 0.  z  5  1
  4.1950  1
  4.3910  1
  4.6300  1
  4.9110  1
  5.2150  1
```

4.3 The output file (Always, and called "`em1dtmfwd.out`")

The output from program EM1DFMFWD is a file called "`em1dfmfwd.out`". It is either in the same format as the predicted data files output from program EM1DTM (see Section 2.2.4) if noise has not been added to the data, or it is in the same format as the observations files for program EM1DTM (see Section 2.1.2) with the standard deviation of the noise added to each datum written out in place of *uncert_a*. In addition, if noise has been added, the actual noise added to each datum and the total χ-squared sum of the noise are appended to the bottom of the file `em1dtmfwd.out` along with the noise-free data.

Examples:

```
  4 -4.4300 -4.4300 -4.4300 4.4300 4.4300 4.4300 4.4300 -4.4300 -0.0000
../../em1dtm/tcw_step
  1    2
0.12700E-01   100.00       0.0000      -0.0000     z     5    1
0.10560      1  0.87981E-04
0.13660      1  0.51448E-04
0.17330      1  0.30607E-04
0.21590      1  0.18656E-04
0.27600      1  0.10594E-04
```

```
  4 -4.4300 -4.4300 -4.4300 4.4300 4.4300 4.4300 4.4300 -4.4300 -0.0000
../../em1dtm/tcw_step
  1    2
0.12700E-01   100.00       0.0000      -0.0000     z     5    1
0.10560      1  0.87096E-04 v   0.17596E-05
0.13660      1  0.43412E-04 v   0.10290E-05
0.17330      1  0.22261E-04 v   0.10000E-05
0.21590      1  0.23660E-04 v   0.10000E-05
0.27600      1  0.87247E-05 v   0.10000E-05

Added noise, N(0,1).           Added noise.
  -0.8853E-01                  -0.8853E-06
  -0.8036                      -0.8036E-05
  -0.8346                      -0.8346E-05
   0.5003                       0.5003E-05
  -0.1869                      -0.1869E-05

Total chi-squared noise added =   1.6354

Noise-free data:
  4 -4.4300 -4.4300 -4.4300 4.4300 4.4300 4.4300 4.4300 -4.4300 -0.0000
../../em1dtm/tcw_step
  1    2
0.12700E-01   100.00       0.0000      -0.0000     z     5    1
0.10560      1  0.87981E-04
0.13660      1  0.51448E-04
0.17330      1  0.30607E-04
0.21590      1  0.18656E-04
0.27600      1  0.10594E-04
```

5. Data conversion program "`xyz2td1d.exe`"

The program `xyz2td1d` takes an XYZ-columns-like data file formatted with the data for each sounding location on a single line of the file and with each column a datum at a different delay time or receiver orientation/location and produces a file appropriate for input to program EM1DTM. The parameters for the data in each column are specified in a control file `xyz2td1d.in` . Lines beginning with either kind of slash ("/" or "\") in the columns file are treated as comments and are ignored.

The name of the control file is hard-wired to `xyz2td1d.in` . The first two lines of this control file are the names of the input columns file and the EM1DTM observations file that is to be written out. The third line of `xyz2td1d.in` contains the number of columns in the columns file. All the remaining lines in `xyz2td1d.in` except the very last two, contain the parameters that describe each column in turn in the columns file. The possible descriptions of each column are:

`ignore`	this column is to be ignored;
`x`	the x-coordinate of each sounding;
`y`	the y-coordinate of each sounding;
`elev`	the elevation (above sea level or some other datum) of each sounding;
`z m|f`	the height of the transmitter above the ground, and whether this height is in metres (`m`) or feet (`f`);
`rx`	the x-coordinate of the receiver relative to the same origin as used to specify the segments of the transmitter loop;
`ry`	the y-coordinate of the receiver relative to the same origin;
`rz`	the height of the receiver above the ground;
`nt`	the number of measurement times to be used if not all the values in the columns file are to be actually inverted for a specific sounding (only works for the z-component measurements);

or

```
un  x|y|z  <t>  <aunc>
```

or

```
<momr>  x|y|z  1|2|3|4|5|6  p|w  <t>|<t1>,<t2>  <punc>  <aunc>
```

where

`<momr>` is the dipole moment of the receiver (A/m^2);

`x|y|z` is the receiver orientation;

`1|2|3|4|5|6` indicates the normalisation of the data (note that the flags for B-field data are different from those for EM1DTM):

- 1 = voltage in micro-Volts,
- 2 = voltage in milli-Volts,
- 3 = voltage in Volts,
- 4 = B field in femto-Tesla,
- 5 = B field in pico-Tesla,
- 6 = B field in nano-Tesla;

`p|w` indicates whether measurements are at a point time or over a time window:

- `p` = point time,
- `w` = window;

`<t>|<t1>,<t2>` either the point measurement time for the datum in this column if the preceding flag is p, or the start and end times of the measurement window;

`<punc>` is the percentage uncertainty in the datum in this column; and

`<aunc>` is the minimum absolute uncertainty in the datum in this column.

The second-from-last line of the control file `xyz2td1d.in` has the remaining information about the transmitter:

`<ntsegs> <xt1> <yt1> <xt2> <yt2> ... <tcwfile> 1|2|3`

where

`<ntsegs>`	is the number of segments in the transmitter loop;
`<xti>`	is the x-coordinate (m) of the start of the i-th segment;
`<yti>`	is the y-coordinate (m) of the start of the i-th segment;
`<tcwfile>`	is the name of the file containing the transmitter current waveform information;
`1|2|3`	indicates units of measurement times provided: 1 = micro-seconds, 2 = milli-seconds, 3 = seconds.

The final line of the control file `xyz2td1d.in` is:

`al|av|de <naver>|<ndeci>`

where either

`al`	indicates that all the soundings are to be considered, or
`av`	indicates that each group of 2×`<naver>`+1 soundings is to be averaged to give a new single sounding, or
`de`	indicates that the data are to be decimated down to every 1 in `<ndeci>` soundings.

Upper case is understood in `xyz2td1d.in` as well as lower case.

Notes:

- Program EM1DTM does not currently accept measurement time windows, only point measurement times, and there are no plans to change this. Hence, the implementation of the ability to supply sounding-by-sounding measurement uncertainties is not consistent with measurement windows.
- If sounding-by-sounding uncertainties are supplied for one measurement time, they are assumed to be supplied for all measurement times. If no sounding-by-sounding uncertainties are supplied, the default operation is to use the survey-wide absolute and percentage uncertainties specified in the information lines for the columns containing the observations.