

Manual for running the program "EM1DFM"

Version 1.0

Developed under the IMAGE consortium research project

INVERSION AND MODELLING OF APPLIED GEOPHYSICAL ELECTROMAGNETIC DATA

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

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1. Overview

The name "EM1DFM" derives from: electromagnetics ("EM"), one-dimensional models ("1D"), frequency-domain observations ("F"), and magnetic (dipole) sources and receivers ("M"). This inversion program is designed to construct one of four types of 1D models, using any type of geophysical frequency domain loop-loop data using one of four variations of the inversion algorithm.

Observations

The observations are the inphase and/or quadrature components of

- the secondary H-field normalized by the primary (i.e., free-space) field in ppm, or
- the secondary H-field normalized by the primary field in %, or
- the secondary H-field in A/m, or
- the total H-field in A/m.

Receiver coils can be oriented in x-, y- or z-directions, and they can be at any position relative to their respective magnetic dipole transmitter. Transmitters can be at any height, can be oriented in the x-, y- or z- directions, and any frequency or set of frequencies may be involved. All the observations (in any combination) to be used to construct the one-dimensional model at a particular horizontal location are grouped together as one "sounding". Measurement uncertainties can be in the same units as the observations or as relative uncertainties in percent.

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Inversion

The inversion program can construct ...

- an electrical conductivity model (with magnetic susceptibility fixed), or
- a strictly-positive magnetic susceptibility model (with conductivity fixed), or
- both conductivity and strictly-positive susceptibility models, or
- both conductivity and susceptibility (with no positivity constraint) models.

Models of the Earth are composed of many layers of uniform conductivity/susceptibility with fixed interface depths. The value of the conductivity/susceptibility in each layer is sought by the inversion. Multiple soundings can be handled in a single run of the program. Each sounding is interpreted independently with a one-dimensional model produced under the sounding location. When all soundings have been inverted, a composite two-dimensional model is written out to facilitate interpretation of a line of soundings.

There are four variations of the inversion algorithm:

- constant (user-supplied) trade-off parameter in the objective function being minimized, 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 generalized cross validation (GCV) criterion, or
- the trade-off parameter is automatically chosen using the L-curve criterion.

Full flexibility of the sum-of-squares measure of model structure is provided. The balance between conductivity and susceptibility components is adjustable (if both are active in the inversion). The balance between "flattest" and "smallest" parts of both conductivity and susceptibility components is also adjustable. Reference models can be included in either or both the "smallest" and "flattest" parts, and additional user-supplied weighting of the layers in the model can be incorporated.

Clearly, many permutations of model type, data type and algorithm choice are possible, therefore the program is significantly more complex to manage than previous UBC-GIF inversion codes. Also, input file structures are complicated in order to facilitate this flexibility.

Documentation is provided in four parts.

1. [Background theory](#) is provided in an Acrobat PDF document. It summarizes the detailed mathematical basis of the forward modelling and inversion algorithms.
2. The document you are reading now is the "Manual for Program EM1DFM". It contains detailed descriptions of the main input file, the observations file, model files, and output files and messages. There are also brief descriptions of two utility programs and the independent forward modelling program.
3. [Examples](#) are given showing application of the inversion algorithm to synthetic and real field data sets.
4. The two components of the [graphical user interface](#) (GUI) are described using two frames-based HTML documents.

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2. Background

Detailed background theory is provided in a [separate PDF document](#).

3. Input & Output Files

3.1 Input files

3.1.1 Main input file (Required, and called "em1dfm.in")

This is the main input file containing the parameters specifying the model and inversion algorithm types, the name of the file containing the observations, and information specifying the various starting and reference models.

The structure of the file "em1dfm.in" is as follows. Click the parameter name for details. Note that parameters vary depending on exactly what type of inversion has been requested. Please read the specifications very carefully.

| Line # | Parameter(s) | Description | Comment |
|--------|----------------------------|------------------------------------------|-------------------------------------|
| 1 | rootname | root for names of output files | String with length <= 20 characters |
| 2 | obsfname | name of file containing the observations | String with length <= 99 characters |
| 3 | mtype | type of model in the inversion | |
| 3a | stconfname | starting conductivity model | String with length <= 99 characters |

| | | | |
|----|------------------------------------------------|------------------------------------------------------------|----------------------------------------------------------------------------|
| 3b | stsusfname | starting susceptibility model | String with length <= 99 characters |
| 3c | rsconfname | reference (smallest), or background, conductivity model | String with length <= 99 characters |
| 3d | rssusfname | reference (smallest), or background, susceptibility model | String with length <= 99 characters |
| 3e | rzconfname | reference (flattest) conductivity model | String with length <= 99 characters, "NONE" if no ref model is supplied |
| 3f | rzsusfname | reference (flattest) susceptibility model | String with length <= 99 characters, "NONE" if no ref model is supplied |
| 4 | NONE | information about additional model weights | String with length <= 99 characters |
| 5 | DEFAULT <i>acs acz ass asz</i> | coefficients of model norm components | Real numbers >= 0 |
| 6 | iatype | type of inversion algorithm | Integer |
| 7 | iapara(s) | additional inversion algorithm parameter(s) | Real number(s) |
| 8 | maxniter | maximum number of iterations in an inversion | Positive integer |
| 9 | DEFAULT | stretch factor for logarithmic barrier term | Required if <i>mtype</i> =2,3; otherwise omit |
| 10 | DEFAULT | small number for convergence tests | Positive real number |
| 11 | DEFAULT | number of explicit evaluations of Hankel transform kernels | Integer |
| 12 | outflg | flag indicating amount of output | Warning** |

** Set *outflg* = 2, or 3 only if very few soundings are being processed.

[See below for two examples.](#)

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NOTE: For all file names and their paths, please avoid spaces. The Fortran 90 code can not handle spaces in file names and paths to files. For example, do not place programs under the "c:\Program Files" directory on a Windows machine. This goes for all file names.

Input file details by line number:

- **line 1**, *rootname* is the root for the names of all output files. [↑](#)
- **line 2**, *obsfname* is the name of the file containing the observations (see section [3.1.2](#)). [↑](#)
- **line 3**, *mtype* indicates the type of model in the inversion. Your choice here affects exactly what is required for several other parameters, especially the starting and reference models. Please check all parameter lines carefully.
 - *mtype* = 1 implies just conductivity is active in the inversion;
 - *mtype* = 2 implies just susceptibility (with positivity constrained by means of a logarithmic barrier term) is active in the inversion;
 - *mtype* = 3 implies both conductivity and susceptibility are active with susceptibility constrained to be positive;
 - *mtype* = 4 implies both conductivity and susceptibility are active but with no constraints on the susceptibility; [↑](#)
- **line 3a**, *stconfname* is the name of the file containing the starting conductivity model (see section [3.1.3](#) for the format). **Note:** this can be a layers only file (layer thicknesses but no conductivity column) if the best-fitting halfspace is to be used as the starting model. See also the [GUI instructions](#), section on "starting conductivity model".
 - Required if *mtype* = 1, 3 or 4;
 - omit if *mtype* = 2. [↑](#)
- **line 3b**, *stsusfname* is the name of the file containing the starting susceptibility model (see section [3.1.3](#) for the format).
 - Omit if *mtype* = 1.
 - For *mtype*=2: starting susceptibility model, **OR** layers-only file (layer thicknesses but no susceptibility column) if the best-fitting halfspace is to be used as the starting model.
 - For *mtype*=3, 4: starting susceptibility model, **OR** value of halfspace susceptibility, **OR** "default" if the best-fitting halfspace is to be used as the starting model. See also the [GUI instructions](#), section on "starting susceptibility model". [↑](#)
- **line 3c**, *rsconfname* is a file name (format as for all models), **OR** a value for a halfspace **OR** "default" if the best-fitting halfspace is to be used. This file or parameters is used as:
 - the **reference** conductivity model for the **smallest** component of the model norm (see section [3.1.3](#)).
 - the **background** conductivity model if only susceptibility is active in the inversion.
 - Required if *mtype* = 1, 3 or 4, and *acs* > 0, or if *mtype* = 2
 - Enter "none" if not required. [↑](#)
- **line 3d**, *rssusfname* is a file name (format as for all models), **OR** a value for a halfspace **OR** "default" if the best-fitting halfspace is to be used. This file or parameters is used as:
 - the **reference** susceptibility model for the **smallest** component of the model norm (see section [3.1.3](#))
 - the **background** susceptibility model if only conductivity is active in the inversion.
 - Required if *mtype* = 2, 3 or 4, and *ass* > 0, or if *mtype* = 1
 - Enter "none" if not required. [↑](#)
- **line 3e**, *rzconfname* is a file name (format as for all models), **OR** a value for a halfspace **OR** "default" if the best-fitting halfspace is to be used. This file or parameters is used as:
 - the **reference** conductivity model for the **flattest** component of the model norm (see section [3.1.3](#)).
 - optional for *mtype* = 1, 3, or 4. If such a model is supplied in a file whose name is given here then it will be used in the inversion,
 - if "none" is given there will be no **reference** conductivity model in the flattest component of the model norm. [↑](#)
- **line 3f**, *rzsusfname* is a file name (format as for all models), **OR** a value for a halfspace **OR** "default" if the best-fitting halfspace is to be used. This file or parameters is used as:
 - the **reference** susceptibility model for the **flattest** component of the model norm (see section [3.1.3](#))
 - optional for *mtype* = 2, 3, or 4. If such a model is supplied in a file whose name is given here then it will be used in the inversion,
 - If "none" is given there will be no reference susceptibility model in the flattest component of the model norm. [↑](#)
- **line 4**, either
 - "NONE" 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 weights for the model norm (see section [3.1.4](#) for the format of this file). [↑](#)
- **line 5**, Coefficients of model norm components:
 - if *mtype* = 1, the two parameters *acs* and *acz* are required, or,
 - if *mtype* = 2, the two parameters *ass* and *asz* are required, or,
 - if *mtype* = 3 or 4 enter either:
 - the string "DEFAULT" and all four parameters *acs*, *acz*, *ass* and *asz* are required, or
 - the six parameters *Ac*, *As*, *acs*, *acz*, *ass* and *asz*, where the value of *Ac* is A^C in the expression for the model norm below, the value of *As* is A^S , the

value of acs is α_s^c , the value of acz is α_z^c , the value of ass is α_s^s , and the value of asz is α_z^s :[↑](#)

$$\begin{aligned} \phi_m &= \alpha_s^c \|\mathbb{W}_s^c(m^c - m_{s,ref}^c)\|^2 + \alpha_z^c \|\mathbb{W}_z^c(m^c - m_{z,ref}^c)\|^2, \text{ for } mtype = 1, \text{ or} \\ \phi_m &= \alpha_s^s \|\mathbb{W}_s^s(m^s - m_{s,ref}^s)\|^2 + \alpha_z^s \|\mathbb{W}_z^s(m^s - m_{z,ref}^s)\|^2, \text{ for } mtype = 2, \text{ or} \\ \phi_m &= A^c \left(\alpha_s^c \|\mathbb{W}_s^c(m^c - m_{s,ref}^c)\|^2 + \alpha_z^c \|\mathbb{W}_z^c(m^c - m_{z,ref}^c)\|^2 \right) + \\ &\quad A^s \left(\alpha_s^s \|\mathbb{W}_s^s(m^s - m_{s,ref}^s)\|^2 + \alpha_z^s \|\mathbb{W}_z^s(m^s - m_{z,ref}^s)\|^2 \right) \quad \text{for } mtype = 3 \text{ or } 4 \end{aligned}$$

- **line 6**, *iatype* indicates the type of inversion algorithm to be used,
 - *iatype* = 1 implies a fixed, user-supplied value for the trade-off parameter,
 - *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 7**, Parameters required by the specified inversion algorithm:
 - if *iatype* = 1, the value of the trade-off parameter is expected, or
 - if *iatype* = 2, both 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 at any one iteration are expected (in terms of *mfac* where $\phi_d^{n+1, tar} = \max(chifac \times N, mfac \times \phi_d^n)$; see eq (58) section 2.5.3 of the theory section), or
 - if *iatype* = 3 or 4, the greatest allowed decrease in the trade-off parameter at any one iteration (in terms of *bfac* where $\beta^{n+1} = \max(\beta^*, bfac \times \beta^n)$; see eq (62) of the theory section);[↑](#)
- **line 8**, *maxniter*s is the maximum number of iterations to be carried out in an inversion;[↑](#)
- **line 9**, Logarithmic barrier term stretch factor:
 - either "DEFAULT" can be entered to indicate that the default value of 1 is to be used as the coefficient in the logarithmic barrier term, or
 - some other value (a strictly positive real number) can be entered (only required if *mtype* = 2 or 3);[↑](#)
- **line 10**, "Small" number for convergence tests:
 - 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;[↑](#)
- **line 11**, Number of explicit evaluations of Hankel transform kernels:
 - either "DEFAULT" can be entered to indicate the kernel of the Hankel transforms is to be explicitly evaluated the default number of times (= 50), or,
 - if there are concerns about the accuracy of the Hankel transform computations, a number greater than 50 can be entered on this line;[↑](#)
- **line 12**, *outflg* is the flag indicating the amount of output from the program. (**WARNING: it is highly recommended that *outflg* = 3 or 4 is NOT specified if there are more than a few soundings to be inverted in a single run.**)
 - *outflg* = 1 implies the output of a brief convergence / termination report for each sounding plus the final two-dimensional composite model (cond &/or susc) for all the soundings, and the corresponding forward-modelled data. If only one sounding is being considered the model(s) are output in one-dimensional format.
 - *outflg* = 2 implies output as for *outflg* = 1 **plus** an iteration by iteration summary of the various components of the objective function.
 - *outflg* = 3 implies output as for *outflg* = 2 **plus** the one-dimensional models and corresponding predicted data for each iteration for each sounding. The diagnostics file is also produced.
 - *outflg* = 4 implies output as for *outflg* = 3 **plus** any line-search information from misfit, GCV function or L-curve curvature versus trade-off parameter. Also produced is a diagnostics file for the LSQR solution routine if it is used. [↑](#)

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Two example input files:

eg 1:

```
test      ! Root for output file names.
test.obs  ! Name of the observations file.
1         ! Model type -- just conductivity.
start.con ! Starting conductivity model file.
ref.con   ! Reference conductivity model file.
back.sus  ! Background susceptibility model file.
NONE      ! Reference (flattest) conductivity.
NONE      ! Additional model weights.
0. 1.     ! alpha s & alpha z.
1         ! Type of inversion algorithm -- fixed trade-off param.
10.       ! The value of the trade-off parameter.
15        ! Maximum number of iterations.
DEFAULT   ! Convergence test parameter.
DEFAULT   ! Number of evaluations of the Hankel transform kernel.
3         ! Amount of output.
```

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eg 2:

```
hssmz     ! Root for output file names.
hssmz.obs ! Name of the observations file.
3         ! Model type -- cond. & susc. (with posit.).
layers.dat ! Starting conductivity model.
0.        ! Starting susceptibility model.
```

```

DEFAULT          ! Reference conductivity model.
0.               ! Reference susceptibility model.
NONE            ! Reference (flattest) conductivity.
NONE            ! Reference (flattest) susceptibility.
NONE            ! Additional model weights.
DEFAULT 0.01 1. 0.01 1. ! Cond.-susc. balance, acs, acz, ass & asz.
3               ! Type of inversion algorithm -- GCV.
0.5            ! Max. decrease of trade-off param. at an iteration.
15             ! Maximum number of iterations.
DEFAULT        ! Coefficient in log barrier term.
DEFAULT        ! Convergence test parameter.
DEFAULT        ! Number of evaluations of the Hankel transform kernel.
1              ! Amount of output -- minimum.

```

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3.1.2 Observations file (Required)

Recall that you should avoid spaces for all file names and their paths.

The file that contains the observations and all the survey parameters, with five lines including parameters as follows:

1. the number of soundings;
2. the x- and y-coordinates of each sounding, and the number of frequencies per sounding;
3. each frequency, and the number of transmitters for each frequency;
4. the dipole moment of each transmitter, their z-coordinates and orientations, and the number of receivers for each;
5. the last line contains all of
 - o the dipole moment of each receiver,
 - o the transmitter-receiver separation in the x- and y-directions,
 - o the z-coordinate and orientation of each receiver,
 - o what type of normalization has been applied to the observations,
 - o whether inphase and/or quadrature data are present,
 - o the actual observed field values for this receiver, and
 - o the type of uncertainties and their values.

The structure of the observations file is as follows. Click on the letter labels for variable names, and for parameter details:

Line# Params

```

1  A
2  B|C|D
3  E|F|G
4  H|I|J
5  K|L|M|N|O|P|Q|R|S|T

```

See [example](#) below, and also the separate set of [examples](#).

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Observations file parameter definitions:

- **A.** *nsounds* is the number of soundings; [↑](#)
- **B.** *soundx_a(i_s)* is the x-coordinate of the i_sth sounding; [↑](#)
- **C.** *soundy_a(i_s)* is the y-coordinate of the i_sth sounding; [↑](#)
- **D.** *nfreqs_a(i_s)* is the number of frequencies for the i_sth sounding; [↑](#)
- **E.** *freq_a(i_f,i_s)* is the frequency (Hz) of the i_fth frequency for the i_sth sounding; [↑](#)
- **F.** *nt_a(i_f,i_s)* is the number of transmitters for the i_fth frequency for the i_sth sounding; [↑](#)
- **G.** *momt_a(i_t,i_f,i_s)* is the dipole moment (A m²) of the i_tth transmitter for the i_fth frequency for the i_sth sounding.
 - o This number is used as a simple scaling within the program. If *momt_a* = 2, then the forward-modelled observations are twice what they would be if *momt_a* = 1;
 - o See NOTE under [momr_a\(i_r,i_t,i_f,i_s\)](#); [↑](#)
- **H.** *zt_a(i_t,i_f,i_s)* is the z-coordinate (metres, negative upwards from zero on the Earth's surface) of the i_tth transmitter for the i_fth frequency for the i_sth sounding; [↑](#)
- **I.** *ot_a(i_t,i_f,i_s)* is the orientation of the i_tth transmitter for the i_fth frequency for the i_sth sounding ("x" for an x-directed dipole, "y" for a y-directed dipole, and "z" for a vertical (downward-directed) dipole); [↑](#)
- **J.** *nr_a(i_r,i_f,i_s)* is the number of receivers for the i_rth transmitter for the i_fth frequency for the i_sth sounding; [↑](#)
- **K.** *momr_a(i_r,i_t,i_f,i_s)* is a scale factor for the i_rth receiver for the i_tth transmitter for the i_fth frequency for the i_sth sounding which allows the incorporation of any necessary parameters of the receiver that might mean the observations are not simply point measurements of the H-field.
 - o An example of necessary parameters could be coil area and/or number of turns and/or orientation (e.g., *momr_a* = -1 for an upward-pointing z-directed receiver dipole).
 - o This number simply appears as a scale factor within the code - if *momr_a* = 2, then the forward-modelled observations are twice what they would be if *momr_a* = 1;
 - o NOTE: Some common data formats (such as DIGEM coaxial data - not coplanar data) require *momr_a* = -1 to make these data compatible with the normalization convention used by EM1DFM. The first [example](#) requires this type of normalization; [↑](#)
- **L.** *trx_a(i_r,i_t,i_f,i_s)* is the transmitter-receiver separation (m) in the x-direction between the i_rth receiver and the i_tth transmitter for the i_fth frequency for the i_sth sounding; [↑](#)
- **M.** *try_a(i_r,i_t,i_f,i_s)* is the transmitter-receiver separation (m) in the y-direction between the i_rth receiver and the i_tth transmitter for the i_fth frequency for the i_sth sounding; [↑](#)
- **N.** *zr_a(i_r,i_t,i_f,i_s)* is the z-component (metres, negative upwards from zero on the Earth's surface) of the i_rth receiver for the i_tth transmitter for the i_fth frequency for

the i_s th sounding;↑

- **O.** $or_a(i_r, i_t, i_f, i_s)$ is the orientation of the i_r th receiver for the i_t th transmitter for the i_f th frequency for the i_s th sounding.
 - "x" for an x-directed dipole,
 - "y" for a y-directed dipole, and
 - "z" for a vertical (downward-directed) dipole;
- **P.** $ontype_a(i_r, i_t, i_f, i_s)$ is the type of normalization of the data/datum for the i_r th receiver for the i_t th transmitter for the i_f th frequency for the i_s th sounding.
 - $ontype_a = 1$ indicates the data are values in ppm of the secondary magnetic field normalized by the free-space magnetic field,
 - $ontype_a = 2$ indicates the data are values in % of the secondary magnetic field normalized by the free-space magnetic field,
 - $ontype_a = 3$ indicates the data are values of the secondary H-field in A/m, and
 - $ontype_a = 4$ indicates the data are values of the total H-field in A/m;↑
- **Q.** $octype_a(i_r, i_t, i_f, i_s)$ Observation type for the i_r th receiver for the i_t th transmitter for the i_f th frequency for the i_s th sounding:
 - $octype_a = "b"$ indicates both inphase and quadrature observations are present ,
 - $octype_a = "i"$ just the inphase observation is present,
 - $octype_a = "q"$ just the quadrature datum.↑
- **R.** $obs_a(i_r, i_t, i_f, i_s)$ is the pair of inphase and quadrature observations, or just the inphase observation, or just the quadrature observation, for the i_r th receiver for the i_t th transmitter for the i_f th frequency for the i_s th sounding;↑
- **S.** $utype_a(i_r, i_t, i_f, i_s)$ indicates the form in which the uncertainties are provided for the i_r th receiver for the i_t th transmitter for the i_f th frequency for the i_s th sounding
 - $utype_a = "v"$ for absolute uncertainties in the same units as the observations, and
 - $utype_a = "p"$ percentage uncertainties.↑
- **T.** $uncert_a(i_r, i_t, i_f, i_s)$ is the pair of uncertainties for the inphase and quadrature observations, or the uncertainty in just the inphase observation, or the uncertainty in just the quadrature observation, for the i_r th receiver for the i_t th transmitter for the i_f th frequency for the i_s th sounding.↑

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Observations File Discussion:

This structure of the observations file is designed to be as general as possible, enabling the program to handle any conceivable survey configuration. The lines in the file form a series of nested loops. Repetition occurs over the indices

$$i_r = 1, \dots, nr_a(i_t, i_f, i_s); i_t = 1, \dots, nt_a(i_f, i_s); i_f = 1, \dots, nfreq_a(i_s); \text{ and } i_s = 1, \dots, nsounds.$$

In other words,

- line 5 is repeated for each receiver for a particular transmitter for a particular frequency for a particular sounding;
- line 4 and the associated line(s) 5 are repeated for each transmitter for a particular frequency for a particular sounding;
- line 3 and the associated line(s) 4 and line(s) 5 are repeated for each frequency for a particular sounding; and
- line 2 and the associated line(s) 3, line(s) 4 and line(s) 5 are repeated for each particular sounding.

All the information for a particular receiver is expected on the same single line in the file.

Example observations file for a single sounding:

```

1
0. 0. 5
880. 1
1. -40. z 1
1. 8.1 0. -40. z 1 b 2.474 30.29 v 1.00 1.58
7213. 1
1. -40. z 1
1. 8.1 0. -40. z 1 b 75.52 203.4 v 3.94 9.92
55840. 1
1. -40. z 1
1. 6.3 0. -40. z 1 b 261.2 208.3 v 13.2 11.0
5848. 1
1. -40. x 1
-1. 8.1 0. -40. x 1 b 13.44 43.13 v 1.00 2.12
1082. 1
1. -40. x 1
-1. 8.1 0. -40. x 1 b 2.035 10.93 v 1.00 1.00

```

This would be the observations file for a single sounding (that is, a single one-dimensional model) at $x = 0$ m, $y = 0$ m for an airborne-type configuration.

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- There are three frequencies for the horizontal coplanar loop configuration (880, 7213, 55840 Hz);
 - a z-directed magnetic dipole transmitter (dipole moment = 1 A m^2) and receiver (dipole moment = 1 A m^2) for each frequency separated by 8.1 m, 8.1 m and 6.3 m respectively in the x-direction, 0 m in the y-direction;
 - both transmitter and receiver for each frequency are at a height of 40 m above the Earth's surface,
- There are two frequencies for the coaxial loop configuration (5848 and 1082 Hz);
 - an x-directed magnetic dipole transmitter (dipole moment = 1 A m^2) and receiver (dipole moment = -1 A m^2) for both frequencies separated by 8.1 m in the x-direction and 0 m in the y-direction;
 - both transmitter and receiver for each frequency are at a height of 40 m above the Earth's surface.
- The observations are values of the secondary magnetic field normalized by the free-space field and expressed in terms of parts-per-million (ppm).
- Both inphase and quadrature components of the field are supplied.
- The uncertainties are expressed in absolute terms in the same units as the observations (i.e., ppm).

Example observations file for EM-31 data for two soundings

```

2
60.0 0. 1
9800. 4
1 -1.0 z 1
-1. 3.66 0.0 -1.0 z 2 q -0.6613E+01 v 0.3307E+00
1 -1.0 y 1
-1. 3.66 0.0 -1.0 y 2 q -0.5286E+01 v 0.2643E+00
1 -0.05 z 1

```

```

-1.   3.66   0.0  -0.05 z  2  q   0.8821E+01  v  0.4410E+00
 1    -0.05   y    1
-1.   3.66   0.0  -0.05 y  2  q   0.9712E+01  v  0.4856E+00
60.0  -10.0   1
9800.  4
 1    -1.0    z    1
-1.   3.66   0.0  -1.0  z  2  q  -0.6665E+01  v  0.3332E+00
 1    -1.0    y    1
-1.   3.66   0.0  -1.0  y  2  q  -0.4623E+01  v  0.2311E+00
 1    -0.05   z    1
-1.   3.66   0.0  -0.05 z  2  q  -0.9256E+01  v  0.4628E+00
 1    -0.05   y    1
-1.   3.66   0.0  -0.05 y  2  q  -0.8282E+01  v  0.4141E+00

```

This would be the observations file for EM31-type data for two soundings,

- Sounding locations are at $x = 60$ m & $y = 0$ m and $x = 60$ m & $y = -10$ m.
- There is one frequency (9.6 kHz),
- There are four instrument positions:
 - at waist height (1 m) and on the ground (0.05 m),
 - held both normally (vertical transmitter and receiver coil axes) and on its side (horizontal coil axes).
- The transmitter and receiver coils are separated by 3.66 m in the x-direction. Only the quadrature part of the normalized secondary H-field (in %) is provided as data,
- The uncertainties are absolute in %.

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3.1.3 Files for reference and starting models

Starting conductivity model file (Required if $mtype = 1, 3$ or 4)

This is the file containing the starting conductivity model for all soundings if conductivity is active in the inversion. 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. If conductivity is active in the inversion, 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 for mode $mtype = 1, 3$ or 4 (i.e. conductivity is active in the inversion).

This file can also be a layers-only file to indicate that the best-fitting halfspace is to be used as the starting model. See also the [input file specifications](#).

The structure of this file is as follows (just as for all 1D model files). For a layers-only file the conductivity column is left blank.

```

nlayers
thicks_a(1)      con_a(1)
thicks_a(2)      con_a(2)
...
thicks_a(nlayers-1) con_a(nlayers-1)
0.               con_a(nlayers)

```

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- $nlayers$ is the number of layers in the model,
- $thicks_a(j)$ is the thickness in metres of the j th layer and
- $con_a(j)$ is the conductivity in S/m of the j th layer.

Here is an example:

```

12
4.7987  0.30E-03
5.0994  0.30E-03
5.7584  0.30E-03
6.9101  0.30E-03
8.8117  0.30E-03
11.941  0.30E-03
17.194  0.30E-03
26.311  0.30E-03
42.785  0.30E-03
73.931  0.30E-03
135.76  0.30E-03
0.0     0.30E-03

```

This would be the file for a conductivity model made up of 12 layers (including the basement halfspace). The thicknesses of the first eleven layers increase from 4.7987 m to 135.76 m. This model is a homogeneous halfspace of 0.3 milliSeimens per m.

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Starting susceptibility model file (Required if $mtype = 2$)

This file contains the starting susceptibility model for all soundings if susceptibility is active in the inversion. The file contains the number of layers, and the thickness (m) and susceptibility (SI units) of each layer. A dummy value for the thickness of the basement halfspace is required, but nothing is done with it after it is read in.

If only susceptibility is active (i.e., $mtype = 2$), the inversion program gets it's information about the number of layers in the model and their thicknesses from this file. If

both conductivity and susceptibility are active (i.e., $mtype = 3$ or 4), the program gets the number of layers and their thicknesses from the starting conductivity model - see [above](#). All other models (e.g., reference models) read in must then have the same number of layers with exactly the same thicknesses.

The structure of this file is as follows (just as for all 1D model files). For a layers-only file the susceptibility column is left blank.

```
nlayers
thicks_a(1)      sus_a(1)
thicks_a(2)      sus_a(2)
...
thicks_a(nlayers-1) sus_a(nlayers-1)
0.               sus_a(nlayers)
```

- $nlayers$ is the number of layers in the model,
- $thicks_a(j)$ is the thickness in metres of the j th layer and
- $sus_a(j)$ is the susceptibility in SI units of the j th layer.

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

The parameter describing the reference conductivity model for the **smallest** component of the model norm if one is required for the inversion, or describing the reference conductivity model if only susceptibility is active in the inversion. The parameter is either "NONE", **OR** a file **OR** a value for a halfspace **OR** "default" if the best-fitting halfspace is to be used. It is required if $mtype = 1, 3$ or 4 and $acs > 0$, or if $mtype = 2$. If a file is used, it must have the same format as the starting conductivity model file (see [above](#)), and it must have the same number of layers with exactly the same thicknesses as the starting conductivity and/or susceptibility model.

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File for reference susceptibility model (for smallest model component) (Optional)

The parameter describing the reference susceptibility model for the **smallest** component of the model norm if one is required for the inversion, or describing the reference susceptibility model if only conductivity is active in the inversion. That is, this model is required if $mtype = 2, 3$ or 4 and $ass > 0$, or if $mtype = 1$. The parameter is either "NONE", **OR** a file **OR** a value for a halfspace **OR** "default" if the best-fitting halfspace is to be used. If a file is used, it must be in the same format as all model files (see [above](#)), and must have the same number of layers with exactly the same thicknesses as the starting conductivity and/or susceptibility model.

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File for reference conductivity model (for flattest model component) (Optional - not available in the GUI)

The parameter describing the reference conductivity model for the **flattest** component of the model norm if one is required for the inversion. Whether or not this parameter is specified in "emldfm.in" determines whether or not such a reference model plays a part in the inversion. The parameter is either "NONE", **OR** a file **OR** a value for a halfspace **OR** "default" if the best-fitting halfspace is to be used. If a file is used, it must be in the same format as the starting conductivity model file (see section [above](#)), and must have the same number of layers with exactly the same thicknesses as the starting conductivity and/or susceptibility model.

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File for reference susceptibility model (for flattest model component) (Optional - not available in the GUI)

The parameter describing the reference susceptibility model for the **flattest** component of the model norm if one is required for the inversion. Whether or not this parameter is specified in "emldfm.in" determines whether or not such a reference model plays a part in the inversion. The parameter is either "NONE", **OR** a file **OR** a value for a halfspace **OR** "default" if the best-fitting halfspace is to be used. If a file is used, it must be in the same format as the starting susceptibility model file (see section [above](#)), and must have the same number of layers with exactly the same thicknesses as the starting conductivity and/or susceptibility model.

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3.1.4 File for additional model-norm weights(Optional)

The file containing the information about the additional weighting of the layers for some or all of the four possible components of the model norm: smallest and flattest components for conductivity and susceptibility.

- The first line of this file must contain two (if $mtype = 1$ or 2) or four (if $mtype = 3$ or 4) integers (which can either have the value 0 or 1) to indicate that weights are being supplied for use in the two or four components of the model norm
 - e.g., "1 0" for $mtype = 1$ implies that additional weights are supplied for use in the smallest component of the model norm but not the flattest component for only conductivity active in the inversion;
 - "1 0" for $mtype = 2$ implies that additional weights are supplied for use in the smallest component of the model norm but not the flattest component for only susceptibility active in the inversion;
 - "1 0 1 0" for $mtype = 3$ or 4 implies that additional weights are supplied for both the smallest component of the conductivity portion of the model norm and the smallest component of the susceptibility portion of the model norm, but not for the flattest components, when both conductivity and susceptibility are active in the inversion.
- The second line of this file must contain the number of layers in the model. The order of the four possibilities must be the same as shown below, with any set of weights that is not needed by the program simply omitted.

```
ics icz iss isz
nlayers
(uswcs_a(j), j = 1, ..., nlayers )
(uswss_a(j), j = 1, ..., nlayers )
(uswcz_a(j), j = 1, ..., nlayers-1)
(uswsz_a(j), j = 1, ..., nlayers-1)
```

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- *ics*, *icz*, *iss* & *isz* are the four integers that indicate the presence of weights for the smallest and flattest components of the model norm for conductivity and the smallest and flattest components of the model norm for susceptibility (if *mtype* = 2, *ics* & *icz* are omitted),
- *nlayers* is the number of layers in the model;
- *uswcs_a(j)* is the weight for the *j*th layer in the smallest component of the conductivity portion of the model norm;
- *uswss_a(j)* is the weight for the *j*th layer in the smallest component of the susceptibility portion of the model norm;
- *uswcz_a(j)* is the weight for the difference between the *j*th and (*j*+1)th layers in the flattest component of the conductivity component of the model norm; and
- *uswsz_a(j)* is the weight for the difference between the *j*th and (*j*+1)th layers in the flattest component of the susceptibility 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

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3.2 Output files

Recall that you should avoid spaces for all file names and their paths.

3.2.1 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 line 12](#) of the input file). Any error messages generated by the program will also be written to the standard output, and also to the file "emldfm.out", which is described next.

Example of output messages:

We use here the [first input file example](#) "emldfm.in" from section 3.1.1, and the [first observations file example](#) from section 3.1.2. Our starting conductivity file is the one from section 3.1.3, and the reference models were: conductivity = 10^{-4} S/m and susceptibility = 0 SI units. Since *outflg* = 3, the following was written to the standard output:

```
PROGRAM "EM1DFM" (v1.0).

Start at 17:34:57.344, 28/06/2000.

Sounding 1 (0.0,0.0).
Initial phid= 2080.0, beta= 10.000, phim= 0.0000, Phi= 2080.0.
Iteration 1: phid= 1168.7, beta= 10.000, phim= 0.19895, Phi= 1170.7.
Iteration 2: phid= 736.22, beta= 10.000, phim= 0.18341, Phi= 738.06.
Iteration 3: phid= 380.57, beta= 10.000, phim= 0.24765, Phi= 383.05.
Iteration 4: phid= 114.11, beta= 10.000, phim= 0.30980, Phi= 117.20.
Iteration 5: phid= 12.815, beta= 10.000, phim= 0.15531, Phi= 14.368.
Iteration 6: phid= 6.2389, beta= 10.000, phim= 0.18378, Phi= 8.0767.
Iteration 7: phid= 6.0415, beta= 10.000, phim= 0.13129, Phi= 7.3544.
Iteration 8: phid= 5.6881, beta= 10.000, phim= 0.15350, Phi= 7.2230.
Iteration 9: phid= 5.7826, beta= 10.000, phim= 0.14203, Phi= 7.2029.
Convergence.

Final conductivity model written to "test.con".
Predicted data written to "test.prd".

The End! [17:35:52.387, 28/06/2000]
```

This shows the iteration-by-iteration variation of the components of the objective function: the misfit, the trade-off parameter, the model norm and the complete objective function.

For exactly the same example, but for *outflg* = 1, the output gives only a summary of the final state of the inversion. Note that the final values of the components of the objective function are also printed out.

```
PROGRAM "EM1DFM" (v1.0).

Start at 17:43:57.855, 28/06/2000.

Sounding 1 (0.0,0.0).
Convergence: n= 9, phid= 5.7826, beta= 10.000, phim= 0.14203, Phi= 7.2029.

Final conductivity model written to "test.con".
Predicted data written to "test.prd".

The End! [17:44:50.798, 28/06/2000]
```

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The possible status messages, and their explanation are as follows:

| Status message | Explanation |
|-------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Convergence | Convergence according to the criteria given in eqs. 68 & 69 of the document " Background for Program EM1DFM ". That is, the relative change in the objective function from one iteration to the next and the relative change in the model norm are less than the convergence parameter on line 10 of the input parameter file. |
| Convergence (small gradient). | Convergence according to the criterion given in eq. 70 of the document " Background for Program EM1DFM ". That is, the gradient is essentially zero. |

| | |
|----------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Target misfit not attained: convergence to minimum | For inversion algorithm 2 the target misfit could not be reached, but convergence to the minimum misfit has occurred. |
| No suitable step found. | No step length was found that decreased the objective function, even after being decreased by a factor of 2^{*nmax} . See eq. 55 in section 2.5 of the document " Background for Program EM1DFM ". See also the diagnostics file, section 3.2.8 . |
| Max number of iterations done without convergence. | The convergence criteria have not been satisfied in the specified maximum number of iterations. |
| Starting susceptibilities reset because of small values. | When positivity is being enforced, the starting values of the susceptibilities are bumped up to be at least 0:001 SI units. |

The possible parameters that could be listed (next to "convergence" in the above example) are:

| | |
|--------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <i>n</i> | The iteration number. |
| <i>phid</i> | The misfit. |
| <i>beta</i> | The trade-off parameter. |
| <i>phim</i> | The model norm. |
| <i>gamma</i> | The coefficient of the logarithmic barrier term. |
| <i>phiLB</i> | The logarithmic barrier term. |
| <i>Phi</i> | The whole objective function. |
| <i>(Phi)</i> | Previous objective function: previous ϕ_d , ϕ_m & ϕ_{LB} and current β & γ ** **see eq. 57 of the document " Background for Program EM1DFM ". |

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3.2.2 The main output file (Always, and called "em1dfm.out")

This file contains a copy of all the progress reports that are written to the standard output (see section [3.2.1](#) above). The extent of these reports depends on the parameter *outflg* (see line 12, section [3.1.1](#)). In addition, a summary of the inputs read in by the program are printed at the top of this file.

For the first example given in section [3.2.1](#) above, the file "em1dfm.out" is:

```
PROGRAM "EM1DFM" (v1.0).

Run started at 11:57:59.223, 29/06/2000.

Reading inputs . . .
Filename root:           "test".
Number of soundings:     1.
Observations file:      "test.obs".
Model type:              1 (conductivity).
Starting conductivity file: "start.con".
Ref. (small.) cond. file: "ref.con".
Background susc. file:   "back.sus".
Ref. (flat.) cond. file: NONE.
Additional model weights: NONE.
alpha s:                 0.00.
alpha z:                 1.00.
Inversion algorithm:     1 (fixed trade-off parameter).
Supplied trade-off parameter: 10.00.
Max. number of iterations: 15.
Convergence param. (default): 0.100E-01.
No. of lambdas (default): 50.
Level of output:        3.
Finished reading inputs.

Sounding 1 (0.0,0.0).
Initial phid= 2080.0, beta= 10.000, phim= 0.0000, Phi= 2080.0.
Iteration 1: phid= 1168.7, beta= 10.000, phim= 0.19895, Phi= 1170.7.
Iteration 2: phid= 736.22, beta= 10.000, phim= 0.18341, Phi= 738.06.
Iteration 3: phid= 380.57, beta= 10.000, phim= 0.24765, Phi= 383.05.
Iteration 4: phid= 114.11, beta= 10.000, phim= 0.30980, Phi= 117.20.
Iteration 5: phid= 12.815, beta= 10.000, phim= 0.15531, Phi= 14.368.
Iteration 6: phid= 6.2389, beta= 10.000, phim= 0.18378, Phi= 8.0767.
Iteration 7: phid= 6.0415, beta= 10.000, phim= 0.13129, Phi= 7.3544.
Iteration 8: phid= 5.6881, beta= 10.000, phim= 0.15350, Phi= 7.2230.
Iteration 9: phid= 5.7826, beta= 10.000, phim= 0.14203, Phi= 7.2029.
Convergence.

Conductivity model: "test.con".
Predicted data:     "test.prd".
Diagnostics:        "test 001.dgns".

The End! [11:59:26.530, 29/06/2000]
```

For the second example given in section [3.2.1](#) above, for *outflg* = 1, the file "em1dfm.out" is:

```
PROGRAM "EM1DFM" (v1.0).
Run started at 17:43:57.893, 28/06/2000.
Reading inputs ...
```

```

Filename root:                "test".
Number of soundings:          1.
Observations file:           "test.obs".
Model type:                   1 (conductivity).
Starting conductivity file:   "start.con".
Ref. (small.) cond. file:    "ref.con".
Background susc. file:       "back.sus".
Ref. (flat.) cond. file:     NONE.
Additional model weights:    NONE.
alpha s:                      0.00.
alpha z:                      1.00.
Inversion algorithm:         1 (fixed trade-off parameter).
Supplied trade-off parameter: 10.00.
Max. number of iterations:   15.
Convergence param. (default): 0.100E-01.
No. of lambdas (default):    50.
Level of output:             1.
Finished reading inputs.

Finished reading inputs.

Sounding 1 (0.0,0.0).
Convergence: n= 9, phid= 5.7826, beta= 10.000, phim= 0.14203, Phi= 7.2029.

Conductivity model: "test.con".
Predicted data:     "test.prd".

The End! [17:44:50.798, 28/06/2000]

```

For the possible listed quantities, see section [3.2.1](#). Any error messages generated by the program because of premature termination are written to this file as well as to the standard output.

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3.2.3 The final model(s) (Always)

If only a single sounding is being inverted,

- the final one-dimensional conductivity model (if conductivity is active in the inversion, i.e., *mtype* = 1, 3 or 4) will be written to the file "*rootname.con*". It has the same format as the input one-dimensional conductivity models (see section [3.1.3](#)),
- the final one-dimensional susceptibility model (if susceptibility is active in the inversion, i.e., *mtype* = 2, 3 or 4) will be written to the file "*rootname.sus*". It has the same format as the input one-dimensional susceptibility models (see section [3.1.3](#)).

If two or more soundings are being inverted, the final one-dimensional conductivity models for all soundings (if conductivity is active in the inversion) are written to the file "*rootname_ con.mod*", and the final one-dimensional susceptibility models for all soundings (if susceptibility is active in the inversion) are written to the file "*rootname_ sus.mod*". The structure of these files is as follows:

```

Number of layers:  nlayers
Layer thicknesses (m):  thicks_a(1) . . . thicks_a(nlayers-1)
Number of soundings:  nsounds
Sounding x- & y-coordinates, Conductivities (S/m) ...
soundx_a(1)  soundy_a(1) val_a(1,1) . . . val_a(nlayers,1)
. . .
soundx_a(nsounds)  soundy_a(nsounds) val_a(1,nsounds) . . . val_a(nlayers,nsounds)

```

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- *nlayers* is the number of layers in the one-dimensional models for all soundings,
- *thicks_a(j)*, *j* = 1, . . . , *nlayers*-1, are the thicknesses of the layers in the one-dimensional models,
- *nsounds* is the number of soundings,
- *soundx_a(i)* and *soundy_a(i)*, *i* = 1, . . . , *nsounds*, are the x- and y-coordinates of the soundings, and
- *val_a(j,i)* is the value of the model (either conductivity in S/m or susceptibility in SI units) in the *j*th layer for the *i*th soundings.

If susceptibility is being written out, then "Conductivities (S/m)" on line 4 is replaced with "Susceptibilities (SI units)". The final model(s) for each sounding are appended to this/these file(s) as soon as the inversion for each sounding has completed.

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3.2.4 The final forward-modelled data (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 [3.1.2 above](#)), but without the information about the uncertainties. The data for each sounding are appended to this file as soon as the inversion for each sounding has completed.

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3.2.5 Final components of the objective function (Always if *nsounds* > 1)

If there are more than one sounding, the components of the objective function (see section 2.5.1 of the document "**Background for "EM1DFM"**") for the final model for each sounding are written out to the file "*rootname_phis.out*". All information for a sounding is written on one line in this file. The possible column headings are:

x The x-coordinate of the sounding.

y The y-coordinate of the sounding.
phid The misfit.
beta The trade-off parameter.
phim The model norm.
gamma The coefficient of the logarithmic barrier term.
phiLB The logarithmic barrier term.
Phi The whole objective function.
phim con The conductivity part of the model norm.
phim sus The susceptibility part of the model norm.

The values are appended to this file on completion of the inversion for each sounding.

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3.2.6 Iteration-by-iteration one-dimensional models for each sounding (If *outflg* >= 3)

If *outflg* >= 3, the one-dimensional conductivity and/or susceptibility model(s) obtained at each iteration in the inversion for each sounding are written out.

- The conductivity models are written to the files "*rootname_ isound_ iter. con*" where *isound* is the number of the sounding and *iter* is the number of the iteration (*iter* = 0 indicates the starting conductivity model). These files have the same format as the input conductivity files (see section [3.1.3](#)).
- The susceptibility models are written to the files "*rootname_ isound_ iter. sus*" where *isound* is the number of the sounding and *iter* is the number of the iteration (*iter* = 0 indicates the starting susceptibility model). These files have the same format as the input susceptibility files (see section [3.1.3](#)).
- If only conductivity is active in the inversion, the background susceptibility is written out to the file "*rootname_ isound. sus*".
- If only susceptibility is active in the inversion, the background conductivity is written out to the file "*rootname_ isound. con*".

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3.2.7 Iteration-by-iteration forward-modelled data for each sounding (If *outflg* >= 3)

If *outflg* >= 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 and *iter* is the number of the iteration (*iter* = 0 indicates 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 (including their uncertainties) for each sounding are also written out in this format to the file "*rootname_ isound. dobs*".

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3.2.8 Diagnostics for each iteration for each inversion (If *outflg* >= 3)

If *outflg* >= 3, the values of all the interesting quantities at each iteration for each sounding are written to the file(s) "*rootname_ isound. dgrns*", where *isound* is the number of the sounding. The possible quantities in these files are summarized in the following table. References to equations are from section 2.5 of the document "Background for "EM1DFM".

| | |
|----------------|----------------------------------------------------------------------------------------------------------------------------|
| <i>tau</i> | The convergence parameter (see eqs. 68 & 69). |
| <i>epsilon</i> | The small number against which the norm of the gradient is compared (eq. 70) |
| <i>nnmax</i> | The max. number of times the step length can be halved. |
| <i>Iter</i> | Iteration number. |
| <i>normg</i> | The norm of the gradient. |
| <i>phid</i> | The misfit. |
| <i>beta</i> | The trade-off parameter. |
| <i>phim</i> | The model norm. |
| <i>gamma</i> | The coefficient of the logarithmic barrier term. |
| <i>phiLB</i> | The logarithmic barrier term. |
| <i>Phi</i> | The whole objective function. |
| (<i>Phi</i>) | Previous objective function: previous ϕ_d , ϕ_m & ϕ_{LB} and current β & <i>gamma</i> . See eq. (57). |
| <i>lambda</i> | The step length. |
| <i>normdm</i> | The norm of the change in the model |
| <i>normm</i> | The norm of the model. |

The same status message as that written to the standard output and *em1dfm.out* is also written to this file.

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3.2.9 Misfit line search values (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 - see section 2.5.3 of the document "Background for "EM1DFM"), 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 to the file "*phidvsbeta*". There is just a single such file for a whole run of the program with information from each iteration separated by pairs of dashed lines. Note that 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.

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3.2.10 GCV function line search values (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 - see section 2.5.4 of the document "Background for "EM1DFM"), 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 to the file "gcvvsbeta". There is just a single such file for a whole run of the program with information from each iteration separated by pairs of dashed lines. Note that 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.

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3.2.11 L-curve line search diagnostics (If *outflg* = 4 and *iatype* = 4)

If *outflg* = 4, and *iatype* = 4 (i.e., a line search over the curvature of the L-curve is used at each iteration to choose the trade-off parameter - see section 2.5.5 of the document "Background for "EM1DFM"), the values of the trade-off parameter and the corresponding values of the linearized misfit and the model norm during each line search at each iteration of each inversion are written to the file "phisvsbeta", and the values of the trade-off parameter and the corresponding values of the curvature computed in log-log/linear space are written to the files "curlovsbeta"/"curvlivsbeta". There is just a single version of each of these files for a whole run of the program with the information for each iteration separated from that for others by pairs of dashed lines.

3.2.12 Diagnostics for LSQR subroutine (If *outflg* = 4)

If *outflg* = 4, diagnostics are written out from Saunder's LSQR subroutine to the file "lsqr.out". **Warning:** this file can become very large very quickly if there is more than one sounding.

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4. The forward-modelling program "EM1DFMFWD"

The program "EM1DFMFWD" provides a means of forward-modelling a data-set for given layered conductivity and susceptibility models. It uses exactly the same algorithm as that used within program EM1DFM (see section 2.3 in the document "Background for "EM1DFM"). The option of adding Gaussian random noise to the forward-modelled data is available. Four input files, which are described below, are required: a control file "em1dfmfwd.in", a file containing the frequencies, and transmitter and receiver locations and orientations (in nearly the same format as an observations file for program EM1DFM), and two files with the layered conductivity and susceptibility models for which the forward modelling is desired (in the format for program EM1DFM).

Recall that you should avoid spaces for all file names and their paths.

Control file `em1dfmfwd`:

| Line # | Parameter | Explanation | Comment |
|--------|---------------------------------------|---------------------------------------------------------------------------|----------------------------------|
| 1 | <i>obstypefname</i> | name of file containing the survey parameters; | Character string of length <= 99 |
| 2 | <i>confname</i> | conductivity model; | Character string of length <= 99 |
| 3 | <i>susfname</i> | susceptibility model; | Character string of length <= 99 |
| 4 | <i>nlambdas</i> | number of explicit evaluations of Hankel transform kernels; integer >= 50 | |
| 5 | <i>nchar</i> | flag indicating if noise is to be added; | Character string of length = 1 |
| 5a | <i>perc thre seed</i> | percentage, threshold and seed. | real #, real #, pos integer |

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Control file parameter definitions:

- *obstypefname* is the name of the file containing the frequencies, and the transmitter and receiver orientations and relative positions - this file has exactly the same format as an observations file for program EM1DFM (see the EM1DFM manual section [3.1.2](#)), but excluding the actual observations and uncertainties; ↑
- *confname* is the name of the file containing the conductivity model in the same format as all one-dimensional models for program EM1DFM (see the EM1DFM manual section [3.1.3](#)); ↑
- *susfname* is the name of the file containing the susceptibility model (with the same number of layers and same layer thicknesses as the conductivity model) in the same format as all one-dimensional models for program EM1DFM (see the EM1DFM manual section [3.1.4](#)); ↑
- *nlambdas* is the number of values of λ at which the kernels of the Hankel transforms are explicitly computed; ↑
- *nchar* indicates whether Gaussian noise is to be added to the forward-modelled data: *nchar* = "y" indicates yes, *nchar* = "n" indicates no;
- (not required if *nchar* = "n"),
 - *perc* is the percentage of the absolute value of a datum that is used as the standard deviation of the noise added to that datum,
 - *thre* is the minimum value (in the same units as the forward-modelled data are to be output) of the standard deviation of the noise to be added to any datum, and
 - *seed* is a positive integer used as the seed in the random number generator (the same seed will give the same sequence of random numbers: different seeds will give different sequences). ↑

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EM1DFMFWD output

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 EM1DFM (see the EM1DFM manual section [3.2.4](#)) if noise has not been added to the data, or it is in the same format as the observations files for program EM1DFM (see the EM1DFM manual section [3.1.2](#)) with the standard deviations of the noise added to each data written out in place of *uncert_a*. In addition, if noise has been added, the actual noise added to each datum and the total chi-squared sum of the noise are appended to the bottom of the file `em1dfmfwd.out` along with the noise-free observations.

An example of the control file `em1dfmfwd.in` is:

```
test.obstype! Name of the observations-type file.
sigma.in    ! Conductivity model file.
suscs_hs.in ! Susceptibility model file
100        ! Number of evaluations of the Hankel transform kernel.
y          ! Is noise to be added?
```

and the observations type file "test.obstype" is

```

1
0. 0. 5
880. 1
1. -40. z
1. 8.1 0. -40. z 1 b
7213. 1
1. -40. z
1. 8.1 0. -40. z 1 b
55840. 1
1. -40. z
1. 6.3 0. -40. z 1 b
5848. 1
1. -40. x
-1. 8.1 0. -40. x 1 b
1082. 1
1. -40. x
-1. 8.1 0. -40. x 1 b

```

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The conductivity and susceptibility model files "sigma.in" and "susc_hs.in" are:

```

3
20.0 0.005
30.0 0.005
0.0 0.0001
-----
3
20.0 0.0
30.0 0.0
0.0 0.0

```

The resulting output file "em1dfmfwd.out" is:

```

1
0. 0. 5
880. 1
1. -40. z
1. 8.1 0. -40. z 1 b 2.474 30.29 v 1.00 1.58
7213. 1
1. -40. z
1. 8.1 0. -40. z 1 b 75.52 203.4 v 3.94 9.92
55840. 1
1. -40. z
1. 6.3 0. -40. z 1 b 261.2 208.3 v 13.2 11.0
5848. 1
1. -40. x
-1. 8.1 0. -40. x 1 b 13.44 43.13 v 1.00 2.12
1082. 1
1. -40. x
-1. 8.1 0. -40. x 1 b 2.035 10.93 v 1.00 1.00

Added noise, N(0,1) Added noise
inphase quadrature inphase quadrature
-8.85E-02 -0.804 -8.85E-02 -1.27
-0.835 0.5 -3.29 4.96
-0.187 -1.04 -2.46 -11.4
-1.27 0.361 -1.27 0.765
1.11 1.34 1.11 1.34

Total chi-squared noise added = 7.478

Noise-free data:

1
0. 0. 5
880. 1
1. -40. z
1. 8.1 0. -40. z 1 b 2.563 31.56
7213. 1
1. -40. z
1. 8.1 0. -40. z 1 b 78.81 198.4
55840. 1
1. -40. z
1. 6.3 0. -40. z 1 b 263.7 219.8
5848. 1
1. -40. x
-1. 8.1 0. -40. x 1 b 14.71 42.37
1082. 1
1. -40. x
-1. 8.1 0. -40. x 1 b 0.930 9.59

```

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5. Utility programs

5.1 "AB1DCON"

Program AB1DCON converts airborne horizontal-coplanar observations in the format for program AB1D (see the JACI Annual Report for 1994) into the format required by program EM1DFM. The name of the AB1D control file is required via the standard input. This file, and the corresponding file containing the columns of data, are then read and the information rewritten to a file in the format described in the EM1DFM manual section [3.1.2](#).

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5.2 "MKMODEL"

This program generates a conductivity or susceptibility model in the format required by program EM1DFM (see the EM1DFM manual section [3.1.3](#)). The depth to the top of the basement halfspace and the number of layers in the model (including the basement halfspace) are required from the standard input. The thicknesses, t_j , of the layers are then computed using the formula:

$$t_j = t_1 \xi^{j-1}, \quad j = 2, \dots, M-1,$$

where the factor $\xi = 1.134$, and the thickness of the top layer, t_1 , is obtained by inverting the expression

$$z_M = \sum_{j=1}^{M-1} t_1 \xi^{j-1},$$

NOTE: There are three [examples](#) provided on a separate page.

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Authored by [Colin Farquharson](#), July 2000
Modified to HTML by [Francis Jones](#), July 2000.