Norsk Regnesentral
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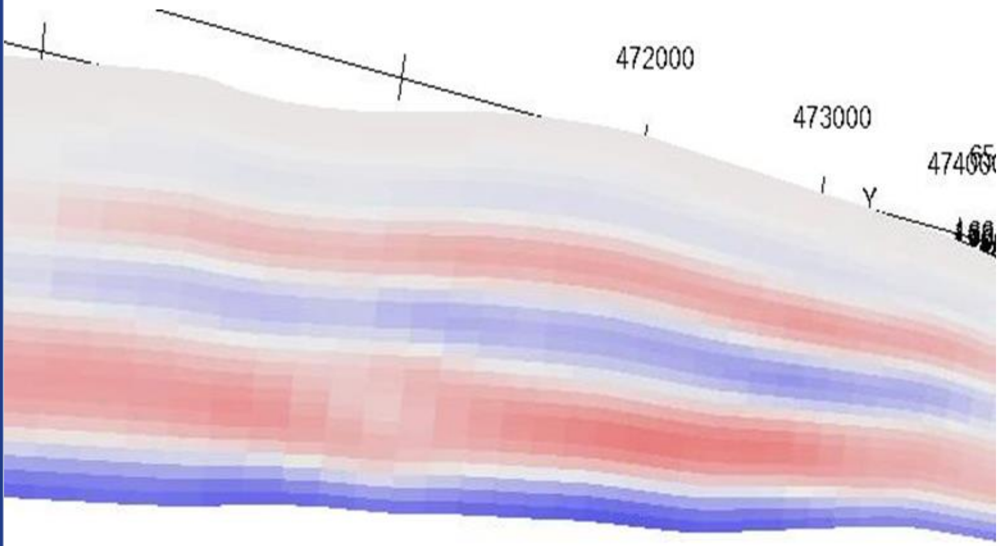
Note

Seismic Forward

User manual – version 4.1



Note no.

Authors Pål Dahle, Anne-Randi Syversveen and Maria Vigsnes

Date 13. sep. 2016

Norsk Regnesentral

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Authors **Pål Dahle, Anne-Randi Syversveen and Maria Vigsnes**

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Abstract

This note describes Seismic Forward, a tool for generating synthetic seismic from elastic parameters vp, vs and density.

The following scientists at Norwegian Computing Center (NR) has contributed to development of Seismic Forward:

- Pål Dahle
- Ragnar Hauge
- Marie Lilleborge
- Per Røe
- Anne Randi Syversveen
- Maria Vigsnes

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Contents

1 Introduction

The software seismic_forward is a tool for generating synthetic reflection seismic from elastic parameters vp, vs and density. The elastic parameters are given in an Eclipse grid. The program is written in C++. The program takes as input argument a model file of XML format, described in Section 4. The main output is synthetic seismic in SegY format and in a Storm grid (which can easily be imported to RMS). The seismic can be given in both time and depth, and seismic for various angles/offsets can be generated. Various output parameters can be selected and written on Storm or SegY format.

News in version 4.0 and version 4.1 are presented in Section 2. Section 3 gives a brief description of the theory and the implementation, and Section 4 gives a description of how to build a model file. Section 5 gives description of file formats and references respectively.

2 Release notes

2.1 Version 4.0

Seismic with NMO-stretch

The main new feature is the option to generate seismic with NMO-stretch – both for PP and PS data. The seismic is modelled for a set of specified offsets. Theory and relevant commands to include in the model file are given in Sections 3.5 and 4.5, respectively.

Data written to file sequentially

In order to save memory, the seismic traces are written to SegY files sequentially as calculated in the program. The option <memory-limit> is therefore removed. If seismic in Storm format is requested, the entire output grid will be stored in memory; hence seismic in Storm format may not be feasible for very large grids.

All pre-stack seismic on the same SegY file

When modelling seismic for more than one angle or offset and pre-stack seismic output is requested (Sections 4.7.14 to 4.7.17), all data are written to the same SegY file. This means that the names of the SegY files will not include any angle or offset numbering. The angle or offset of each specific seismic trace is given in the "trace header" of the SegY file (see Section 5.2). For seismic with NMO-stretch, output of the seismic time prior to NMO-correction can be requested by the command < seismic-time-prenmo-segy> (see Figure 7 for example).

Only seismic stack on Storm grid

When modelling seismic for more than one angle or offset, only stacked seismic is available in Storm format. This means that for instance the commands <seismic-time> and <seismic-stack><time-storm> give identical output. If seismic for one specific angle or offset is requested on Storm format, the seismic modelling must be run with only this angle or offset. In previous versions, the default value for <seismic-time> and <seismic-depth> was 'yes', but in this version, default is 'no'.

Depth conversion and time shift performed differently

The seismic is now <u>only</u> modelled in time and is converted into depth and shifted in time afterwards if output seismic in depth or time shift is requested (it was modelled directly in depth in previous versions). This may give some small changes in the seismic compared to previous versions. Theory related to the depth conversion and time shift is given in Section 3.6.

Parallelization

The seismic modelling part of the code is parallelized. The speed is dependent on the number of threads that are used in the parallelization. The tool uses all available threads unless the user specifies an upper limit (Section 4.11 <max-threads>). The CPU-usage is further dependent on the number of traces generated compared to written, e.g. if number of angles/offsets is large and only stacked seismic is written, a good CPU-usage will be achieved. The resampling of depth and elastic parameters is not parallelized.

Large models/grids

Large models and/or seismic grids might give memory problems. In this case the number of traces that the tool can have in the memory at the time can be limited by the command 4.10 <traces-in-memory>. However, this will not reduce the memory during regridding of surfaces and elastic parameters. For large models/grids, output of seismic in Storm format is not recommended.

Changed name of command from <depth> to <top-time>

The command for specifying the time value corresponding to the top reservoir in Section 4.6.4 has changed to <top-time>.

<top-time-constant>

When this command is used, the top point is found directly from the Eclipse grid. In previous versions the top point was found from the resampled top surface. This may give some shift in seismic time compared to previous versions.

Sorting of traces in SegY files

The traces in the SegY files has an inline sorting (for a given inline position, all xline positions follows successively). The inline and xline traces are sorted by increasing number, and when more than one angle or offset is requested (pre-stack seismic), all traces for a given inline/xline position are given successively.

Wavelet from file

Earlier versions of the tool have sometimes had problems with extracted wavelets (wavelet from file, section 4.3.2), giving seismic with strange or undefined values. The ‘ad hoc’ solution has been to add extra zeros at the start and end of the wavelet. This problem is now solved in version 4.0, i.e. no extra zeros are needed.

N layers from file

The command <nlayers-from-file> is removed from this version. Windows for seismic output in time and depth can be specified with the commands in Section 4.6.8 <time-window> and 4.6.9 <depth-window>.

2.2 Version 4.1

Offset seismic without stretch

Seismic according to offset but without NMO-stretch can be generated using the command in Section 4.5.4 <offset-without-stretch>. See section 3.5.3 for further details.

Parallelization

The resampling of depth surfaces and elastic parameters have been parallelized, as have the export of properties to SegY file. Properties include elastic properties as well as additional properties requested by the user.

Removal of negative thicknesses

Negative thicknesses can be automatically set to zero by using the command <remove-negative-delta-z> described in Section 4.1.7.

Resampling of parameters to SegY grid using interpolation

The vertical resampling of parameters into depth or time according to the SegY grid can now be performed by an interpolation rather than an index based mapping. This is activated using the command <resampl-param-to-segy-with-interpol> described in Section 4.1.8. The lateral resampling is performed as earlier with centre point interpolation, see Sections 3.2 and 3.3.

3 Algorithm

The output grid may cover the whole Eclipse grid, or a specified sub volume of the Eclipse grid.

First, we resample the depth of each layer in the Eclipse grid by Delaunay triangulation, and store the values in a grid, see Section 3.2. As default, we use centre points in the triangulation, but there is an option to use corner point interpolation. Then we calculate reflection coefficients layer by layer, see Section 3.1. For this, we need to resample the elastic parameters, see Section 3.3. The elastic parameters are interpolated by Delaunay triangulation, using centre points in top and bottom of cells, in a similar way as for the depth interpolation. The values are stored in a grid. In inactive cells, where no values for elastic parameters exist, we use default values provided by the user. The user also must provide default values for use above and below reservoir. Cells with thickness smaller than 0.1m, or another user defined limit, get the value from the cell above.

Then we calculate two way travel time (measured in ms) for each layer k:

$$\mathrm{twt(k)} = \mathrm{twt(k-1)} + 2000[\mathrm{z(k)} - \mathrm{z(k-1)}]/\mathrm{vp(k)}$$

Here z(k) is the depth in layer k. The values are stored in a grid.

The seismic is calculated trace by trace, by using the following convolution formula:

$$\mathrm{seis}(t) = \sum_{k=0}^{n} c(k)\mathrm{Wavelet}[twt(k) - t] \qquad (1)$$

Here c(*k*) is the reflection at layer no *k*, and *Wavelet* is the wavelet specified either as an input file or as a Ricker wavelet with a user specified peak frequency, see Section 3.4. *twt(k)* is the two way travel time at layer no *k*.

3.1 Calculation of reflection coefficients

We use an Aki Richards type linearization of the Zoeppritz equations, given by Stolt and Weglein (1985). See also the Crava user documentation, Dahle et al (2011).

For PP seismic, angle θ and time t we have

$$c(t,\theta) = a_1 \frac{\Delta Vp}{\overline{Vp}} + a_2 \frac{\Delta Vs}{\overline{Vs}} + a_3 \frac{\Delta\rho}{\bar{\rho}} \qquad (2)$$

Here $\Delta Vp = Vp(t+) - Vp(t-)$, where $t+$ and $t-$ are on each side of a cell border, $\overline{Vp} = 0.5 * \left(Vp(t+) + Vp(t-)\right)$, and similar for Vs and ρ. The coefficients a_1, a_2, and a_3 are given by

$$a_1 = 0.5(1 + tan^2\theta)$$

$$a_2 = -4\left(\frac{\overline{Vs}}{\overline{Vp}}\right)^2 sin^2\theta$$

$$a_3 = 0.5(1 - a_2)$$

Here θ is the offset angle.

For PS seismic, we have

$$a_1 = 0$$

$$a_2 = 2\frac{\sin\theta}{\cos\varphi}\left(\left(\frac{\overline{Vs}}{\overline{Vp}}\right)^2 sin^2\theta - \frac{\overline{Vs}}{\overline{Vp}}\cos\theta\cos\varphi\right)$$

$$a_3 = \frac{\sin\theta}{cos\varphi}\left(-0.5 + \left(\frac{\overline{Vs}}{\overline{Vp}}\right)^2 sin^2\theta - \frac{\overline{Vs}}{\overline{Vp}}\cos\theta\cos\varphi\right)$$

Here, φ is the PS reflection angle, given by $\sin\varphi = Vs/Vp \cdot \sin\theta$.

3.2 Resampling of depth

Each layer in the Eclipse grid is resampled to a regular grid. The grid resolution in (x, y) is the same as for the seismic output data.

The default is to use centre point interpolation. The routine loops all eclipse cells, and for each cell (i, j), we collect centre point in top or bottom of cell (i, j) and the neighbour points (i+1, j), (i+1, j+1) and (i, j+1). The area defined by these four points is divided into two triangles by Delaunay decomposition in the xy-plane, see Figure 1.

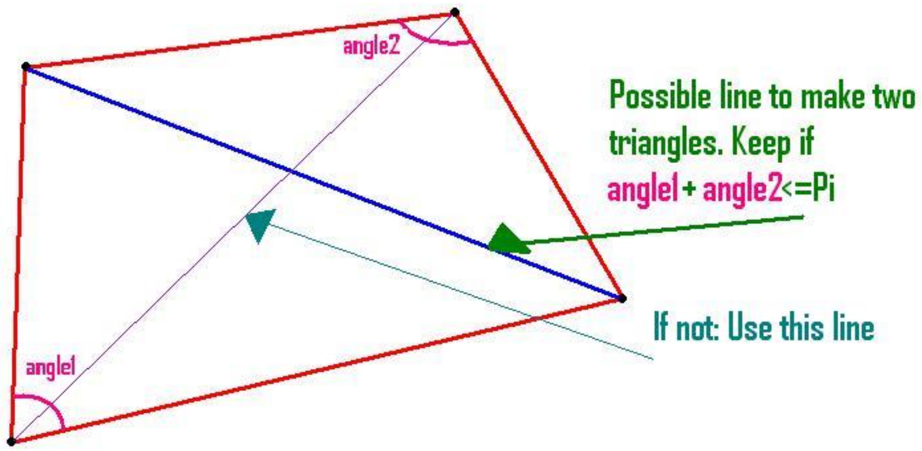

Figure 1: Illustration of Delaunay triangulation.

Each triangle defines a local surface, and all points that are inside a triangle get their z value from this surface.

We are given a polygon described by its four corner points, and a rectangle R (in some sense equivalent to a grid we want to write values to), see Figure 2. To loop over the entries of the R-grid more easily, a linear transformation (i.e. rotation) of the coordinates of the polygon corners is done so that the coordinate axes are parallel to the rectangle sides. From these coordinates we find the extreme x- and y- values of the polygon (i.e. a rectangle S which contains the polygon that also has the same polar angle as R). Then we loop over the intersection of S and R to fill in the entries that lies inside the polygon we started with.

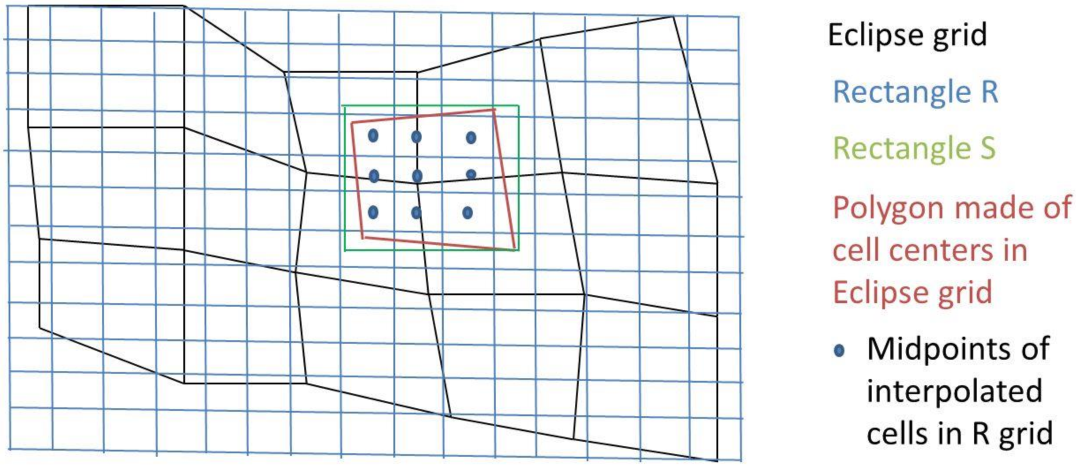

Figure 2: Resampling of depth. The resampled grid is shown in blue, and the eclipse grid in black.

Alternatively, we can use corner point interpolation, and collect corners of each eclipse cell. The area within these points is divided into two triangles, as described above. The corner point algorithm is not suitable if the grid contains reverse faults, which means that cells in different layers overlap each other. If the grid contains large cells which are not overlapping, corner point interpolation could be the best choice.

For points in the resampled grid that are not covered by the eclipse grid, the following procedure is used: We start in the "centre of mass" of the entries in the resampled surface that has written a value to it. Then it works outwards in squares of increasing "radii": For each entry that has not got a value written to it yet, the average of the values written to its neighbours is filled in. This routine is done in case R has some nonempty intersection with the compliment of the eclipse grid for the given layer. If this occurs, we set the values outside the eclipse grid by using this method. If the intersection is empty for all of R, the algorithm will not write any values to the surface.

3.3 Resampling of elastic parameters

This is done in a similar way as for the depth. In order to calculate reflections, we need to resample values on both top and bottom of cells. If a cell is inactive, default values for the parameters are used in triangulation. For inactive cells with thickness less than a given limit (default is 0.1 meters), the value in the cell above is used.

Since we use centre of cells, an edge around the eclipse grid is not treated by this algorithm, see Figure 3. In this region, we use mirroring values to the outside of the eclipse grid, and then filling out unwritten values on the inside by triangulation. If a cell is inactive, default values for the parameters are used in triangulation.

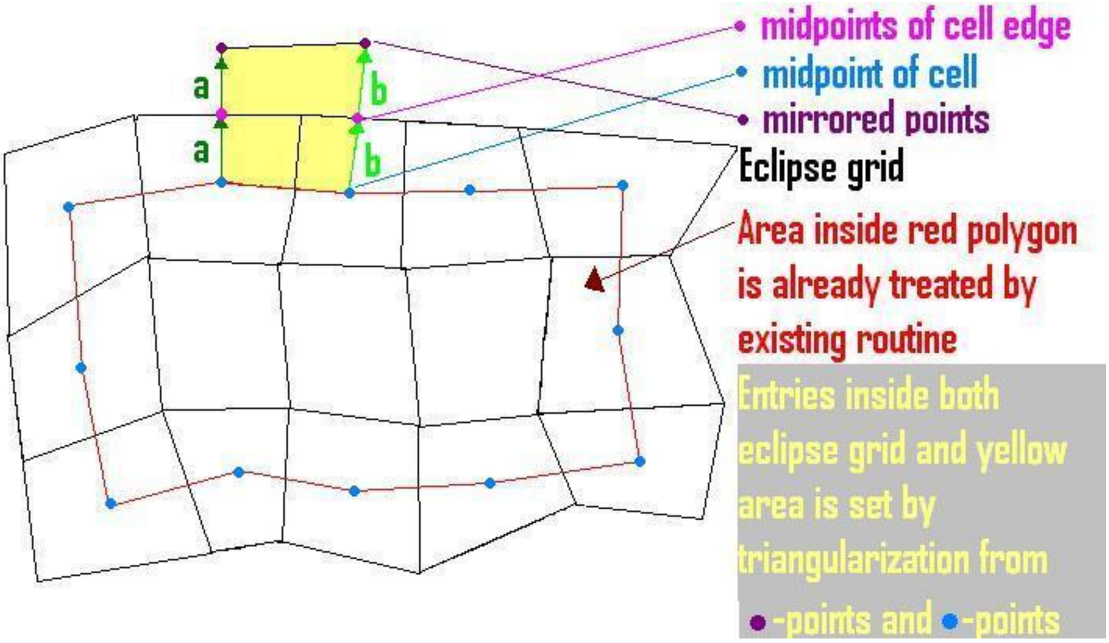

Figure 3: Treatment of edges when resampling elastic parameters.

3.4 Wavelet

The wavelet can either be specified as a Ricker wavelet, by specifying the peak frequency, or the wavelet can be given as an input file.

When the Ricker wavelet is used, the wavelet is evaluated from an analytical expression when calculating the seismic from Equation 1.

When the wavelet is specified in an input file, the only supported file format at the time is Landmark ASCII Wavelet (see Section 5.4). When the seismic trace is calculated, an interpolation from the sampled wavelet is performed; hence the outcome depends on the sampling density. We do a refinement of the wavelet in order to get a better interpolation. In order to refine the sampling density of the input wavelet, the wavelet is Fourier transformed and number of samples is increased before it is inverted back. The number of samples is increased so that the time sampling (time between each sample) is ~1ms. See example of refinement in Figure 4.

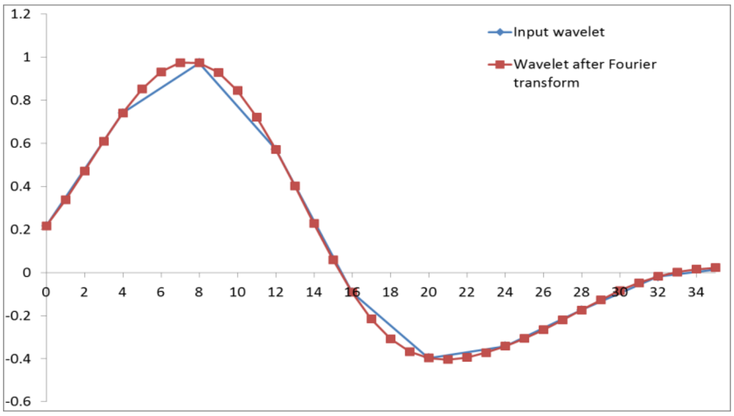

Figure 4: Refinement of sampling density of the wavelet.

3.5 NMO-stretch

Normal move out (NMO) is the effect the offset has on the arrival time of the reflection. The offset is the distance between a seismic source and a receiver; see Figure 5. Increasing offset induces an increasing delay in the arrival time of a reflection from a horizontal surface. A plot of arrival times versus offset has a hyperbolic shape. To be able to flatten each event to its associated zero-offset arrival time, the seismic must be NMO-corrected. NMO-correction is basically a shift of the seismic in time. An effect of NMO is a stretching of the wavelet form with increasing offset, referred to as NMO-stretch. The NMO-stretch is highest at far offsets and at early times, where the NMO-correction is the most severe.

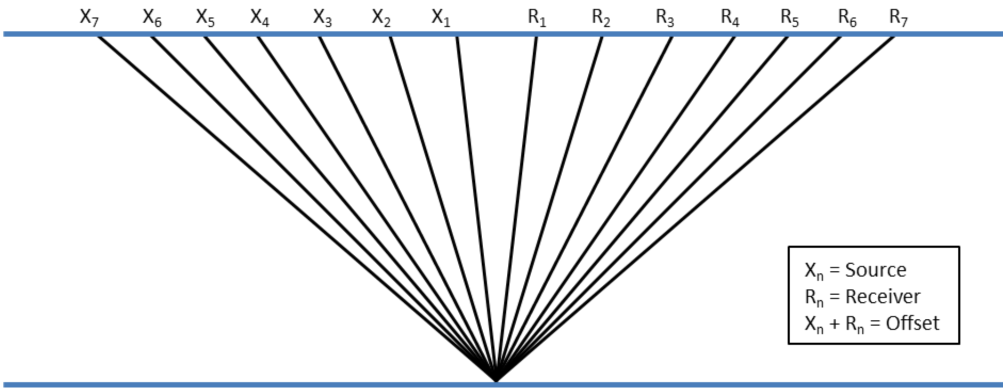

Figure 5: Path from source to receiver for seismic traces with various offsets.

3.5.1 Generation of seismic with NMO-stretch

Seismic with NMO-stretch is generated according to specified offsets. At first the root-mean-square velocity (RMS velocity) is calculated for all reflectors/layers including the seafloor. The interval velocity in the overburden must be estimated in order to get the RMS velocities in the reservoir. This is calculated from user specified sea layer values (Section 4.5.1 <seafloor-depth> and 4.5.2 <velocity-water>) and top reservoir values. The RMS velocity at layer *k* is given as:

$$v_{rms,k} = \sqrt{\frac{\sum_{i=0}^{k} v_i^2 t_i}{T_{0,k}}} \ ,$$

where v_i and t_i are the interval velocity and the two-way-time (TWT) of layer *i* and $T_{0,n}$ is the TWT at zero offset down to layer *k*.

Secondly the TWT down to each layer is calculated for every offset, see Figure 6. TWT to layer *k* for offset *x* is given as:

$$T_{x,k} = \sqrt{T_{0,k}^2 + \frac{x^2}{v_{rms,k}^2}}\,. \qquad (3)$$

The offset angle is calculated for each offset and layer by using the RMS velocity. The offset angle at layer *k* for offset *x* is given as:

$$\theta_{x,k} = \tan^{-1}\left(\frac{x}{v_{rms,k} \cdot T_{0,k}}\right).$$

The corresponding reflection coefficient at layer *k* for given offset *x*, $c(\theta_{x,k})$, is calculated according to Equation 2. The seismic trace at time *t* is calculated as:

$$\text{seis}(t) = \sum_{k=0}^{n} c(\theta_{x,k})\text{Wavelet}[T_{x,k} - t]. \qquad (4)$$

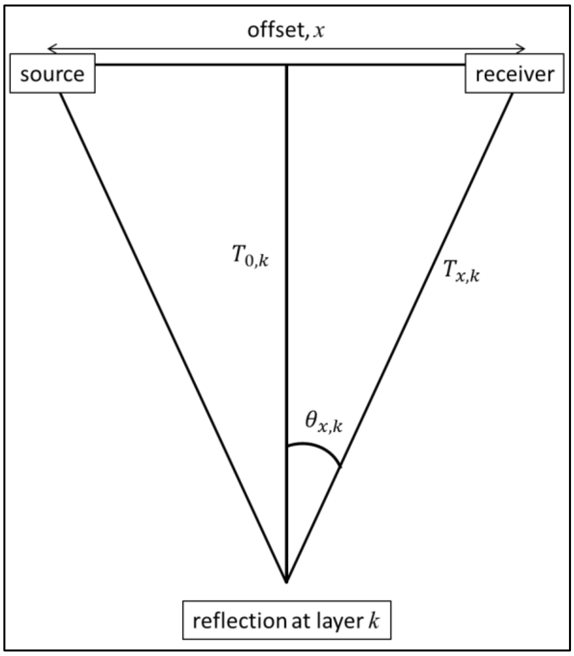

Figure 6: Geometry of a seismic reflection at layer *k*.

3.5.2 NMO-correction

The seismic in Equation 4 is regularly sampled in time, i.e. $t = [t_0, t_0 + \Delta t, t_0 + 2\Delta t, \ldots]$. For each time sample, *t*, the corresponding t_x is calculated according to Equation 3. In order to calculate t_x the RMS velocity is resampled according to *t* using linear interpolation. The generated seismic is resampled into t_x by using a cubic spline interpolation. The resampled seismic is NMO-corrected. See Figure 7 and Figure 8 for examples of seismic before and after

NMO-correction. The NMO-stretch is visible at far offsets in Figure 8. As a comparison, Figure 9 shows the same example of a seismic gather generated without NMO-stretch.

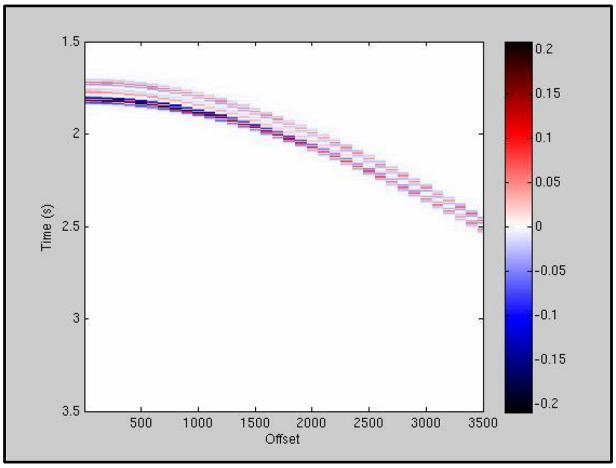

Figure 7: Example of seismic gather for offsets from 0 to 3500m.

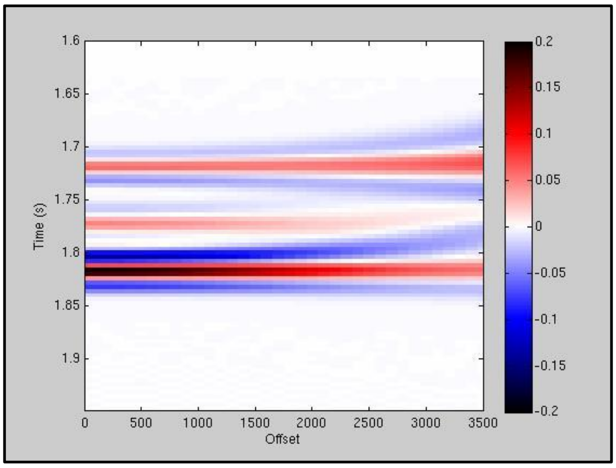

Figure 8: Example of seismic gather after NMO-correction for offsets from 0 to 3500m.

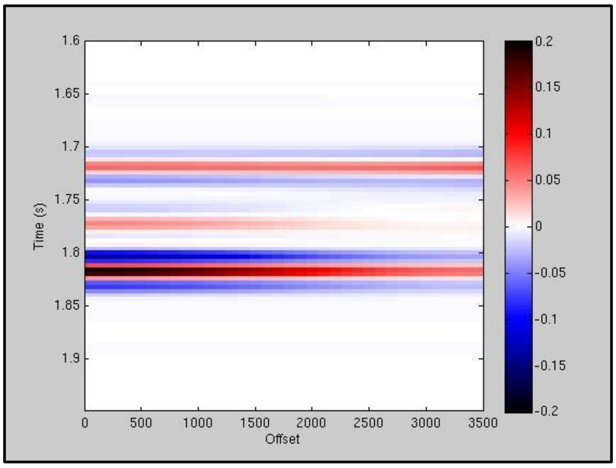

Figure 9: Example of seismic gather generated without NMO-stretch for offsets from 0 to 3500m.

3.5.3 Offset seismic without NMO-stretch

Seismic can be generated according to specified offsets without taking into account the increasing delay in the arrival time with offset, i.e. without NMO-stretch. The offset seismic without NMO-stretch is generated by the same procedure as seismic with NMO-stretch given in Section 3.5.1; however the offset $x = 0$ in Equation 3, giving $T_{x,k} = T_{0,k}$. The seismic is hence generated according to the zero-offset TWT, but with reflection angles corresponding to the geometry in Figure 6. No NMO-correction is performed on this seismic.

3.6 Depth conversion and time shifts

The generated seismic is regularly sampled in time i.e. $t = [t_0, t_0 + \Delta t, t_0 + 2\Delta t, \dots]$, and resampled into t_x in case of seismic with NMO-stretch. Depth converted and time-shifted seismic is established from the generated seismic in time by interpolating the amplitudes into new grids in depth or time, respectively.

Depth conversion:

At first, the depths z_t corresponding to $t = [t_0, t_0 + \Delta t, t_0 + 2\Delta t, \dots]$ are found through linear interpolation based on the relation between depth and TWT at each layer of the reservoir (from the re-gridding of the model). Hence the seismic that is generated according to t can also be associated with z_t.

In order to get regularly sampled seismic in depth, the seismic is interpolated into $z = [z_0, z_0 + \Delta z, z_0 + 2\Delta z, \dots]$. This is done using cubic spline interpolation, given that the seismic is "sampled" according to z_t.

Seismic time shift:

The seismic is shifted in time basically using the same procedure as the depth conversion. The shifted times t_s corresponding to t are found through linear interpolation based on the relation between TWT and shifted TWT at each layer of the reservoir. The seismic is regularly sampled into the shifted times using cubic spline interpolation, given that the seismic is "sampled" according to t_s.

4 Model file reference manual

We describe how to build a model file for the Seismic Forward program. The model file mainly follows the XML format, but we also use the character '#' for commenting, meaning that the rest of the line after such a character is read as comments. XML files are built with start and end tags, encapsulating other tags or values. All model files start with <seismic-forward> and end with </seismic-forward>.

All commands are optional, unless otherwise stated. A necessary command under an optional is only necessary if the optional is given.

4.1 <elastic-param> (necessary)

Description: Contains Eclipse grid file name, default values and name of elastic parameters in file. Interpolation method for depth values can optionally be chosen here, and a limit for treating cells as zero thickness cells can be set.

Example:

```
<elastic-param>
  <eclipse-file > test_2006.grdecl </eclipse-file>
  <default-values>
    <vp-top>  3800 </vp-top>
    <vp-mid>  3400 </vp-mid>
    <vp-bot>  3800 </vp-bot>
    <vs-top>  1200 </vs-top>
    <vs-mid>  1900 </vs-mid>
    <vs-bot>  2100 </vs-bot>
    <rho-top> 2400 </rho-top>
    <rho-mid> 2400 </rho-mid>
    <rho-bot> 2400 </rho-bot>
  </default-values>
  <parameter-names>
    <vp>  VP_2006-07-01   </vp>
    <vs>  VS_2006-07-01   </vs>
    <rho> DENS_2006-07-01 </rho>
  </parameter-names>
</elastic-param>
```

4.1.1 <eclipse-file> (necessary)

Description: Name of Eclipse grid file with elastic parameters. Figure 10 shows how to export a grdecl file from RMS.

Argument: File name.

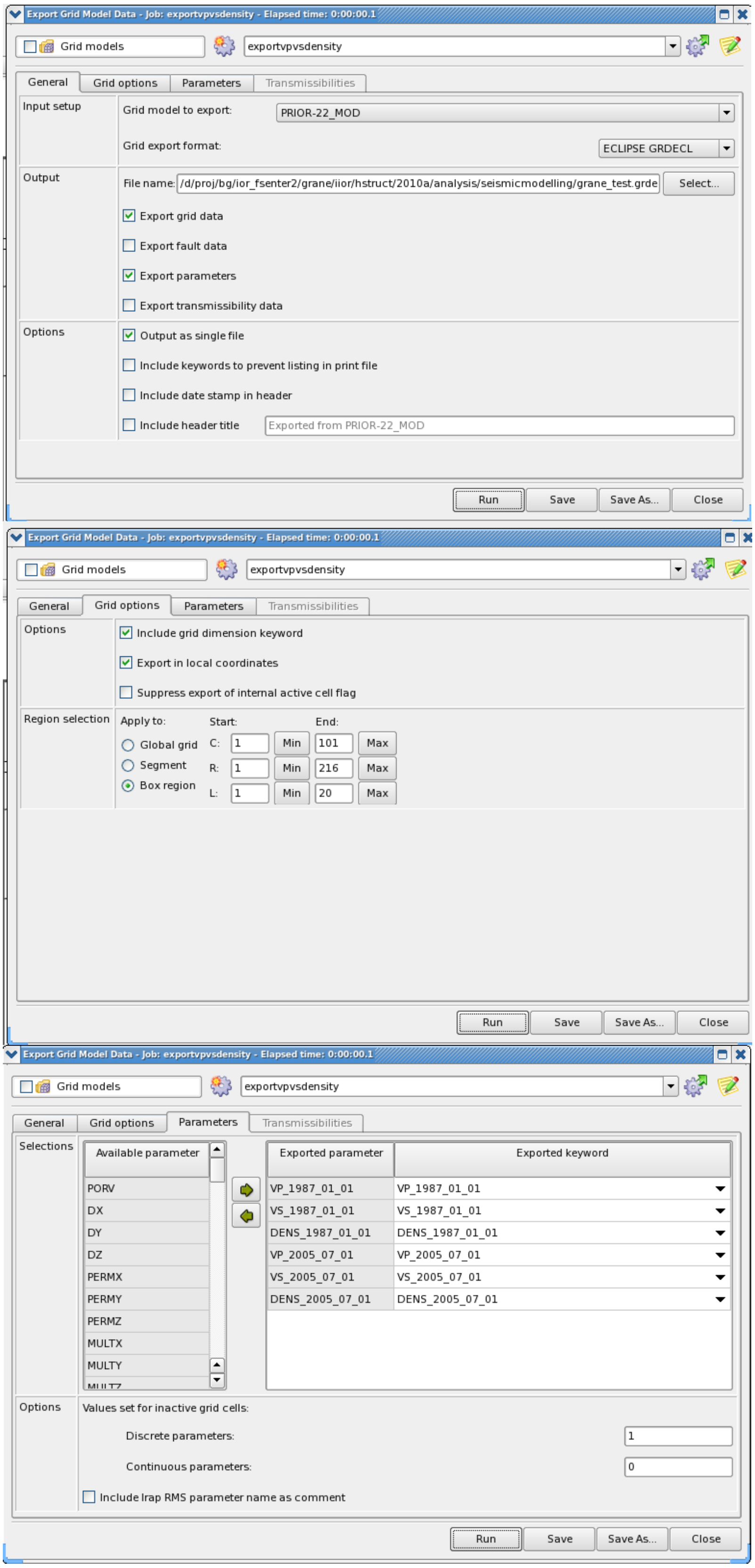

Figure 10: Export of grdecl file from RMS.

4.1.2 <default-values> (necessary)

Description: Values of vp, vs, and rho over and under reservoir, and in missing cells within reservoir.

4.1.2.1 <vs-top> (necessary)

Description: Default value of vp above reservoir.

Argument: double

4.1.2.2 <vp-mid> (necessary)

Description: Default value of vp within reservoir. To be used at places with missing data.

Argument: double

4.1.2.3 <vp-bot> (necessary)

Description: Default value of vp below reservoir.

Argument: double

4.1.2.4 <vs-top> (necessary)

Description: Default value of vs above reservoir.

Argument: double

4.1.2.5 <vs-mid> (necessary)

Description: Default value of vs within reservoir. To be used at places with missing data.

Argument: double

4.1.2.6 <vs-bot> (necessary)

Description: Default value of vs below reservoir.

Argument: double

4.1.2.7 <rho-top> (necessary)

Description: Default value of density above reservoir.

Argument: double

4.1.2.8 <rho-mid> (necessary)

Description: Default value of density within reservoir. To be used at places with missing data.

Argument: double

4.1.2.9 <rho-bot> (necessary)

Description: Default value of density below reservoir.

Argument: double

4.1.3 <parameter-names> (necessary)
Description: Name of elastic parameters in Eclipse file

4.1.3.1 <vp> (necessary)
Description: Name of vp parameter in Eclipse file

Argument: String

4.1.3.2 <vs> (necessary)
Description: Name of vs parameter in Eclipse file

Argument: String

4.1.3.3 <rho> (necessary)
Description: Name of density parameter in Eclipse file

Argument: String

4.1.4 <extra-parameters>
Description: Name and default value of extra parameter. This command must be repeated for each extra parameter.

In order to write the extra parameters to time or depth segy files the commands <extra-parameters-time-segy> (Section 4.7.20) and/or <extra-parameters-depth-segy> (Section 4.7.21) under <output-parameters> must be given.

4.1.4.1 <name> (necessary)
Description: Name of extra parameter in Eclipse file

Argument: String

4.1.4.2 <default-value> (necessary)
Description: Default value of extra parameter

Argument: double

4.1.5 <cornerpt-interpolation-in-depth>
Description: Using corner point interpolation instead of centre point interpolation when interpolating the depth of each layer in the Eclipse grid.

Argument: Yes or no, default is no.

4.1.6 <zero-thickness-limit>
Description: If cell thickness is less than this limit, it should be treated as a zero thickness cell, and get its value from the cell above. The value is in meters.

Argument: double, default is 0.1.

4.1.7 <remove-negative-delta-z>

Description: If cell thickness is negative, thickness can be automatically set to zero by using this keyword.

Argument: Yes or no, default is no.

4.1.8 <resampl-param-to-segy-with-interpol>

Description: Vertically resample elastic or extra parameters into depth or time samples of SegY grid using interpolation rather than index mapping.

Argument: Yes or no, default is no.

4.2 <angle>

Description: Offset angle for seismic. Seismic cubes with offset angle ***theta-0***, ***theta-0* + *dtheta***, ***theta-0* +** 2***dtheta**…..***theta-max***, will be generated. The command is optional, and if not given, only zero offset seismic is generated.

Example:

```
<angle>
   <theta-0>    0 </theta-0>
   <dtheta>     5 </dtheta>
   <theta-max> 30 </theta-max>
</angle>
```

4.2.1 <theta-0>

Description: Smallest offset angle.

Argument: double, default is 0.0.

4.2.2 <dtheta>

Description: Increment for offset angle.

Argument: double, default is 0.0.

4.2.3 <theta-max>

Description: Largest offset angle.

Argument: double, default is 0.0.

4.3 <wavelet> (necessary)

Description: Specifies which wavelet to use. One of the two commands <ricker> or <from-file> must be specified.

4.3.1 <ricker>

Description: The Ricker wavelet.

Example:

```
<wavelet>
 <ricker>
  <peak-frequency> 20 </peak-frequency>
 </ricker>
</wavelet>
```

4.3.1.1 <peak-frequency> (necessary)

Description: Peak frequency for Ricker wavelet

Argument: double

4.3.2 <from-file>

Description: Wavelet is specified in an input file.

Example:

```
<wavelet>
 <from-file>
  <format>    Landmark             </format>
  <file-name> wavelet_landmark.wvl </file-name>
 </from-file>
</wavelet>
```

4.3.2.1 <format> (necessary)

Description: Format of wavelet file. So far, only Landmark (Landmark ASCII Wavelet) is implemented. See Section 5.4 for description of Landmark ASCII Wavelet format.

Argument: Landmark

4.3.2.2 <file-name> (necessary)

Description: Filename of wavelet file. The Landmark ASCII Wavelet format is supported as wavelet input file (see Section 5.4).

Argument: String

4.3.3 <scale>

Description: Scaling factor for wavelet. An increase in impedance gives a positive peak.

Argument: double, default is 1.0.

4.4 <white-noise>

Description: Adding white noise to the cube with reflection coefficients at each layer of the Eclipse grid. The white noise is sampled from a Normal distribution with zero mean and a specified standard deviation. This results in coloured noise in the seismic, and the noise model is consistent with the model in Buland and Omre (2003).

Example:

```
<white-noise>
 <standard-deviation> 0.02   </standard-deviation>
 <seed>               123456 </seed>
</white-noise>
```

4.4.1 <standard-deviation>

Description: Standard deviation to the white noise.

Argument: double, default is 1.0.

4.4.2 <seed>

Description: Seed number. If this command is not given, a random seed number will be used.

Argument: integer

4.5 <nmo-stretch>

Description: When this command is specified, a seismic gather according to the specified offsets is generated for each position. The arrival time for each offset is modelled with hyperbolic NMO. The seismic is thereafter NMO-corrected to the associated zero-offset time, giving NMO-stretch in the modelled data. In order to perform NMO-correction, the seafloor depth and velocity in water is required. This command is prioritized before <angle> (Section 4.2), which means that if both <nmo-stretch> and <angle> are specified, <angle> is ignored.

Example:

```
<nmo-stretch>
 <seafloor-depth>  200 </seafloor-depth>
 <velocity-water> 1500 </velocity-water>
 <offset>
   <offset-0>      0 </offset-0>
   <doffset>      50 </doffset>
   <offset-max> 2000 </offset-max>
 </offset>
</nmo-stretch>
```

4.5.1 <seafloor-depth> (necessary)

Description: Depth of seafloor.

Argument: double

4.5.2 <velocity-water> (necessary)

Description: Velocity in water.

Argument: double

4.5.3 <offset>
Description: Offset for seismic. Seismic traces will be generated for offset ***offset-0***, ***offset-0* + *doffset***, ***offset-0* +** 2***doffset***…..***offset-max***. The command is optional, and if not given, only zero offset seismic is generated.

4.5.3.1 <offset-0>
Description: Smallest offset.

Argument: double, default is 0.0.

4.5.3.2 <doffset>
Description: Increment for offset.

Argument: double, default is 0.0.

4.5.3.3 <offset-max>
Description: Largest offset.

Argument: double, default is 0.0.

4.5.4 <offset-without-stretch>
Description: If this command is specified, seismic is generated according to offset; however without NMO-stretch. In practice, this means that the arrival time for each offset is assumed identical to zero-offset, and no NMO-correction is applied. This option will give seismic similar, but not identical to the <angle> option since seismic is generated for constant offset gathers rather than constant angle gathers.

Argument: Yes or no, default is no.

4.6 <output-grid> (necessary)
Description: Specifies the dimensions of the resulting seismic grid and a possible window for output files.

The area used in the forward modelling can be defined in four different ways.

By default, the area is defined by the Eclipse grid, automatically calculated as the smallest rectangle covering the active cells in the Eclipse grid. Otherwise, the area can be specified by any of the following three commands (prioritized order):

1) <area-from-segy>, where area is specified by a SegY file.

2) <area>, where a rectangle area can be specified.

3) <area-from-surface>, where area is specified by a Roxar text file.

The modelling interval is from top reservoir minus one wavelet length to bottom of reservoir plus one wavelet length. The time value corresponding to the top reservoir can be specified under <top-time>, and the cell size of the seismic grid can be specified under <cell-size>. For

SegY output format, the segy indexes can be specified under <segy-indexes> and UTM precision under <utm-precision>. Output window in time or depth can be specified under <time-window> and <depth-window>.

Example:

```
<output-grid>
  <top-time>
     <top-time-constant> 1200 </top-time-constant>
   </top-time>
  <cell-size>
    <dx> 50 </dx>
    <dy> 50 </dy>
    <dz>  1 </dz>
    <dt>  4 </dt>
  </cell-size>
  <area-from-surface> top.irap </area-from-surface>
  <time-window>
    <top> 1000 </top>
    <bot> 2000 </bot>
  </time-window>
</output-grid>
```

4.6.1 <area-from-surface>

Description: A surface on Roxar text format is used to specify area. This command is not active if <area> or <area-from-segy> is given.

Argument: String with name of Roxar text surface file.

4.6.2 <area-from-segy>

Description: A segy file is used to specify area. Some standard SegY trace header formats are recognized, see Section 5.3. Other formats can be specified by the user, by using the key words <il0>, <xl0>, <utmxLoc>, and <utmyLoc>.

4.6.2.1 <filename> (necessary)

Description: Name of segy file.

Argument: String with name of segy file.

4.6.2.2 <il0>

Description: Byte number for inline start in trace header in the given file.

Argument: integer

4.6.2.3 <xl0>

Description: Byte number for crossline start in trace header in the given file.

Argument: integer

4.6.2.4 <utmxLoc>

Description: Byte number for location of x coordinate in trace header in the given file.

Argument: integer

4.6.2.5 <utmyLoc>

Description: Byte number for location of y coordinate in trace header in the given file.

Argument: integer

4.6.3 <area>

Description: Defines the area of the seismic cube. See Figure 11 for an illustration of the parameters required. If specified, all parameters must be given. This command is not active if <area-from-segy> is given.

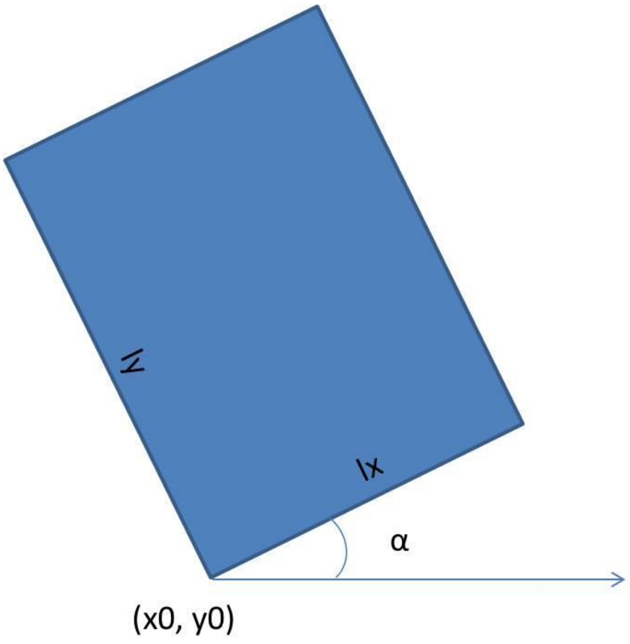

Figure 11: Illustration of area parameters.

4.6.3.1 <x0> (necessary)

Description: x coordinate of lower left corner point, see Figure 11.

Argument: double

4.6.3.2 <y0> (necessary)

Description: y coordinate of lower left corner point, see Figure 11.

Argument: double

4.6.3.3 <lx> (necessary)

Description: Length of area in local x direction, se Figure 11.

Argument: double

4.6.3.4 <ly> (necessary)
Description: Length of area in local y direction, see Figure 11.

Argument: double

4.6.3.5 <angle> (necessary)
Description: Rotation angle of area, see Figure 11.

Argument: double

4.6.4 <top-time>
Description: Specifies time value corresponding to top of reservoir. When modelling seismic with the <nmo-stretch> option (Section 4.5), the top time value is used in calculation of rms-velocity down to top reservoir, and hence should be given a realistic value. This is also important when modelling seismic in depth.

4.6.4.1 <top-time-surface>
Description: Specifies a surface in time corresponding to top reservoir. The surface must be of type Roxar text. If the surface contains missing areas, the seismic will be missing (set to zero) in these areas.

Argument: String with name of Roxar text surface file.

4.6.4.2 <top-time-constant>
Description: Specifies a constant time value corresponding to top reservoir. The constant time corresponds to the top point of the Eclipse grid.

Argument: double, default value is 1000.0.

4.6.5 <cell-size>
Description: The cell size in the seismic grid is given here.

4.6.5.1 <dx>
Description: Cell size in x direction. If <area-from-segy> is given, dx is taken from segy file.

Argument: double, default value is 25m.

4.6.5.2 <dy>
Description: Cell size in y direction. If <area-from-segy> is given, dy is taken from segy file.

Argument: double, default value is 25m.

4.6.5.3 <dz>
Description: Cell size in vertical direction, for seismic in depth domain.

Argument: Double, default value is 4m.

4.6.5.4 <dt>

Description: Cell size in vertical direction, for seismic in time domain.

Argument: Double, size given in ms. Default value is 4ms.

4.6.6 <segy-indexes>

Description: Specifies the inline and crossline start point and the axis of the inline direction for grid output on SegY format. The command should not be used if <area-from-segy> is used, then the geometry is taken from the input segy file.

The inline and crossline directions are determined based on the geometry parameters specified under <area> and <cell-size>. By specifying <inline-direction> to "x" the inline and crossline directions are basically swopped.

Example:

```
<segy-indexes>
  <inline-start>     5 </inline-start>
  <xline-start>      5 </xline-start>
  <inline-direction> y </inline-direction>
</segy-indexes>
```

4.6.6.1 <inline-start>

Description: Location of inline start.

Argument: integer, default is 0.

4.6.6.2 <xline-start>

Description: Location of crossline start.

Argument: integer, default is 0.

4.6.6.3 <inline-direction>

Description: Axis of the inline direction. Legal arguments are x and y.

Argument: String, default is y.

4.6.6.4 <inline-step>

Description: Step size and direction for stepping along inline, where positive numbers mean positive inline direction and negative numbers mean negative inline direction.

Argument: Positive or negative integers, default is 1.

4.6.6.5 <xline-step>
Description: Step size and direction for stepping along crossline, where positive numbers mean positive inline direction and negative numbers mean negative inline direction.

Argument: Positive or negative integers, default is 1.

4.6.7 <utm-precision>
Description: Specifies the numerical precision of the UTM-coordinates in the header of the output segy file. *The precision is limited by the size of an integer (2^{31} - 1). If the precision exceeds this limit, i.e. if the number of significant digits exceeds ~10, a message will be given and no SegY file will be written.*

Argument: possible arguments are 0.0001, 0.001, 0.01, 0.1, 1, 10, 100, 1000 and 10000, default is 0.1.

4.6.8 <time-window>
Description: Specifies a time window for all output files in time.

4.6.8.1 <top>
Description: Specifies the top of the time window.

Argument: double

4.6.8.2 <bot>
Description: Specifies the bottom of the time window.

Argument: double

4.6.9 <depth-window>
Description: Specifies a depth window for all output files in depth.

4.6.9.1 <top>
Description: Specifies the top of the depth window.

Argument: double

4.6.9.2 <bot>
Description: Specifies the bottom of the depth window.

Argument: double

4.7 <output-parameters>
Description: Keyword to specify output variables from the program.

Example:

```
<output-parameters>
 <prefix>             parameters </prefix>
 <elastic-parameters> yes        </elastic-parameters>
 <reflections>        yes        </reflections>
</output-parameters>
```

4.7.1 <prefix>

Description: Name prefix of all output files.

Argument: String, default is empty string.

4.7.2 <suffix>

Description: Name suffix of all output files.

Argument: String, default is empty string.

4.7.3 <elastic-parameters>

Description: Writes resampled vp, vs, rho in Storm format to files "*prefix*+_vp_+*suffix* +.storm", "*prefix*+_vs_+*suffix*+.storm" and "*prefix*+_rho_+*suffix*+.storm". Depth is not correct; the output grid is a regular grid with the resampled values in each layer of the Eclipse grid.

Argument: Yes or no, default is no.

4.7.4 <reflections>

Description: Writes a cube with reflection coefficients at each layer of the Eclipse grid at the minimum specified angle or offset. The reflections are written in Storm format to file "*prefix*+_reflections_*theta*_ +*suffix*+.storm" or "*prefix*+_reflections_*offset*_ +*suffix*+.storm", where *theta* is the angle given under <theta-0> (Section 4.2.1) and *offset* is the offset given under <offset-0> (Section 4.5.3.1). If white noise is added to the reflections (Section 4.4), reflections with white noise are written to file "*prefix*+_reflections_noise_*theta*_+*suffix*+.storm" or "*prefix*+_reflections_noise_*offset*_+*suffix*+.storm".

Argument: Yes or no, default is no.

4.7.5 <zvalues>

Description: Writes depth values for each layer in the Eclipse grid in Storm format to file "*prefix*+_zgrid_+*suffix*+.storm".

Argument: Yes or no, default is no.

4.7.6 <twt>

Description: Writes two way travel time for zero offset in Storm format to file "*prefix*+_twt_+*suffix*+.storm".

Argument: Yes or no, default is no.

4.7.7 <vrms>

Description: Writes root-mean-square (RMS) velocity in Storm format to file "*prefix*+_vrms_+*suffix*+.storm".

Argument: Yes or no, default is no.

4.7.8 <twt-offset-segy>

Description: Writes two-way-time for each seismic gather for each offset (as specified in 4.5.3) in Segy format "*prefix*+_twt_offset_+*suffix*+.segy". The two-way-time will be written according to time-window if specified (4.6.8).

Argument: Yes or no, default is no.

4.7.9 <time-surfaces>

Description: Writes top and bottom of reservoir in time in Storm format to files "*prefix*+_toptime_+*suffix*+.storm" and "*prefix*+_bottime_+*suffix*+.storm".

Argument: Yes or no, default is no.

4.7.10 <depth-surfaces>

Description: Writes top and bottom of reservoir in depth in Storm format to files "*prefix*+_ topeclipse _+*suffix*+.storm" and "*prefix*+_ boteclipse _+*suffix*+.storm".

Argument: Yes or no, default is no.

4.7.11 <seismic-time>

Description: Writes the seismic stack of all angles as specified under command <angle> in Section 4.2, or for seismic with nmo-stretch (Section 4.5) writes the seismic stack of all offsets as specified under command <offset> in Section 4.5.3. The seismic is written in Storm format to file "*prefix*+_seismic_time_stack_+*suffix*+.storm".

Argument: Yes or no, default is no.

4.7.12 <seismic-timeshift>

Description: Writes seismic shifted in time as a stack of all angles specified under command <angle> in Section 4.2, or for seismic with nmo-stretch (Section 4.5) a stack of all offsets as specified under command <offset> in Section 4.5.3. The parameter <timeshift-twt> (Section 4.8) must also be given. The seismic is written in Storm format to file "*prefix*+_seismic_timeshift_stack_+*suffix*+.storm".

Argument: Yes or no, default is no.

4.7.13 <seismic-depth>

Description: Writes the seismic in depth as a stack of all angles specified under command <angle> in Section 4.2, or for seismic with nmo-stretch (Section 4.5) a stack of all offsets as specified under command <offset> in Section 4.5.3. The seismic is written in Storm format to file "*prefix*+_seismic_depth_stack_+*suffix*+.storm".

Argument: Yes or no, default is no.

4.7.14 <seismic-time-segy>

Description: Writes seismic in time in SegY format to file "*prefix*+_seismic_time_+*suffix*+.segy". See Section 5.2 for description of the chosen SegY format. The entire angle or offset gather for each position is written.

Argument: Yes or no, default is no.

4.7.15 <seismic-timeshift-segy>

Description: Writes seismic shifted in time in SegY format to file "*prefix*+_seismic_timeshift_+*suffix*+.segy". See Section 5.2 for description of the chosen SegY format. The parameter <timeshift-twt> (Section 4.8) must also be given. The entire angle or offset gather for each position is written.

Argument: Yes or no, default is no.

4.7.16 <seismic-depth-segy>

Description: Writes seismic in depth in SegY format to file "*prefix*+_seismic_depth_+*suffix*+.segy". See Section 5.2 for description of the chosen SegY format. The entire angle or offset gather for each position is written.

Argument: Yes or no, default is no.

4.7.17 <seismic-time-prenmo-segy>

Description: Writes seismic in time in SegY format to file "*prefix*+_ seismic_time_ prenmo_+*suffix*+.segy". See Section 5.2 for description of the chosen SegY format. This command is only relevant for seismic with nmo-stretch (Section 4.5), and writes the entire offset gather for each position prior to nmo correction.

Argument: Yes or no, default is no.

4.7.18 <elastic-parameters-time-segy>

Description: Writes resampled vp, vs, rho in time in SegY format to files "*prefix*+_vp_time_+*suffix* +.segy", "*prefix*+_vs_time_+*suffix*+.segy" and "*prefix*+_rho_time_+*suffix*+.segy". See Section 5.2 for description of the chosen SegY format.

Argument: Yes or no, default is no.

4.7.19 <elastic-parameters-depth-segy>

Description: Writes resampled vp, vs, rho in depth in SegY format to files "*prefix*+_vp_depth_ +*suffix*+.segy", "*prefix*+_vs_depth_+*suffix*+.segy" and "*prefix*+_rho_depth_+*suffix*+.segy". See Section 5.2 for description of the chosen SegY format.

Argument: Yes or no, default is no.

4.7.20 <extra-parameters-time-segy>

Description: Writes the extra parameters from the Eclipse grid resampled in time in SegY format to files "*prefix*+_+*parameter-name*+_time_+*suffix*+.segy". See Section 5.2 for description of the chosen SegY format.

Argument: Yes or no, default is no.

4.7.21 <extra-parameters-depth-segy>

Description: Writes the extra parameters from the Eclipse grid resampled in depth in SegY format to files "*prefix*+_+*parameter-name*+_depth_+*suffix*+.segy". See Section 5.2 for description of the chosen SegY format.

Argument: Yes or no, default is no.

4.7.22 <seismic-stack>

Description: Writes the seismic stack of all angles as specified under command <angle> in Section 4.2, or for seismic with nmo-stretch (Section 4.5) writes the seismic stack of all offsets as specified under command <offset> in Section 4.5.3.

Example:

```
<seismic-stack>
  <time-storm>  yes </time-storm>
  <depth-storm> yes </depth-storm>
  <time-segy>   yes </time-segy>
  <depth-segy>  yes </depth-segy>
</seismic-stack>
```

4.7.22.1 <time-storm>

Description: Writes the seismic stack in time in Storm format to file "*prefix*+_seismic_time_stack_+*suffix*+.storm"

Argument: Yes or no, default is no.

4.7.22.2 <timeshift-storm>

Description: Writes the seismic stack shifted in time in Storm format to file "*prefix*+_seismic_timeshift_stack_+*suffix*+.storm". The parameter <timeshift-twt> (Section 4.8) must also be given.

Argument: Yes or no, default is no.

4.7.22.3 <depth-storm>

Description: Writes the seismic stack in depth in Storm format to file "*prefix*+_seismic_depth_stack_+*suffix*+.storm"

Argument: Yes or no, default is no.

4.7.22.4 <time-segy>
Description: Writes the seismic stack in time in SegY format to file "*prefix*+_seismic_time_stack_+*suffix*+.segy". See Section 5.2 for description of the chosen SegY format.

Argument: Yes or no, default is no.

4.7.22.5 <timeshift-segy>
Description: Writes the seismic stack shifted in time in SegY format to file "*prefix*+_seismic_timeshift_stack_+*suffix*+.segy". See Section 5.2 for description of the chosen SegY format. The parameter <timeshift-twt> (Section 4.8) must also be given.

Argument: Yes or no, default is no.

4.7.22.6 <depth-segy>
Description: Writes the seismic stack in depth in SegY format to file "*prefix*+_seismic_depth_stack_+*suffix*+.segy". See Section 5.2 for description of the chosen SegY format.

Argument: Yes or no, default is no.

4.8 <timeshift-twt>
Description: TWT used for time-shifted seismic is read from Storm file. This command has only effect if at least one of the output parameters <seismic-timeshift> (Section 4.7.12) or <seismic-timeshift-segy> (Section 4.7.15) is given.

Argument: File name.

4.9 <ps-seismic>
Description: Generate PS seismic instead of PP seismic.

Argument: Yes or no, default is no.

4.10 <traces-in-memory>
Description: Specifies the maximum number of seismic traces that is handled at the time in the program.

Argument: integer, default is 100 000.

4.11 <max-threads>
Description: Specifies the maximum number of threads that can be used by the program.

Argument: integer, default is maximum available threads.

5 File formats

5.1 XML model file example

```
<seismic-forward>
  <elastic-param>
    <eclipse-file > test_2006.grdecl </eclipse-file>
    <default-values>
      <vp-top>  3800 </vp-top>
      <vp-mid>  3400 </vp-mid>
      <vp-bot>  3800 </vp-bot>
      <vs-top>  1200 </vs-top>
      <vs-mid>  1900 </vs-mid>
      <vs-bot>  2100 </vs-bot>
      <rho-top> 2400 </rho-top>
      <rho-mid> 2400 </rho-mid>
      <rho-bot> 2400 </rho-bot>
    </default-values>
    <parameter-names>
      <vp>  VP_2006-07-01   </vp>
      <vs>  VS_2006-07-01   </vs>
      <rho> DENS_2006-07-01 </rho>
    </parameter-names>
    <extra-parameters>
      <name> SCO2diff_2011_09_12_2009_08_20 </name>
      <default-value> 0.0 </default-value>
    </extra-parameters>
  </elastic-param>

  <wavelet>
   <from-file>
    <format>    Landmark             </format>
    <file-name> wavelet_landmark.wvl </file-name>
   </from-file>
  </wavelet>

  <white-noise>
   <standard-deviation> 0.02   </standard-deviation>
   <seed>               123456 </seed>
  </white-noise>

  <nmo-stretch>
   <seafloor-depth>  200 </seafloor-depth>
   <velocity-water> 1500 </velocity-water>
   <offset>
     <offset-0>      0 </offset-0>
     <doffset>      50 </doffset>
     <offset-max> 2000 </offset-max>
   </offset>
  </nmo-stretch>
```

```
  <output-grid>
   <top-time>
     <top-time-constant> 1200 </top-time-constant>
   </top-time>
   <area>
    <x0>  540000 </x0>
    <y0> 6710000 </y0>
    <lx>    4000 </lx>
    <ly>   10000 </ly>
    <angle>   45 </angle>
   </area>
   <cell-size>
    <dx> 50 </dx>
    <dy> 50 </dy>
    <dz>  1 </dz>
    <dt>  4 </dt>
   </cell-size>
   <segy-indexes>
     <inline-start>     5 </inline-start>
     <xline-start>      5 </xline-start>
     <inline-direction> y </inline-direction>
     <inline-step>      1 </inline-step>
     <xline-step>      -1 </xline-step>
   </segy-indexes>
  </output-grid>

  <output-parameters>
   <prefix> parameters </prefix>
   <suffix> grid       </suffix>
   <elastic-parameters> yes </ elastic-parameters>
   <reflections>        yes </reflections>
   <zvalues>            yes </zvalues>
   <twt>                yes </twt>
   <time-surface>       yes </time-surface>
   <depth-surface>      yes </depth-surface>
   <seismic-time-segy>  yes </seismic-time-segy>
   <seismic-depth-segy> yes </seismic-depth-segy>
   <elastic-parameters-time-segy> yes </elastic-parameters-time-segy>
   <elastic-parameters-depth-segy>yes </elastic-parameters-depth-segy>
   <extra-parameters-time-segy>   yes </extra-parameters-time-segy>
   <extra-parameters-depth-segy>  yes </extra-parameters-depth-segy>
   <seismic-stack>
     <time-storm>  yes </time-storm>
     <depth-storm> yes </depth-storm>
     <time-segy>   yes </time-segy>
     <depth-segy>  yes </depth-segy>
   </seismic-stack>
  </output-parameters>

</seismic-forward>
```

5.2 SegY header format for output

The following numbers are used in the trace header in SegY output files:

Variable	**Byte number**
Offset in meters or angle in degree	37
Start time/depth in seismic trace	109
X coordinate	181
Y coordinate	185
Inline number	189
Crossline number	193

5.3 SegY header formats for input

The following formats are recognized in input files (<area-from-segy>):

	Seisworks	**IESX**	**SIP**	**Charisma**	**SIPX**
Variable	Byte number	Byte number	Byte number	Byte number	Byte number
X coordinate	73	73	181	73	73
Y coordinate	77	77	185	77	77
Inline number	9	221	189	5	181
Crossline number	21	21	193	21	185

5.4 Landmark ASCII Wavelet input file

The Landmark ASCII Wavelet file has 4 headers before the wavelet sampling follows with one sample on each line;

1. Format
2. Number of samples
3. Sample number for zero time
4. Time sampling in *ms*

Example:

```
Landmark ASCII Wavelet
23
12
4
0
-1.84436E-05
-0.000220463
-0.001927747
-0.012221013
-0.055374287
-0.174860489
-0.36509521
-0.433627901
-0.077581906
0.620928647
1
0.620928647
-0.077581906
-0.433627901
-0.36509521
-0.174860489
-0.055374287
-0.012221013
-0.001927747
-0.000220463
-1.84436E-05
0
```

6 References

Buland, A. and Omre, H.(2003). Bayesian linearized AVO inversion. *Geophysics*, 68:185-198.

Dahle, P., Fjellvoll, B., Hauge, R., Kolbjørnsen, O., Syversveen, A.R., Ulvmoen, M. (2011) CRAVA User Manual version 0.9.9. NR Note SAND/03/2011.

Stolt, R.H. and Weglein, A.B. (1985). Migration and inversion of seismic data. *Geophysics*, 50:2458-2472.