Preparing input data for joint PP/PS inversion

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ABSTRACT

Joint inversion of PP and PS seismic data, utilising the inherent AVO information, was established as a useful interpretive technique several years ago. Subsequently, a ProMAX module was written to perform the computations on either models or seismic field data. While the software has existed for some time and has been released to sponsors, clear instructions for use of the module did not exist; and it was only by detailed examination of the source code, and the thesis on which it was based, that the user could learn about the requirements for input data as well as the format of the output data. This chapter details the steps necessary to prepare input data for the joint inversion and describes the output in some detail. A help file now exists for the ProMAX joint inversion module which guides a novice user in the preparation of input data, running of the module, and identification of output traces. The help file is included as an appendix to this chapter.

INTRODUCTION

Inversion of seismic data is the procedure by which a seismic interpreter relates the observed seismic response to useful rock properties in the earth. Techniques for inverting PP seismic reflection data have existed for many years. With the advent of technology for the identification and processing of converted PS seismic data, a potential new source of rock property information emerged, and methods were devised to invert PS data as well. Since any seismic profile for which a PS wavefield can be recorded also has an associated PP reflection wavefield, a logical extension of conventional inversion is to jointly invert both PP and PS data over the same subsurface zone in order to obtain more rock property information than is available from either data set alone. The background for joint PP/PS inversion, using AVO information from both data sets, is described in some detail by Larsen (1999), based on earlier work by Simin et al. (1996), Stewart (1990), Xu and Bancroft (1997), and others. The ProMAX inversion operation closely follows Larsen's work and was written by Xinxiang Li.

While conventional seismic inversion uses a single seismic trace, assumed to be at vertical incidence, to invert for impedance, the joint inversion algorithm uses several seismic traces which share a common subsurface reflection or conversion point, but which have different angles of incidence. By using PP reflection traces from several offset ranges and PS traces also from several offset ranges, not only can PP impedance and PS impedance be computed, but additional rock property parameters as well. The text which follows, in conjunction with the appendix, describes how to prepare input for the joint inversion module from raw gathers of PP reflection traces and PS converted traces.

INPUT DATA PREPARATION

The starting point for PP data preparation is gathers of traces sorted by CDP and absolute offset, while for PS data, gathers of traces mapped to CCP (common conversion point) and sorted by CCP and absolute offset are required. Any CDP gathers not having corresponding CCP gathers may be discarded, and vice versa, since there should be a one-to-one correspondence between CDP and CCP numbers. There are three skeleton processing flows illustrated in the help file (appendix) which may then be used to properly composite and arrange the traces from these two data sets.

The first flow illustrates the creation of limited-offset stack traces from either CDP or CCP gathers (It is assumed that PP and PS data will be processed separately at this stage). As can be seen, the flow consists of input of one or the other of the PP or PS data sets, NMO correction, and a cascade of conditional loops, each of which accepts only traces having absolute offsets within the limits specified in the IF statement. Within each loop, a sort operation first orders the traces by absolute offset and forms new ensembles. Next, a new operation 'Mean offset' computes the mean offset for each ensemble and creates a new trace header, 'meanoff', in which to post the value. Each limited-offset ensemble is then written out to a disc file as the last operation in the loop. The product of this flow is one file per conditional loop, each containing the decimated CDP or CCP gathers whose individual trace offsets fall within the corresponding offset range and whose traces all contain a new trace header whose value is the mean offset for each decimated gather.

Input for the second skeleton flow consists of the set of files created by the first flow; that is, sets of limited-offset CDP or CCP gathers with the new 'meanoff' header in each trace. The flow consists of a short sequence of operations, repeated once for each set of limited-offset gathers. In each sequence, the corresponding file of limited-offset ensembles is stacked by CDP (or CCP), then post-stack time migrated using Kirchhoff migration or other suitable algorithm, and finally depth converted. The last step before output of each file of migrated limited-offset stack traces is the placement of the 'meanoff' header in the 'aoffset' (absolute offset) header slot for use by the joint inversion algorithm. To recap, each file of limited-offset CDP or CCP gathers is stacked, migrated, and depth converted, and the mean offset value posted to the absolute offset trace header slot before writing out the resulting limited-offset PP or PS stack traces as a new file. It should be emphasized that this flow is not the only possible one for reducing the limited-offset ensembles to migrated, depth-converted limited-offset stack traces. Other sequences can certainly be constructed, depending upon data quality and the interpretation objectives. NMO correction can be deferred from the first flow, for example, and some form of pre-stack migration used in the second, instead of CDP stack and post-stack migration. Likewise, post-stack time migration and depth conversion can be replaced with post-stack depth migration, and so forth.

At this point, the processor may wish to 'flatten' the limited-offset PP and PS stack traces to a common horizon. While a flow is not shown for this procedure, one possible procedure is the following. For each file of migrated, depth-converted limited-offset stack traces generated above:

- In the 'Trace Display' operation, hand-pick the desired horizon event, and create a horizon pick file.

- In the 'Horizon Flattening' operation apply the horizon picks for each trace file, and shift the horizon event to the desired output depth (should be the same for all the PP and PS limited-offset stack panels).

- Check 'Trace Display' for all the limited-offset stack panels (the event chosen for the flattening horizon should be flat and shifted to the same depth on each panel).

- Write each flattened limited-offset panel to a new file.

The final procedure in the data preparation for joint PP-PS inversion is simply to merge the various limited-offset stack traces into a single file with the traces in the order expected by the operation. A skeleton flow to accomplish this step is shown in the help file. It consists of a 'Disc data input' operation to read in the PP limited-offset stack trace file for the first limited-offset range, followed by a sequence of 'Disc data insert' operations, one for each of the remaining PP limited-offset stack trace files as well as for each of the PS limited-offset stack trace files. The files should be read in order, starting with the PP limited-offset stack file with the smallest average offset, the PP limited-offset stack with the next smallest average offset, and so on.

After all the PP limited-offset files have been read, the PS limited-offset files are read, starting with the smallest average offset, etc. The 'Disc data insert' operation should always be used in the 'after' mode, so that trace files are appended, one after the other. Each 'Disc data insert' operation updates the DS_SEQNO trace headers of the traces in the file being read so that the traces from the first 'Disc data insert' have a DS_SEQNO of 2, the second 'Disc data insert' 3, and so on.

An 'Inline sort' operation following the input of all the data files then uses the primary sort key 'CDP' and the secondary sort key 'DS_SEQNO' to place the limited-offset PP and PS stack traces into the order expected by the 'Joint PP&PS AVO inversion' ProMAX module.

To reiterate, the inversion module expects, for each CDP (CCP), an ensemble consisting of the PP limited-offset traces in order of increasing mean offset, followed by the corresponding PS limited-offset traces, also in order of increasing mean offset (remember that mean offset has been placed in the AOFFSET trace headers in the second pre-processing flow).

DATA OUTPUT FROM JOINT INVERSION

Prior to the work reported here, it was difficult for the uninitiated processor to correctly identify the data traces output from the 'Joint PP&PS AVO inversion' module. The number and type of output data traces is determined not only by the number and type of input traces, but also by parameter choices within the module. Every input CDP ensemble of PP and PS traces leads to a corresponding output CDP ensemble containing at least one trace, but possibly many traces, depending upon input data and parameter selection.

In the most general case, each output ensemble will consist of N groups of four impedance traces, where N is the number of relative depth shifts to be tested between the horizon event on the input PP traces and the same event on PS traces. Each group of four impedance traces consists of a P impedance trace (delta I /I), an S impedance trace (delta J/J), a lambda*rho trace {delta(lambda*rho)/ (lambda*rho)}, and a lambda/mu trace {delta(lambda/mu)/(lambda/mu)}, in that order. To make the traces within the ensemble distinguishable from one another, each contains four new trace headers:

- 'IMPEDANC' (values 1, 2, 3 or 4)
- 'VZSHIFT' (relative depth shift between PP and PS input traces)
- 'SHIFTIDX' (shift index number)
- 'ZSTART' (start depth for the inversion—depth of first output sample value)

Using one or more of these new headers, the output data file can be sorted into impedance panels of various kinds, the most common being P or S impedance as a function of depth and CDP for a constant relative PP/PS depth shift value.

If the processor is confident that the horizon-flattening process has been done accurately, then the 'shift_opt' parameter in the joint inversion module may be set to 'false', causing only one set of four impedance traces to be created for each output CDP, and thereby greatly shrinking the size of the output data file. Limiting the range of depths for the inversion computation (using the 'zstart' and 'zend' parameters) will limit the length of the output traces. Finally, if no PS traces are available for joint inversion, the parameter 'noffPS' will be zero, and the joint inversion module creates a single output trace per CDP—the P impedance. In this case, a set of input ensembles with only PP traces leads to the output of a single P impedance panel.

CONCLUSIONS

The process of joint PP/PS inversion has been clarified with a more detailed explanation for preparing required input data, and a description of output expected from the joint inversion module. Further clarification should result from a careful reading of the joint inversion help file, attached as an appendix.

ACKNOWLEDGEMENTS

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REFERENCES

Larsen, J.A., 1999, AVO inversion by simultaneous P-P and P-S inversion, M.Sc. Thesis, University of Calgary, Department of Geology and Geophysics.

Simin, V., Margrave, G.F., and Yang, G.C., 1996, AVO measurements for P-P and P-S data in the Blackfoot 3C-3D dataset: CREWES Research Report, Vol. **8**, Ch. 42.

Stewart, R.R., 1990, Joint P and P-SV inversion: CREWES Research Report Vol. **2**, pp 112-115.

Xu, Y. and Bancroft, J.C., 1997, Joint analysis of PP and PS seismic data: CREWES Research Report, Vol. **9**.

APPENDIX

The content of this appendix is the help file associated with the ProMAX joint PP/PS inversion module.

Simultaneous PP and PS Inversion

This module performs seismic inversion for AVO analysis of selected portions of a seismic data set. The inversion can be done for pure compressional-wave data (PP data), but the module is primarily intended to perform a simultaneous inversion based on the theory presented in the M.Sc. thesis by Jeffrey Larsen. In this technique, both compressional (PP) and converted-wave shear (PS) traces are used to provide estimates of not only compressional-wave impedance (delta I /I), but also shear-wave impedance (delta J /J), and the Lame' parameters, {delta (lambda*rho)/(lambda*rho)} and {delta (lambda/mu)/(lambda/mu)}. The computations are performed on gated portions of PP and PS seismic traces obtained by partial stacking, over limited ranges of offsets, of input PP CDP gathers and PS CCP gathers. These are prepared by sorting (CDP gathers), mapping (CCP gathers), and NMO correction (both CDP and CCP gathers); stacking; migration; and conversion to depth. Because of the difficulty of matching PP and PS seismic traces exactly in depth, a range of depth shifts between PP and PS data may be specified, and the inversion carried out for each shift in the range. The data presented to this program must consist of gathers sorted by CDP (CCP) and DS_SEQNO. In each gather will be first a set of PP limited-offset stack traces, followed by a set of PS limited-offset stack traces; each trace previously migrated, converted to depth, and having its absolute offset trace header set to the mean offset for the corresponding partial stack. Suggested flows for input data preparation are described below.

The output data, on the other hand, will consist of a series of gathers, each corresponding in CDP to one of the input gathers, but containing four traces for each of the PP-PS depth shift values requested. The four traces correspond to P-impedance (delta I/I), S-impedance (delta J/J), {delta (Lambda*rho)/(lambda*rho)}, and {delta (Lambda/mu)/(Lambda/mu)}, respectively, computed over the requested depth range at the specified PP-PS shift, and they contain new trace headers that allow them to be identified and sorted by impedance trace type as well as shift value for archival output and display.

Theory

The main objective of interpretation of seismic data is the extraction of information most closely related to the lithology and/or fluid content of the rocks being imaged. The quantity most closely related to seismic trace amplitudes, and that best characterizes rock properties, is the elastic impedance (or more properly the differential impedance), which can be extracted from a seismic reflectivity trace, given some additional rock velocity knowledge. Theoretical knowledge about the variation of reflectivity with offset (some form or approximation of the Zoeppritz equations) can also be used to refine impedance estimates, if the input traces correspond to non-zero source-receiver offsets. When observations of more than one wave mode (like PS converted-waves) are available for the same seismic profile, estimates of other rock properties in addition to the compressional impedance can be made. Among these is the differential shear impedance, and rock property parameters related to coupled P and S wave propagation like the Lame' parameters Lambda/Mu and Lambda*Rho. The theory outlined in the Larsen thesis describes how weighting factors depending on offset are obtained for both PP and PS data, and how the trace amplitudes are subsequently combined, using these weighting factors, to obtain compressional impedance, shear impedance, Lambda/Mu, and Lambda*Rho traces.

Usage

Data Preparation

The PP/PS joint inversion module requires the input data to be in a particular arrangement, which requires some pre-processing on the part of the user. Specifically, the required input consists of CDP gathers, each gather containing N PP traces and M PS traces, where N is the number of PP offset ranges used and PS is the number of PS offset ranges used. Each trace is the result of stacking NMO-corrected PP or PS traces from a limited range of offsets and contains the mean offset for the particular group of prestack traces in the AOFFSET trace header, as well as a value in the DS_SEQNO header which distinguishes the trace as being PP or PS and coming from a particular limited-offset stack range. The final requirement for the input traces is that they have been converted to depth, and optionally flattened to a common event. Following are some suggested flows for preparing the data gathers required by the joint PP/PS inversion. It is understood that 'CDP' actually means CCP (common conversion point) for PS data:

A flow to create either PP or PS limited-offset CDP gathers with mean offset computed and stored in trace headers. This flow uses a ProMAX module called 'mean offset' by D. Henley:

```
Disc Data Input  (the raw PP or PS CDP gathers)
Normal Moveout   (apply normal moveout so that traces
                  can be stacked later in limited
                  offset ranges)
IF     (test for AOFFSET between XMIN1 and XMAX1)
     Inline Sort  (sort over CDP and AOFFSET to create
                   limited-offset CDP ensembles)
     Mean Offset  (compute mean offset, place in new
                   MEANOFF trace header; also set
                   DS_SEQNO header to user parameter)
     Disc Data Output (the limited-offset PP or PS CDP
```

```
                       gathers, with proper headers)
ENDIF
IF     (test for AOFFSET between XMAX1 and XMAX2)
       Inline Sort
       Mean Offset
       Disc Data Output (limited-offset PP or PS CDP
                         gathers)
ENDIF
IF     (test for AOFFSET between XMAX2 and XMAX3)
       Inline Sort
       Mean Offset
       Disc Data Output (limited-offset PP or PS CDP
                         Gathers)
ENDIF
etc.
```

A flow to stack the limited-offset CDP gathers, (optionally migrate them), and move the mean offset to the AOFFSET trace header:

```
Disc Data Input (a set of limited-offset CDP gathers
                 created by the previous flow for either
                  PP or PS traces)
CDP ensemble stack  (stack all input traces by CDP)
Kirchhoff time migration (or other suitable poststack
                          migration operation)
Depth conversion  (convert traces from time to depth
                   Before output)
Trace Header Math  (set AOFFSET = MEANOFF)
Disc Data Output (limited-offset CDP stack traces, in
                  depth, for one offset range, for either
                  PP or PS, with AOFFSET containing the
                  Mean offset for each input CDP gather)
Disc Data Input (the next set of limited-offset CDP
                 gathers created by the previous flow for
                 either PP or PS traces)
CDP ensemble stack  (stack all input traces by CDP)
Kirchhoff time migration (or other poststack migration)
Depth conversion  (convert traces from time to depth
                   Before output)
Trace Header Math  (set AOFFSET = MEANOFF)
Disc Data Output (limited-offset CDP stack traces, in
                  depth, for one offset range, for either
                  PP or PS, with AOFFSET containing the
                  Mean offset for each input CDP gather)
etc.
```

Further processing will be required if it is desired to flatten the depth sections created above to a specific horizon. This processing should precede the compositing operation below, which creates the final CDP gathers for input to joint inversion. A suggested approach is to take each output file created in the preceding flow, display it as a panel in 'Trace Display', hand pick the desired flat horizon event to create a horizon pick file, and apply the horizon pick file to the traces in the file using the 'Horizon Flattening' operation. Care should be taken to pick the same loop, (or trough, or zero-crossing) on the flat horizon event on all the panels, and to use the same desired output time (depth, actually) on each 'Horizon Flattening' operation.

A flow to composite the separate PP and PS limited-offset stacks into gathers for joint PP/PS inversion:

```
Disc Data Input (first limited-offset PP stack traces for
                 first PP offset range)
Disc Data Insert (second limited-offset PP stack traces
                 For second PP offset range)
.....
Disc Data Insert (last limited-offset PP stack traces for
                  final PP offset range)
Disc Data Insert (first limited-offset PS stack traces
                  for first PS offset range)
Disc Data Insert (second limited-offset PS stack traces
                  For second PS offset range)
.....
Disc Data Insert (last limited-offset PS stack traces for
                  last PS offset range)
Inline Sort  (sort data on CDP, DS_SEQNO)
Disc Data Output (CDP gathers of limited-offset PP and PS
                  stack traces, properly labeled with
                  AOFFSET equal to the average offset
                  for each trace)
```

Parameters

noffPP

This parameter is the number of PP limited-offset stack traces to be expected in each input CDP gather. Default is 3 (near stack, middle stack, far stack)

noffPS

This is the number of PS limited-offset stack traces to be expected in each CDP gather. The gathers must be sorted so that all 'noffPP' PP traces precede the 'noffPS' PS traces. There should be a maximum of noffPP + noffPS traces per gather. A particular CDP may have missing traces as long as the DS_SEQNO header of each trace present correctly indicates to which limited-offset stack the trace belongs (see Data Preparation above). Default is 3 (near stack, middle stack, far stack). If this parameter is set to zero, the resulting inversion is a PP inversion only, and no PS traces should be present in the input gathers (if they are present, they will be ignored and warning messages printed)

off_opt

This parameter simply selects whether or not to obtain the maximum trace offset value from the database or whether to read it from the next parameter. 'True' means select from database, 'false' means read from parameter. Default is 'true' *hmax*

This is the maximum offset value parameter supplied by the user, if the previous parameter is set to 'false'. This value is used simply as an endpoint for building parameter and coefficient tables. It is not used in the actual computations.

vp_opt

This parameter selects whether to obtain the Vp interval velocity vs depth function from the database ('true') or to enter it from the keyboard ('false'). Default is 'true'

vpf

This parameter is the file selector for choosing an interval velocity function labelled 'VID' from the database. It is active only if the vp_opt parameter above is 'true'.

vps

This parameter receives the keyboard input for the Vp interval velocity function, if the vp_opt parameter is 'false'. The function is entered as hyphenated time-velocity pairs separated by commas. Each set of time-velocity pairs is preceded by its corresponding CDP number and a colon, and followed by a slash.

vs_opt

This parameter selects whether to obtain the Vs interval velocity vs depth function from the database ('true') or to enter it from the keyboard ('false'). Default is 'true'

vsf

This parameter is the file selector for choosing an interval velocity function labelled 'VID' from the database. It is active only if the vs_opt parameter above is 'true'.

vss

This parameter receives the keyboard input for the Vs interval velocity function, if the vs_opt parameter is 'false'. The function is entered as hyphenated time-velocity pairs separated by commas. Each set of time-velocity pairs is preceded by its corresponding CDP number and a colon, and followed by a slash.

scalp

This parameter receives the trace scale factors for the PP traces. Since a table of these factors is created by interpolation for all offsets, the supplied factors need not correspond to actual trace header offsets, but only to fall within the accepted range of offsets for the data set. If no values are supplied, all the scale factors are set to unity. The scale factors are entered as hyphenated offset-scale factor pairs separated by commas. Each set of offset-factor pairs is preceded by its corresponding CDP number and a colon, and followed by a slash.

scals

This parameter receives the trace scale factors for the PS traces. Since a table of these factors is created by interpolation for all offsets, the supplied factors need not correspond to actual trace header offsets, but only to fall within the accepted range of offsets for the data set. If no values are supplied, all the scale factors are set to unity. The scale factors are entered as hyphenated offset-scale factor pairs separated by commas. Each set of offset-factor pairs is preceded by its corresponding CDP number and a colon, and followed by a slash.

scaltype

This parameter selects whether to apply the prceding scale factors to the RMS trace amplitude or to the average absolute trace amplitude. Default is 'RMS'

maxangle

This is the maximum allowable incident angle to use in constructing the parameter and coefficient tables. Its default is 50 degrees.

shift_opt

This switch parameter chooses whether to apply a series of shifts to the PS traces and to perform the inversion for each of the shifts. Choosing this parameter to be 'true' leads to the generation of a lot of output traces (4 traces for each shift value for each CDP). The default setting is 'true'.

maxshift

This parameter chooses the maximum depth shift applied to the PS traces relative to the PP traces. The traces will then be incrementally shifted from +maxshift to -maxshift and an inversion with its four output traces computed at each incremental shift value. The shift increment will be whatever depth sample increment is native to the depth-converted input traces. The default value is 20.0 (m or ft, whichever units are used in the data).

zstart

This parameter determines the depth at which the inversion will begin. The inversion is only computed for the selected range of depth. If this and the next parameter are defaulted, the entire input trace(s) is inverted.

zend

This parameter determines the depth at which the inversion will stop. The inversion is only computed for the range of depths selected by this parameter and the previous one. If both parameters are defaulted, the entire input trace(s) is inverted.

Output Data

The number and length of output traces for each input trace ensemble depends not only upon the number and type of input traces, but also upon the choice of a number of parameters in the inversion algorithm. In the most general case, where joint inversion is performed on CDP ensembles of PP and PS input traces, for a variety of relative depth shifts between PP and PS data, over a range of depths, each output CDP ensemble consists of four impedance traces for each depth shift value in the range generated by the input parameters. Each trace consists of impedance values between the minimum and maximum depths specified in the parameters; and within each group of four impedance traces, the P impedance trace (delta I/I) precedes the S impedance trace (delta J/J), followed by {delta(lambda*rho)/(lambda*rho)} and {delta(lambda/mu)/(lambda/mu)}. All the traces output from the joint inversion contain four new trace header fields which can be used to identify and sort them. These header fields are 'IMPEDANC' (= 1,2,3, OR 4); 'VZSHIFT' (contains the actual depth shift between PP and PS input traces); 'SHIFTIDX' (contains the index of the shift, useful for sorting); and 'ZSTART' (contains the start depth of the inversion, the depth of the first output impedance sample). After running 'Joint PP&PS AVO inversion', for example, an 'inline sort' with the primary sort key 'IMPEDANC', secondary sort key 'SHIFTIDX', and tertiary sort key 'CDP' will yield a set of ensembles (panels), the first of which is the P impedance traces for each CDP for the first relative depth shift between PP and PS data, the second is the P impedance traces for each CDP for the second relative depth shift, etc. The P impedance panels are followed by the S impedance panels, one for each shift, then the Lame' parameter panels.

Clearly, there is potential to unsuspectingly generate a great deal of output data. If there are 100 input CDP ensembles of 3 PP and 3 PS traces each, prepared as described above, and if the start depth of the inversion is zero, the end depth maximum, and if 10 relative shifts per inversion are requested, the relatively modest input of 600 traces will lead to an output of 4000 output traces of the same length (100 ensembles containing 10 groups of 4 traces each). If the processor is relatively confident of the proper registration in depth of the PP and PS traces as prepared for input, the output can be cut by a factor of 10 by choosing the parameter shift_opt to be false; in which case, only 4 impedance traces will be created for each output CDP. Furthermore, if the impedance is only required over a small depth range around the target horizon, the zstart and zend parameters can be chosen to limit the length of the output impedance traces. Finally, if no PS traces are available to do joint inversion, the parameter noffPS can be set to zero; in which case only one trace (P impedance) is created per output CDP.