Wide-Azimuth, Far-Offset, First-Break Positioning: A User’s Manual

(Hydrometronics First-Break Analysis)

Noel Zinn
Hydrometronics LLC
www.hydrometronics.com
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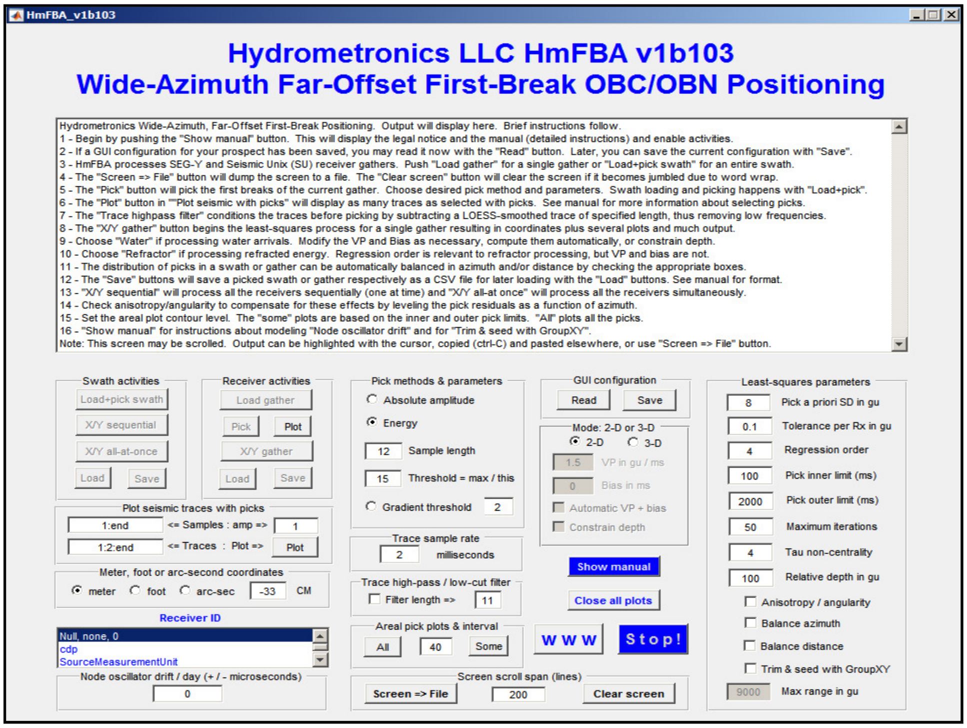
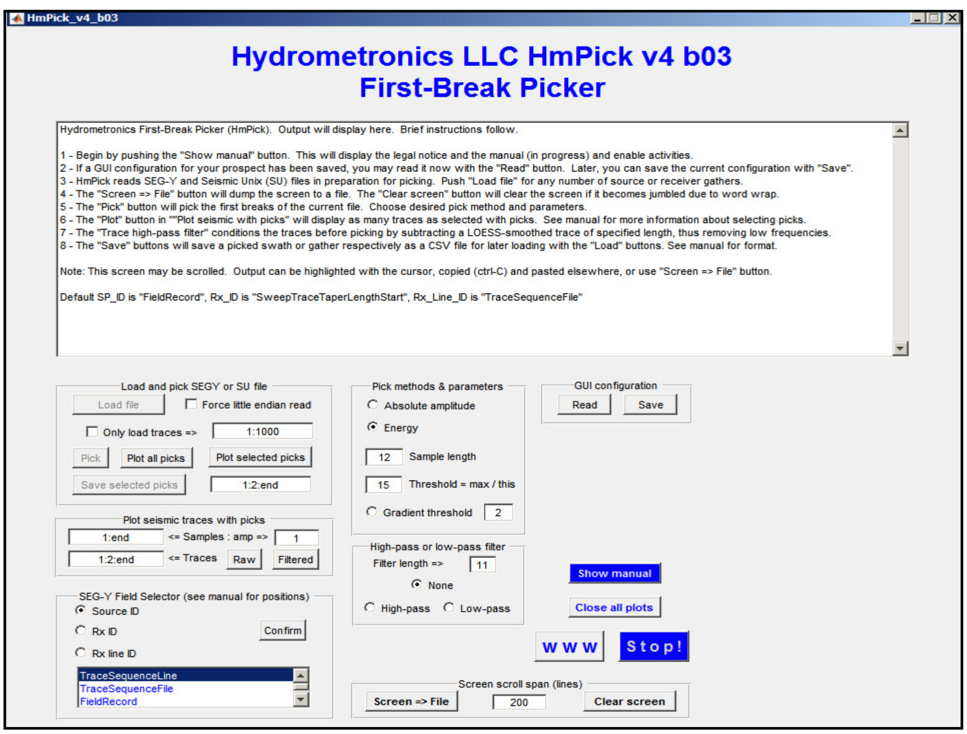

HmFBA_v1b103
Hydrometronics LLC HmFBA v1b103
Wide-Azimuth Far-Offset First-Break OBC/OBN Positioning
Hydrometronics Wide-Azimuth, Far-Offset First-Break Positioning. Output will display here. Brief instructions follow.
1 - Begin by pushing the "Show manual" button. This will display the legal notice and the manual (detailed instructions) and enable activities.
2 - If a GUI configuration for your prospect has been saved, you may read it now with the "Read" button. Later, you can save the current configuration with "Save".
3 - HmFBA processes SEG-Y and Seismic Unix (SU) receiver gathers. Push "Load gather" for a single gather or "Load+pick swath" for an entire swath.
4 - The "Screen => File" button will dump the screen to a file. The "Clear screen" button will clear the screen if it becomes jumbled due to word wrap.
5 - The "Pick" button will pick the first breaks of the current gather. Choose desired pick method and parameters. Swath loading and picking happens with "Load+pick".
6 - The "Plot" button in ""Plot seismic with picks" will display as many traces as selected with picks. See manual for more information about selecting picks.
7 - The "Trace highpass filter" conditions the traces before picking by subtracting a LOESS-smoothed trace of specified length, thus removing low frequencies.
8 - The "X/Y gather" button begins the least-squares process for a single gather resulting in coordinates plus several plots and much output.
9 - Choose "Water" if processing water arrivals. Modify the VP and Bias as necessary, compute them automatically, or constrain depth.
10 - Choose "Refractor" if processing refracted energy. Regression order is relevant to refractor processing, but VP and bias are not.
11 - The distribution of picks in a swath or gather can be automatically balanced in azimuth and/or distance by checking the appropriate boxes.
12 - The "Save" buttons will save a picked swath or gather respectively as a CSV file for later loading with the "Load" buttons. See manual for format.
13 - "X/Y sequential" will process all the receivers sequentially (one at time) and "X/Y all-at once" will process all the receivers simultaneously.
14 - Check anisotropy/angularity to compensate for these effects by leveling the pick residuals as a function of azimuth.
15 - Set the areal plot contour level. The "some" plots are based on the inner and outer pick limits. "All" plots all the picks.
16 - "Show manual" for instructions about modeling "Node oscillator drift" and for "Trim & seed with GroupXY".
Note: This screen may be scrolled. Output can be highlighted with the cursor, copied (ctrl-C) and pasted elsewhere, or use "Screen => File" button.
Swath activities
Receiver activities
Pick methods & parameters
GUI configuration
Least-squares parameters
Show manual
Close all plots
W W W
Stop!
Screen => File
Clear screen


HmPick_v4_b03
Hydrometronics LLC HmPick v4 b03
First-Break Picker
Hydrometronics First-Break Picker (HmPick). Output will display here. Brief instructions follow.
1 - Begin by pushing the "Show manual" button. This will display the legal notice and the manual (in progress) and enable activities.
2 - If a GUI configuration for your prospect has been saved, you may read it now with the "Read" button. Later, you can save the current configuration with "Save".
3 - HmPick reads SEG-Y and Seismic Unix (SU) files in preparation for picking. Push "Load file" for any number of source or receiver gathers.
4 - The "Screen => File" button will dump the screen to a file. The "Clear screen" button will clear the screen if it becomes jumbled due to word wrap.
5 - The "Pick" button will pick the first breaks of the current file. Choose desired pick method and parameters.
6 - The "Plot" button in ""Plot seismic with picks" will display as many traces as selected with picks. See manual for more information about selecting picks.
7 - The "Trace high-pass filter" conditions the traces before picking by subtracting a LOESS-smoothed trace of specified length, thus removing low frequencies.
8 - The "Save" buttons will save a picked swath or gather respectively as a CSV file for later loading with the "Load" buttons. See manual for format.
Note: This screen may be scrolled. Output can be highlighted with the cursor, copied (ctrl-C) and pasted elsewhere, or use "Screen => File" button.
Default SP_ID is "FieldRecord", Rx_ID is "SweepTraceTaperLengthStart", Rx_Line_ID is "TraceSequenceFile"
Load and pick SEGY or SU file
Pick methods & parameters
GUI configuration
SEG-Y Field Selector (see manual for positions)
Show manual
Close all plots
W W W
Stop!
Screen => File
Clear screen

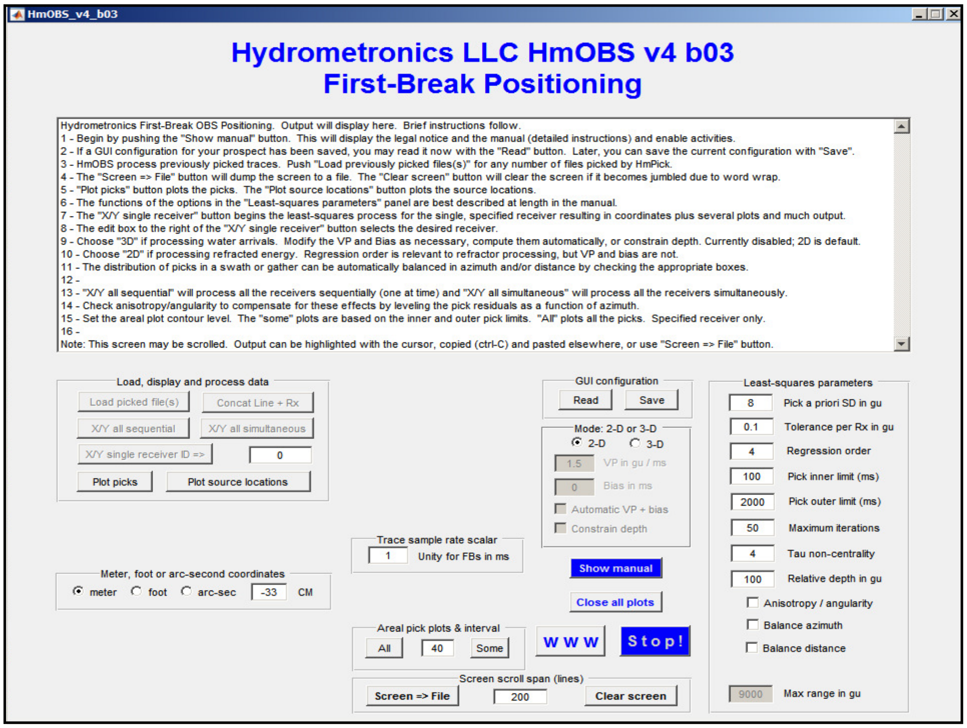


Table of Contents

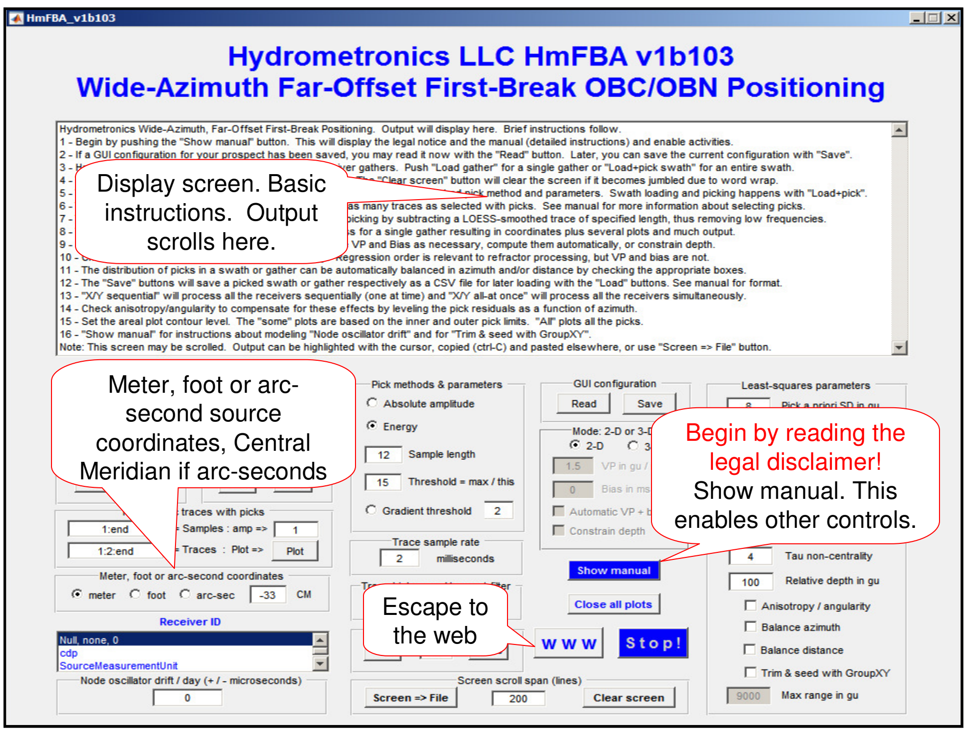
Overview

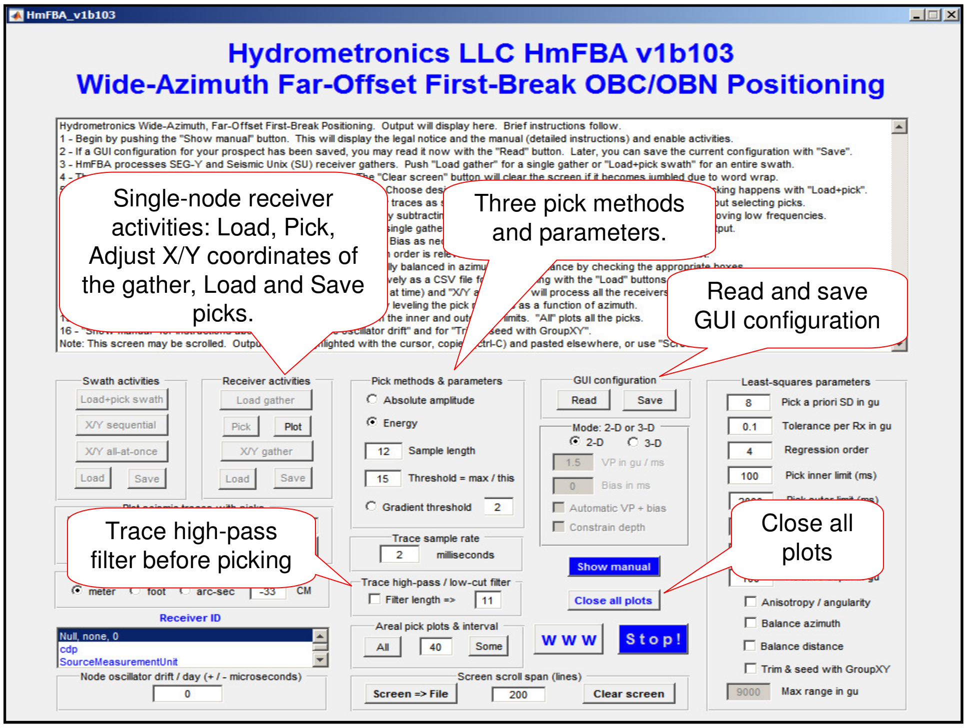
- Hydrometronics First-Break Analysis loads, picks and adjusts direct water-arrival and/or wide-azimuth, far-offset refracted-arrival OBS receiver gathers in SEG-Y or Seismic Unix (SU) formats receiver-by-receiver, shot by shot or an entire swath for best position.
- Computations are done in map projection grid units (gu, which are meters or feet) determined by the SEG-Y or SU. Described later.
- FBA picks first breaks using three very different methods with user-selectable parameters, saves and loads first breaks as CSV files (see Appendix 2 for format), and optionally conditions seismic traces with a high-pass filter for better picking.
- Seismic traces with their first-break picks plotted can be viewed.
- Picks can be viewed in areal contour plots as additional QC.
- FBA solves for receiver or swath vertical velocity gradient (in 2-D mode), optionally balances geometry, optionally compensates for anisotropy/angularity, trims & seeds with GroupXY, and provides diagnostic QC statistics and graphics.
- FBA provides rapid feedback from picking to positions.
- If interested in having your data processed in FBA or in trying FBA yourself, then contact Hydrometronics LLC:
  - www.hydrometronics.com
  - noel.zinn@hydrometronics.com

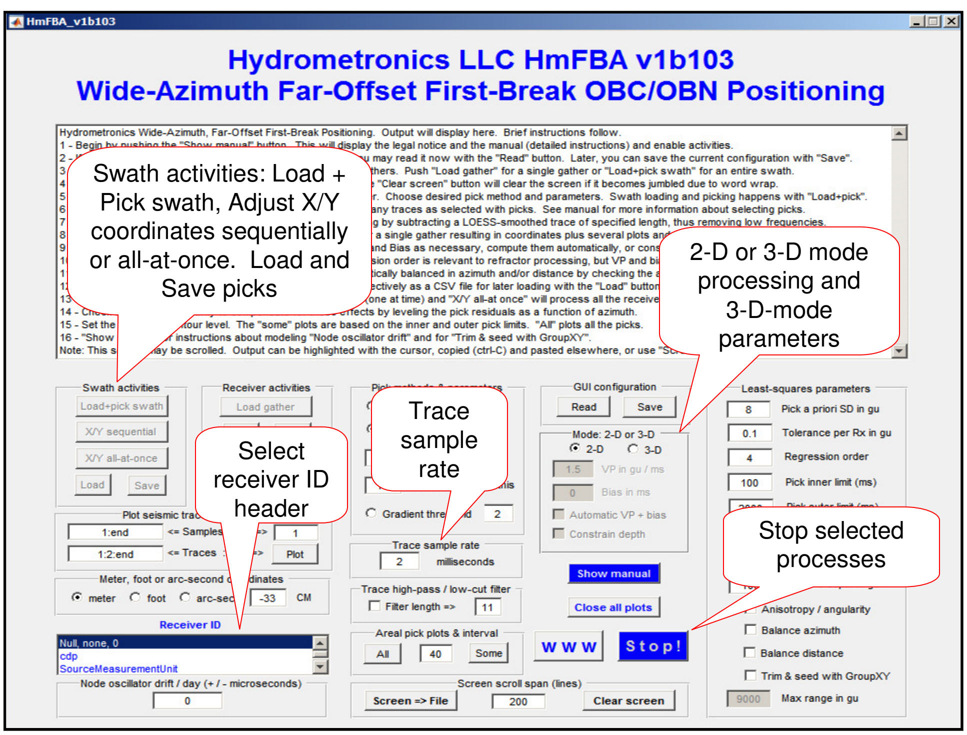
Evolution of FBA

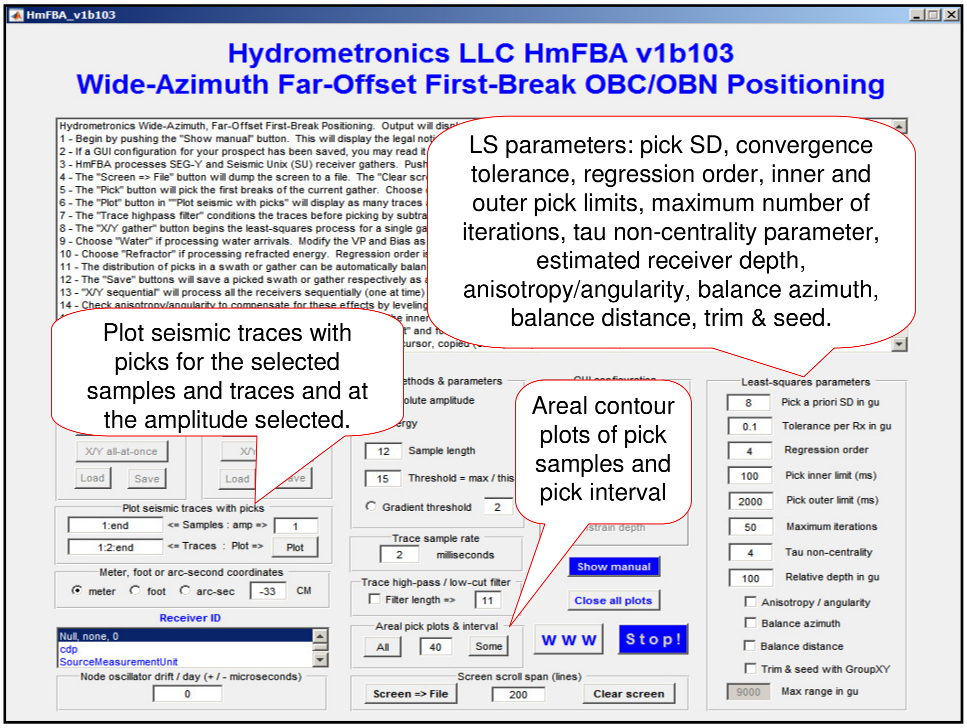
- Hydrometronics First-Break Analysis began with HmFBA, which continues as a self-contained application that picks and positions receiver gathers.
- Responding to a need to process shot gathers, HmFBA was split into HmPick, which picks shot or receiver gathers and produces an ASCII interchange file of picks that can be opened in a spreadsheet, and HmOBS, which reads any number of pick files and positions receivers by least squares similarly to HmFBA.
- Together HmPick and HmOBS provide additional functionality than HmFBA alone, but they can be used separately (HmPick as just a picker, for example).
- The manual you are reading now is an HmFBA manual that has been supplemented with notes on the different functionality of HmPick or HmOBS. Most of what you read about HmFBA applies to either HmPick or HmOBS.

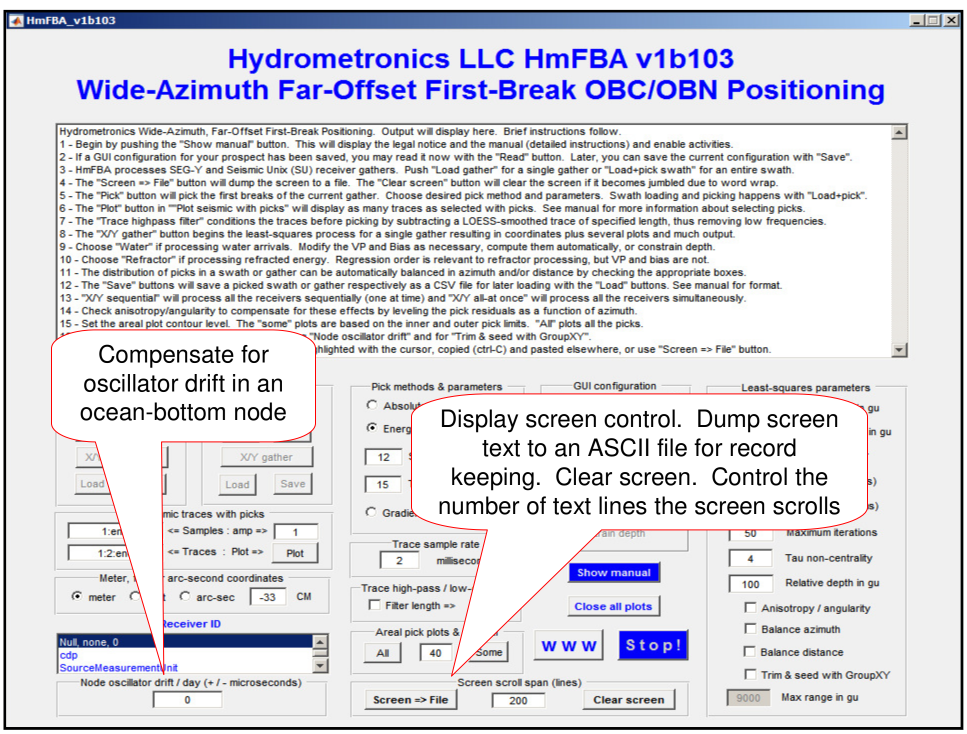
A Tour of the Applications

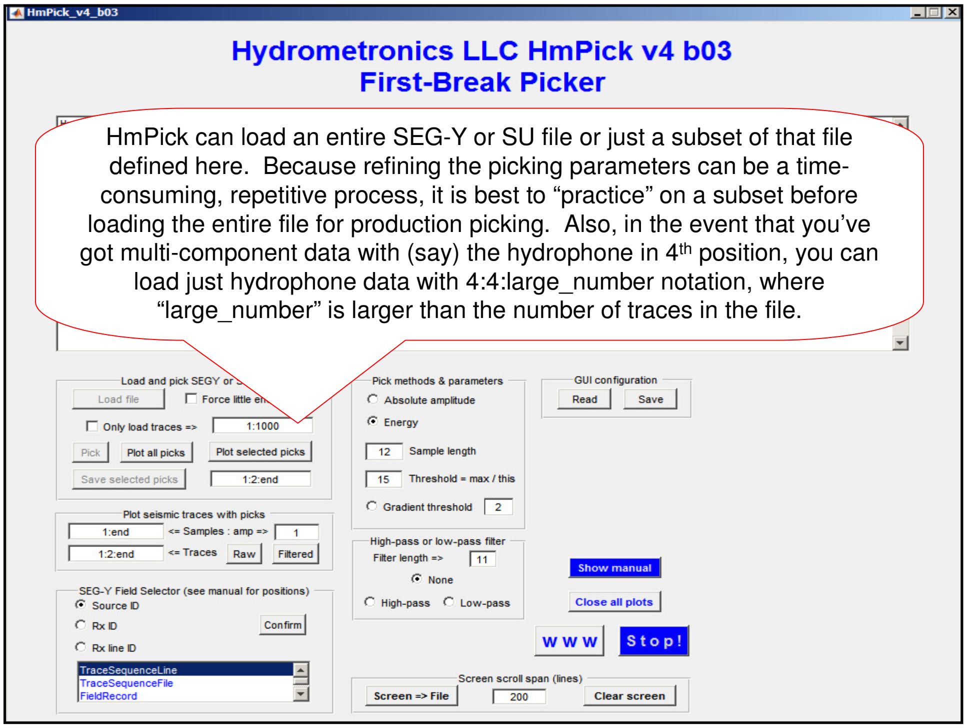


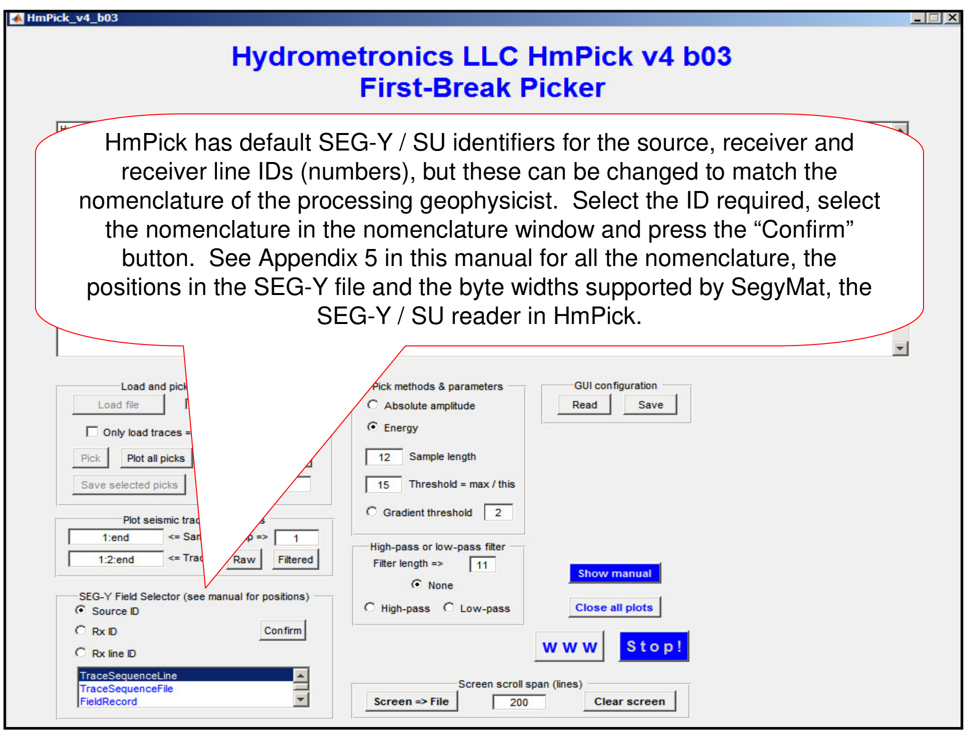

HmFBA_v1b103
Hydrometronics LLC HmFBA v1b103
Wide-Azimuth Far-Offset First-Break OBC/OBN Positioning
Single-node receiver activities: Load, Pick, Adjust X/Y coordinates of the gather, Load and Save picks.
Three pick methods and parameters.
Read and save GUI configuration
Trace high-pass filter before picking
Close all plots
Swath activities
Receiver activities
Pick methods & parameters
GUI configuration
Least-squares parameters
Show manual
Close all plots
Stop!
Screen => File
Clear screen

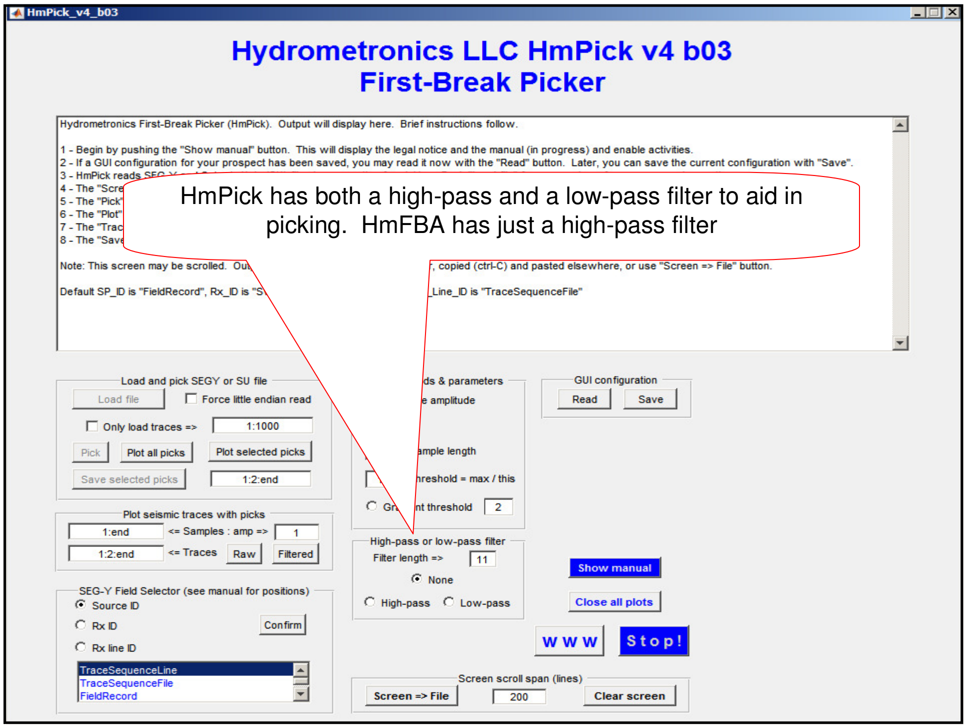

HmFBA_v1b103
Hydrometronics LLC HmFBA v1b103
Wide-Azimuth Far-Offset First-Break OBC/OBN Positioning
Swath activities: Load + Pick swath, Adjust X/Y coordinates sequentially or all-at-once. Load and Save picks
2-D or 3-D mode processing and 3-D-mode parameters
Trace sample rate
Select receiver ID header
Stop selected processes
Swath activities
Receiver activities
GUI configuration
Least-squares parameters
Receiver ID
Show manual
Close all plots
Stop!
Screen => File
Clear screen

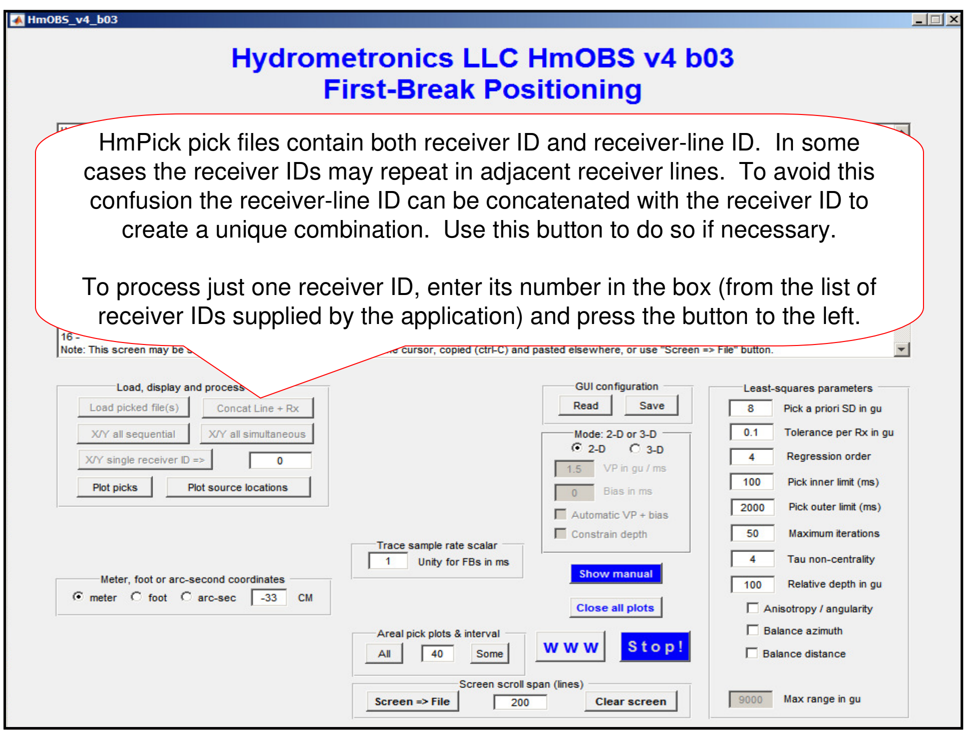

HmFBA_v1b103
Hydrometronics LLC HmFBA v1b103
Wide-Azimuth Far-Offset First-Break OBC/OBN Positioning
LS parameters: pick SD, convergence tolerance, regression order, inner and outer pick limits, maximum number of iterations, tau non-centrality parameter, estimated receiver depth, anisotropy/angularity, balance azimuth, balance distance, trim & seed.
Plot seismic traces with picks for the selected samples and traces and at the amplitude selected.
Areal contour plots of pick samples and pick interval
Least-squares parameters
Show manual
Close all plots
W W W
Stop!
Screen => File
Clear screen


HmFBA_v1b103
Hydrometronics LLC HmFBA v1b103
Wide-Azimuth Far-Offset First-Break OBC/OBN Positioning
Compensate for oscillator drift in an ocean-bottom node
Display screen control. Dump screen text to an ASCII file for record keeping. Clear screen. Control the number of text lines the screen scrolls
Node oscillator drift / day (+ / - microseconds)
Screen scroll span (lines)
Screen => File
Clear screen


HmPick_v4_b03
Hydrometronics LLC HmPick v4 b03
First-Break Picker
HmPick can load an entire SEG-Y or SU file or just a subset of that file defined here. Because refining the picking parameters can be a time-consuming, repetitive process, it is best to “practice” on a subset before loading the entire file for production picking. Also, in the event that you’ve got multi-component data with (say) the hydrophone in 4th position, you can load just hydrophone data with 4:4:large_number notation, where “large_number” is larger than the number of traces in the file.
Load file
Only load traces =>
1:1000
Pick
Plot all picks
Plot selected picks
Save selected picks
1:2:end
Plot seismic traces with picks
1:end
<= Samples : amp =>
1
1:2:end
<= Traces
Raw
Filtered
SEG-Y Field Selector (see manual for positions)
Source ID
Rx ID
Rx line ID
Confirm
TraceSequenceLine
TraceSequenceFile
FieldRecord
Pick methods & parameters
Absolute amplitude
Energy
12
Sample length
15
Threshold = max / this
Gradient threshold
2
High-pass or low-pass filter
Filter length =>
11
None
High-pass
Low-pass
GUI configuration
Read
Save
Show manual
Close all plots
W W W
Stop!
Screen scroll span (lines)
Screen => File
200
Clear screen


HmPick_v4_b03
Hydrometronics LLC HmPick v4 b03
First-Break Picker
HmPick has default SEG-Y / SU identifiers for the source, receiver and receiver line IDs (numbers), but these can be changed to match the nomenclature of the processing geophysicist. Select the ID required, select the nomenclature in the nomenclature window and press the “Confirm” button. See Appendix 5 in this manual for all the nomenclature, the positions in the SEG-Y file and the byte widths supported by SegyMat, the SEG-Y / SU reader in HmPick.
Load file
Pick
Plot all picks
Save selected picks
1:end
1:2:end
Raw
Filtered
SEG-Y Field Selector (see manual for positions)
Source ID
Rx ID
Rx line ID
Confirm
TraceSequenceLine
TraceSequenceFile
FieldRecord
Pick methods & parameters
Absolute amplitude
Energy
12
Sample length
15
Threshold = max / this
Gradient threshold
2
High-pass or low-pass filter
Filter length =>
11
None
High-pass
Low-pass
GUI configuration
Read
Save
Show manual
Close all plots
W W W
Stop!
Screen scroll span (lines)
Screen => File
200
Clear screen


HmPick_v4_b03
Hydrometronics LLC HmPick v4 b03
First-Break Picker
HmPick has both a high-pass and a low-pass filter to aid in picking. HmFBA has just a high-pass filter
Load and pick SEGY or SU file
GUI configuration
Read
Save
Plot seismic traces with picks
SEG-Y Field Selector (see manual for positions)
High-pass or low-pass filter
Show manual
Close all plots
Stop!
Screen scroll span (lines)
Screen => File
Clear screen


HmOBS_v4_b03
Hydrometronics LLC HmOBS v4 b03
First-Break Positioning
HmPick pick files contain both receiver ID and receiver-line ID. In some cases the receiver IDs may repeat in adjacent receiver lines. To avoid this confusion the receiver-line ID can be concatenated with the receiver ID to create a unique combination. Use this button to do so if necessary.
To process just one receiver ID, enter its number in the box (from the list of receiver IDs supplied by the application) and press the button to the left.
Load, display and process
Concat Line + Rx
X/Y single receiver ID =>
GUI configuration
Least-squares parameters
Trace sample rate scalar
Meter, foot or arc-second coordinates
Areal pick plots & interval
Show manual
Close all plots
Stop!
Screen scroll span (lines)
Screen => File
Clear screen

Receiver Activities (Single Node)

- **“Load gather”** loads a previously-prepared receiver gather of seismic data in SEG-Y or Seismic Unix (SU) binary format
- **“Pick”** uses the selected method, parameters, trace sample rate and optional high-pass filter to pick and plot the first breaks.
- **“X/Y gather”** processes the picks of a single gather as observations and adjusts the receiver coordinates using the selected least-squares parameters including geometry balancing in either 3-D mode (water) or 2-D mode (refractor & water). Adjustment can be repeated any number of times with the current picks in order to get the parameters right, perhaps for later swath processing.
- **“Load”** loads a CSV file of a previously-picked gather.
- **“Save”** saves the picks to a CSV file. This can be useful if the gather is large and loading and picking are slow.
- Load/Save CSV format in Appendix 2.

Swath Activities (Multiple Nodes)

- **“Load+pick swath”** loads a swath of seismic receiver gathers in SEG-Y or Seismic Unix (SU) binary format and uses the selected pick method, pick parameters and optional high-pass filter to pick the first breaks and save them to memory.
- “**X/Y sequential**” processes the swath of receivers in 2-D mode (refractor & water) or 3-D mode (water) one-by-one using different regression coefficients for every receiver and adjusts the coordinates using the least-squares parameters selected.
- “**X/Y all-at-once**” processes the swath of receivers only in 2-D mode (refractor & water) simultaneously using the same regression coefficients for the entire swath and adjusts the swath using the least-squares parameters selected.
- **“Save”** saves the swath of picks in memory to a CSV file for later loading into FBA or for analysis outside of FBA.
- **“Load”** loads a previously saved swath of picks in CSV format into memory. “Load+pick swath” can be time consuming, but “Load” is quick. Therefore, always “Save” your picked swath.
- Load/Save CSV format in Appendix 2.

Pick Methods and Parameters

- **“Absolute amplitude”** requires “sample length” and a divisor (called “this”) to determine the threshold. The mean absolute value of the 10 largest trace amplitudes is determined (called “max”). The threshold is max / this. The mean absolute amplitudes of a rolling sample length are determined. When the threshold is exceeded the pick is the mean of the current rolling sample length.
- **“Energy”** is the same as above except that energy (amplitude squared) is used instead of absolute amplitude.
- NB: Both **absolute amplitude** and **energy** use the same parameters, but their performance with those parameters will differ. Because there are two parameters, selection is an iterative process of experimentation. In general, a larger threshold (which means a smaller divisor called “this”) tends to pick later in the trace, smaller thresholds pick earlier.
- **“Gradient threshold”** method computes the normalized mathematical gradient along the trace and picks the first above a specified threshold. Increase the default threshold for noisy data (e.g.10); decrease for clean data (e.g. 1). Larger thresholds (the only parameter) tend to pick later in the trace, smaller thresholds pick earlier.
- See Acknowledgements at end of this manual for a reference.

Least-Squares Parameters - 1

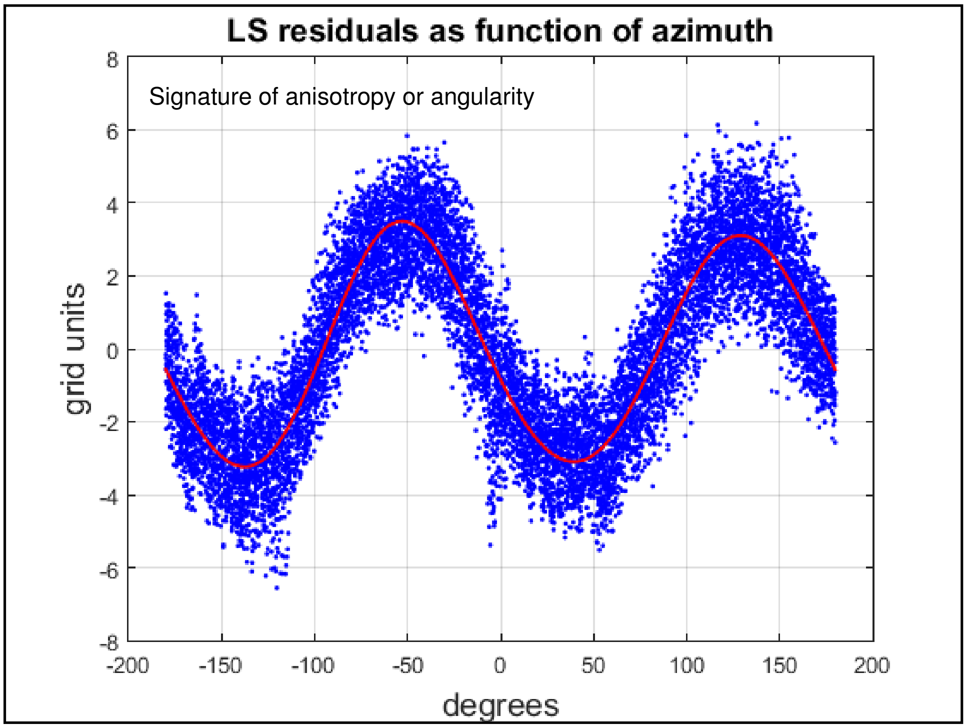
- “**Pick *a priori* SD in gu**” is an assessment of the standard deviation in grid units (gu) of a first-break pick as a surveying observation. Decreasing this SD will increase the computed UV.
- Iteration stops when the shift in coordinates from the last iteration is less than the **“Tolerance per Rx in gu”**
- **“Regression order”** is the order of the Chebyshev regression equation that converts picks in milliseconds into observations in grid units. 2-D mode (refractor & water) only.
- **“Pick inner and outer limit (ms)”** define the selection of picks.
- Iteration stops when **“Maximum iterations”** is reached.
- **“Tau non-centrality”** is the number of tau statistics used for outlier detection and elimination. For high degrees of freedom tau is close to the normal statistic. A non-centrality of 2 is aggressive (trims about 5% of the data), 3 is relaxed (trims < 0.3% of the data) and 4 trims only the worst outliers. Use 100 if you don’t want outlier rejection. See Acknowledgements and Glossary for more on the Tau Method.
- **“Relative receiver depth in gu”** (difference between gun and receiver depth in grid units) is used for computing slant ranges in 2-D mode (refractor & water), though slant ranges are compensated by the regression equation, so accuracy is not critical.

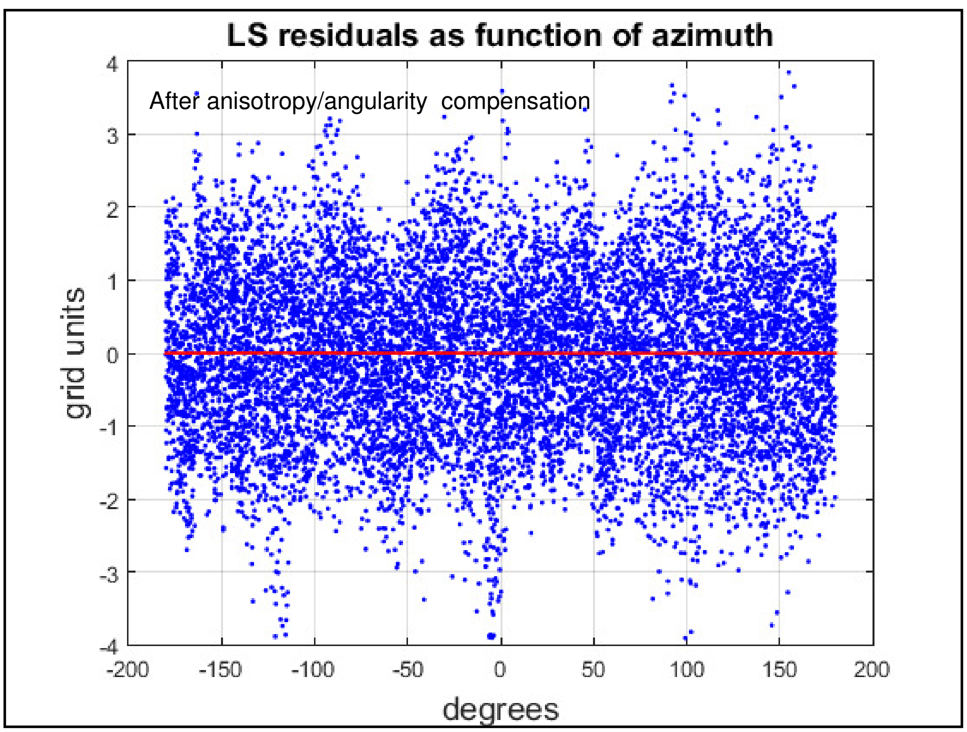
Least-Squares Parameters - 2

- **“Anisotropy/angularity”** is either on or off. Anisotropy is variation in seismic velocity as a function of direction or travel. Angularity is a directional source-array effect. Both can sometimes be seen in the least-squares adjustment plot, **“LS residuals as a function of azimuth”** as a red, wavy line of the mean residuals with two peaks and two troughs over 360 degrees. Selecting anisotropy/angularity complements the picks with the (diminishing) mean residual as a function of azimuth until the red line is nearly flat. Of course, this will have some effect on the coordinates computed, so use anisotropy / angularity prudently.
- The next two plots offer examples of a prospect with anisotropy / angularity before and after compensation.
- **“Balance azimuth”** and **“Balance distance”** randomly decimates picks from overpopulated azimuth sectors and/or distance rings in order to achieve better-balanced geometry for the purpose of solving for biases and velocity gradients in either 3-D mode (water) or 2-D mode (refractor & water). If automatic geometry balancing is chosen, every solution is unique. It cannot be repeated because the observation set will be different the next time the adjustment is run. Nevertheless, the results will be consistently within the error bars (i.e. uncertainties, SDs) reported by the application.

Least-Squares Parameters - 3

- **“Trim & seed with GroupXY”** offers some special features. Without checking this feature, the seeding of the iterative least-squares adjustment is with the barycenter of the sources selected with the inner and outer pick limits. Usually this works just fine. By checking this feature, the seeding of the adjustment is with the GroupX and GroupY coordinates in the SEG-Y or SU files. This may speed up the iteration, or the GroupXY coordinates may be just wrong, in which case you don’t want to do it. Another benefit of checking “Trim & seed with GroupXY” (if the GroupXY coordinates are correct) is that the picks are trimmed on distance, i.e. within the limits in the **“Max range in gu”** edit box. This offers a distinct advantage when picking is poor, i.e. when distant sources present with near-zero picks, as often happens with large, far-offset files. Those picks will be edited out as unreasonable without polluting the adjustment. If you want seeding only, chose a large **“Max range in gu”**. If you want trimming and seeding, then choose a reasonable **“Max range in gu”**. You cannot have trimming without seeding.


LS residuals as function of azimuth
Signature of anisotropy or angularity
grid units
degrees
8
6
4
2
0
-2
-4
-6
-8
-200
-150
-100
-50
0
50
100
150
200


LS residuals as function of azimuth
After anisotropy/angularity compensation
grid units
degrees
4
3
2
1
0
-1
-2
-3
-4
-200
-150
-100
-50
0
50
100
150
200

3-D Mode Parameters

- Certain parameters are operative only in 3-D mode (water). These are:
  - **"VP in gu / ms"** (velocity of propagation or slope)
  - **"Bias in ms"** (static offset or intercept)
  - **"Automatic VP + bias"**
  - **"Constrain depth"**
- If "Automatic VP + bias" and "Constrain depth" are <u>not</u> selected, then the adjustment is done with the VP and bias entered. The adjustment does report a slope and intercept that serve as a guideline for adjusting VP and bias manually, if desired.
- "Automatic VP + bias" computes the VP (slope) and bias (intercept) automatically with or without the constraint of depth, but restraining depth gives best results.
- "Constrain depth" constrains the entered depth (found among the least-squares parameters) as an observation with an SD of 20cm in appropriate grid units, but this is only effective if "Automatic VP + bias" is also selected. Constraining depth without automatic VP and bias computation is likely to cause large residuals.
- Also, constraining depth requires a fully-populated weight matrix, which, for an extremely large job (probably in very deep water considering Snell's Law), may strain computer resources.
- See 3-D mode (water) guidelines later in the manual.

Other Controls - 1

- **"Meter, foot or arc-second coordinates".** Source coordinates in SEG-Y and SU headers are typically reported in map-projection grid units by industry (meters or feet). Academic institutions may report in geographical arcseconds. If arcseconds, then choose a Central Meridian in degrees so that internal computations can be done in wide-zone Transverse Mercator in meters.
- **"GUI configuration".** "Read" or "Save" all the parameters set in the GUI. Use these controls for sharing set-ups with colleagues or for returning to a previous project. You may need to click the "2-D" or "3-D" buttons to enable the right displays.
- **"Stop!"** stops receiver picking, swath load + pick, and receiver and swath adjustments, all of which can be time consuming.
- **"w w w"** gets you to the World Wide Web via the Hydrometronics home page.
- **"Close all plots"**. Matlab plots consume memory and, thus, affect performance. FBA generates a lot of plots. <u>Regularly close plots not in use</u>.

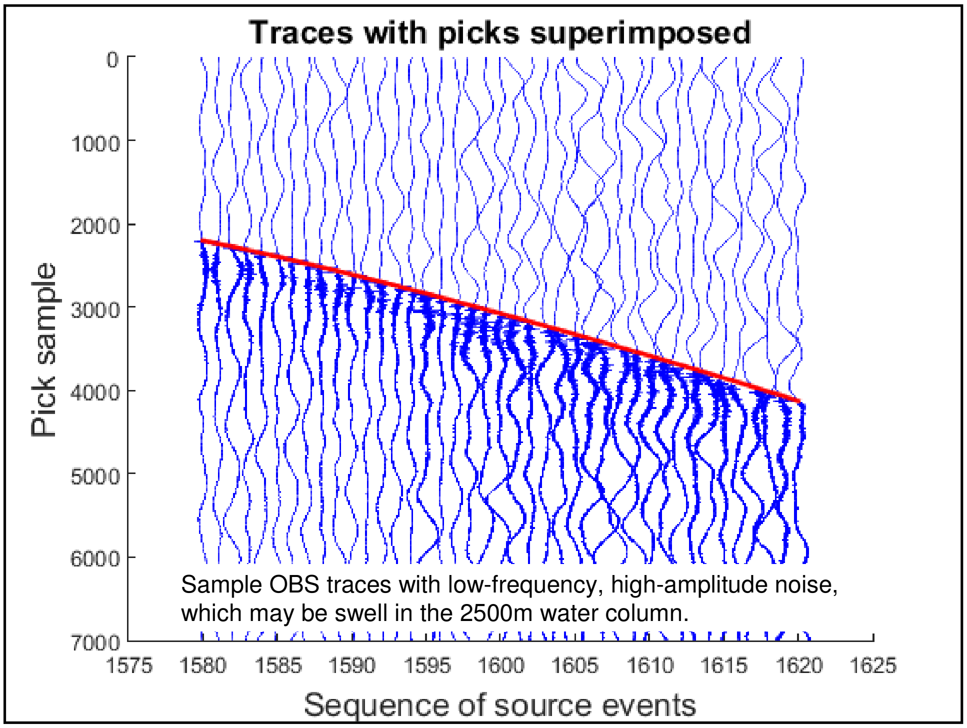
Other Controls - 2

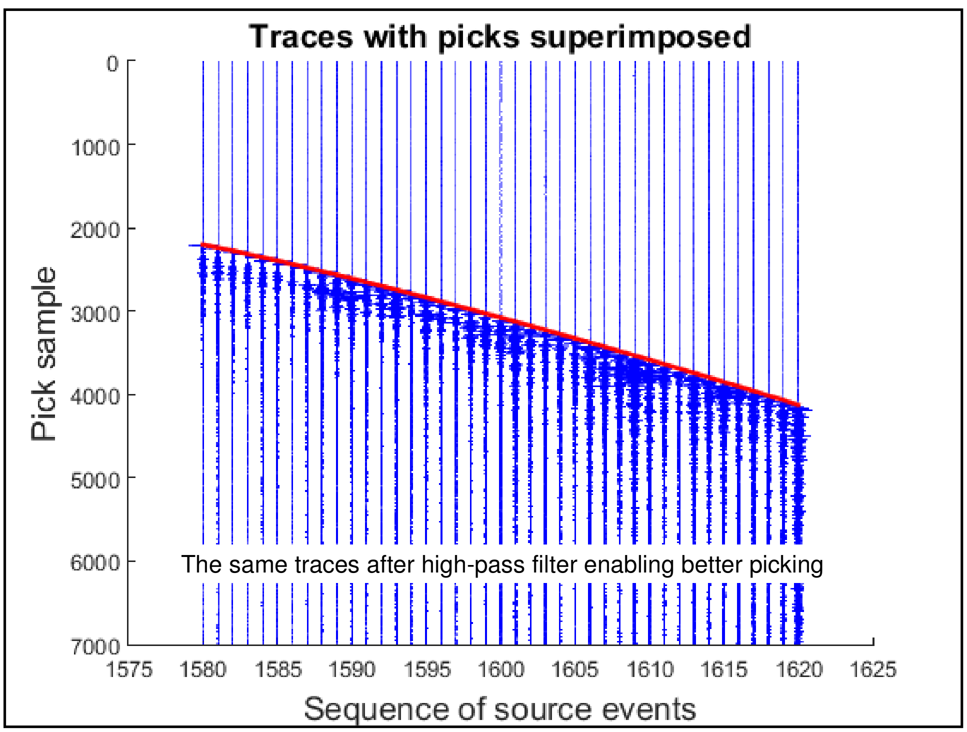
- **“Receiver ID”** (list box in the lower left of the FBA GUI). FBA processes receiver gathers either individually (in “receiver activities”) or *en masse* (in “swath activities”) by selecting, loading and picking a number of gathers all together. It is handy, especially in swath activities, for the receivers to have unique ID numbers. SEG-Y and SU receiver gathers are prepared by geophysicists, but it is apparently not standard among geophysicists where, among the available SEG-Y headers, to place the receiver IDs. Consequently, the list box in the lower left of the FBA GUI allows the user to choose which header to associate with the receiver ID. This choice must be made before picking the gather. If you don’t know which header it is, you may have to use a SEG-Y viewer to find out. If the receiver ID is not among the headers, then use the top, default choice (“Null, none, 0”). In this case the receivers will be numbered sequentially during swath processing.
- **“Screen => File”** dumps the entire display screen (up to 3000 lines) to a text file with a name of your choice. The file can then be edited.
- **“Clear screen”** if needed before “Screen => File” or if the screen gets jumbled due to incorrect word wrap.
- **“Screen scroll span”** is the number of text lines the display screen will scroll. More lines = slower performance, but more lines may be necessary for swath activities to see all receiver coordinates.

Other Controls - 3

- **“Mode: 2-D or 3-D”** applies only to single-node receiver and “X/Y sequential” swath activities. It switches the processing mode from 3D for use with direct water arrivals to 2D for use with seismic energy that arrives by water and/or by one or more refractors. 3-D mode (water) produces different (but similar) plots and statistics, which are exhibited near the end of this user’s manual. In 3-D mode (water) the VP (acoustic velocity of propagation) and bias (sum of picking and instrumental) fields become active. Enter those values if you know them, otherwise use the defaults.
- **“Trace high-pass / low-cut filter”** conditions the traces before picking by subtracting a quadratic LOESS-smoothed trace from the actual trace. This effectively cuts out the low frequencies that might be due to tides, swell or waves in deep water, chop in shallow water, instrumental characteristics, et cetera. Specify the length of the LOESS smoother. This may – or may not - improve picking.

- An example of the high-pass filter is shown in the next two slides of sample traces from an ocean-bottom seismometer (OBS) 2465m deep on a mid-Atlantic ridge near the Azores. There is more information on the plots exhibited in this user’s manual on a later page of the manual and in the Acknowledgments.


Traces with picks superimposed
0
1000
2000
3000
4000
5000
6000
7000
Pick sample
1575
1580
1585
1590
1595
1600
1605
1610
1615
1620
1625
Sequence of source events
Sample OBS traces with low-frequency, high-amplitude noise,
which may be swell in the 2500m water column.


Traces with picks superimposed
0
1000
2000
3000
4000
5000
6000
7000
Pick sample
1575
1580
1585
1590
1595
1600
1605
1610
1615
1620
1625
Sequence of source events
The same traces after high-pass filter enabling better picking

Other Controls - 4

- **“Plot seismic traces with picks”.** The previous two pages exhibit plots made with this control.
- Samples and traces are selected with Matlab syntax:
  - 1000:3000 is every trace or sample from 1000 to 3000
  - 1000:2:3000 is every even trace or sample from 1000 to 3000
  - 1001:2:3000 is every odd trace or sample from 1001 to 2999
- An **“amp”** of 1 means that the maximum trace amplitude will occupy the division between the traces. An “amp” of 2 means that the maximum amplitude will occupy twice the division between the traces … and so on, for “amp” values less than 1, too.
- After picking a gather the number of traces and samples are shown in the output screen for reference and written to the samples and traces window. Remember these numbers. They can be found again by scrolling the output screen.
- Picks are plotted on the traces as QC of their quality.
- The seismic trace plot can be zoomed for more detail … or select fewer traces and/or samples.
- This control works only for single-node (not swath) gathers.
- Automatic Gain Control (AGC) is not offered. If you have to use AGC to see a refractor, you probably can’t pick it automatically!

Other Controls - 5

- **“Node oscillator drift / day (+ / - microseconds)”.** This feature compensates for *in situ* oscillator drift in an ocean-bottom node, which can be identified by systematic shifts in first-break positions if the wide-azimuth, far-offset seismic picks are segmented on offset and by other ways beyond the scope of this manual. This feature uses the relative times of the seismic traces in the SEG-Y or SU data. If positive (+) it adds the drift to the earliest picks as a function of time and subtracts the drift from the latest picks as a function of time. If negative (-), the reverse.
- This feature will change coordinates, so use it with great caution!
- This feature applies only to receiver activities (single node) and not to swath activities (multiple nodes) because multiple node will have different drifts.
- This feature applies to both 2-D and 3-D modes (receiver activities).
- The default drift is zero (0), that is, no drift applied.

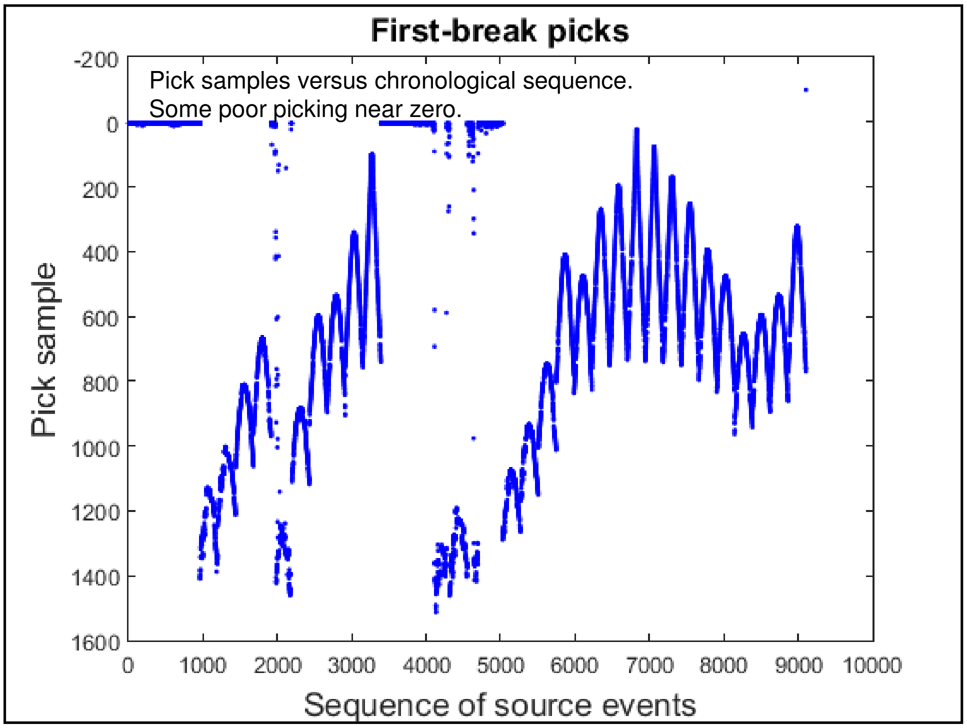
2-D Mode Processing

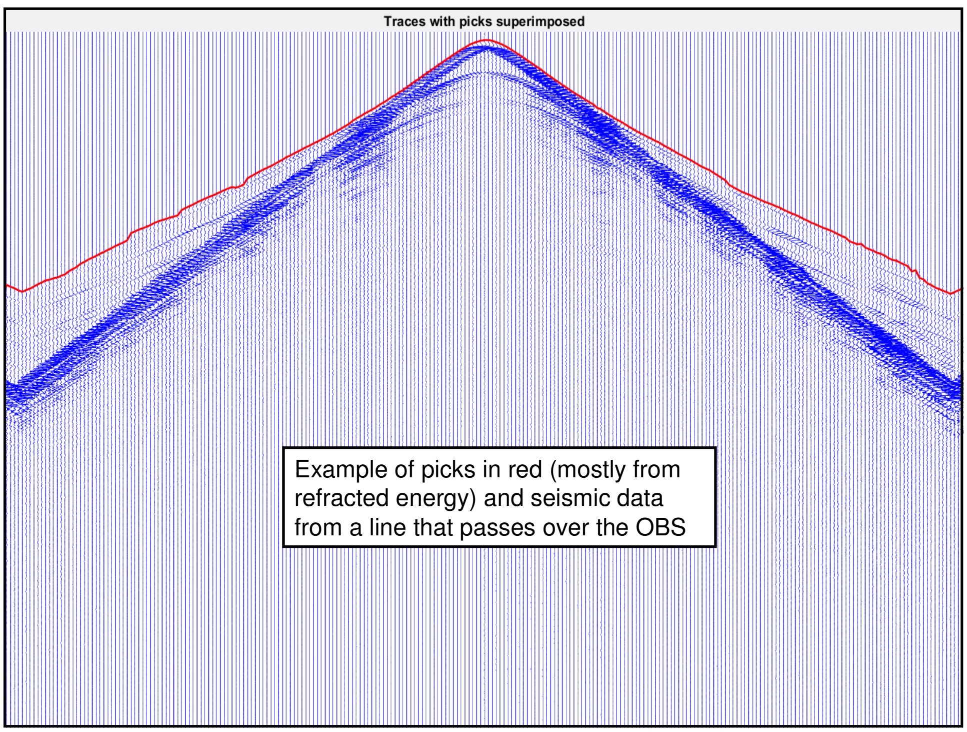
2-D Mode Processing – 1

Picking Quality Control

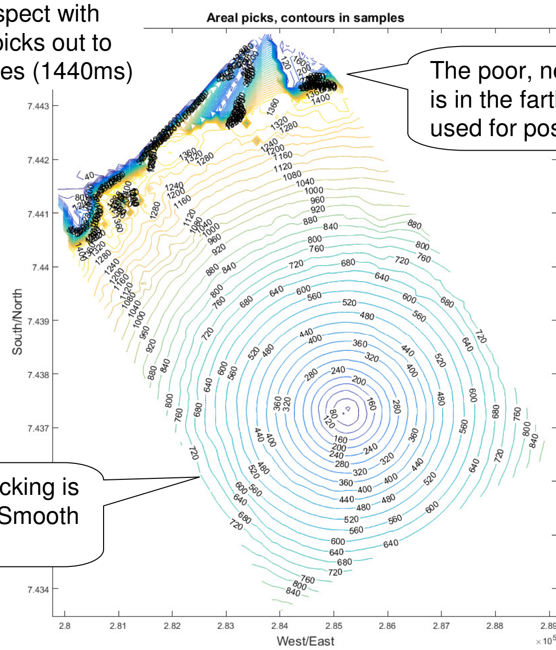
- FBA offers three very different picking methods: absolute amplitude, energy and gradient
- It can be daunting to choose the right pick method and parameters for your prospect, but FBA offers three kinds of QC plots to help:
  - Pick samples versus chronological sequence
  - Seismic trace plots with picks
  - Pick-sample areal contour plots (all picks or some, i.e. only those between the specified inner and outer limits) can be created
- The next three plots in this manual exhibit these QC plots from an example ION Geophysical prospect. See Acknowledgements.
- Additionally, a plan view of the shot lines is shown with the innermost direct water-arrival picks edited out.

- Least-squares adjustments after picking are quick and can be rapidly repeated with different parameters to judge which picks work best in the least-squares adjustment
- Least-squares adjustments provide their own quality metrics that, by inference, help guide the picking


First-break picks
Pick samples versus chronological sequence.
Some poor picking near zero.
Pick sample
-200
0
200
400
600
800
1000
1200
1400
1600
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
Sequence of source events

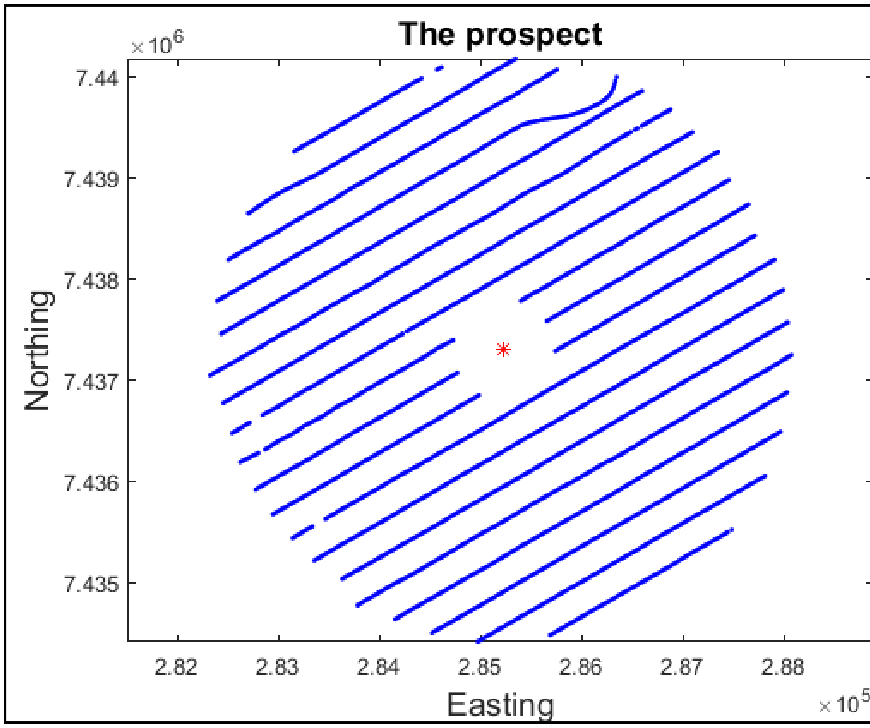

Traces with picks superimposed
Example of picks in red (mostly from
refracted energy) and seismic data
from a line that passes over the OBS

Same prospect with excellent picks out to 720 samples (1440ms)



The poor, near-zero picking is in the farthest offsets not used for positioning

Here the picking is excellent. Smooth contours.



2-D Mode Processing – 2

2-D Mode versus 3-D Mode

- Acoustics (e.g. USBL) are a refined (precise) observable. First-breaks are crude (imprecise) in a random sense and they are biased by picking and instrumental delays. Acoustics are expensive to acquire. First-breaks are essentially free on an OBC/OBN/OBS crew.
- FBA calibrates biases by having a good balance of azimuth and offset. A skilled user assures this by parameter selection and/or by automatic geometry balancing described on the next slide.
- FBA has two modes of operation:
  - 2-D (refracted or water arrivals or both, single receiver or swath)
  - 3-D (water-arrival-only, single-node or swath "X/Y sequential")
- In very deep water direct water arrivals can (if shots are close enough to the detector) provide for an adequate balance of offset and azimuth and sufficient numbers to compensate for pick imprecision. See the 3-D Mode Processing section later in this manual for more details.
- In shallower water, and in many deep water prospects, too, most useful first-break seismic energy arrives at the receiver via the water AND one or more refractors, in which the velocity of propagation may vary. In 2-D mode, FBA solves for this velocity gradient with a Chebyshev regression equation that relates pick time in milliseconds to distance in grid units while also solving for delay biases. Depth is not solved in 2-D mode.

2-D Mode Processing – 3

Automatic Geometry Balancing

- In both 3-D mode (water) and 2-D mode (refractor & water), first-break positioning works best if the source locations are balanced in azimuth and offset (distance) with respect to the receiver.
- FBA provides tools to achieve this manually
- FBA also provides for automatic geometry balancing in azimuth and distance for rapid processing when manual intervention is not timely or possible.
- Also, FBA supports simultaneous swath adjustment, which minimizes the effects of geometry imbalance
- Automatic geometry balancing works by decimating azimuth sectors and/or offset rings (you can choose one or the other or both) that are overpopulated with respect to the average
- In order to achieve a uniformly-balanced geometry, the picks in the overpopulated rings or sectors are decimated randomly
- Therefore, if automatic geometry balancing is chosen, every solution is unique. It cannot be repeated because the observation set will be different the next time the adjustment is run. Nevertheless, the results will be consistently within the error bars (i.e. uncertainties, SDs) reported by the application.

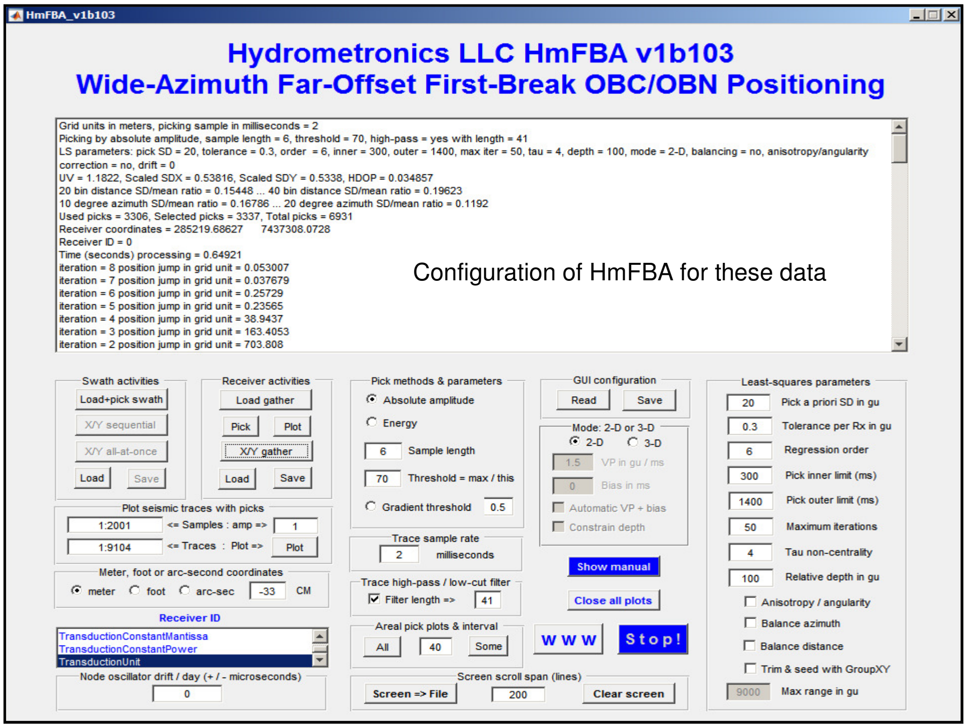
2-D Mode Processing – 4

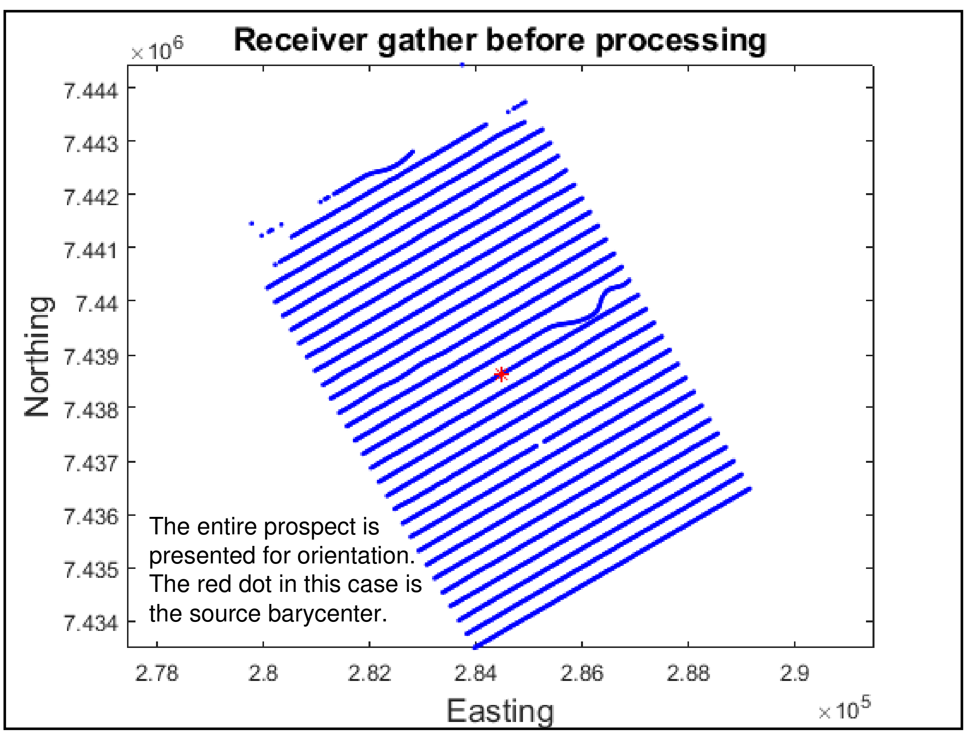
Comments on Snell's Law

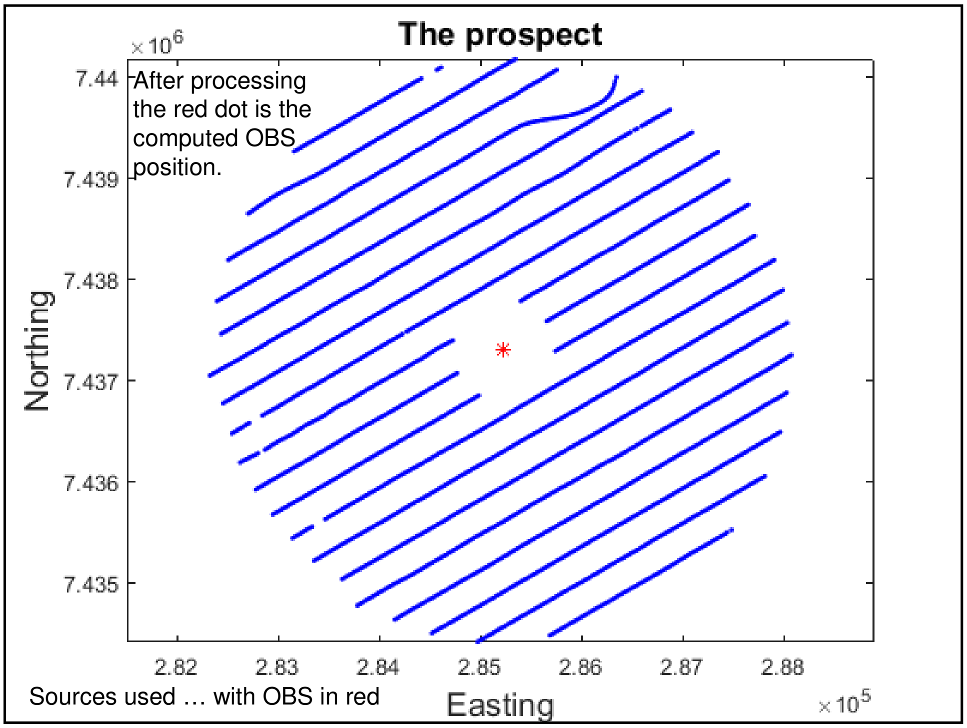
- Snell's Law states that the ratio of the sines of the angles of incidence and refraction is equal to the ratio of the velocities of the respective media
- When the refractive angle is 90°, that is, when the seismic energy travels along the boundary of the media, then the critical angle of incidence is asin(v1/v2). If the angle between the source and the receiver is more than the critical angle, then direct water energy arrives after the refracted energy (which may be weaker than the later direct arrival).
- V1 for water is about 1.5m/ms. V2 for shale is about 2.0m/ms. V2 for igneous rock is about 5.5m/ms.
- Therefore, the critical angles are about 49° for shale and 16° for igneous.
- In 1000m of water the farthest horizontal distance from the receiver to assure that energy through the water arrives first is:
  - 1000m * tan(49°) ≈ 1150m ***or*** 1000m * tan(16°) ≈ 287m
- In 1000m of water that direct water-arrival slant range is:
  - 1000m / cos(49°) ≈ 1524m ≈ 1016ms ***or*** 1000m / cos(16°) ≈ 961m ≈ 641ms
- In 100m of water, divide these numbers by 10.
- These facts imply that, when positioning receivers with dedicated first-break runs, more picks than anticipated may be arriving through a refractor depending upon your offset from the receiver and your picking parameters, which can be tuned to pick later water arrivals.

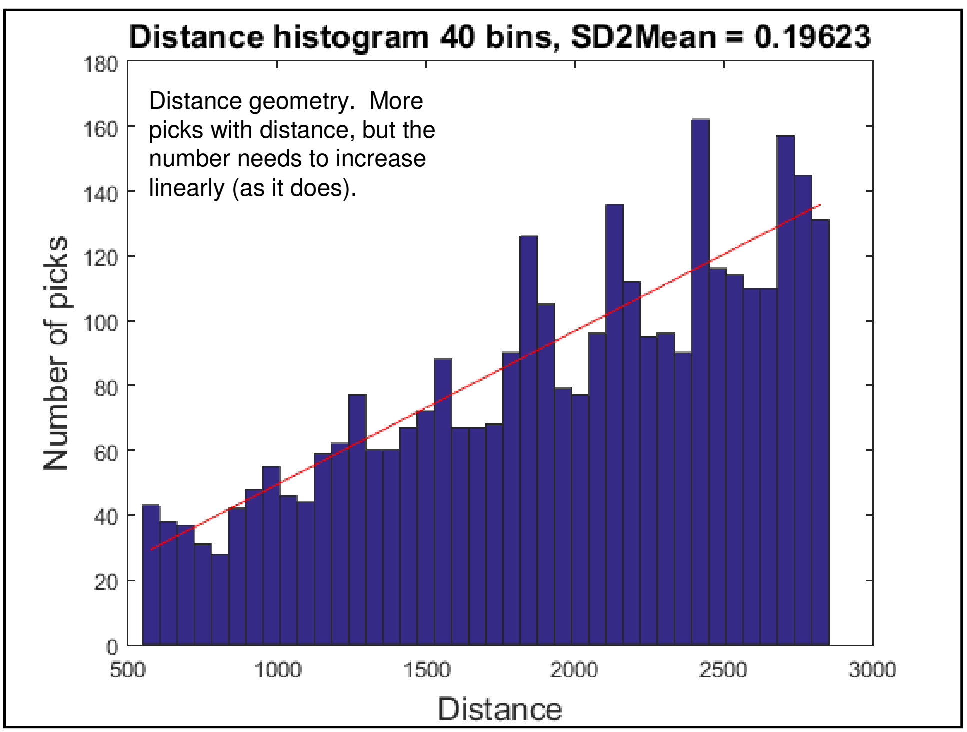
2-D Mode Processing – 5

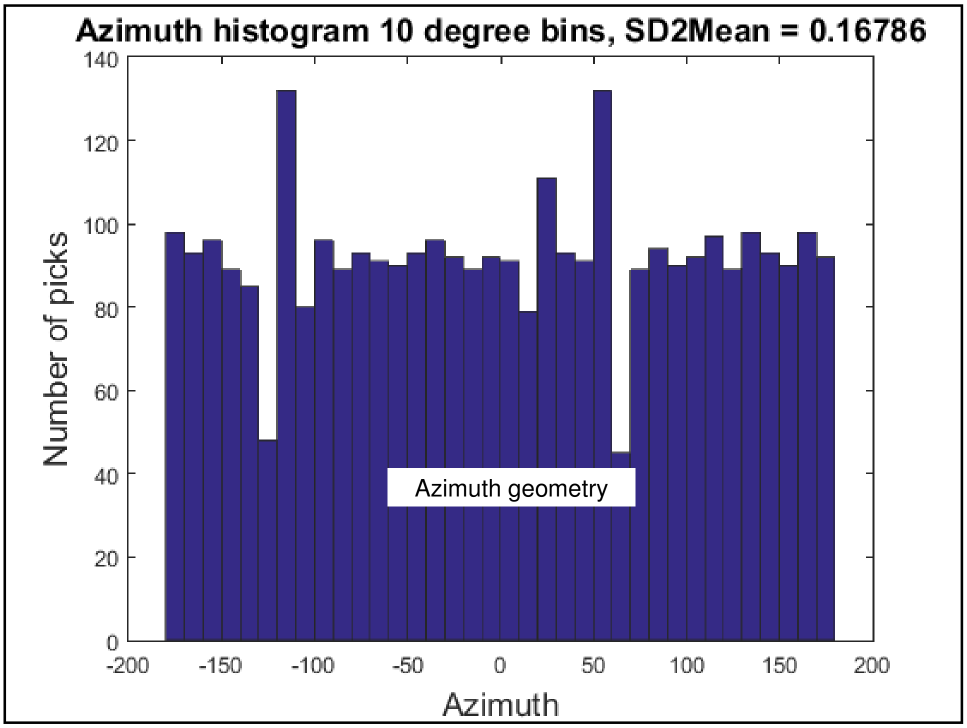
- The next five plots from the same ION Geophysical prospect show distance and azimuth distribution as:
  - FBA configuration
  - Plan view of the receiver gather before processing
  - Plan view of the receiver gather after processing
  - A 40 bin (sloping) histogram of distance after processing
  - A 10 degree (flat) histogram of azimuth after processing
- Inner and outer limits of distance (processing a "donut") are one way to achieve balance in azimuth and distance manually.
- Automatic geometry balancing is another.
- 2-D Mode Processing continues after the plots.


HmFBA_v1b103
Hydrometronics LLC HmFBA v1b103
Wide-Azimuth Far-Offset First-Break OBC/OBN Positioning
Grid units in meters, picking sample in milliseconds = 2
Picking by absolute amplitude, sample length = 6, threshold = 70, high-pass = yes with length = 41
LS parameters: pick SD = 20, tolerance = 0.3, order = 6, inner = 300, outer = 1400, max iter = 50, tau = 4, depth = 100, mode = 2-D, balancing = no, anisotropy/angularity correction = no, drift = 0
UV = 1.1822, Scaled SDX = 0.53816, Scaled SDY = 0.5338, HDOP = 0.034857
20 bin distance SD/mean ratio = 0.15448 ... 40 bin distance SD/mean ratio = 0.19623
10 degree azimuth SD/mean ratio = 0.16786 ... 20 degree azimuth SD/mean ratio = 0.1192
Used picks = 3306, Selected picks = 3337, Total picks = 6931
Receiver coordinates = 285219.68627 7437308.0728
Receiver ID = 0
Time (seconds) processing = 0.64921
iteration = 8 position jump in grid unit = 0.053007
iteration = 7 position jump in grid unit = 0.037679
iteration = 6 position jump in grid unit = 0.25729
iteration = 5 position jump in grid unit = 0.23565
iteration = 4 position jump in grid unit = 38.9437
iteration = 3 position jump in grid unit = 163.4053
iteration = 2 position jump in grid unit = 703.808
Configuration of HmFBA for these data
Swath activities
Load+pick swath
X/Y sequential
X/Y all-at-once
Load
Save
Receiver activities
Load gather
Pick
Plot
X/Y gather
Load
Save
Pick methods & parameters
Absolute amplitude
Energy
6 Sample length
70 Threshold = max / this
Gradient threshold 0.5
GUI configuration
Read
Save
Mode: 2-D or 3-D
2-D 3-D
1.5 VP in gu / ms
0 Bias in ms
Automatic VP + bias
Constrain depth
Least-squares parameters
20 Pick a priori SD in gu
0.3 Tolerance per Rx in gu
6 Regression order
300 Pick inner limit (ms)
1400 Pick outer limit (ms)
50 Maximum iterations
4 Tau non-centrality
100 Relative depth in gu
Anisotropy / angularity
Balance azimuth
Balance distance
Trim & seed with GroupXY
9000 Max range in gu
Plot seismic traces with picks
1:2001 <= Samples : amp => 1
1:9104 <= Traces : Plot => Plot
Trace sample rate
2 milliseconds
Show manual
Meter, foot or arc-second coordinates
meter foot arc-sec -33 CM
Trace high-pass / low-cut filter
Filter length => 41
Close all plots
Receiver ID
TransductionConstantMantissa
TransductionConstantPower
TransductionUnit
Areal pick plots & interval
All 40 Some
W W W
Stop!
Node oscillator drift / day (+ / - microseconds)
0
Screen scroll span (lines)
Screen => File 200 Clear screen


Receiver gather before processing
× 10^6
7.444
7.443
7.442
7.441
7.44
7.439
7.438
7.437
7.436
7.435
7.434
Northing
2.78
2.8
2.82
2.84
2.86
2.88
2.9
Easting
× 10^5
The entire prospect is presented for orientation. The red dot in this case is the source barycenter.


The prospect
$\times 10^6$
7.44
7.439
7.438
7.437
7.436
7.435
Northing
After processing
the red dot is the
computed OBS
position.
2.82
2.83
2.84
2.85
2.86
2.87
2.88
$\times 10^5$
Easting
Sources used … with OBS in red

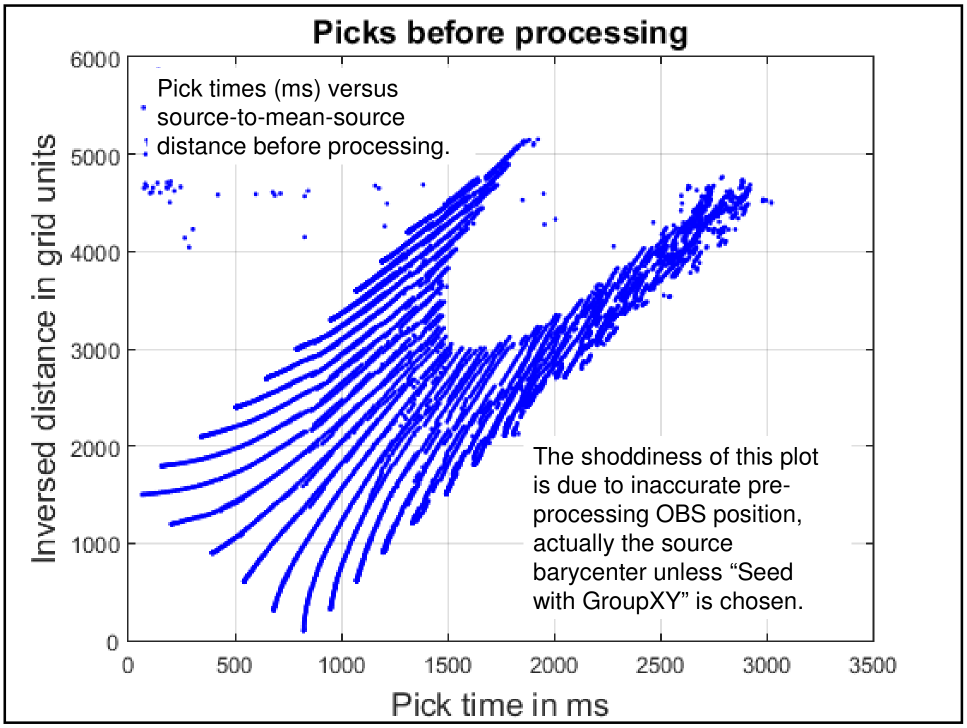

Distance histogram 40 bins, SD2Mean = 0.19623
Distance geometry. More
picks with distance, but the
number needs to increase
linearly (as it does).
Number of picks
180
160
140
120
100
80
60
40
20
0
500
1000
1500
2000
2500
3000
Distance

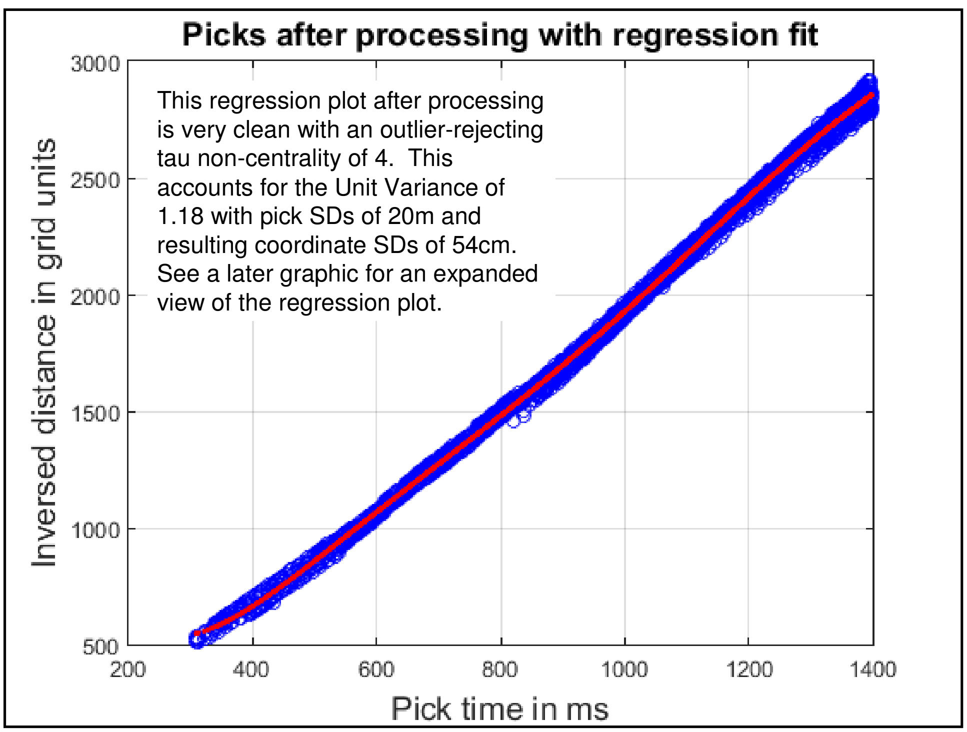


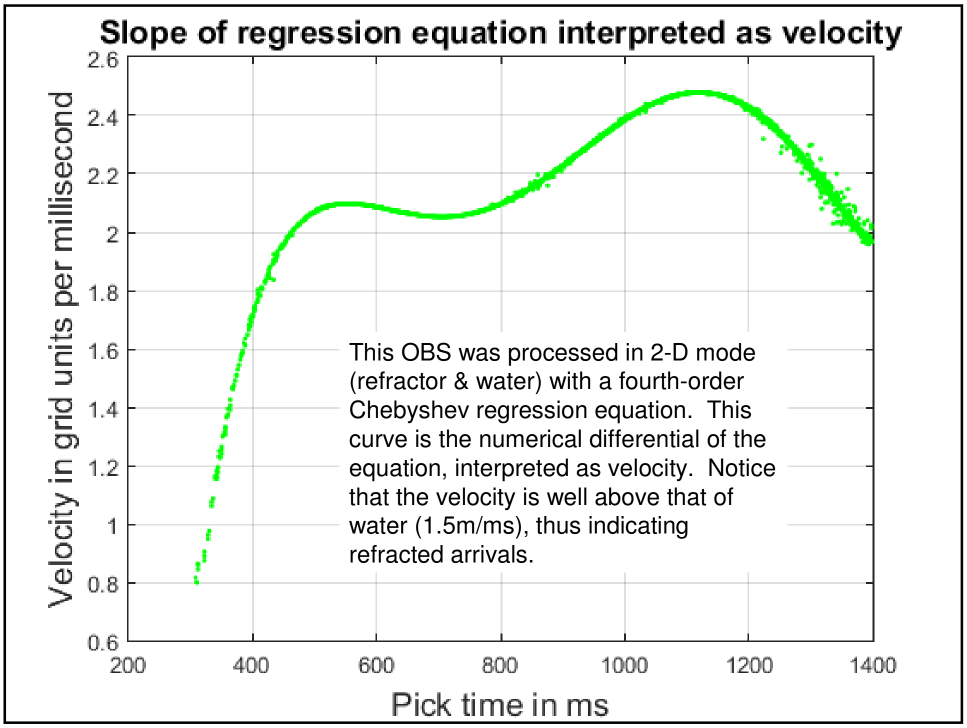
2-D Mode Processing - 6

- Notice that the gather has shrunk through the use of pick limits. An inner limit can eliminate the direct water arrivals as determined by depth and Snell's Law. An outer limit (or creative picking) can be used to eliminate refracted arrivals for water-only processing.
- Decisions on the right limits can be based upon the histograms (previously shown, discussed next) and the least-squares statistics (discussed later)
- In addition to histogram presentation (do they look balanced?), histograms have SD2Mean statistics (the ratio of the SD of the bin variations to the mean or regressed bin size) that should be as small as possible.
- SD2Mean < 0.3 is OK, especially for the finer bins (40 bins for distance and 10 degrees for azimuth), but not essential
- Get the best you can get manually … or balance geometry automatically.
- After achieving a good balance of distance and azimuth manually or automatically, turn your attention to the first-break picks

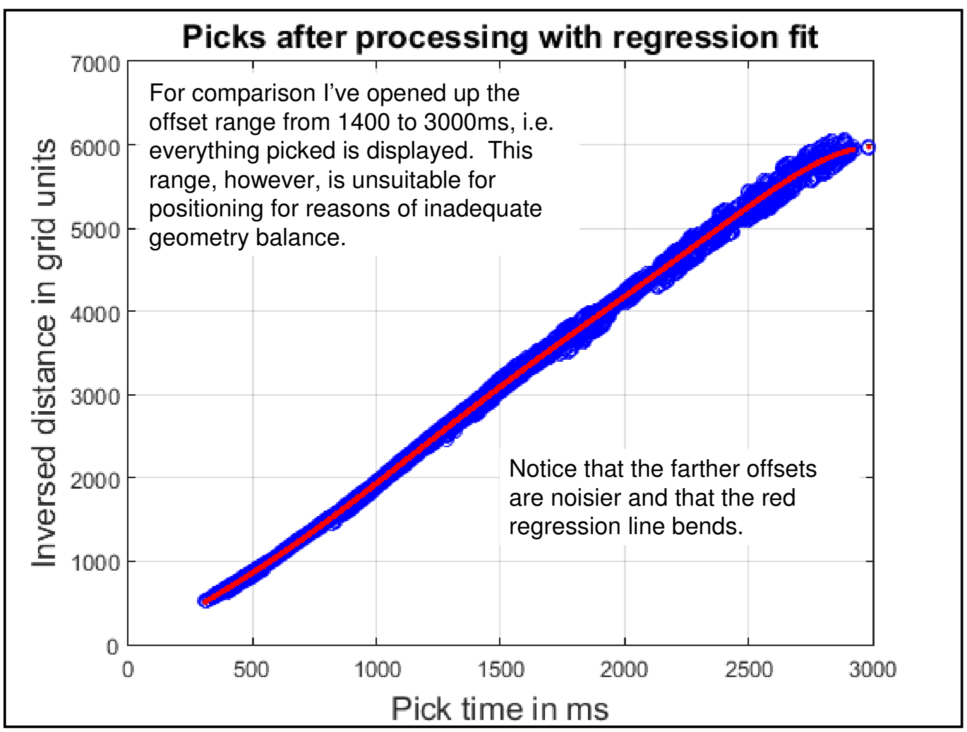
- The next four plots show:
  - The picks in ms versus the distance from the source to the mean source before processing
  - The picks in ms versus the distance from the source to the adjusted receiver position after processing with Chebyshev regression equation in red
  - The slope of the Chebyshev regression equation as velocity (in 2-D mode)
  - Another Chebyshev regression equation with longer offset for comparison
- 2-D Mode Processing continues after the plots


Picks before processing
Pick times (ms) versus
source-to-mean-source
distance before processing.
The shoddiness of this plot
is due to inaccurate pre-
processing OBS position,
actually the source
barycenter unless "Seed
with GroupXY" is chosen.
Inversed distance in grid units
Pick time in ms
0
1000
2000
3000
4000
5000
6000
0
500
1000
1500
2000
2500
3000
3500


Picks after processing with regression fit
This regression plot after processing
is very clean with an outlier-rejecting
tau non-centrality of 4. This
accounts for the Unit Variance of
1.18 with pick SDs of 20m and
resulting coordinate SDs of 54cm.
See a later graphic for an expanded
view of the regression plot.
Inversed distance in grid units
Pick time in ms
500
1000
1500
2000
2500
3000
200
400
600
800
1000
1200
1400



Slope of regression equation interpreted as velocity
Velocity in grid units per millisecond
Pick time in ms
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
200
400
600
800
1000
1200
1400
This OBS was processed in 2-D mode (refractor & water) with a fourth-order Chebyshev regression equation. This curve is the numerical differential of the equation, interpreted as velocity. Notice that the velocity is well above that of water (1.5m/ms), thus indicating refracted arrivals.



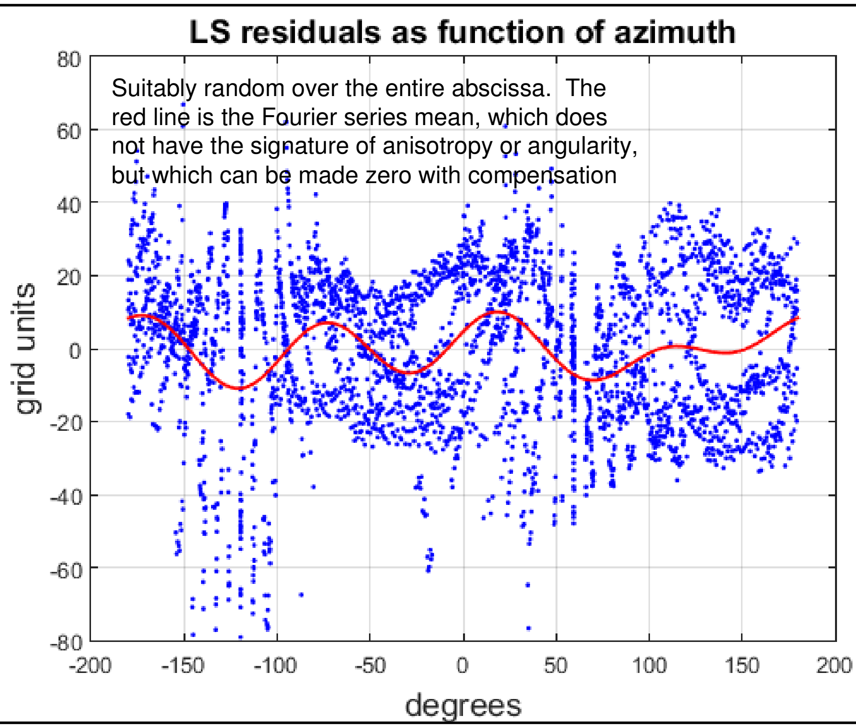
Picks after processing with regression fit
Inversed distance in grid units
Pick time in ms
7000
6000
5000
4000
3000
2000
1000
0
0
500
1000
1500
2000
2500
3000
For comparison I've opened up the offset range from 1400 to 3000ms, i.e. everything picked is displayed. This range, however, is unsuitable for positioning for reasons of inadequate geometry balance.
Notice that the farther offsets are noisier and that the red regression line bends.

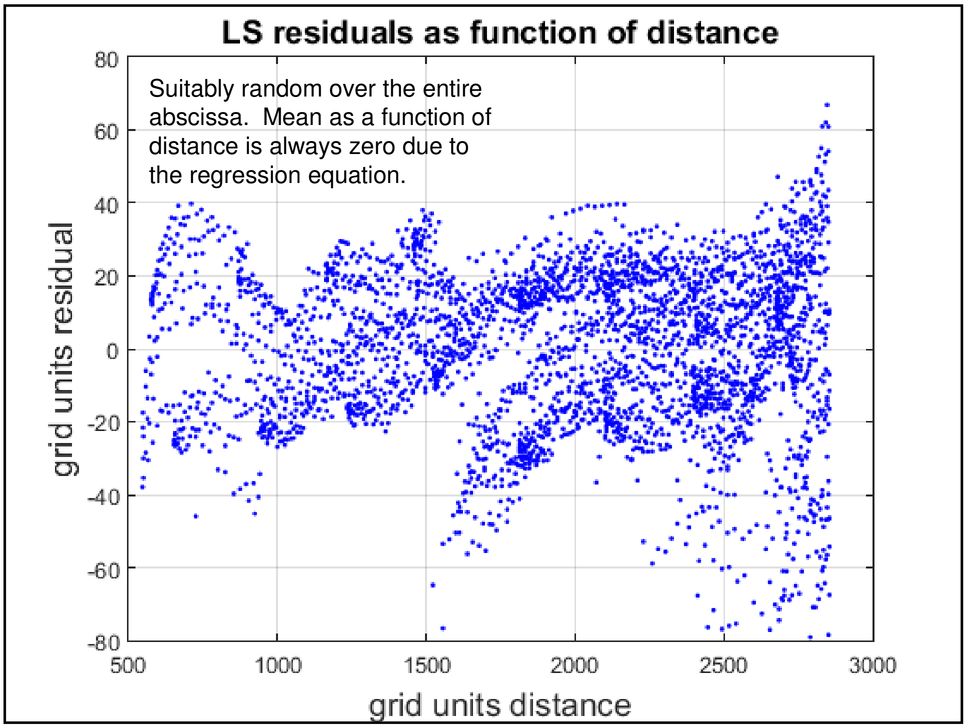
2-D Mode Processing – 7

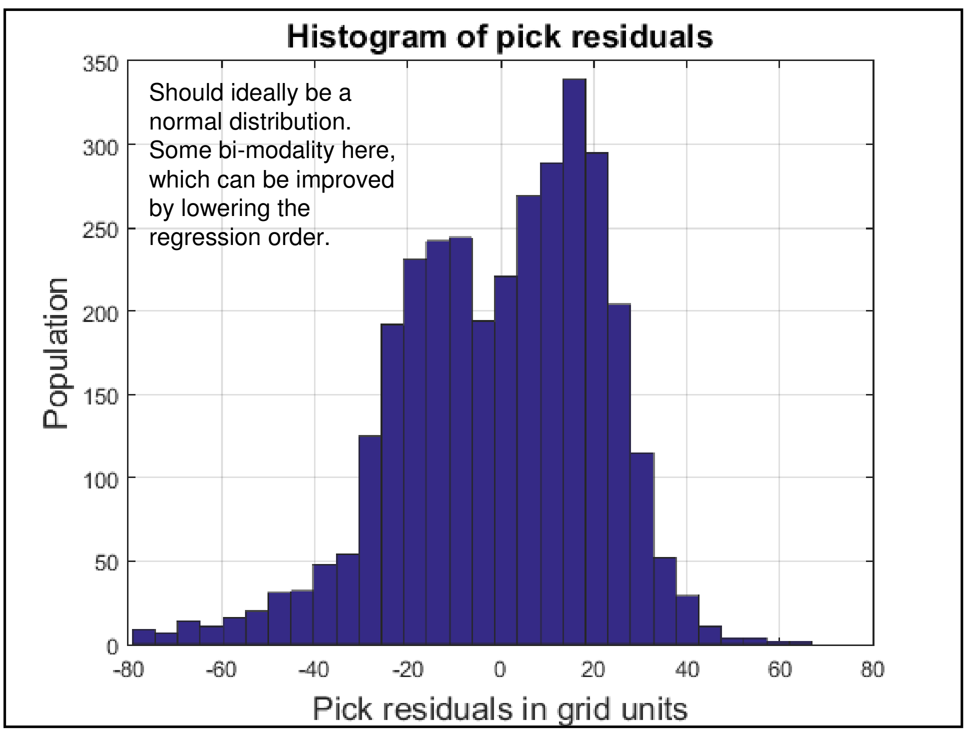
Chebyshev Regression and Velocity

- In 2-D mode (refractor & water), the Chebyshev regression of first-break pick time (ms) to horizontal distance (in gu) is refreshed at every iteration of the least-square adjustment.
- The red Chebyshev regression line relates a pick time to a horizontal distance for the adjustment of the receiver's position.
- Note that the Chebyshev regression equation curve does not start at (0,0). This static offset near the origin accounts for instrumental delays (on average) and picking bias (on average).
- The numerical differential of the regression line estimates velocity in the refractor.
- First breaks are seismic data. Skill and interpretation are as important as science in processing seismic data.

- We've looked at pick residuals. The next three plots are least-squares (LS) residuals:
  - LS residuals as functions of azimuth
  - LS residuals as functions of distance
  - LS residuals as histogram




LS residuals as function of distance
Suitably random over the entire abscissa. Mean as a function of distance is always zero due to the regression equation.
grid units residual
grid units distance
80
60
40
20
0
-20
-40
-60
-80
500
1000
1500
2000
2500
3000


Histogram of pick residuals
Should ideally be a normal distribution. Some bi-modality here, which can be improved by lowering the regression order.
Population
Pick residuals in grid units
350
300
250
200
150
100
50
0
-80
-60
-40
-20
0
20
40
60
80

2-D Mode Processing - 8

- A good least-squares adjustment converges on the final coordinates at the rate of about an order of magnitude per iteration
- FBA accomplishes this, especially in the early iterations, despite the refracted observations themselves changing slightly at each successive iteration due to revised Chebyshev regression coefficients, despite outlier rejection and despite automatic geometry balancing, all of which slow convergence in the later iterations
- The least-squares criterion is that the sum of the squares of the residuals is a minimum.
- Those residuals are shown on the previous three slides

- Finally, we turn to the numerical statistics provided by FBA
- Anything can be copied from the display screen and pasted elsewhere as required, e.g. as in a report.
- Alternatively, the “Screen => file” button will save the display screen as a text file with a name selected by the user.
- The next slide shows the results for the adjustment so copied.

2-D Mode Statistics

Grid units in meters, picking sample in milliseconds = 2
Picking by absolute amplitude, sample length = 6, threshold = 70, high-pass = yes with length = 41
LS parameters: pick SD = 20, tolerance = 0.3, order = 6, inner = 300, outer = 1400, max iter = 50, tau = 4, depth = 100, mode = 2-D, balancing = no, anisotropy/angularity correction = no, drift = 0
UV = 1.1822, Scaled SDX = 0.53816, Scaled SDY = 0.5338, HDOP = 0.034857
20 bin distance SD/mean ratio = 0.15448 ... 40 bin distance SD/mean ratio = 0.19623
10 degree azimuth SD/mean ratio = 0.16786 ... 20 degree azimuth SD/mean ratio = 0.1192
Used picks = 3306, Selected picks = 3337, Total picks = 6931
Receiver coordinates = 285219.68627 7437308.0728
Receiver ID = 0
Time (seconds) processing = 0.6028
iteration = 8 position jump in grid unit = 0.053007
iteration = 7 position jump in grid unit = 0.037679
iteration = 6 position jump in grid unit = 0.25729
iteration = 5 position jump in grid unit = 0.23565
iteration = 4 position jump in grid unit = 38.9437
iteration = 3 position jump in grid unit = 163.4053
iteration = 2 position jump in grid unit = 703.808
iteration = 1 position jump in grid unit = 607.5953
Processing begins ...

8 iterations are mandatory in 2D mode (refractor & water).

Read bottom to top!

Notice the configuration parameters in the red box at the top.

See glossary for definitions

2-D Mode Processing - 9

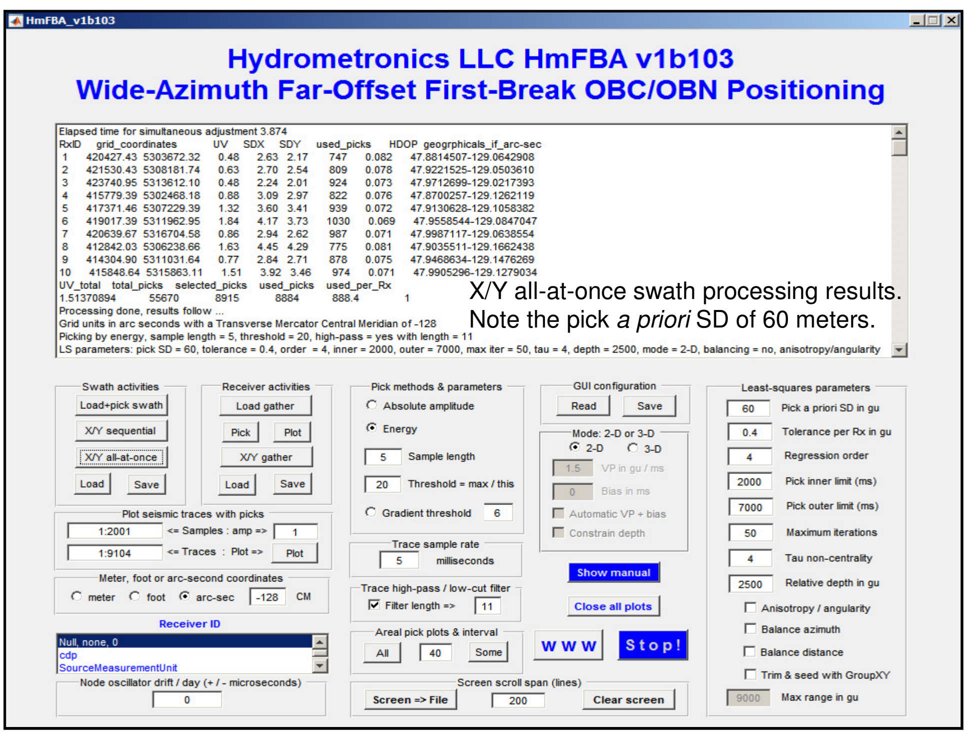
- The least-squares adjustment can be controlled by the LS parameters: pick SD, convergence tolerance, regression order (if in 2-D mode), inner and outer pick limits, maximum number of iterations, tau non-centrality, depth (relative to source), anisotropy / angularity, geometry balancing, trimming & seeding.
- If you increase the pick SD, the unit variance (UV) will compensate by going down, and vice versa.
- The coordinate uncertainties from the inverse normal matrix are scaled by the UV and, therefore, are independent of pick SD.
- Choose a convergence tolerance that is small, but not so small that it runs up the iterations to the limit.
- In 2-D mode (refractor & water), regression order has an effect. Experiment. Order 2 should always work. Orders 3 and 4 are generally good. Higher orders are possible. For a flat refractor, regressions order 1 yields additional information: slope (VP) and intercept (sum of the biases). See next slide.
- Choose inner and outer limits to isolate the water arrivals or to find a clean refractor, for example.
- The maximum number of iterations is a fail-safe number. If the convergence tolerance is too low, iterations may increase.

2-D and 3-D Swath Processing

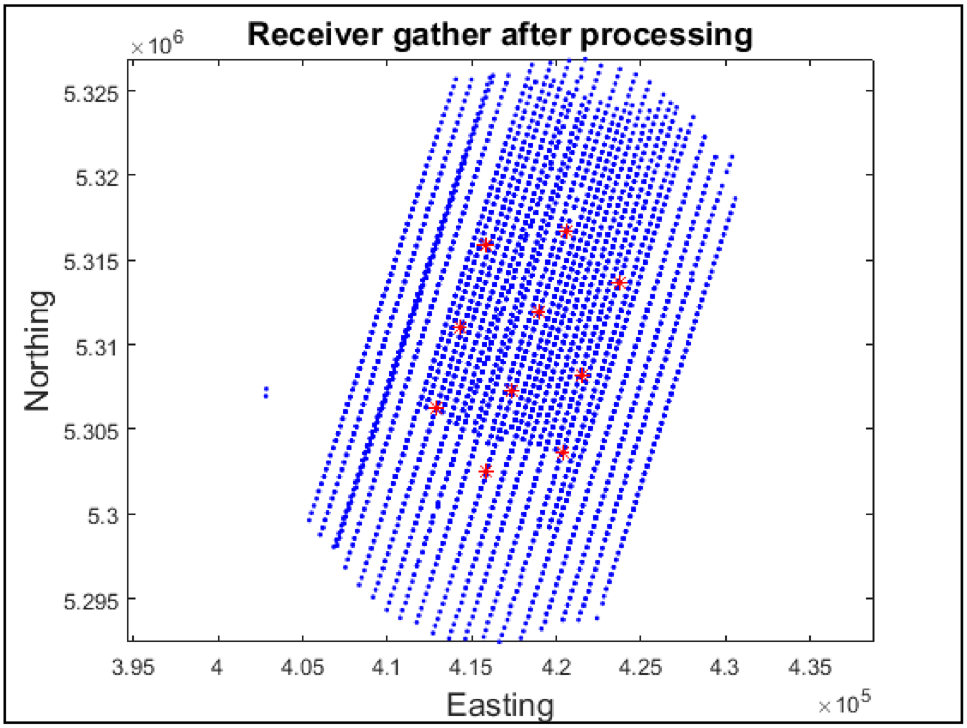
Swath Processing

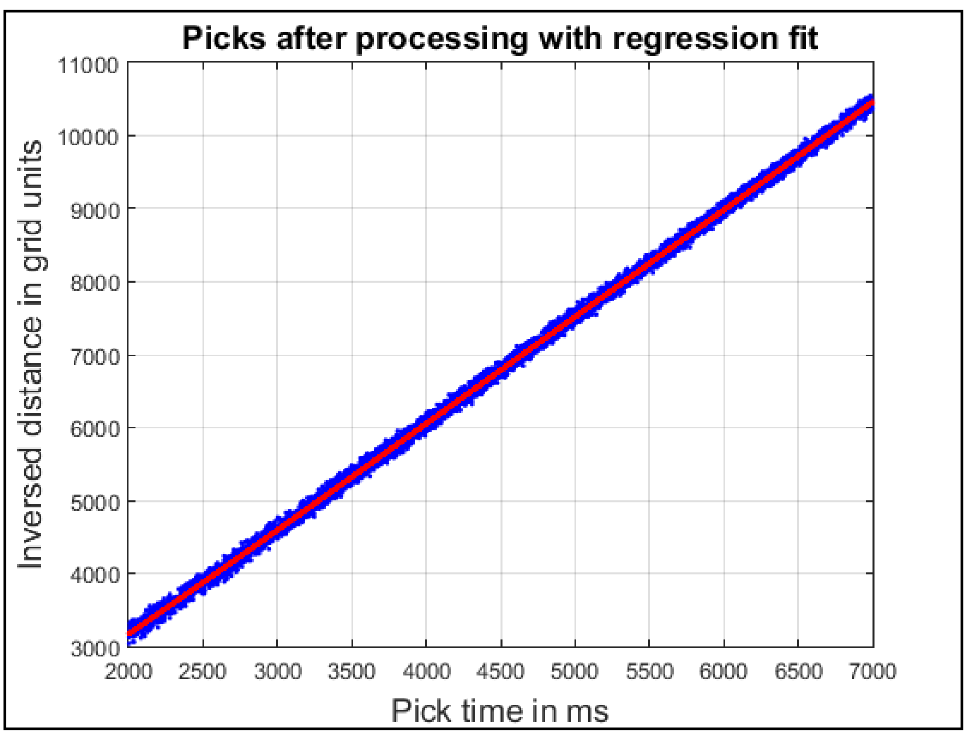
- "X/Y sequential" swath processing is nothing more than *en masse,* automatic, single-node, 2-D mode or 3-D mode processing without the (time and space-consuming) graphics.
- "X/Y all-at-once" swath processing brings more to the party. All nodes are processed simultaneously in a single, 2-D mode (refractor & water) adjustment with the same Chebyshev regression coefficients. In many prospects, this is an advantage, but not always.
- Multi-receiver plots in this manual are generated from the positioning of several ocean-bottom seismometers (OBS) from the NSF-funded MGL0910 "ETOMO" survey west of Oregon, USA. See Acknowledgements at the end for more details about the survey.

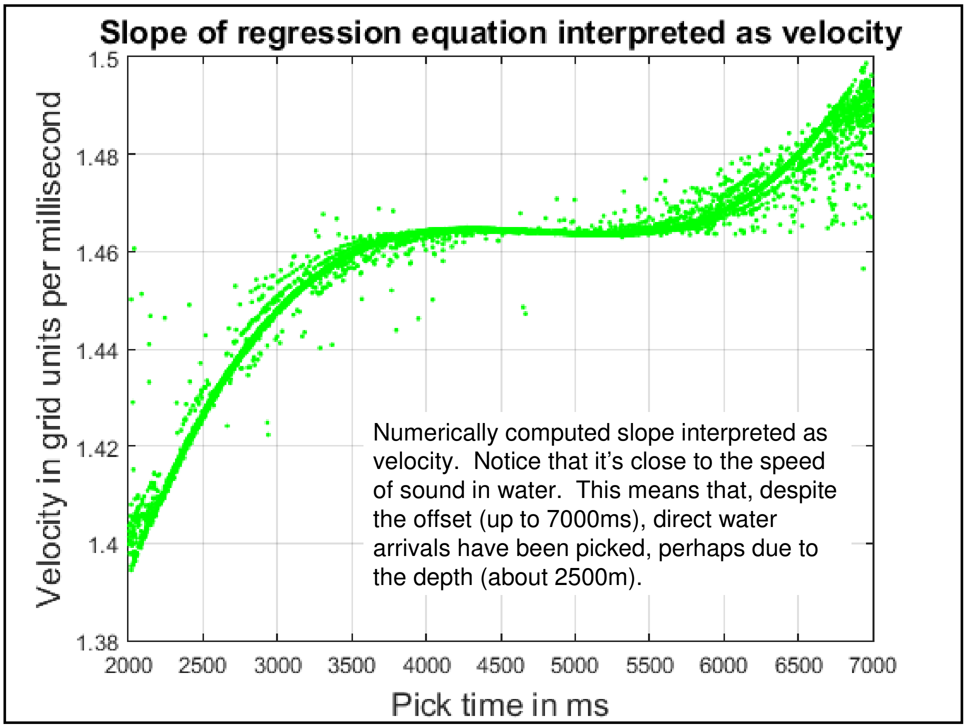
- The following "X/Y all-at-once" plots are:
  - FBA configuration
  - Plan view
  - Chebyshev regression equation
  - Numerically-computed velocity
  - Pick residuals versus pick time
  - Histogram of pick residuals
  - Swath output statistics

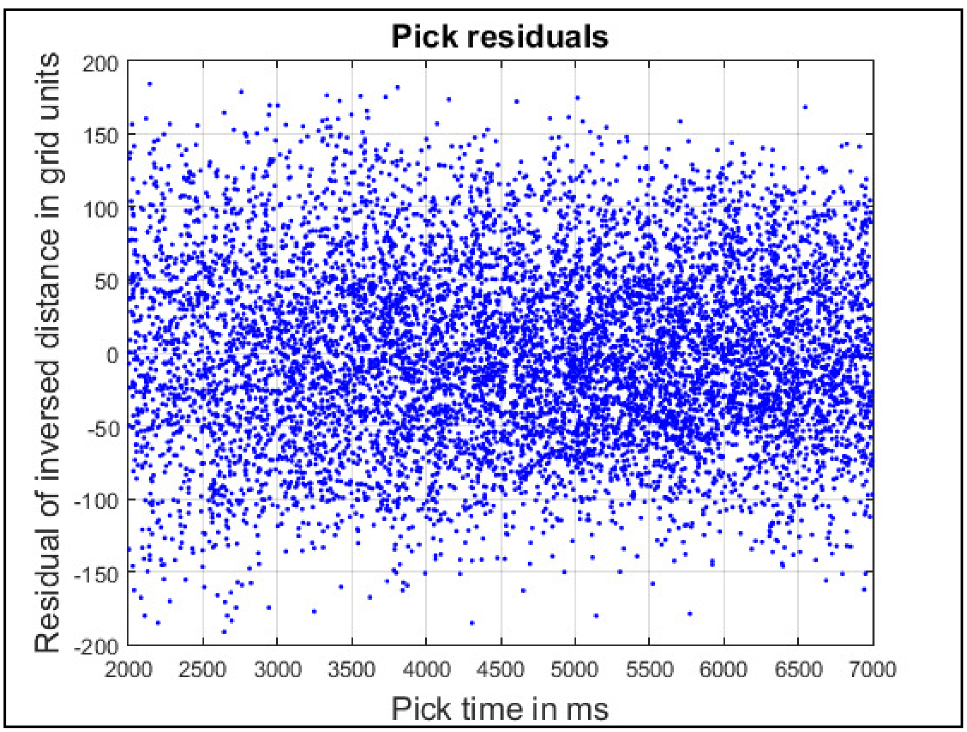


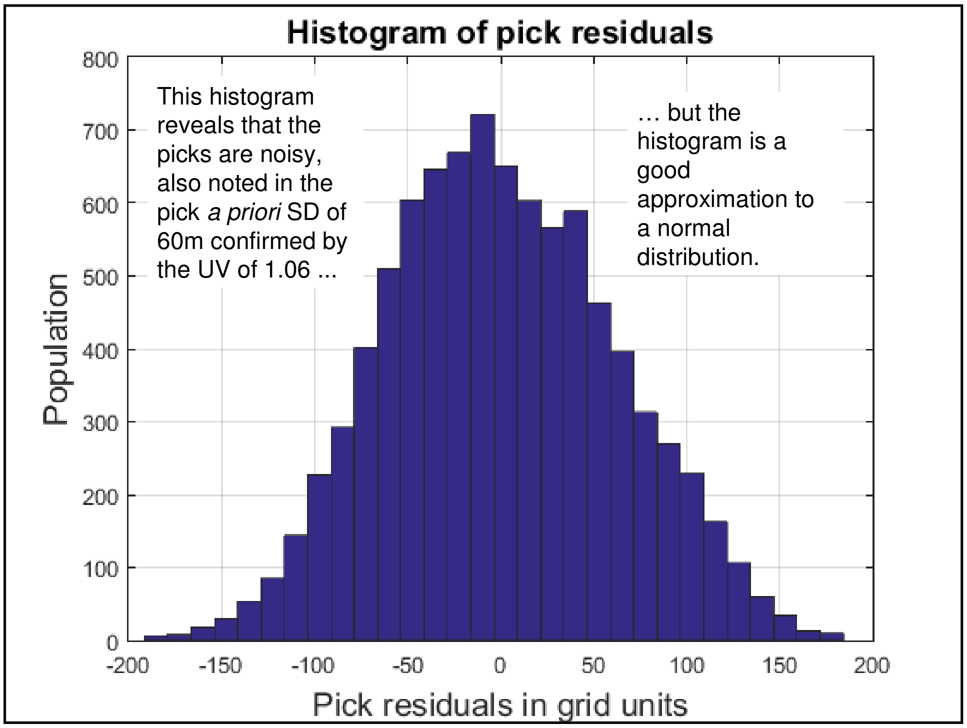
X/Y all-at-once swath processing results.
Note the pick *a priori* SD of 60 meters.


Receiver gather after processing
×10^6
5.325
5.32
5.315
5.31
5.305
5.3
5.295
Northing
3.95
4
4.05
4.1
4.15
4.2
4.25
4.3
4.35
Easting
×10^5


Picks after processing with regression fit
11000
10000
9000
8000
7000
6000
5000
4000
3000
Inversed distance in grid units
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
7000
Pick time in ms


Slope of regression equation interpreted as velocity
Velocity in grid units per millisecond
1.5
1.48
1.46
1.44
1.42
1.4
1.38
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
7000
Pick time in ms
Numerically computed slope interpreted as velocity. Notice that it's close to the speed of sound in water. This means that, despite the offset (up to 7000ms), direct water arrivals have been picked, perhaps due to the depth (about 2500m).


Pick residuals
Residual of inversed distance in grid units
200
150
100
50
0
-50
-100
-150
-200
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
7000
Pick time in ms



Swath Output Statistics (“X/Y all-at-once” is always in 2-D mode)

Explanation by column:
1 – Receiver sequence number
2 – Easting
3 – Northing
4 – SD Easting
5 – SD Northing
6 – Number of used first breaks for this receiver
7 – Latitude (only with SEG-Y in arcseconds)
8 – Longitude (only with SEG-Y in arcseconds)

Elapsed time for simultaneous adjustment 3.874

RxID	grid_coordinates		UV	SDX	SDY	used_picks	HDOP	geogrphicals_if_arc-sec
1	420427.43	5303672.32	0.48	2.63	2.17	747	0.082	47.8814507-129.0642908
2	421530.43	5308181.74	0.63	2.70	2.54	809	0.078	47.9221525-129.0503610
3	423740.95	5313612.10	0.48	2.24	2.01	924	0.073	47.9712699-129.0217393
4	415779.39	5302468.18	0.88	3.09	2.97	822	0.076	47.8700257-129.1262119
5	417371.46	5307229.39	1.32	3.60	3.41	939	0.072	47.9130628-129.1058382
6	419017.39	5311962.95	1.84	4.17	3.73	1030	0.069	47.9558544-129.0847047
7	420639.67	5316704.58	0.86	2.94	2.62	987	0.071	47.9987117-129.0638554
8	412842.03	5306238.66	1.63	4.45	4.29	775	0.081	47.9035511-129.1662438
9	414304.90	5311031.64	0.77	2.84	2.71	878	0.075	47.9468634-129.1476269
10	415848.64	5315863.11	1.51	3.92	3.46	974	0.071	47.9905296-129.1279034

UV_total	total_picks	selected_picks	used_picks	used_per_Rx	
1.51370894	55670	8915	8884	888.4	1

Processing done, results follow ...

Configuration parameters

Grid units in arc seconds with a Transverse Mercator Central Meridian of -128
Picking by energy, sample length = 5, threshold = 20, high-pass = yes with length = 11
LS parameters: pick SD = 60, tolerance = 0.4, order = 4, inner = 2000, outer = 7000, max iter = 50, tau = 4, depth = 2500, mode = 2-D, balancing = no, anisotropy/angularity correction = no

Iteration “jump” used picks elapsed time (NB: “jump” is the sum of the squares of the receiver position shifts)
Time (seconds) processing = 0.71412
8 0.016503362 8884 0.67442209
…….
1 0.02725147 8914 0.32697193
Elapsed time for bookeeping and first regression 0.23694
Elapsed time for bookeeping 0.17665
Process begins ... please wait

3-D Mode Processing

3-D Mode Processing - 1

- Wide-azimuth, far-offset 2-D mode processing is the strength of FBA, but the application offers a full complement of features for 3-D mode processing of direct water arrivals (no refractor involvement) as a single node (“X/Y gather”) or in a swath (“X/Y sequential”). See earlier in the manual for more information.
- See also the previous comments on Snell’s Law to assess your offset geometry and learn whether you’re getting only water arrivals. FBA in 3-D mode will, of course, process refracted arrivals, too, but refracted geometry is different (more bent than a water arrival). Including refracted arrivals in a 3-D mode adjustment can skew results. Although there are clues in the output graphics, in the velocity plot and in the seismic data plot, the FBA adjustment doesn’t know if you’re including refracted arrivals or not.
- In the years before GNSS dominated land surveying (and maybe still to some extent), electronic distance measuring (EDM) equipment needed to be calibrated for both a scale error (velocity of propagation or VP) and a static offset (bias)
- A first break is also subject to VP and bias. Therefore, the main 3-D mode controls allow for a manual input of VP and bias. VP can be measured empirically in your prospect with an ocean probe, but bias (e.g. picking and instrumental delays) is just a guess best left at zero for starters.

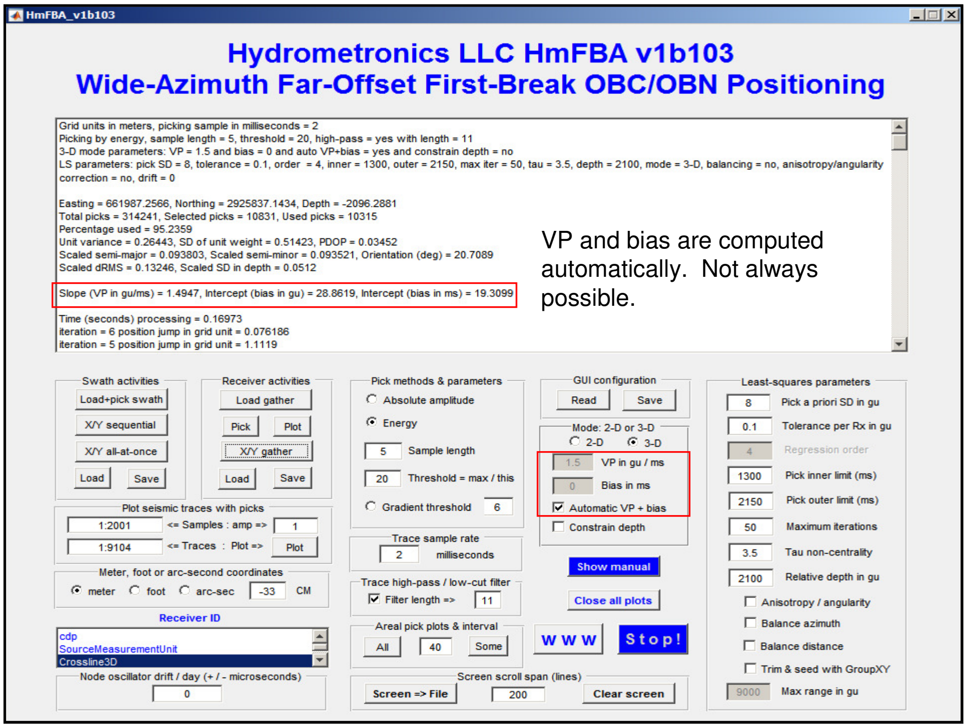
3-D Mode Processing - 2

- The four approaches to 3-D mode processing in FBA are:
  - A 3-D mode solution can be computed using only *a priori* VP and bias inputs. FBA provides a linear regression (first order) of the picks versus the straight-line distances between the sources and the computed 3-D position that provides *a posteriori* VP and bias. By splitting the differences between the *a priori* and *a posteriori* parameters, the process can be iterated until both are the same.
  - FBA can do this automatically (by checking “Automatic VP + bias”), but less successfully than manually because of the high correlation (especially in poor offset geometry) between the static bias and depth. It should be obvious by the number of iterations, the depth and the *a posteriori* parameters when “Automatic VP + bias” is not successful.
  - If the receiver depth is known (perhaps by prospect bathymetry), then depth can be constrained. The depth constraint is most successful if “Automatic VP + bias” is also checked (the default).
  - Depth can also be constrained with manually-entered VP and bias, but large residuals are possible if there is a conflict between the depth and the entered VP and bias due to their correlation.
- In all these four approaches the reported graphics and statistics (iterations, *a posteriori* VP and bias, unit variance, percentage of used picks, computed depth) provide strong guidance about which is the most successful.

3-D Mode Processing - 3

- Our 3-D mode example derived from FairfieldNodal data in deep water (2100m). See Acknowledgements.
- VP and bias are computed automatically, possible because there are lots of data.

- The next two slides exhibit the configuration and 3-D mode output statistics.
- The next slide is a plan view in 3D
- Then follow three histograms of the pick residuals and the distance and azimuth geometry balance
- Finally, pick time versus offset distance is shown



3-D Mode Output Statistics

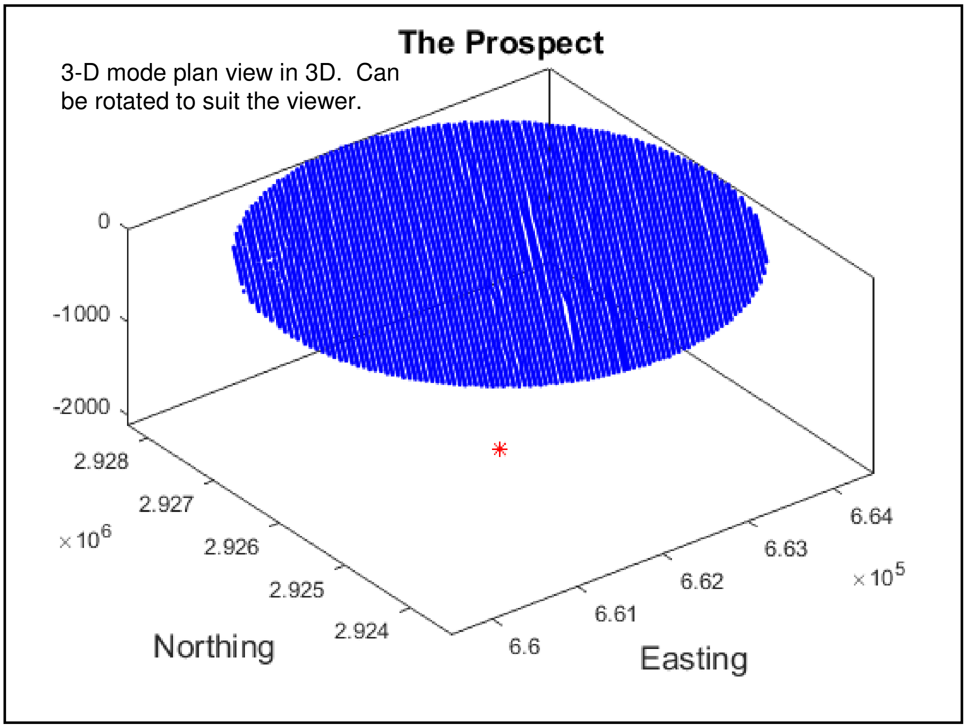
Grid units in meters, picking sample in milliseconds = 2
Picking by energy, sample length = 5, threshold = 20, high-pass = yes with length = 11
3-D mode parameters: VP = 1.5 and bias = 0 and auto VP+bias = yes and constrain depth = no
LS parameters: pick SD = 8, tolerance = 0.1, order = 4, inner = 1300, outer = 2150, max iter = 50, tau = 3.5, depth = 2100, mode = 3-D, balancing = no, anisotropy/angularity correction = no, drift = 0

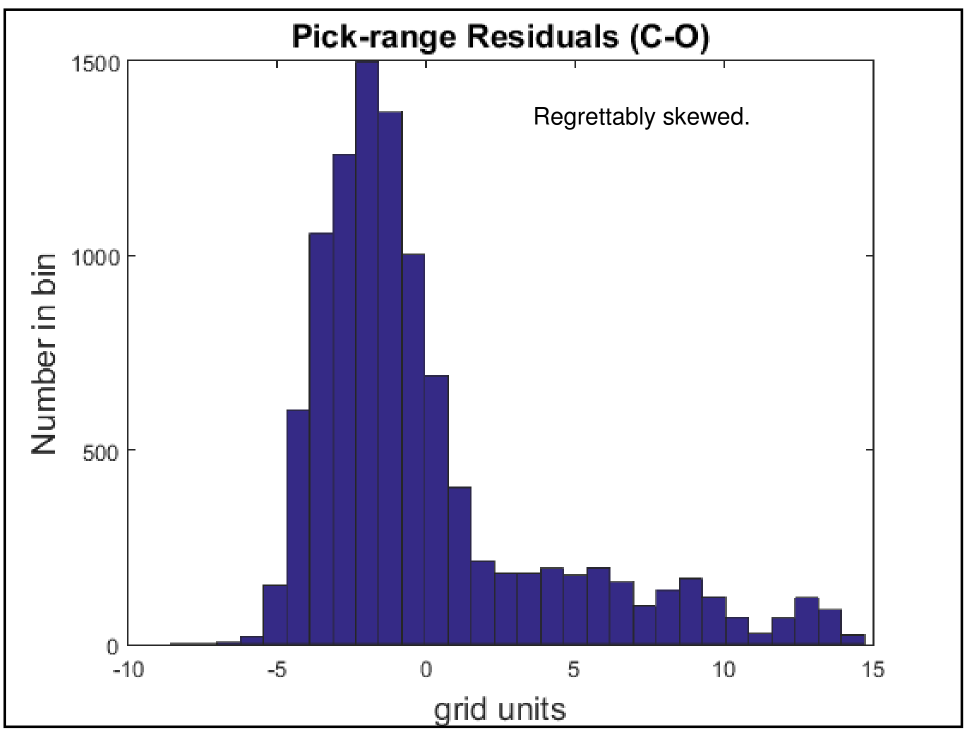
Easting = 661987.2566, Northing = 2925837.1434, Depth = -2096.2881
Total picks = 314241, Selected picks = 10831, Used picks = 10315
Percentage used = 95.2359
Unit variance = 0.26443, SD of unit weight = 0.51423, PDOP = 0.03452
Scaled semi-major = 0.093803, Scaled semi-minor = 0.093521, Orientation (deg) = 20.7089
Scaled dRMS = 0.13246, Scaled SD in depth = 0.0512

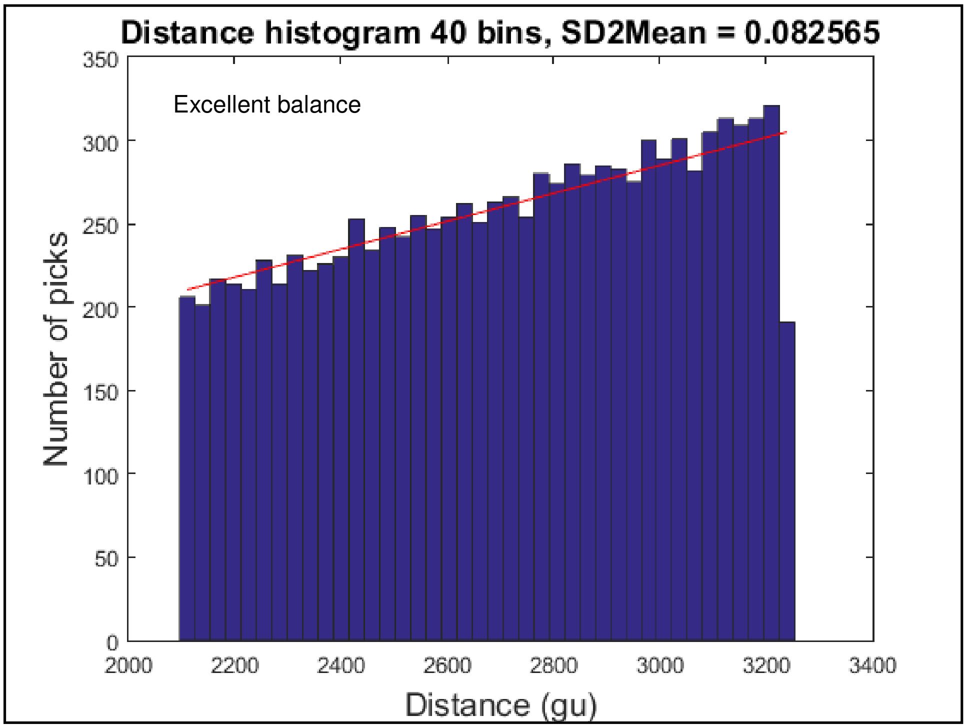
Slope (VP in gu/ms) = 1.4947, Intercept (bias in gu) = 28.8619, Intercept (bias in ms) = 19.3099

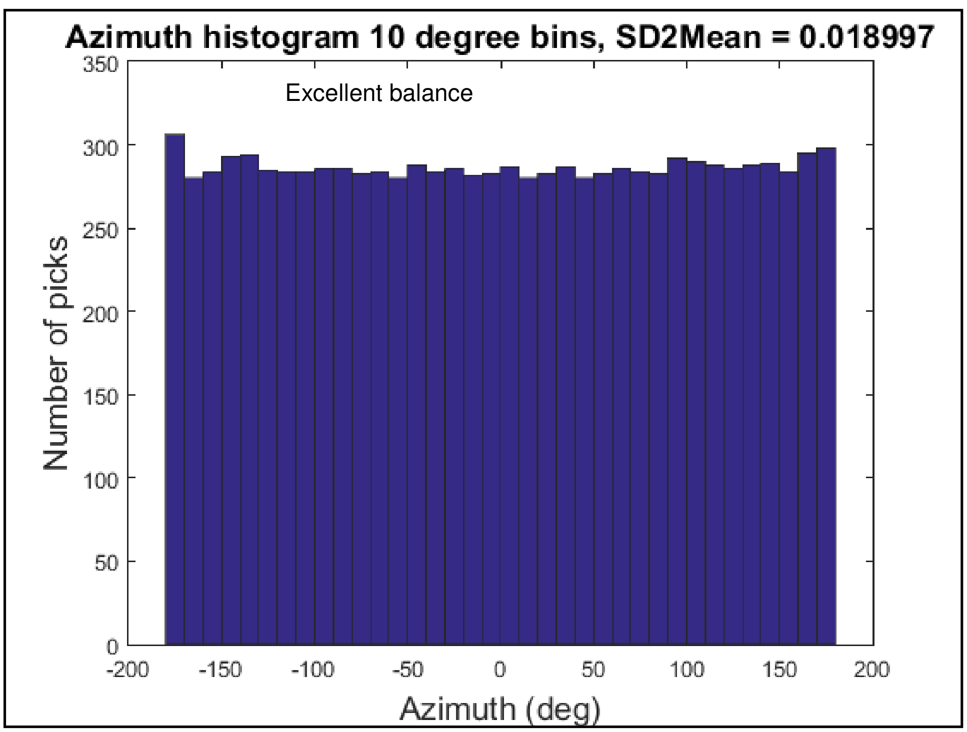
Time (seconds) processing = 0.16973
iteration = 6 position jump in grid unit = 0.076186
…….
iteration = 1 position jump in grid unit = 1576.896
Processing begins ...

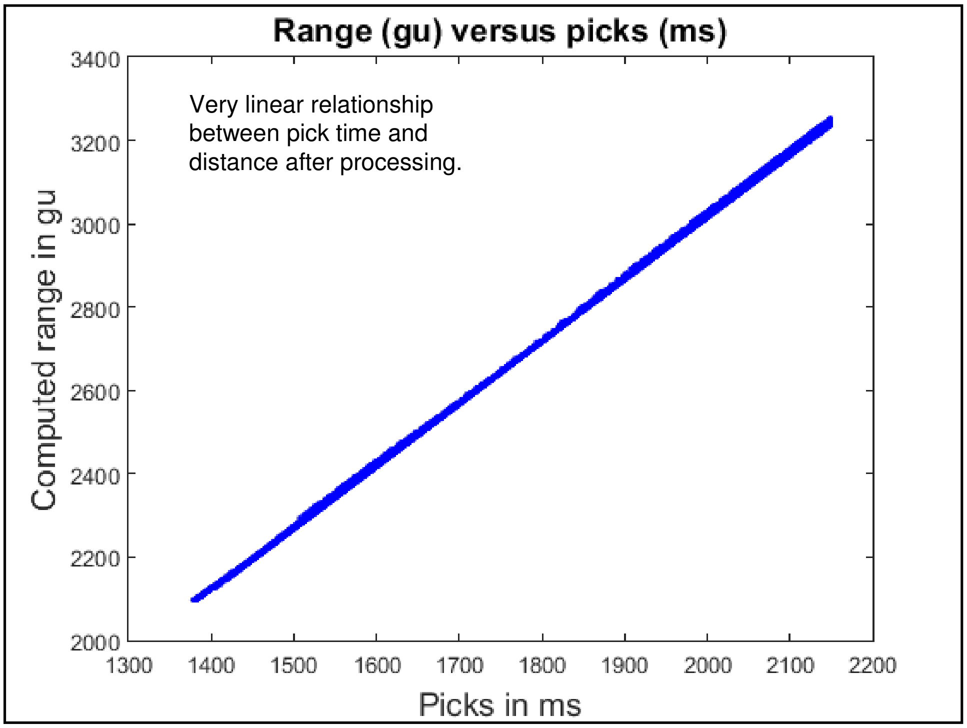
Rapid convergence


The Prospect
3-D mode plan view in 3D. Can be rotated to suit the viewer.
0
-1000
-2000
2.928
2.927
2.926
2.925
2.924
×10^6
Northing
6.6
6.61
6.62
6.63
6.64
×10^5
Easting


Pick-range Residuals (C-O)
Regrettably skewed.
Number in bin
1500
1000
500
0
-10
-5
0
5
10
15
grid units


Distance histogram 40 bins, SD2Mean = 0.082565
Excellent balance
Number of picks
Distance (gu)
0
50
100
150
200
250
300
350
2000
2200
2400
2600
2800
3000
3200
3400


Azimuth histogram 10 degree bins, SD2Mean = 0.018997
Excellent balance
Number of picks
Azimuth (deg)
0
50
100
150
200
250
300
350
-200
-150
-100
-50
0
50
100
150
200



Concluding Comments - 1

There are many ways to position OBS receivers. Dedicated, high-frequency, positioning acoustics (e.g. USBL) are the most common way ... and the most expensive in time and equipment.

Direct, seismic-airgun, water-arrival first break positioning lines are also possible. Extra time is required, but no extra equipment. Unfortunately, the first-break observable is much cruder than the acoustic observable, and there are first-break picking delays and instrumental delays that are difficult to calibrate. Therefore, direct water-arrival first breaks are not the same as dedicated acoustics.

A third technique is to use wide-azimuth, far-offset production seismic data, lots of them. This is the cheapest technique since no dedicated positioning lines are required. Vastly more data are available than in water-arrival first break positioning, so the statistics of large numbers make up for the coarse quality of the first-break observations. Because data are observed at all azimuths and offsets, picking and instrumental delays are easily calibrated.

Concluding Comments - 2

On the other hand, far-offset seismic data may arrive horizontally through one or more refractors. These refracted data are subject to geological velocity gradients that must be calibrated. They are in FBA with a Chebyshev regression equation for a single node or an entire swath and with anisotropy/angularity compensation. It's all a matter of statistics. With a crude observable like a first break, the statistics are in your favor with all the data in a wide-azimuth, far-offset receiver gather. And the outliers are easy to clean up with all those data, too.

FBA will process one receiver gather at a time while providing copious QC graphics and statistics for the analysis of the best parameters, or process a swath of receiver gathers both sequentially and simultaneously, which provides added benefits. Automatic geometry balancing in FBA is an effective way to achieve excellent results on a receiver-by-receiver basis.

Appendix 1: Acknowledgements - 1

- Thanks to FairfieldNodal and to ION Geophysical for permission to exhibit in this manual FBA plots derived from their data.
- The facilities of IRIS Data Services, and specifically the IRIS Data Management Center, were used for access to some waveforms, related metadata, and/or derived products used in testing FBA. IRIS Data Services are funded through the Seismological Facilities for the Advancement of Geoscience and EarthScope (SAGE) Proposal of the National Science Foundation under Cooperative Agreement EAR-1261681
- FBA test data was provided by instruments from the Ocean Bottom Seismograph Instrument Pool (http://www.obsip.org) which is funded by the National Science Foundation under cooperative agreement OCE-1112722
- A link to the R/V Marcus G. Langseth Endeavour Tomography Expedition (MGL0910 “ETOMO”) survey follows: http://ds.iris.edu/data/reports/2009/09-014/
- The Principal Investigators of the NSF-funded survey on the mid-Atlantic ridge near the Azores (MGL 1305) provided data for the testing of FBA. Two plots in this user’s manual are derived from this survey. A link to the MGL 1305 survey report follows: http://www.whoi.edu/sbl/liteSite.do?litesiteid=90993

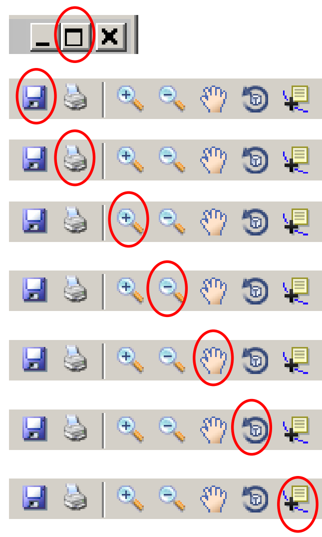
Appendix 1: Acknowledgements - 2

- "The Statistics of Residuals and The Detection of Outliers", Allen J. Pope, 1976, NOAA Technical Report NOS 65 NGS 1, the outlier detection scheme in FBA.
  - https://www.ngs.noaa.gov/PUBS_LIB/TRNOS65NGS1.pdf
- "Using Cross-Correlated Head-Wave and Diving-Wave Seismic Energy To Position Ocean Bottom Seismic Cables", a University of Houston GEOL 7333 Seismic Wave and Ray Theory term paper by Noel Zinn (1999), overall approach and a generic first-break picker
  - http://www.hydrometronics.com/downloads/GEOL%207333%20Term%20Paper.pdf
- SegyMAT: Read and Write SEG-Y and SU files using Matlab
  - http://segymat.sourceforge.net/
- Agus Abdullah, PhD, Ensiklopedi Seismik Online, gradient threshold first-break picking method
  - http://ensiklopediseismik.blogspot.com/2014/05/first-break-picker.html

Appendix 2: Saved file format

Column 1 is pick in ms
Column 2 is source Easting or longitude
Column 3 is source Northing or latitude
Column 4 is source ID
Column 5 is receiver ID (or concatenated line-receiver ID)
Column 6 is milliseconds since the first trace
Column 7 is receiver-line ID
Column 8 is group X
Column 9 is group Y
Column 10 is (computed) offset
Column 11 is receiver ID (again)

Appendix 3: Matlab Plot Controls



Expand to full screen

Save in 16 formats

Print

Zoom in

Zoom out

Pan

Rotate 3D figure

Mark coordinates

Reset to original view …right click with cursor in plot

Appendix 4: Hardware, Software and Security Requirements

Hardware, Software and Security

- FBA was developed using a 64-bit version of Matlab (R2016a) on 64-bit Windows 7 on a 64-bit quad-core Intel Xeon CPU with 16 and later 48GB RAM and tested on a quad-core Intel i7 with 8GB RAM and a dual-core Intel i7 with 4GB of RAM
- A 64-bit CPU and 64-bit Windows is required for FBA.
- FBA was not tested on 64-bit Vista or Windows 8 or 10, but I expect that it will run on those OSs. XP is not recommended.
- FBA was not tested on Intel i3 or i5 CPUs or any equivalent AMD CPU, but I expect that it will run on them
- 4GB of RAM may be adequate for small gathers, but at least 8GB and as many as 48GB may be required for production depending upon the size of the gathers, thus the requirement for 64 bits.
- FBA is provided with a KEYLOK III (blue) security dongle, which enables you to run FBA on any Windows computer. The application may be copied freely.
- The blue KEYLOK III dongle does not require the installation of drivers, finding them in the Windows OS.
- Demonstration versions of FBA will have time-limited dongles.

Blue Security Dongle

- Contents of the “Dongle driver and utility” folder of the USB drive on which FBA was provided
  - VerifyKey.exe (checks for proper dongle installation)
  - USBKey64.sys (driver for 64-bit CPU required by FBA)
- The blue security dongle installs its drivers automatically upon installation. Wait for the process to complete.
- The utility VerifyKey.exe will confirm proper installation of the driver.
- Troubleshooting: The driver itself is located in the dongle driver and utility folder. To manually install the driver use Control Panel => System => Device manager => double click on USBKey or USB Dongle => Driver => Update Driver => browse to the driver in the dongle drivers and utilities folder.

MCR Installation

FBA is complied Matlab software that requires the installation of the Matlab Compiler Runtime (MCR). The MCRInstaller (supplied by The MathWorks for free and without royalty) is large because it will support all of Matlab on your computer. The MCR is like the .NET framework for Visual Studio languages or the Java Virtual Machine (JVM) for Java. The MCR supports compiled Matlab programs.

The installer can be found on the supplied USB drive or at: http://www.mathworks.com/products/compiler/mcr/index.html.

Copy or download the 64bit Windows version for Matlab Release 2016a to the target machine. Execute the MCR installer.

Place the FBA executable in the desired folder. Execute by double-clicking. This will launch splash.png, which can be any splash screen you desire by this name (even your company logo).

Troubleshooting the MCR Installation

If the MCR is not "seen" add MCR path to the PATH variable within Environment variables. One way to do that is Right Click on "My Computer" => Properties => Advanced System Settings => Click on "Environment Variables". In the "System Variables" dialog box, click on Path variable and add the MCR path to it which is typically "C:\Program Files\MATLAB\MATLAB Compiler Runtime \v83\runtime\win64" for a 64 bit Windows system. Check first to see where the MCR is located, then copy that path.

Another way to add the path to use the System Properties dialog box. Open Control Panel => Performance and Maintenance => System. In the box that opens, click the "Advanced" tab to obtain the dialog box. Click the button "Environment Variables". The dialog box lists variables that apply only to the current user and those that apply to the whole system. Add a path to the MCR as above.

Finally, using the command prompt, PATH can be appended by the command path = %path%; path_to_MCR. Appending the path this way lasts only until reboot. Better to use one of the previous methods.

If the MCR path needs to be added, a reboot may be required.

Appendix 5a: SegyMat Position IDs

"Position"	"Precision"	"Trace_Header_Name"
000	int32	TraceSequenceLine
004	int32	TraceSequenceFile
008	int32	FieldRecord
012	int32	TraceNumber
016	int32	EnergySourcePoint
020	int32	cdp
024	int32	cdpTrace
028	int16	TraceIdenitifactionCode
030	int16	NSummedTraces
032	int16	NStackedTraces
034	int16	DataUse
036	int32	offset
040	int32	ReceiverGroupElevation
044	int32	SourceSurfaceElevation
048	int32	SourceDepth
052	int32	ReceiverDatumElevation
056	int32	SourceDatumElevation
060	int32	SourceWaterDepth
064	int32	GroupWaterDepth
068	int16	ElevationScalar
070	int16	SourceGroupScalar
072	int32	SourceX
076	int32	SourceY
080	int32	GroupX
084	int32	GroupY
088	int16	CoordinateUnits
090	int16	WeatheringVelocity
092	int16	SubWeatheringVelocity
094	int16	SourceUpholeTime
096	int16	GroupUpholeTime
098	int16	SourceStaticCorrection

Appendix 5b: SegyMat Position IDs

100	int16	GroupStaticCorrection
102	int16	TotalStaticApplied
104	int16	LagTimeA
106	int16	LagTimeB
108	int16	DelayRecordingTime
110	int16	MuteTimeStart
112	int16	MuteTimeEND
114	uint16	ns
116	uint16	dt
118	int16	GainType
120	int16	InstrumentGainConstant
122	int16	InstrumentInitialGain
124	int16	Correlated
126	int16	SweepFrequenceStart
128	int16	SweepFrequenceEnd
130	int16	SweepLength
132	int16	SweepType
134	int16	SweepTraceTaperLengthStart
136	int16	SweepTraceTaperLengthEnd
138	int16	TaperType
140	int16	AliasFilterFrequency
142	int16	AliasFilterSlope
144	int16	NotchFilterFrequency
146	int16	NotchFilterSlope
148	int16	LowCutFrequency
150	int16	HighCutFrequency
152	int16	LowCutSlope
154	int16	HighCutSlope
156	int16	YearDataRecorded
158	int16	DayOfYear
160	int16	HourOfDay

Appendix 5c: SegyMat Position IDs

162	int16	MinuteOfHour
164	int16	SecondOfMinute
166	int16	TimeBaseCode
168	int16	TraceWeightningFactor
170	int16	GeophoneGroupNumberRoll1
172	int16	GeophoneGroupNumberFirstTraceOrigField
174	int16	GeophoneGroupNumberLastTraceOrigField
176	int16	GapSize
178	int16	OverTravel
180	int32	cdpX
184	int32	cdpY
188	int32	Inline3D
192	int32	Crossline3D
196	int32	ShotPoint
200	int16	ShotPointScalar
202	int16	TraceValueMeasurementUnit
204	int32	TransductionConstantMantissa
208	int16	TransductionConstantPower
210	int16	TransductionUnit
212	int16	TraceIdentifier
214	int16	ScalarTraceHeader
216	int16	SourceType
218	int32	SourceEnergyDirectionMantissa
222	int16	SourceEnergyDirectionExponent
224	int32	SourceMeasurementMantissa
228	int16	SourceMeasurementExponent
230	int16	SourceMeasurementUnit
232	int32	UnassignedInt1
236	int32	UnassignedInt2

Appendix 6: Glossary of Terms

Adjust (Adjustment). Correct(s) observations to compensate for random error. The least-squares criterion is that the sum of the squares of the corrections (residuals) be minimum. See least-squares adjustment.

Angularity. Variation in seismic energy onset as a function of source-array geometry and direction or travel.

Anisotropy. Variation in seismic velocity as a function of direction or travel.

A posteriori is Latin for "from what comes later", that is, statistical values determined after an adjustment, based on posterior experience.

A priori is Latin for "from what precedes", that is, statistical values assumed before an adjustment, based on prior knowledge.

Bias is a deviation from the truth in some systematic way that can be written into an observation equation and solved for, i.e. calibrated. Also called systematic error.

Blunder or Outlier or Spike. A blunder is a mistake, that is, an observation occurring outside of the expected probability distribution. An example in surveying might be using the wrong back sight. Other examples might be an acoustic reflection or erroneous data communication.

Chebyshev regression equation is a mathematical expression of the form $y = a_0T_0(z) + a_1T_1(z) + \ldots + a_nT_n(z)$, where $a_0, a_1, \ldots, a_n$ are empirically-determined coefficients, where $T_0(z)= 1$, $T_1(z)= z$ and $T_{i+1}(z)= 2zT_i(z) - T_{i-1}(z)$, and where $z = ((x\text{-}\min(x)) - (\max(x)\text{-}x)) / (\max(x)\text{-}\min(x))$. The regression order is the highest positive integer power in the equation. These Chebyshev terms of the first kind (T) are orthogonal in the domain -1 to 1, thus the compression of x into z. This orthogonality eliminates the multicollinearity of normal polynomial regression and, thus, is an improvement over previous methods. The x's are pick times and the y's are distances corresponding to the picks.

C-O is "computed minus observed", another expression for residual.

Convergence. See least-squares adjustment.

Correlation is a measure of the statistical dependence between variables. A correlation coefficient is the covariance divided by the product of the associated standard deviations, varying between +1 and -1, where +1 is complete positive dependence, -1 is complete negative dependence and 0 is no dependence at all, that is, completely random.

Covariance is a measure of the linked variation of the two random variables. It is a product of the inverse normal matrix. See normal matrix.

CSV. Comma separated value.

Degrees of freedom (DoF) are the number "knowns" (observations) minus the number of "unknowns" (coordinates or parameters) in an adjustment. Also called redundancy.

Design matrix. See observation equation.

Deterministic. A deterministic process is one in which no randomness is involved in the development of future states of the process, that is, it will always produce the same output from a given starting condition. Compare stochastic.

DOP is Dilution of Precision, a measure of adjustment geometry. HDOP (horizontal) is 2D and PDOP (positional) is 3D.

DRMS is Distance Root Mean Square or radial error, the square root of the sum of the variances in the X and Y axes. See normal matrix.

An **error** can be a blunder, a bias or a random error.

gu, grid unit. The unit (meter or foot) of the map projection of the source coordinates.

Inverse normal matrix. See normal matrix

Iteration. See least-squares adjustment.

Least squares (LS) adjustment is an algorithm for adjusting systems of observation equations by finding the minimum value for the sum of the squares of the residuals. Because observation equations are often linearized, the adjustment begins with a seed value for the coordinates and iterates (repeats the adjustment by replacing the last seed position with the latest coordinates) until convergence, that is, until the change from one iteration to the next is less than some tolerance. See observation equation.

Linear describes an equation or an expression in which all variables are of degree 1, that is, no higher powers or transcendentals.

Linearization. See observation equation.

LOESS is an unweighted version of LOWESS, which is "locally weighted scatter-plot smoothing", basically a rolling quadratic used as a smoother of time-series data.

Measurement is the physical process of determining the value of a quantity, such as a distance or angle or time. Also called an observation. All measurements have error.

Multicollinearity (also collinearity) is a statistical phenomenon in which two or more predictor variables in a multiple regression model are highly correlated, meaning that one can be linearly predicted from the others with a non-trivial degree of accuracy (Wikipedia).

Non-centrality. See Tau.

Normal (or Gaussian) distribution is the "bell-shaped" probability distribution that describes most random errors. It is characterized by a mean and a variance. Named after the mathematician Karl Friedrich Gauss (1777-1855)

Normal matrix and inverse normal matrix. The normal matrix is a product of a least-squares adjustment. It is the transpose of the design matrix times the design matrix. There may be weighting, too. See design matrix, which leads you to observation equation. The inverse normal matrix is also a product of a least-squares adjustment. It is the inverse of the normal matrix. It is also called the variance-covariance matrix of the coordinates. The diagonal terms are the variances of the coordinates. The off-diagonal terms are the covariances of the coordinates. The square root of the trace of the inverse normal matrix is the DRMS.

OBC / OBN / OBS. Ocean-Bottom Cable / Node / Seismometer.

Observation. In the context of FBA, an observation is a positioning measurement, typically a first break.

An **observation equation** expresses an observation in terms of the knowns and unknowns. The classic observation equation is that for an observed range in terms of known source coordinates (s) and unknown receiver coordinates (r), namely, Range = ((Xs-Xr)^2 + (Ys-Yr)^2)^0.5. This is a non-linear equation, that is, the powers of the unknowns are greater than first order or unity (1). To be used in a least-squares adjustment it must be linearized by using the first-order terms of a Taylor's series expansion of the observation equation (not discussed further). The coefficients of the first-order terms of a Taylor's series expansion comprise the elements of the design matrix.

Outlier. See blunder.

Precision (sometimes called resolution) is the consistency of a time series of observations or the coordinates derived from those observations (blunders and biases having been removed).

Probability is the likelihood (quantified between 0 and 1) of a random event to happen. A probability of 0 is no likelihood; a probability of 1 is certainty.

A **probability distribution** is the mathematical relationship between event (such as the value of an observation) and it's probability of occurrence. The two probability distributions discussed in FBA are the normal and the tau.

Random error is a deviation from the truth for stochastic reasons having to do with the imperfections of the measurement process. Random error averages out to the truth, unlike bias or blunder.

Redundancy. See degrees of freedom.

Regression is a statistical model that defines the expected value of one variable in terms of the value(s) of one or more other variables. Linear regression is first order. Quadratic regression is second order. Higher-order regressions are possible (as in FBA).

Regression equation. See Chebyshev regression equation.

Regression order. See Chebyshev regression equation.

A **residual** is the difference between an observation and its adjusted value.

SEG-Y is a standard format for storing seismic data developed by the Society of Exploration Geophysics (SEG)

Seismic Unix (SU) is a format for storing seismic data, a variation of SEG-Y, part of an open source seismic utilities package supported by the Center for Wave Phenomena at the Colorado School of Mines.

Semi-major and semi-minor are the axes of an error ellipse derived by rotating the variance-covariance matrix to the orientation at which the covariances become zero.

Snell's Law states that the ratio of the sines of the angles of incidence and refraction is equal to the ratio of the velocities of the respective media.

Standard deviation or Sigma (σ). Standard deviation is the square root of the variance. Sigma is the lower-case Greek letter σ that is generally used to represent the standard deviation. See variance.

Standard deviation of unit weight is the square root of the unit variance (UV), often reported as SD0 or σ0.

A **stochastic** process is one in which the effect is randomly related to the cause in some non-deterministic way that can only be described probabilistically. See deterministic.

Systematic error. See bias.

Tau, Tau Method, non-centrality. Tau is an obscure probability distribution that, for large degrees of freedom, is extremely close to the normal distribution, but which differs for low degrees of freedom. The Tau Method is an outlier rejection scheme developed by Allen J Pope, an American geodesist, in the 1970s. See Acknowledgements for a link to his paper. The Tau Method is an alternative to the Delft Method developed by W. Baarda, a Dutch geodesist, in the 1960s. The non-centrality parameter is the number of tau statistics to use for outlier rejection. Since FBA adjustments typically enjoy high degrees of freedom, one tau statistic is about the same as one normal-distribution standard deviation. In FBA a tau non-centrality of 2 will trim about 5% of the data, 3 will trim < 0.3% of the data, and so on.

Trace. (1) Sequence of recorded seismic amplitudes, (2) sum of the diagonal terms of a matrix.

The **Unit Variance (UV)** is a the sum of the squares of the weighted residuals divided by the degrees of freedom. If the *a priori* standard deviations are a correct assessment of the true random errors of the observations (biases and blunders excluded), then the UV computed in the adjustment will equal unity (1).

USBL is Ultra Short Baseline, an acoustic system providing one range (distance), an inclination angle and an angle relative to vessel centerline.

Variance is the mean of the squared residuals. See residual. The square root of the variance is the standard deviation.

Variance-covariance matrix. See normal matrix.

Velocity of Propagation (VP). Speed of sound in water.

A **vertical velocity gradient** is a variation in seismic velocity as a function of offset between the source and the receiver. Energy traveling farther are more likely to dive into deeper, faster refractors.

Weight is the inverse square of the *a priori* standard deviation assigned to an observation.