# Raypath interferometry for dummies: a processing guide

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# ABSTRACT

The near-surface layer of the earth often causes serious degradation of seismic reflection images due to the irregularity of its thickness and composition. The effects include loss of signal bandwidth as well as phase/timing mismatch of specific reflection events between seismic traces recorded at neighbouring shot or receiver surface stations. In earlier work we have introduced interferometric methods to remove these effects, and have shown that what we term the 'raypath domain' is an effective one in which to work. We have demonstrated the methods on both synthetic and real data, but have not described the details. In this work, we present specific processing flows from the ProMAX processing environment and describe in detail how to apply raypath interferometry to a 2D seismic line.

# INTRODUCTION

Raypath interferometry actually embodies two distinct and independent concepts, either of which can be applied on its own: raypath-consistency, and interferometry. The processing flows we have constructed are modular enough that while they are easily combined to apply the complete raypath interferometry method, they may be also be used independently. Our previous work is summarized in Henley (2006, 2007) and Henley and Daley (2007, 2008, and 2009).

# Interferometry

Interferometry is a broad spectrum of techniques encompassing many branches of physics; but the application we discuss here is one of the simpler ones. In brief, we propagate a seismic imaging wavefield into the earth, to be reflected from rock layers and perturbed by passage through the irregular near-surface; and we compare it with a 'reference wavefield', ostensibly containing no perturbations, in order to characterize the near-surface irregularities and remove their effects from the propagated wavefield.

There are two parts to this method: we construct or otherwise obtain a reference wavefield; and we cross-correlate this reference wavefield with the imaging wavefield, create inverse filters from the cross-correlations, and apply the inverse filters to the imaging wavefield to remove the near-surface perturbations from the image. This particular implementation of interferometry we also refer to as 'statics deconvolution'. Some of the processing flows we present here are devoted to creating estimates of the 'reference wavefield', which we also refer to as 'pilot traces', and to obtaining inverse filters for deconvolving the raw seismic traces.

# **Raypath-consistency**

For most of the history of seismic processing, near-surface corrections have been approximated by 'static' time shifts applied to entire seismic traces (the assumption of stationarity), and these 'statics' have been derived, for the most part, by assuming that the correction for all traces with a common surface location for source or receiver would be the same. This is the so-called 'surface-consistency' assumption; and it works well enough for a wide variety of situations, particularly when the average velocity of the near-surface earth materials is much less than that of the underlying layers (Figure 1). There are many real situations, however, where these conditions do not apply, and nearsurface corrections are neither stationary nor surface-consistent (Figure 2). To accommodate these situations while still allowing surface-consistency when it is present, we introduced the more general concept of 'raypath-consistency', in which the nearsurface corrections for all seismic raypaths originating or terminating at a surface location are the same *for a given raypath angle*. This means that instead of a constant time shift, or inverse filter to be applied to every trace associated with a particular surface location, the time shift or inverse filter will also vary with near-surface raypath angle.



- •Near-surface raypath segments vertical: surface-consistent
- •Single point Sources and receivers : surface-consistent, single event arrival
- •Single travel path between each source and receiver: single event arrival

FIG. 1. Near-vertical raypaths in the near surface mean that all raypaths beginning or ending at a particular surface point will share a common near-surface delay, or static (surface-consistency). This means, as well, that all events recorded with one source and one receiver share the same static (stationarity).



•Near-surface raypath segments not vertical: no surface-consistency

•Source or receiver *arrays*: no surface-consistency, several event arrivals

#### •Multi-paths allowed between sources and receivers: several event arrivals

FIG. 2. When near-surface raypath angles are not constrained to be near-vertical by Snell's law, near-surface raypath segment lengths can vary with both reflection depth and offset, so surface-consistency and stationarity are both destroyed. Source and/or receiver arrays and multi-path arrivals mean that a single static is no longer the most appropriate correction for near-surface effects.

At first consideration, it seems that we've complicated the problem by introducing more variables. There is, however, a simple and convenient transformation of the raw seismic data traces that brings us quite naturally into the domain of near-surface raypath consistency—the radial trace domain. Figure 3 shows a raypath schematic for one trace from a seismic shot gather, in which we see that the near-surface raypath angle is different at both source and receiver location for every different reflector. Because of the way in which the data are remapped in the radial trace transform, however, a trace in the R-T domain (Figure 4) has a constant raypath angle at the source and the same raypath angle, in parallel, at each of the receivers contributing to the radial trace. Whereas an ordinary shot or receiver gather consists of a group of traces having raypath schematics similar to that in Figure 3, but with different shot-receiver distances; the R-T transform of a shot or receiver gather is a group of traces having raypath schematics similar to that in Figure 4, but with different near-surface raypath angles.



Geometry of a trace in X-T domain

# Raypath angle is an increasing function of event time for each trace in the X-T domain





Geometry of a trace in R-T domain

# Raypath angle constant in all layers for each trace in the R-T domain

FIG. 4. Raypath schematic for a single trace in the radial trace (R-T) domain.

This leads very naturally to the concept of a common-angle gather, in which all the radial traces with the same near-surface raypath angle for an entire seismic line are sorted by surface location, as in Figure 5. This plot is analogous to a common-offset gather for

conventional X-T data. Interestingly, raypath-consistent (or angle-consistent) statics show up on this gather as vertically aligned reflection event disturbances, while those which are surface consistent also show up as diagonally aligned disturbances, parallel to the apparent raypath angle for this particular gather. Figure 6 shows another common-angle gather, for a different raypath angle. Common-angle gathers associated with large apparent velocities (shallower raypath angles) contain only the shallow reflections, while those at small apparent velocities (steeper raypath angles) include deeper reflections, as well. Hence, if we use a full set of common-angle gathers for residual statics correction, the higher velocity gathers will yield solutions for the shallow reflections, and the lower velocity ones will solve for shallow and deep reflections together (or, with proper correlation windowing, just the deep reflections), leading naturally to non-stationary statics. The key to non-stationary statics is to derive and apply the near-surface (statics) solutions for each common-angle gather independently. Note that if the statics for a particular line are strictly surface-consistent, all the solutions for the different commonangle gathers will be very similar and redundant.



FIG. 5. Common angle gather for the apparent velocity of -890 m/s (apparent velocity is the 'angle' parameter). Raypath-consistent static disturbances line up vertically, surface-consistent ones line up diagonally, parallel to the raypath angle at the right edge of the live data zone.

Whether or not common-angle gathers are used to actually derive statics corrections, they can be useful diagnostics on their own; and they often demonstrate higher S/N than the original shot/receiver gathers from which they are derived.



FIG. 6. Common angle gather for the apparent velocity of -1500 m/s. The higher apparent velocity means a shallower near-surface raypath angle.

While we've indicated that statics deconvolution and raypath-consistency are two independent parts of the raypath interferometry method, and can be used separately, the processing flows presented below demonstrate the entire raypath interferometry technique from start to finish.

# **RAYPATH INTERFEROMETRY IN STEPS**

#### **Creating common-angle gathers**

In preparation for raypath interferometry, the raw trace gathers (usually source gathers) of a seismic line should undergo the following rudimentary processing steps:

- Apply elevation statics.
- Attenuate any strong coherent noise (direct arrivals, ground roll, etc.).
- Deconvolve traces (to improve signal bandwidth).

While these steps aren't essential, they do tend to improve the results. The first step in creating common-angle gathers is to transform all the raw data gathers to the radial trace (R-T) domain (usually source gathers, since reflections are often better sampled in the source domain). The ProMAX processing flow shown in Figure 7 creates R-T source gathers from the input source gathers (in this example, filtered and deconvolved). The 'Normal Moveout Correction' shown in this flow need only use an approximate velocity function, since the objective is just to approximately flatten reflections. The moveout is restored to the data after the interferometry process.

Editing Flow: (460) R-T shot gathers		ProMAX 2D Processes			
Add Delete	Execute View Exit	Data Input / Output			
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Trace Header Math		Disk Data Output	SEG-Y Input		
Normal Moveout Corre	ction	SEG-A Input	SEG-Y Output		
Bandpass Filter		SEG-B Input	Unicos Cray SEG-Y Input		
Radial trace transfo		Radial trace transform	?		
Disk Data Output -> :	Transform switch		Forward radial transform		
Trace Display	Number of traces in transform		300		
	Switch for dip transform		Radial fan transform		
	Minimum radial trace velocity	in m/sec	-1000.		
	Maximum radial trace velocity		500.		
	Time co-ordinate for radial tr	0.			
	Offset co-ordinate for radial		0.		
	Nominal offset increment for X	5.			
		o. No time-reverse			
	Time-reverse switch for X-T traces Interpolation method to be used in radial transform				
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	Exponent to be used for 'soft		4		
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		Extract Database Files	Merge Database Files*		
		Database/Header Transfer	Database Parameter Merge*		
		Create CDP Database*	Pad Traces		
		Header Values	<b>Remove Padded Traces</b>		
		Header Delete	CDP Taper		
		Trace Header Math	Trace Length		
		Trace Math	2D Land Geometry Spreadshe		
		2D Marine Geometry Spreadsheet			
		Inline Geom Header Load	Graphical Geometry QC*		
▶		Source Receiver Geom Check* MORE	ASCII to Header		
		Crooked Line Layout			
		Crooked Line Overview	Assign midpoints		
		Track Model	Track Average		
		Track Collection	Track Offset		
		Track Import	Track Export		

Flow for reading shot gathers and transforming to the radial trace domain. Parameters in the RT transform are data-dependent. Minimum and maximum velocities should define a fan which captures most of the gather...number of traces should be at least 300-500 to avoid aliasing shot gather. Normal moveout correction need only use an approximate function

FIG. 7. A processing flow for creating R-T transforms from X-T shot gathers.

Figure 8 shows an example of a source gather and its radial trace transform. Note that the appearance of the reflections is largely unchanged by the transform. Note, as well, that the R-T transform usually contains many more traces than its original source gather, in order to avoid aliasing, and to increase the redundancy of the resulting angle gathers. Although the transform in the illustrated flow only specifies 300 output traces, we would normally use at least twice as many. Instead of source-receiver offset, the horizontal dimension of the R-T gather is apparent velocity (the angle of each particular radial trace).



FIG. 8. Ordinary NMO corrected shot gather (left), compared to its radial trace transform (right). The same reflections can be easily identified on both gathers. Each trace in the original shot gather shows the energy recorded at one receiver for that shot. Each trace in the R-T transform, however, represents energy recorded from the shot into several receivers sequentially (see Figure 4).

Figure 9 is the flow which sorts the RT gathers into common-angle panels, which are analogous to common-offset gathers in X-T space. Although we show an 'Inline Sort' operation in this flow, the sorting can actually be done more quickly within the 'Disk Data Input' operation. Notice that the primary sort field is designated as 'Signed source-receiver offset'. The reason for this is that this trace header is used to carry the 'apparent velocity' in the radial trace domain. Figures 5 and 6 are examples of common-angle gathers, each corresponding to a different raypath angle, or 'apparent velocity'.

Editing Flow: (470) n	nake R-T angle gathers	ProMAX 2D Processes			
Add Delete	Execute View Exit	Data Input / Output			
Disk Data Input <- sh	ot R-T gathers	Disk Data Input I	)isk Data Insert		
Inline Sort		ine Sort	Input		
Disk Data Output -> s	Select new PRIMARY sort key	Signed source-receiver offse	t Output t s Cray SEG-Y Input		
Trace Display	PRIMARY sort order	Ascending	s Cray SEG-Y Output		
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	Number of traces in buffer	172000	oenix Output		
	Buffer type	Disk	e Difference Modeling		
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	End-Of-Ensemble	1	etics for Lin. V(X,Z)		
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	Multiple pass?	Yes No	ve to Tape		
		List/Restore from Tape 0	OPF Compare for QC*		
		MORE	•		
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			ASCII to Header		
		MORE			
		Crooked Line Layout			
			Assign midpoints		
			'rack Average		
			'rack Offset		
4		Track Import	'rack Export		

Flow for sorting radial trace gathers into 'constant-angle gathers'. The 'offset' header of each radial trace contains the apparent velocity used to gather the samples for that trace from the original X-T shot gather; so sorting by signed offset, then external source location creates a 'constant-angle gather' for each apparent velocity value.

FIG. 9. Processing flow for creating common-angle gathers from R-T transforms of shot gathers. Another term for common-angle gather is constant-angle gather.

#### **Creating pilot traces**

The task of creating pilot traces, or the 'reference wavefield' for interferometry can be done in many ways, and not every method works for every data set. What we illustrate here is an approach that worked well for a particular set of seismic data from the MacKenzie Delta, where statics were demonstrably not surface-consistent. In general, pilot traces are created by averaging together various groups of raw input traces in order to capture the common character of the events while attenuating random noise and averaging out the misalignment between traces. One way to do this, illustrated here, is to pick one or more horizons on the brute stack, then to use the horizon picks to flatten the events on individual trace gathers so that they can be enhanced by trace mixing to form pilot traces for use with the raw traces of the input gathers. Figure 10 shows our MacKenzie Delta example with two picked horizons visible. As can be seen, the horizons are picked simply with an eye to aligning the respective events for later smoothing.



Brute stack shown with shallow and deep pilot trace horizons

FIG. 10. MacKenzie Delta brute stack, with two picked horizons used to guide the smoothing used to create pilot traces from common-offset gathers.

Figure 11 displays a processing flow for applying the horizon picks to individual gathers (in this case, common-angle gathers). The first 'Horizon Flattening' operation applies a set of horizon picks as time shifts to roughly align the traces in each gather; the 'Trace Mixing' creates the pilot traces, and the second 'Horizon Flattening' removes the flattening from the pilot traces. 'Spectral Shaping' is used to optionally broaden the band of the pilot trace events. The 'Trace Muting' operation is used to mute portions of the input gather that do not actually conform to the picked horizon used for flattening (pilot traces are muted below the yellow horizon when aligned using the yellow horizon, and muted above the yellow horizon when aligned using the red horizon).

Editing Flow: (490) n	make shot pilot traces	ProMAX 2D Processes			
Add Delete	Execute View Exit	Data Input / Output			
Disk Data Input <- sh	ot angle gathers	Disk Data Input	Disk Data Insert		
Horizon Flattening		Disk Data Output	SEG-Y Input		
Trace Mixing	Tra	nce Mixing	and the utput		
Spectral Shaping	Trace mixing algorithm	Weighted Mix	Cray SEG-Y Input		
Horizon Flattening	Exclude 'hard' zeroes?	Yes	Cray SEG-Y Output		
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		Tape Dump*	Archive to Tape		
		List/Restore from Tape	OPF Compare for QC*		
		MORE			
		Geometry / Headers			
		Database/Header Compare	Geometry Header Preparation		
		Extract Database Files	Merge Database Files*		
		Database/Header Transfer	Database Parameter Merge*		
		Create CDP Database*	Pad Traces		
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Flow for creating pilot traces for one picked horizon from constant-angle gathers. First horizon flattening applies horizon times, second removes them after trace mixing. Spectral shaping whitens pilot traces, trace muting zeros portions of pilot traces which do NOT conform to the picked horizon. This flow is applied once for each horizon picked on the brute stack to create sets of horizon pilot traces.

FIG. 11. A processing flow for creating 'pilot traces' using a picked reflection horizon. This flow processes all the common-angle gathers for a line, creating pilot trace common-angle gathers, one pilot trace gather for each input common-angle gather.

#### **Preparing the correlation panels**

When using more than one horizon to guide the creation of pilot traces by trace mixing, each horizon will result in a complete set of pilot traces, with portions of the traces muted. To combine the results from two or more separate horizons into a complete set of composite pilot traces, the separate files resulting from the processing flow in Figure 11 must be merged and summed. Figure 12 is the processing flow which merges and matches the pilot traces from two different horizons (each contained in a separate disk file created by the processing flow in Figure 11), and Figure 13 is the flow which sums the pilot traces from two horizons are used, the flows in Figures 12 and 13 must be used more than once, to incrementally merge and add the pilot trace segments from additional horizons.

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Override input data's sample interval? Yes No Header Preparatio   Observe datasets to merge? Yes No   Observe dataset boundaries? Yes No   Database/Header Transfer Database Parameter Merge*   Create CDP Database* Pad Traces   Header Values Remove Padded Traces   Header Values Remove Padded Traces   Header Dalete CDP Taper   Trace Header Math Trace Length   Trace Header Load Graphical Geometry Spreadshe   2D Marine Geometry Spreadsheet Cooked Line Geom Spreadsh   Inline Geom Header Load Graphical Geometry QC*   Source Receiver Geom Check* ASCII to Header								
Force datasets to merge? Yes No Observe dataset boundaries? Yes No Observe dataset boundaries? Yes No Database/Header Transfer Database Parameter Merge Database/Header Transfer Database Parameter Merge* Create CDP Database* Pad Traces Header Values Remove Padded Traces Header Delete CDP Taper Trace Header Math 2D Land Geometry Spreadsheet* Crooked Line Geom Spreadsheet*Crooked Line Geom Spreadsheet* Database/Header Load Graphical Geometry QC* Source Receiver Geom Check* ASCII to Header MORE			-			-		
Observe dataset boundaries? Yes No Header Preparatio   Observe dataset boundaries? Database?Header Transfer Database Piles*   Database/Header Transfer Database Parameter Merge*   Create CDP Database* Pad Traces   Header Database Remove Paded Traces   Header Database Remove Paded Traces   Header Database Composition   Trace Header Math Trace Length   Trace Math 2D Land Geometry Spreadsheet   2D Marine Geom Header Load Graphical Geometry QC*   Source Receiver Geom Check* ASCII to Header			•	· ·	cerval?			
Database Journal 1935   Database / Header Transfer   Database Parameter Merge*     Database/Header Transfer   Database Parameter Merge*     Create CDP Database*   Pad Traces     Header Values   Remove Padded Traces     Header Dalete   CDP Taper     Trace Header Math   Trace Length     Trace Math   2D Land Geometry Spreadsheet     2D Marine Geometry Spreadsheet Coole   Graphical Geometry QC*     Source Receiver Geom Check*   ASCII to Header     HORE   Hore				-				Header Preparation
Create CDP Database*   Pad Traces     Header Values   Remove Padded Traces     Header Delete   CDP Taper     Trace Header Math   Trace Length     Trace Header Math   2D Land Geometry Spreadsheet     Convect Receiver Geom Check*   ASCII to Header     HORE   HORE		Ubserve da	taset bound	aries?	- BACLAC		nerge bat	abase Files*
Header Values Remove Padded Traces   Header Dolete CDP Taper   Trace Header Math Trace Length   Trace Math 2D Land Geometry Spreadshe   2D Marine Geometry Spreadsheet* Crooked Line Geom Spreadshe   Inline Geom Header Load Graphical Geometry QC*   Source Receiver Geom Check* ASCII to Header   HORE HORE								
Header Delete CDP Taper   Trace Header Math Trace Length   Trace Math 2D Land Geometry Spreadshe   2D Marine Geometry Spreadsheet* Crooked Line Geom Spreadsh   Inline Geom Header Load Graphical Geometry QC*   Source Receiver Geom Check* ASCII to Header   HORE HORE								
Trace Header Math   Trace Length     Trace Math   2D Land Geometry Spreadshet     2D Marine Geometry Spreadshet   2D rooked Line Geom Spreadshet     Inline Geom Header Load   Graphical Geometry QC*     Source Receiver Geom Check*   ASCII to Header     HORE								
Trace Math   2D Land Geometry Spreadshe     2D Marine Geometry Spreadsheet*Crooked Line Geom Spreadshe     Inline Geom Header Load   Graphical Geometry QC*     Source Receiver Geom Check*   ASCII to Header     HORE   HORE								
2D Marine Geometry Spreadsheet*Crooked Line Geom Spreadsh Inline Geom Header Load Graphical Geometry QC* Source Receiver Geom Check* ASCII to Header HORE								
Inline Geom Header Load Graphical Geometry QC* Source Receiver Geom Check* ASCII to Header HORE								
Source Receiver Geom Check* ASCII to Header HORE								
					Source	Receiver Geom Check*		
					MORE .			
						Line Layout		
Crooked Line Overview Assign midpoints		•						
Track Model Track Average		`						
Track Collection Track Offset Track Import Track Export								
Track Imbort Track Export					TLACK .	LINDOL	TLACK EXT	IOT C

Flow to merge two sets of horizon pilot traces. The disk data insert adds a new set of horizon pilot traces, so that the output is a set of constant-angle gathers with two horizon pilot traces at every shot position. These traces will be summed in the subsequent flow to make composite pilot traces.

FIG. 12. A processing flow to merge two sets of pilot traces created by using the flow in Figure 11 to create two separate pilot trace files, one for each horizon. Since the trace headers for traces from the two files will be identical, they will be merged into pairs of traces with common headers, which can subsequently be summed by the processing flow in figure 13.

Editing Flow: (490c) sum pilot trace pairs	ProMAX 2D Processes			
Add Delete Execute View Exit	Data Input / Output			
Disk Data Input <- shot angle pilot traces	Disk Data Input	Disk Data Insert		
Trace Math Trace Nath		SEG-Y Input		
Diele Date Outwate > a		SEG-Y Output		
Trace Display NODE of operation	Trace/Trace	Unicos Cray SEG-Y Input		
TYPE of trace/trace operation	Add Traces	Unicos Cray SEG-Y Output		
Honor ensemble boundaries	Yes No	Floppy Input		
How to handle odd ensemble trac		SeisWorks Seismic Input		
	SeisWorks 2D Seismic Info*	Insight Data Output		
	SeisWorks Horizon Input*	SeisWorks Horizon Output*		
	SS Phoenix Input	SS Phoenix Output		
	Landmark SEG-Y Input	Finite Difference Modeling		
	Landmark SEG-Y Output	Null Data File		
	Optimum Sweep Analysis	Synthetic Trc Generation		
N N	Vibroseis Sweep Generation	Synthetics for Lin. V(X,Z)		
₹	Dataset Utilities*	Tape Copy*		
	Tape Dump*	Archive to Tape		
	List/Restore from Tape	OPF Compare for QC*		
	MORE			
	Geometry / Headers			
	Database/Header Compare	Geometry Header Preparation		
	Extract Database Files	Merge Database Files*		
	Database/Header Transfer	Database Parameter Merge*		
	Create CDP Database* Header Values	Pad Traces		
		Remove Padded Traces		
	Header Delete Trace Header Math	CDP Taper Trace Length		
	Trace Math	2D Land Geometry Spreadshee		
	2D Marine Geometry Spreadsheet			
	Inline Geom Header Load	Graphical Geometry OC*		
	Source Receiver Geom Check*	ASCII to Header		
	MORE	ANGLI UV HEAUEL		
	Crooked Line Layout			
	Crooked Line Overview	Assign midpoints		
	Track Model	Track Average		
	Track Collection	Track Offset		
	Track Import	Track Export		
	1			

Flow to sum the horizon pilot trace pairs created by the previous flow. If more than two sets of horizon pilot traces are created, the previous flow and this one must be repeated for each new set of horizon pilot traces.

FIG. 13. This processing flow sums the adjacent traces of the pilot trace pairs created by the flow in Figure 12 in order to create composite pilot traces like those in Figure 14.





FIG. 14. A pilot trace common-angle gather corresponding to the common-angle gather for apparent velocity -231 m/s. Every input common angle gather will have a corresponding pilot trace gather like this one

The processing flows in Figures 11, 12, and 13 each process all the common-angle gathers for an entire line, so each raw common-angle gather will have its own unique corresponding pilot trace panel. In order to prepare for the cross-correlation of raw common-angle gather traces with their corresponding pilot traces, the processing flow in Figure 15 must be run, to merge the separate input files and create pairs of raw and pilot traces, matched by surface location.

Editing Flow: (500) make an	ngle trace pairs		ProMAX 21	7 Processes	;
Add Delete Execut			Input / Output		
Disk Data Input <- shot and	le pilot sum	Disk	Data Input	Disk Data	a Insert
Disk Data Insert <- sl		Disk Data	Insert	?	ut
Disk Data Output -> si Inser	tion mode		Merged		put ay SEG-Y Input
	mary ordering		Ascending		ay SEG-Y Output
	ondary ordering		Ascending		but
	imum traces per output	ensemble	1150		Seismic Input
	data from other lines/		Yes No		ata Output
	t dataset		shot angle gathers		Horizon Output*
Propa	qate input file histor	v	Yes No		x Output
	read option	•	Sort		fference Modeling File
Sel	ect primary trace head	ler entry	ntry Signed source-receiver offset		Trc Generation
Sele	ect secondary trace he	ader entry	External source locati	ion number	s for Lin. $V(X,Z)$
Sele	ect tertiary trace hea	der entry	No trace header entry	selected	*
Sor	t order for dataset		*:*/		о Таре
Pre	sort in memory or on d	lisk?	Memory		re for QC*
Overr	ide input data's sampl	e interval	? Yes No		
Force	datasets to merge?		Yes No		Header Preparation
Observ	ve dataset boundaries?		Yes No		abase Files*
			ase/Header Transfer		Parameter Merge*
<b>k</b>		Creat	e CDP Database*	Pad Trace	es
			r Values		added Traces
			er Delete	CDP Taper	
			e Header Math e Math	Trace Ler	ngth Seometry Spreadshee
			rine Geometry Spreadshee		
			e Geom Header Load		l Geometry QC*
		Sourc	e Receiver Geom Check*	ASCII to	
		MORE			
			ed Line Layout		
			ed Line Overview	Assign mi	
			: Model : Collection	Track Ave Track Off	
			Import	Track Ext	
			1	TLUCK DA	

This flow takes the composite pilot traces from the previous flow and merges them with their corresponding raw traces from the constant-angle gathers to create trace pairs for correlation.

FIG. 15. This processing flow merges the corresponding traces from input common-angle gathers and pilot trace common-angle gathers to prepare for cross-correlation between each input trace and its unique pilot trace.

# Cross-correlating and deriving inverse filters

Figure 16 shows the processing flow which performs the cross-correlations between raw and pilot traces and "conditions" the cross-correlation functions. The two 'Trace Math Transform' operations accomplish this conditioning by 1) raising the samples of each cross-correlation to an integer power (3, 4, or 5 work well), then 2) applying a Hanning window to the modified cross-correlation function. The conditioning has the effect of whitening the cross-correlation function without adding any new peaks, favouring the largest peak and emphasizing peaks nearest the zero cross-correlation lag. Note that the cross-correlation functions normally use most of the length of the input traces, excluding possibly the earliest parts. As well, the cross-correlation length should exceed twice the absolute value of the largest static expected in the data. The flow shown in Figure 17 simply derives an inverse filter for each conditioned cross-correlation. The length of the inverse filter is normally chosen to be the same as the length of the

input cross-correlation function, in order to be able to correct the largest statics captured by the correlation functions.

Editing Flow: (480) correlate shot trace pai			Processes	
Add Delete Execute View Exit	Data Input / Outp	ut		
Disk Data Input <- shot R-T angle pairs	Disk Data Input		Disk Data Insert	
	Cross Correlation		200 U Z	
Trace Math Transforms How should the input traces be	correlated?	PAIRS		Input
Trace Math Transforms Length of traces input to cross Disk Data Output -> s	correlation	1600.		Output
Trace Display Output cross correlation length		400.		
Normalize the output correlation		Ves No		Input
Get cross correlation start tim		Yes No		ut
Primary start time header wor		Live source n	number	Output*
Secondary start time header w		Signed source	e-receiver offset	
Specify cross correlation sta		-1000:1:50/		Modeling
	Optimum Sweep Ana Vibroseis Sweep ( Dataset Utilities Tape Dump* List/Restore from MORE Geometry / Header	Seneration ** 1 Tape	Synthetic Trc Ger Synthetics for L Tape Copy* Archive to Tape OPF Compare for (	in. V(X,Z)
	Database/Header		Geometry Header	Proparatio
	Extract Database		Merge Database F	
	Database/Header 1	ransfer	Database Paramete	
	Create CDP Databa	ise*	Pad Traces	
	Header Values		Remove Padded Tra	aces
	Header Delete		CDP Taper	
	Trace Header Math Trace Math	1	Trace Length 2D Land Geometry	Correndebe
		w Spreadsheet	*Crooked Line Geo	
	Inline Geom Heade		Graphical Geomet:	
	Source Receiver (	eom Check*	ASCII to Header	
	MORE			
	Crooked Line Layo			
	Crooked Line Over	view	Assign midpoints	
	Track Model		Track Average	
	Track Collection Track Import		Track Offset Track Export	

This flow creates the 'statics distribution functions' used to deconvolve the constant-angle traces. The correlations use basically the entire input trace and its matching composite pilot trace, and the output correlation length is long enough to include any conceivable 'static'. The first trace math transform raises each sample to an odd power (often 5) to whiten the function without adding new peaks, while the second applies a Hanning window.

FIG. 16. This processing flow produces the 'conditioned' correlation functions used in the next step to derive inverse filters to undo the statics of each common-angle gather. The length of traces selected for the cross-correlation should include most of the length of the input traces for the common-angle gathers at the steepest angles, and the length of the output correlation should be larger than twice the largest possible static in the data. Start times for the correlations should avoid direct arrivals or early muting.

Editing Flow: (510a)	derive R-T shot inverse		ProMAX 2D	Processes	;
Add Delete	Execute View Exit	Data Input / Outpu	ut		
Disk Data Input <- sł	not statics functions sum	Disk Data Input		Disk Data	
Filter Generation	Fil	ter Generation		?	ut put
Trace Display	Filter option		Inverse		ay SEG-Y Input
	Type of operator		Time domain		ay SEG-Y Output
	Percent additive noise facto	or and the second se	0.01		put
	Trace length for the filter tr	ace	400.		Seismic Input
	Time on input trace representi		200.		ata Output
	Apply tapers to input wavelet		Yes No		Horizon Output*
	Taper type	into output fiftoff.			x Output
	Percent flat for time window	<i>r</i> amning	50.		fference Modeling
	Output filter or filtered wave		Filter Result		File Trc Generation
	Normalize output filter?		Yes No		s for Lin. $V(X,Z)$
	Spectral plot?		Yes No		*
	Write filter trace to disk dat	aset?	Yes No		о Таре
	Output dataset filename		shot inverse	filters 1	re for QC*
		MORE			
		Geometry / Header:			
		Database/Header C Extract Database			Header Preparation tabase Files*
		Database/Header T			Parameter Merge*
		Create CDP Databa		Pad Trace	
		Header Values		Remove Pa	added Traces
		Header Delete		CDP Taper	c
		Trace Header Math	1	Trace Ler	
		Trace Math			Geometry Spreadshee
					ine Geom Spreadshe
		Inline Geom Heade Source Receiver G		ASCII to	l Geometry QC*
		MORE	eom cneck-	ASCII CO	neauer
		Crooked Line Layo	ut		
		Crooked Line Over		Assign mi	idpoints
		Track Model		Track Ave	
►.		Track Collection		Track Of	fset
		Track Import		Track Ext	ort

Although the output functions of the previous flow can be applied as 'match filters' to their corresponding raw constant-angle traces, this flow can be used to derive inverse filters, instead. The inverse filter option seems to give a broader band result; probably because the 'whitening' applied to the correlation function by raising samples to a power is rather modest.

FIG. 17. This simple flow derives full bandwidth inverse filters for the conditioned cross-correlation functions created by the flow in Figure 16.

Figures 18 and 19 show examples of the conditioned cross-correlation functions obtained. Most of the functions shown in these two examples are quite clean, with only small side-lobes; but some of the functions in Figure 18, particularly in the vicinity of the large statics deviations, exhibit more than one peak. This can indicate the presence of multi-path phenomena; but inverse filters derived from such correlation functions are perfectly capable of deconvolving the static and reducing the multi-path to a single arrival simultaneously.



FIG. 18. A set of 'conditioned cross-correlation functions', or "statics functions" obtained for one common-angle gather (apparent velocity = -429 m/s) for the MacKenzie Delta data. These functions consist mostly of a central peak, with minor side ripples. Some functions in the vicinity of the large statics anomalies show more than one peak, indicative of multi-path phenomena.



FIG. 19. Three sets of 'conditioned cross-correlation functions' corresponding to three different common-angle gathers. Note the similarity of the functions from panel to panel; apparently statics functions vary only slowly with angle.

# Applying the inverse filters

The flow needed to apply statics deconvolution is shown in Figure 20. The flow shown actually applies the conditioned cross-correlation functions by 'correlation', but by re-setting the first parameter to 'convolution', the inverse filters can be applied instead, which usually results in results with broader bandwidth. Figure 21 shows the comparison between a raw common-offset gather and the 'corrected' gather after applying inverse filters.

Editing Flow: (520a)	apply shot R-T filters		ProMAX 2D	Processes
Add Delete	Execute View	Exit	Data Input / Output	
Disk Data Input <- sh		DATE	Disk Data Input	Disk Data Insert
			Application	ene u Leput
Dick Data Output -> cl			Correlation	tput
Bandpass Filter	Application option			ray SEG-Y Input
Trace Display	Re-apply trace mute af	ter filte		ray SEG-Y Output
	Average multiple filte	rs?	Yes No	nput
	Time on input filter r	epresenti		s Seismic Input
	SELECT filter dataset			ions sum <mark>Data Output</mark>
			SeisWorks Horizon Input*	SeisWorks Horizon Output*
			SS Phoenix Input	SS Phoenix Output
			Landmark SEG-Y Input	Finite Difference Modeling
			Landmark SEG-Y Output	Null Data File
			Optimum Sweep Analysis	Synthetic Trc Generation
			Vibroseis Sweep Generation	Synthetics for Lin. V(X,Z)
			Dataset Utilities*	Таре Сору*
			Tape Dump*	Archive to Tape
			List/Restore from Tape	OPF Compare for QC*
			Geometry / Headers Database/Header Compare	Geometry Header Preparation
			Extract Database Files	Merge Database Files*
			Database/Header Transfer	Database Parameter Merge*
			Create CDP Database*	Pad Traces
			Header Values	Remove Padded Traces
			Header Delete	CDP Taper
			Trace Header Math	Trace Length
			Trace Math	2D Land Geometry Spreadshee
	▶		2D Marine Geometry Spreadsheet	
			Inline Geom Header Load	Graphical Geometry QC*
			Source Receiver Geom Check*	ASCII to Header
			MORE	
			Crooked Line Layout	
			Crooked Line Overview	Assign midpoints
			Track Model	Track Average
			Track Collection	Track Offset
1			Track Import	Track Export
1				

This flow applies the match filters or inverse filters to the constant-angle gathers, trace-by-trace. If the shot statics functions are used, then filter application is by correlation; if inverse filters, then convolution. It is particularly useful to use the trace display to look at each constant-angle gather to judge the effectiveness of the filter application.

FIG. 20. A processing flow to apply the inverse filters derived from conditioned cross-correlation functions to the traces of the common-angle gathers. This particular example applies the conditioned correlation functions, themselves, by cross-correlation. To use the inverse filters, the 'Application option' parameter in the 'Filter Application' module would be set to 'Convolution'.



Typical common angle gather before and after interferometric correction

FIG. 21. A common-angle gather before (left) and after (right) being corrected by deconvolving the inverse filters derived from conditioned cross-correlations of the raw traces and pilot traces. The S/N of the deconvolved gather is sometimes less than that of the raw gather, but statics are improved.

#### **Inverting common-angle gathers to source gathers**

Figures 22 and 23 show the flows needed to first re-sort the common-angle traces back to R-T source gathers, then to invert the R-T gathers back to X-T source gathers. As in the flow for creating the common-angle gathers, the actual sorting can be accomplished during the 'Disk Data Input', and will probably run faster. Note that 'Signed source-receiver offset' continues to carry the angle, or 'apparent velocity' until the data are formally inverted from the R-T domain in the next flow (Figure 23). In the 'Radial Trace Transform' operation, which is used to apply the inverse R-T transform, the parameters must be as shown in order to ensure a proper inversion to X-T, with the proper number of traces, correct offset headers, etc. The 'Normal Moveout Correction' operation restores moveout to the source gathers so that they may be treated like raw gathers and processed to CMP stack.

Editing	r Flow: (530)	remake R-T shot gathers	ProMAX 2	D Processes
Add	Delete	Execute View Exit	Data Input / Output	
Disk D	ata Input <-	shot angle gathers corr 1+	Disk Data Input	Disk Data Insert
Inline	Sort	Inl	ine Sort	200 Input
Bandpa	ss Filter	Select new PRIMARY sort key	External source location r	output
	ata Output ->	SI PRIMARY sort order	Ascending	s Cray SEG-Y Input s Cray SEG-Y Output
Trace	Display	Select new SECONDARY sort key	Signed source-receiver of	
	SECONDARY sort order	Ascending	orks Seismic Input	
	Select new TERTIARY sort key	No trace header entry sele		
		Maximum traces per output ensem	-	orks Horizon Output*
		Number of traces in buffer		oenix Output
			172000	e Difference Modelin
		Buffer type Sort key which controls End-Of-Ensemble	Disk	Data File
			Primary	etic Trc Generation
			Yes No	etics for Lin. V(X,Z
		Compress data before sorting?		Сору*
	Multiple pass?	Yes No	ve to Tape	
		List/Restore from Tape	OPF Compare for QC*	
			MORE Geometry / Headers	
			Database/Header Compare	Geometry Header Preparatio
			Extract Database Files	Merge Database Files*
			Database/Header Transfer	Database Parameter Merge*
			Create CDP Database*	Pad Traces
			Header Values	Remove Padded Traces
			Header Delete	CDP Taper
			Trace Header Math	Trace Length
		R.	Trace Math	2D Land Geometry Spreadsh
			2D Marine Geometry Spreadshee	
			Inline Geom Header Load	Graphical Geometry QC*
			Source Receiver Geom Check*	ASCII to Header
			MORE	
			Crooked Line Layout	Assign midpoints
			Track Model	Track Average
			Track Collection	Track Offset
			Track Import	Track Export
			75	

This flow sorts the corrected constant-angle gathers back into shot radial trace transforms.

FIG. 22. A processing flow for sorting corrected common-angle gathers to R-T source gathers for inversion back to the X-T domain. The sort can also be done in the 'Disk Data Input' operation, where it is usually faster.

Editing Flow: (540) inverse R-T shot	ProMAX 2	) Processes	
Add Delete Execute View Exit	Data Input / Output		
Disk Data Input <- shot R-T gathers corr 1+	Disk Data Input	Disk Data Insert	
Trace Mixing	Disk Data Output	SEG-Y Input	
Radial trace transfor	Radial trace transform	?	
Normal Moveout Correct Transform switch		Inverse radial transform	
Disk Data Output -> sl		1	
Trace Display Switch for dip transform		Radial fan transform	
Minimum source-receiver offset	in metres	0.	
Maximum source-receiver offset		9.	
Method for offset increment co		Linear offsets	
	Time co-ordinate for radial trace origin in sec		
Offset co-ordinate for radial	-	0. 0.	
Time-reverse switch for X-T tr	-	No time-reverse	
Interpolation method to be use		Soft neighbor	
Exponent to be used for 'soft		1	
Refractive index computation m		Constant	
Reflactive index computation m	MORE	constant	
	Geometry / Headers		
	Database/Header Compare	Geometry Header Preparation	
	Extract Database Files	Merge Database Files*	
	Database/Header Transfer	Database Parameter Merge*	
	Create CDP Database*	Pad Traces	
	Header Values	Remove Padded Traces	
	Header Delete Trace Header Math	CDP Taper	
	Trace Header Math	Trace Length 2D Land Geometry Spreadshee	
	2D Marine Geometry Spreadshee		
L L	Inline Geom Header Load	Graphical Geometry OC*	
•	Source Receiver Geom Check*	ASCII to Header	
	MORE	Aberr co neader	
	Crooked Line Layout		
	Crooked Line Overview	Assign midpoints	
	Track Model	Track Average	
	Track Collection	Track Offset	
	Track Import	Track Export	
	( <del>-</del>		

This flow applies the inverse radial trace transform to obtain the corrected shot gathers. The parameters in the radial trace transform operation must be set as shown in order to properly invert the transform. The trace mixing operation is optional, but may be used sparingly (no more than 3 to 5) to improve redundancy of the corrections. Normal moveout correction removes the approximate function applied in the first flow.

FIG. 23. The inverse Radial Trace Transform flow, which restores the static-corrected data to the X-T domain. The parameters should be as shown, to properly invert the transform.

#### DISCUSSION

As can be seen, none of the processing flows needed to do raypath interferometry are complicated. We have chosen to break the process up into short, readily monitored steps, and to include a Trace display operation at the end of each flow, in order to visually monitor the operation. Observing the data, gather by gather, as it proceeds from raw X-T source gathers with visible statics down through the various stages of the raypath interferometric process can give the processor a more intuitive feel for the data and can help detect problems before processing the complete data set. As currently conceived, raypath interferometry will remain an interactive process, rather than being folded into a large 'black box' operation.

The processing flows used to produce pilot traces, merge them with raw traces, crosscorrelate the traces, and apply the inverse filters can be run on ordinary source or receiver gathers without ever going to the R-T domain. Likewise, the flows used to create common-angle gathers can also be used to create the gathers for diagnostic purposes, entirely independent of raypath interferometry.

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