Lessons in Spatial Sampling

Or . . . "Does Anybody Know the Shape of a Wavefield?"

Norm Cooper - Mustagh Resources Ltd., Calgary, Canada

In a homogeneous, isotropic, infinite half space (remember those regimes from Geophysics 101?) a propagating wavefield from a simple impulsive source will be spherical. If we introduce velocity gradients or layers, the wavefield becomes elliptical. Further perturbations of the subsurface create additional complexities in the shape of a wavefield. Our job as exploration geophysicists is to observe those complexities when and where portions of the wavefield return to the earth's surface. From these observations we attempt to infer what subsurface geologic features may exist that caused the irregularities. In a realistic setting, this is a formidable task.

Figure 1

An example of remote sensing (from cover of "PinPressions" toy)

(This stunt performed by an expert - DON"T TRY THIS AT HOME.)

Imagine a wavefield has propagated to a reflector. As it encounters the structures on that reflector, the shape of the wavefield will adopt the shape of the structures. That shape remains with the wavefield as it returns to the surface where we measure it. The wavefield at the surface is the net result of all distortions introduced to the wavefield during its travels in the subsurface.

The topic of spatial sampling addresses the requirements for discretely sampling a wavefield in order to preserve sufficient information to resolve features of importance to us. This means we must sample our data appropriately, not just in the common source domain, but also in the receiver, offset and CDP domains.

Note in figure 2 that a 2D seismic line recorded with 20-meter group intervals does not necessarily result in CDP's with 20 meter sampling of offset. Noise not properly sampled will not behave the way we might think. If 2D programs present such problems, imagine the complexity due to irregular offset sampling in 3D programs.

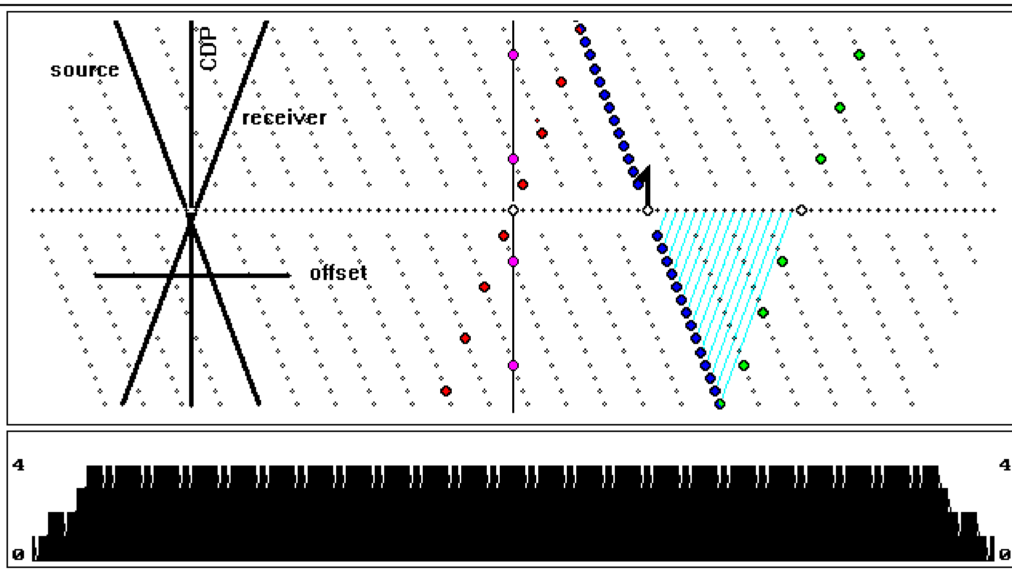

Figure 2

A portion of a 2D stacking chart for a line with a receiver interval of 20 meters and a source interval of 80 meters. The sources were located coincident with receiver points.

Note that each shot record will sample receivers every 20 meters. However, each receiver gather will only sample a shot every 80 meters and each CDP only samples recorded traces every 160 meters.

Spatial resolution is integrally tied to temporal (or vertical) resolution. Figure 3 demonstrates this concept. The left column of figures represents data sampled at just 20 Hz for three different spatial sample intervals. Sampling at 10 m and 20 m intervals provides adequate imaging, but the 40 m version is aliased (note the "checkerboard" pattern and the ambiguity as to dip direction). The right column represents data sampled at 40 Hz for the same spatial sample intervals. Note that aliasing now begins at 20 m sampling and the 40 m version is 100 percent aliased (dips now appear flat).

Events that may be appropriately sampled in space for one bandwidth of data may not be sufficiently sampled in space for higher frequencies. Required spatial sampling is determined by wavefield complexity as well as expected imaging bandwidth. Both parameters must be carefully and realistically considered.

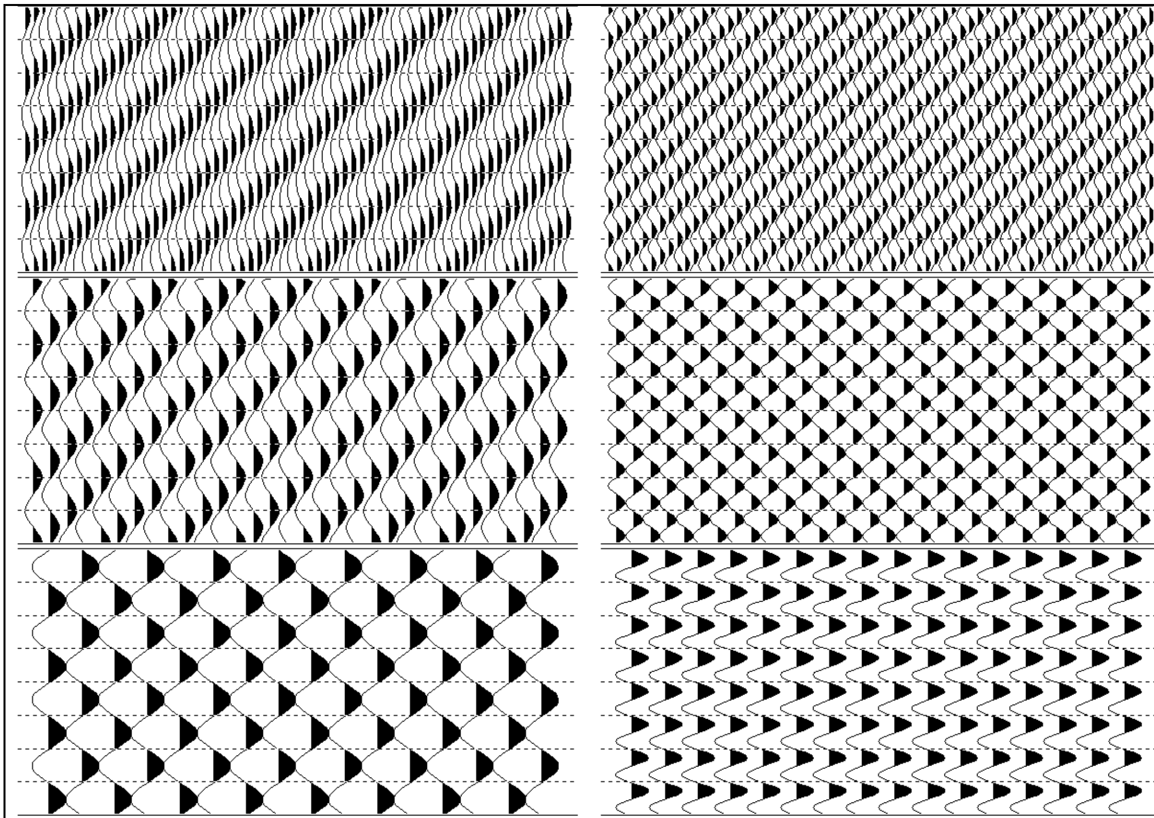

Figure 3
A simple two-dimensional wavefield sampled in time and space.

Left side is 20 Hz monochromatic data while the right side is 40 Hz.
The top figures represent 10 m trace intervals; the middle set 20 m intervals
with 40 m trace intervals on the bottom.

What about spatial prediction filters and interpolations? Can we reconstruct or simulate smaller spatial samples by techniques such as mid-point scatter and re-binning in 3-D's or by using FX Prediction filters? The answer is definitely yes . . . or no . . . depending on a variety of factors. Mother nature allows us to cheat under favorable circumstances, but penalizes us heavily if we are reckless about our application of such methods.

Our final processed image quality depends on the statistical significance of our patterns of measurement. Can't we just hit a zoom/sharpen button on a computer console and have our images instantly enhanced . . . just like they do in the movies?

Maybe.

If you don't understand the concept of aliasing, you should probably attend this tutorial. If you ***think*** you do understand it, you should definitely attend !!

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Or . . . Does Anybody Know the Shape of a Wavefield ??

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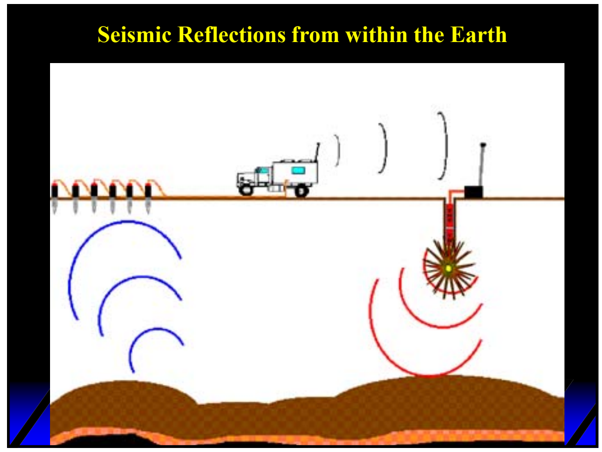

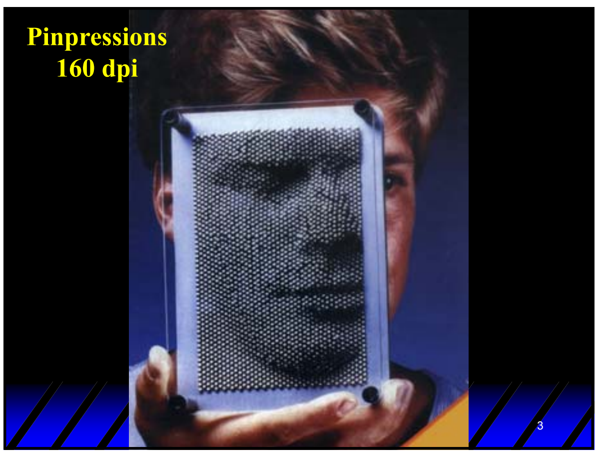

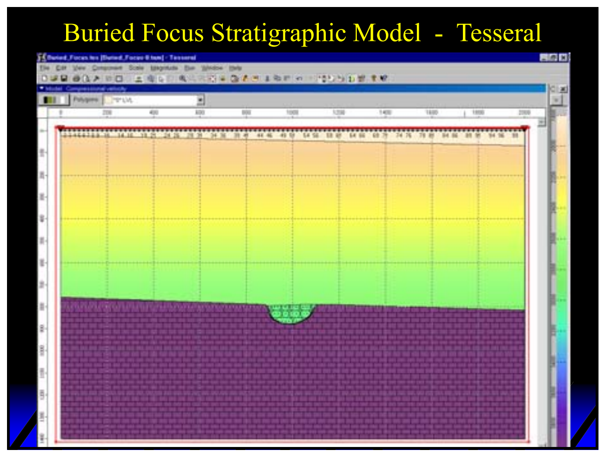

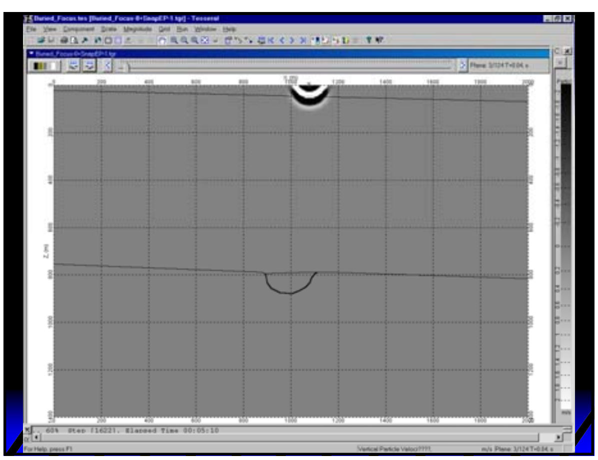

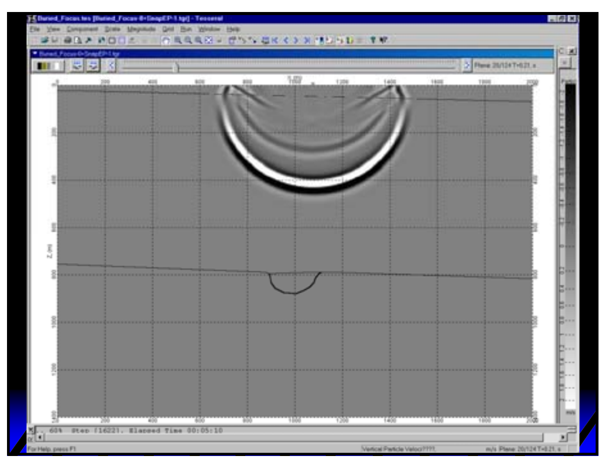

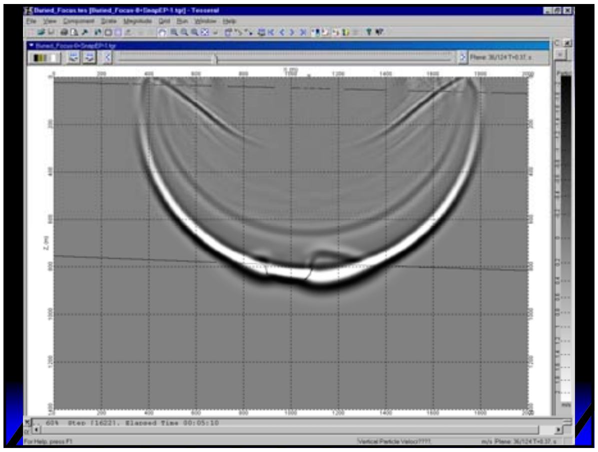

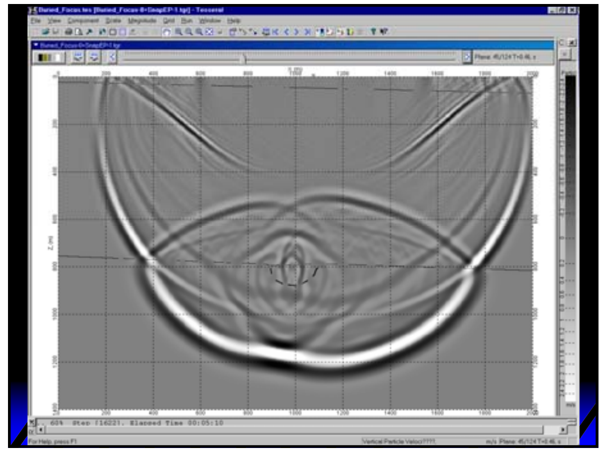

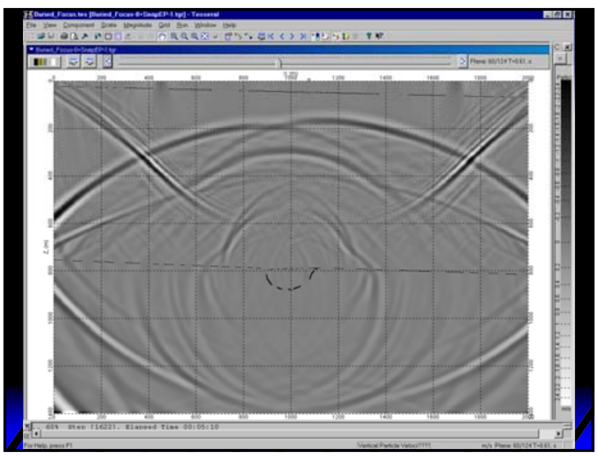

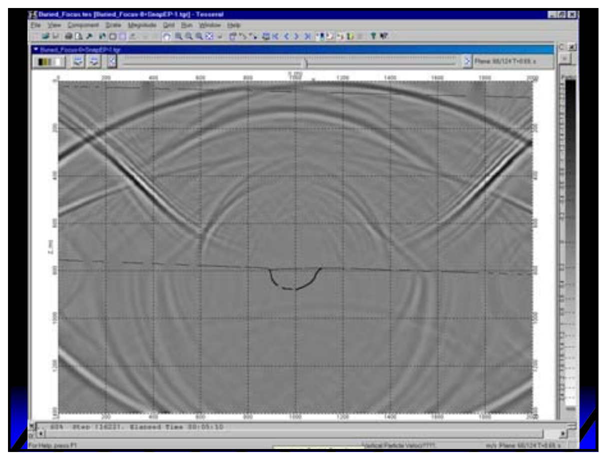

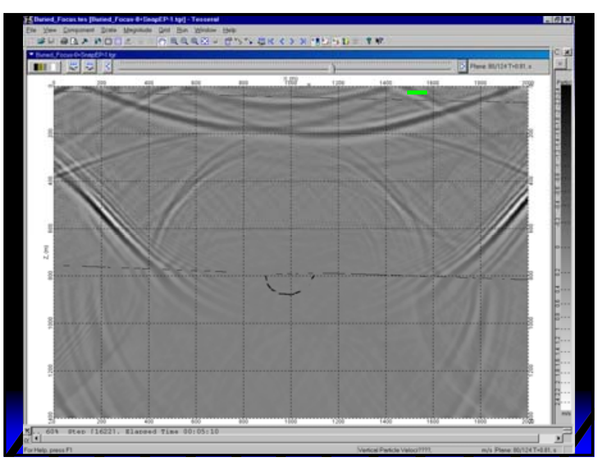

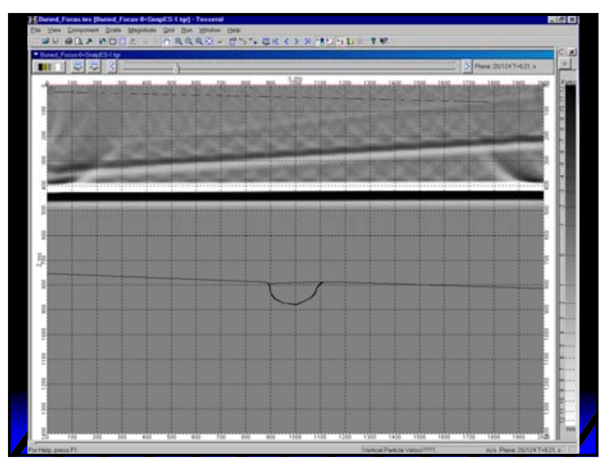

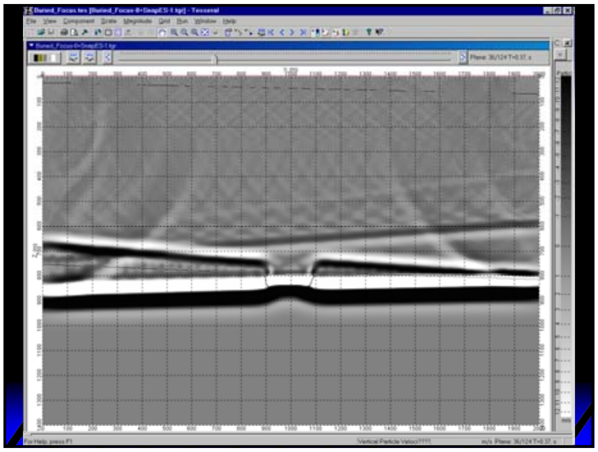

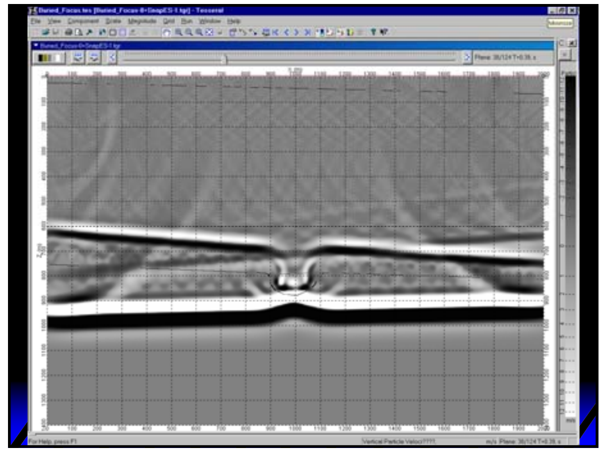

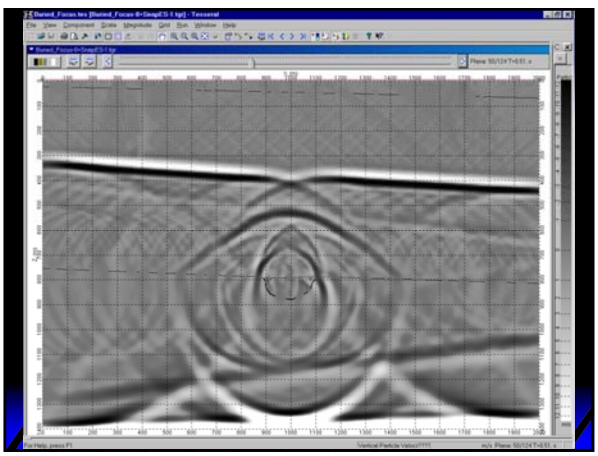

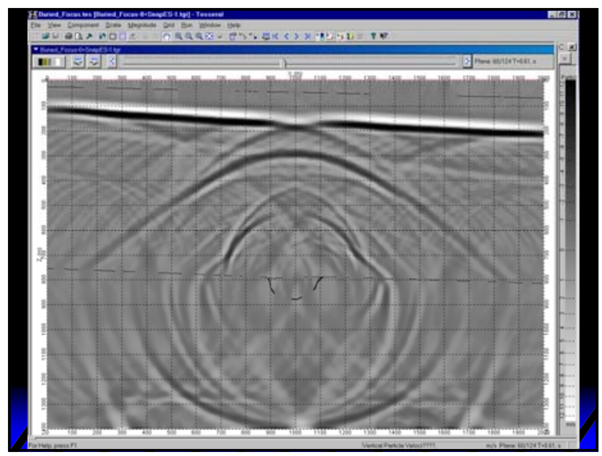

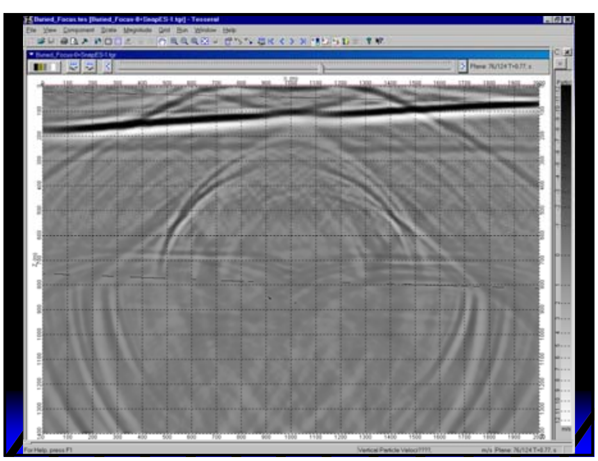

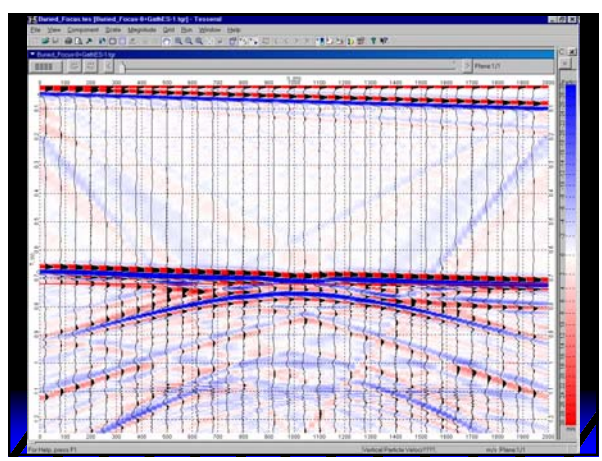

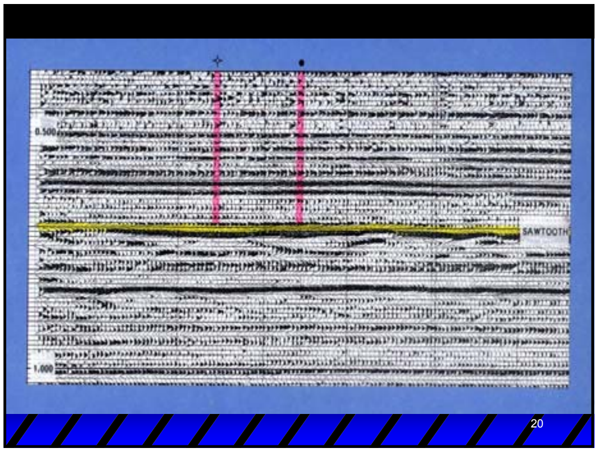
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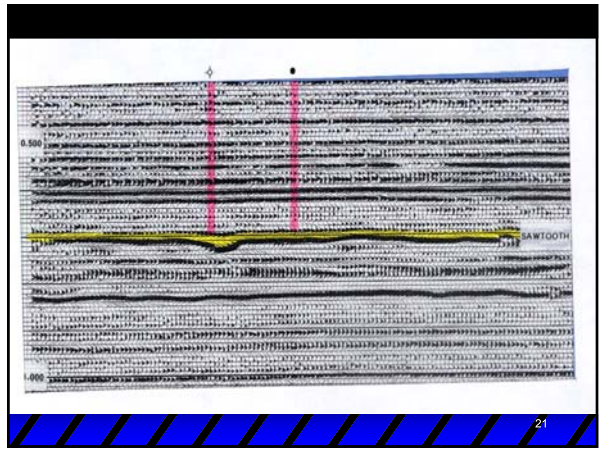
SAWTOOTH
1.000
20


0.500
SAWTOOTH
1.000
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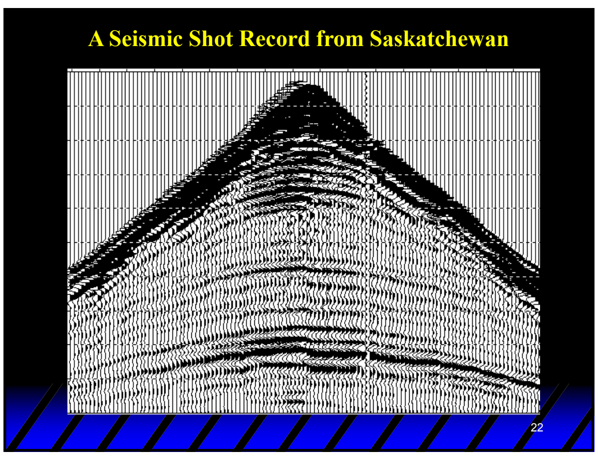
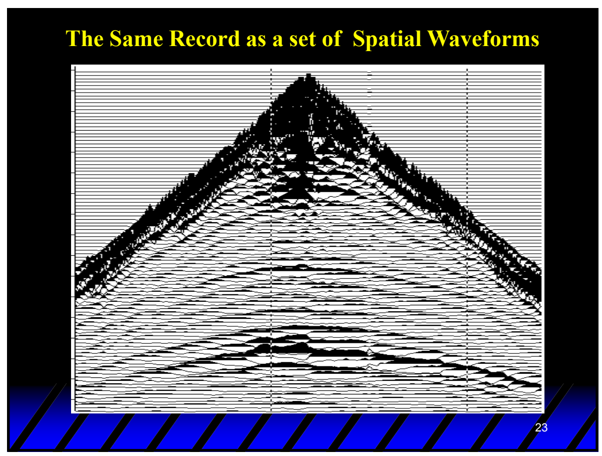
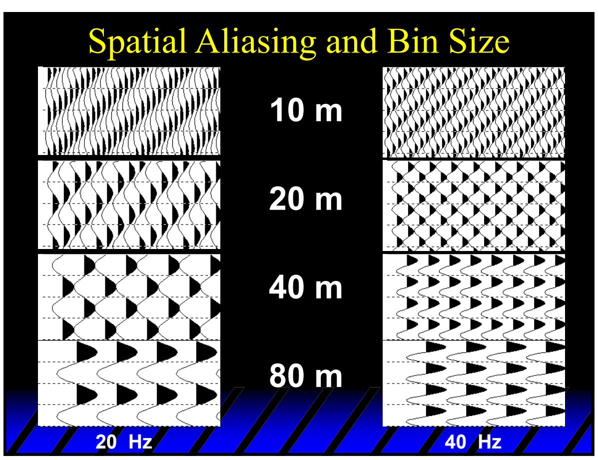
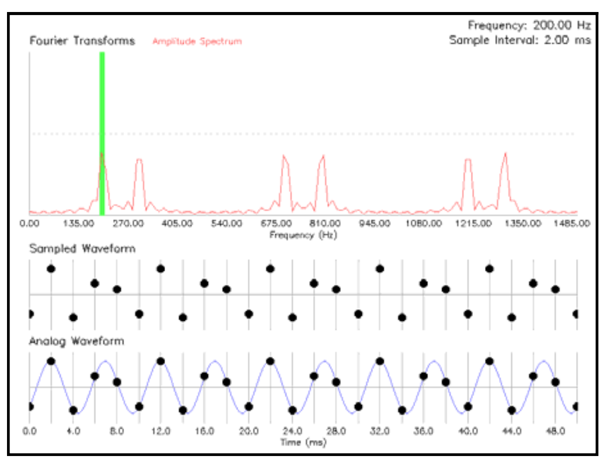
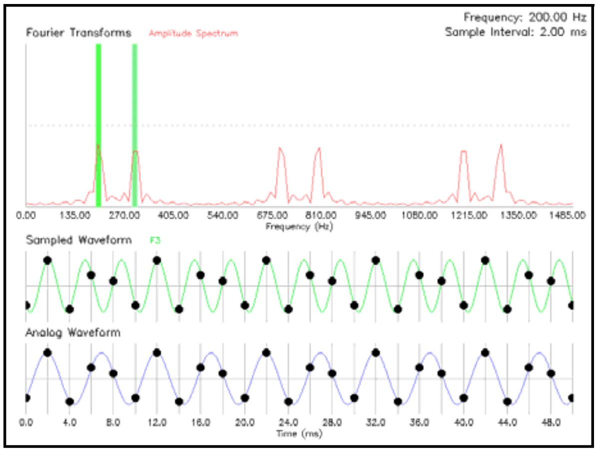
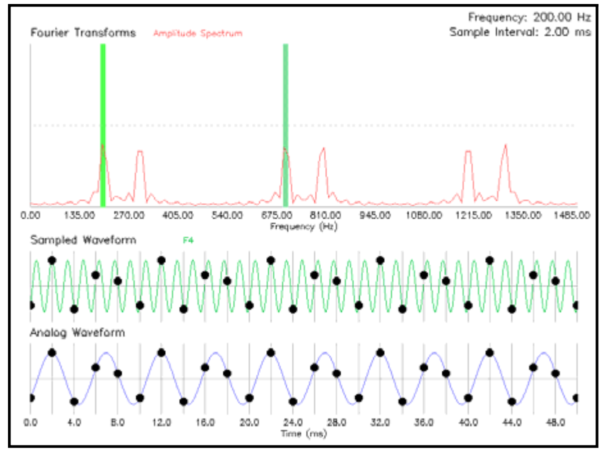

A Seismic Shot Record from Saskatchewan
22

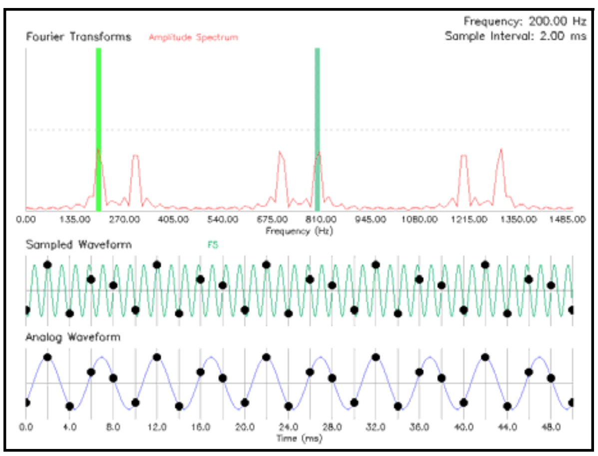

The Same Record as a set of Spatial Waveforms
23

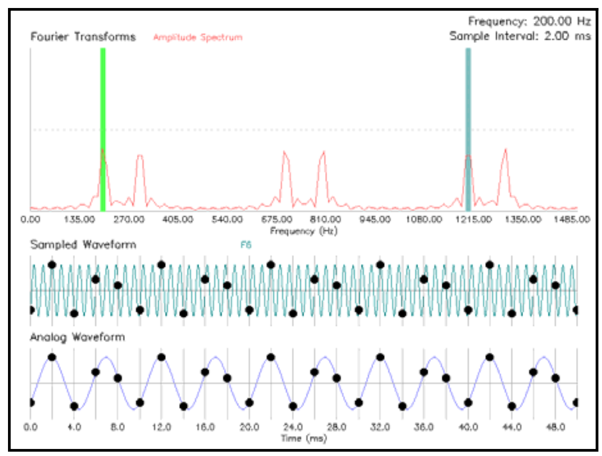

Spatial Aliasing and Bin Size
10 m
20 m
40 m
80 m
20 Hz
40 Hz

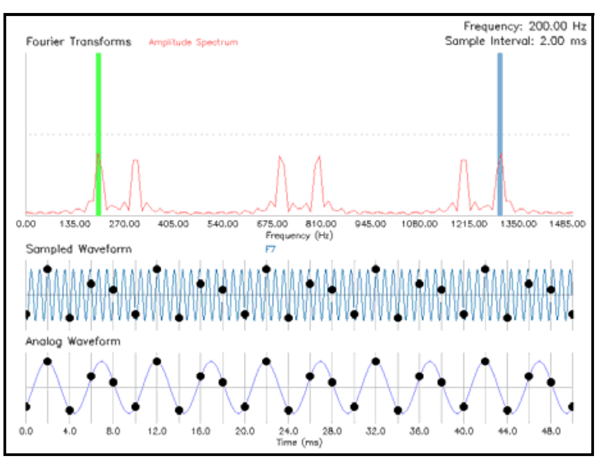

Fourier Transforms
Amplitude Spectrum
Frequency: 200.00 Hz
Sample Interval: 2.00 ms
0.00
135.00
270.00
405.00
540.00
675.00
810.00
945.00
1080.00
1215.00
1350.00
1485.00
Frequency (Hz)
Sampled Waveform
Analog Waveform
0.0
4.0
8.0
12.0
16.0
20.0
24.0
28.0
32.0
36.0
40.0
44.0
48.0
Time (ms)

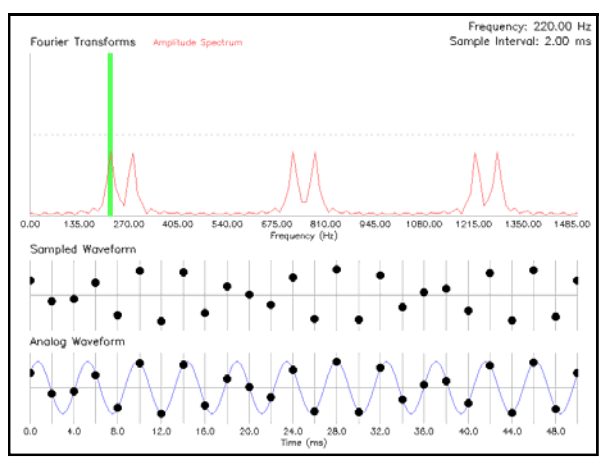

Frequency: 200.00 Hz
Sample Interval: 2.00 ms
Fourier Transforms
Amplitude Spectrum
0.00 135.00 270.00 405.00 540.00 675.00 810.00 945.00 1080.00 1215.00 1350.00 1485.00
Frequency (Hz)
Sampled Waveform
F3
Analog Waveform
0.0 4.0 8.0 12.0 16.0 20.0 24.0 28.0 32.0 36.0 40.0 44.0 48.0
Time (ms)


Frequency: 200.00 Hz
Sample Interval: 2.00 ms
Fourier Transforms
Amplitude Spectrum
0.00 135.00 270.00 405.00 540.00 675.00 810.00 945.00 1080.00 1215.00 1350.00 1485.00
Frequency (Hz)
Sampled Waveform
F4
Analog Waveform
0.0 4.0 8.0 12.0 16.0 20.0 24.0 28.0 32.0 36.0 40.0 44.0 48.0
Time (ms)


Frequency: 200.00 Hz
Sample Interval: 2.00 ms
Fourier Transforms
Amplitude Spectrum
0.00 135.00 270.00 405.00 540.00 675.00 810.00 945.00 1080.00 1215.00 1350.00 1485.00
Frequency (Hz)
Sampled Waveform
F5
Analog Waveform
0.0 4.0 8.0 12.0 16.0 20.0 24.0 28.0 32.0 36.0 40.0 44.0 48.0
Time (ms)


Frequency: 200.00 Hz
Sample Interval: 2.00 ms
Fourier Transforms
Amplitude Spectrum
0.00 135.00 270.00 405.00 540.00 675.00 810.00 945.00 1080.00 1215.00 1350.00 1485.00
Frequency (Hz)
Sampled Waveform
F6
Analog Waveform
0.0 4.0 8.0 12.0 16.0 20.0 24.0 28.0 32.0 36.0 40.0 44.0 48.0
Time (ms)


Frequency: 200.00 Hz
Sample Interval: 2.00 ms
Fourier Transforms
Amplitude Spectrum
0.00 135.00 270.00 405.00 540.00 675.00 810.00 945.00 1080.00 1215.00 1350.00 1485.00
Frequency (Hz)
Sampled Waveform
F7
Analog Waveform
0.0 4.0 8.0 12.0 16.0 20.0 24.0 28.0 32.0 36.0 40.0 44.0 48.0
Time (ms)


Frequency: 220.00 Hz
Sample Interval: 2.00 ms
Fourier Transforms
Amplitude Spectrum
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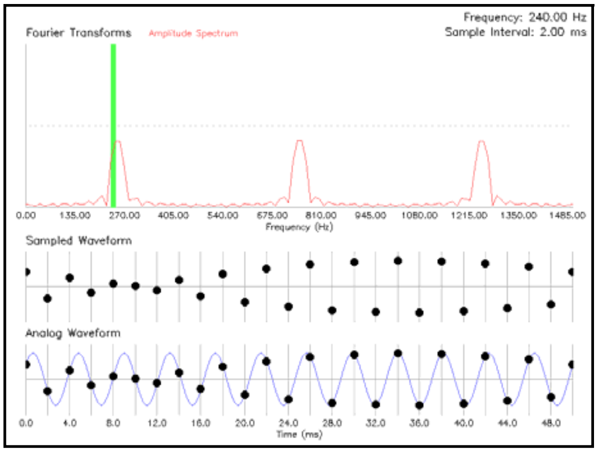
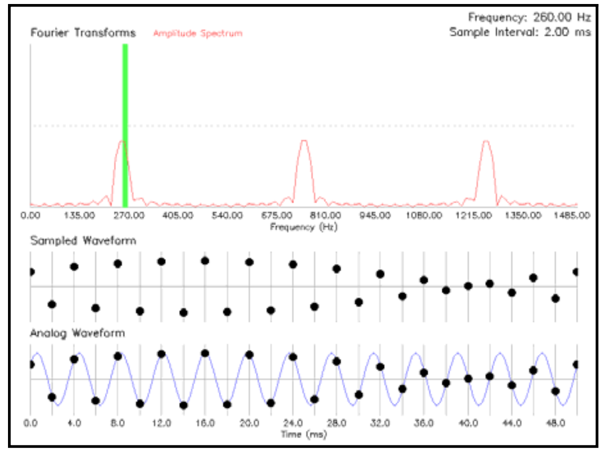
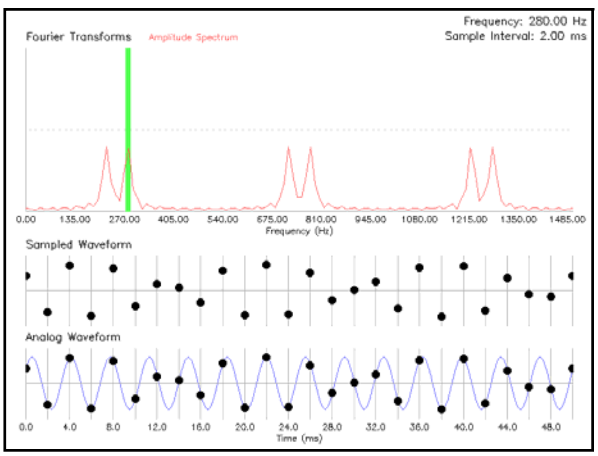
Frequency (Hz)
Sampled Waveform
Analog Waveform
0.0 4.0 8.0 12.0 16.0 20.0 24.0 28.0 32.0 36.0 40.0 44.0 48.0
Time (ms)


Fourier Transforms
Amplitude Spectrum
Frequency: 240.00 Hz
Sample Interval: 2.00 ms
0.00 135.00 270.00 405.00 540.00 675.00 810.00 945.00 1080.00 1215.00 1350.00 1485.00
Frequency (Hz)
Sampled Waveform
Analog Waveform
0.0 4.0 8.0 12.0 16.0 20.0 24.0 28.0 32.0 36.0 40.0 44.0 48.0
Time (ms)


Fourier Transforms
Amplitude Spectrum
Frequency: 260.00 Hz
Sample Interval: 2.00 ms
0.00 135.00 270.00 405.00 540.00 675.00 810.00 945.00 1080.00 1215.00 1350.00 1485.00
Frequency (Hz)
Sampled Waveform
Analog Waveform
0.0 4.0 8.0 12.0 16.0 20.0 24.0 28.0 32.0 36.0 40.0 44.0 48.0
Time (ms)


Fourier Transforms
Amplitude Spectrum
Frequency: 280.00 Hz
Sample Interval: 2.00 ms
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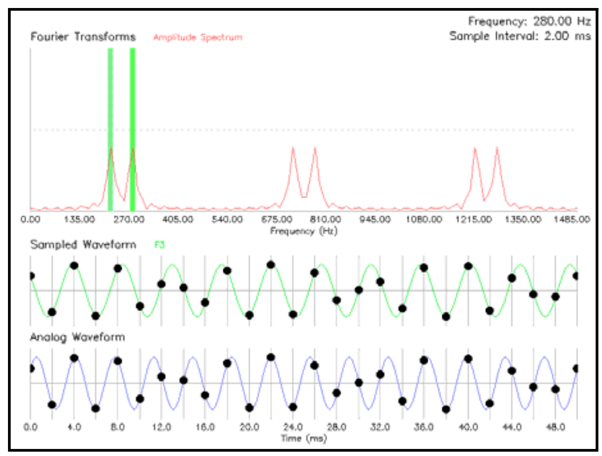
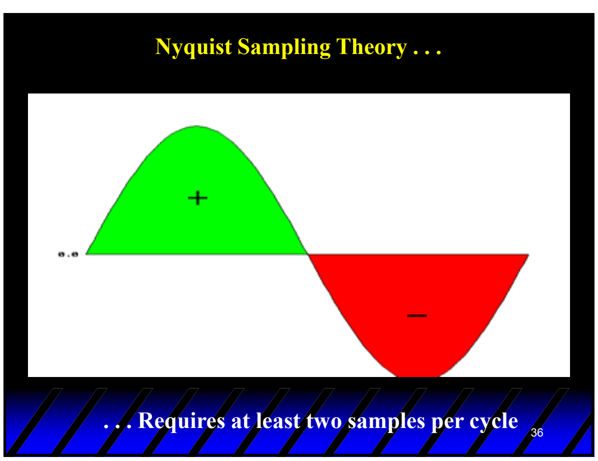
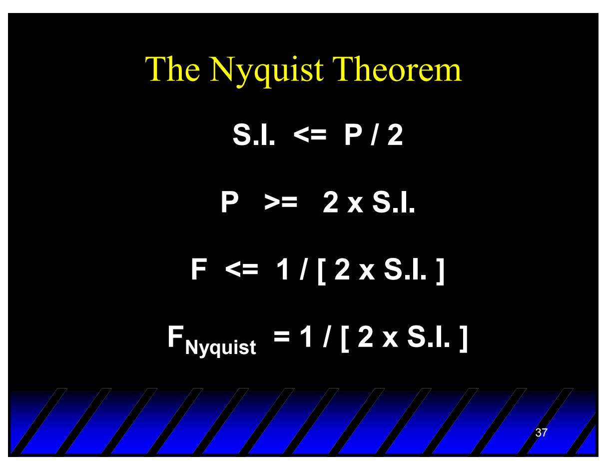
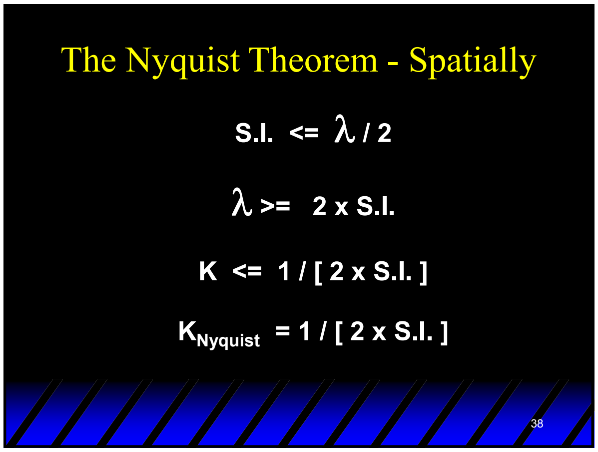
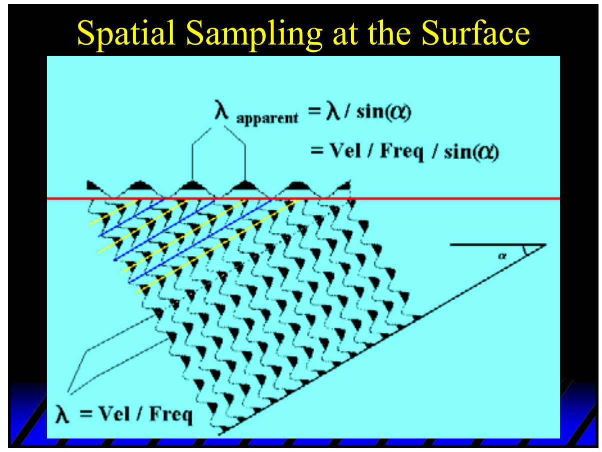
Frequency (Hz)
Sampled Waveform
Analog Waveform
0.0 4.0 8.0 12.0 16.0 20.0 24.0 28.0 32.0 36.0 40.0 44.0 48.0
Time (ms)

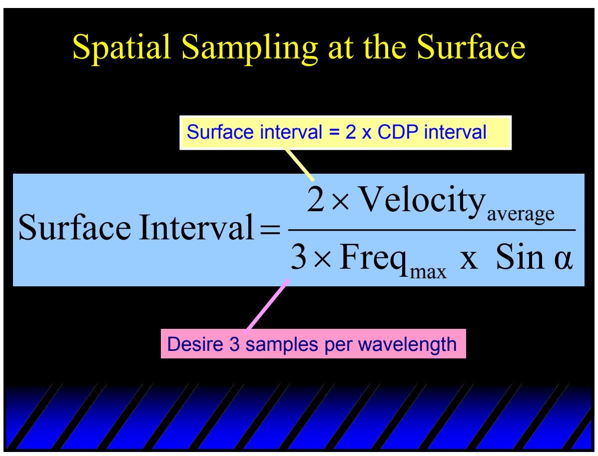

Fourier Transforms
Amplitude Spectrum
Frequency: 280.00 Hz
Sample Interval: 2.00 ms
0.00 135.00 270.00 405.00 540.00 675.00 810.00 945.00 1080.00 1215.00 1350.00 1485.00
Frequency (Hz)
Sampled Waveform
Analog Waveform
0.0 4.0 8.0 12.0 16.0 20.0 24.0 28.0 32.0 36.0 40.0 44.0 48.0
Time (ms)

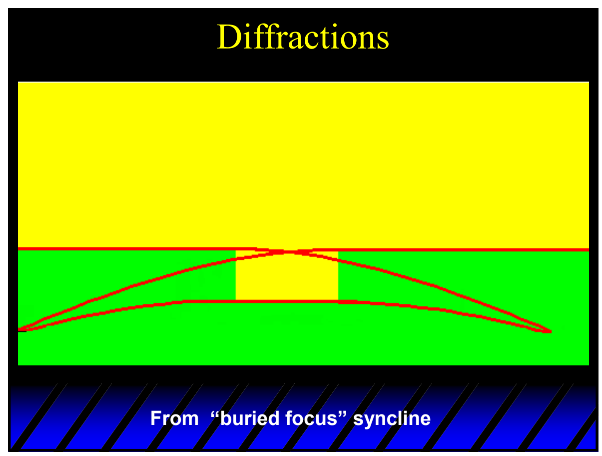

Nyquist Sampling Theory . . .
+
–
. . . Requires at least two samples per cycle
36

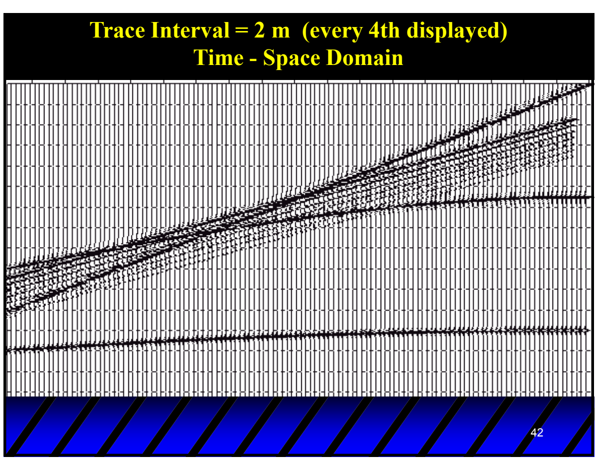

The Nyquist Theorem
S.I. <= P / 2
P >= 2 x S.I.
F <= 1 / [2 x S.I.]
$F_{Nyquist}$ = 1 / [2 x S.I.]
37

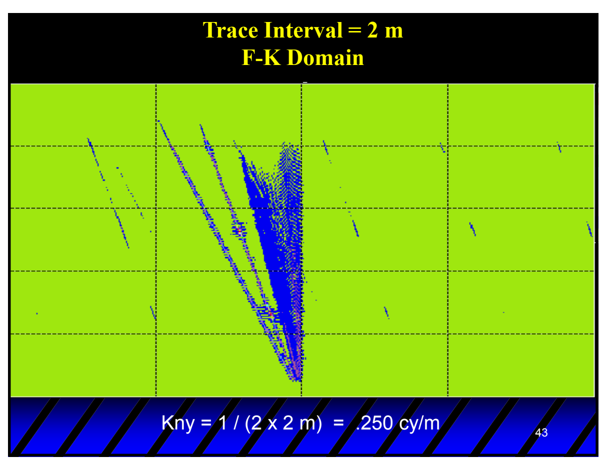

The Nyquist Theorem - Spatially
S.I. <= λ / 2
λ >= 2 x S.I.
K <= 1 / [2 x S.I.]
K_Nyquist = 1 / [2 x S.I.]
38

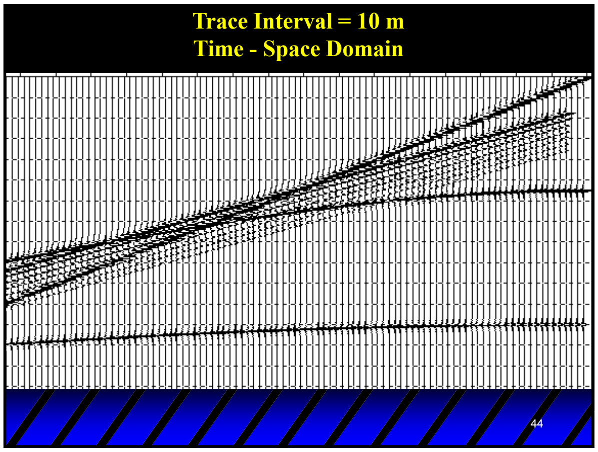

Spatial Sampling at the Surface
λ apparent = λ / sin(α)
= Vel / Freq / sin(α)
α
λ = Vel / Freq

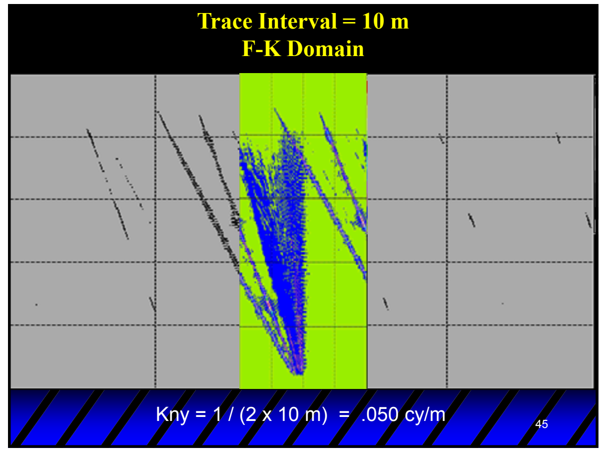

Spatial Sampling at the Surface
Surface interval = 2 x CDP interval
Surface Interval = 2 × Velocity_average / 3 × Freq_max x Sin α
Desire 3 samples per wavelength

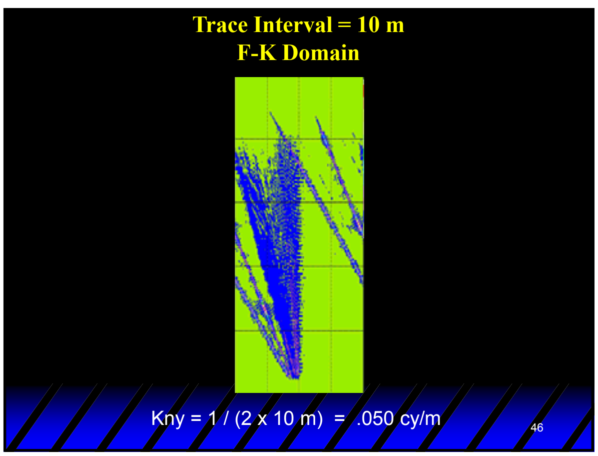

Diffractions
From "buried focus" syncline

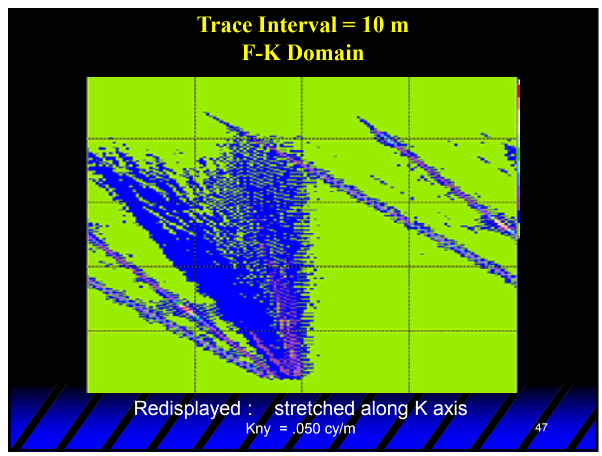

Trace Interval = 2 m (every 4th displayed)
Time - Space Domain
42

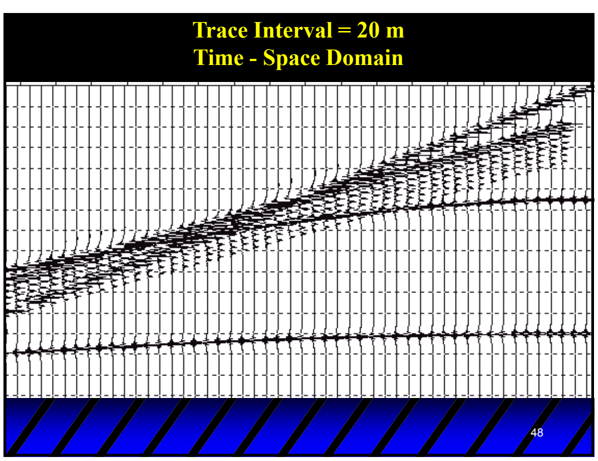

Trace Interval = 2 m
F-K Domain
Kny = 1 / (2 x 2 m) = .250 cy/m
43

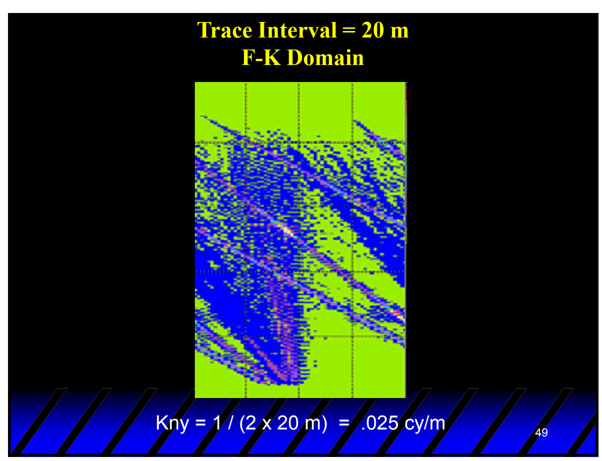

Trace Interval = 10 m
Time - Space Domain
44

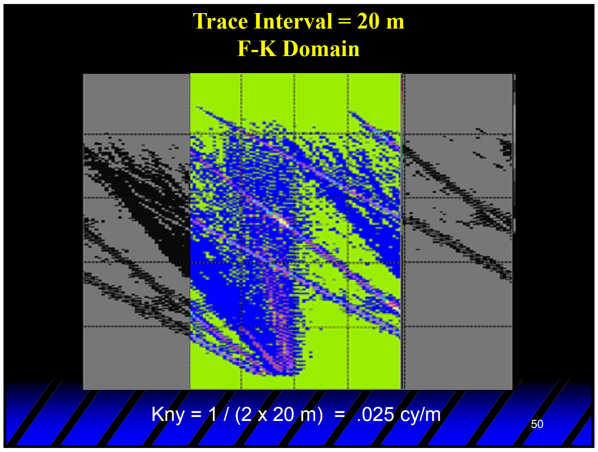

Trace Interval = 10 m
F-K Domain
Kny = 1 / (2 x 10 m) = .050 cy/m
45

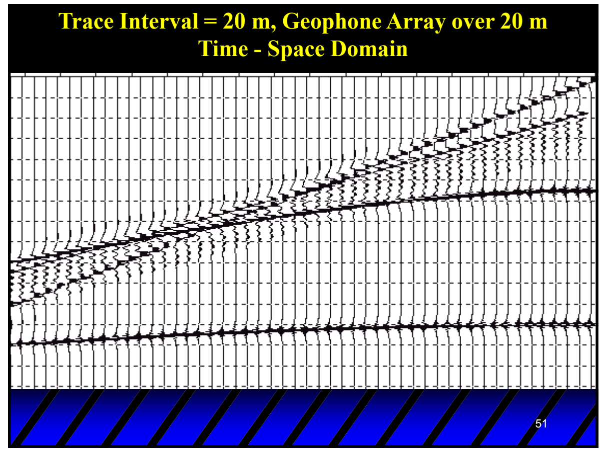

Trace Interval = 10 m
F-K Domain
Kny = 1 / (2 x 10 m) = .050 cy/m
46

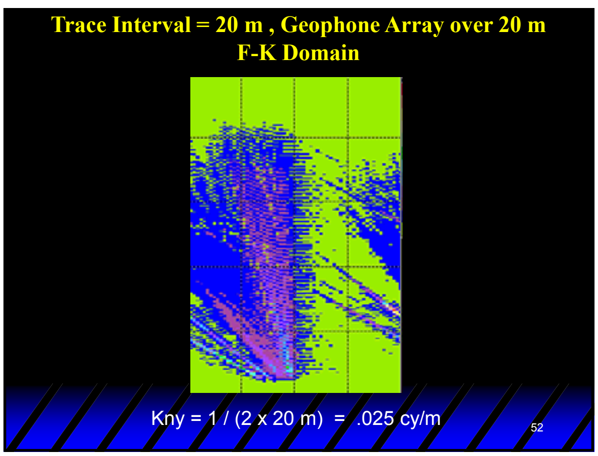

Trace Interval = 10 m
F-K Domain
Redisplayed : stretched along K axis
Kny = .050 cy/m
47

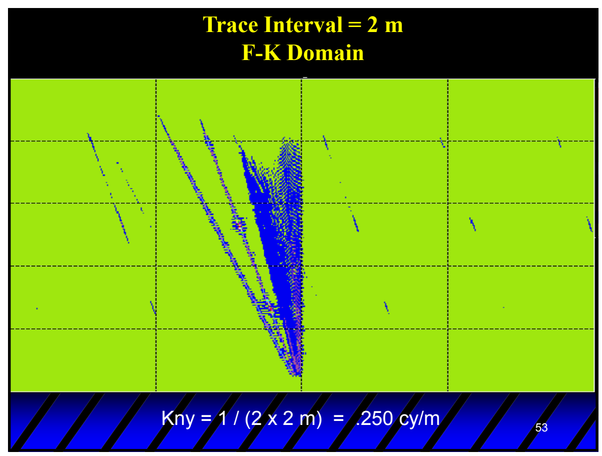

Trace Interval = 20 m
Time - Space Domain
48

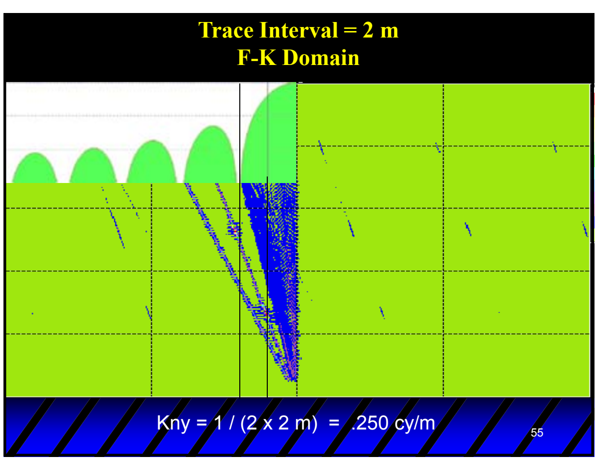

Trace Interval = 20 m
F-K Domain
Kny = 1 / (2 x 20 m) = .025 cy/m
49

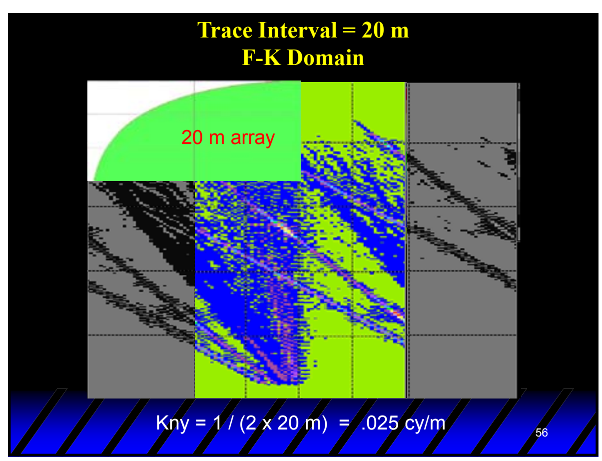

Trace Interval = 20 m
F-K Domain
Kny = 1 / (2 x 20 m) = .025 cy/m
50

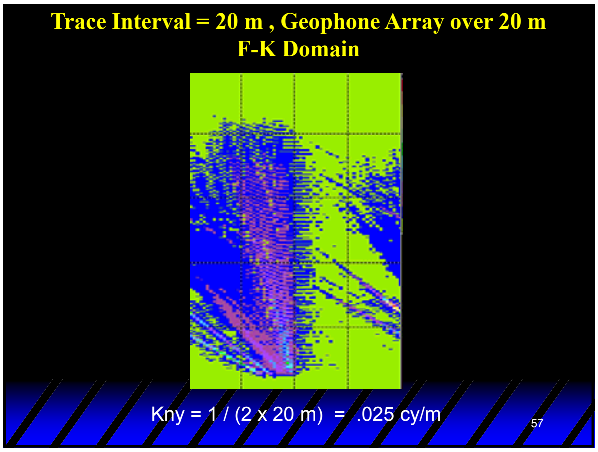

Trace Interval = 20 m, Geophone Array over 20 m
Time - Space Domain
51

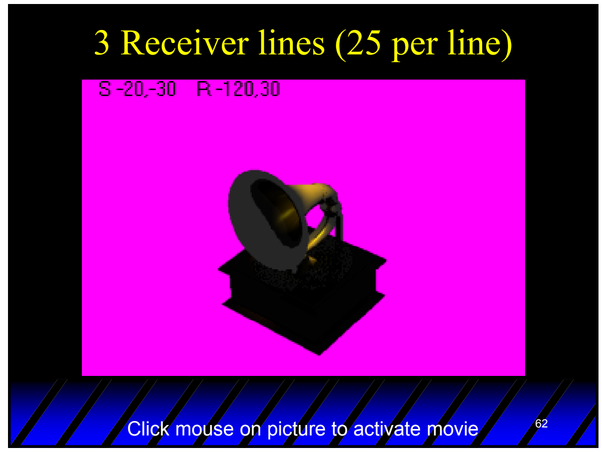

Trace Interval = 20 m , Geophone Array over 20 m
F-K Domain
Kny = 1 / (2 x 20 m) = .025 cy/m
52

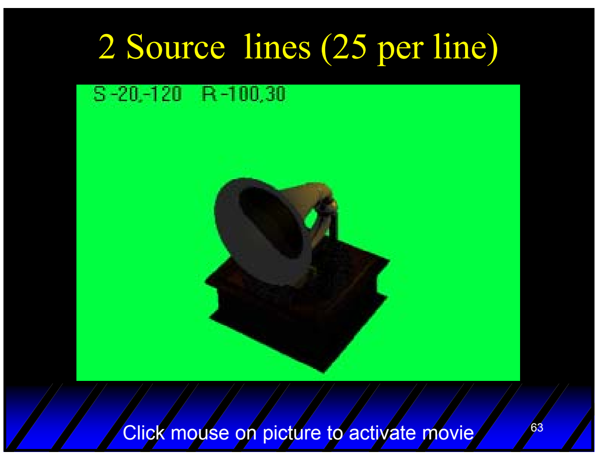

Trace Interval = 2 m
F-K Domain
Kny = 1 / (2 x 2 m) = .250 cy/m
53

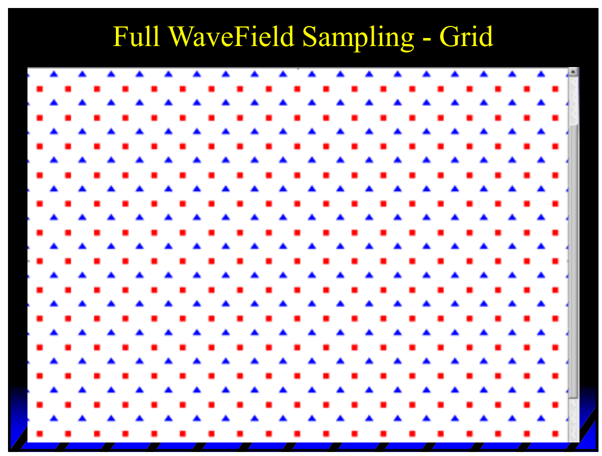

Trace Interval = 2 m
F-K Domain
Kny = 1 / (2 x 2 m) = .250 cy/m
55

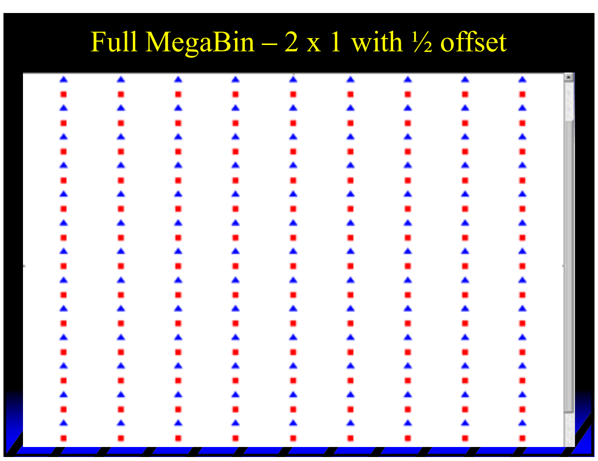

Trace Interval = 20 m
F-K Domain
20 m array
Kny = 1 / (2 x 20 m) = .025 cy/m
56

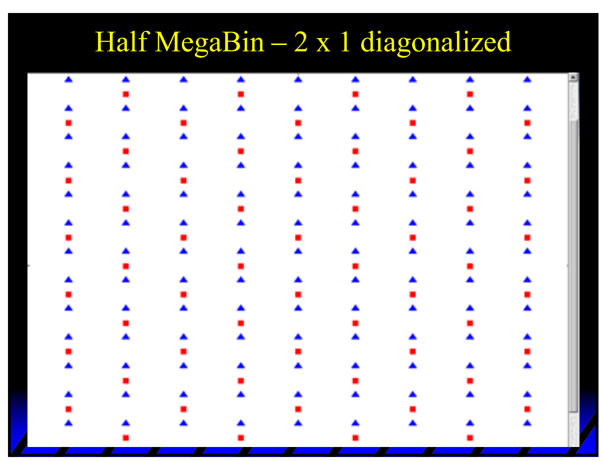

Trace Interval = 20 m , Geophone Array over 20 m
F-K Domain
Kny = 1 / (2 x 20 m) = .025 cy/m
57

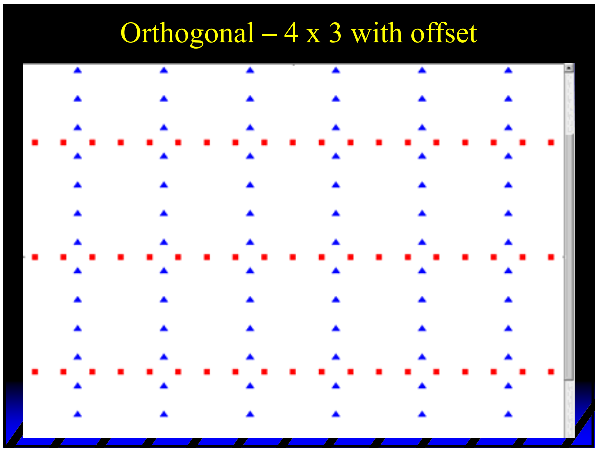

3 Receiver lines (25 per line)
S -20,-30 R -120,30
Click mouse on picture to activate movie
62

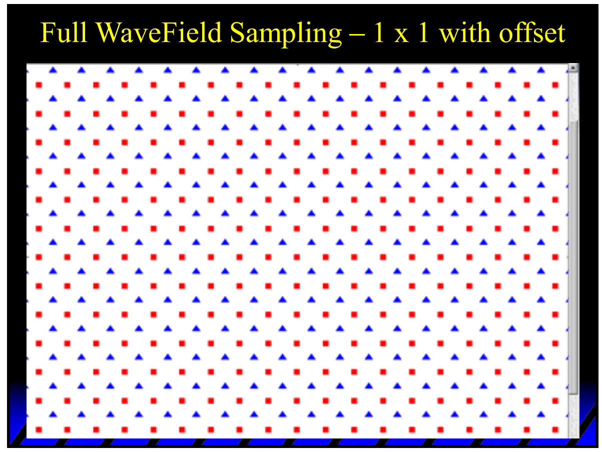

2 Source lines (25 per line)
S -20,-120 R -100,30
Click mouse on picture to activate movie
63

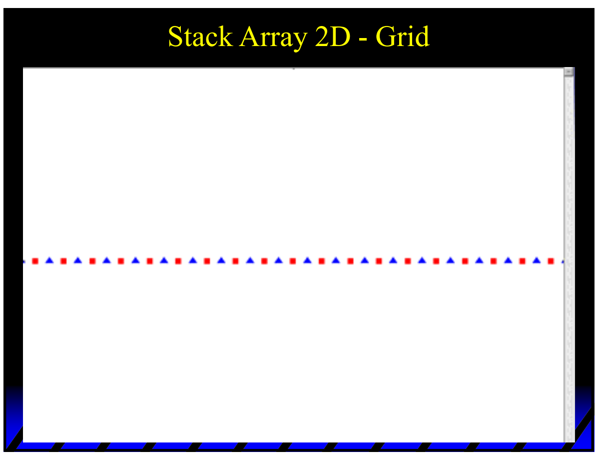

Full WaveField Sampling - Grid

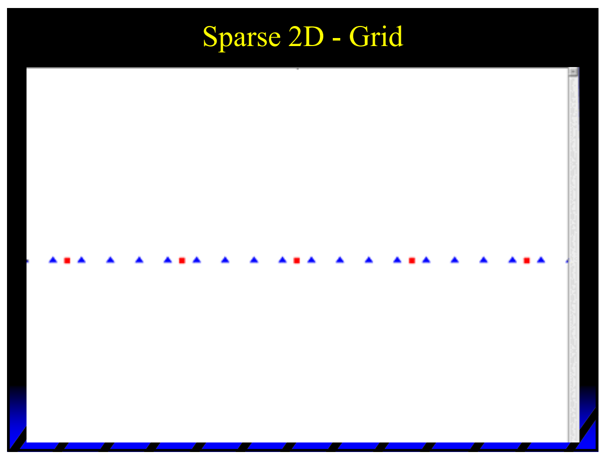

Full MegaBin – 2 x 1 with ½ offset

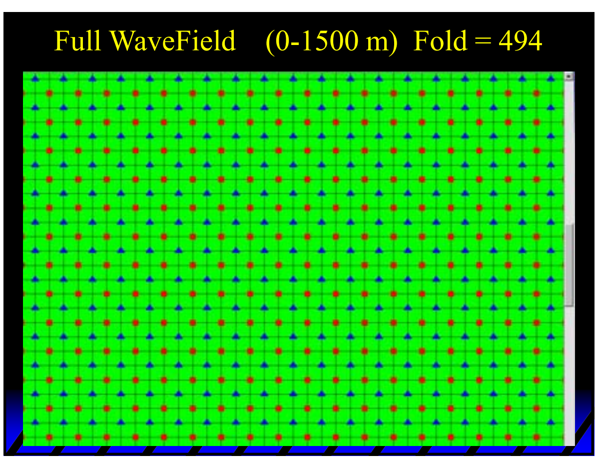

Half MegaBin – 2 x 1 diagonalized

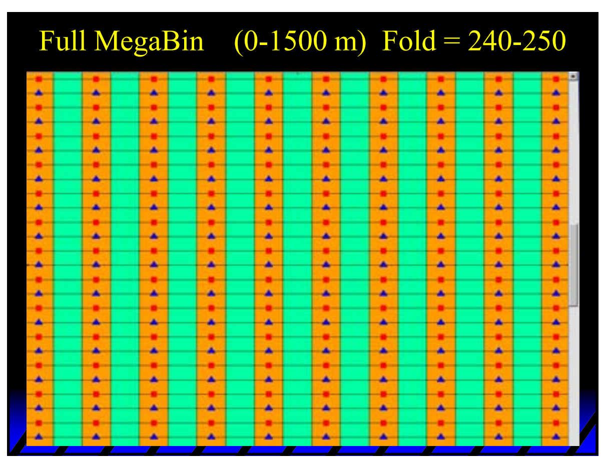

Orthogonal – 4 x 3 with offset

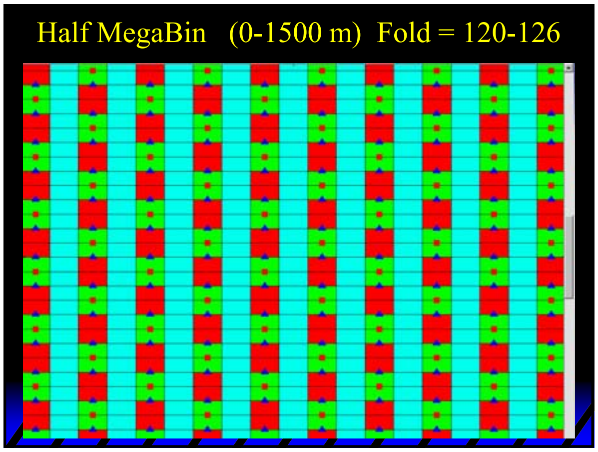

Full WaveField Sampling – 1 x 1 with offset

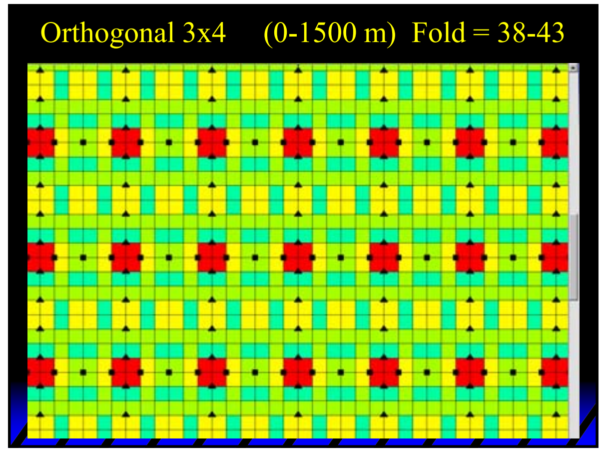

Stack Array 2D - Grid

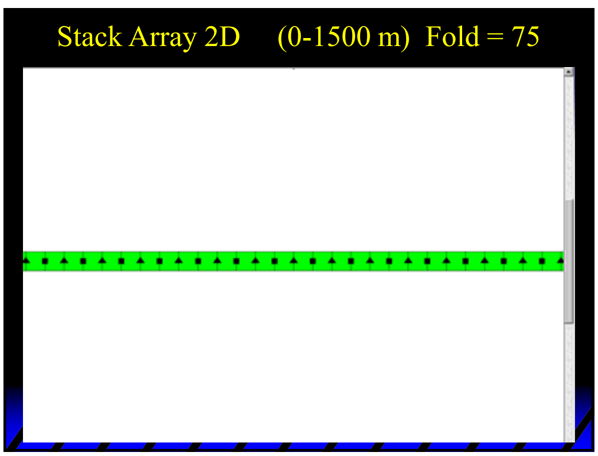

Sparse 2D - Grid

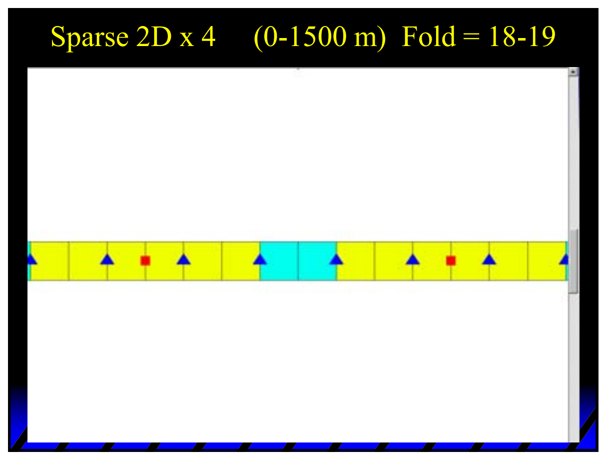

Full WaveField (0-1500 m) Fold = 494

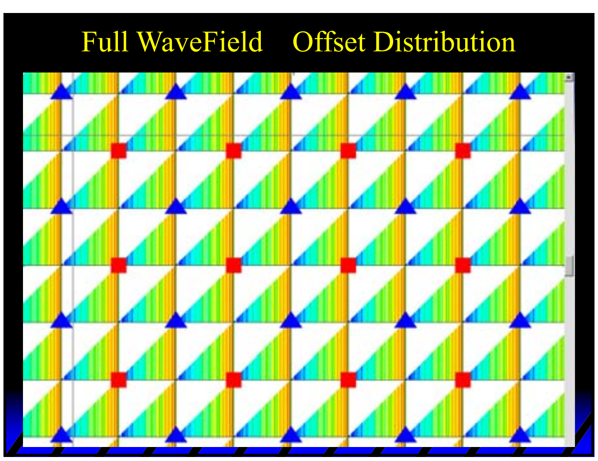

Full MegaBin (0-1500 m) Fold = 240-250

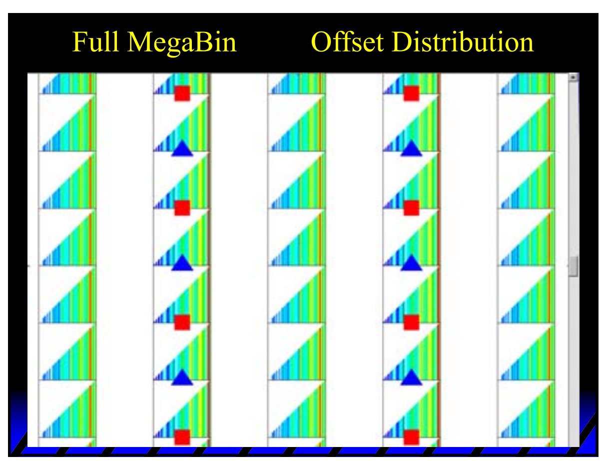

Half MegaBin (0-1500 m) Fold = 120-126

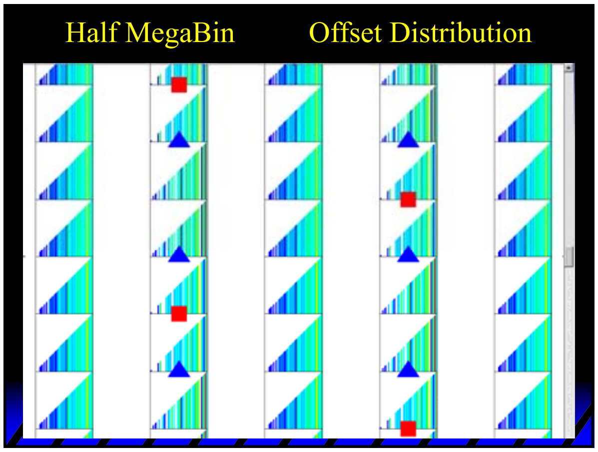

Orthogonal 3x4 (0-1500 m) Fold = 38-43

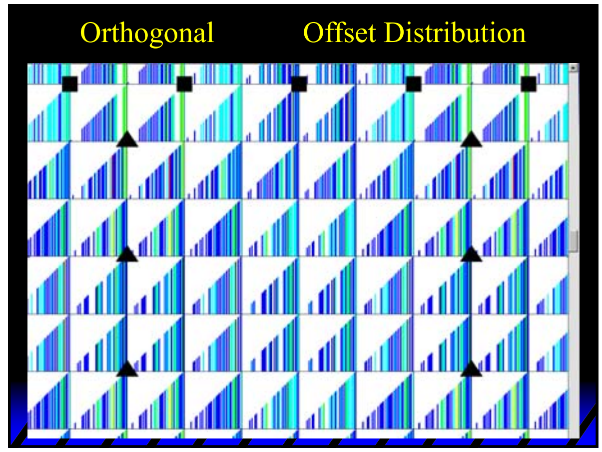

Stack Array 2D (0-1500 m) Fold = 75

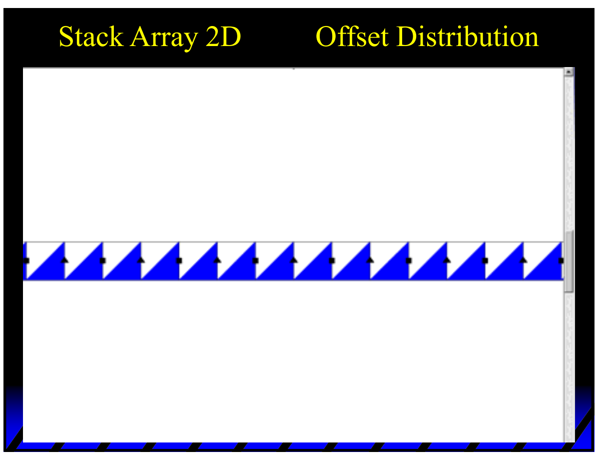

Sparse 2D x 4 (0-1500 m) Fold = 18-19

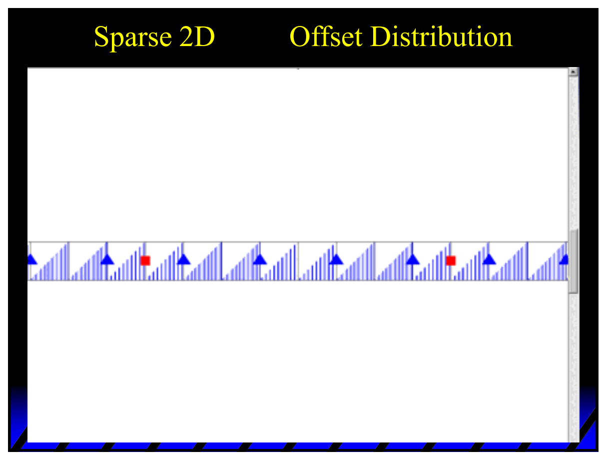

Full WaveField Offset Distribution

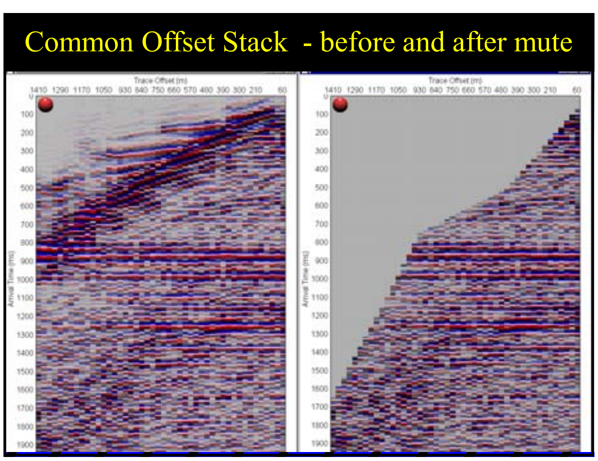

Full MegaBin Offset Distribution

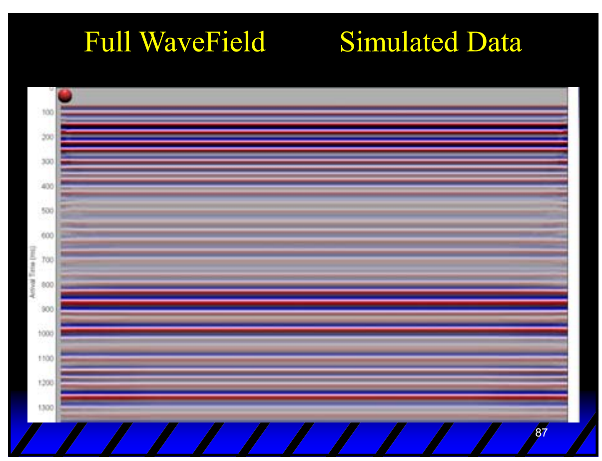

Half MegaBin
Offset Distribution

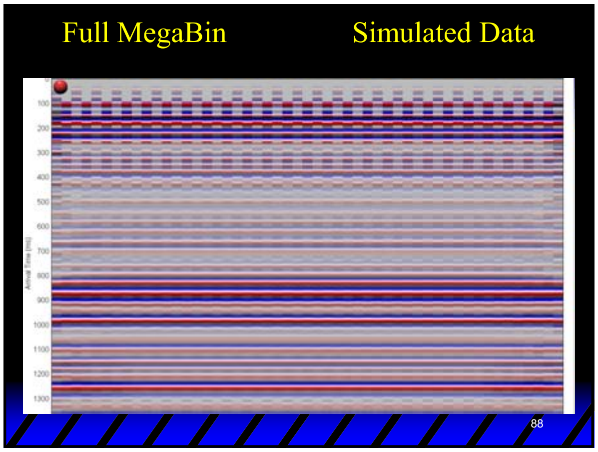

Orthogonal
Offset Distribution

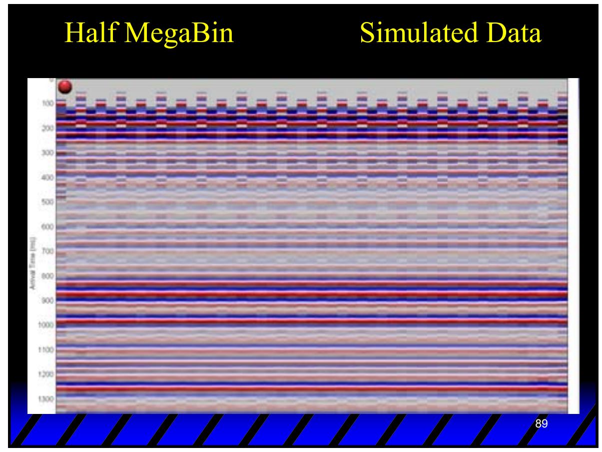

Stack Array 2D
Offset Distribution

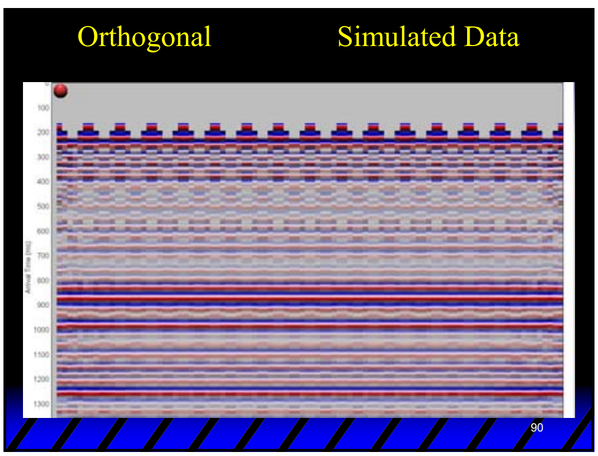

Sparse 2D
Offset Distribution

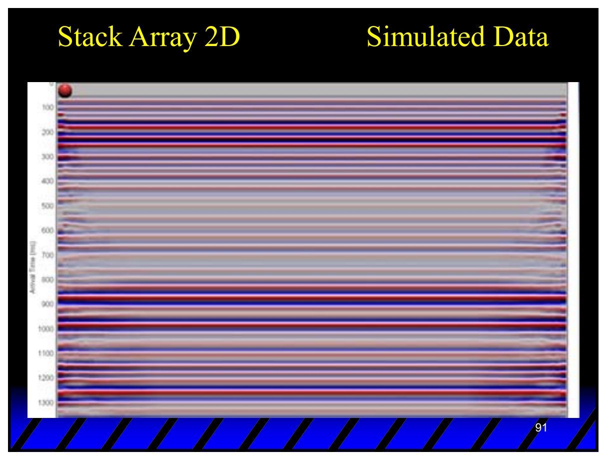

Common Offset Stack - before and after mute

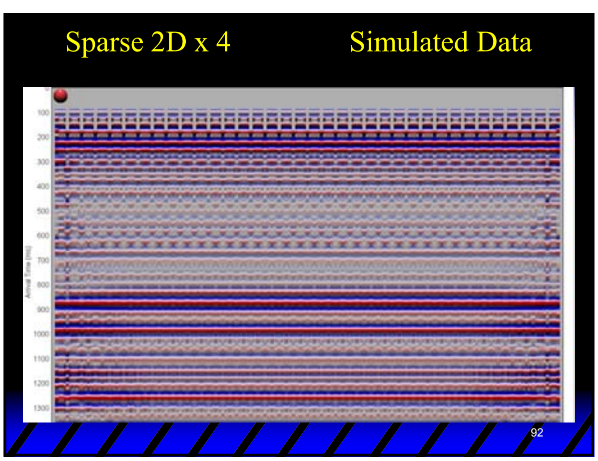

Full WaveField
Simulated Data

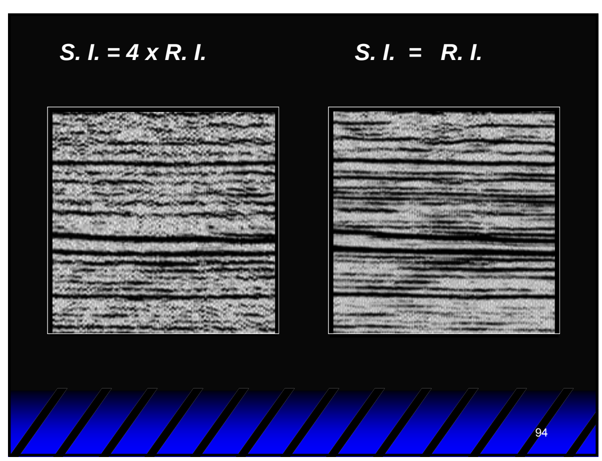

Full MegaBin
Simulated Data
88

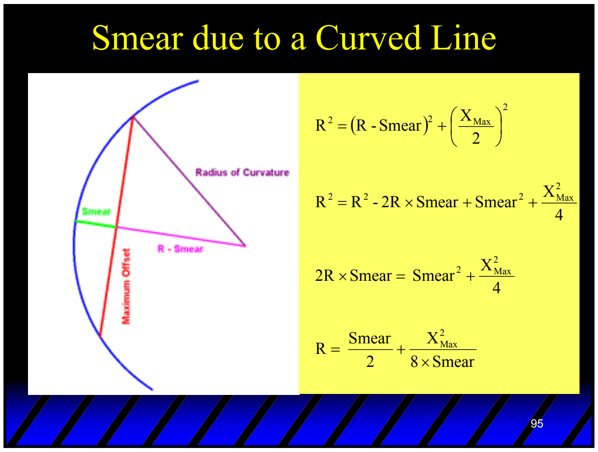

Half MegaBin
Simulated Data
89

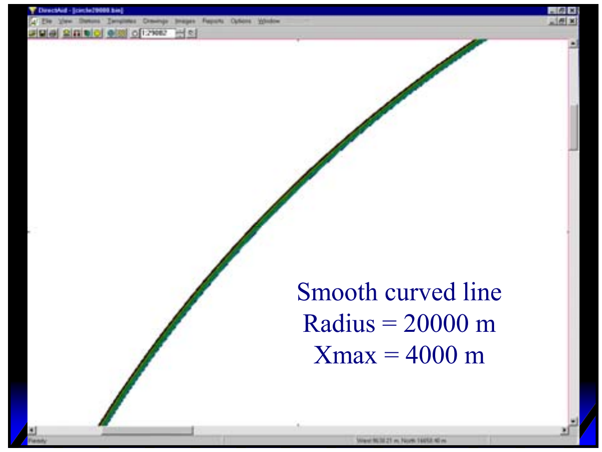

Orthogonal
Simulated Data
90

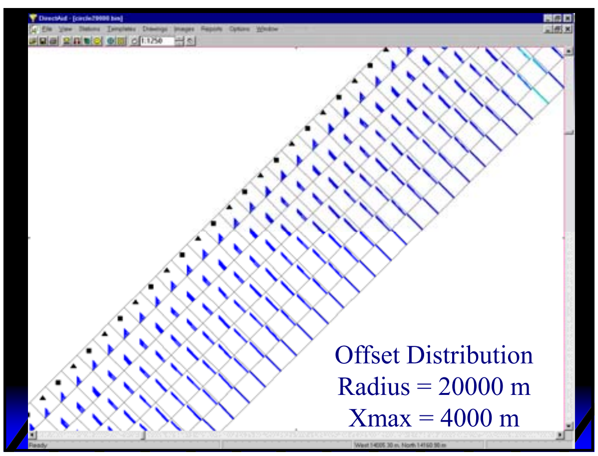

Stack Array 2D
Simulated Data
91

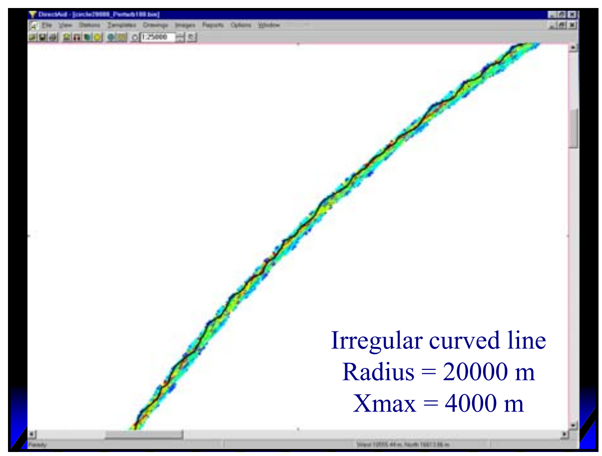

Sparse 2D x 4
Simulated Data
92

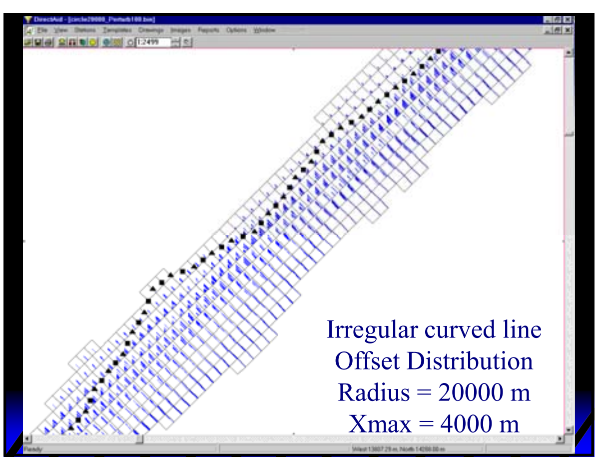

S. I. = 4 x R. I.
S. I. = R. I.
94

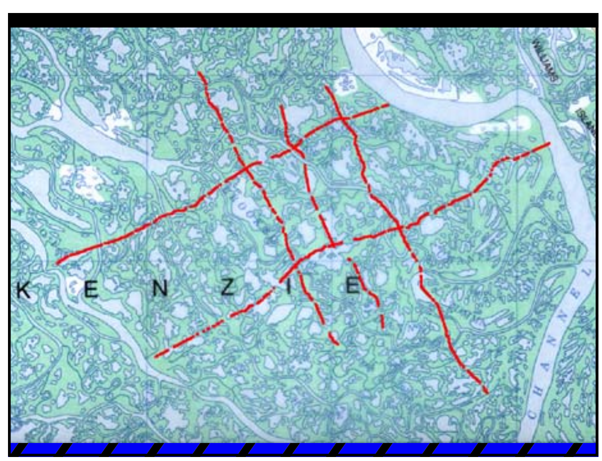

Smear due to a Curved Line
Radius of Curvature
Smear
R - Smear
Maximum Offset
$R^2 = (R - Smear)^2 + \left(\frac{X_{Max}}{2}\right)^2$
$R^2 = R^2 - 2R \times Smear + Smear^2 + \frac{X_{Max}^2}{4}$
$2R \times Smear = Smear^2 + \frac{X_{Max}^2}{4}$
$R = \frac{Smear}{2} + \frac{X_{Max}^2}{8 \times Smear}$
95

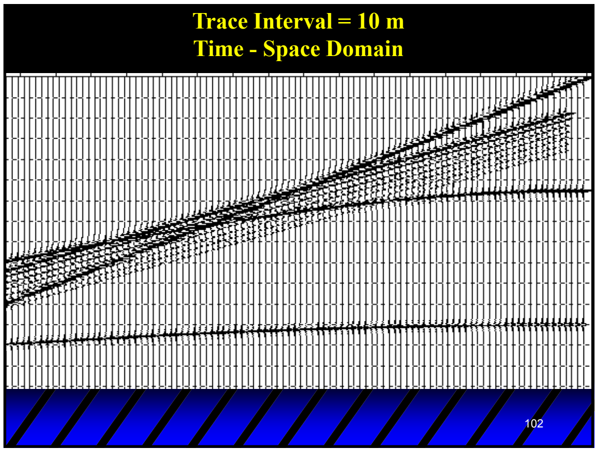

Smooth curved line
Radius = 20000 m
Xmax = 4000 m

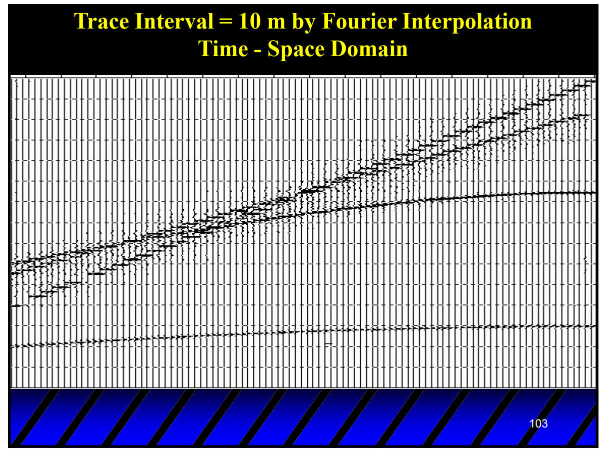

Offset Distribution
Radius = 20000 m
Xmax = 4000 m

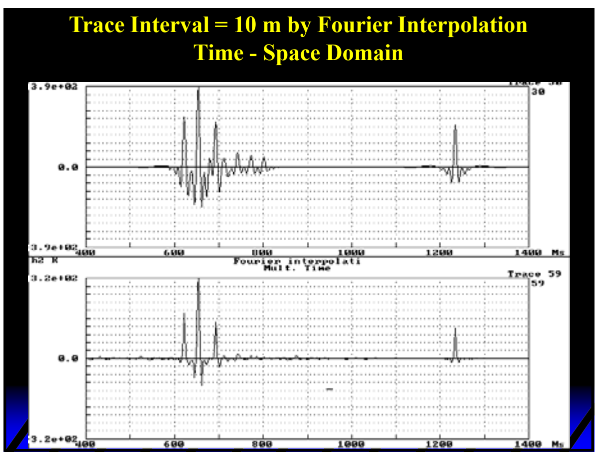

Irregular curved line
Radius = 20000 m
Xmax = 4000 m

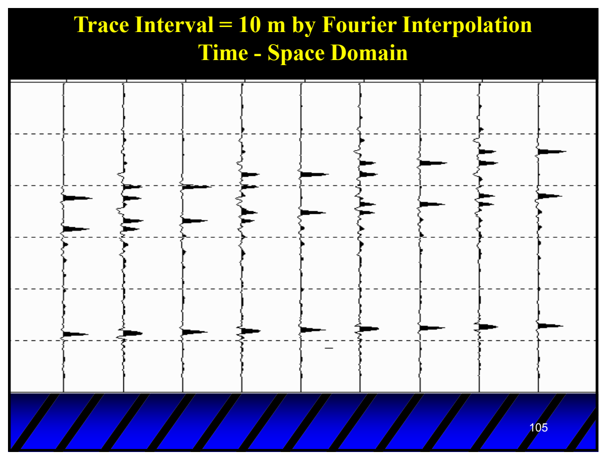

Irregular curved line
Offset Distribution
Radius = 20000 m
Xmax = 4000 m

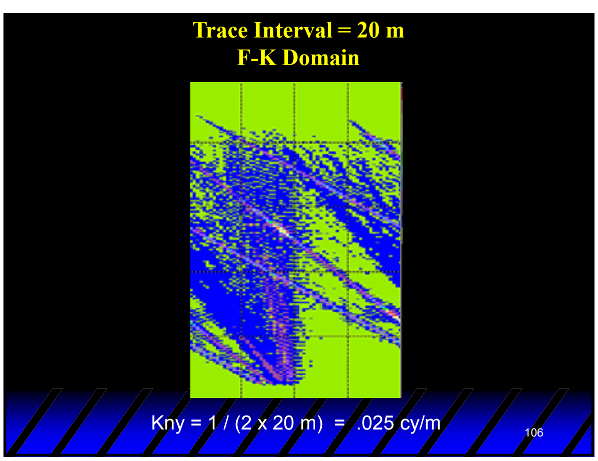

K E N Z I E

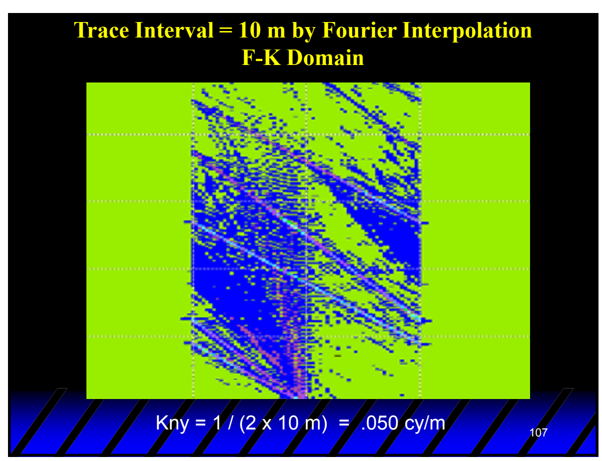

Trace Interval = 10 m
Time - Space Domain
102

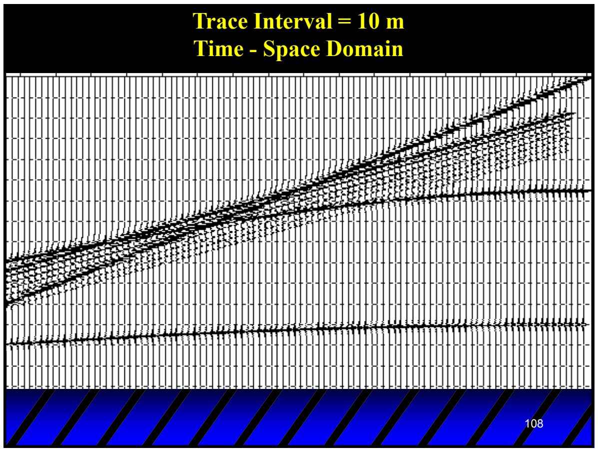

Trace Interval = 10 m by Fourier Interpolation
Time - Space Domain
103

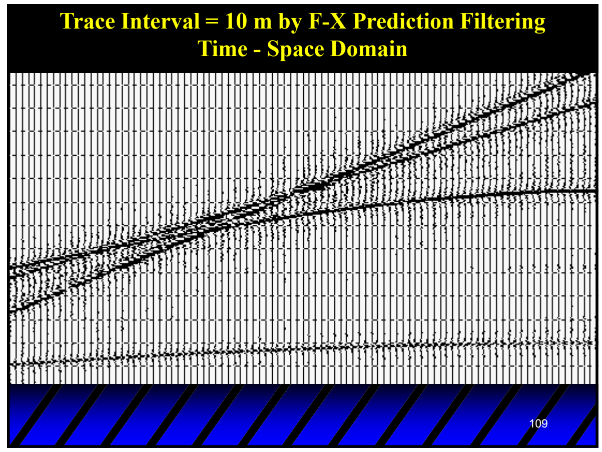

Trace Interval = 10 m by Fourier Interpolation
Time - Space Domain

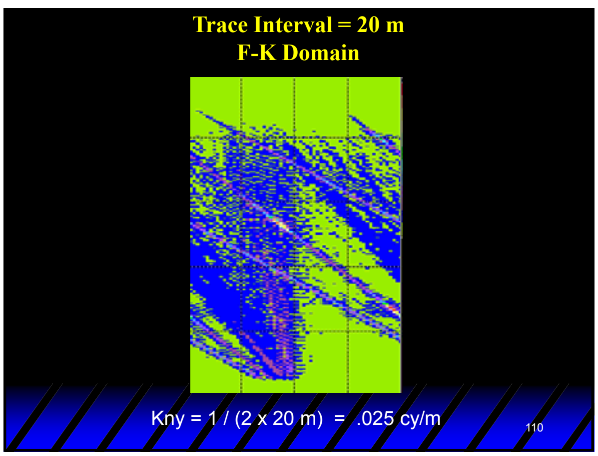

Trace Interval = 10 m by Fourier Interpolation
Time - Space Domain
105

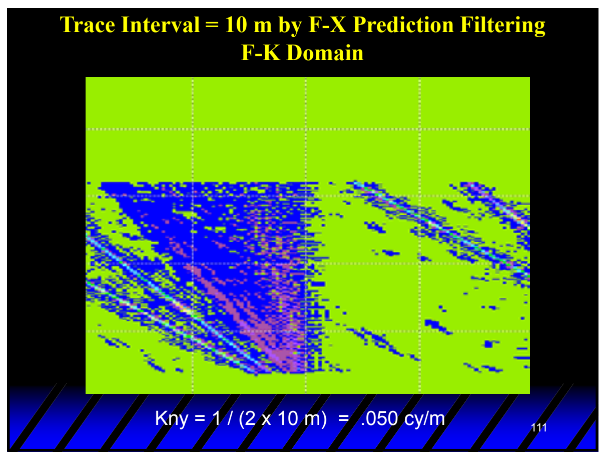

Trace Interval = 20 m
F-K Domain
Kny = 1 / (2 x 20 m) = .025 cy/m
106

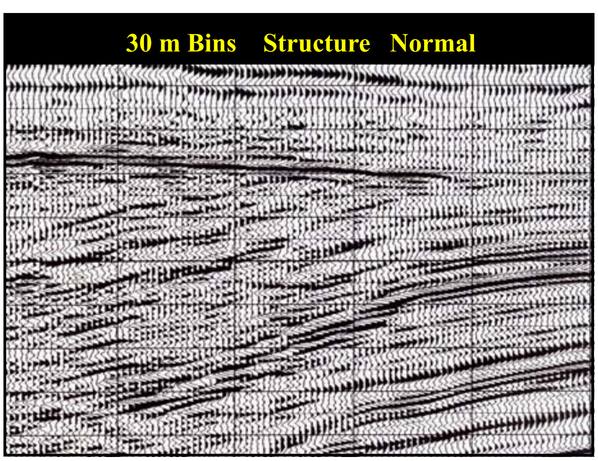

Trace Interval = 10 m by Fourier Interpolation
F-K Domain
Kny = 1 / (2 x 10 m) = .050 cy/m
107

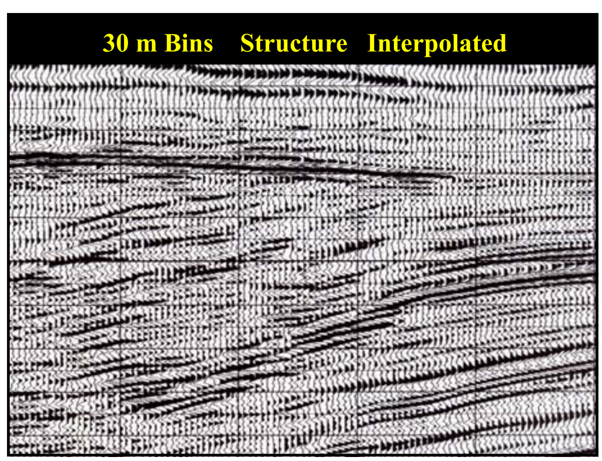

Trace Interval = 10 m
Time - Space Domain
108

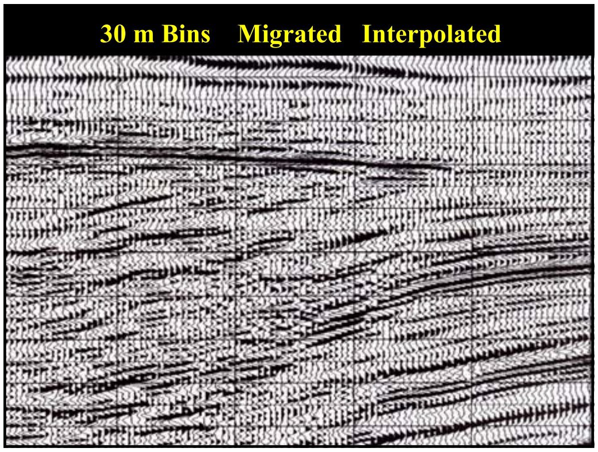

Trace Interval = 10 m by F-X Prediction Filtering
Time - Space Domain
109

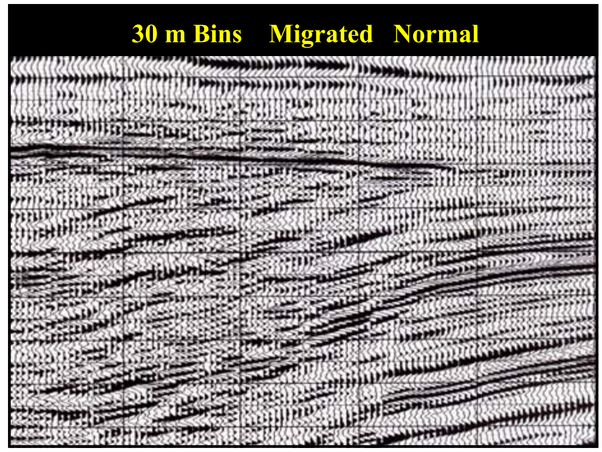

Trace Interval = 20 m
F-K Domain
Kny = 1 / (2 x 20 m) = .025 cy/m
110

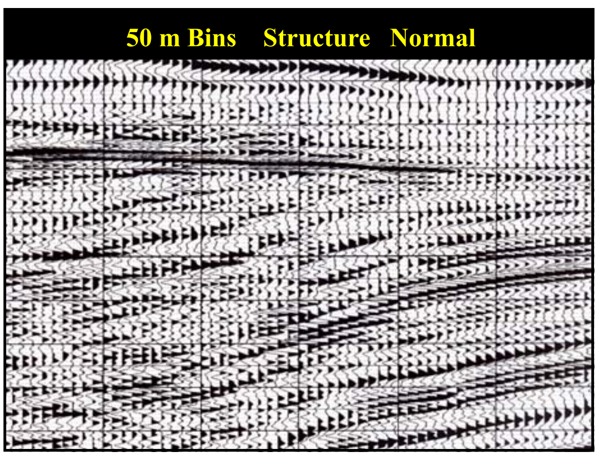

Trace Interval = 10 m by F-X Prediction Filtering
F-K Domain
Kny = 1 / (2 x 10 m) = .050 cy/m
111

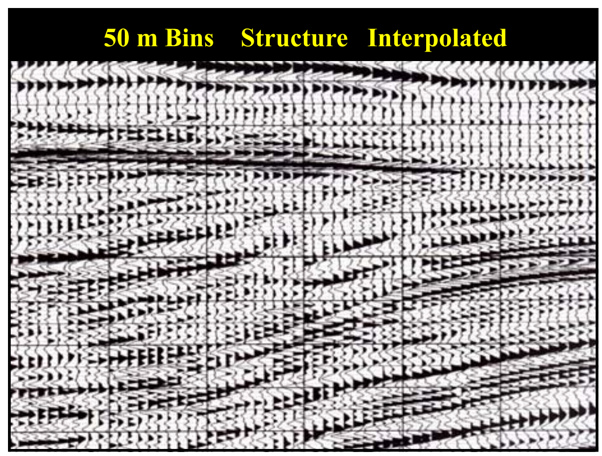

30 m Bins Structure Normal

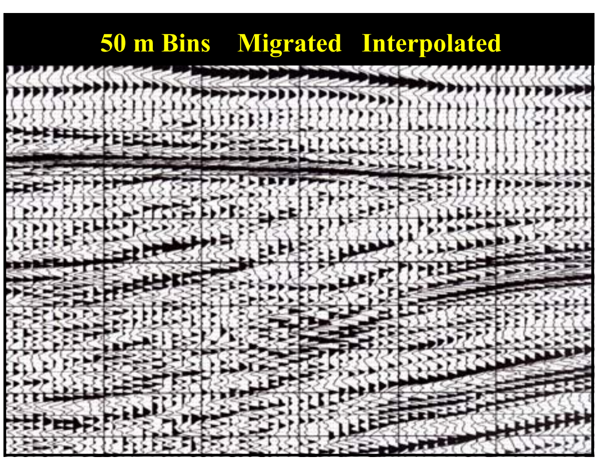

30 m Bins Structure Interpolated

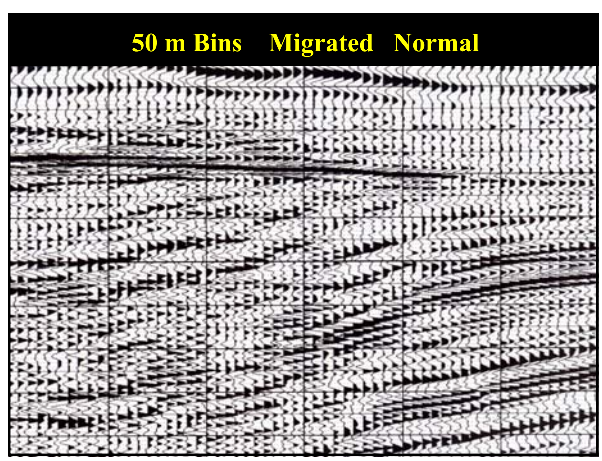

30 m Bins Migrated Interpolated


30 m Bins Migrated Normal


50 m Bins Structure Normal


50 m Bins Structure Interpolated


50 m Bins Migrated Interpolated


50 m Bins Migrated Normal

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