Chapter 4

Designing 3-D Land Seismic Surveys
Introduction

- What is 3-D seismic?
  - closely spaced 2-D lines of sources and receivers that cover an area

- Why 3-D seismic?
  - 3-D migration eliminates misties over dipping reflectors.
  - 3-D migration enhances the horizontal resolution by collapsing diffractions.
  - It presents a more detailed image of the subsurface
Introduction

- **Terminology**
  - *inline*: direction parallel receiver lines
  - *crossline*: direction perpendicular to receiver lines (not necessarily parallel to source lines)
  - *(CMP)*bin*: a small rectangle (or square) that contains all the traces which belong to the same CMP
  - *box (unit cell)*: area bounded by two adjacent receiver lines and two adjacent source lines
  - *patch (template)*: area of all live receivers recording from the same source
Introduction

(Modified after Cordsen et al., 2000)

(Cordsen et al., 2000)
Controlling Factors

- Factors controlling 3-D land survey design
  
  *(independent variables)*
  
  1. Target depth and lateral size
  2. TWTT and RMS velocity to target
  3. Interval velocity immediately above target
  4. Shallowest depth of interest
  5. Maximum expected dip angle
  6. Fold of good 2-D data recorded in the area previously
  7. Dominant and maximum usable frequencies at target
  8. Target dip angle
  9. Interval velocities of weathering and subweathering layers
  10. TWTT and RMS velocity to deepest event of interest
  11. Interval velocity of deepest event of interest
  12. NMO stretch of target
  13. TWTT and RMS velocity of prominent multiple (if any)
Controlling Factors

*Detailed List*

Determine the following parameters from exploration objectives and from existing 2-D seismic data:

- fold of good 2-D data
- steepest dip
- mute for shallow markers needed for isochroning
- target depth and mute distance
- target two-way time
- mute for basement depth and mute distance
- $V_{nt}$ immediately above the target horizon
- $f_{dcm}$ at the target horizon
- $f_{max}$ at the target horizon
- lateral target size
- area to be fully imaged
- layout method.

(Cordsen et al., 2000)
Controlling Factors

Example

- Target depth = 2,000 m
- Target lateral size = 300 m
- TWTT to target = 1.5 s
- RMS velocity to target = 2,700 m/s
- Interval velocity immediately above target = 4,200 m/s
- Shallowest depth of interest = 500 m
- Maximum expected dip angle = 20°
- Fold of good 2-D data recorded in the area previously = 30
- Dominant frequency at target = 50 Hz
- Maximum usable frequency at target = 70 Hz
- Target dip angle = 20°
- Interval velocity of weathering layer = 1,000 m/s
- Interval velocity of subweathering layer = 2,000 m/s
- TWTT to deepest event of interest = 2.5 s
- RMS velocity to deepest event of interest = 4,000 m/s
- Interval velocity of deepest event of interest = 5,500 m/s
- NMO stretch of target = 50%
- TWTT and RMS velocity of prominent multiple = 1.0 s and 1,000 m/s
Survey Parameters

- Parameters of 3-D land survey design
  \( \text{(dependent variables)} \)

1. Migration aperture (apron)
2. Record length
3. CMP Bin Size
4. \( X_{\text{min}} \)
5. \( X_{\text{max}} \)
6. CMP Fold
7. CMP Fold taper
Survey Parameters

**Calculation Table**

<table>
<thead>
<tr>
<th>Desired Fold</th>
<th>( \frac{1}{2} ) to 1 X full 2-D fold = ______</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bin size</td>
<td>a) for target size: ( B = \frac{V_{int}}{4 \times f_{max} \times \sin 0} ) = ______</td>
</tr>
<tr>
<td></td>
<td>b) for alias frequency: ( B = \frac{V_{int}}{N \times f_{dom}} ), ( N = 2 ) to 4 = ______ to ______</td>
</tr>
<tr>
<td></td>
<td>bin size = ______</td>
</tr>
<tr>
<td></td>
<td>( RL = ) ______</td>
</tr>
<tr>
<td></td>
<td>( SI = ) ______</td>
</tr>
<tr>
<td>Desired ( X_{min} ):</td>
<td>( R_{LI} = ) ______</td>
</tr>
<tr>
<td></td>
<td>( S_{LI} = ) ______</td>
</tr>
<tr>
<td></td>
<td>( X_{min} = (R_{LI}^2 + S_{LI}^2)^{1/2} ) = ______</td>
</tr>
<tr>
<td>Desired ( X_{max} ):</td>
<td>number of channels in patch = ______</td>
</tr>
<tr>
<td></td>
<td>number of receiver lines = ______</td>
</tr>
<tr>
<td></td>
<td>channels per line = ______</td>
</tr>
<tr>
<td></td>
<td>cross-line dimension = ______</td>
</tr>
<tr>
<td></td>
<td>in-line dimension = ______</td>
</tr>
<tr>
<td></td>
<td>aspect ratio = cross-line dimension of the patch / in-line dimension of the patch = ______</td>
</tr>
<tr>
<td></td>
<td>( X_{max} = \frac{1}{2} \times (\text{in-line dimension of the patch})^2 + (\text{cross-line dimension of the patch})^2 \frac{1}{2} = ) ______</td>
</tr>
<tr>
<td>Fold:</td>
<td>in-line fold = ( R_{LI} / (2 \times S_{LI}) ) = ______</td>
</tr>
<tr>
<td></td>
<td>cross-line fold = ( \frac{1}{2} \times N_{RL} ) = ______</td>
</tr>
<tr>
<td></td>
<td>total fold = ______</td>
</tr>
<tr>
<td>Migration Apron:</td>
<td>radius of Fresnel Zone = ( \frac{1}{2} \times V_{max} \times (\text{target two-way time} + f_{dom})^{1/2} )</td>
</tr>
<tr>
<td></td>
<td>diffraction energy = ( 0.58 \times \text{target depth} )</td>
</tr>
<tr>
<td></td>
<td>Migration apron = target depth \times \tan \text{(dip)} =</td>
</tr>
<tr>
<td></td>
<td>in-line fold taper = ( [(\text{in-line fold} / 2) - 0.5] \times S_{LI} = )</td>
</tr>
<tr>
<td></td>
<td>cross-line fold taper = ( [(\text{cross-line fold} / 2) - 0.5] \times R_{LI} = (F_{T} + F_{Z}) &lt; \text{total migration apron} &lt; (F_{T} + M_{A}) )</td>
</tr>
<tr>
<td></td>
<td>( T_{MA} = )</td>
</tr>
</tbody>
</table>

(Cordsen et al., 2000)
1. Migration aperture (apron) is affected by:

1. **Fresnel zone:**
   - defined as the portion of a reflector from which reflected energy can reach a detector within half a wavelength from the first reflected energy.
   - Radius of first Fresnel zone:

   \[ R_F \approx \left( \frac{1}{2} \right) V_{RMS} \sqrt{\frac{T_0}{f_d}} \]

   - \( V_{RMS} \): RMS velocity to reflector
   - \( T_0 \): zero-offset TWTT to reflector
   - \( f_d \): dominant frequency at reflector
Survey Parameters (cont.)

1. Migration aperture (cont.):
   1. Fresnel zone (cont.):
1. Migration aperture (cont.):
   2. Diffracted energy:
      - Scattering angles of 30° contain 95% of the diffracted energy. Therefore, migration aperture should be $\geq X_{DE}$:

      \[
      X_{DE} = Z \tan 30^\circ = 0.58Z
      \]

      Z: target depth
Survey Parameters (cont.)

1. Migration aperture (cont.):
   2. Diffracted energy (cont.):

(modified after Cordsen et al., 2000)
Survey Parameters (cont.)

1. Migration aperture (cont.):

3. Migration lateral displacement:
   - Migrating a point on a dipping reflector moves the point in the updip direction a lateral distance $D_x$:

   $$D_x = Z \tan \theta$$

   $Z$: target depth
   $\theta$: maximum expected dip

**Rule:** choose the migration aperture as the largest of $R_F$, $X_{DE}$, and $D_x$. 
Survey Parameters (cont.)

1. Migration aperture (cont.):
   - Example:

   \[ R_F \approx \left(\frac{1}{2}\right)(2700)\sqrt{\frac{1.5}{50}} = 234m \]

   \[ X_{DE} = (0.58)(2000) = 1160m \]

   \[ D_X = (2000)\tan 20^\circ = 728m \]

   \[ \text{Selected Migration Apron} = \text{Max}(R_F, X_{DE}, D_X) = 1160m \]

   - This means that we have to extend the survey area by 1160 m in the updip direction.
Survey Parameters (cont.)

2. Record length ($T_R$): It must satisfy the following:

1. It has to include the deepest event of interest ($T_d$) and allow for its:
   - NMO correction (+ 0.3 s)
   - DMO correction (+ 0.4 s)
   - Migration (+ 0.5 s)

2. It has to allow for maximum static shifts (+ 0.1 s).

3. It has to allow for equipment delays (+ 0.2 s)

Rule: choose $T_R \geq T_d + 1.5$ s.
Survey Parameters (cont.)

5. Record length (cont.):

- **Example:**

\[ T_R \geq 2.5 + 1.5 \geq 4.0 \text{ s} \]

*Choose* \( T_R = 6.0 \text{ s} \).
3. Bin size ($B$):

- Its dimensions are: $SI/2 \times RI/2$.
- The most preferable bin shape is square.
- The S/N ratio is proportional to bin size.
3. Bin size (cont.): It is affected by:

1. **Target size:**
   - Normally, a minimum of three adjacent traces are needed across a target in order to define it confidently on the seismic section.
   - Choose: $B_t \leq \text{target size} / 3$. 
Survey Parameters (cont.)

3. Bin size (cont.):

2. Maximum unaliased frequency:

- For a dipping target, the optimum bin size is given by:

\[ B_f = \frac{V_i}{4 f_{\text{max}} \sin \theta} \]

- \( V_i \): interval velocity immediately above target horizon
- \( f_{\text{max}} \): maximum frequency at target depth
- \( \theta \): maximum expected dip angle

- Choose: \( B \leq B_f \) to avoid spatial aliasing.
- Spatial aliasing limits the usability of highly dipping events.
Survey Parameters (cont.)

3. Bin size (cont.):

3. Lateral resolution:

- Choose: $\frac{\lambda_d}{4} \leq B_r \leq \frac{\lambda_d}{2}$
  - $\lambda_d$: dominant wavelength at target depth
  - $\lambda_d = \frac{V_t}{f_d}$

**Rule:** choose the bin size as the smallest of $B_v$, $B_f$, and $B_r$. 
3. Bin size (cont.):

- Example:

\[
B_t = \frac{300}{3} = 100m
\]

\[
B_f = \frac{4200}{4(70)\sin 20^\circ} = 44m
\]

\[
\frac{4200}{4(50)} < B_r < \frac{4200}{2(50)} = 21m < B_r < 42m
\]

\[
B = \text{Min}(B_t, B_f, B_r) = 30m \times 30m
\]

\[
RI = SI = 2 \times B = 60m
\]
Survey Parameters (cont.)

4. $X_{\min}$:

- The largest minimum offset in a survey.
- It is the minimum offset that belongs to the CMP bin at the exact center of a box.
- In an orthogonal survey, it is the box diagonal:

$$X_{\min} = \sqrt{RLI^2 + SLI^2}$$

**Rule:** choose $X_{\min}$ to be less than 1 - 1.2 of the shallowest depth of interest.
Survey Parameters (cont.)

4. $X_{min}$ (cont.):
Survey Parameters (cont.)

4. $X_{\text{min}}$ (cont.):

- **Example:**

\[
1.0 \times 500 < X_{\text{min}} < 1.2 \times 500 = 500m < X_{\text{min}} < 600m
\]

Choosing $\text{RLI} = \text{SLI} = 360$ m:

\[
X_{\text{min}} = \sqrt{2}(360) = 509m
\]
5. $X_{\text{max}}$:
- The maximum recorded offset in a survey.
- It is half the length of the diagonal of the patch in an orthogonal survey:

$$X_{\text{max}} = \frac{1}{2} \sqrt{[\text{Inline \_ Patch \_ Dimension}]^2 + [\text{Crossline \_ Patch \_ Dimension}]^2}$$
Survey Parameters (cont.)

5. $X_{\text{max}}$ (cont.):

- NRL = 9
- NSL = 9
5. $X_{\text{max}}$ (cont.): It is affected by:

1. **Target depth:**
   - Maximum offset should be greater than or equal to the target depth for several processes to work (e.g., velocity analysis).

Choose $X_{\text{max}} \geq Z$.

- **Example:**

  $X_{\text{max}} \geq 2000 \text{ m}$.
5. $X_{\text{max}}$ (cont.):

2. **Maximum allowable NMO stretch:**

- The stretch introduced by the NMO correction is given by:

$$S_{NMO}(X) \approx \frac{X^2}{2T_0^2V_{RMS}^2}$$

$$\Rightarrow X_{\text{mute}} \approx T_0V_{RMS}\sqrt{2S_{NMO}}$$

- Traces with offsets $> X_{\text{mute}}$ at the target horizon will be muted.

- *(Note: See aspect ratio in a later section for more details.)*

Choose $X_{\text{max}} < X_{\text{mute}}$. 
5. $X_{max}$ (cont.):

2. **Maximum allowable NMO stretch:**
   - **Example:**

   For a typical $S_{NMO} = 0.5$,
   
   $$X_{mute} \approx (1.5)(2700)\sqrt{2(0.5)} = 4050 \text{ m.}$$
   
   Therefore, $X_{max} < 4050 \text{ m.}$
Survey Parameters (cont.)

5. $X_{\text{max}}$ (cont.):

3. **NMO discrimination:**

   - To discriminate NMO effects, we need an offset $X_{NMO}$:
     \[ X_{NMO} = V_{RMS} \sqrt{T_{dom}^2 + 2T_{dom}T_0} \]

   - $T_{dom}$: dominant period at target reflector

   - **Example:**
     \[ X_{NMO} = (2700) \sqrt{(0.02)^2 + 2(0.02)(1.5)} = 664 \text{ m.} \]

   Therefore, $X_{\text{max}} > 664 \text{ m.}$
5. \(X_{\text{max}}\) (cont.):

4. **Multiple cancellation:**
   - In order to cancel prominent multiples, we need an offset \(X_{\text{multi}}\):
     \[
     X_{\text{multi}} = V_{\text{multi}} \sqrt{T_{\text{dom}}^2 + 4T_{\text{dom}}T_{\text{mult}}} 
     \]
   - \(V_{\text{multi}}\): RMS velocity of multiple, \(T_{\text{multi}}\): zero-offset TWTT of multiple

Choose \(X_{\text{max}} > X_{\text{multi}}\).

- **Example:**
  \[
  X_{\text{multi}} = (1000)\sqrt{(0.02)^2 + 4(0.02)(1.0)} = 283 \text{ m.}
  \]
  Therefore, \(X_{\text{max}} > 283 \text{ m.}\)
5. \( X_{max} \) (cont.):

5. **AVO effects:**
   - If AVO (amplitude variation with offset) analysis is expected, larger offsets should be used.
   - For a maximum incidence angle of 30°, the offset required for AVO analysis \( X_{AVO} \) is given by:
     \[
     X_{AVO} = \frac{V_{RMS}T_0}{\sqrt{3}}
     \]
     Choose \( X_{max} > X_{AVO} \).
   - **Example:**
     
     \[
     X_{AVO} = \frac{(2700)(1.5)}{\sqrt{3}} = 2,338 \text{ m}, \text{ therefore, } X_{max} > 2,338 \text{ m.}
     \]
Survey Parameters (cont.)

5. $X_{max}$ (cont.):

**Rule:** choose $X_{max}$ to satisfy all these criteria.

- **Example:**

\[ 2,338 \text{ m} < X_{max} < 4,050 \text{ m} \]
5. $X_{max}$ (cont.):

- **Example:**

  - When choosing the number of receiver lines and number of receivers per line, we have to choose them such that the resulting inline and crossline patch dimensions are divisible by RLI and SLI.
  - Choose a patch consisting of 11 receiver lines each with 61 active receivers.
  - Inline patch dimension = $60(60) = 3600$ m
  - Crossline patch dimension = $10(360) = 3600$ m
  - Number of channels = $11(61) = 671$

$$X_{max} = \left(\frac{1}{2}\right)\sqrt{3600^2 + 3600^2} = \frac{3600}{\sqrt{2}} = 2546\text{m}$$
5. $X_{\text{max}}$ (Example – cont.):

- **RLI** = 360 m
- **SLI** = 360 m
- **NRL** = 11
- **NR** = 61
6. Fold:
   - It is the number of traces in a CMP bin.
   - Stacking $M$ traces enhances the S/N by $\sqrt{M}$.

**Inline Fold** = $F_I = (\frac{1}{2}) (\frac{\text{inline patch dimension}}{SLI})$

**Crossline Fold** = $F_X = (\frac{1}{2}) (\frac{\text{crossline patch dimension}}{RLI})$

**Total Fold** = $F = F_I \times F_X$

**Rule:** choose the 3-D total fold to be 0.5-1 of the fold of good 2-D data.
6. Fold (cont.):
   - **Example:**

\[
\left(\frac{1}{2}\right)(30) < F < (1)(30) = 15 < F < 30
\]

**Inline Fold** = \( F_I = \left(\frac{1}{2}\right)\left(\frac{3600}{360}\right) = 5 \)

**Crossline Fold** = \( F_X = \left(\frac{1}{2}\right)\left(\frac{3600}{360}\right) = 5 \)

**Total Fold** = \( F = 5 \times 5 = 25 \)
7. Fold taper:
   - It is the area around the edges of the full-fold area where the fold builds-up from minimum to full-fold.

\[
\text{Inline Fold Taper} = FT_I = \frac{\text{inline patch dimension}}{4}
\]

\[
\text{Crossline Fold Taper} = FT_X = \frac{\text{crossline patch dimension}}{4}
\]

**Rule:** choose the fold taper to be \(\frac{1}{4}\) of patch dimension.
7. Fold taper (cont.):

- Relation between migration aperture and fold taper

(Cordsen et al., 2000)
7. **Fold taper (cont.):**

- Relation among areas covered by acquisition, processing, and interpretation
Survey Parameters (cont.)

7. Fold taper (cont.):
   • **Example:**

   \[
   \text{Inline Fold Taper} = FT_I = \frac{3600}{4} = 900m
   \]

   \[
   \text{Crossline Fold Taper} = FT_X = \frac{3600}{4} = 900m
   \]
Aspect Ratio

- It is defined as:

\[ R = \frac{\text{Crossline patch dimension}}{\text{Inline patch dimension}} \]

- Narrow-azimuth patches have \( R < 0.5 \), while wide-azimuth patches have \( R > 0.5 \).

- Narrow-azimuth patches are good for analyzing DMO, AVO, and lateral heterogeneities.

- Wide-azimuth patches are good for velocity analysis, static correction, and multiple attenuation.

*Example*: \( R = \frac{3600}{3600} = 1.00 \).
Aspect Ratio (cont.)

Wide-azimuth survey  Narrow-azimuth survey

Modified after (Cordsen et al., 2000)
Aspect Ratio (cont.)

• The 85% rule:
  - $X_{mute}$ defines a circle, while $X_{max}$ defines a rectangle.
  - If we inscribe the $X_{mute}$ circle inside an $X_{max}$ rectangle, we record 27% more traces than we need (i.e., area between $X_{mute}$ circle and $X_{max}$ rectangle will be muted).
  - If we inscribe the $X_{max}$ rectangle inside the $X_{mute}$ circle, we miss recording 36% of our data (i.e., area between $X_{max}$ rectangle and $X_{mute}$ circle will not be muted but not recorded because it’s outside our patch).
  - An optimum compromise is the 85% rule defined as:
    - Choose inline patch dimension = 0.85 * $X_{mute}$.
    - Choose crossline patch dimension = 0.85 * inline patch dimension.
    - Therefore; $R = 0.85$. 

Aspect Ratio (cont.)

Area recorded but muted
(27% of patch area)

Area not recorded but was not to be muted
(36% of mute area)

Area recorded but muted
(27% of patch area)
Aspect Ratio (cont.)

- The 85% rule (cont.):

(Cordsen et al., 2000)
Field Layouts
Displays

- $X_{min}$ distribution within a box
Field Layouts
Displays (cont.)

- Offset distribution within bins
Field Layouts
Displays (cont.)

- Offset distribution in a row of bins

Modified after (Cordsen et al., 2000)
Field Layouts
Displays (cont.)

- Azimuth distribution within bins
Field Layouts

- Full fold
- Orthogonal
- Non-orthogonal
- Brick
- Zigzag
- Star
- Random
1. Receiver lines are laid parallel.
2. Source lines are laid parallel in a direction orthogonal to receiver lines.
3. An area of receivers (patch) is selected (e.g., 4 receiver lines with 480 receivers each).
4. Source at patch edge is shot and recorded.
5. Next source on the same source line (going inside the patch) is shot and recorded by the same current patch.
6. Keep shooting until all sources within the current patch lying on the same source line are finished. This is one salvo.
7. Roll over one source-line interval and begin recording the next salvo.
8. Keep doing this until the end of the current receiver lines. This is one swath.
9. Roll over in the crossline direction half the patch size and begin recording the next swath.
10. Keep doing this until the whole survey is finished.
Swath Shooting Method

(Continued)