Chapter 4

3-D Theory

In marine environments, three-dimensional reflection seismic data is normally acquired in a so-called "wide tow" streamer configuration, illustrated in Figure 4.1. Ironically, the crossline offset range of this data is less than with most land acquisition geometries, so geophysicists often call towed streamer data "narrow azimuth" data. Note that the crossline shot interval, Δs_y, is chosen such that the outermost receiver line on one swath overlaps the innermost receiver line on the previous swath. Figure 4.2 illustrates that such an acquisition geometry produces a regularly sampled crossline CMP axis, if cable feathering is absent. In one sense, this geometry boasts some degree of optimality, as it produces a well-sampled 3-D image at a minimum cost.

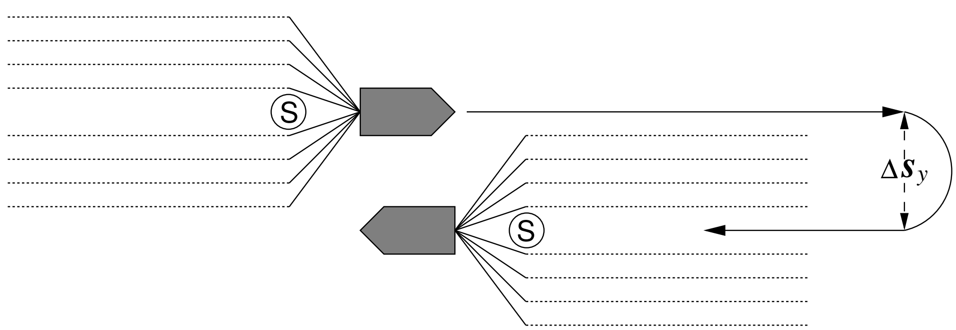

Figure 4.1: Wide tow marine geometry. The acquisition boat tows many (usually 4-12) receiver lines and steams in parallel sail lines. theory3d-narrow-az [NR]

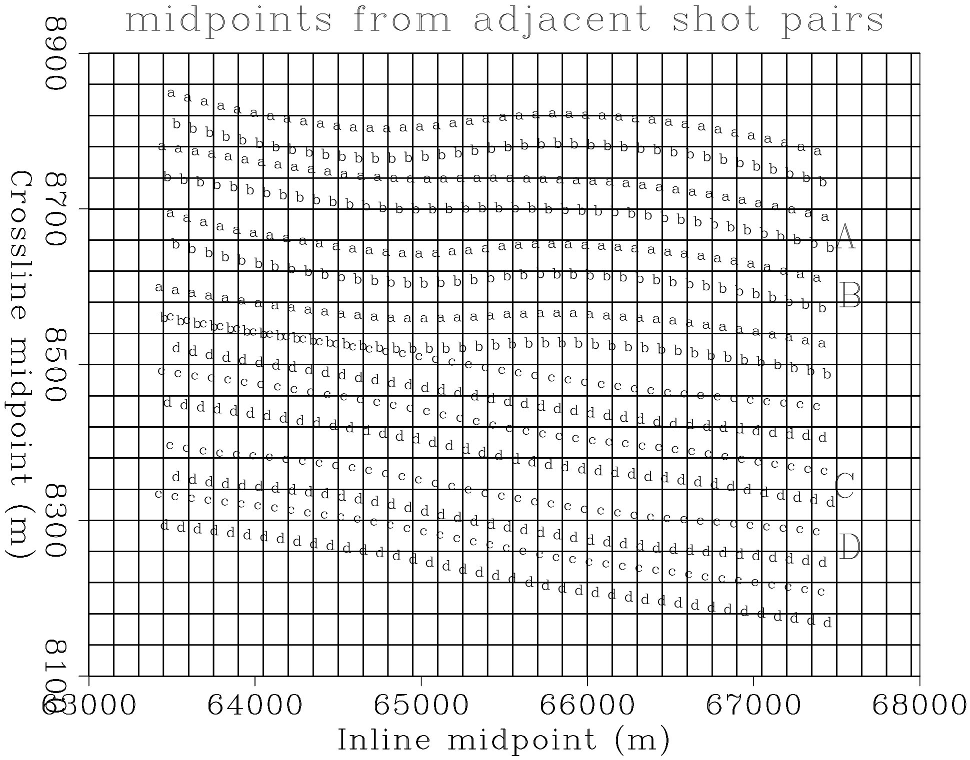

Figure 4.2: Midpoint locations from two adjacent sail lines of the CGG Green Canyon 3-D dataset. The boat tows four streamers and fires two sources alternatively in a "flip-flop" configuration. Midpoints from shot "A" are labeled "a", and so on. Two shot pairs from each sail line are shown. For a fixed ship speed, this geometry doubles crossline midpoint density, at the cost of reduced inline resolution, compared to a single-source configuration. Flip-flop shooting allows one airgun to be recharged while the other shoots, thereby allowing the ship to sail faster than would be possible with one gun. Cable feathering is evident, though not severe. theory3d-cgg-midpoints [ER]

Unfortunately, geometry shown in Figure 4.2 causes the 3-D extension of the SRME method of multiple prediction to fail spectacularly. SRME requires Δs_y to be relatively small– in practice, roughly the same as commonly chosen crossline receiver line spacing parameters (van Borstelen, 2003). 3-D field datasets commonly have a crossline shot interval of up to ten times the crossline receiver line spacing. Workarounds for the 3-D sampling problem include: ignoring crossline structure and using a 2-D prediction, massive (270,000 CPU hours) shot interpolation (Kleemeyer et al., 2003), sparse inversion of the crossline multiple contribution gathers (van Dedem and Verschuur, 2002; Hokstad and Sollie, 2003), and novel acquisition geometries (Paffenholz, 2003). Currently, none of these methods combines proven accuracy with computational/cost efficiency.

The LSJIMP method has good potential to separate 3-D peglegs from wide tow marine data. In Section 3.1, I demonstrated how, in a fairly complex 2-D setting, the HEMNO equation can model some complex multiples as accurately as SRME. In this chapter, I outline a practical extension of my implementation of LSJIMP to work on 3-D wide tow marine data.

4.1 LSJIMP and wide tow marine data

For the particular geometry shown in Figures 4.1 and 4.2, notice that each crossline midpoint gather is occupied by one, and only one receiver line. Therefore, we can conceptualize a 3-D CMP gather as a 2-D CMP gather with nonzero crossline offset, and thus remove the crossline offset axis from five-dimensional CMP-sorted data, saving considerable memory and computational waste. This approach is similar to Biondi's (1997) combination of azimuth moveout (AMO) (Biondi et al., 1998) and common-azimuth wave equation depth migration (Biondi and Palacharla, 1996) for the prestack imaging of primaries in data with narrow-azimuth geometries. Unfortunately, the AMO transformation is not generally valid for multiples.

HEMNO is well-suited to image multiples with the data geometry described above, primarily because HEMNO images pegleg multiples with a vertical time shift. Rather than correlating wavefields across possibly-undersampled axes like migration, HEMNO uses a measurement of the data's zero-offset time dip to account for structure-induced moveout variations. Because the crossline offset axis is removed, the computational cost increase of applying

HEMNO to 3-D data versus 2-D data is only proportional to the number of crossline midpoints.

My particular LSJIMP implementation, presented in Section 2.2.9, uses HEMNO, in conjunction with three amplitude normalization operators to produce a “true amplitude” image of pegleg multiples. From Figure 2.5, recall that Snell Resampling moves multiple energy across offset to make the multiple’s AVO response comparible with its primary. For this reason, the use of Snell Resampling in the crossline direction runs contrary to the stated assumption that we store only one crossline offset bin per 3-D CMP gather. Therefore, in this thesis, I do not apply crossline Snell Resampling for narrow-azimuth data. In practice, little useful angular information is anyway obtained in the crossline direction, since in most cases the data will have a maximum crossline offset of merely a few hundred meters.

4.2 Modifications to the 2-D Theory

In this section I enumerate the necessary modifications to my particular LSJIMP implementation, presented earlier in section 2.2, to move from 2-D data to 3-D data. The narrow azimuth geometry illustrated in this chapter considerably simplifies this move, but for completeness, I nontheless discuss both the narrow azimuth and general 3-D implementations.

- **Regularization operators:** In section 2.1.3 I introduced the three LSJIMP regularization operators. The first (differencing between images, section 2.1.4) and third (crosstalk penalty weights, section 2.1.6) extend to 3-D with no modification. However, in the full 3-D case, the second operator, which differences across offset (section 2.1.5), must operate along both inline and crossline offset axes. Thus the corresponding model residual [equation (2.8)] becomes a vector quantity, as it is nothing more than a finite difference spatial gradient. As mentioned earlier, in the narrow azimuth case, the crossline offset axis is ignored, in which case the operator is the same as in the 2-D case.
- **1-D Imaging of multiples:** The 1-D imaging operator for multiples, derived in section 2.2.1 changes in 3-D. For the full 3-D case, the NMO equation for both primaries and multiples changes. In equations (2.16) and (2.18), the squared inline offset (x^2) changes

to the sum of the squared inline (x_1^2) and crossline offsets (x_2^2):

$$x^2 \Rightarrow x_1^2 + x_2^2, \tag{4.1}$$

where $x_1^2 + x_2^2$ is the squared norm of the offset vector $[x_1 \; x_2]^T$. Equation (4.1) applies to the full 3-D and narrow azimuth cases alike. The difference is in the implementation: in the full 3-D case, a computer program loops over the x_2 axis, but not in the narrow azimuth case, where the crossline offset at a given CMP location must be pre-defined and passed as an input parameter.

- **Amplitude correction operators:** An important quantity for my implementation of LSJIMP was x_p, the width of the primary leg of a pegleg multiple [equation (2.21)]. Like the offset vector in 3-D, x_p also becomes a vector quantity:

$$x_p \Rightarrow \begin{bmatrix} x_{p,1} \\ x_{p,2} \end{bmatrix} = \begin{bmatrix} \frac{x_1 \tau V_{\text{rms}}^2}{\sqrt{(\tau + j\tau^*)^2 \; V_{\text{eff}}^4 \; + \; (x_1^2 + x_2^2)(V_{\text{eff}}^2 - V_{\text{rms}}^2)}} \\ \frac{x_2 \tau V_{\text{rms}}^2}{\sqrt{(\tau + j\tau^*)^2 \; V_{\text{eff}}^4 \; + \; (x_1^2 + x_2^2)(V_{\text{eff}}^2 - V_{\text{rms}}^2)}} \end{bmatrix}. \tag{4.2}$$

  As noted earlier in this chapter, with narrow azimuth data it makes the most sense not to do Snell Resampling in the crossline direction. Still, the crossline offset of the "reduced" CMP gather may still be nonzero, and will affect the value of $x_{p,1}$.

  The differential geometric spreading correction derived in section 2.2.4 remains unchanged, with the exception of substituting equation (4.1) for squared offset in equations (2.23) and (2.24).

  The estimation of a multiple generator's reflection coefficient in 3-D remains similar to the 2-D case, although the model is a function of two varibles, CMPx and CMPy, and the data may (full 3-D) or may not (narrow azimuth) be a function of crossline offset.

- **HEMNO:** HEMNO is strongly dependent on the quantity x_p derived in section 2.2.3 [equation (2.21)]. The zero-offset traveltimes to multiple generator and reflector and the effective velocity are measured at midpoints y_m and y_p, defined specifically for the first-order S102G pegleg in equation (2.26), can be rewritten:

$$y_m \Rightarrow \begin{bmatrix} y_0 - x_{p,1}/2 \\ y_0 - x_{p,2}/2 \end{bmatrix} \text{ and } y_p \Rightarrow \begin{bmatrix} y_0 + (x_1 - x_{p,1})/2 \\ y_0 + (x_2 - x_{p,2})/2 \end{bmatrix}. \tag{4.3}$$

An accurate 3-D dip estimate is also required. Event tracking in 3-D is just as straightforward as in 2-D The only other change required to HEMNO is to change squared inline offset in equation (2.27) to the squared norm of the offset vector, equation (4.1).

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