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Suppression of water bottom multiple energy in beam stacked data

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ABSTRACT

Water-bottom related multiple energy can be a significant problem for processing and interpretation of seismic data. The standard method of NMO stacking CMP gathers to eliminate multiples is often inadequate and does not address the problem of preserving interesting features on prestack data such as AVO and non-hyperbolic moveout. In this paper we examine primary and multiple energy in beam stacked data and a method of isolating the primary energy in this space. We decompose the data into the beam stacked space by means of an iterative least squares inversion of the beam stack operator. We then apply a masking function to the beam stacked data. The primary energy is then forward-modeled simply using the beam stacking operator. We apply our method to real data and obtain encouraging results.

INTRODUCTION

Moveout differences between primary and multiple events are often used to discriminate primary and multiple energy in a CMP gather. Examples of methods which rely on moveout differences are NMO stacking and velocity transforms. NMO stacking can reduce multiple energy but is undesirable because the gathers cannot be reconstructed from the stacked traces. Velocity transforms, on the other hand, are invertible. An invertible transform allow gathers to be transformed from prestack space into velocity space and then back to the prestack space. Also, velocity transforms map primary and multiple energy into two distinct regions of model space. This allows the multiple energy to be separated from the primary energy with a simple masking procedure. Beam stack transforms, like the velocity transform, are invertible and map primary and multiple energy from the gather space into two distinct regions of model space(Biondi, 1990). Because of these two properties, the beam stacked space is a good space to identify and remove multiple energy. The beam stacking operator has additional advantages over velocity transforms. Unlike the velocity transform, beam stack transforms do not assume a global shape for events or constant ampli-

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tude across the event. Beam stack transforms simply model the stepout of events while velocity transforms model hyperbolic or near hyperbolic events. Because of this, beam stacking transforms are more appropriate than velocity transforms for the task of modeling data with non-hyperbolic moveout and AVO.

MULTIPLE SEPARATION THEORY

Reflection seismograms gathered over media with weak lateral velocity variations will exhibit primary and multiple events with different hyperbolic moveout characteristics. The stepout of primary events at a given time and offset are distinctive from the stepout of water bottom related multiple events for the same time and offset. This is because primary energy arrives from much deeper than multiple energy, and primary energy generally has traveled through higher velocity media than the multiple events. Both of these factors tend to cause the primary wavefield to arrive at the surface at an angle of incidence that is much closer to vertical than does the coincident multiple energy wavefield. On CMP gathers the angle of incidence of an upcoming wavefield manifests itself in the stepout of the event. We use the stepout of events to distinguish primary energy from multiple energy.

In a space parameterized by (t, h, p), where p is the stepout of an event, the moveout trends of the primaries and multiples are separated into distinctive regions. The primary and first water bottom related multiple events will follow a surface in this space. The following general character of primary and multiple events in (t, h, p) space are true if $dv/dz >= 0$:

- If stepout and time are constant, the offsets of primary events will be greater than the offsets water bottom related multiple events.

- If offset and stepout are constant, the time at which primary events occur is earlier than the time of water bottom related multiple events.

- If time and offset are constant, the stepout of a primary event is less than the stepout of water bottom related multiple events.

With the prediction of the primary trend and first water bottom related multiple trend a mask can be designed to isolate the multiple energy from the primary energy.

Beam stacking operator

The beam stack operator performs the transform of data parameterized by time and offset (t, h) to data parameterized by time, offset and stepout (t, h, p). The generalized beam stack operator samples each (t, h) location in the data and stacks over a localized window of offsets, $(h-l, h+l)$, with a stacking trajectory function designed to evaluate the local dip of the data. In order to evaluate the dip, the trajectory function must have a slope at the point (t, h) in the data equal to p. The stacking operator is represented by:

$$CMP_{stack}(\bar{t}, \bar{h}, p) \;=\; \frac{1}{\sum_{j=-l}^{l} w(j\Delta h)} \sum_{j=-l}^{l} w(j\Delta h) CMP[T_{p_h}(\bar{h} + j\Delta h), \bar{h} + j\Delta h] \quad (1)$$

where $(\bar{t}, \bar{h})$ is the point in the gather being evaluated, Δh is the half offset interval, $T_{p_h}(\bar{h} + j\Delta h)$ is the stacking trajectory function and $w(j\Delta h)$ is a weighting function(Biondi, 1990). The most elementary trajectory function is a slanting line with a dip that corresponds to the stepout being evaluated. This is often referred to as a local slant stack. The trajectory function in this case is simply:

$$T_{p_h}(h, p) \;=\; \bar{t} + p(\bar{h} + j\Delta h) \quad (2)$$

The resolution of the local slant stack is limited by the Fresnel zone of the the linear trajectory across the curved event. We chose to use a parabolic trajectory for the local stack. The parabolic trajectory estimates the local curvature of the event from the offset and stepout being evaluated (Biondi, 1990). This results in a larger Fresnel zone, which translates to better resolution in the model space. A hyperbolic function is also an option as a stacking trajectory but, unlike the parabolic function, the hyperbolic function is time dependent and thus more computationally expensive to use than the parabolic or local slant stack function. The parabolic approximation of the hyperbolic curvature is quite good for local trajectories. The equation for the parabolic trajectory is:

$$T_{p_h}(h, p) \;=\; \bar{t} + p_h(\bar{h} + j\Delta h) + \frac{\rho}{2}(\bar{h} + j\Delta h)^2 \quad (3)$$

where $\rho = \frac{p_h}{\bar{h}}$ is the curvature term(Biondi, 1990). The curvature term is derived from the Dix equation and thus is based on the curvature of hyperbolic events with the stepout p and offset h. The stepout in equation (4) fills the role of the velocity parameter in the Dix equation. For non-hyperbolic events the curvature may be a misfit to the true event curvature, but for local trajectories this misfit will be minimal. With the Dix assumption the curvature is simply the second derivative of the Dix equation. The Dix equation is:

$$t^2 \;=\; t_0^2 + \frac{h^2}{V(t_0)^2} \quad (4)$$

The curvature is as follows:

$$\rho \;=\; \frac{d^2 t}{d^2 h} = \frac{4}{V^2 t} = \frac{p_h}{\bar{h}} \quad (5)$$

A second variation on the beam stack operator we incorporated is to allow for the length of the stacking trajectories L to vary linearly with zero offset travel time. This increases resolution because the Fresnel zone increases with depth as the curvature of events becomes less. In Figure 1 the results of the adjoint of the beam stacking

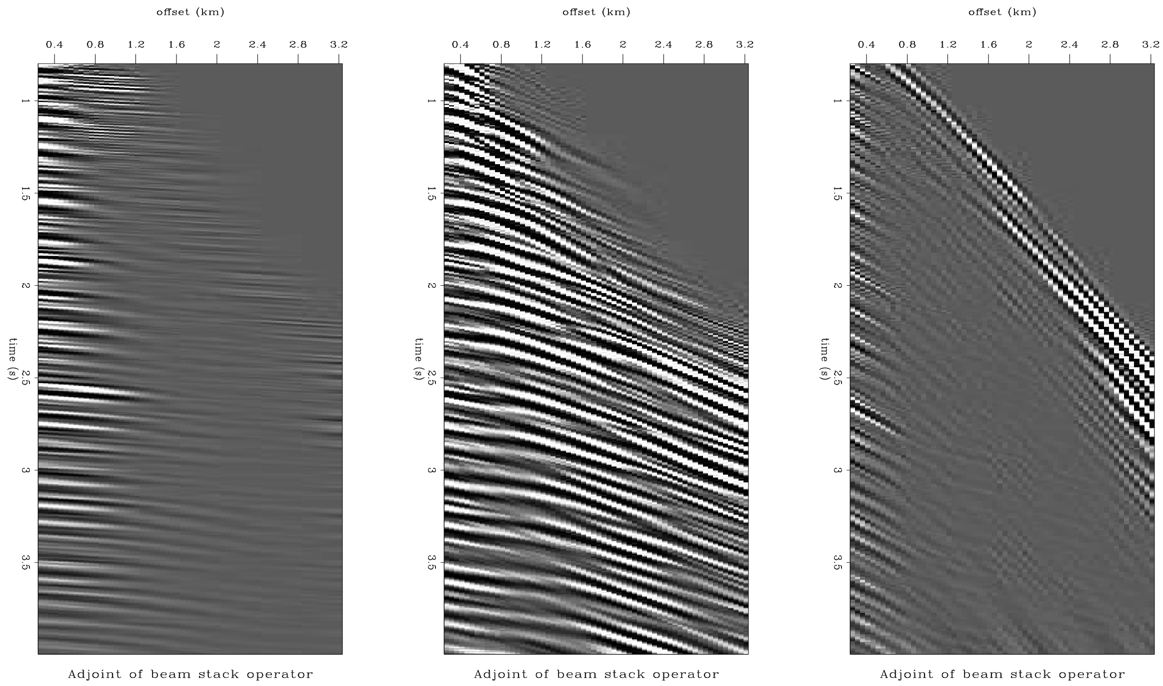

Figure 1: Three slowness slices of the adjoint transform of the beam stacking operator applied to the Mobil AVO gather 807; left $p = 0.03(s/km)$, middle $p = 0.21(s/km)$,right $p = 0.69(s/km)$ curt-cmp807adj [CR]

operator applied to gather 807 of the Mobil AVO data set are shown, while in Figure 2 the results of the least squares inversion of the beam stacking operator applied to the same Mobil gather are shown. We will talk about the inversion in the next section.

Inversion

We chose the forward operation to be the transformation from the beam stacked space to the gather space, thus allowing for an iterative inversion scheme to be applied to the conjugate transform of:

$$\mathbf{Hm(t,h,p)} \approx \mathbf{d(t,h)} \tag{6}$$

where $\mathbf{H}$ is the beam stack operator, $\mathbf{d}$ is the prestack gather and $\mathbf{m}$ is the beam stacked space. We use a least squares estimate of $\mathbf{m}$ that is achieved by minimizing the objective function with respect to the model $\mathbf{m}$.

$$\mathbf{r} \;\; = \;\; ||(\mathbf{d - Hm})||^{\mathbf{2}} \tag{7}$$

where $\mathbf{r}$ is the residual. A step we took to improve resolution was to reduce the effects of the near offset data boundary. Events at data boundaries that are not tangent to the trajectory of the beam have the undesirable problem of not canceling out as they should, often resulting in spurious non-physical events. This problem is especially severe at the near offsets where large amplitude events exist. Truncation effects are

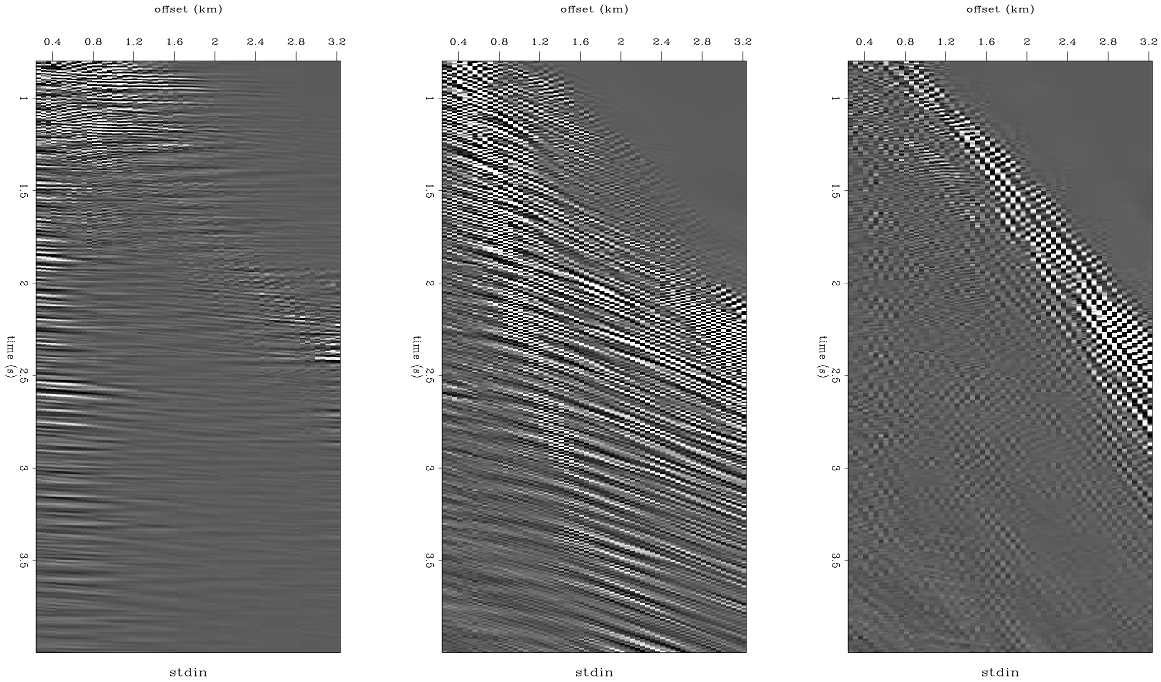

Figure 2: Three slowness slices of the inverse transform of the beam stacking operator applied to the Mobil AVO gather 807; left $p = 0.03(s/km)$, middle $p = 0.21(s/km)$,right $p = 0.69(s/km)$ curt-cmp807bs [CR]

shown at the near offset of the right panel of Figure 1, notice the corresponding image of the inverted beam stacks do not have these artifacts. We reduced the effects of data boundary truncation at the near offset by estimating the data to zero offset. We did this using a near offset interpolation scheme developed by Jun Ji(Ji, 1994).

Masking function

Transformation of CMP data to a space parameterized by (t, h, p) allows the predicted primary and first water bottom related multiple events to be represented by a simple smooth surface. This simple representation of the primary and multiple trends allows for a distinct separation of primary and multiple energy.

The mask we used to separate the multiple energy from the primary energy is a volume in the model space defined by two surfaces; one surface follows the trend of the predicted primary events and the other follows the trend of the predicted first water bottom related multiple events. The predicted trends are determined for offset and time values corresponding to each of the values of stepout evaluated by the beam stack inversion. In order to preserve the multiple energy alone, we retain the energy that resides at near offsets and later times relative to the multiple trend surface, and mute out the energy that resides at far offsets and earlier times relative to the primary trend surface. In the region between these two surfaces we use a linear weighting function. This weighting function is zero at the primary surface and unity at the multiple surface. Building a linear weighting between the predicted primary and multiple trend eliminates many of the effects due to truncation artifacts that would appear if a simple step function were used to separate the energy. Truncation artifacts are a significant problem associated with forward modeling of beam stacked data because events in beam stacked space have significant extent in the offset and stepout dimensions.

We obtained the primary velocity trend by manually picking a velocity scan of a gather 807 of the Mobil AVO dataset Figure 3. With the velocity trend $V(t_0)$ we

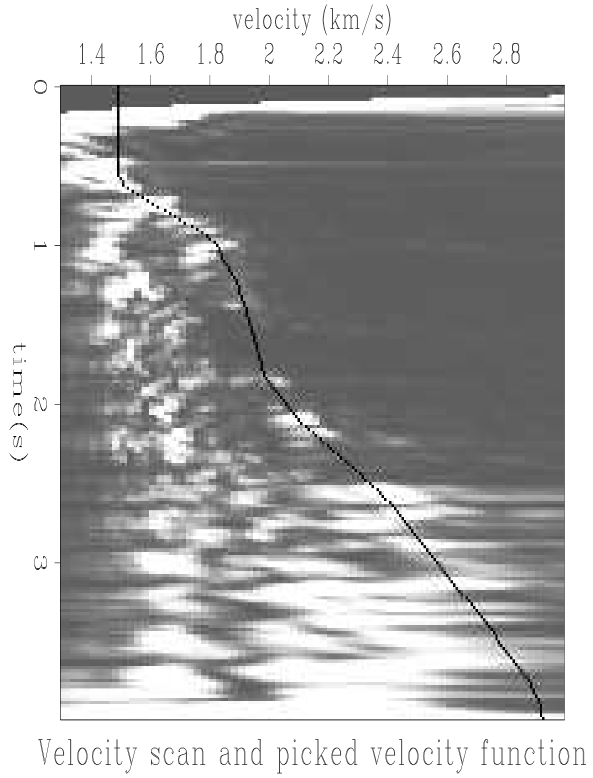

Figure 3: Velocity scan of the Mobil AVO data. The picked velocity function used in this paper is superimposed onto the scan. curt-velplot [CR]

predict for each stepout p:

- The expected offset of the primary trend $h_p(t_0, p)$ for each value of t_0.

- The two way travel time $t_p(t_0, h_p)$ of the primary trend corresponding to the offset $h_p(t_0, p)$.

An analyitic relation between the offset of the primary trend as a function of t_0 is often not possible, because $V_p(t)$ is usually obtained from a velocity scan. In order to construct the primary surface in the (t, h, p) space, we use the relations given below for the offset and two-way travel time of an event, and linear interpolate between the calculated points.

$$h_p(t_0,p) = \frac{pt_0V_p(t_0)^2}{\sqrt{1-(pV_p(t_0))^2}} \tag{8}$$

$$t_p(t_0,h_p) = \sqrt{t_0^2 + \frac{h_p^2}{4V_p(t_0)^2}} \tag{9}$$

The second equation is simply the Dix equation for a hyperbolic event with velocity $V_p(t_0)$, offset h_p and the zero offset travel time t_0. The first equation is derived from Dix equation, but with the time t_p being replaced by the following equation also derived from the Dix equation:

$$t\frac{dt}{dh} = \frac{h}{4V_p(t_0)^2} \tag{10}$$

$$t_p(h_p,p) = \frac{h}{4pV_p(t_0)^2} \tag{11}$$

This is the two way travel time to an event parameterized by velocity $V(t_0)$, at the stepout p and offset h of that event. When this is substituted into the Dix equation the resulting equation for offset is given by equation (1). The above relations are strictly derived from the Dix equation and thus represent the offsets and travel times of the hyperbolic events with zero offset travel time t_0 and stepout p.

We estimate the velocity trend of the multiple energy from the RMS equation. In the following equation the primary velocity trend is $V_p(t_0)$, the zero offset travel time to the water bottom is t_w, the travel time for each interval is Δ_i and v_w is the velocity of the water layer. (Lumley et al., 1994).

$$V_m(t_0+t_w) = \frac{\sum v_i\Delta_i + t_wv_w^2}{t_0+t_w} \tag{12}$$

A Taylor series expansion of the above equation about t_w to the second order gives:

$$V_m(t_0+t_w) = \frac{\sum v_i\Delta_i + t_wv_w^2}{t}\left(1-\frac{t_w}{t_0}+\frac{t_w^2}{t_0^2}\right) \tag{13}$$

$$V_m(t_0+t_w) = \left(V_p^2+\frac{t_w}{t}v_w^2\right)\left(1-\frac{t_w}{t_0}+\frac{t_w^2}{t_0^2}\right) \tag{14}$$

Thus the expressions for the multiple trend are:

$$h_m(t_0,p) = \frac{pt_0V_m(t_0)^2}{\sqrt{1-(pV_m(t_0))^2}} \tag{15}$$

$$t_m(t_0, h_m) = \sqrt{t_0^2 + \frac{h_p^2}{4V_m(t_0)^2}} \quad (16)$$

In beam stacked space the masking volume appears in each stepout panel as an area. The estimate of the multiple energy in beam stacked space is shown in Figure 4. The same three slowness slices of beam stacked space are shown in Figure 2 with out the muting applied. These figures illustrate the form of the muting function for three

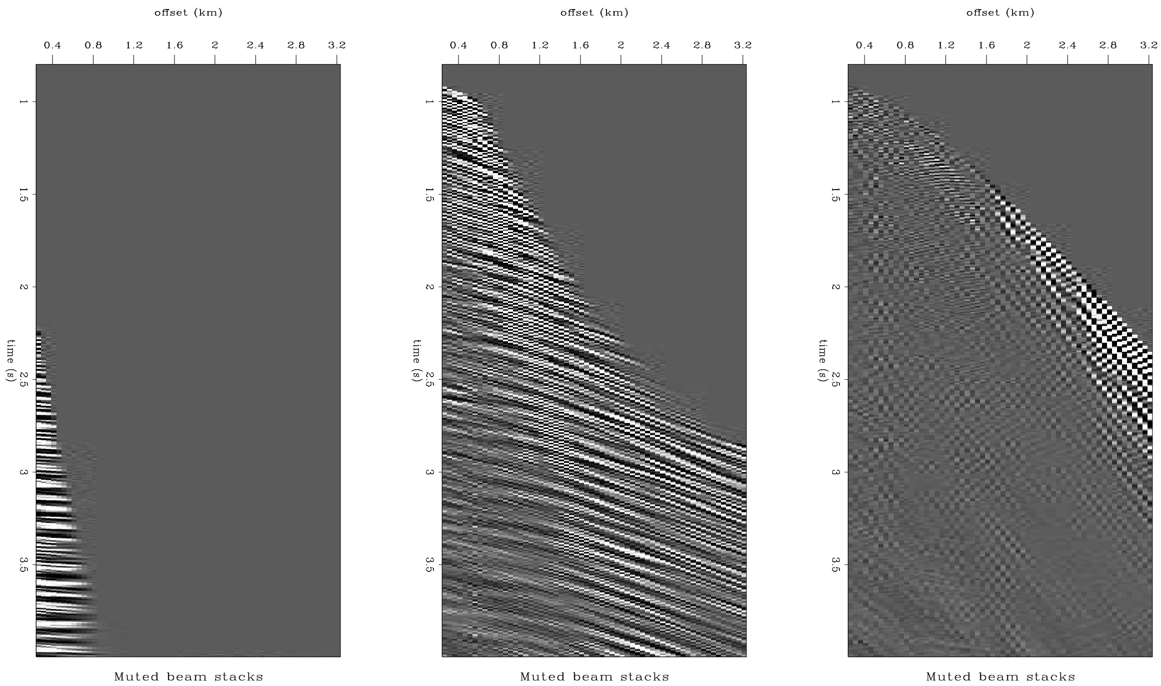

Figure 4: Windowed multiples in beam stacked space; left $p = 0.03(s/km)$, middle $p = 0.21(s/km)$,right $p = 0.69(s/km)$ curt-cmp807m [CR]

stepout slices of the (t, h, p) transformed cube. The energy at later times and near offsets relative to the muting function is preserved because this is exclusively multiple energy while the energy at earlier times and far offsets relative to the muting function have been zeroed because this is the region that exclusively contains primaries. The region between the primary surface and multiple surface is a region of overlap of the multiple and primary energy. An ideal transform to (t, h, p) space would put no energy in this region, but the events in beam stack space have significant extent in the offset direction. Using the linear weighting function gives the appropriate weight to the overlap energy in this region.

The left panel in Figure 4 corresponds to the first stepout value inverted for, $0.03(s/km)$. The separation between primary and multiple energy in this panel is hard to discern because the moveouts of both primary and multiple events are nearly the same near zero offset. The second panel corresponds to a stepout value of $0.21(s/km)$. In this image the train of multiples appear as a discernible trend which tracks linearly at an angle that lies at a stepout of about $2.67(s/km)$. The primary trend has been muted out. The final image in the trio is the panel that corresponds to a stepout value of $0.69(s/km)$. This is the velocity of the water column. Here it can be seen that only the water bottom energy at far offsets is stacked in while all the other locations in the gather contribute very little, as is expected.

REAL DATA EXAMPLE

The results of the multiple suppression are very good. Figure 5 shows the original gather, the multiple suppressed gather and the estimated multiples. The multiple energy that occluded the primaries at 1.8, 2.1, 2.3 and 2.6 seconds of zero offset travel time are essentially removed. The variation in amplitude of the primaries are apparent, though it is not clear if the variations on the deepest primaries are real or due to an inadequacy of the suppression scheme. Weak primary events appear before 1.5 seconds in the suppressed data which are completely occluded in the original gather.

CONCLUSION

The method we have developed here has proven to be effective at removing multiple energy in the case where a simple 1-D velocity function can be assumed. The fundamental parameterization of the beam stacking operators hold promise of this method being applied to more complex multiple reverberation problems, where moveouts in the data are non-hyperbolic and lateral velocity variations exist. We hope to extend the method to 3-D and take full advantage of the information obtained from multi-streamer acquisition.

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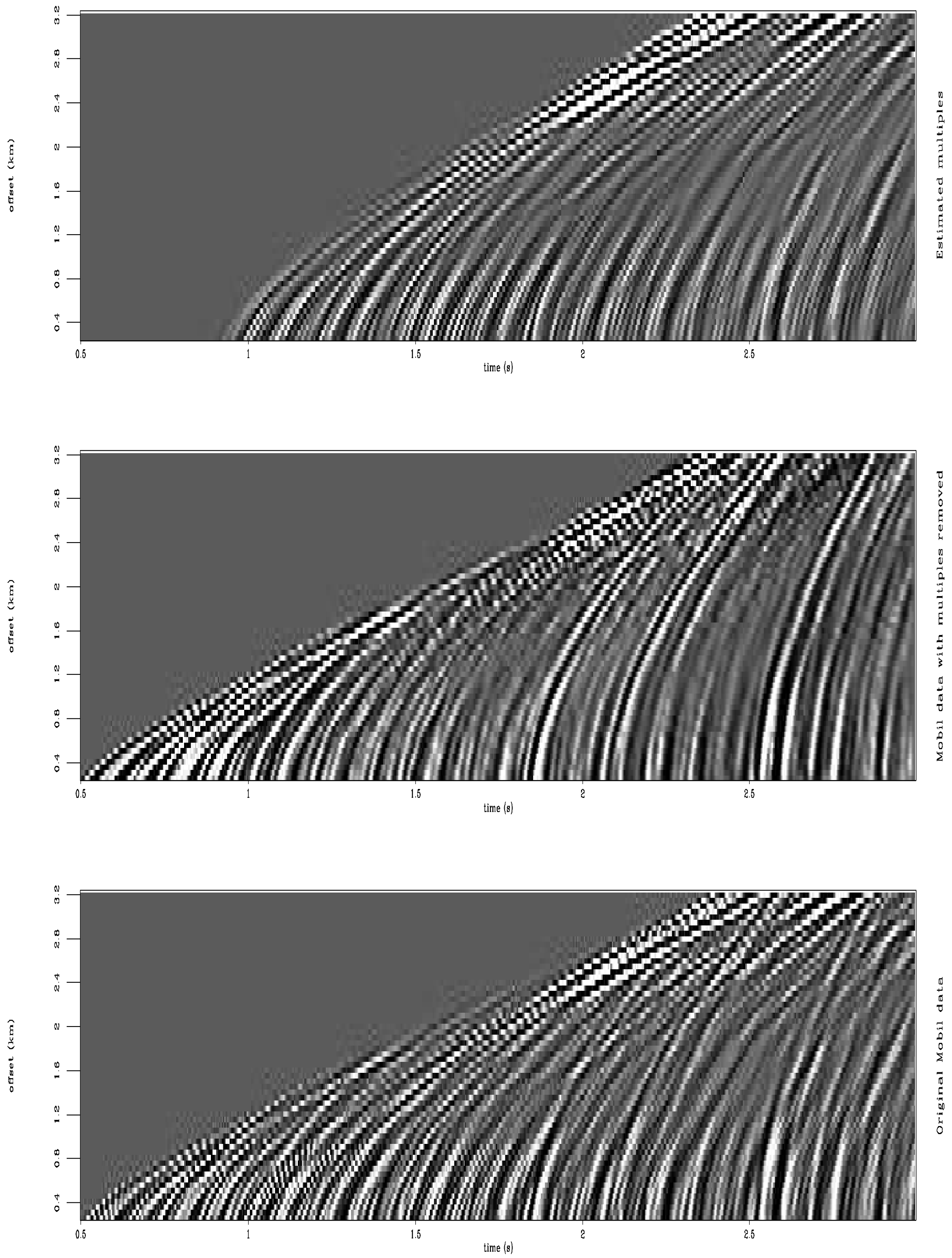

Figure 5: The bottom panel is the original Mobil AVO gather 807. The middle panel is the Mobil gather with the multiples removed. The top panel are the estimated multiples from the Mobil data curt-seq807 [CR]