GEOPHYSICS, VOL. 52, NO. 11 (NOVEMBER 1987); P. 1501–1524, 24 FIGS.

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Experimental investigation of interference from other seismic crews

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ABSTRACT

In a study of the contamination of reflection seismic data by interfering noise from other seismic crews, controlled experiments were performed in the Gulf of Mexico and the North Sea. In each experiment, a survey ship traversed a line several times collecting both data free of and data contaminated by interfering crew noise. In the Gulf of Mexico experiment, the "noise" ship followed a prescribed course about 11 km from the survey ship. In the North Sea experiment, the noise ship was positioned at stationary locations 10 and 40 km broadside to the survey line. Recorded interference noise in both experiments had peak amplitudes well above the 0.5 to 1.5 Pa (5 to 15 μbar) limit beyond which crews typically must agree on time-sharing.

Despite recorded crew noise that was three to eight times higher than levels typically considered acceptable, the conventionally processed common-midpoint stack of the contaminated Gulf of Mexico data shows only slight evidence of the interference noise; in contrast, the North Sea stack is severely contaminated by crew noise as early as 1 s. However, when each unstacked trace is scaled by time-varying weights that vary inversely with the local power in the trace, the crew noise is no longer visible in the contaminated stack of either data set. Trace-weight normalization in this process is designed to ensure that stacked signal amplitudes are generally preserved. A simulated line wherein the actual Gulf of Mexico data are contaminated by crew noise five times stronger than that recorded in the field [yielding effective peak noise values of 7.5 to 20 Pa (75 to 200 μbar)] also shows no evidence of crew noise after inverse-power weighted stacking.

When data processing includes conventional stacking, we recommend that the specified tolerable amount of crew noise be based upon the root-mean-square amplitude of the crew noise *computed over an entire record.* With burst suppression techniques, such as inverse power-weighted stacking, we recommend that the specified level be based upon the duration of the strong-amplitude burst as well. With both criteria, field specifications can be chosen that remain conservative while tolerating considerably more crew-interference noise than in the past. Issues of the influence of crew noise on the analysis of prestack data remain for future study.

INTRODUCTION

Quality control during seismic data acquisition is governed by predefined specifications, or "specs." A spec defines the extent to which a given component of the acquisition system is allowed to be degraded before it must be repaired or acquisition must be delayed. Examples of specs include the number and size of air guns allowed to fail in a source array, the minimum number of vibrators in a Vibroseis crew, the maximum allowable recorded ambient noise level, and the multiplicity of coverage in each cell of a three-dimensional (3-D) survey. All specs should be reconsidered periodically to ensure that they take into account advances in acquisition and processing technology, as well as new demands in interpretation. Specs for the tolerable level of ambient noise in the days of 12-channel or 24-channel acquisition, for example, are not appropriate when we now routinely record with 120-channel and 240-channel streamers and with 96-channel land cables. Like-

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wise, we should be able to tolerate higher ambient noise levels with today's 10^7 Pa-m (100 bar-m) sources than with yesterday's 2×10^6 Pa-m (20 bar-m) sources.

Only through adherence to properly chosen specs can one obtain data that, after processing, will yield results not unacceptably compromised by choices made in acquisition. On the other hand, specs that are inordinately stringent drive up the cost and the time required for a survey. The setting of specs that are neither too severe nor too loose is not straightforward. The task is complicated because the spec requirement for any given component of the acquisition system must truly depend on the seismic system as a whole, including how the data will be processed and how they will be interpreted. Historically, specs have been set conservatively, the philosophy being that it is better to bear the cost of down-time in acquisition than to suffer any compromising of data quality. Indeed, many specs are set by what had worked previously, regardless of whether or not previous specs are or were too conservative.

Here we concentrate on one particular spec used in marine acquisition, the tolerable amount of recorded energy from other seismic crews. We refer to this noise as "interference" or "crew noise." It is not uncommon to have two or more seismic boats operating in a given survey area. When the crew-noise level exceeds a chosen spec [sometimes stated in terms of the largest tolerable peak or root-mean-square (rms) amplitude of interfering crew noise; sometimes included in a general "cable noise" spec], the solution has been for the crews to time-share. In time-sharing, the crews agree to shoot only during predetermined time slots and remain idle while awaiting their slot. This solution is costly, in terms of both delays in completing surveys and costs for idle crew time, particularly in areas such as the North Sea and Beaufort Sea, where data can be collected during only limited times of the year. The high cost and frequency of time-sharing (as much as 60 percent of sea time in some areas during peak activity in the North Sea) have led us to question how much of this practice is truly necessary. We address this question by examining the processed results from two controlled experiments, one from the Gulf of Mexico and one from the North Sea. Although our data examples are from the marine environment, the conclusions are also applicable to problems of interference in land surveys.

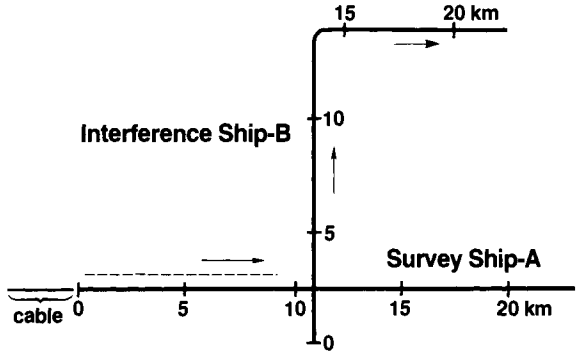

FIG. 1. Relative paths of a survey ship and an interference ship in a controlled crew-noise experiment in the Gulf of Mexico. The small perpendicular ticks on each trackline represent relative positions of the two ships at 5 km intervals along each path. The dashed line above the survey line shows the locations of the sections shown in Figures 7 through 10.

GULF OF MEXICO EXPERIMENT

In this experiment, a 23 km survey line was traversed three times: once to acquire data free of interfering crew noise; once to acquire data while a second seismic "noise" ship followed a prescribed path relative to the survey line (Figure 1); and once again to acquire only interference noise while the noise ship followed its previous path. We refer to these three lines as the "uncontaminated," "contaminated," and "crew-noise-only" lines, respectively. 120 channels were recorded, with a receiver group interval and shot spacing of 25 m. All traverses of the survey line were in the same direction, and the entire experiment was performed within 15 hours, in calm seas. For the contaminated and crew-noise-only lines, the interference ship was always 9 to 12 km away from the survey ship. (For comparison, ships as much as 80 km apart are sometimes forced to time-share because interfering noise levels are judged out-of-spec.) The seismic sources in this experiment had peak-to-trough strengths (in the frequency range 5–128 Hz) of 4×10^6 Pa-m (40 bar-m) for the survey ship and 5×10^6 Pa-m (50 bar-m) for the noise ship. By maintaining different firing intervals for the two sources, we simulated the mis-synchronization that would typically occur when two seismic crews are working in the same area. This mistiming also produced test data in which the arrival time of crew-noise bursts was distributed with equal likelihood over the length of recorded data.

Figure 2 shows five neighboring shot records from the contaminated line (taken 9 km from the start of the line). The crew noise is the strong coherent energy arriving around 3.5 to 4.5 s on the left-most record and at successively later times from one record to the next. This noise has peak amplitudes in the range 1.5 to 4 Pa (15 to 40 μbar), well above the typical crew-noise spec of 0.5 to 1.5 Pa (5 to 15 μbar). Along this part of the line, the shot intervals of the survey ship and the noise ship differ by about 700 ms, causing the first arrival of the crew noise to be delayed by about that amount from one shot to the next. Such mis-synchronization of the survey and noise sources gives rise to time misalignment of the crew noise when the data are sorted into common-midpoint (CMP) gathers for stacking. As shown later, this misalignment is fundamental to our ability to suppress the noise.

Figure 3a shows the peak amplitudes (solid line) of constant-offset (3000 m) traces across the entire 22.5 km (900 shotpoints) of the crew-noise-only line. The curve has an oscillatory appearance because, with the varying arrival time of the crew noise, not all traces contain strong crew noise; for some, the noise arrived during the short period of time (here 2 s) between the maximum recording time and the firing of the next shot. The envelope (dashed line) of the peak-amplitude values varies roughly from 0.8 to 4 Pa (8 to 40 μbar) for these long-offset traces. The considerable variation in envelope amplitude along the line implies areas of locally strong and areas of locally weak crew noise. The corresponding amplitude envelope for the uncontaminated survey (not shown here) has a similar variability. We conclude that these variations in crew-noise strength are caused primarily by variations in water-bottom or sub-water-bottom geology, rather than by array effects associated with varying azimuths and distances between the noise ship and survey streamer.

The upper two curves in Figure 3b are counterparts of the

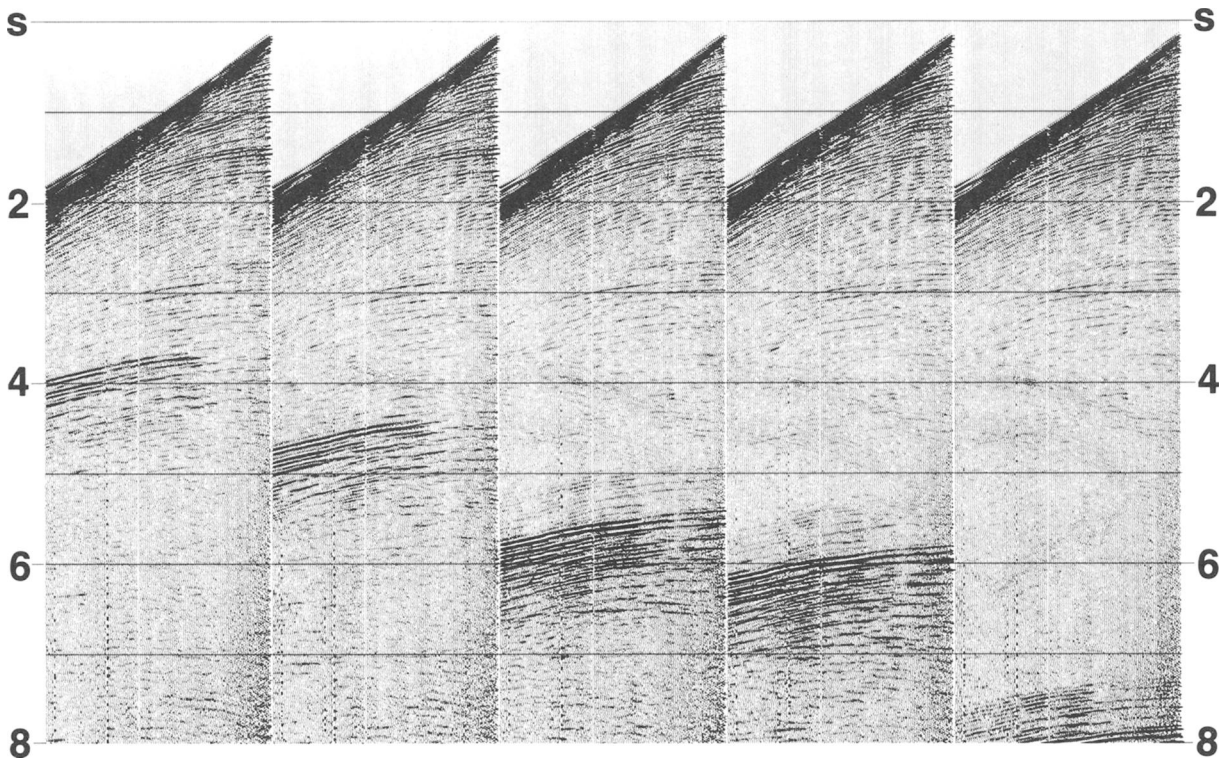

FIG. 2. Five representative neighboring shot records taken 9 km from the start of the crew-noise-contaminated survey line in the Gulf of Mexico experiment. The interfering crew noise in these shot gathers is the strong coherent energy arriving at around 3.5 to 4.5 s on the left shot record and progressively later on the other records. Peak amplitudes of the crew noise are as large as 4 Pa (40 μbar), well beyond the typical Gulf of Mexico spec. These data have been gained to compensate amplitudes only for geometric-spreading decay.

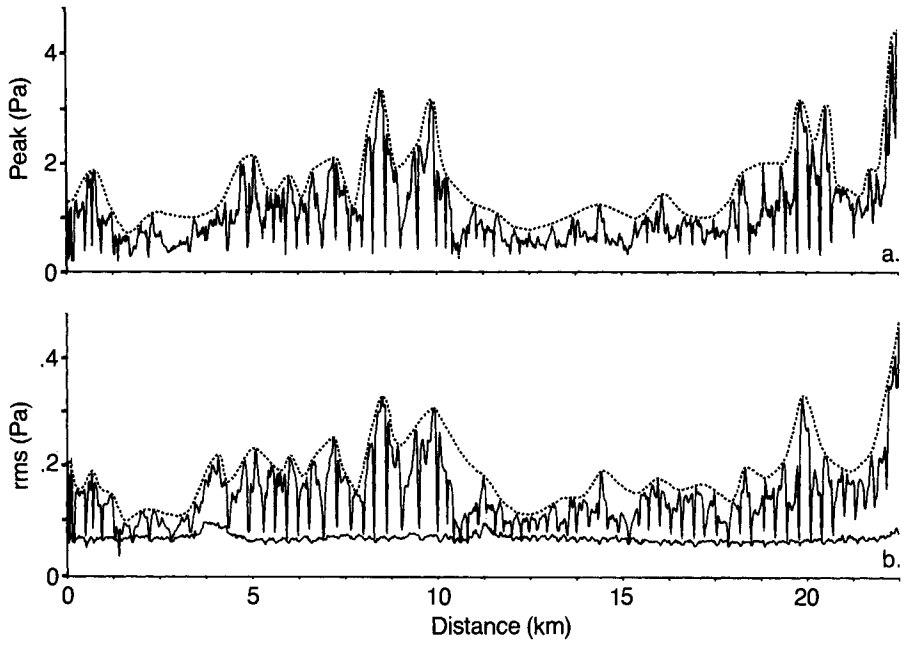

FIG. 3. Amplitude levels on a far-offset (3000 m) trace along the Gulf of Mexico crew-noise-only line. (a) Peak amplitude (oscillatory, solid curve). The variation in the envelope (dashed curve) of peak amplitudes is a result of changing near-water bottom conditions along the line. (b) rms amplitude. The oscillatory, solid curve is the rms amplitude (measured over a duration of 8 s) of the same traces used in (a). The envelope of rms amplitudes (dashed line) also shows considerable variation along the line, but remains well below 0.3 Pa (3 μbar) for most of the line. The lowest curve is the rms amplitude of the traces that do not contain the 1 s or so of strong burst-like crew noise.

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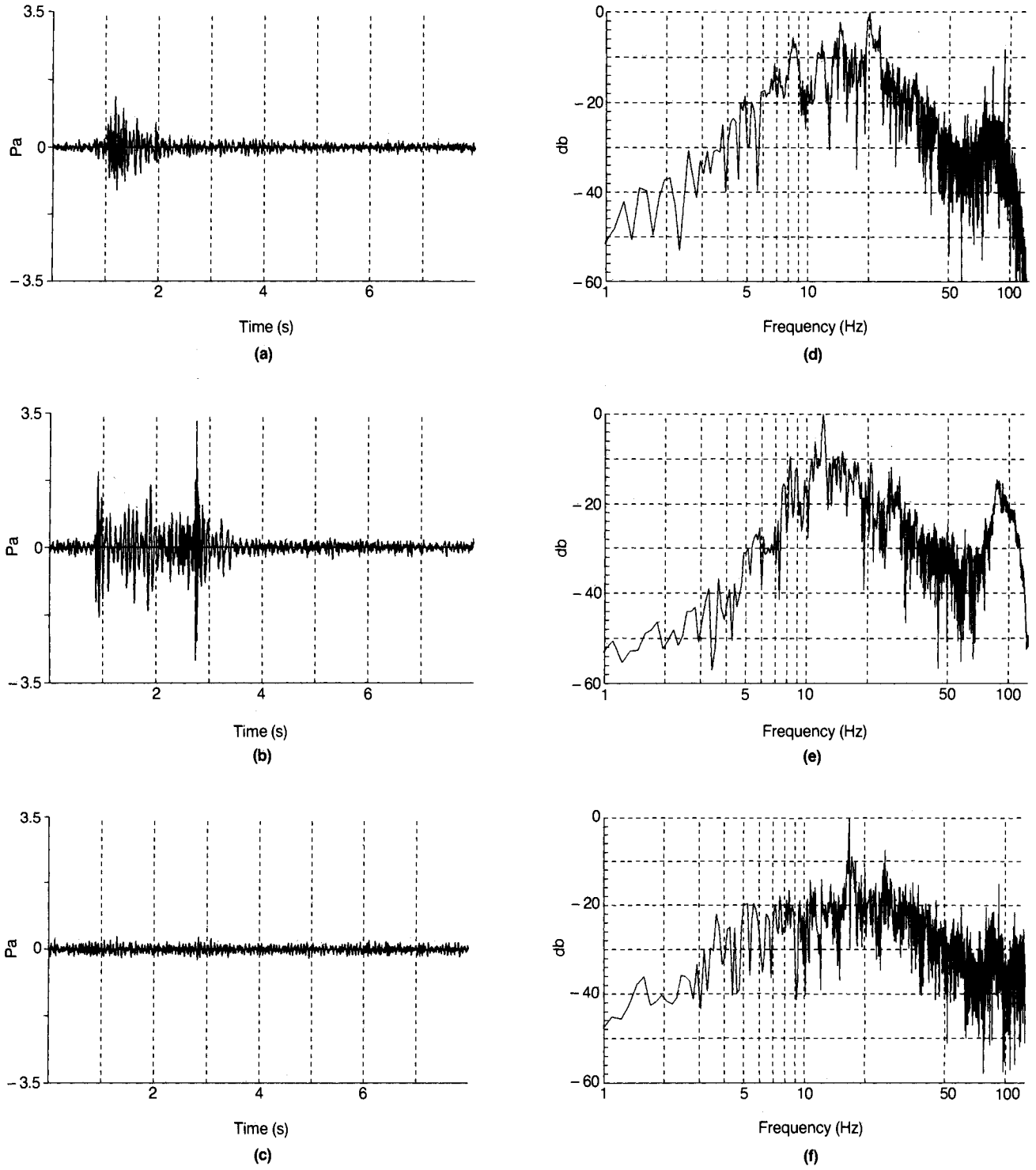

FIG. 4. Representative crew-noise traces and their associated amplitude spectra. (These data unavoidably contain ambient noise as well.) (a) Crew-noise-only trace from the first two-thirds of the Gulf of Mexico line, where the crew noise consisted of only 1 s bursts of low-frequency energy. (b) Crew-noise-only trace taken from the last one-third of the line, where the crew noise consisted of both low-frequency bursts and 100 ms bursts of high-frequency energy. (c) Trace of ambient noise only. (d), (e), and (f) Amplitude spectra for the traces shown in (a), (b), and (c).

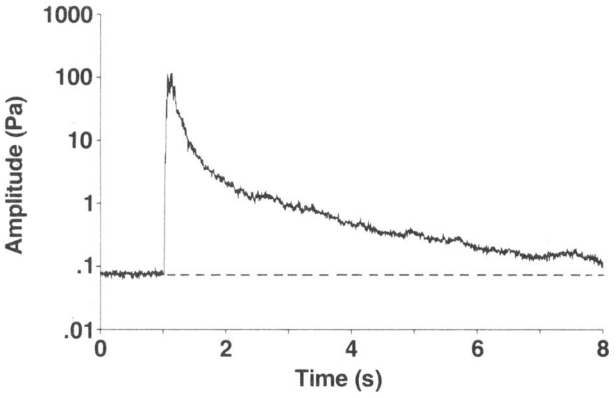

FIG. 5. Signal amplitude recorded by a hydrophone group 1700 m from the source in the uncontaminated line. At each time sample, the amplitude is the average trace magnitude over 100 successive shot records in the Gulf of Mexico experiment.

envelope and amplitude curves shown in Figure 3a, but these are rms amplitudes measured over the 8 ms duration of the traces. The curves for rms amplitude parallel those for peak amplitude simply because the rms amplitudes are dominated by the strong early arrivals of crew noise. Significantly, however, even at the noisiest crew-noise locations (at around 8 to 10 km) the rms amplitude is just 0.3 Pa (3 μbar), within commonly used specs for ambient noise.

Not only the amplitude but also the character of the crew noise changes along the line. Figure 4 shows representative, constant-offset traces (offset of 3000 m) and their spectra, extracted from near the beginning and near the end of the crew-noise-only line. For comparison, Figure 4 also shows a trace from a postsurvey, ambient-noise strip. Trace 4a contains a low-frequency (<25 Hz) crew-noise burst and a relatively constant, low level of noise elsewhere, while trace 4b has a high-frequency (75–120 Hz), short-duration component as well as the low-frequency component. The strong low-frequency noise extends over roughly 1 s, and the duration of the strong, high-frequency component is limited to about 100 ms. Both components are thus of limited duration (i.e., they are "burst-like") compared to the full 8 s length of the trace.

Apparently the high-frequency component, which appeared only in the last 300 shots, is sensitive to the geology near the water bottom; but its exact transmission mechanism is unknown. Where both high-frequency and low-frequency components exist, however, we find that the two components travel with different group velocities, indicating that the strong crew noise propagates as dispersive waves. In routine pro-

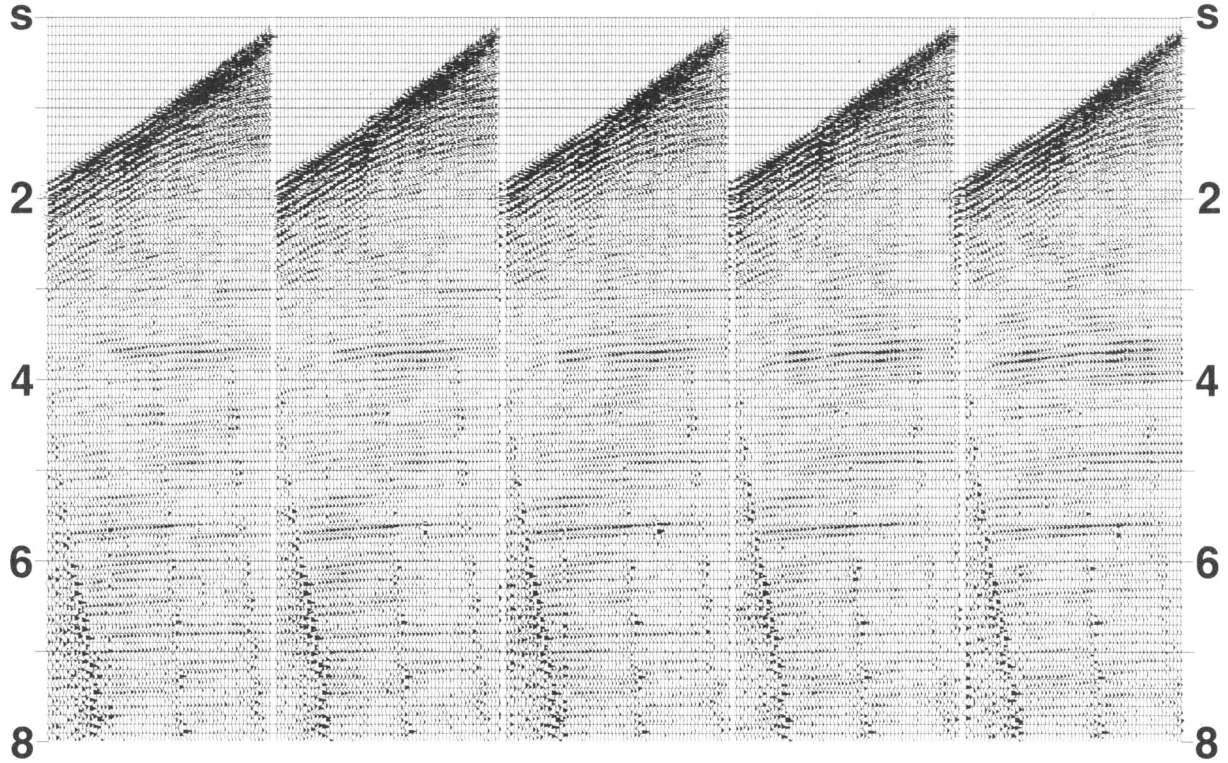

FIG. 6. CMP gathers from the Gulf of Mexico crew-noise-contaminated line. The crew noise (anomalous amplitudes that are most evident after 4 s) is now disorganized relative to the coherent appearance on the shot records (Figure 2).

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cessing of seismic data, frequency filtering would typically exclude the high-frequency noise. Such noise, however, might still be observed in the field and influence decisions as to whether or not a survey is within spec.

Consider the zones of low-level noise following the bursts in Figures 4a and 4b. Those zones must contain some amount of residual, persistent crew noise, whose variance would add to the variance of the ambient noise. Since the noise levels in those zones are comparable to the level of ambient noise seen in Figure 4c, one might conclude that the persistent crew noise that follows the burst is weaker than the ambient noise. We cannot be certain of the noise level, however, because the noise strips and crew noise-contaminated traces could not be acquired simultaneously, and ambient-noise levels measured on different noise strips varied considerably. (rms values varied from 0.05 to 0.1 Pa for this offset, and were as much as 0.35 Pa for short-offset traces.) Nevertheless, rms amplitudes of the portions of traces following the crew-noise bursts (bottom curve in Figure 3b) were roughly 0.07 Pa, consistent with the measured ambient-noise levels.

For comparison with the levels of non-burst-like noise seen in Figures 3 and 4, Figure 5 shows typical temporal behavior of uncontaminated data traces taken from a number of shot records. The amplitudes shown in Figure 5 are sample-by-sample, rms-average magnitudes for the first 100 traces recorded by the hydrophone group 1700 m from the source. Just as noise amplitudes vary considerably along the line, details of the signal behavior can vary substantially as well. We note here only general characteristics of the curve in Figure 5: (1) early amplitudes exceed 100 Pa, substantially more than the 1.5 to 4 Pa observed for the crew noise; (2) amplitudes decline generally monotonically and are still decreasing at a record time of 8 s; and (3) the amplitude level at 8 s ($\sim$0.2 Pa) is higher than the ambient noise level (0.08 Pa) observed prior to the first arrival.

The late energy in Figure 5 is either coherent reflections from beneath the line of survey and hence can be stacked coherently after proper normal-moveout (NMO) correction, or it is source-generated noise that may or may not stack coherently. If in an N-fold stack this late energy stacks incoherently, the source-generated noise gets the same $N^{-1/2}$ treatment as does the ambient noise and (as we show later) the crew noise; crew noise, if it stacks coherently, is preserved intact.

SUPPRESSION OF THE CREW NOISE WITH CONVENTIONAL CMP STACKING

As long as the firing intervals of the survey and noise sources differ, crew noise arrives at different times on neighboring shot records. Thus, when the data are sorted into CMP gathers and corrected for NMO, the crew noise is misaligned and will be attenuated with just conventional CMP stacking, the most powerful general tool available for suppressing noise. Figure 6 shows five adjacent CMP gathers from the contaminated line in our Gulf of Mexico experiment. Because the survey source and noise source were not synchronized, the noise is sporadic and incoherent along the hyperbolic trajectories that we associate with moveout of signal. As a result, conventional N-fold CMP stacking, wherein all traces are weighted equally (by $1/N$), will suppress the crew-noise bursts relative to signal by a factor $M^{1/2}/N$, where M is the number

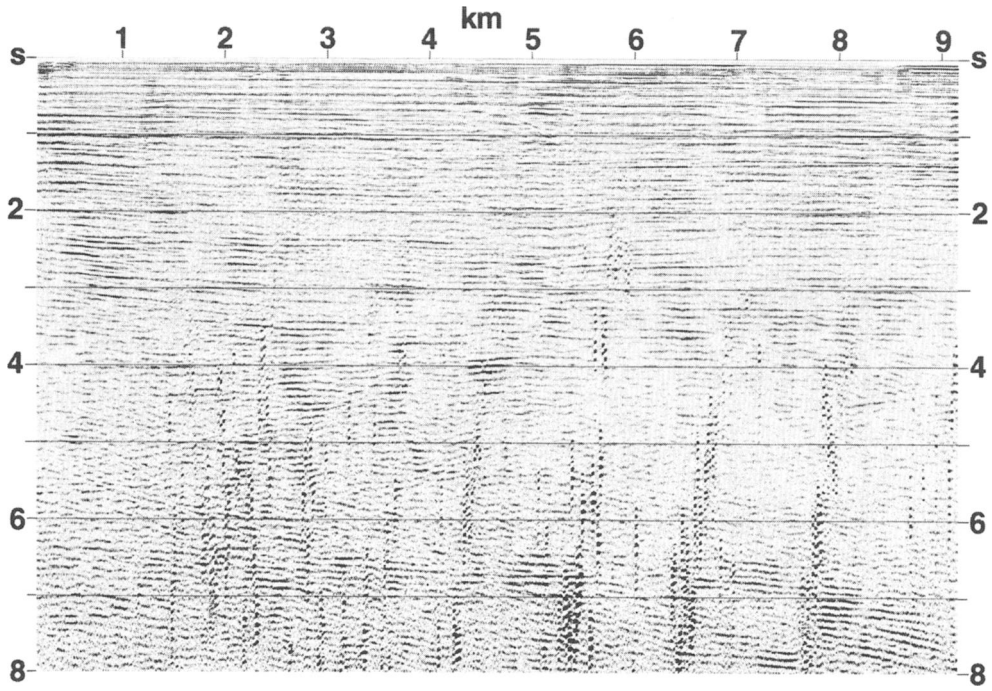

FIG. 7. Near-trace section of the Gulf of Mexico crew-noise-contaminated line. The crew noise appears as the isolated, vertical wave trains that occur sporadically throughout the section.

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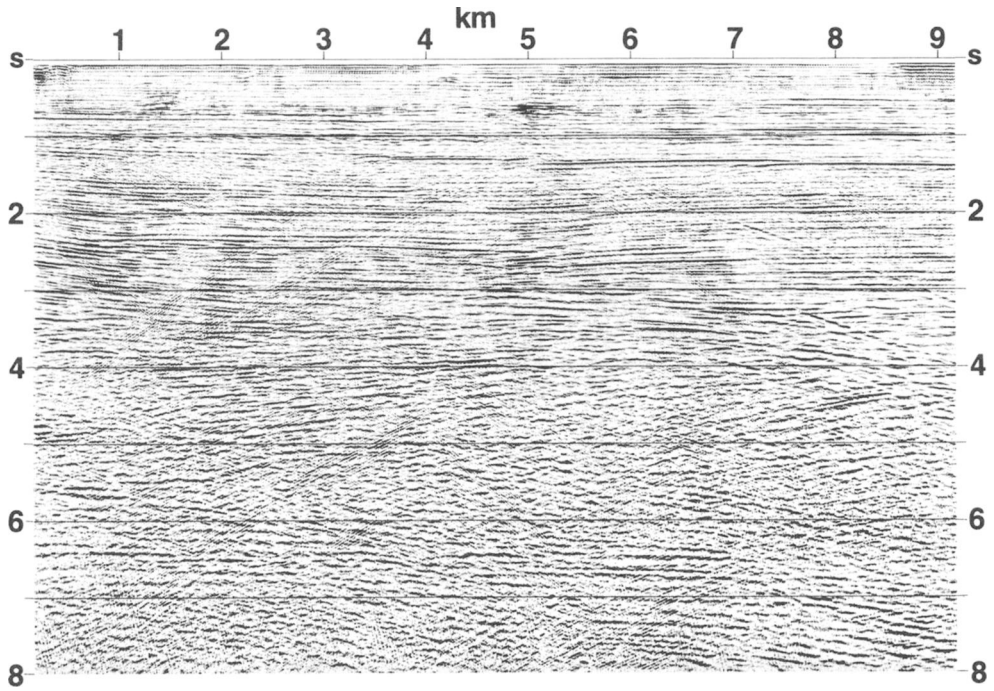

FIG. 8. CMP stack of the Gulf of Mexico crew-noise-contaminated line. The crew noise is apparent only deep in the section, below 5 s. Compare with Figures 9 and 10. All these data have been processed and displayed so as to preserve relative trace amplitudes.

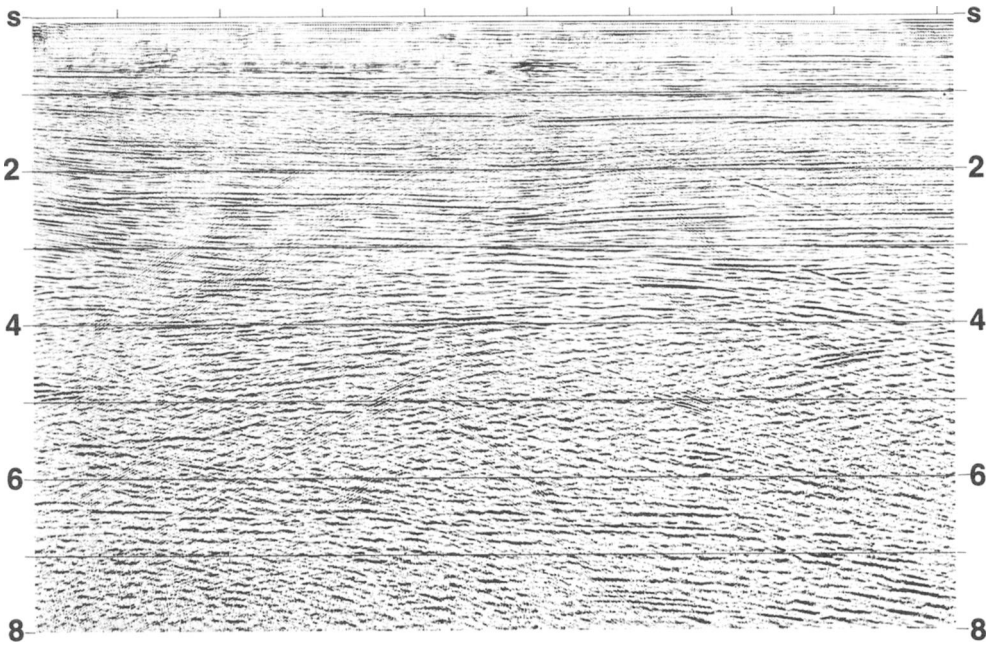

FIG. 9. CMP stack of the Gulf of Mexico uncontaminated line. Much of the extraneous coherent energy seen in the contaminated line (Figure 8) is also seen here, implying that much of this energy is generated from the survey source, not from the interfering noise source.

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of traces on which the burst noise appears at any given time. From Figure 4a, we might call the data between about 1 and 2 s "burst noise." We also observe that the 1 s burst occupies about 10 percent of the 10 s shot interval. We therefore expect that at any given time, typically six of the 60 traces within a CMP gather of the Gulf of Mexico data will have the strong burst noise.

The power of conventional CMP stacking for suppressing crew noise can be demonstrated by comparing a near-trace section with a conventional 60-fold stack of the noise-contaminated Gulf of Mexico data (Figures 7 and 8). The near-trace section is just single-fold, and yet even here the crew noise poses a problem only below 2 s. Above 2 s, the strength of the survey source, which is significantly closer to the streamer than is the noise source, is sufficient to overpower any contaminating effects from the crew noise. Below 2 s, the crew noise appears as strong-amplitude wave trains on isolated traces.

The 60-fold CMP stack in Figure 8 shows none of the noise bursts seen in the near-trace section in Figure 7. Close inspection of Figure 8 does show a variety of events that could be coherent noises of one sort or another. However, comparison of the contaminated stack with an identically processed 60-fold stack of the uncontaminated data (Figure 9) shows many of the same events. Such energy, therefore, must have been generated by the survey source. Only deep in the data (below 5 s) does the contaminated stack show evidence of noise that is absent from the uncontaminated data.

The sections shown in Figures 8 and 9, as well as all subsequent sections from the Gulf of Mexico experiment, were processed identically. The processing included deterministic signature deconvolution, NMO correction (all with the same velocity field) and stack, statistical deconvolution after stack, and time-varying band-pass filtering. Relative amplitudes between all sections have been preserved in the display of each section.

Just how should the crew noise appear on these processed, stacked sections? The answer depends upon the relative positions and courses of the survey ship and the noise ship, and upon the relative synchronization of the two sources. Figure 10 shows the stacked data from the crew-noise-only line displayed with the same geometric-spreading correction and other gain treatment as for the contaminated and uncontaminated stacks in Figures 8 and 9. The broad arching pattern is characteristic of a noise ship traversing a path across a survey line, such as in Figure 1. The fact that the noise appears from top to bottom throughout the section (although it is relatively weak in the shallow portion) stems from the mis-synchronization of the two sources. Figure 10 thus shows the level of crew noise that we should expect in the contaminated stack shown in Figure 8. Above 3.5 s, crew-noise contamination is not an issue with these data. Conventional processing alone has reduced the crew noise to the extent that only at late times does it even become evident.

The weak amplitude of the crew noise in the contaminated stack is consistent with the measured amplitudes of the noise bursts (4 Pa) and the source-generated amplitudes seen in Figure 5. If we assume that at any given time the burst noise occurs on six of the 60 traces in an NMO-corrected CMP

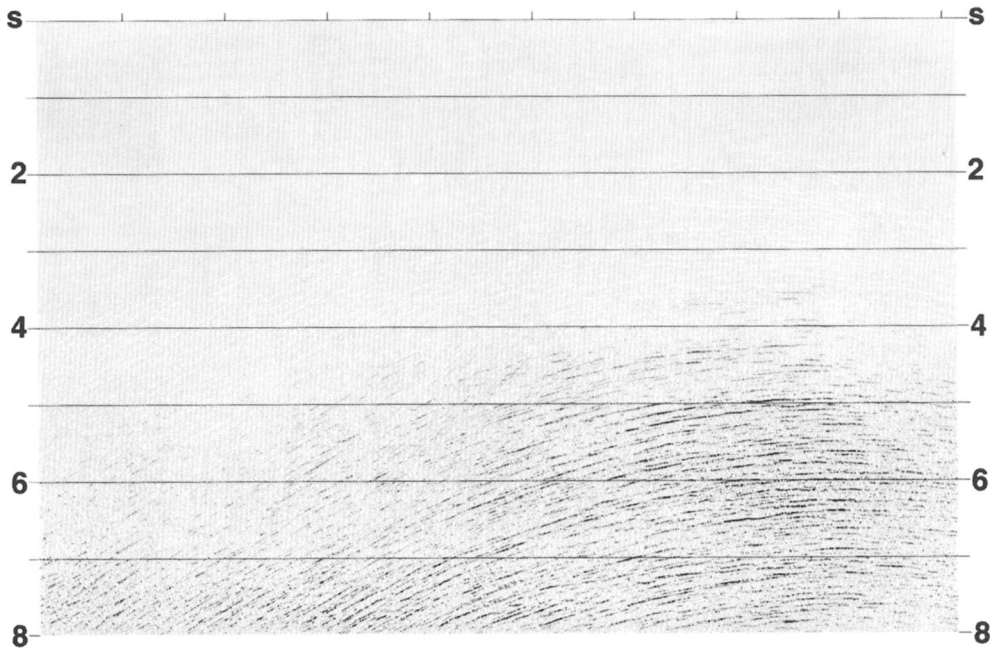

FIG. 10. CMP stack of the crew-noise-only line displayed with the same gain as the contaminated and uncontaminated stacks in Figures 8 and 9. Crew noise is clearly not an issue above 3.5 s.

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gather and that the burst noise on those six traces stacks incoherently, the crew-noise level after stacking is about $(6)^{1/2}(4)/60 = 0.16$ Pa. For comparison, from Figure 5 the amplitude of coherent signal would be about 0.3 Pa at 5 s and about 0.2 Pa at 8 s. These implied signal and noise levels are consistent with the levels of signal and crew noise seen in Figure 8.

SUPPRESSION OF CREW-NOISE BURSTS WITH WEIGHTED CMP STACKING

The character and organization of crew noise in shot records and CMP gathers suggest two general approaches for attacking the noise beyond what can be achieved in conventional CMP stacking. On shot records, the noise is coherent from trace to trace and could be attacked with a dip filter, provided the moveout of the noise across a record differs sufficiently from that of the signal. Moveout of crew noise, however, depends upon the azimuth and distance between the interfering source and the survey streamer. When the interfering source is ahead of the streamer, moveouts of crew noise and signal will be in the same direction and can also be comparable; hence dip filtering to suppress the noise could attack the signal as well. Such is the case for the crew noise seen on the shot records in Figure 2. Similarly, in areas of complex structure where the signal can have a wide range of moveout on shot records, an attack on crew noise based on its moveout would discriminate against portions of the signal. Moreover, whereas ship A may be situated such that the crew noise from ship B can be discriminated on the basis of moveout, it is possible that ship A's energy cannot be discriminated from the signal recorded by ship B. Fortunately, dip filtering is unnecessary.

For noises, such as crew noise, that are burst-like and occur on only a portion of the traces across each CMP gather, the locally anomalous amplitudes of the noise itself can be exploited to supplement the noise-suppression power of the CMP stack. Examples of approaches to crew-noise suppression that discriminate on the basis of noise amplitude are median stacking and trimmed-mean stacking (Farmer and Haldorsen, 1985), comparison of contaminated data traces with uncontaminated reference traces (Akbulut et al., 1984), and noise blocking, either along traces or across different gatherings of traces, such as CMP gathers and common-offset gathers. Median stacking and noise blocking can be effective, but they generally require considerable computation; moreover, noise blocking requires selection of a specified threshold parameter for defining the amplitudes that are considered anomalous.

An efficient alternative to these approaches is to apply data-determined, independent time-varying weights to the traces within each CMP gather. Two particularly simple types of weighting schemes are inverse-amplitude and inverse-power weighting, wherein rms amplitude and power are measured over short, sliding time windows (Embree, 1968; Gimlin and Smith, 1980). To preserve general signal amplitudes in any such scheme, the sum of the weights for all the traces in a CMP gather is made equal to unity. Inverse-amplitude weighting is analogous to performing a fast automatic gain control (AGC) on the data prior to stacking. Stacking with inverse-power weighting, sometimes referred to as diversity stacking, is particularly potent in suppressing anomalously strong noise of limited duration. This trace-weighting scheme requires only that signal amplitude be roughly uniform from trace to trace.

Consider, for example, stacks of the schematic six-fold CMP gather shown in Figure 11. Trace 4 contains an isolated burst that is substantially stronger than the aligned signal. With uniform weighting, this strong burst-like event will dominate the stack trace even though stacking reduces its strength relative to that of signal by a factor of six. Weighting each of the traces by the inverse of its rms amplitude or power (computed over, say, a 200 ms window) will further reduce the relative contribution of the noisy trace when the data are stacked. Consequently, the stack will show signal with the burst noise virtually eliminated.

Such weighted stacking techniques have been used successfully in land acquisition and processing for years, and yet they are relatively unused in the marine environment. Inverse-power weighting (diversity stacking) of consecutive Vibroseis records, for example, is commonly used to reduce cultural noise such as that caused by motor vehicles or animals. Such noises in land acquisition are considerably stronger (relative to signal) than any crew noise encountered in marine surveying. Although diversity stacking in Vibroseis acquisition typically applies to vertical stacking, as opposed to the CMP stacking discussed here, the rationale (i.e., attacking anomalous, high-amplitude noise) is the same for both applications.

Let us compare the actions of uniform (i.e., conventional), inverse-amplitude, and inverse-power weighting on the contaminated Gulf of Mexico data. We focus on a zone deep in the data where the crew-noise contamination is greatest. Figure 12a shows a closeup view taken from the lower right corner (the noisiest portion) of the contaminated section in Figure 8. These data show coherent energy (crew noise) that dips from the lower left to the upper right corners. Figure 12b shows the stacked data that result from the application of inverse-amplitude trace weighting. Here the rms amplitude used in the weighting was computed over a 200 ms sliding time window, and, as required to help preserve the amplitude

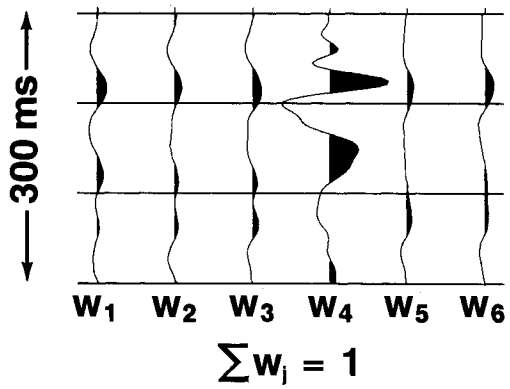

FIG. 11. Schematic six-fold CMP gather with one trace contaminated by burst-like noise. By choosing the trace weights w_j to be inversely proportional to the amplitude or power of each trace (computed over a short time window, for instance 150 or 200 ms), the burst-noise contamination of the stack trace can be dramatically reduced.

of the signal, the trace weights sum to unity. The coherent crew noise that was so evident in the uniform weighted stack is reduced substantially in the inverse-amplitude weighted stack, but it is still present, especially in the lower left of the section. However, inverse-power weighting (with weights also computed over 200 ms windows, Figure 12c), has removed all remnants of the crew noise.

Figures 12a, 12b, and 12c differ only in the amount of crew noise that has survived the stack. The signal is virtually identical in every case. For reference, the same portion of the section from the uniformly weighted stack of the uncontaminated data is shown in Figure 12d. The uncontaminated section differs only slightly from the inverse-power weighted stack of Figure 12c. The differences, which are due in part to different realizations of ambient background noise in the two data sets, are remarkably small considering that the paths of the boat and streamer could not have been identical for the two line traverses. The slight differences between the signals, which are also evident between the conventional stacks of the contaminated and uncontaminated lines (Figures 12a and 12d), support the contention that the differences are not due to inverse-power weighting. Moreover, such differences in signal exist in zones clearly uncontaminated by interference noise, and hence cannot be attributed to the presence of the noise.

Prior to 5 s, the signal strength is high enough that the crew noise is barely noticeable even on the conventional stack (compare Figures 8 and 9). On close examination (closeups not shown here), comparison of the earliest 3 s of the contaminated and uncontaminated lines in Figures 8 and 9 shows these sections to be nearly identical; they are remarkably close considering that the data were acquired in different survey passes. Although inverse-amplitude and inverse-power weighting are not necessary for this shallower zone, it is important that application of either (if used) does not cause departures from the results with uniform trace weights. The inverse-power weighted stack of the shallow, contaminated data (not shown here) is indeed nearly identical to the uniform weighted stack. Thus, even though inverse-power weighting is not necessary prior to 5 s in these data, it is satisfying to confirm that the use of such weighting does not degrade the section.

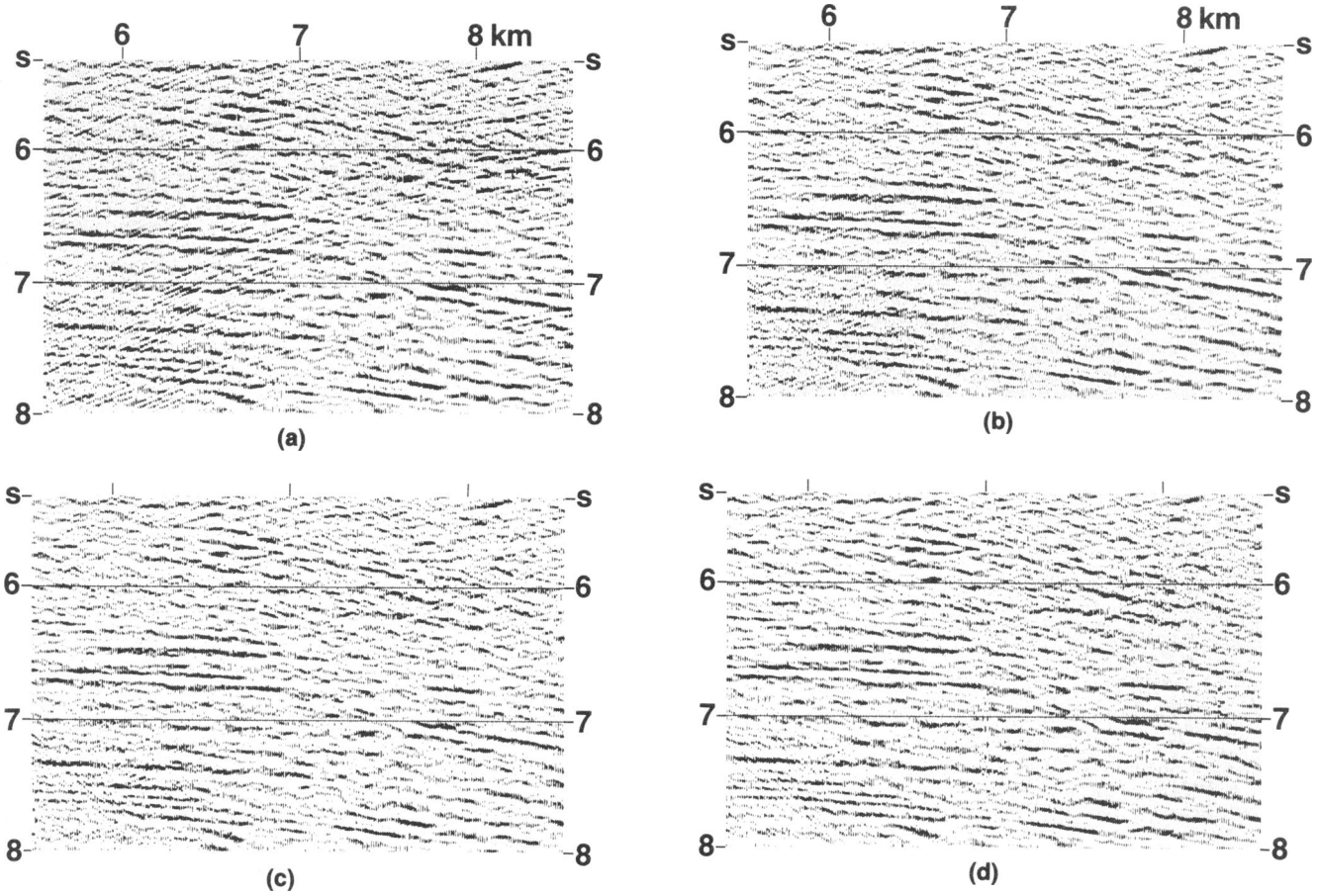

FIG. 12. Closeups of a deep part of the crew-noise-contaminated line after stacking with (a) uniform trace weights (conventional stacking), (b) inverse-amplitude trace weights, and (c) inverse-power trace weights. (d) Same portion of the section from the uncontaminated line (stacked with uniform trace weights). The crew noise is the coherent energy dipping from lower-left to upper-right in (a). Inverse-amplitude weighting suppresses most of the crew noise, but some noise still appears in the stack. No crew noise is apparent in the inverse-power weighted stack.

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A SIMPLE MODEL FOR QUANTIFYING BURST-NOISE SUPPRESSION

Having seen the benefits of inverse-amplitude and inverse-power weights in suppressing crew noise, we now use a simple model to quantify the relative noise-suppression power of these weighting schemes.

Let $A(t)$ be the amplitude of a weighted stack of N data traces, $x_i(t)$:

$$A(t) = \frac{\sum_{i=1}^{N} w_i x_i(t)}{\sum_{i=1}^{N} w_i}, \tag{1}$$

where w_i are the trace weights. The denominator normalizes the stack so that it preserves the amplitude of the input signal. Now let the data be composed of three components: signal $S(t)$ that is identical in every trace, random ambient noise, and crew noise.

Recalling Figure 4a, we might say that the trace consists of a low level of random noise $n_i(t)$ that is the sum of the ambient noise and persistent crew noise, plus a zone of strong-amplitude crew noise, which we call "burst noise" $b_i(t)$. For simplicity in our model, we assume that burst noise is present on the first M of the N traces in a gather and, through mis-synchronization of time intervals for the signal and burst noise sources, it is incoherent across those M traces, just as is $n_i(t)$ across all N traces. (In our notation, henceforth, we do not explicitly show the dependence on time t.) We have

$$x_i = \begin{cases} S + n_i + b_i & i = 1, \ldots, M \\ S + n_i & i = M+1, \ldots, N. \end{cases} \tag{2}$$

Substituting equation (2) into equation (1) yields the weighted stack,

$$A = S + \frac{\sum_{1}^{N} w_i n_i}{\sum_{1}^{N} w_i} + \frac{\sum_{1}^{M} w_i b_i}{\sum_{1}^{N} w_i}. \tag{3}$$

Thus, the stack trace is seen to have a component of ambient plus low-level, persistent crew noise

$$\bar{n} = \frac{\sum_{1}^{N} w_i n_i}{\sum_{1}^{N} w_i}, \tag{4}$$

a burst, crew-noise component

$$\bar{b} = \frac{\sum_{1}^{M} w_i b_i}{\sum_{1}^{N} w_i}, \tag{5}$$

and a total stack error e which is just

$$e = A - S = \bar{n} + \bar{b}. \tag{6}$$

One way to choose the weights w_i is so that the expected power in the total stack error is minimum. These optimum weights, a special case of the results of Krey (1969), are given by

$$w_i = \begin{cases} (\sigma_{b_i}^2 + \sigma_{n_i}^2)^{-1} & i = 1, \ldots, M \\ \sigma_{n_i}^{-2} & i = M+1, \ldots, N, \end{cases} \tag{7}$$

where $\sigma_{n_i}^2$ is the expected power of the random noise n_i, and $\sigma_{b_i}^2$ is the expected power of the burst noise b_i.

While none of these noise powers is known for field data, a realizable alternative is to measure the average power in windows along each trace. In our simplistic model, these power measurements approximate

$$P_i = \begin{cases} S^2 + \sigma_{b_i}^2 + \sigma_{n_i}^2 & i = 1, \ldots, M \\ S^2 + \sigma_{n_i}^2 & i = M+1, \ldots, N. \end{cases} \tag{8}$$

The similarity between the optimum weights in equation (7) and the measurable powers suggests that we try the suboptimal weights

$$w_i = P_i^{-1},$$

or, more generally,

$$w_i = P_i^{-m}, \tag{9}$$

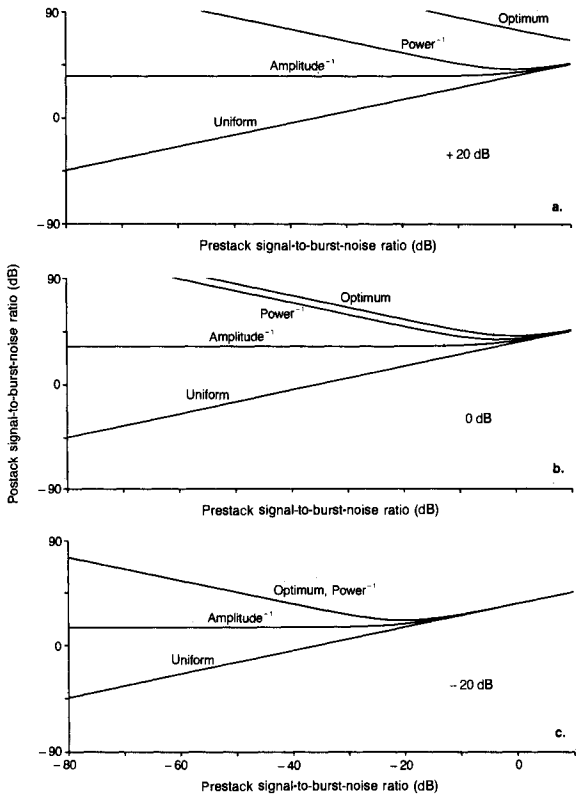

FIG. 13. Effectiveness of different weighting schemes for suppressing burst noise. Plotted are the poststack signal-to-burst noise (SBN) ratio versus the prestack SBN ratio for a 60-fold stack. The three plots are for prestack signal-to-random noise ratios of (a) +20 dB, (b) 0 dB, and (c) −20 dB. The curves in each plot are for uniform, inverse-amplitude, and inverse-power trace weighting schemes [see equations (8) and (9)], and for optimum trace weights [see equation (7)].

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for some choice of exponent m. In stacking seismic data, the exponent m is typically 0, 1/2, or 1. An exponent of 0 corresponds to the uniform trace weights used in conventional stacking; each sample is weighted by $1/N$. An exponent of 1/2 corresponds to weighting each sample in the sum by the inverse of the local rms amplitude (typically measured over a small time gate, say two to four times the dominant period). This is equivalent to applying a form of fast AGC to each data trace that preserves relative signal amplitude on the stacked result. A value of 1 for the exponent weights each sample by the inverse of the local power (again measured over a small time gate).

The expected poststack powers in the random noise and burst noise [equations (4) and (5)] can be calculated using the weights given by equations (8) and (9). Expressions for these powers are derived in the Appendix, under the assumption that the variance of the random noise is the same on all N traces and the variance of the burst noise is the same on all M traces on which it appears. Because neither the burst noise nor the persistent crew noise is truly stationary over their zones of occurrence (see, for example, Figures 4a and 4b), these assumptions about the variances are not strictly valid in practice. The basic inferences that we draw from these simplifying assumptions, however, are valid. For our simplistic model, the poststack signal-to-random-noise (SRN) ratio and poststack signal-to-burst-noise (SBN) ratio depend upon the prestack SRN ratio, prestack SBN ratio, the number N of data traces averaged, the number M of traces contaminated by burst noise, and the exponent m in equation (9).

One measure of the effectiveness of the stacking weights in suppressing the burst-like noise is the poststack SBN ratio. Figures 13a, 13b, and 13c show this quantity plotted as a function of prestack SBN ratio, under the special case $M = 1$, for a fixed stacking fold of 60 and for three different values of prestack SRN ratio, -20, 0, and $+20$ dB. In each figure, curves are shown for $m = 0$, 1/2, and 1. In addition, the optimum trace-weight curve [using weights from equation (7)] is shown for comparison. The relative shapes of the curves for different values of m remain the same in all three figures.

For small burst amplitude relative to signal amplitude (right side of Figure 13), the data model in essence consists of just signal and random noise. The three weighting schemes always treat the signal identically, and, for small burst amplitude, they treat random noise nearly identically. Thus, as expected, when the prestack SBN ratio is large, the inverse-amplitude and inverse-power schemes do not sense differences in amplitude from one trace to another. Notice also that the prestack SBN ratio at which the curves converge decreases as the SRN ratio decreases. Burst noise looks like random noise until its amplitude becomes significantly larger than the level of the prestack random noise.

The actions of the three weighting schemes begin to differ

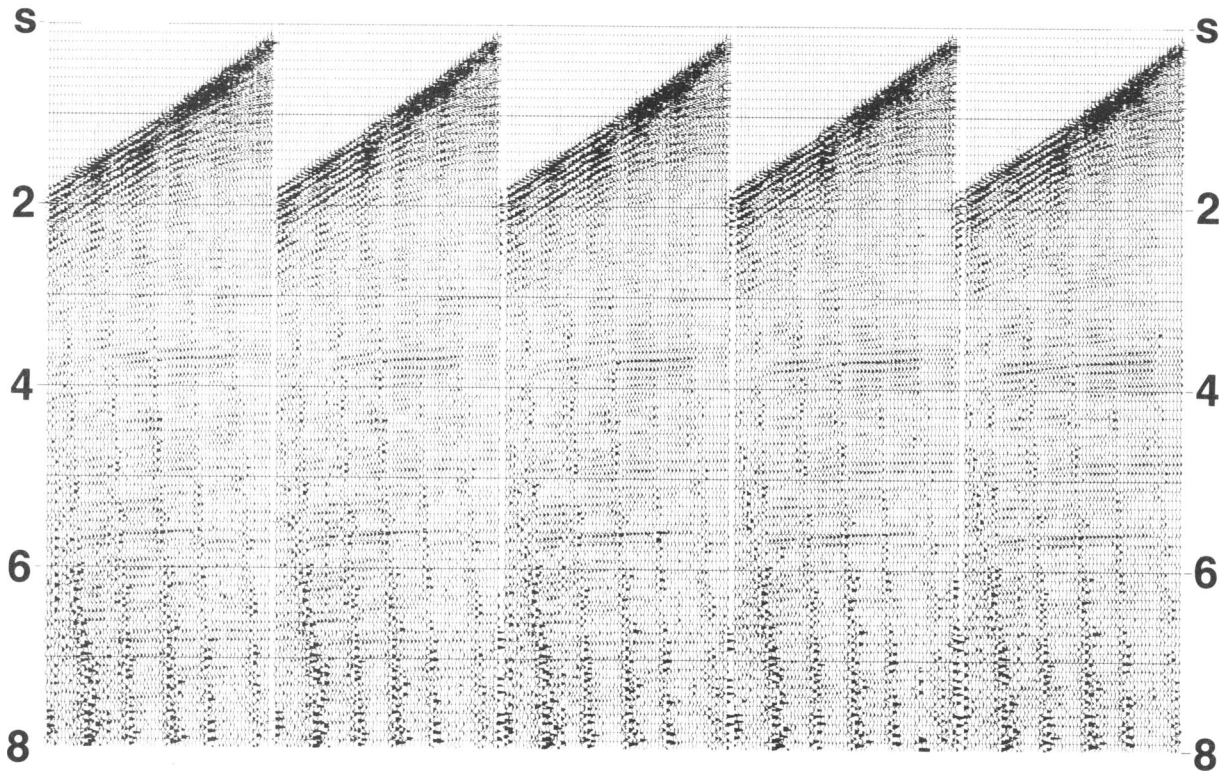

FIG. 14. CMP gathers from an experiment simulating a survey contaminated by noise from two interference boats. These gathers are from the same locations as those in the noise-contaminated line of the Gulf of Mexico experiment (Figure 6). The data were created by adding shot records from the contaminated line and "shot" records from the crew-noise-only line. The number of contaminated traces is now typically twice that from the field experiment.

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when burst amplitudes are relatively large, such as in the deep data in Figure 12. The best that uniform weights can do is to suppress a burst by a factor equal to $1/N$, as shown in the linear relationship between the poststack SBN ratio and prestack SBN ratio seen in Figure 13.

Inverse-amplitude weighting tends to equalize the amplitudes of the data prior to the summation. No matter how large the burst, it will be scaled down to the same amplitude, i.e., the amplitude level of the signal plus random noise. Thus, as the prestack SBN ratio becomes small, the poststack SBN ratio always tends toward a constant level. When the prestack SRN ratio is high, this level is equal to the decibel level corresponding to the fold of the data. For example, for a prestack SRN ratio equal to +20 dB and 60-fold data (Figure 13a), the poststack SBN ratio approaches a value close to 20 log 60 = +36 dB. Lower prestack SRN ratios (as in Figure 13c) result in lower limiting values of the poststack SBN ratio.

The effectiveness of inverse-power weighting for suppressing burst-like noise, on the other hand, actually *increases* as burst-noise amplitude increases. This behavior is reflected in each of the graphs in Figure 13, where the poststack SBN ratio is seen to improve as the prestack SBN ratio becomes progressively lower. In the limit as the burst amplitude goes to infinity, the product of the burst amplitude and the inverse-power weight goes to zero. The effect is to exclude the trace (and hence its signal as well as its noise) from the stack. This action simply lowers the fold by the number of traces on which the bursts appear at a given time, consequently decreasing somewhat the poststack SRN ratio relative to the ratio seen in the absence of burst noise.

SIMULATED EXPERIMENTS

The particular combination of experiments done in the Gulf of Mexico field tests allows some flexibility for simulating other types of crew-noise experiments. We simulated two different experiments: (1) two noise ships interfering with the survey boat, and (2) a single noise ship with a source strength five times stronger than the actual strength of the noise source used in the field.

In the first of these experiments, data contaminated by two noise ships were simulated by adding together shot records from the contaminated survey line and "shot" records from the line in which just crew noise and ambient noise were recorded. Although the paths of the two ships were unchanged for the two experimental lines, the noise-source timing differed. No attempt was made to match the firing times of the noise source in the two lines; thus, the crew noise from the two separate lines does not add in phase.

Simulated CMP gathers at the same locations as in the single-interference-ship line (Figure 6) are shown in Figure 14. As expected, the number of traces contaminated with crew noise has roughly doubled. Figure 15a shows a CMP stack of the deep section with uniform trace weights, and Figure 15b shows a CMP stack with inverse-power trace weights, for the simulated two-interference-ships line. Comparison of these sections with the corresponding uncontaminated section in Figure 12d shows that even with two noise ships, the final section is not compromised after application of inverse-power weights. Just as in the single-interference-boat experiment, we find (result not shown here) that uniform trace weights are sufficient to suppress the burst-like noise in the shallow section, but inverse-power weights are required to suppress the noise in the deep section.

The peak crew-noise amplitude levels in the preceding examples were around 1.5 to 4 Pa. Although such levels exceed the typical Gulf of Mexico spec for crew noise, the final inverse-power weighted stacks showed no significant differences from the uncontaminated stack. Now consider the situation in which the crew noise is *five times stronger*, thus yielding 7.5 to 20 Pa of peak crew noise on the survey data. In places, this level is more than an order of magnitude beyond commonly used crew-noise specs. These large interference levels were simulated by scaling up the crew-noise-only records and adding them to the records from the uncontaminated line. We note, however, that the crew-noise-only records actually contain ambient noise as well as crew noise. By merely scaling up these records we would be increasing not only the crew noise, but the ambient noise as well. We could

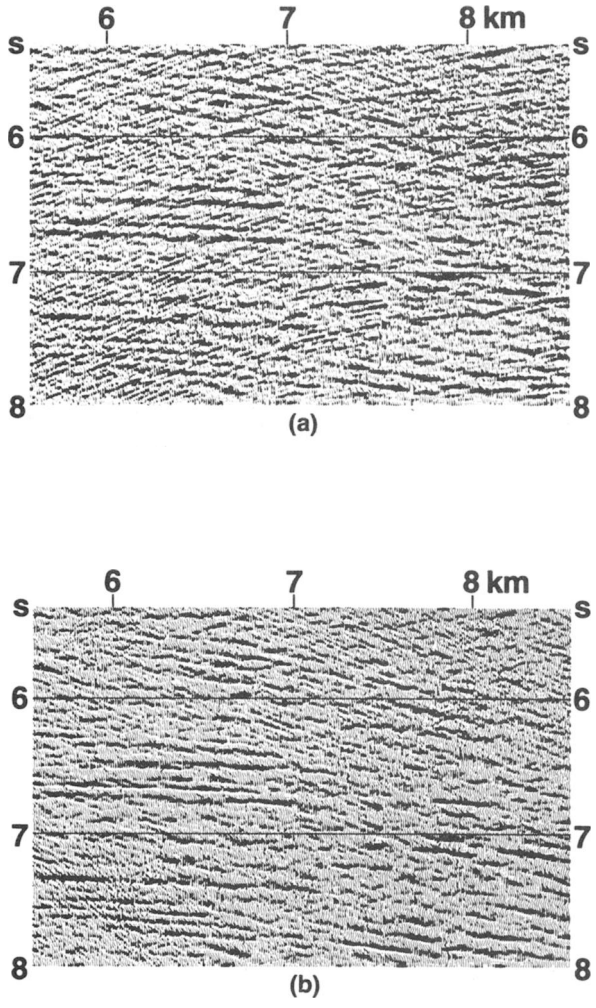

FIG. 15. Closeups of stacked data from the simulated two-interference-boat experiment. (a) Deep section stacked with uniform trace weights. (Compare with Figures 12a and 12d.) (b) Deep section stacked with inverse-power trace weights. (Compare with Figure 12d.)

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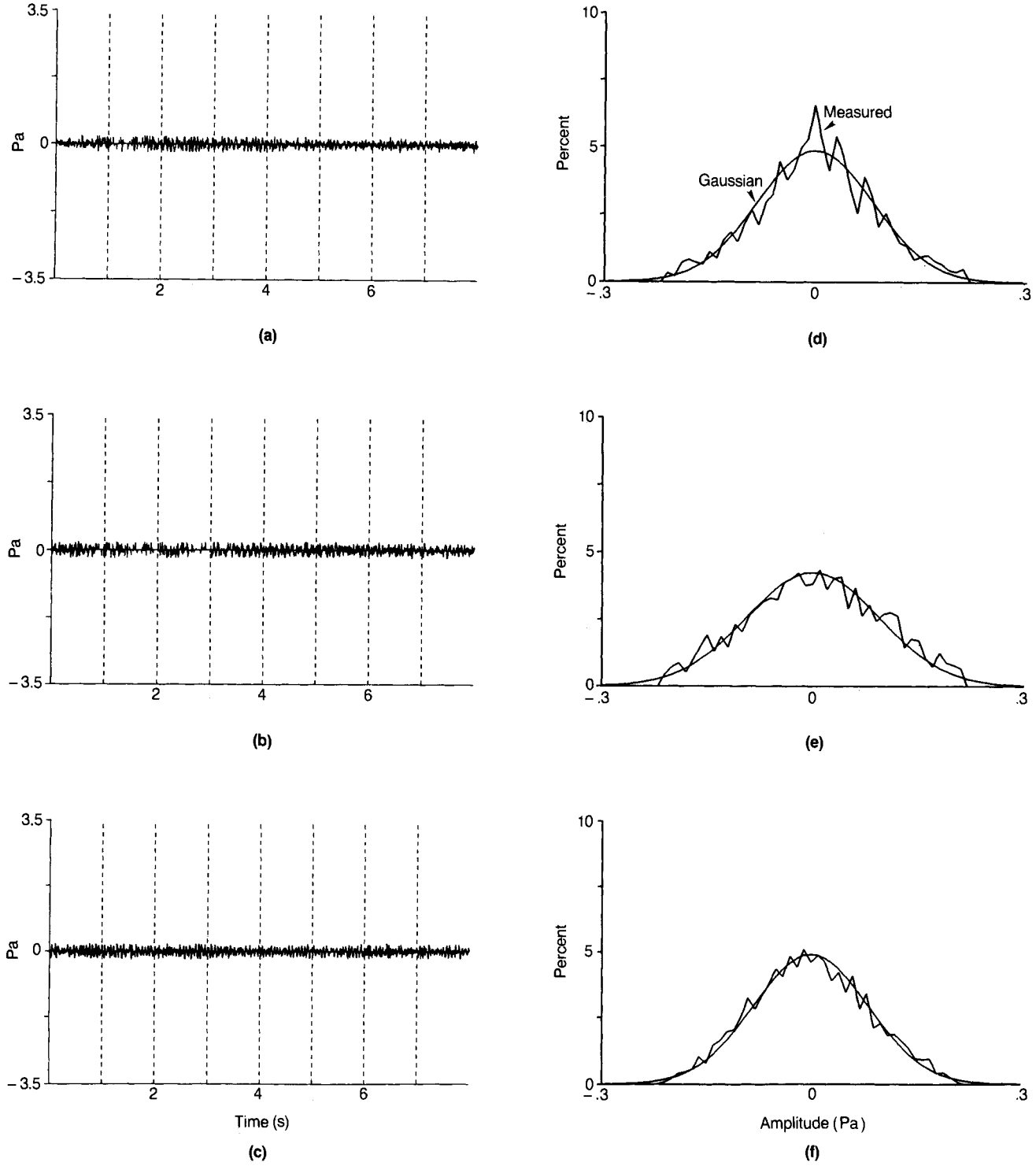

FIG. 16. (a), (b), and (c). Same crew-noise and ambient-noise traces as in Figures 4a–4c after zeroing all amplitude values that exceed three times the standard deviation of the (offset-dependent) ambient noise. These traces represent the data discarded from traces in simulating the Gulf of Mexico crew noise that was five times stronger. They are assumed in the simulation to consist primarily of random background noise. The histograms of trace amplitude values in (d), (e), and (f) have an approximately Gaussian shape (smooth curve), consistent with the assumption that the removed energy is primarily ambient noise.

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thus be simulating an experiment in which the ambient noise was accentuated beyond *its own* spec for acceptability.

To mitigate this problem, we removed low-amplitude samples from the crew-noise records prior to scaling. In doing so, we recognize that the removed samples may contain some low-level, persistent crew noise as well as ambient noise. To minimize bias associated with removal of crew-noise contributions, we removed only those samples with an absolute value lower than three times the estimated rms value for the ambient noise, as estimated from noise strips taken at the beginnings and ends of lines. Unfortunately (but not surprisingly) the level of ambient noise observed on the noise strips had enough variation from one strip to the next to make it impossible to determine whether the removed samples contained crew noise or merely natural variations in the ambient-noise level. Only if the rms ambient-noise level could be measured accurately all along the line, rather than just at the ends, could the rms value of the residual crew noise in the removed samples be estimated.

Figure 16 shows the samples removed from the representative traces shown in Figure 4, along with histograms of the amplitudes of those samples. Note that the histograms are approximately Gaussian, as we might expect for ambient noise. The rms values of the removed samples for all the far traces are comparable to the amplitudes shown in the bottom curve of Figure 3b. Because the removed samples have a histogram shape and an rms level close to those of the ambient noise, we believe that they are predominantly ambient noise and that the simulation of strong interference is best done by excluding these samples.

Figure 17 shows the uniform weighted stack for the line with a simulated crew-noise level that is five times the actual crew-noise strength. As compared with the subtle appearance on the stack of the field data in Figure 8, the crew noise is now distinctly noticeable. While it has the same general spatial pattern as in the contaminated line, the crew noise in the simulated experiment is a different realization of the noise. Hence, the crew noise on the simulated and field-contaminated sections can be compared only in overall character. The crew noise in Figure 17 is discernible as shallow as 3.5 s. Above 3.5 s some coherent noise exists with moveout similar to that of the crew noise, but again we must conclude that such noise is generated by the survey ship's source because the same noise appears on the uncontaminated section in Figure 9.

Closeup views of the deep part of the simulated strong crew-noise section are shown in Figure 18. Comparison of the uniform weighted stack in Figure 18a with the actual contaminated stack in Figure 12a shows the increased level of crew noise. As before, however, the use of inverse-power trace weights removes the burst-like noise (Figure 18b). The uniform weighted stack of the earliest 3 s of the simulated section

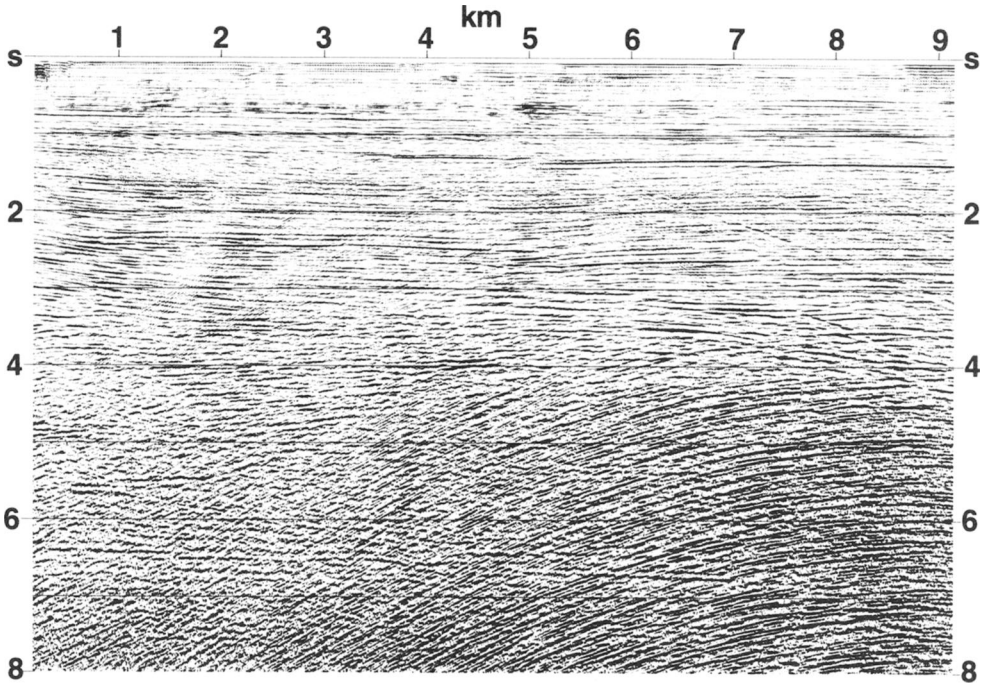

FIG. 17. CMP stacked section (uniform weights) of the experiment in which the crew-noise source strength is simulated to be five times what it was in the actual Gulf of Mexico experiment. Peak crew-noise amplitudes here range from 7.5 to 20 Pa (75 to 200 μbar), more than an order of magnitude above typical crew-noise specs for the Gulf of Mexico.

(not shown here) shows no degradation compared with the shallow sections from the contaminated and uncontaminated lines. The early reflection signal is strong enough to surmount the crew noise even though the simulated peak noise amplitude is as high as 20 Pa.

NORTH SEA EXPERIMENT

The amplitude level, frequency content, and duration of crew noise for a given separation between the survey line and the interference boat vary considerably from one area to another. No doubt, this is due to variations in the material properties and structure of the water-bottom and sub-water-bottom layers. As mentioned, ships as much as 80 km apart are sometimes forced to time-share because the interfering noise levels exceed specified limits. In contrast, seismic boats can often be as close as 15 km and still not generate noise that exceeds prescribed specs. As a check on the observations and conclusions from the Gulf of Mexico crew-noise experiment, we consider results from a second controlled experiment, this one performed in the North Sea.

In this experiment, a survey line was recorded several times, with an interference ship stationed at different distances and azimuths from the survey ship. The source strength of the interference ship was three times that of the survey ship: 7.5 $\times 10^6$ Pa-m (75 bar-m) versus 2.5 $\times 10^6$ Pa-m (25 bar-m). Figure 19 shows stacked data from the reference line, a line that had no crew-noise contamination. The data are 48-fold with 25 m shot and group intervals. The processing sequence included NMO correction and stack, predictive deconvolution after stack, time-varying filtering, and programmed gain. The same stacking velocity field, picked from the uncontaminated data, was used for both the reference line and the contaminated lines. A number of contaminated lines were recorded during the experiment; here we consider only two of the more troublesome lines.

Line A

For the first line (line A), the noise ship was stationed 10 km broadside to the center of the survey line. The source-cycle times for the survey and noise ships differed by more than 1 s. As in the Gulf of Mexico experiment, the discernible crew noise appears to be burst-like and presumably travels as a trapped wave at or near the water bottom.

Figure 20 shows the uniform weighted stack for line A. For a combination of reasons, the amplitude of the crew noise in this stack is relatively higher than in the Gulf of Mexico data; for the North Sea data the CMP multiplicity is lower, the strength of the noise-boat source is relatively greater than that of the survey source, and the duration of the interference noise is longer. (The longer the duration of crew noise, the more traces in a CMP gather will be contaminated at any given time sample.) The crew noise is apparent even in the shallow part of Figure 20, even more so than in the Gulf of Mexico data that simulated crew-noise contamination from a noise source more than five times as strong as the survey source.

Inverse-power weighted stacking of line A (Figure 21) has done an excellent job in suppressing the crew noise from the contaminated section. Some discrepancies can be observed between the reflections seen in Figure 21 and those in the uncontaminated stack in Figure 19, but they are due neither to the crew noise nor to the inverse-power weighting. They are primarily the result of differences in subsurface coverage (caused by navigational uncertainties and possible differences in cable feathering) for the two lines. This conclusion is substantiated by comparing CMP stacks (not shown) where no data-dependent processes (such as predictive deconvolution) were performed. A comparable discrepancy in the signal observed in Figures 19 and 21 exists even in the shallow section, where the data are unaffected by either processing or crew noise.

To the extent that the differences in signal shape seen in Figures 19 and 21 are attributable to differences in subsurface coverage, we can draw an important inference about the level of detail that can be extracted from processed data. In comparing stacked data produced by different processes (e.g., different choices for wavelet processing; inverse-power weighting versus uniform trace weighting prior to CMP stacking), we

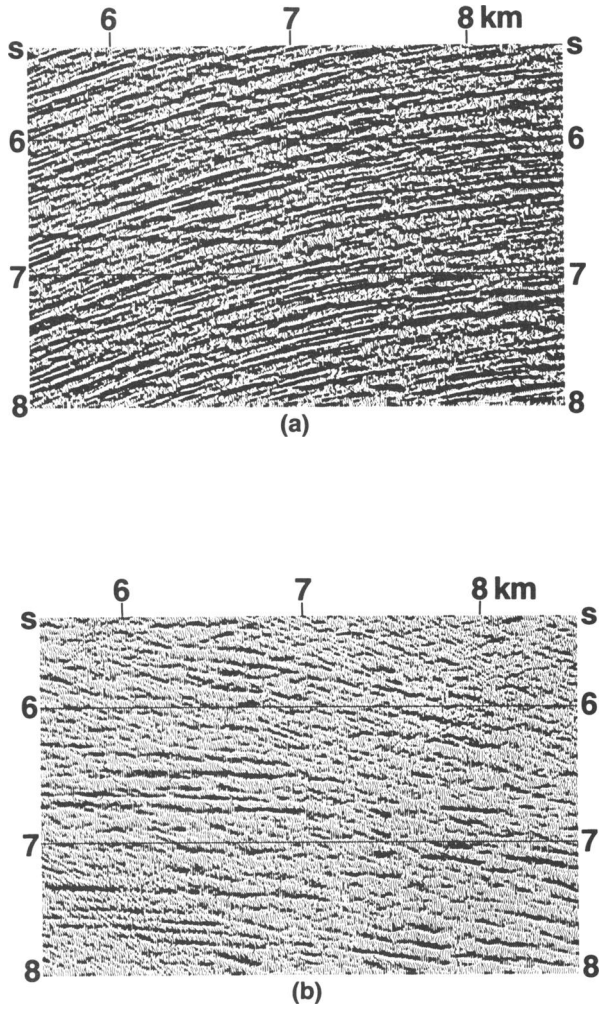

FIG. 18. Closeups of the simulated crew-noise experiment (crew noise here is five times stronger than the actual experiment). Deep section stacked with (a) uniform trace weights and (b) inverse-power trace weights.

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often form preferences for one or the other result on the basis of the perceived approximation to accuracy in wavelet detail. Based on the test results here, however, we should be wary that processing-related differences in signal detail often may be insignificant compared to position-related differences. (For 2-D surveying, streamer-position data historically have not even been collected.)

Line B

The importance of mis-synchronization between the survey and interference sources is illustrated in a second North Sea crew-noise-contaminated line (line B, Figure 22). The noise ship was stationed 40 km broadside to the center of the survey line, and the cycle time of its source was purposely kept near that of the survey source. Because of the nearly identical cycle times of the survey source and noise source, the crew noise on this section appears in localized zones rather than throughout the section. In the test, the firing time of the crew-noise source was changed periodically. As a result, the contaminated zones alternately occur at middle and late times. At this 40 km distance the crew noise was substantially weaker than in line A, but it had longer burst durations of about 1.5 to 2 s.

Because the firing times of the noise source and the survey source were nearly synchronized, the crew noise survives conventional CMP stacking with considerable strength despite the weaker noise levels. Also because of the synchronization of the sources, too many traces in a given CMP gather are contaminated by the crew noise for inverse-power weighting to be effective. The CMP gathers in Figure 23 illustrate the problem of source synchronization. Between 2 and 3 s in CMPs 5, 6, and 7, nearly every trace is contaminated with crew noise. Although the noise is not perfectly coherent from trace to trace after NMO correction, it still dominates the stack in this zone because of its strength relative to the signal.

Closeups of the zone around 2 to 3 s in line B (Figure 24) illustrate again the relative crew-noise suppression capabilities of uniform, inverse-amplitude, and inverse-power weighted stacks. The progressive shrinking of the crew-noise-contaminated zone as the exponent m in the trace-weighting expression [equation (9)] increases from 0 to 1/2 and to 1 is directly related to the number of contaminated traces within the CMP gathers. From our earlier discussions, inverse-power weighting is more effective than inverse-amplitude weighting in suppressing burst-like noise and hence can accommodate more contaminated traces within a CMP gather. Nevertheless, even inverse-power weighting cannot adequately suppress the crew noise when all traces in a gather are contaminated.

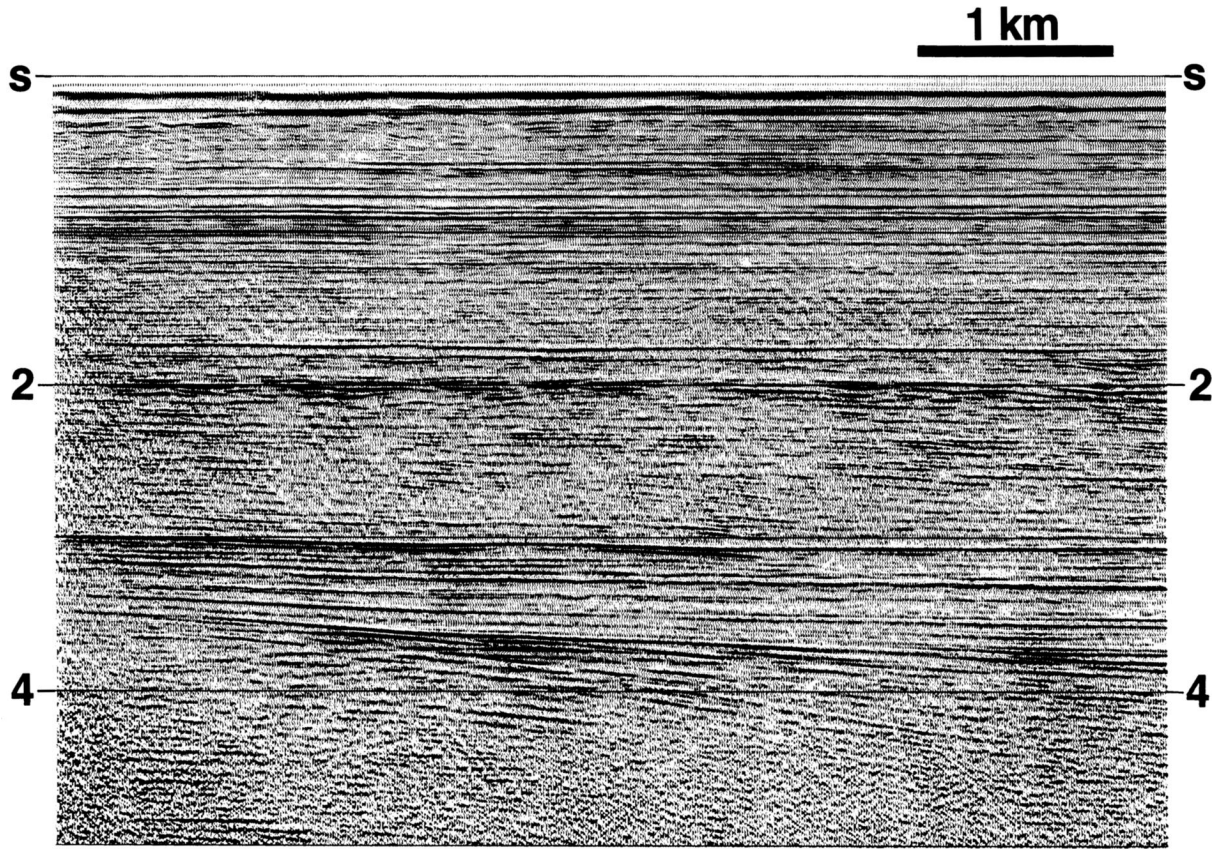

FIG. 19. Conventional CMP stack of data from the uncontaminated reference line in a controlled crew-noise experiment in the North Sea.

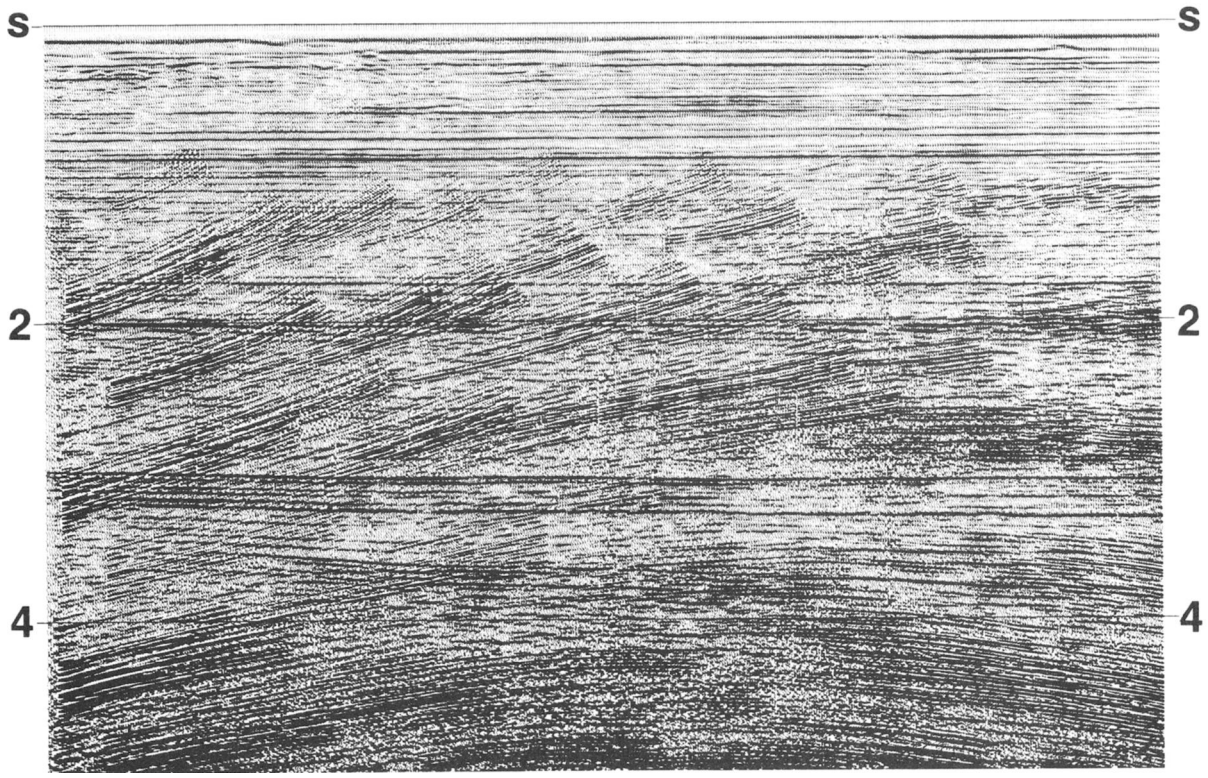

FIG. 20. Conventional CMP stack for crew-noise-contaminated line A of the North Sea experiment. The noise ship was 10 km broadside to the center of the line. The strength of the noise source was about three times that of the survey source.

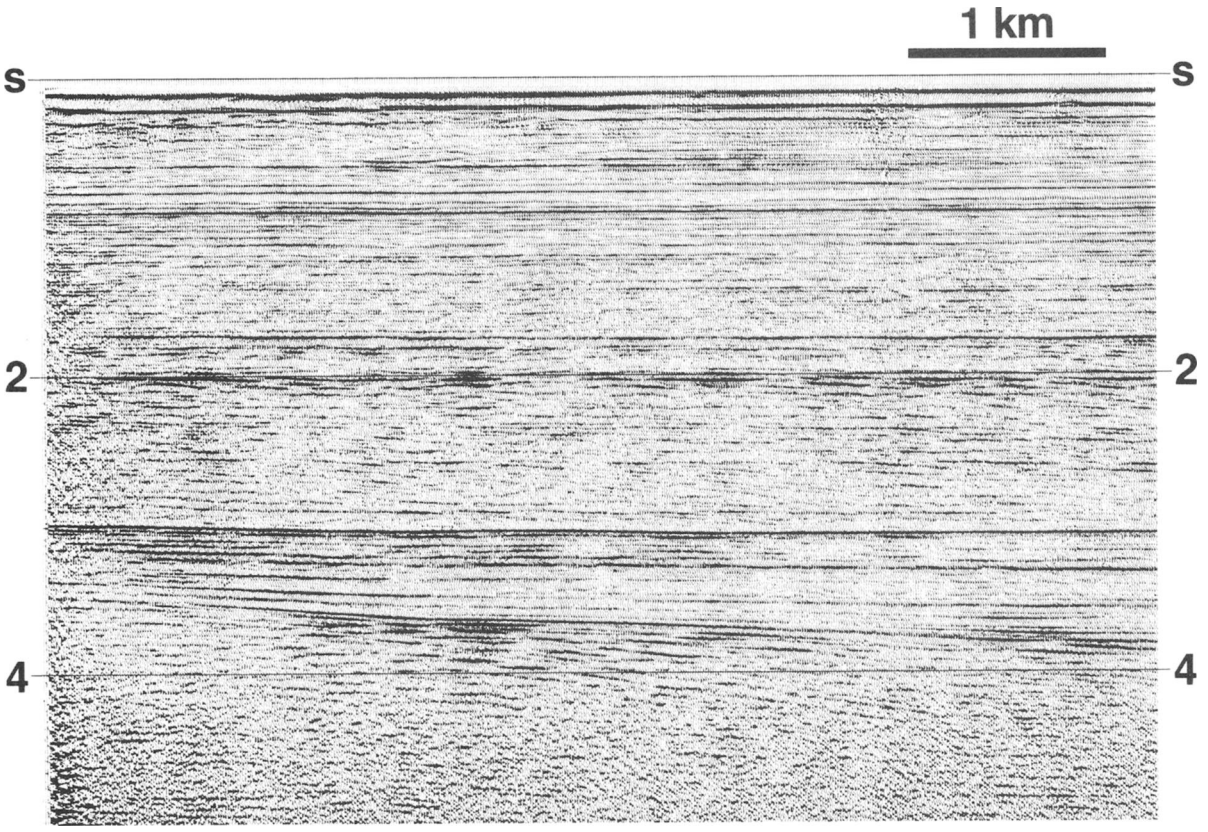

FIG. 21. Inverse-power weighted stack line A from the North Sea experiment. Compare with the uncontaminated section in Figure 19. Differences in reflection character and continuity are attributable to differences in subsurface coverage, not to the presence of the crew noise.

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CREWS WITH DIFFERING SOURCE TYPES

The sources used in the Gulf of Mexico and North Sea tests were impulsive. Commonly on land, and to some extent in marine surveys, either the survey source or the noise source may be a vibrator generating a long-duration sweep. We now examine the prospects for crew-noise suppression when one or both of the crews uses a vibratory source.

When uniform-weight stacking is used, the problem is almost identical regardless of whether neither crew, one crew, or both crews use a vibrator. In any of these cases, the received interference is just an incoherent background noise occurring on a few traces (impulsive interference) or many traces (vibrator interference) in the CMP gather. Further, since with linear sweeps correlation is approximately just a phase-only filter, the energy in the interfering noise is unchanged after correlation; it is therefore immaterial whether data are conventionally stacked before or after correlation. The important characterization of the noise is its long-term rms level, not the details of its waveform. Therefore, if one relies solely on uniform-weight stacking for interference reduction, there is no advantage in using vibrators instead of impulsive sources.

Now consider the use of weighted stacking, such as with inverse-power weighting. Suppose first that the survey ship uses an impulsive source, and that the interference is from a vibrator. The interference noise is rather constant along any given trace. Since each trace in a CMP gather appears to have an additional constant-power noise component, weighted stacking of the type described here simply degenerates to uniform stacking and, hence, is of no benefit.

If the roles of the survey crew and noise crew are reversed, the vibrator crew sees impulsive noise superimposed on its uncorrelated records and can expect good results from weighted (vertical) stacking prior to correlation. This approach is practical only for land applications because the continuous motion of marine sources precludes sufficient redundancy for vertical stacking. Postcorrelation, weighted stacking can be used in either land or marine surveys, but the situation becomes much the same as in removing the sweep interference from impulsive data. While compressing the sweep data, the correlation process spreads the impulsive noise over each entire trace; hence, weighted stacking again has no advantage over uniform stacking.

If both crews are using vibrators, the constant interference levels nullify any potential benefits from weighted stacking, both before and after correlation.

Other techniques are available for removing impulsive noise from vibrator data. For example, the noise block, which involves an upper amplitude limit with a slowly adapting threshold, is routinely used for vibrator data in land surveys and gives excellent rejection of burst-like noise. With noise blocking, the vibrator crew can overcome the interference from crews using impulsive sources.

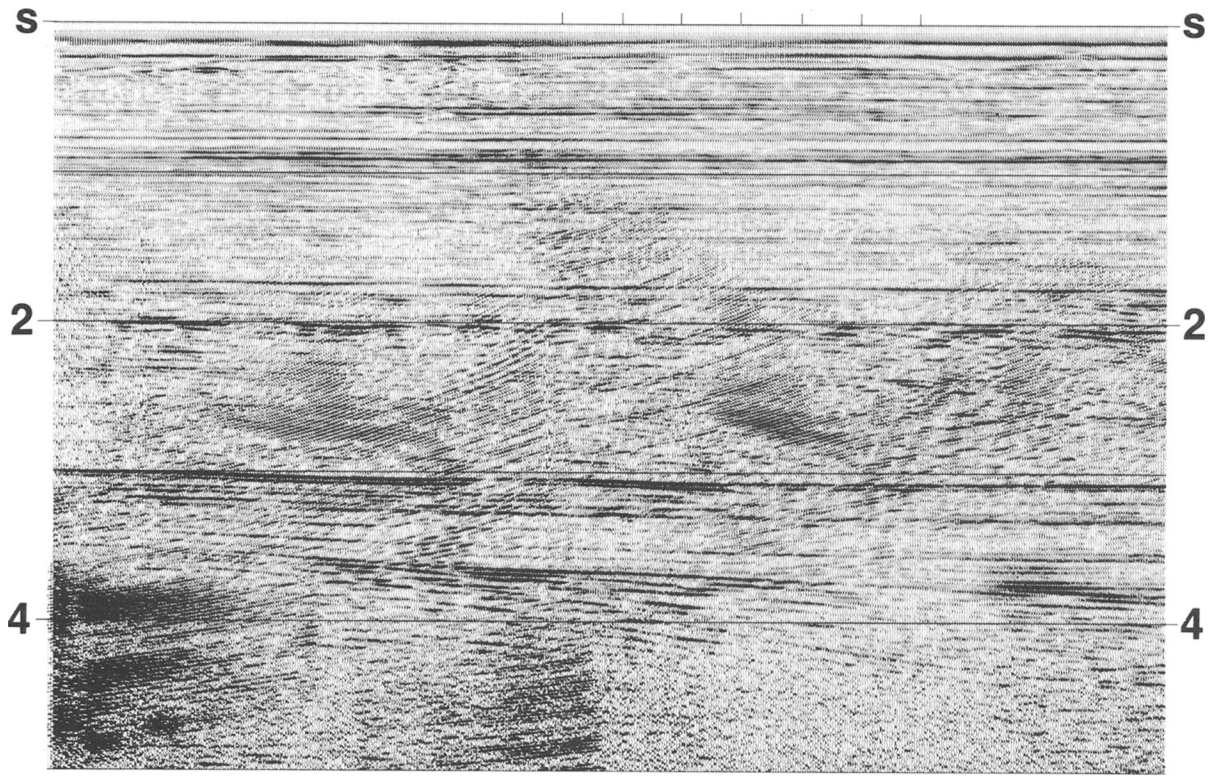

FIG. 22. Conventional CMP stack for crew-noise-contaminated line B from the North Sea experiment. The noise ship was 40 km broadside to the center of the line; the survey and noise sources were purposely shot at nearly identical cycle-time intervals.

PRESTACK DATA PROCESSING AND ANALYSIS

Through the preceding examples we have seen that crew-noise levels judged well outside current field specs can have an insignificant effect on CMP stacked data. Moreover, we have seen that inverse-power weighting can be highly effective in removing crew noise from CMP stacks while preserving details of signal amplitude and wavelet character. Thus, it would seem that with the combination of current processing and acquisition technologies one need not be troubled by levels of crew noise well beyond those that were judged unacceptable in the past. Nevertheless, it may be argued that today's interpretational needs place stiffer demands on acquisition and processing. Today we seek more resolution in processed data; we concern ourselves more with preserving wavelet amplitude and phase, and with doing so for reflection events having an increased range of dips; and we have renewed interest in analyzing variations in amplitude as a function of reflection angle in unstacked data. Moreover, one might suspect that the ability to image data effectively and to attack other types of noise in processing may be compromised either by the presence of the crew noise or by special action taken to suppress the noise.

There might be concern about data-dependent statistical processes such as predictive deconvolution, velocity analysis, and residual statics estimation, as well as deterministic processes such as dip filtering, prestack full or partial migration, and multiple suppression by weighted stacking. Evaluation of the interaction between crew noise, methods for its suppression, and the many processes routinely applied to enhance and image signal is a large and complex matter beyond the scope of this paper. Definitive conclusions about the interaction between crew noise and prestack issues in processing and interpretation must await the results of future studies. Our preliminary assessment, however, leads us to believe that interpretation of prestack data, as well as special processing to enhance and image the signal in prestack data, can tolerate considerably more crew noise than is allowed by current field specs, much as we have shown in our CMP stacks of the experimental data presented.

To cite one example, consider the analysis of reflection amplitude with offset. Such analysis is primarily applicable to shallower data, where the range of reflection angles in a gather is sufficiently large to observe the interpretable angle dependence. In the single-fold, near-trace section from our Gulf of Mexico experiment (Figure 7), observe again that the earliest 2 s of data show no evidence of crew-noise contamination despite the fact that the typically applied field spec was exceeded considerably. If crew noise is strong enough to be a problem at a depth of interest, robust methods for discarding outliers in fitting amplitude versus reflection angle might be employed. One might choose, for example, to minimize the ℓ_1 norm (Claerbout and Muir, 1973) rather than to use least-

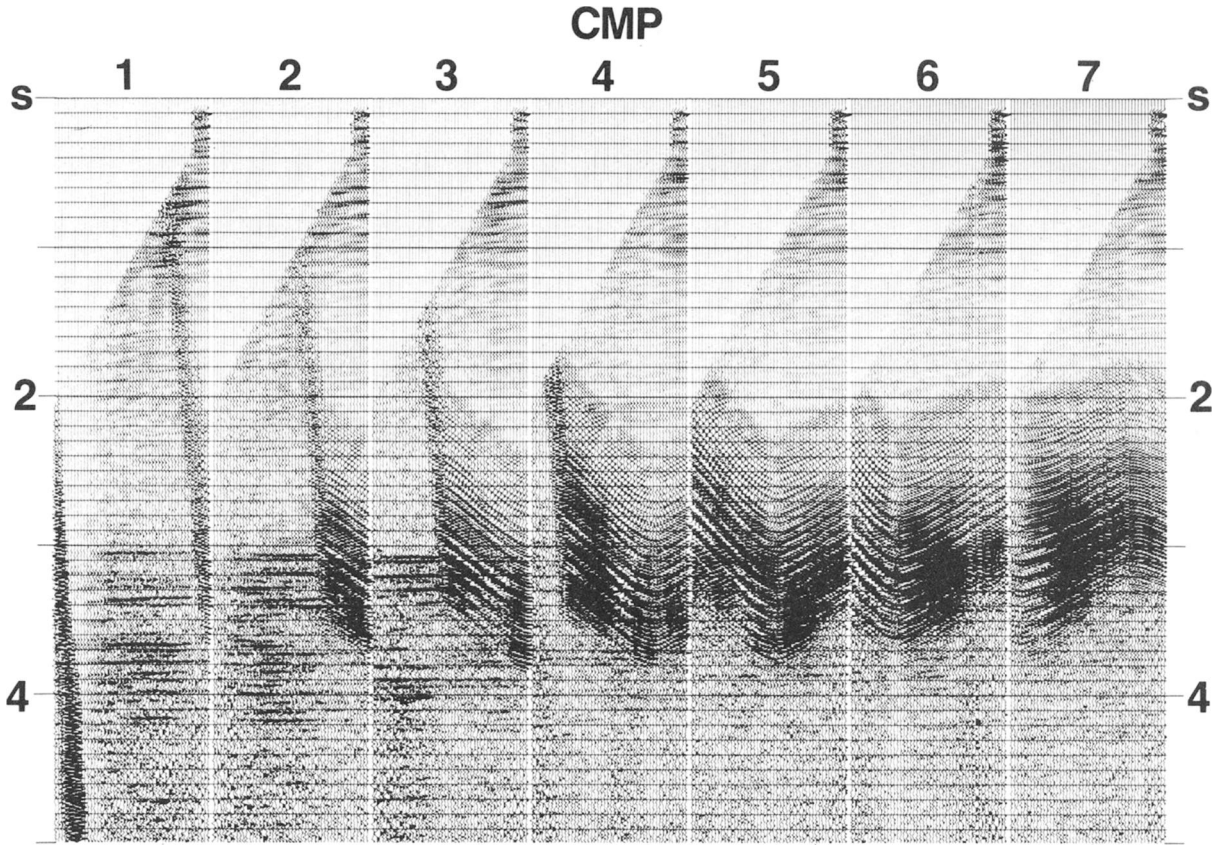

FIG. 23. NMO-corrected CMP gathers taken from line B at the locations indicated by the tick marks at the top of Figure 22. The near synchronization of the survey and noise sources causes the crew noise to appear on many (and sometimes all) traces in some CMP gathers within the zone between 2 and 3 s.

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squares theory. Again, such conjecture is as yet untested; further study is needed.

SUGGESTIONS FOR CREW-NOISE SPECS

The results from the Gulf of Mexico experiment and the North Sea experiment indicate that current crew-noise specs based on the allowable peak-amplitude level of crew noise are likely too stringent. Moreover, they do not take into account the properties of crew noise and how conventional CMP stacking, perhaps augmented by trace-weighting schemes, exploits those properties to suppress the noise in final, processed data. The noise, which appears ominously organized on shot records, is erratic across traces within CMP gathers. As a result, conventional, uniform-weighted stacks respond not to the *peak* noise amplitude, but rather to the *rms* amplitude at each time sample across a gather.

In general, a well-chosen spec should take into account geologic environment, acquisition parameters, and processing steps, and yet it should be easily implemented in the field. Based on our understanding from the previous examples, the severity of crew-noise contamination will depend on several factors, including signal strength from target zones, near-surface or sea-floor properties, relative strengths of the survey and interference sources, the number of interfering crews, the duration of the strong portion of the crew noise, CMP fold, and the type of stacking to be performed on the data (i.e., conventional, inverse-power weighted, etc.). Here we lay the groundwork for two different crew-noise specs, one based on conventional CMP stacking and one based on burst-removal techniques, such as inverse-power weighted stacking.

First consider the situation in which the data will be stacked conventionally with uniform trace weights. In the absence of crew noise, the fundamental noise spec is that for ambient noise, typically the rms amplitude measured over an entire signal-free trace. We propose considering crew noise just the same as ambient random noise because it also is incoherent across the CMP gather (its distribution in time is immaterial). Just as for ambient noise, it is unnecessary to form CMP gathers in the field so as to measure the crew-noise level across the gather; rather, the rms crew-noise level can simply be measured over the duration of representative crew-noise-contaminated noise strips. The rms levels of ambient noise and crew noise within the seismic bandwidth can thus be

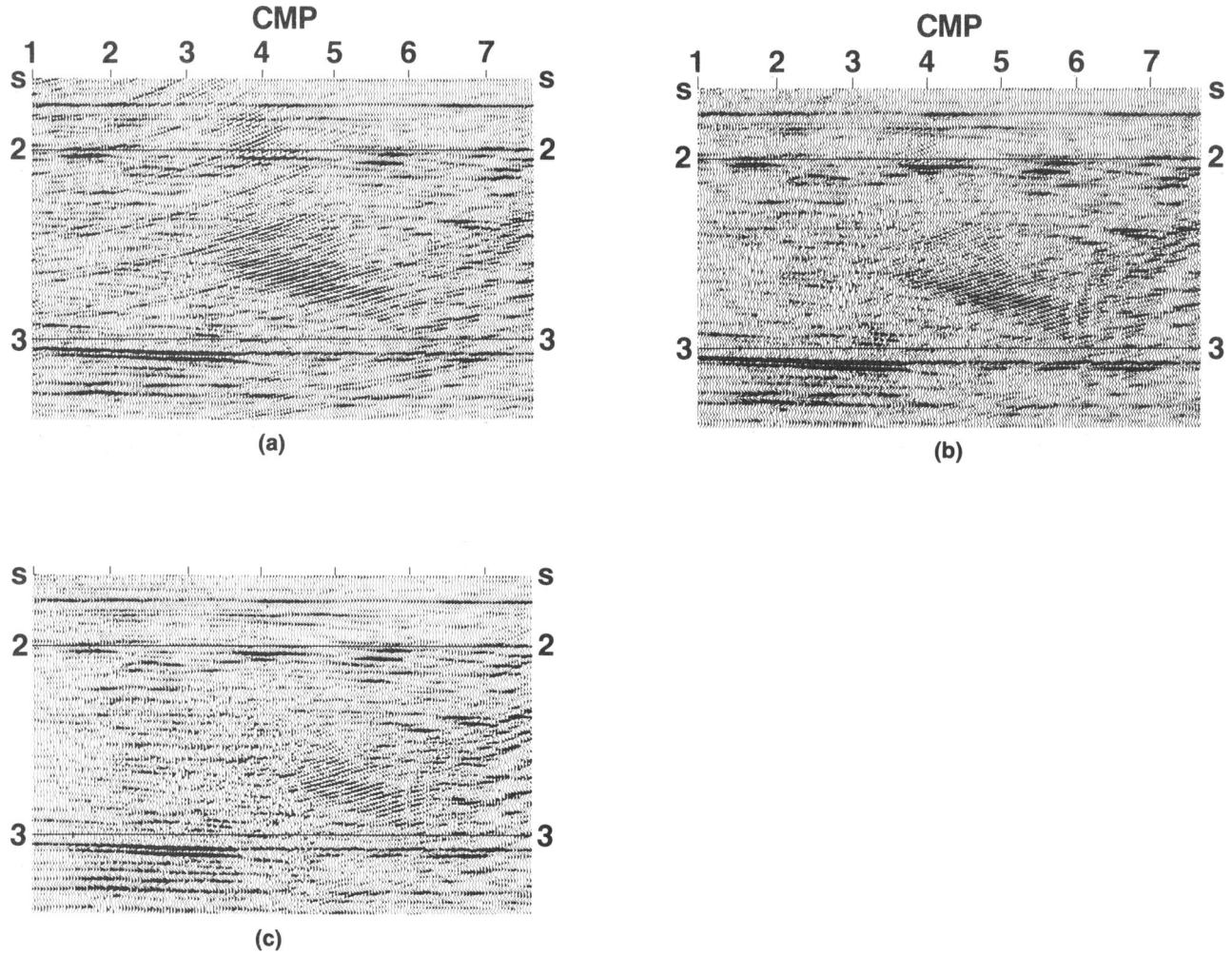

FIG. 24. Closeups of the zone between 2 and 3 s for line B with (a) uniform weighted stack, (b) inverse-amplitude weighted stack, and (c) inverse-power weighted stack. CMP gathers at locations 1–7 are shown in Figure 23.

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measured simultaneously and compared against a single cable-noise spec.

Next consider the spec based on inverse-power trace weighting or some other burst-removal technique. The appropriate spec involves a combination of the duration of the strong burst noise, measured as a percentage of the shot firing interval and the rms amplitude measured over the portions of traces that exclude the burst noise (again, band-limited to within the band of signal frequencies). The greater the percentage a trace is corrupted by a crew-noise burst, the larger the number of traces contaminated by strong noise that will be effectively removed from an inverse-power-weighted stack. A spec that takes into account inverse-power weighted stacking thus has two components: the effective reduction in fold due to some traces being assigned very small weights, and the rms level of the noise on the remaining traces that will be included in the stack.

The actual measurements can be done with the field quality-control capabilities of modern digital streamer systems, with readily available analog instrumentation, or by an operator using a visual display such as an oscilloscope. Digital systems are particularly well suited because measurements can be made and results presented in an easily understandable form without requiring additional calculations by the operator. Although acceptable results can be obtained with available analog devices such as meters, counters, and limiters, probably at least a few simple calculations will be required from the operator. The visual method sometimes used in today's surveys involves displaying the noise strip along with a sinusoid of known amplitude for comparison. This method is subjective and, at best, is probably not an accurate way to estimate the percentage of the trace contaminated by crew noise.

APPLICATIONS OF THE RECOMMENDED CREW-NOISE SPEC

Recall that our noise-contaminated Gulf of Mexico data would be judged far outside typical current specs based on the peak amplitude of the noise. The rms level of the combined crew noise and ambient noise (as measured over the entire length of a trace) was shown in Figure 3b to be 0.1 to 0.3 Pa on a long-offset trace and was as much as 0.5 Pa at shorter offsets. These levels are just at the usual 0.3 to 0.5 Pa spec for cable noise. Thus, the contaminated Gulf of Mexico data would be within the recommended crew-noise spec, and, consistent with the results seen in Figure 8, the uniformly weighted CMP stack should be of good quality.

For weighted stacking, we note that the duration of the strong crew noise was approximately 1 s; hence, about 10 percent of the 10 s cycle was contaminated. This means that of the 60 traces in our CMP gather, roughly six traces were contaminated by crew-noise bursts over any given time window. Since inverse-power weighting had the effect of automatically deleting those traces (in the late, weak-signal zones, where the noise was troublesome), the net action was to reduce the CMP fold at depth from 60 to 54. The rms level of the remaining crew noise and ambient noise after the strong bursts have been removed was less than 0.1 Pa (bottom curve, Figure 3b). A 0.1 Pa level on 54 traces is comparable to a 0.105 Pa level on 60 traces. Either is well within the cable-noise spec, and the quality of the resulting inverse-power weighted section was found to be comparable to that of the uncontaminated section.

Suppose that our experimental survey data had contamination from two or more other seismic crews. Since the firing intervals of the sources of the different crews generally differ (or can be chosen to do so), our 60-fold CMP gathers would typically have noise on $6n$ traces, where n is the number of noise sources. Where weighted stacking could be used, the decision to time-share could rationally be based on the tolerable reduction of CMP fold. For argument, suppose that three crews are operating in an area, that five traces within a CMP gather are typically contaminated at any given time by any single noise ship, and that a reduction from 60 fold to 45 fold (a 15 percent reduction in S/N ratio) poses no problem for the final, processed stacks. Then, with inverse-power weighting, our survey data can tolerate contamination from as many as three other seismic crews. Hence, all three of the crews can operate simultaneously; none would need to go idle. The tradeoff would be a decrease in fold, at depth, from 60 to 50 and a marginal increase in processing effort of less than 5 percent, offset by an increase in productivity of each crew by a factor of three.

CONCLUSION

Specs used in the quality control of seismic data acquisition should be set with consideration as to how the entire seismic system (from acquisition through final processing and interpretation) responds to any given factor in the field. Typically, specs are not based on this system viewpoint and, to assure data quality, have been highly conservative. This overly conservative practice seems to be true also for the spec that limits the tolerable amount of interfering noise from other seismic crews.

In the Gulf of Mexico experiment, the crew-noise spec was exceeded by as much as a factor of 3 to 8, and yet *unstacked* data showed no degradation from 0 to 2 s and conventional, uniform-weighted CMP stacked sections showed negligible degradation down to 5 s. In the deeper part of the section, where the crew noise did manage to survive the conventional stack (weakly), the use of inverse-power trace weights readily suppressed the noise. In the simulated experiment, where the crew-noise spec was exceeded by about *an order of magnitude*, the inverse-power weighted stack was also uncompromised. As long as the firing intervals of different survey crews operating in an area are different, several crews can conduct their surveys simultaneously under conditions in which typical current specs have allowed only one crew at a time.

We propose a basis for defining the crew-noise spec that is appropriate to the empirically observed characteristics of the noise. Rather than a spec based upon the peak amplitude of the crew noise, we recommend one based upon the rms amplitude measured over entire traces. This spec, which is more suitable for conventional CMP stacking than are current ones based on peak amplitude, is readily measurable with digital telemetry systems already in use in the field. Alternatively, for

inverse-power-weight stacking (or other methods of suppressing large-amplitude noise) the appropriate spec would involve a combination of the percentage of the traces in a CMP gather corrupted by noise burst at any time, the tolerable reduction in fold, and the rms amplitude of the portions of crew-noise-only traces that exclude the burst. With onboard quality control in today's digital telemetry systems, a spec based on such measurements could be readily implemented in the field. For either type of spec, measurements should be done on data band-limited to the signal-frequency band. While the proposed specs can be considerably more tolerant than the old standards, in the sense that less time-sharing would be called for, they can remain conservative in that they ensure stacked data will be effectively free of crew-noise contamination.

For reflection times of less than about 2 s, the proposed specs remain conservative for prestack data as well. Future study may show that more stringent specs are required for detailed stratigraphic interpretation and analysis of deeper prestack data.

ACKNOWLEDGMENTS

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APPENDIX

EXPECTED POWERS IN POSTSTACK RANDOM NOISE AND BURST NOISE

We derive here the variances for the poststack random noise [$\bar{n}$ in equation (4)] and the poststack burst noise [$\bar{b}$ in equation (5)]. We assume, for simplicity, that the variance of the random noise on all N traces is the same value σ_n^2 and the variance of the burst noise on all M traces where it appears is σ_b^2. The variance of $\bar{n}$, the random noise component in the stack, is

$$\sigma_{\bar{n}}^2 = \frac{\sigma_n^2 \sum_1^N w_i^2}{\left(\sum_1^N w_i\right)^2} = \frac{\sigma_n^2 \sum_1^N P_i^{-2m}}{\left(\sum_1^N P_i^{-m}\right)^2}, \tag{A-1}$$

where the w_i are the constant weights [see equations (8) and (9)] applied to the traces. From equation (8),

$$\sigma_{\bar{n}}^2 = \frac{\sigma_n^2[(N-M)(S^2+\sigma_n^2)^{-2m} + M(S^2+\sigma_n^2+\sigma_b^2)^{-2m}]}{[(N-M)(S^2+\sigma_n^2)^{-m} + M(S^2+\sigma_n^2+\sigma_b^2)^{-m}]^2}. \tag{A-2}$$

The same procedure applied to the poststack burst noise of equation (5) yields

$$\sigma_{\bar{b}}^2 = \frac{\sigma_b^2 \sum_1^M w_i^2}{\left(\sum_1^N w_i\right)^2} = \frac{M\sigma_b^2(S^2+\sigma_n^2+\sigma_b^2)^{-2m}}{[(N-M)(S^2+\sigma_n^2)^{-m} + M(S^2+\sigma_n^2+\sigma_b^2)^{-m}]^2}. \tag{A-3}$$

We can gain some insight into weighted stacking by examining equations (A-2) and (A-3). First, the poststack SRN ratio is relatively insensitive to the prestack SBN ratio, regardless of the choice of weighting. To see this, consider uniform weighting $m = 0$. Equation (A-2) then reduces to

$$\sigma_{\bar{n}}^2 = \frac{\sigma_n^2}{N}.$$

The reduction in noise-to-signal ratio achieved by stacking is the same as this reduction in noise power because, with the normalized weights, stacked signal power equals unstacked signal power. Now consider either inverse-power ($m = 1$) or inverse-amplitude ($m = 1/2$) weighting and the two limiting cases $\sigma_b \to 0$ and $\sigma_b \to \infty$, with S and σ_n held fixed. As $\sigma_b \to 0$, equation (A-2) gives $\sigma_{\bar{n}}^2 \to \sigma_n^2/N$, as above. As $\sigma_b \to \infty$, we get $\sigma_{\bar{n}}^2 \to \sigma_n^2/(N-M)$, the same action as when the CMP fold is reduced from N to $N-M$. $\sigma_{\bar{n}}^2$ varies monotonically between these two limiting values.

Consider next the action of weighted stacking on burst noise. For very small burst noise, i.e., $\sigma_b \ll S$, equation (A-3) gives

$$\sigma_{\bar{b}}^2 \approx \frac{M}{N^2}\sigma_b^2,$$

independent of the weighting scheme used. (Since σ_b is small, it cannot affect the values of the weights.) When $\sigma_b \gg S$, however, the choice of weighting scheme can make a large difference. As $\sigma_b/S \to \infty$, equation (A-3) approaches

$$\sigma_{\bar{b}}^2 = \frac{M}{(N-M)^2}\sigma_b^{2-4m}(S^2+\sigma_n^2)^{2m}. \tag{A-4}$$

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For the three different weighting schemes, we get the following.

Uniform weighting ($m = 0$):

$$\sigma_{\bar{b}}^2 = \frac{M}{(N-M)^2}\,\sigma_b^2 \to \infty \quad \text{as} \quad \sigma_b \to \infty.$$

Inverse-amplitude weighting ($m = 1/2$):

$$\sigma_{\bar{b}}^2 = \frac{M}{(N-M)^2}\,(S^2 + \sigma_n^2) = \text{constant} \quad \text{as} \quad \sigma_b \to \infty.$$

Inverse-power weighting ($m = 1$):

$$\sigma_{\bar{b}}^2 = \frac{N}{(N-M)^2}\,\frac{(S^2 + \sigma_n^2)^2}{\sigma_b^2} \to 0 \quad \text{as} \quad \sigma_b \to \infty.$$

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