shot records with surface angles ranging from $-60°$ to $+60°$ requires 117 p-values. Both of the migrated images in Figure 2 are acceptable, even the image that used only 31 p's. The prediction of 935 p-values provided by Stork and Kapoor's criterion (here the width of migration region is 12,000 m) would make delayed-shot migration less efficient than common-shot migration, in violation of their (2004) no free lunch postulate.

Third, delayed-shot migration has seen industrial use for nearly two decades (Whitmore, 1995), with no particular objections raised to its p-sampling until now. Given useful delayed-shot migrated results with far fewer p-values than we use, is there a sampling issue at all?

Etgen (2005) addressed this question and suggested that the success of delayed-shot migration depends on the presence of an unaliased source antenna, i.e., well-sampled common-receiver gathers. This suggestion is more vague than our criterion, and it stops short of requiring that any specific sampling conditions be imposed in forming the delayed-shot records. Our criterion, rather than ensuring a high-quality image (which can often be obtained with fewer p's), gives necessary and sufficient conditions for the recovery of all the original unaliased data from the process of slant stack $\rightarrow$ migration $\rightarrow$ demigration $\rightarrow$ inverse slant stack. When the conditions are met for forming unaliased delayed-shot records given — in our paper and restated above — our criterion gives a sufficient condition for delayed-shot migration to give images similar to common-shot migration.

Fourth, according to Stork and Kapoor (2004), we claim that their sampling equation for N_p depends on aperture, not migration region. To this, we plead guilty. We based this remark on their (2004) statement, "$X_{max} = (n_x{}^* d_x)$ is the width of the region we desire to propagate over or about twice the aperture, $X_{max} = 2.0^*$Aperture." Indeed, Stork and Kapoor's equation for N_p depends on aperture as we claim, unless the word *about* somehow changes the value of X_{max} in their 2004 abstract to W_m in their Discussion.

Fifth, we agree with Stork and Kapoor that the advantage of the (surface) angle gathers provided by delayed-shot migration (e.g., Figure 4a in our paper) is limited. However, that advantage should not be underestimated. These gathers allow a certain amount of further processing and muting, and they certainly give some information about the correctness of the migration velocity field. As we show in our Figure 4b and c, subsurface angle gathers can be obtained from delayed-shot migration, and they are similar in quality to those obtainable from common-shot migration.

We finally come to the key point made by Stork and Kapoor. We assume when they state that "the output space often requires greater sampling than the input space because the process of migration spreads the data out," they refer to sampling in p's. If that is the case, then we disagree, and we use the example of the very successful Gaussian beam-migration method of Hill (2001).

Gaussian beam migration (or any slant-stack migration) of common-receiver methods is a form of delayed-shot migration, which swings slant-stacked traces (localized delayed-shot records) over a full-migration aperture. As Hill points out, this method produces good results when the p-sampling obeys a rule similar to our disputed criterion, with N_s now representing the number of shot points contained in the local slant stack. Here, N_s is typically much smaller than the number of shots in a spread length so that the Gaussian window is typically much shorter than a spread length). For Gaussian beam migration, the migration aperture can be enormous, compared with $N_s \Delta x_s$, so Stork and Kapoor's objection, if correct, should apply to Gaussian beam migration even more than it does to delayed-shot WEM. This objection seems to be crucial to Stork and Kapoor's assertions, and the fact that Gaussian beam migration produces good images refutes it.

In summary, we have presented delayed-shot migration as an efficient alternative to common-shot migration under certain conditions, which we stated in our paper. We do not claim that delayed-shot migration is universally applicable, and we thank Stork and Kapoor for giving us the chance to repeat this point. We disagree with Stork and Kapoor's assertion that the number of p's needed for delayed-shot migration depends on the migration width. Rather, we believe that our published criterion, which allows the inverse processes to migration and slant stack to reconstruct the unaliased portion of the original data, is sufficient for delayed-shot migration to give good images when it is applicable. If our objective is merely to produce a good image (and not to reconstruct the original data) then, when delayed-shot migration is applicable, it might be possible to use a smaller number of p's.

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Response to the reply

Response by Christof Stork and Jerry Kapoor

We propose that the underlying differences in our perspective from that of Zhang et al. are that Zhang et al. determine the number of P-values necessary to "reasonably image the major structure," while we try to determine the number of P-values "necessary to use all aspects of the data for imaging." We base our perspective on sampling theory, while Zhang et al. justify their analysis mainly on examples and practical experience. While Zhang et al. do claim their formula of P-values is for a complete migration, the fact that the formula only works during convenient circumstances — despite the linearity of the problem — undermines its validity.

We strongly agree that practical experience counts for a lot in dealing with seismic data, but we urge caution on the following: (1) Using the number of P-values proposed by Zhang et al. will subtly reduce the quality for the expensive parts of the image, such as the high-frequency components, the deep components, the steep dips, and possibly transmission through complex velocities that scatters energy. (2) Zhang et al. are making their speed claims by comparing their empirical number of P-values with migrating all shots of shot migration, without considering the similar empirical justification for decimation of shot gathers.

The difference of these perspectives is highlighted with synthetic examples that are noise free and ones that include noise. Because seismic surveys have significant data redundancy (e.g., fold), the effects of decimation are not apparent when migrating noise-free synthetic data. Yet the decimation is apparent when migrating synthetic data that includes noise, because the reduced-data redundancy also does not cancel the noise. Thus, the use of noise-free synthetic data will indicate the minimum amount of P-values needed to "reasonably image the major structure" while the use of synthetic data with noise will indicate the amount of P-values "necessary to use all aspects of the data for imaging."

Because of noise in seismic data, our imaging algorithms should preserve the redundancy of the seismic data. Or, if we are losing some redundancy through decimation, we should be aware of the level of decimation so that we do it deliberately and carefully, particularly in light of changing acquisition parameters. Moreover, understanding the level of decimation between different migrations lets us better compare migrations.

The circumstances that Zhang et al. state are necessary for effective delayed-shot migration are long spread length and small shot interval. We propose that the reason these conditions aid delayed-shot migration is that they also produce a considerable data redundancy where the decimation of migrating a limited number of P-values is less apparent. We think their proposed equations and justifications should hold for short spread length because of the linearity of the problem.

We demonstrate how linearity should hold for any cable length with the following example: Consider migrating a data set with long spread length and small shot interval which Zhang et al. state is necessary for efficient delayed-shot migration. Break the delayed-shot migration down into numerous identical delayed-shot migrations of common-offset sections and stack them after migration. Because of the linearity of migration, the stack of these numerous identical migrations will produce the same result as migrating all the data in one migration. If each common-offset section is a onefold section, the migration of each individual section should image fully a structure in constant velocity if it migrates all components of the data. But using the equation for the number of P-values proposed by Zhang et al. will not fully reconstruct the image for a singlefold common-offset section for typical marine-survey parameters.

Just as migrating an impulse with the specified number of P-values produces a circle with artifacts, migrating the common-offset sections with the same P-values will produce artifacts. The stacked image of noise-free synthetic data will not have artifacts because the extra redundancy cancels the artifacts. The fact that each delayed-shot migration of one-fold common-offset section doesn't reconstruct fully the image — when other migration schemes do reconstruct fully the image — demonstrates the decimation when using too few P-values — as proposed by Zhang et al. for typical marine streamer data.

Essentially, this linearity argument says that the migration parameters should not depend on how much data you have, such as maximum offset, which appears in the Zhang et al. equation.

We acknowledge that delayed-shot migration is a nice approach to 3D wave-equation migration that may offer practical advantages in some situations. But we do not think that one of those advantages is that a complete delayed-shot migration is mathematically more efficient than a complete-shot migration for typical marine-streamer survey geometries. Moreover, if your interpretation objective involves the expensive components of the image — such as the high-frequency components, the deep components, the steep dips, and transmission through complex velocities that scatter energy — underutilizing the data by migrating a limited number of P-values can affect your interpretation.