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A Comparison Of 3D Multi-Component (9C) Data Image Volumes Acquired With Conventional and Simultaneous Source Techniques (KWP Phase II)

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Summary

The main goal of this project is to help make the seismic acquisition of multi-component (9C) data commercial to our industry. It is not realistic to expect 9C data to be acquired in the same metered time as 1C or 3C data. However, with step changes in acquisition methodology, 3C geophones, processing resources, data compression and reconstruction technologies we believe the recording of high quality cost effective 9C seismic surveys is realistic. With the main goal in mind we designed our test volumes to address four major objectives.

First, we set out to obtain a high quality and high density S-wave sourced data set conducive to attribute analysis and interpretation by the industry. Second, to acquire a high resolution P-wave volume utilizing a single, short sweep with the Fire-At-Will (FAW) simultaneous sourcing technique. Third, to collect a Nyquist gridded oversampled survey with both S and P-wave sources for empirical Compressive Sensing (CS) evaluation. Last, we wanted to take a cursory proof-of-concept look at FAW acquisition with S and P-wave Vibroseis units simultaneous sourcing. As it turns out the last objective, the FAW sourcing technique, may hold the key to the commerciality of future 9C seismic data acquisitions. Also, the CS technology could provide another step change in the commercial application of Shear wave acquisition technology.

Theory

The technology and the desire to acquire and interpret 9C seismic data volumes has been a part of the industry since the 1970's. Up to the present time a couple of major hurdles have prevented the viability of 9C seismic data acquisitions. One hurdle pertains to the requirement of different Vibroseis units that produce horizontal component motion. Also, the source point (SP) must be recorded with a vertical Vibroseis motion and two orthogonal horizontal motions into 3C geophones. This requires a minimum of three times the source effort over 1C and 3C recordings. Due to the extra acquisition time and cost, 9C surveys have been rare in our industry.

The other hurdle concerns the processing complexities of the multi-component data. Depending on the components to be interpreted, six to nine times the amount of data must be handled. Also, special component sorting and rotation algorithms are required. Therefore, processing and interpreting the 9C data sets that do exist have been largely R&D projects. The lack of industry experience in the processing of S-wave data volumes has led to turn-around time issues for the interpreter. We believe that the commercial application of 9C seismic acquisition will lead to the commercial aspect of processing and interpretation.

In this project, we collected five, multi-component, data volumes covering six square miles of surface area in the Permian Basin of West Texas, approximately 20 miles SE of Midland. The seismic parameters were designed to address 9C sourcing productivity through simultaneous source techniques. Two of the data sets provide a conventional S- and P-wave baseline. Also, we acquired oversampled source and receiver gridded data that can be decimated as if deployed with CS design technology and reconstructed back to the oversampled grid. This yields empirical data along with the reconstructed data to evaluate the CS claim of a comparable image to seismic surveys recorded in a conventional Nyquist manner with four to nine times the source and receiver trace density.

Method

The experiment was acquired into a six-square-mile surface area. Twenty-two, three-mile-long E/W receiver lines (RL) spaced at 495 ft with 192 3C receivers per line (RP) on 82.5 ft surface intervals defined the receiver configuration. Forty-eight, two-mile-long N/S source lines (SL) at 330 ft intervals with 256 potential SPs at 41.25 ft spacing were available for sourcing and deployed orthogonal relative to the receiver lines. Due to the culture in the oil field over 1/3 of the SPs could not be acquired. A total of 10 P-wave Vibroseis units and 8 S-wave Vibroseis units were available for the project. The bandwidth of the P-wave source sweep was 2-110 Hz and 1-55 Hz for the S-wave sweep.

The P-wave baseline volume T1 was acquired in a conventional, no simultaneous sourcing, flip/flop manner with two Vibroseis units synchronized to comprise a set. Four of the two Vibroseis sets were positioned over the 6 square miles for production efficiency. In theory with a 6 sec sweep and a 6 sec listen a source point could be recorded every 12 sec, in reality a point was recorded every 22 sec. The baseline P-wave source grid was 990 ft SL with 82.5 ft SP, 1270 total points. T2 was the high density P-wave data set sourced with a single short 6 sec sweep and 10 single Vibroseis units utilizing the FAW acquisition methodology. The FAW approach allows the Vibroseis operator to initiate the sweep upon SP arrival disregarding the other Vibroseis sets. With the 10 single Vibroseis units scattered over the six square miles, SPs were acquired at 3 sec intervals. The production rate allowed for the maximum source grid utilization of 330 ft SL and 41.25ft SP, 7395 total points.

The S-wave baseline survey T3 utilized four, two Vibroseis sets deployed in the conventional flip/flop sourcing manner. The sweep length was 16 sec coupled with 8 sec of listen time. Two orthogonal S-wave component motions (2C) were acquired for each SP. It took 103 sec on average to get both the motions. The SL grid for T3 was 990 ft with 165 ft SP intervals, 639 total 2C SPs were acquired. The high resolution S-wave volume T4 was parameterized with four, two Vibroseis sets using an 8 sec sweep with an 8 sec slip time for the Slip-Sweep (Rozemond,1996) acquisition technique. It took close to a minute for an average 2C SP or 30 sec per motion. The source grid was 330 ft SL and 82.5 ft SP intervals, 3318 total 2C points. The FAW technique permits the most SPs in a metered time frame. However, being familiar with Slip-Sweep acquisition the decision was made to record the high density S-wave data set T4 with the Slip-Sweep methodology. Yet, we wanted to get a look at the FAW methodology applied to a 9C survey.

Unfortunately, at the end of our research budget for this project, we had just enough time to take a cursory look at a FAW volume T5 with 990 ft SL and 165 ft SPs. We tested a potential alternate commercial application by combining P- and S-wave Vibroseis units. Eight single S-wave Vibroseis units along with two P-wave Vibroseis units utilized a sweep length of 16 sec and acted completely independent of the others. The Vibroseis operator initiated the sweep upon SP arrival. The test completed, 629 SPs with an average production rate of 24.3 seconds for each 2C SP. Figure 1, summarizes all the test parameters and timing. A pictorial view of the source and receiver layout for each data volume is presented in Figure 2. It is a good visual aid for presenting the source density difference of the data volumes. Figure 3 displays the fold in the natural bin dimensions associated with each volume.

Summary Test Parameters
Actual Time (Time On Vib Point + Travel)

4195 3C Receivers: Lines 495' Stations 82.5'

Data Set	Description “ = Seconds	S Line (Feet)	S Station (Feet)	SP #	Actual Time “ = Seconds
1 **	1-6” (C) 4 sets of 2	990 P-	82.5	1270	22” (7:45 hrm)
2 **	1-6” FAW 10 sets of 1	330’ P-	41.25	7395	3” (6:08 hrm)
3	1-16” (C) 4 sets of 2	990 S-	165	636*2	103” 2 Motions (18:15 hrm)
4 **	1-8” (8”S) 4 sets of 2	330 S-	82.5	3318*2	59.5” 2 Motions (54.5 hrm)
5a	1-16” FAW 8 sets of 1	990 S-	165	629*2	24.3” 2 Motions (4:13 hrm)
5b	1-16” FAW 2 sets of 1	990 P-	165	636	9.8”(1:44 hrm) extrapolate 8 vibs

** Test 1,2 and 4 Can Be Compressive Sensing (CS) Decimated and Reconstructed **

Note: 1,3 Conventional Flip/Flop – 2,5 FAW Fire-At-Will – 4 Slip Sweep

Figure 1: Source Parameter Summary Table

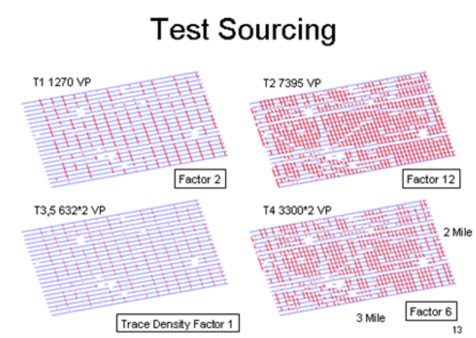

Figure 2: Source (Red) and Receiver (Blue) Deployment

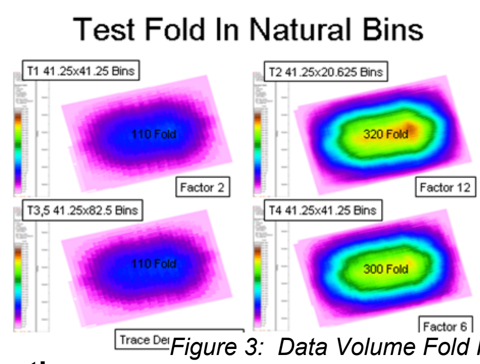

Figure 3: Data Volume Fold Range In Natural Bins

Observations

The first step in the evaluation of the data volumes begins with the extra pre-processing steps associated with the 9C data volumes. These data have been recorded with three-3C source gathers (SG) associated with each SP. The S-wave data components as recorded in the field are shown in Figure 4. The subscripts i and x signify the field component source and receiver orientation relative to the receiver line direction. Therefore, Ri and Si represent an inline horizontal receiver pointed in the RL direction and a source motion in the RL direction. Rx and Sx are the orthogonal receiver direction and source motion. The data is sorted pre-rotation so that for each combined S-wave SG, both motions are associated with every 2C receiver location.

For example, with every source and receiver location there are 4 traces; SiRi, SiRx, SxRi and SxRx. After rotation as depicted in Figure 5 these data are ready to be processed as the transverse – transverse (TT) and the radial – radial (RR) volumes. The cross diagonals (RT) and (TR) can also be processed, especially as a rotation check. Normally the cross diagonals have little data on them, compared to the TT and RR volumes. A rotated SP is shown in Figure 6, which happens to show the “perfect case” in that the source and receivers lie on a 2D line as pictured in the middle part of Figure 4. Note that the RR-SG has significant P-wave contamination, considered normal and not usually an issue in the processed data. The TT-SG shows nearly all S-wave data. In a perfect world without anisotropy and positioning errors there would be little or no data on the cross diagonals.

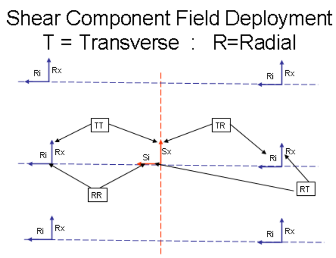

Figure 4: Field Deployment 2C Source Red – Receiver Blue

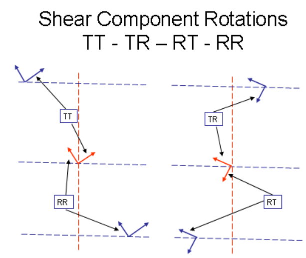

Figure 5: Transverse – Radial Component Quad Rotations

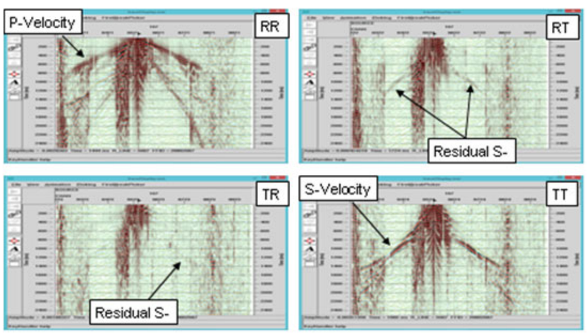

Figure 6: Receiver Residual Statics T1(L): T5 (R)

1. GEOMETRY QUALITY CONTROL
2. SHEAR WAVE COMPONENT ROTATION
3. REFRACTION STATICS
4. FAW SOURCE NOISE SUPPRESSION
5. VELOCITY ANALYSIS (0.5 BY 0.5 MILE GRID)
6. RESIDUAL STATICS
7. PRE-STACK TIME MIGRATION

Figure 7: P and S Processing Sequence

The bulk of the residual data observed is likely due to the field positioning errors of the source and receivers. If the deployment errors for the equipment is within ±5 degrees on average the recording crew has performed well. Orientation errors can be reduced via processing with advance component rotation algorithms that use hodogram analysis for example. Since the receivers are fixed 90 degrees inside the geophone case the issues are easier to address and fix than the source component errors as the orthogonality of the sources are not ensured. An advantage for the source rotation algorithms lie with the compass that is placed on the mast of each Vibroseis unit with the component orientations recorded. After component rotation, the same processing steps and algorithms that are used for P-wave processing can be used for S-wave, an advantage of S-wave sourced data over converted shear wave data. The processing sequence is shown in Figure 7. A Pre-Stack Time Migration (PSTM) time equivalent comparison of the conventional sourced baseline test, both P and S versus their simultaneous sourced counterparts are pictured in Figure 8. No issues with simultaneous sourcing are noted. An East-to-West line from the PSTM processed P-wave T2 FAW data volume is displayed along with the S-wave counterpart from the T4 S-wave Slip-Sweep volume in Figure 9. Both volumes demonstrate good image quality.

Frequency–Wavenumber (FK) spectral analysis of the primary P and S data is displayed in Figure 10. The FK data shows good P bandwidth. However, the S-wave data exhibits upper end bandwidth frequencies of 1/4 to 1/3 lower than the P-wave data. The S-wave high frequencies with an approximate 2:1 VPS ratio were expected to be closer to 1/2 the P-wave upper end.

We are most excited about the data quality and the production rate of the T5 P and S-wave FAW volume. Because we were at the end of our project budget, we could only source 990 ft SLs and 165 ft SPs. However, with 8 S and 2 P Vibroseis units we sourced 629, 2C, S-wave SPs and 636 P-wave SPs over the 6 square miles in 4 hr and 15 min. The quality of the data as shown in Figure 11, is remarkable for 1/2 day of sourcing. These data are displayed with their equivalent time conventional baseline counterparts for quality control.

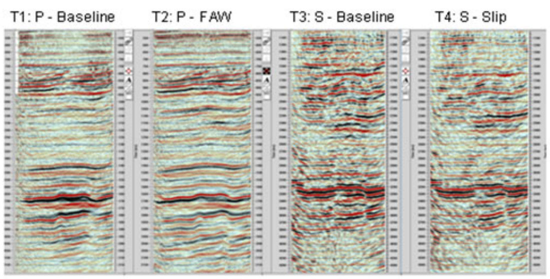

Figure 8: Conventional vs Simultaneous Sourcing

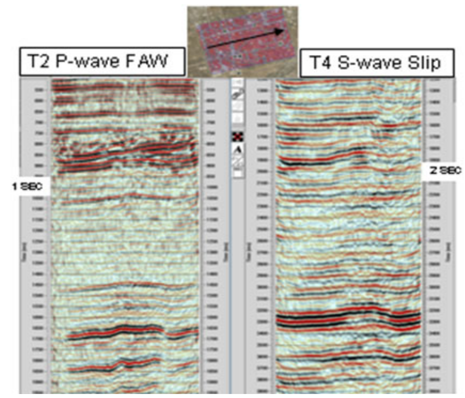

Figure 9: P-Wave (L) PSTM S-Wave (R)

Figure 10: T2 FAW P-Wave (L) - T4 Slip S-Wave (R)

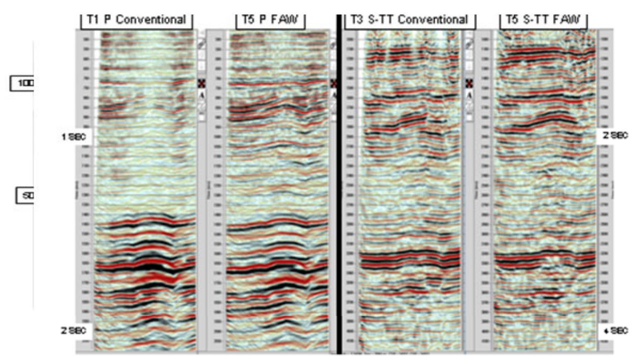

Figure 11: P and S FAW Data vs Conventional Baseline

Conclusion

We acquired a high-quality and high density 9C seismic data volume with admirable crew acquisition timing. The application of the slip-sweep mode for the S-wave portion of the survey was successful in providing quality at a reasonable crew production rate. The P-wave sourced data volume recorded with the FAW source technique yielded excellent data with a phenomenal production rate. It needs to be stated that the production rate for both the Slip-Sweep and FAW simultaneous source method is scalable up or down depending upon the number of Vibroseis units that are deployed. With the Slip-Sweep method however, the production rate is bounded by the slip time. The FAW method has the advantage of no production rate limit.

The CS technology can be applied to a survey with simultaneous or conventional sourcing to improve production efficiency by at least a factor of 2. The CS technology is expected to yield similar seismic images compared to traditional surveys with two-to-three times the receiver and source stations occupied. Regrettably, at the time of this writing the CS decimation and reconstruction results that will validate the CS claims for this area are in progress and not available for presentation.

What has us the most enthusiastic about the potential commercial aspect of 9C seismic acquisition lies in the FAW methodology applied to both the P and S-wave sourcing, individually or combined. The cursory test (T5) that deployed eight single S- and two single P-wave Vibroseis units, all with 16 seconds of sweep length, appears to realize the commercial application of the FAW technology. The test only took 4 hours and 13 minutes to acquire 636 P-wave SPs and 629 shear wave 2C SPs, or 24.3 sec per point. The data quality, as shown in Figure 11, compares favorably with their time-equivalent T1 and T3 conventional counterparts.

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