PAPER D

High Resolution Cross-well Seismic Data Acquisition System

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Summary

A new hardware system for acquisition of high frequency cross-well seismic data has been developed for the Seismic Tomography Project. The receiving system employs a 9-element array of hydrophone detectors and an optional 3-component accelerometer detector. Detected signals are digitized downhole at sample rates of 50 to 1000 microseconds. Downhole filters, gain, stacking depth, and sample rates are controlled from the surface. The data are recorded on disk and tape in SEG Y format. Each detector sonde operates as a node on a local-area-network; therefore, additional sondes can be easily added to the system. The receiver system is operationally specified to 10,000 psi and 125 C on standard oil field 7-conductor wirelines. The system is designed to operate with the high frequency piezoelectric source, e.g., 200 Hz to 4,000 Hz, but can be used with minor changes with other sources. The pieozelectric source is the cylindrical bender design and has two active elements. The two elements are assembled into a balanced mechanical structure which can be operated in phase for a dominant monopole or out of phase as a vertical dipole. Power is delivered to the source via standard industry wireline. The source is designed for deep hole operation to 5,000 psi and 125 C. This new hardware is available for experiments ranging from cross-well imaging surveys and vertical seismic profiles to in-situ measurements of rock properties.

Introduction

The hardware described herein addresses two related data acquisition problems which plague the volume and quality of cross-well seismic data - the speed of acquiring the data and the fidelity of the recordings. This aspect of cross-well seismology is important for it affects our assessment of the potential and limitations of the cross-well method for imaging and in-situ measurements of rock properties.

As cross-well seismology emerges as a tool for reservoir characterization and reservoir monitoring, the problem of high speed data acquisition continues to limit its use. Even today, after many successful applications of the method, routine surveys are rarely larger than 2500 shot-receiver points because of the long time its takes to acquire each record. Not only does this limit the size of the dataset, ultimately it limits access to wells, particularly in producing fields where shut down for seismic tomography is, more often than not, difficult to obtain. Although speed itself is not the primary need of the Tomography Project, there is the need to obtain larger more complete datasets for 2D and 3D imaging purposes. We believe the new system is capable of recording a 10,000 shot-receiver survey in 24-48 hours, perhaps two to ten times faster than other systems routinely available today.

Perhaps even more important is the quality or fidelity of the recordings. Fidelity refers to the accuracy at which the recording reproduces the input seismic signal. It is measured in terms of detector sensitivity, distortion, signal-to-noise ratio, bandwidth, dynamic range, and dynamic resolution. Our new system makes improvements in two areas. First, the signals are digitized downhole, thus eliminating the contamination and distortion experienced by analog transmission on long and varying quality wirelines. Second, the system is capable of recording to a Nyquist frequency of 10,000 Hz, though a 4000 Hz high cut filter is available for the control of aliasing. These and other features (e.g, floating point gain, low harmonic distortion, etc) combine to give the system a dynamic range of over 120 dB with 16 bits of instantaneous resolution. This high resolution recording system is designed and built to out specifications by Century Geophysical Corporation, a leading manufacturer of digital logging equipment for years.

All of this detection and recording bandwidth is useless unless a broadband downhole source is available. For this purpose, we have acquired a cylindrical piezoelectric bender source from Southwest Research Institute. The source radiates in the band of about 300 Hz to over 5000 Hz and operates on standard wireline. We have added a feature allowing it to be driven either a monopole for enhanced p-waves or dipole for enhanced s-waves.

General System Overview

A general system block diagram is shown in Figure 1. The downhole system consist of a 9-element hydrophone array and a 2-element piezoelectric source. Two surface computers (one in the source truck and one in the receiver truck) provide joint control and monitoring of all aspects of the data acquisition survey. These computers communicate via a high-speed optical link (19,200 baud) and share in common the survey parameters.

The entire downhole receiver system functions in a sense as a local area network (LAN), in that each element is a "node" which can be polled using its hard-wired ID, or can transmit data at its own behest. Software running in parallel on the two surface computers controls system configuration, including selecting the source signature, receiver sampling rates, analog and digital gains, stacking depth, and filter settings. These control computers also monitor cable depth and provide display of user selected recorded data traces. The data is recorded in SEG-Y format.

For purposes of description, the system is conveniently separable into two major subsystems, each having both surface and downhole components:

(1) Downhole receiver & surface control system
(2) Downhole source & surface control system

The surface hardware includes two Compu-log computers with the following general specifications:

- 25 MHz 80386
- 25 MHz DSP for digital communications and real-time processing
- MS/DOS with multi-tasking
- High-speed optical link between computers
- 120 MByte disk (max. 32 MByte file size)
- 60 MByte cartridge backup
- SEG-Y format recording

System Operation

The system can be operated in two basic modes. Set-up mode allows, under manual control, repeated testing and display of various survey parameters . In this mode the system does not use the information about survey geometry. Each shot is acquired, displayed, and written to disk under the operator's control. Spectral analysis, correlation, and display on the receiver system provide additional quality control on the survey set-up. Data can be offloaded to other systems for further enhancement and display.

For operations in automated mode, the survey software provides a acquisition design for a fixed detector array and a moving or scanning source. Each source point is stored as an individual record (common-receiver-gather) in a SEG-Y data file. The ranges of source and detector depths and coverage angles are specified prior to the start of the survey. Wireline moves are orchestrated by the software after completion of source scan. Source and detector positions are monitored by the computers during the move, and an alarm sounds when the next scheduled depths is reached. When the operator is ready the new recording sequence is then initiated to acquire the next shot gather. Thus data is recorded and written to disk with little or no operator intervention.

All survey parameters can be modified by the operator while data is being recorded. These changes are written into a log file and into the SEG-Y trace headers. Although system limitations do not allow SEG-Y files to exceed 32 mbytes, in practice this is not a severe limitation, as typical acquisition strategies would store 320 kbytes per source-gather (1 source record and 9 detector records, each 32 kbytes long). Thus each SEG-Y file could contain up to 100 source points, sufficient in most cases to record an entire source scan.

The new system substantially decreases the amount of time required to complete a cross-well survey. Data is double buffered in the downhole sondes, and thus transmission of data from a completed shot can continue during recording of the subsequent shot. At 38.4 kbaud, all nine 16 kword signals can be transmitted in 1 minute. In principle, this means that the complete shoot/move/ready-to-shoot sequence can be completed in the time it takes to shoot and move, without waiting for data transmission delays. For typical waveform (sweeps or pulse codes) lengths and recording times, a 64-fold vertical stack can be completed in approximately one minute. Moves take less than 30 seconds. Therefore, a fan of 100 source positions would require about two hours to complete. Data backup to streaming tape requires about 15 minutes, and can be accomplished during re-positioning of the receiver string and the source. Later versions of the software will do backup on removeable disks during data acquisition, and thus require no additional time for this process. The increase in number of receivers to nine from our earlier 3-receiver system translates in to a 3-fold decrease in acquisition time. Thus, we can complete surveys at least three times faster, and with considerably better quality control, than previously.

Description of the Subsystems

Receiver Sub-System

The receiver subsystem consists of a computer controller and, in its present configuration, nine separate and independent downhole receiver sondes, each of which acquires data digitally and communicates with the surface computer. Power for the downhole array is supplied from the surface. The system is interfaced to a digital encoder for monitoring wireline depth.

A master control and telemetry unit interface to the cable with a Schlumberger 7-conductor cablehead. High speed 16-bit digital signal processors (DSPs) are distributed at each hydrophone. These DSPs control the digitization rate and amplifier gain, and stacks the signal in one of two 16 kword buffers. The buffers allow data transmission during acquisition and during array movement for greatly increased throughput. Two low and two high cut filters (or out) can be set by from the surface. Additional filter settings can be obtained by switching the filter cards.

Surface control & recording system: Traces may be monitored on the receiver truck and plotted on a dot matrix printer. A custom software package displays and prompts the operator according to a user-specified shooting pattern. From the surface, the operator may configure the downhole digitizer as follows:

- sampling rate
- record length
- low cut filters
- high cut filters
- downhole digital gains
- downhole static gains
- recording delays
- vertical stack depth

Due to the high speed of the DSP at each detector sonde, the number of stacks per second is limited only be the record length and the sampling rate. Data are recorded in SEG-Y format on a 120 megabyte hard disk. A 60 megabyte tape drive is used for data archive. Future plans will replace the tape drive with a removable hard disk for faster transfer.

Downhole sondes. The detectors are OAS deep ocean hydrophones. The sondes are designed to allow easy upgrade to 3-component geophones or accelerometers. Each hydrophone is housed in a slotted stainless steel enclosure connected with 7-conductor logging cable. As described above, each sonde has a dedicated DSP for digitization. The design specifications call for total harmonic distortion of less than 0.02% with fixed gain, a noise floor at the input to the digitizer gain stage of less than 100 microvolts RMS, and input noise at the preamplifier of less than 10 nanovolts/root Hz. These specs are either met or exceeded in the delivered system. Downhole sonde specifications summary:

- OAS model E-4SD hydrophone; (can use one 3-comp VSP sonde)
- 16-bit DSP;
- 16 bit A/D;
- 50μs sample interval from 50μs to 1ms;
- 16,384 sample records;
- stacking to 32,768 signals;
- hi-cut filter at 2KHz or 4KHz;
- lo-cut filter: none; lo (250 Hz); hi (350 Hz);
- analog gains 60dB; 100dB;
- digital gain x1, x10, x100, or Tracking;
- programmable delay in 50μs intervals to 1s;
- communicate w/ surface at 38.4kbaud
- operation to 10,000 psi
- design to 125 C; operational to 110 C

Data are telemetried to the surface at a maximum rate of 38,400 baud over up to 20,000 feet of 7-conductor (15/32") wireline, starting at the end of the stacking period and continuing through array movement and the next acquisition period.

The housings are less than 3 inches in diameter, about 4.5 feet long, and capable of withstanding pressures up to 10,000 psi. Seven conductor cableheads for interconnecting sondes have a minimum breaking strength of 2,500 lbs. The cableheads are rated to 5,000 psi.

Source Sub-System

Surface control system: The source truck controller is equipped with a digital signal generator (DAC) and monitor (ADC) linked to the power amplifier driving the downhole source. The source Compu-log also monitors the wireline and maintains communications with the receiver system via the optical link. This unit provides the source wavelet using an input table:

- amplitudes specified in 20 μs intervals
- 8-bit resolution
- 32K samples (total time 1.6384 s)
- pulses or sweep signal
- variable repeat / delay (incl. quasi-random) within 1.6 sec. table
- variable repeat / delay for stacking of full source pulse
- +/- 10V D/A w/ smoothing filters

A 24KVA linear power amplifier is used to drive the piezoelectric source. The present amplifier has one channel but is being upgraded (summer 1990) to three independent channels for driving up to three source elements with multiphase wavelets. The linearity of the amplifier is an essential feature for it allows the reproduction of sweeps, complex waveforms, and pulse code sequences.

Downhole source. This source design has been used repeatedly over the last four years and has seen hundreds if not thousands of hours of operation. Our source is slightly modified from the original version built for Standard Oil nearly four years ago. In particular, the two active ceramic sections are symmetrically balanced between high power transformers which allow either in-phase or out-of-phase drives. Also, the structure is mass balanced to reduce spurious modes of vibration associated with vertical asymmetry. The far-field wavelet radiated by this source is proportional to the current drawn, thus it can be shaped (open loop) from within a linear system. The source is probably best suited for pulse operation though it has been successfully used in the sweep mode.

The source is approximately 4.5 inches in diameter and nearly twelve feet long. It is packaged for standard oil field operation and resembles standard logging tools.

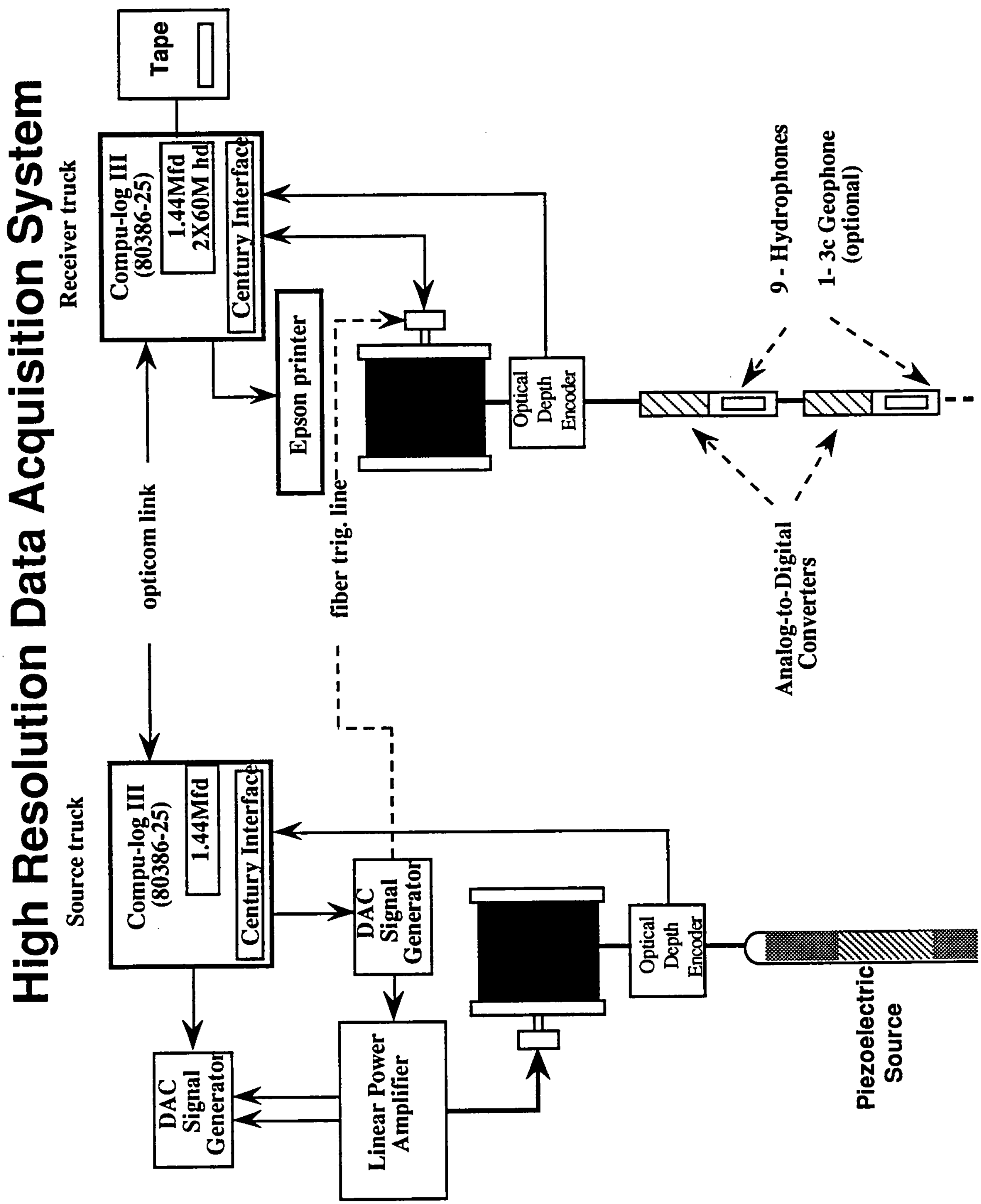

Figure 1. Schematic diagram of the high resolution data acquisition system