

Absolute strain determination from a calibrated seismic field experiment

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ABSTRACT

The concepts of displacement and strain are fundamental to our understanding of how elastic waves propagate in the subsurface, but accurate absolute determination of these quantities is rare. In August 2009, a field experiment was conducted on University of Calgary lands near Priddis, Alberta (Rothney Astrophysical Observatory) using various seismic sources (minivibe, weight drop) and receivers (geophones, accelerometers and broadband seismometers). A 3-component shot gather using a weight-drop source was recorded by 8 broadband seismometers and used to verify the absolute instrumental response of 80 3-C 10 Hz geophones, recorded using the university's ARAM-24 acquisition system. Although significant lateral amplitude variability is evident, an empirically derived average response for the ARAM system agrees with manufacturer specs to within < 4 in the frequency range 2-40 Hz, representing the bandwidth overlap between the geophone and seismometer systems. Based on this calibration, the strain associated with ground roll and refracted P- and S-wave energy is $\sim 10^{-7}$.

INTRODUCTION

Seismic surveys are typically acquired and processed without absolute calibration of the recorded data, since in general only relative amplitude information is required to address exploration and production issues (e.g., AVO). Consequently, it is not generally possible to calculate absolute ground displacement or strain, although these are fundamental parameters for seismic wave propagation. In contrast, seismometers used for global seismology are calibrated to enable meaningful inferences of earthquake moment or magnitude. Thus, data recorded by a broadband seismometer can easily be corrected for instrument response and used for calibration of displacement and/or strain.

On August 5, 2009 a seismic field experiment was carried out at the Rothney Astrophysical Observatory southwest of Calgary (Figure 1). The experiment included tests of different types of sources (mini-vibe, weight drop) and receivers. Available at the time were 8 Trillium 240 broadband seismometers, which were awaiting deployment to seismograph stations in various parts of southern and northern Alberta. This provided an opportunity to record the source tests using the seismometers for purposes of accurate calibration.

THEORY

The goal of this part of the experiment is to determine components of the elastic strain tensor, which is given by (Aki and Richards, 1980)

$$e_{ij} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right), \quad (1)$$

where $\mathbf{u}(t)$ is the particle displacement. Both geophones and seismometers record particle velocity rather than displacement; in practice, it is therefore necessary to integrate the recorded seismograms (traces) and subsequently compute the spatial derivatives using adjacent traces.

Before processing the data, an instrument-response correction is applied to account for frequency-dependent amplitude and phase effects in the system. Seismometers are capacitive force-balance systems whose frequency response can be written as

$$y(t) = H * v, \tag{2}$$

where $y(t)$ is the recorded time series (in units of V), $v = \partial u / \partial t$ is the ground velocity (in units of m/s), $*$ denotes convolution and H is the transfer function, given in the frequency domain by (e.g., Bogert, 1961)

$$H_s(\omega) = K_s \frac{\prod_{i=1}^N \omega - z_i}{\prod_{j=1}^M \omega - p_j}. \tag{3}$$

In this expression, K_s is the sensitivity (units V/m/s) and depends on ω_0 , the reference frequency. In addition, z_i , $i = 1, \dots, N$ are called zeros and p_j , $j = 1, \dots, M$ are called poles. In general, both poles and zeros are complex.

Geophones are resonant mass-coil systems whose transfer function may be expressed as (Hons and Stewart, 2006)

$$H_g = K_g \frac{(\omega / \omega_N)^2}{-(\omega / \omega_N)^2 + 2j\lambda\omega / \omega_N + 1}, \tag{4}$$

where λ is the damping factor. The geophone natural frequency (ω_N) often lies within the bandwidth of interest, resulting in undesirable wavelet distortion and phase effects (Hons

Table 1. Transfer-function parameters for the Trillium-240 seismometer.

Poles ($M = 7$) (radians/s)	Zeros ($N = 4$) (radians/s)
-1.82E-02 1.80E-02	0.00E+00 0.00E+00
-1.82E-02 -1.80E-02	0.00E+00 0.00E+00
-1.73E+02 0.00E+00	-1.08E+02 0.00E+00
-1.96E+02 2.31E+02	-1.61E+02 0.00E+00
-1.96E+02 -2.31E+02	
-7.32E+02 1.45E+03	$K_s = 1200$ V/m/s
-7.32E+02 -1.45E+03	Reference frequency: 1 Hz

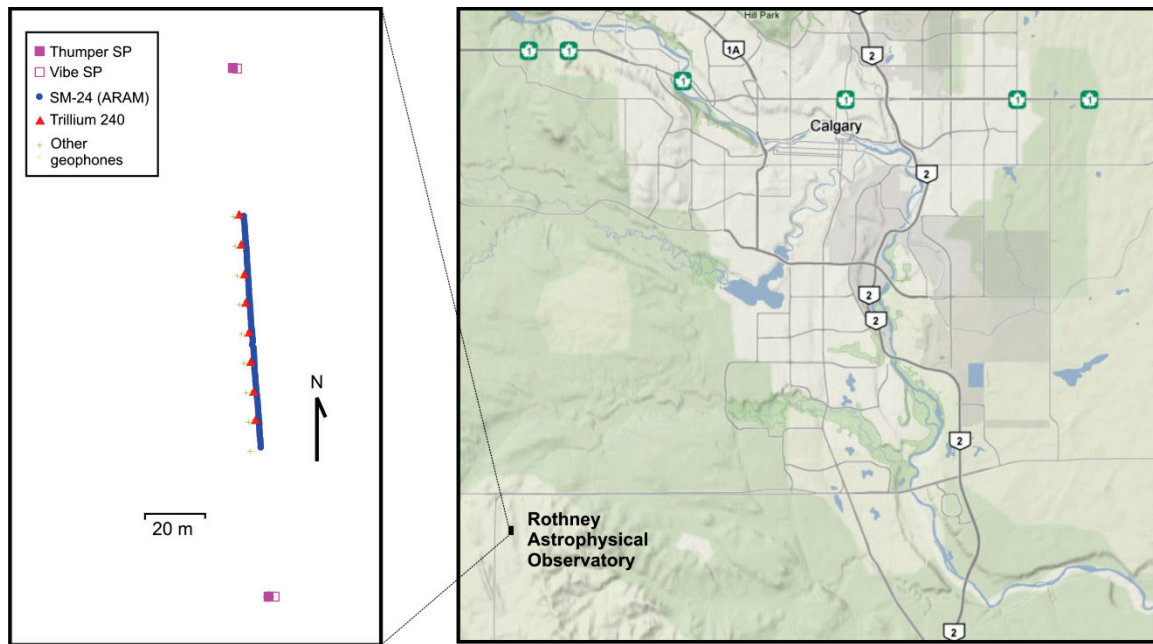


Fig. 1. Location of the August 5, 2009 field experiment near Priddis. Receivers were laid out along an 80-m profile, in an approximately N-S direction. Along the ARAM line, 80 3-C geophones were deployed at a 1-m spacing. One metre west of the ARAM line, 8 Trillium 240 broadband 3-C seismometers were installed at a 10-m spacing.

and Stewart, 2006).

In the present study, the seismometers are Nanometrics Trillium-240, 3-component instruments with flat response from 240 s to 35 Hz. The transfer-function specifications of these instruments are listed in Table 1. Within the Trillium-240 the sensors are mounted in a so-called Galperin configuration, in which 3 identical sensors are mounted at an angle of 54.7° from the vertical (Galperin, 1955). Output signals are transformed electronically within the unit into standard Cartesian co-ordinates, and were recorded with a fixed gain of 10^6 at a sampling rate of 0.01 s using a Nanometrics Taurus 24-bit digital seismograph. The 3-C geophones are I/O Sensor SM-24 10 Hz geophones, recorded at 2 ms sample rate using the university's ARAM system. The transfer-function responses of these two sensors are compared in Figure 2.

DATA ACQUISITION AND PROCESSING

The seismometers and geophones were deployed along a roughly N-S line as indicated in Fig. 1. Seismometers were installed into a shallow hole and leveled with the aid of a cement block placed at the bottom of the hole (Fig. 3). Since the seismometers are designed for autonomous operation at a remote observatory location, GPS timing is used to synchronize the instruments. Accordingly, each seismometer was connected to a GPS antenna mounted onto a wooden stake beside the instrument. The system, including the portable digital seismograph system, was powered using a 12-V battery and protected from moisture using a plastic bag. The geophones were deployed with a spacing of 1-m along a line located 1-m east of the seismometers. Both seismometers and geophones were oriented such that one horizontal channel (N-component for the seismometer,

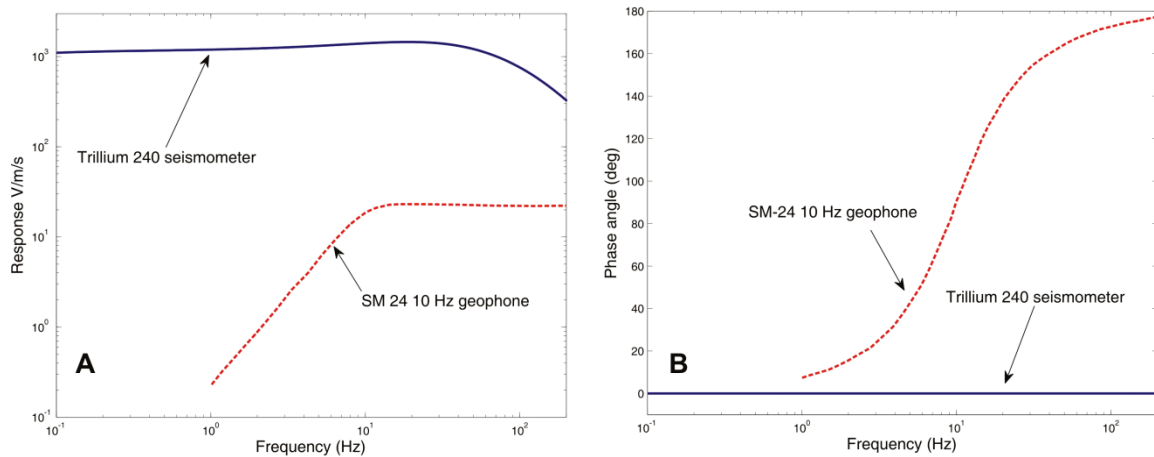


Fig. 2. Comparison of the theoretical transfer-function response of the Trillium-240 seismometer and the SM-24 geophone. As an active system that requires power, the seismometer amplitude response is significantly greater than that of the geophone.

radial-component for the geophones) was aligned with the profile. The source positions were offset 50-m from the seismic profiles in an effort to avoid saturation or even causing damage to the seismometers. It was subsequently determined based on the recorded data that this precaution was likely not necessary.

Taurus digital seismograph systems record the 3-C output from the Trillium-240 seismometers into a continuous ringbuffer, in which data packets are synchronized and time-tagged using GPS. One-minute data files for each channel were extracted from the Taurus ringbuffer and converted to SEG-Y format, with a start time based on the ARAM system clock time for each shot record. Since the ARAM system clock is not synchronized to GPS time, a time offset of a few seconds was observed. This mismatch was corrected by manually picking the first arrival for the respective traces closest to the source-point, and applying this as a bulk time shift in order to align the records.

Unfiltered data for a representative weight-drop shot record are plotted in Fig. 4. This shot record was used as the basis for subsequent calculations. In addition to the first arrival (refracted P wave) visible in the radial and transverse components, the data appear to contain strongly dispersive ground roll and multipath refracted waves that create a narrow-band, ringy signature with generally good correlation between the seismometer and geophone data. The vertical component data from the ARAM system contains a distinctive, high-frequency linear arrival that represents the air wave from the weight-drop source. This arrival is not discernible in the seismometer data.

The seismometer instrument response was removed using a simple deconvolution procedure. For each component, the seismic trace was transformed to the frequency domain by FFT and divided by the transfer function (Fig. 2) multiplied by the digitizer gain to yield calibrated spectra. Figure 5 compares the calibrated vertical ground-velocity spectrum from a seismometer (units: m) with the equivalent spectrum from a geophone (units: V). The upper frequency limit for the seismometer spectrum is determined by the anti-alias filter in the system, which applies at 40 (Hz). In the bandwidth from 6-40 Hz, the two spectra show strong qualitative similarities, but below 6 Hz they begin to diverge,

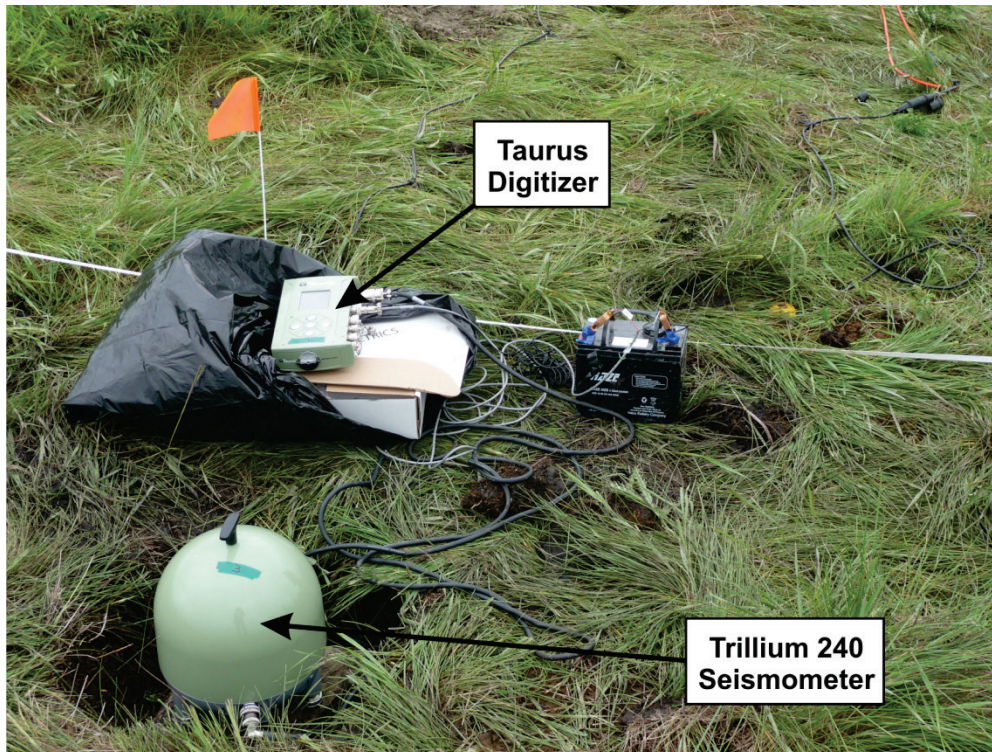


Fig. 3. Layout of the field experiment. Top panel shows the procedure for installing the Trillium-240 seismometer and Taurus digital seismograph. Lower panel shows the weight-drop source.

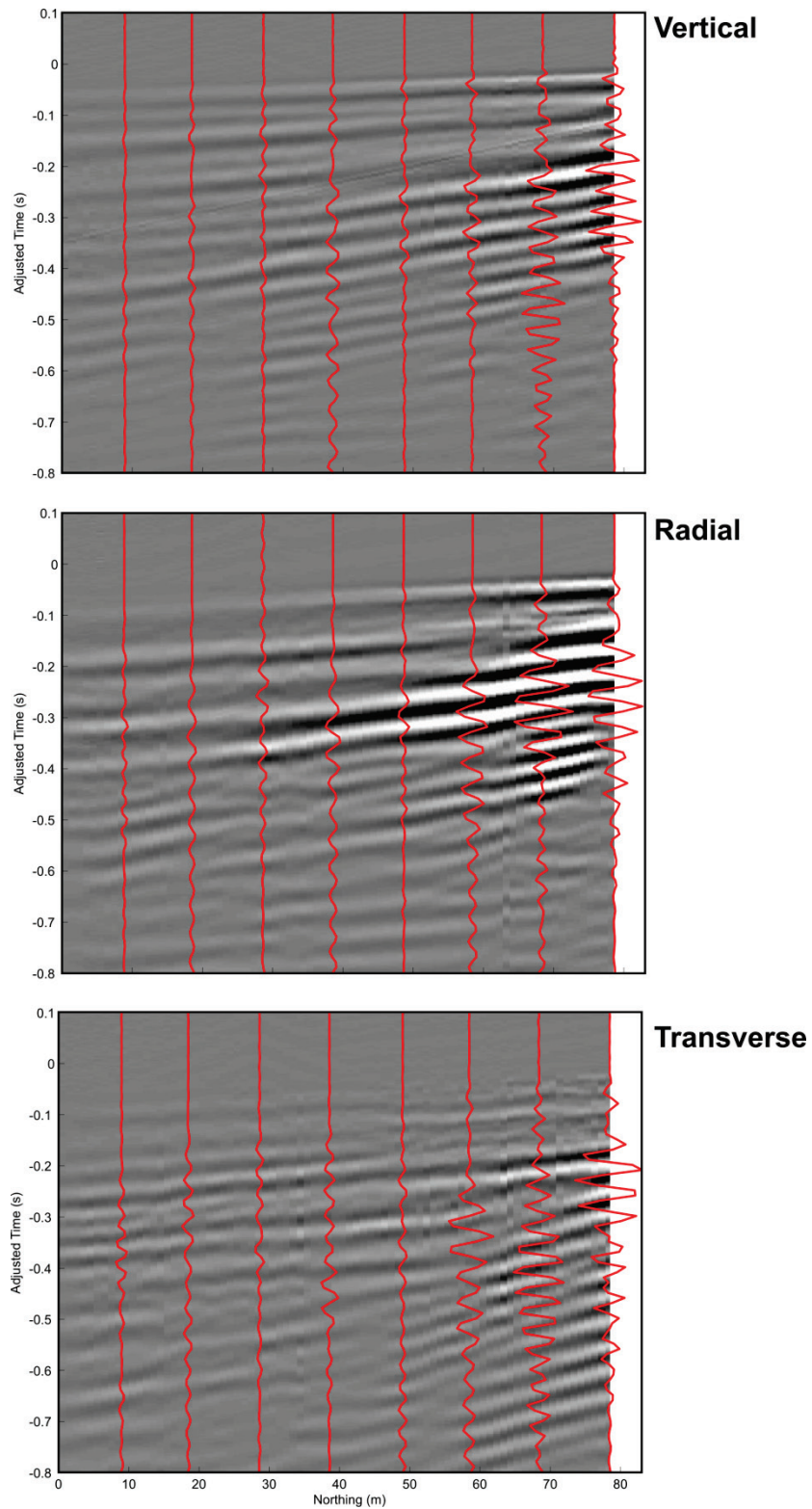


Fig. 4. Representative weight-drop shot record (unfiltered). 3-C data from the ARAM system are plotted using gray scale, overlaid by traces from the seismometers. The two datasets were aligned by applying a bulk time shift (see text).

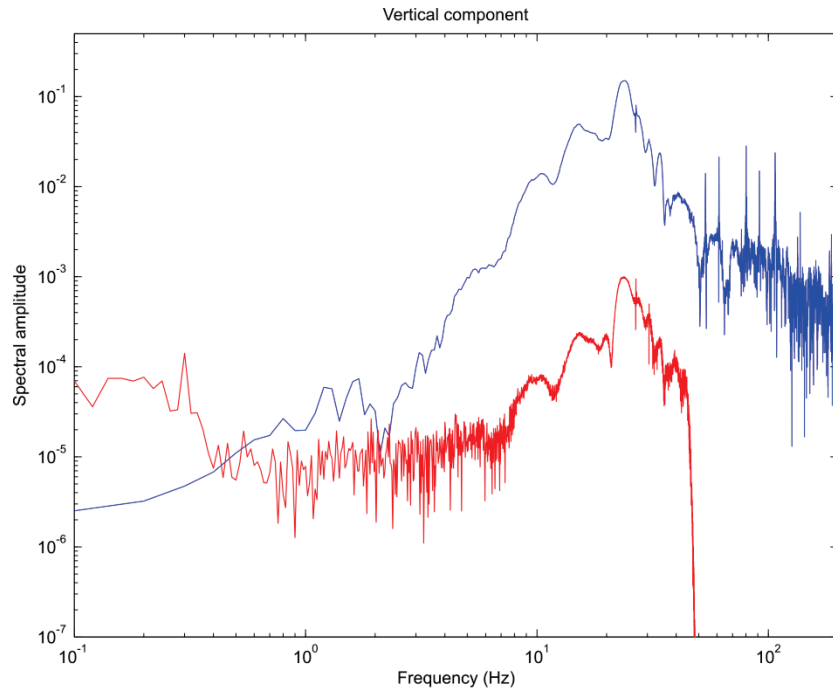


Fig. 5. Comparison of a calibrated vertical-component spectrum for the Trillium-240 seismometer (lower curve; red) with the corresponding raw spectrum for the SM-24 geophone – ARAM system (upper curve; blue).

as the seismometer is influenced by the strong global microseismic noise peak at ~ 0.17 Hz resulting from wave activity in the world's oceans (Peterson, 1993).

In order to derive an empirical instrument response of the SM-24 – ARAM system, observed spectra for 8 of the geophone channels (those closest to the seismometers) were divided by the calibrated response of the seismometers. For each component, a mean empirical instrument response function was calculated by averaging the results over the 8 available spectra. Fig. 6 shows the results obtained for the vertical component (very similar results, not shown, were obtained for the transverse and radial components). Also indicated in this plot is the theoretical transfer function (solid red line) from the manufacturer of the geophone, as well as two reference curves (dashed) scaled by a factor of 2 and 4, respectively.

Relatively good agreement is observed between the empirical response spectrum obtained from the ratio of the raw geophone spectra and the calibrated seismometer spectrum. For example, below the natural frequency of the geophone (10 Hz), the spectral ratio exhibits an increasing response versus frequency that parallels the expected curve, whereas above the natural frequency the spectral ratio fluctuates around the expected response (to within a factor of ~ 2). This suggests that the gain within the ARAM acquisition system is close to unity, so that the recorded amplitude values are approximately what is expected for the output from the geophone (in V). Deviation from the theoretical curve may reflect differences in ground conditions and coupling of the seismometer and geophone.

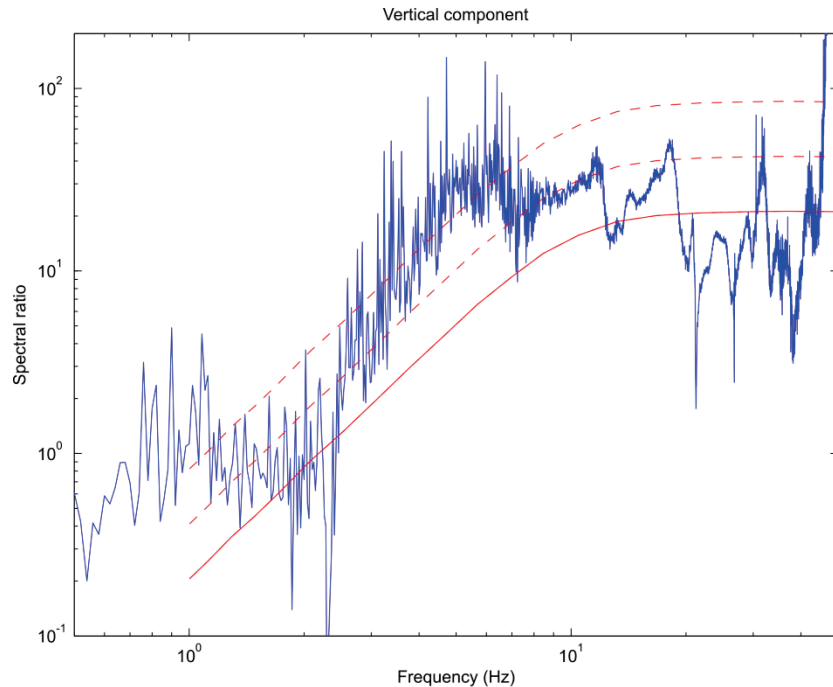


Fig. 6. Average empirical instrument response of the SM-24 geophones (vertical component) as recorded using the ARAM system. This is derived by normalizing the geophone spectrum by the calibrated response of the seismometers. The solid curve (red) shows the theoretical response of the geophone. The two dashed curves show the theoretical response multiplied by 2 and 4, respectively.

Finally, in order to compute components of the strain tensor, the response-corrected seismic traces, $v(t)$, must be integrated:

$$u(t) = \int v(t) dt \quad . \quad (5)$$

Strain components can be evaluated using the displacement seismograms by taking differences for adjacent traces. Given the layout of the field data, the only direction in which a spatial derivative can be reliably estimated is in the radial (N-S) direction. Figure 7 shows these strain components calculated using the vertical, radial and transverse geophone recordings. The maximum strain values associated with the observed seismic wavefield from the weight-drop source at a distance of > 50 m is found to be of the order 10^{-7} .

CONCLUSIONS

The experiment was successful in determining components along a single column of the strain tensor, corresponding to the radial orientation (N-S in this case). The absolute strain amplitudes for the ground roll and multiply-refracted waves is found to be of the order 10^{-7} . To obtain this, the instrument response of the SM-24 geophones recorded by the ARAM system was determined empirically by comparison with a well-calibrated earthquake seismometer system (Nanometrics Trillium 240 seismometer and Taurus digital seismograph). The recording gain of the ARAM system is found to be close to

unity, resulting in a net instrument response close (within a factor of 4) to the manufacturer's reported response of the geophone. Deviations from the expected response most likely reflect variations in the ground conditions and/or coupling of the sensors.

ACKNOWLEDGMENTS

Kayla Bonham is thanked for providing field photographs and fruitful discussion.

REFERENCES

- Aki, K., Richards, P.G., 1980. *Quantitative Seismology*, Freeman and Co., New York.
- Bogert, B.P., 1961. The transfer function of a short-period vertical seismograph. *Bulletin of the Seismological Society of America*, 51, pp. 503-513.
- Galperin, E. I. (1955). Azimuthal method of seismic observations (in Russian). Moscow, Gostoptechizdat 80.
- Hons, M.S. and Stewart, R.R., 2006. Transfer functions of geophones and accelerometers and their effects on frequency content and wavelets. *CREWES Research Report — Volume 18*.
- Peterson, J., 1993. Observations and modelling of background seismic noise. Open-file report 93-322, U. S. Geological Survey, Albuquerque, New Mexico.

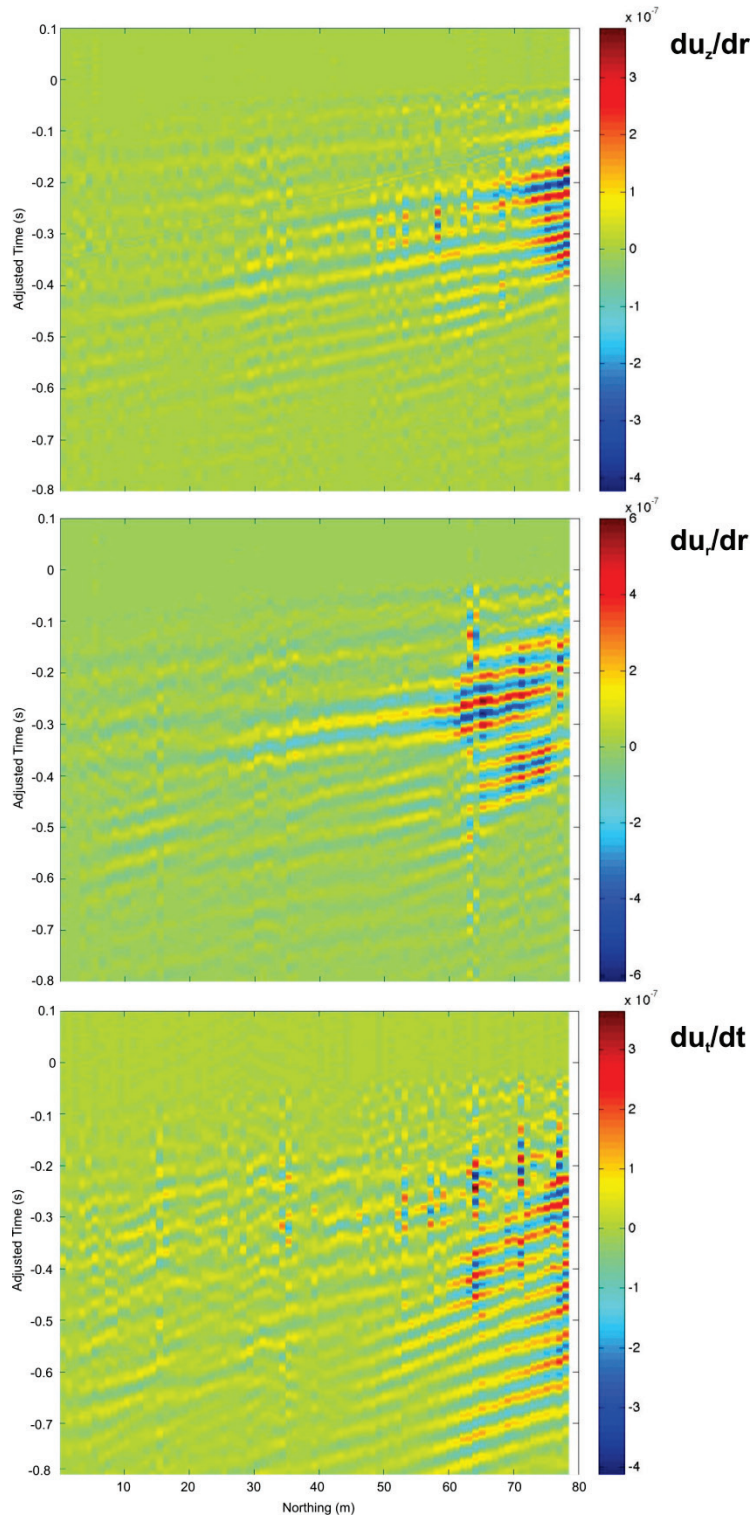


Fig. 7. Calculated strain components for a weight-drop seismic record.