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VERTICAL MODAL RESPONSES OF MONTICELLO DAM:
RESULTS FROM AN AIR-GUN DYNAMIC TEST

by

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Abstract

Dynamic testing of Monticello Dam, a concrete arch structure located near Sacramento, California, has been carried out by firing an air gun at pressures as high as 13.8 MPa (2000 psig) in the reservoir. The air gun, by a release of high-pressure air in the reservoir, provides a wide-band (0.2 Hz to more than 100 Hz) and high-energy excitation source for dam testing. More than ten modes of vibration were excited by each air gun shot and the maximum acceleration of the dam was 0.05 g. The most striking feature of the time-history records is a slowly-decaying 23.1 Hz resonance motion in the vertical-component records, which is absent in the horizontal-component records. This motion is interpreted to be the result of interference of elastic waves propagating vertically in the dam and reflected at the top surface of the dam and at its base. The observed vertical vibration mode at Monticello Dam provides a magnifying mechanism for vertical ground motions and has significance with regard to dam safety evaluation.

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INTRODUCTION

Importance of Full Scale Dynamic Testing

Full scale dynamic testing plays an important role in the earthquake response and safety analysis of arch dams. In currently used finite-element methods applied to the dynamic response of dams, the natural frequencies of an arch dam-reservoir-foundation system cannot be computed accurately because of the lack of knowledge of the hydrodynamic effects and the uncertainty of the foundation properties (Hutchinson and TsiCNias, 1981). Consequently, experimentally determined resonance frequencies and mode shapes are needed in order to verify the numerical results of the finite-element method. In addition, experimentally determined damping coefficients of the various modes are necessary inputs for the finite-element computations.

Summary of Existing Testing Methods

Currently, there are primarily three methods employed in the dynamic testing of arch dams. The first method is the rotating mass shaker method in which two counter-rotating masses generate a linear sinusoidal force (Rouse and Bouwkamp, 1967; Clough et al., 1982; Clough et al., 1984a; Clough et al., 1984b). Rotating mass shakers have been used extensively for dynamic testing of dams and they can be used typically to a maximum frequency of 10 Hz. One limitation of this method is that the arrangement of the shaker system may not significantly excite some vibration modes if the shakers are located near the nodal points of these modes (Clough et al., 1984b).

Dam vibrations caused by wind or water waves impinging upon the dam upstream surface, or spilling of the reservoir, are measured in ambient vibration tests (Clough et al., 1984a; Clough et al., 1984b). These excitation sources, particularly the wind and the water waves, of course cannot be controlled and the vibrations are usually limited to low amplitudes. In addition, two requirements must be met in order to obtain accurate results for estimating modal parameters: the excitation source should stay constant in local peak amplitude during the period of measurement, and the spectrum of the excitation source should have a constant amplitude in the frequency band occupied by the significant dam vibration modes.

The third of the current methods is the popper method (Ostrom and Kelly 1977), in which a sudden release of compressed air at 0.35 - 0.69 MPa (50 - 100 psig) from a 1475 cm³ (90 in³) popper is accomplished by a differential-pressure piston-driven mechanism. Pressure waves propagate through the water to load the upstream face of the dam. The advantage of the popper method is that the equipment is less cumbersome than that of the rotating mass shaker method. However, the popper used by Ostrom and Kelly (1977) is limited to relatively low levels of energy output.

A New Method

In order to extend the current methods of dam dynamic testing, a new technique was employed. A 655 cm³ (40 in³)-volume air gun fired at

pressures as high as 13.8 MPa (2000 psig) was used in the reservoir as the excitation source, and dam responses were recorded at three locations on the crest of Monticello Dam near Sacramento, California. Excitation of the dam's vibration modes using an air gun is based on the same principle as that of the popper; i.e., the loading forces are transmitted to the upstream face of the dam by pressure waves from the sudden release of compressed air.

The advantages of the air gun are a higher-energy output and faster rise time than those of the popper. The faster rise time is a result of a different triggering mechanism and it results in a wider source frequency spectrum. The air gun employed in this experiment has approximately nine times more energy output than the popper previously used (Ostrom and Kelly, 1977), and the pressure amplitude spectrum extends from 0.2 Hz to more than 100 Hz.

Because the air gun provides a relatively high-energy and wide-band source of excitation, more than ten modes of vibration were excited by each air gun shot. These modes were identified by analysis of the Fourier spectrum of the free-vibration portion of the records.

The present paper is concerned with a high-frequency, primarily vertical vibration mode identified in the test. The records show that this mode has a much lower damping value (~ 0.0017 of critical) than those modes in which flexural-type motions dominate. This type of modal response with the small damping ratio has not been reported previously.

DESCRIPTION OF DAM

Monticello Dam is a 92.7 m (304-foot)-high, single-arch concrete dam which was built by the U. S. Bureau of Reclamation (1959). It has a crest length of 318.5 m (1045 ft) and is constructed of 19 separate vertical blocks each of which is 16.8 m (55 ft) long. The dam is located on Putah Creek approximately 48.3 km (30 miles) west of Sacramento, California. Figure 1 shows the plan, upstream elevation, and a typical section of the dam. The abutment rocks are of Venado Formation, an Upper Cretaceous marine formation consisting of highly tilted beds of sandstone, mudstone, and shale (Emerson and Rich, 1966).

TEST EQUIPMENT

The excitation source for the test was a Bolt Technology Model DHS-600 air gun with a 655 cm³ (40 in³)-volume firing chamber, and a maximum operating pressure of 13.8 MPa (2000 psig). A Worthington Model SAB four-stage compressor which has a maximum discharge pressure of 24.1 MPa (3500 psig) and a flow rate of 0.453 m³/min (16 cfm) at 17.2 MPa (2500 psig) supplied air to the gun. The compressor was powered by a diesel engine and the entire air supply unit was trailer-mounted.

Motion sensors used in the test were Mark Products L-4C electromagnetic geophones that have a natural frequency of 1 Hz, 5.5 k coil resistance, and a 271.65 V-s/m (6.9 V-s/in) transduction constant. The outputs of the geophones at each measuring station were amplified and digitally recorded by a Sprengnether LID amplifier and a DR100 digital recorder. An anti-aliasing low-pass filter in each recorder was set at 50 Hz with an attenuation rate of 30 dB/octave. Each recording channel digitized the data at 200 samples/s.

TEST PROCEDURE

The air gun was suspended on a wire rope from a frame attached to a pontoon boat. Three nylon ropes attached to the two anchors driven into sandstones on opposite cliffs of the reservoir and to the dam crest held the boat in place. During the tests the air gun was positioned near the horizontal reference line of the dam (Figure 1) and 11 m (36 ft) from the vertical dam axis. A flexible hose carried compressed air from storage tanks on the dam crest to the air gun. The compressor and the diesel engine were turned off while collecting data.

Three sets of geophones were attached to the dam crest; one set at the joint between blocks 11 and 12 (Center Crest), another set at the joint between blocks 15 and 16 (Right Quarter Point, facing downstream), and the last set at the joint between blocks 7 and 8 (Left Quarter Point). At each location the geophones were oriented radial and tangential to the dam as well as vertically.

The vertical geophones were leveled by a spirit bubble, whereas the horizontal geophones were leveled by the geophone release test (Asten, 1977). After leveling, the geophones were attached to the dam using plaster of Paris. Each set of geophones was connected to a Sprengnether 3-channel amplifying and recording system in which digital sampling of the three recorders was synchronized to within 1 ms.

The air gun was fired at depths of 9.14 m (30 ft), 24.38 m (80 ft), 39.62 m (130 ft), and 54.86 m (180 ft), in order to determine the effect of source depth on the excitation of different modes of vibration. A minimum of ten shots were fired at each depth in order to determine the repeatability of source excitation, and data were recorded for each shot. Fifteen shots were fired at a pressure of 6.9 MPa (1000 psi) and thirty one shots were fired at 13.8 MPa (2000 psi). At the time of the tests the water level in the reservoir was at an elevation of 136.7 m (428.7 ft) above sea level.

TEST RESULTS

The Fourier spectrum of each geophone record of the dam's motion in its free vibration contains more than ten distinct peaks. The lower-frequency peaks observed in these spectra show good correlation with the modal frequencies determined by the rotating mass shaker method (Rouse and Bouwkamp, 1967). A high-frequency (23.1 Hz) vibration with predominant motion in the vertical direction was the most notable feature of the records. This high-frequency motion was observed in the records for all four depths of the air gun.

Figures 2a, 2b, and 2c show the velocity records of the vertical, radial, and tangential motions of the dam at the Left Quarter Point for an air gun depth of 9.14m (30 ft). Figures 3a, 3b, and 3c are the corresponding motions at the Right Quarter Point, and Figures 4a, 4b, and 4c are results from the Center Crest.

The slowly-decaying 23.1 Hz vibration in the vertical-component records, which is absent in all the horizontal-motion records, is clearly evident in Figures 2a and 3a. The amplitude of this vertical motion at the Center Crest is lower than the two quarter points by a factor of approximately 3.

Inspection of Figures 2a, 3a, and 4a shows that this vertical vibration

mode existed before firing the air gun. After firing the air gun, these records show ~0.45 s of forced oscillations at the air gun bubble oscillation frequency of 28.2 Hz. The remaining portion of the records represent free vibration of the dam.

The amplitude of this 23.1 Hz free vibration was increased by a factor of 5 or more compared to the ambient vibration prior to the air gun excitation. This motion decayed slowly at the two quarter point locations, whereas the corresponding motion at the dam Center Crest decayed much more rapidly.

The damping ratio of the vertical motions at the two quarter points was estimated by fitting an envelope to the last 2.6 s of the records in Figures 2a and 3a using the equation

$$C/C_{Cr} = \frac{1}{2\pi k} \ln(A_n/A_{n+k}) \quad (1)$$

in which A_n and A_{n+k} are the peak amplitudes of motion separated by k cycles. The damping ratio obtained from Figures 2a and 3a is 0.0017 of critical, which is ten times smaller than the damping ratios of the first five flexural modes obtained by Rouse and Bouwkamp (1967) in a previous test of Monticello Dam.

The Fourier spectra of the free-vibration portion of the time-history records shown in Figures 2a, 2b, and 2c are presented in Figures 5a, 5b, and 5c, respectively. Corresponding Fourier spectra of the records at the Right Quarter Point and Center Crest are depicted in Figures 6a, 6b, 6c and Figures 7a, 7b, 7c, respectively. A portion of the vertical motion recorded immediately before the firing of air gun is also analyzed for each of the measuring stations with the results shown in the figure pairs 8a and b, 9a and b, and 10a and b.

ANALYSIS OF RESULTS

The Vertical Vibration Mode

The time-history records (Figures 2 - 4) indicate that the 23.1 Hz vertical motions represent a predominantly vertical vibration mode of the dam. This conclusion is corroborated by the Fourier spectra in Figures 5 - 10. In the comparison of the spectra of the vertical- and the radial-component motions at the Left Quarter Point (Figures 5a and 5b), the peaks show one-to-one correspondence; i.e., the vertical- and radial-component spectral peaks occur at the same frequencies with similar relative amplitudes, except for the largest amplitude peak in Figure 5a at 23.1 Hz. The corresponding peaks at 23.1 Hz for radial motion in Figure 5b and for tangential motion in Figure 5c are negligibly small.

Further evidence for the existence of this vertical mode is obtained by examination of the spectra of the three-component motions at the Right Quarter Point (Figures 6a, 6b, and 6c) and at the Center Crest (Figures 7a, 7b, and 7c) which show a behavior similar to that of the Left Quarter Point. This one-to-one correspondence of spectral peaks in the vertical and radial components with the exception of the 23.1 Hz motion indicates that this motion is the only primarily vertical vibration mode excited in the test.

The Fourier spectra of the vertical ambient vibration records prior to firing (Figures 8b, 9b, and 10b) have two prominent peaks at 23.1 Hz and 60 Hz. The peak at 60 Hz is the result of the electrical coupling of the AC

power line at the dam crest into the recording amplifiers. The 23.1 Hz peak demonstrates that the dam was oscillating in this vertical resonance mode before firing the air gun.

Because this mode has motion primarily in the vertical direction, it is interpreted to be the result of interference of elastic waves propagating vertically in the dam and reflected at the top surface of the dam and at the base. The existence of this vertical vibration mode indicates that the stiffness properties of the basement rock are significantly different from those of the concrete. The observation that the amplitude of the vertical vibration at the Center Crest decays much more rapidly than the amplitudes at the other two crest locations suggests that the Center Crest is near a nodal point of the vertical vibration mode. However, possible variations of basement stiffness properties along the base of the dam may also contribute to this behavior.

The exact mode shape of this vertical vibration mode can not be ascertained from our data because there were only three measuring stations on the dam crest and none on the downstream surface of the dam. An attempt to narrow-band filter the time-history records in order to obtain the relative phase relationship between the vertical motions at the Left and Right Quarter Points was hampered by the interference from another resonance mode at 27.8 Hz (Figures 5a, 5b, and 5c).

The damping ratio of the vertical motions at the two quarter points is one order of magnitude lower than that reported for previously determined flexural modes. This result can be explained in terms of the damping mechanisms of the different modes. One damping mechanism of the flexural modes is energy dissipation in the construction joints separating the vertical blocks, whereas this damping mechanism does not exist for the vertical vibration mode. The low bulk energy dissipation in the concrete results in a low damping coefficient for the vertical mode.

Significance of the Vertical Vibration Mode

Safety evaluation for a concrete dam subjected to a seismic event depends on many factors, such as (i) peak ground acceleration, duration, and frequency content, (ii) dam foundation characteristics, (iii) vibrational modes of the dam, and (iv) the possible existence of stress concentrations within the dam or at the dam-abutment or dam-basement rock interfaces. Because the strength of concrete is low in tension, one major consideration for a conservative earthquake analysis is the presence of tensile stress.

If the frequency of the lowest vertical vibration mode is located above the frequency band of the earthquake ground motion spectrum, then vertical tensile stresses will not develop in the bulk of a dam from vertical ground acceleration with amplitudes less than 1 g. However, if the frequency of a vertical vibration mode is located within the frequency band of the ground motion spectrum, consideration must be given to this magnifying mechanism which can amplify the ground motion and cause tensile stresses to develop within the dam or at the dam-basement rock interface.

With the exception of Okamoto (1973), only horizontal motions (radial and tangential) are reported in the field tests of arch dams. Furthermore, existing analytical methods usually include only modes with predominant motion in the radial and tangential directions.

The general neglect of the vertical modes probably arises from the

knowledge that dams have considerable inherent strength in the vertical direction. Also, the natural frequencies of the vertical modes in arch dams are located above the frequency band of interest for most recorded earthquake ground motions. However, high frequency vertical ground motion have been recently recorded.

During the 1979 Imperial Valley Earthquake ($M_S = 6.9$), one vertical acceleration record at a distance of 6 km (3.73 mi) from the Imperial Fault shows a maximum acceleration exceeding 0.6 g (Figure 11a). The Fourier spectrum of this record (Figure 11b) shows an approximately constant amplitude from 0.2 Hz to 25 Hz (Bycroft, 1980). Another vertical accelerogram recorded at Imperial Valley shows a peak value in excess of 1.6 g (Brady et al., 1980).

If an arch dam that has structural characteristics similar to those of Monticello Dam is subjected to a vertical ground motion such as that depicted in Figures 11a and 11b, the low damping coefficient of the vertical vibration mode and the high vertical ground acceleration imply that many cycles of vertical tensile stresses could develop at certain locations within the dam. A combination of these vertical tensile stresses with the tensile stresses induced by horizontal motions and other loads could cause excessive cracking to occur in the concrete.

CONCLUSIONS

A new dynamic method of dam testing has been successfully employed to determine modal properties of an arch dam. Experimental results from Monticello Dam show the existence of a primarily-vertical vibration mode which has not been reported in any previous dynamic tests of arch dams. The identified mode, which has a frequency of 23.1 Hz and a damping ratio of 0.0017 of critical, has significance with regard to safety evaluation of concrete dams.

The following investigations should be undertaken to complement the results of this study:

1. Additional field tests with more measuring stations along the crest and downstream surface of the dam in order to obtain a better description of the shape of the identified mode and its damping characteristics.
2. Tests on other concrete dams to search for the vertical vibration behavior observed at Monticello Dam.
3. Numerical modeling of concrete dams under 3-dimensional design earthquake loading conditions which include the vertical mode as part of the analysis.
4. Using system identification techniques (e.g. Schiff, 1972; Beck, 1978) in order to determine the frequencies, mode shapes, and damping ratios of the modes simultaneously excited by an air gun.

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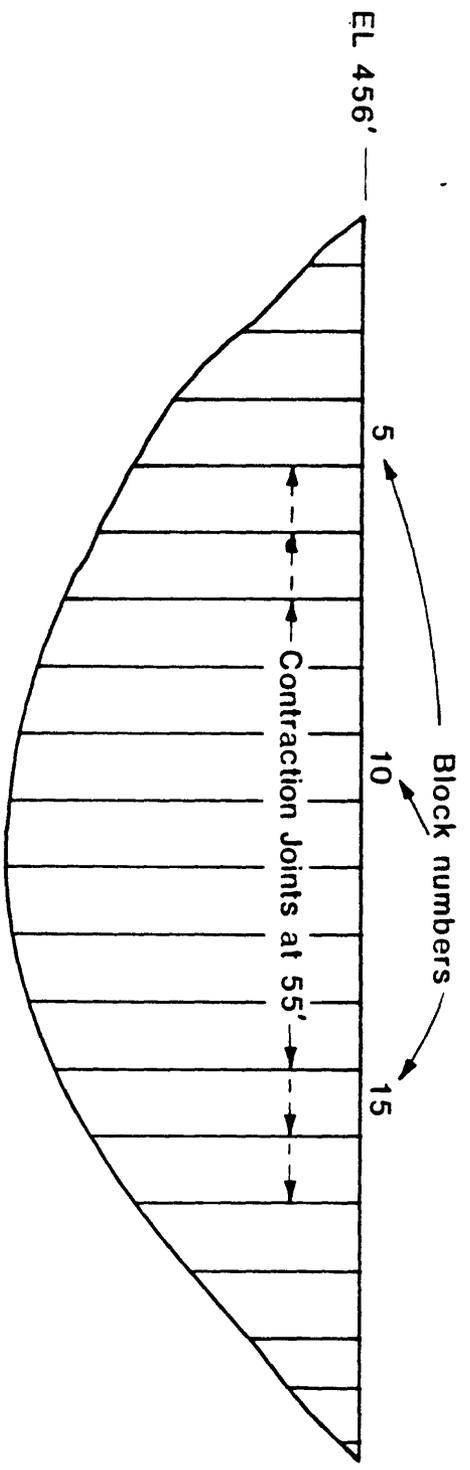
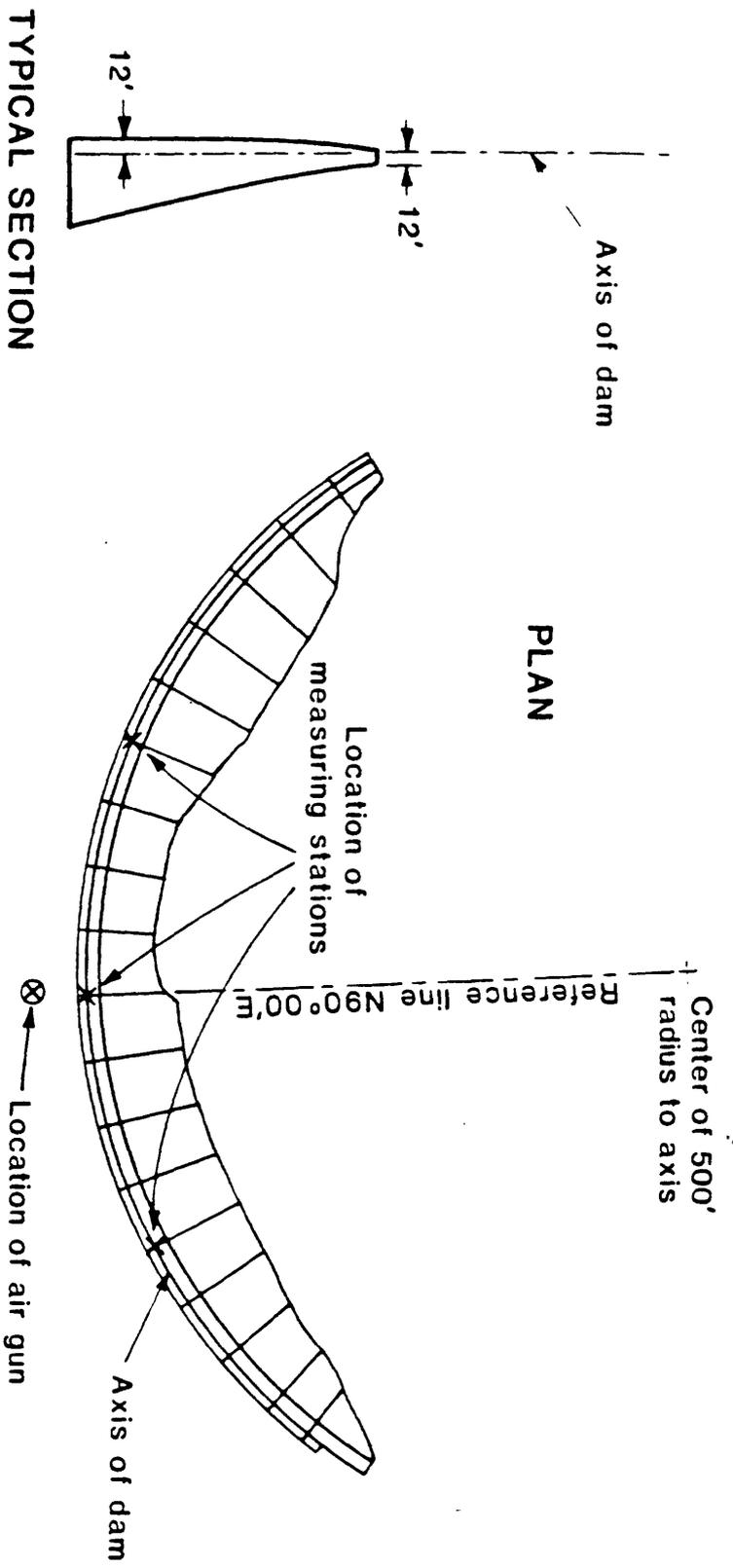


Fig. 1. Plan, upstream elevation, and a typical cross section of Monticello Dam, California, showing location of measuring stations and air gun source.

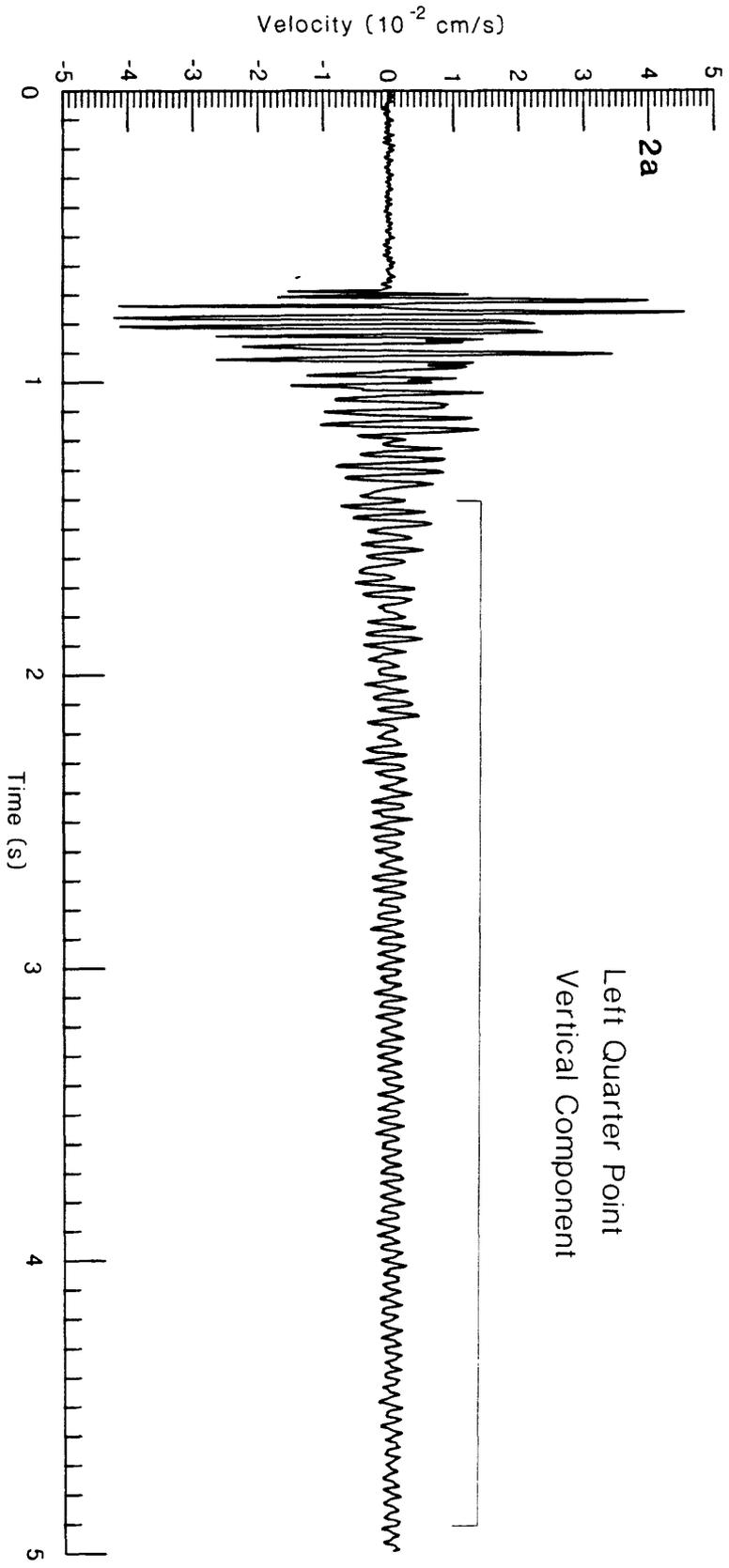


Fig. 2a. The vertical motions excited by the air gun and recorded at the Left Quarter Point. The bracketed section of the free vibration part of the record is the section used for Fourier spectrum computation.

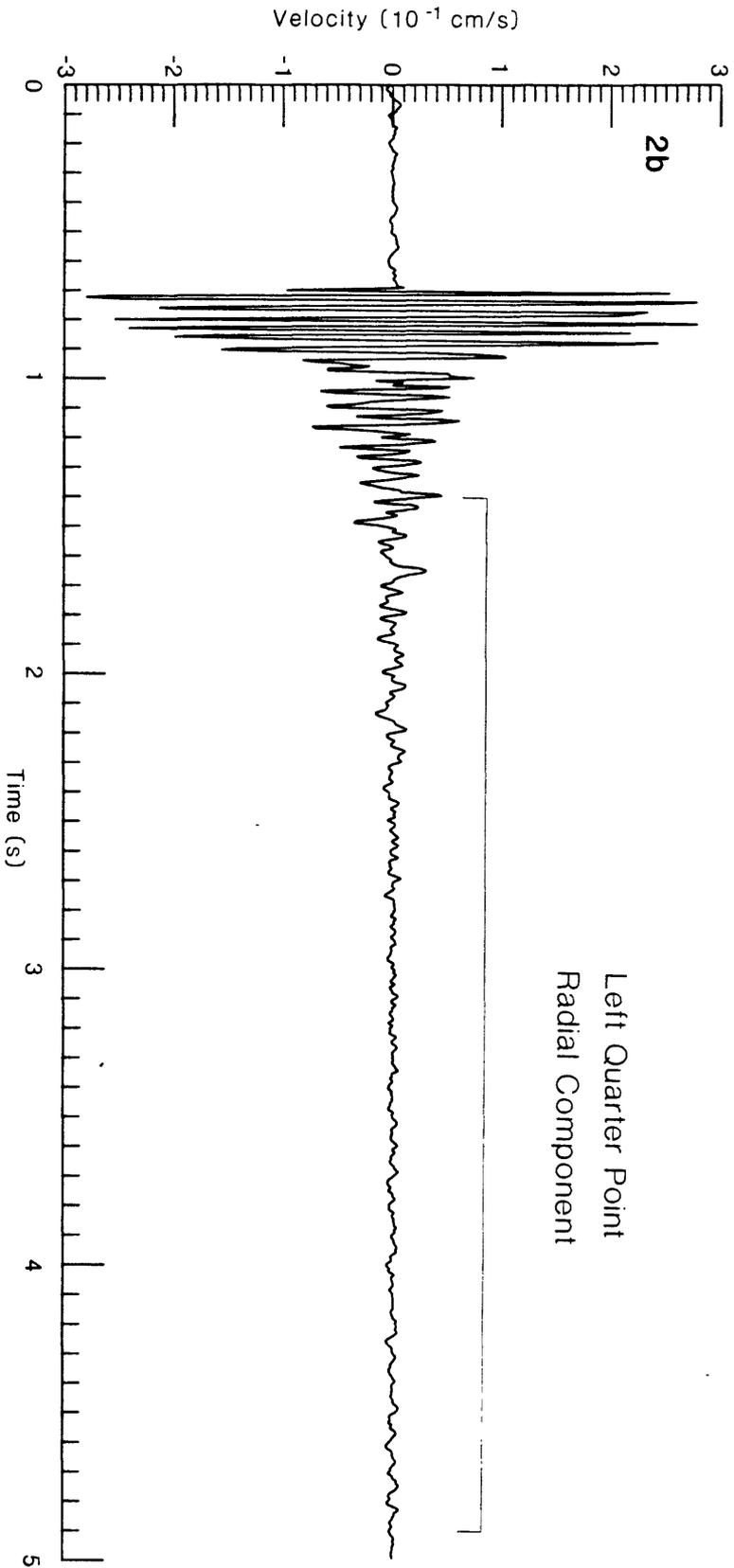


Fig. 2b. The radial motions excited by the air gun and recorded at the Left Quarter Point. The bracketed section of the free vibration part of the record is the section used for Fourier spectrum computation.

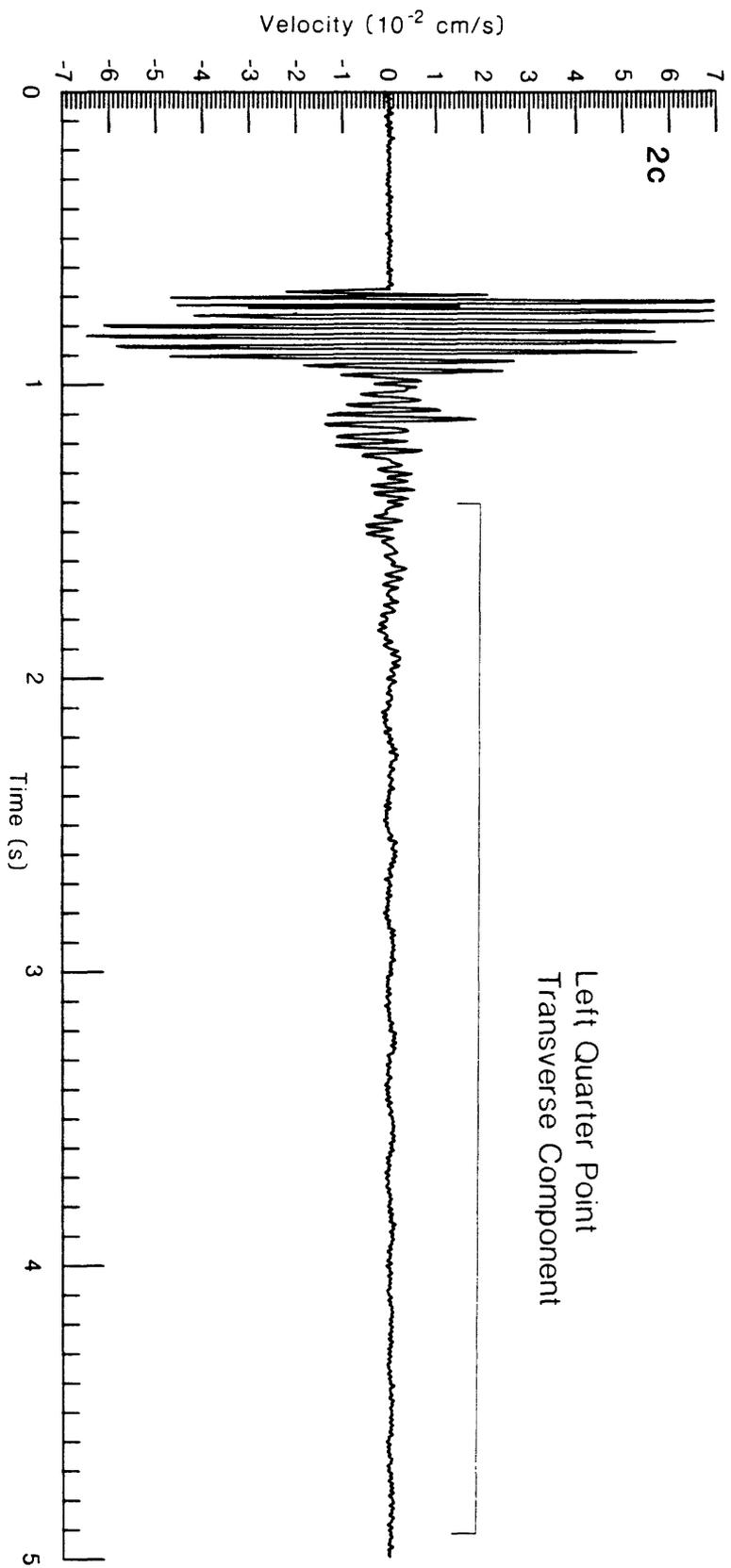


Fig. 2c. The tangential motions excited by the air gun and recorded at the Left Quarter Point. The bracketed section of the free vibration part of the record is the section used for Fourier spectrum computation.

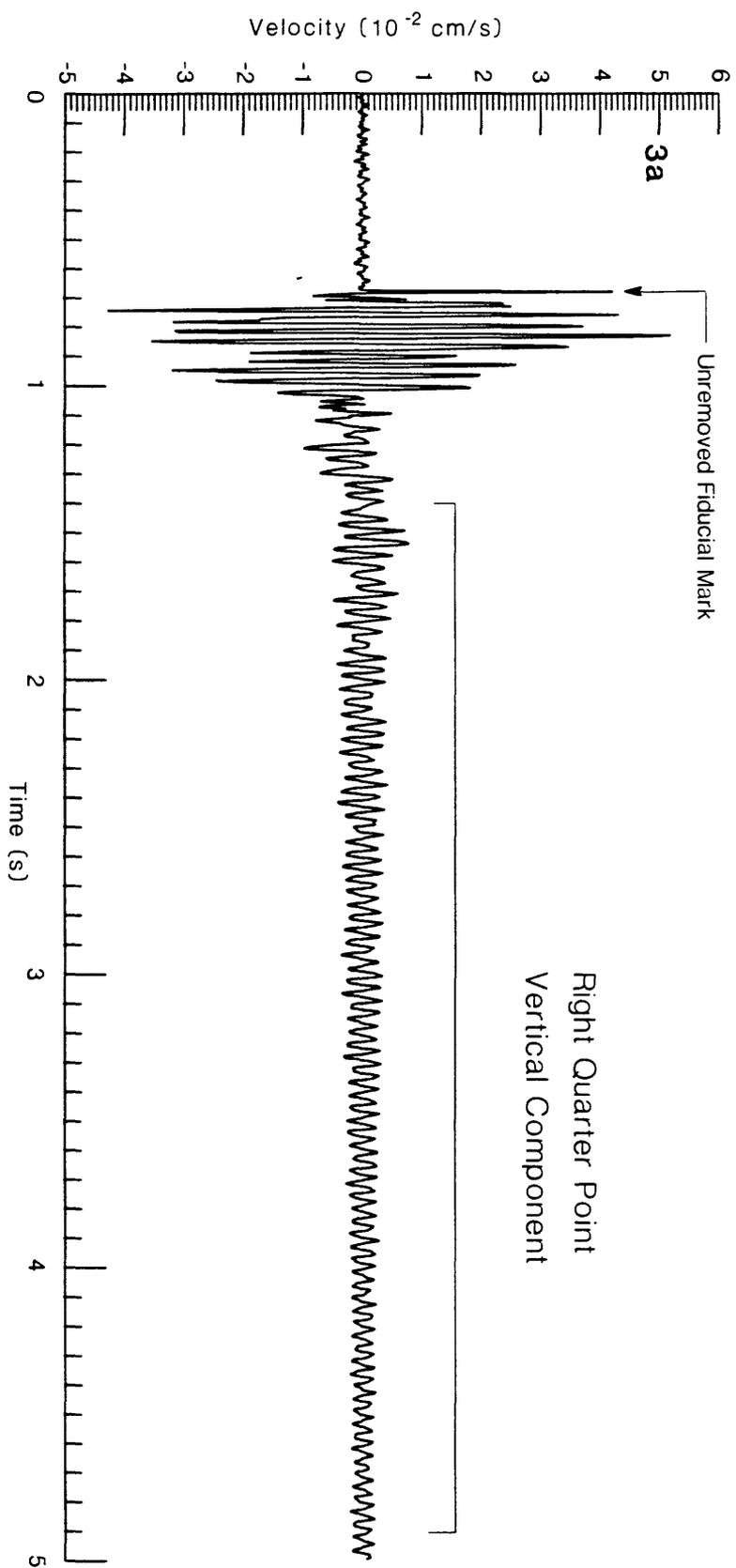


Fig. 3a. The vertical motions excited by the air gun and recorded at the Right Quarter Point. An unremoved fiducial time mark is also indicated. The bracketed section of the free vibration part of the record is the section used for Fourier spectrum computation.

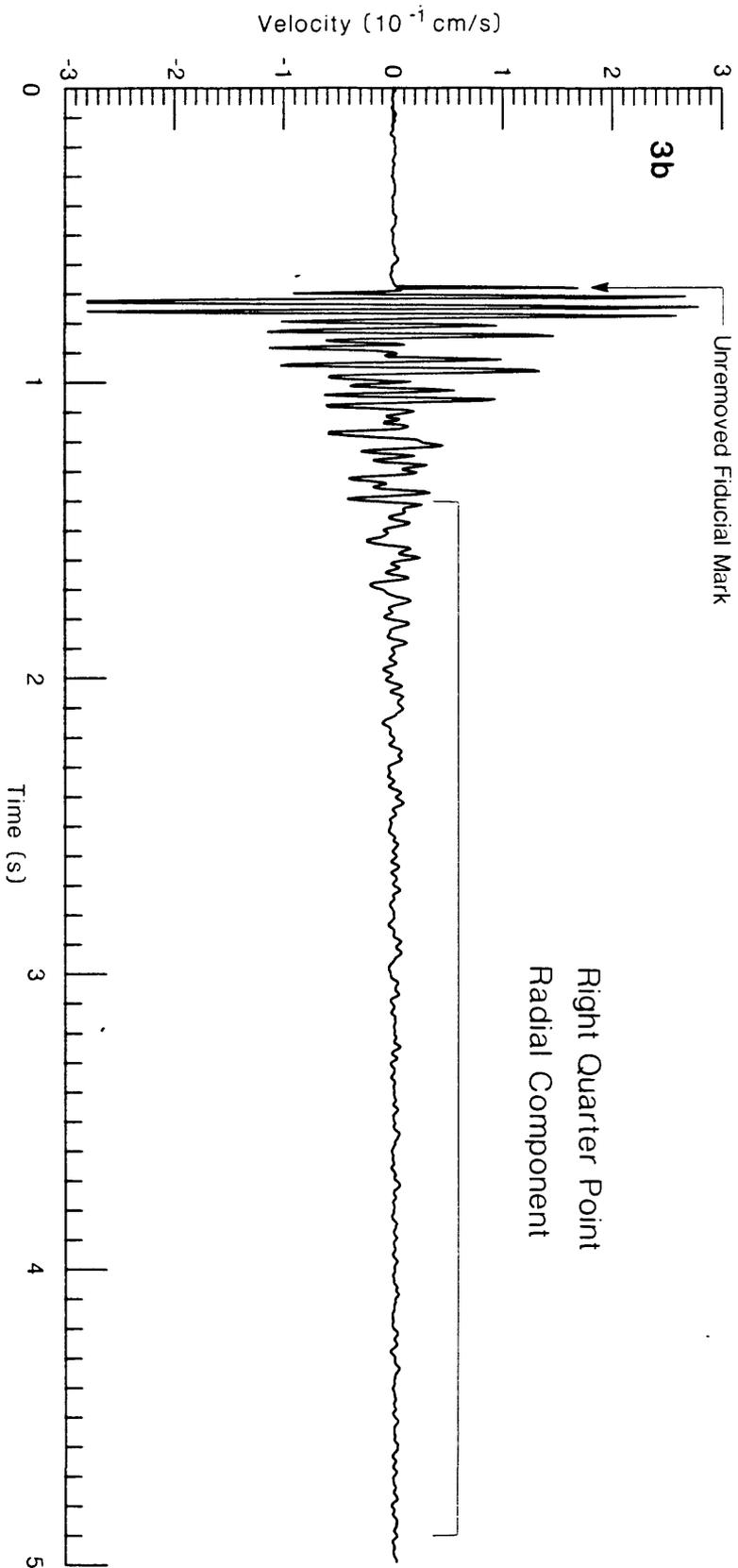


Fig. 3b. The radial motions excited by the air gun and recorded at the Right Quarter Point. An unremoved fiducial time mark is also indicated. The bracketed section of the free vibration part of the record is the section used for Fourier spectrum computation.

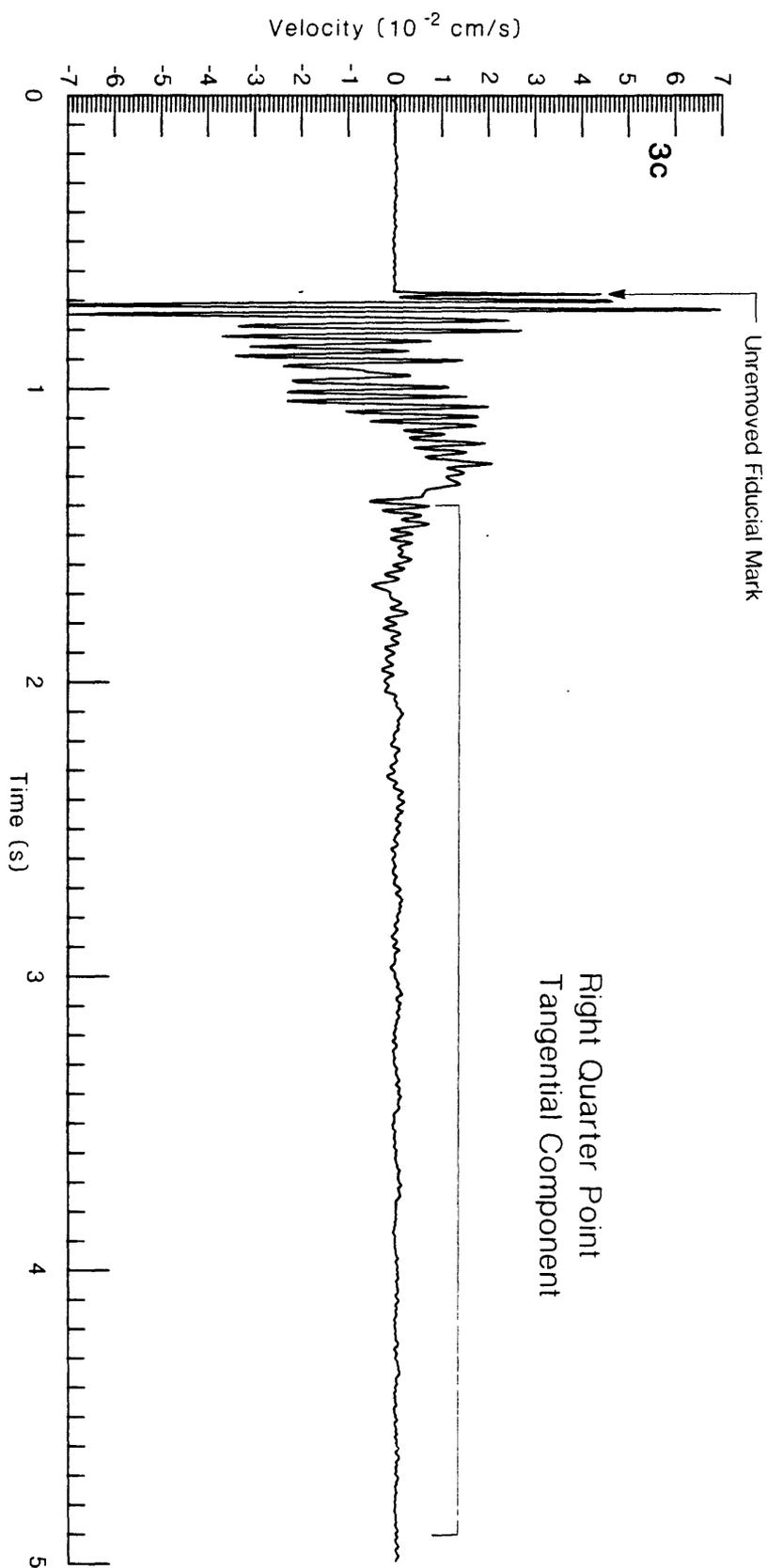


Fig. 3c. The tangential motions excited by the air gun and recorded at the Right Quarter Point. An unremoved fiducial time mark is also indicated. The bracketed section of the free vibration part of the record is the section used for Fourier spectrum computation.

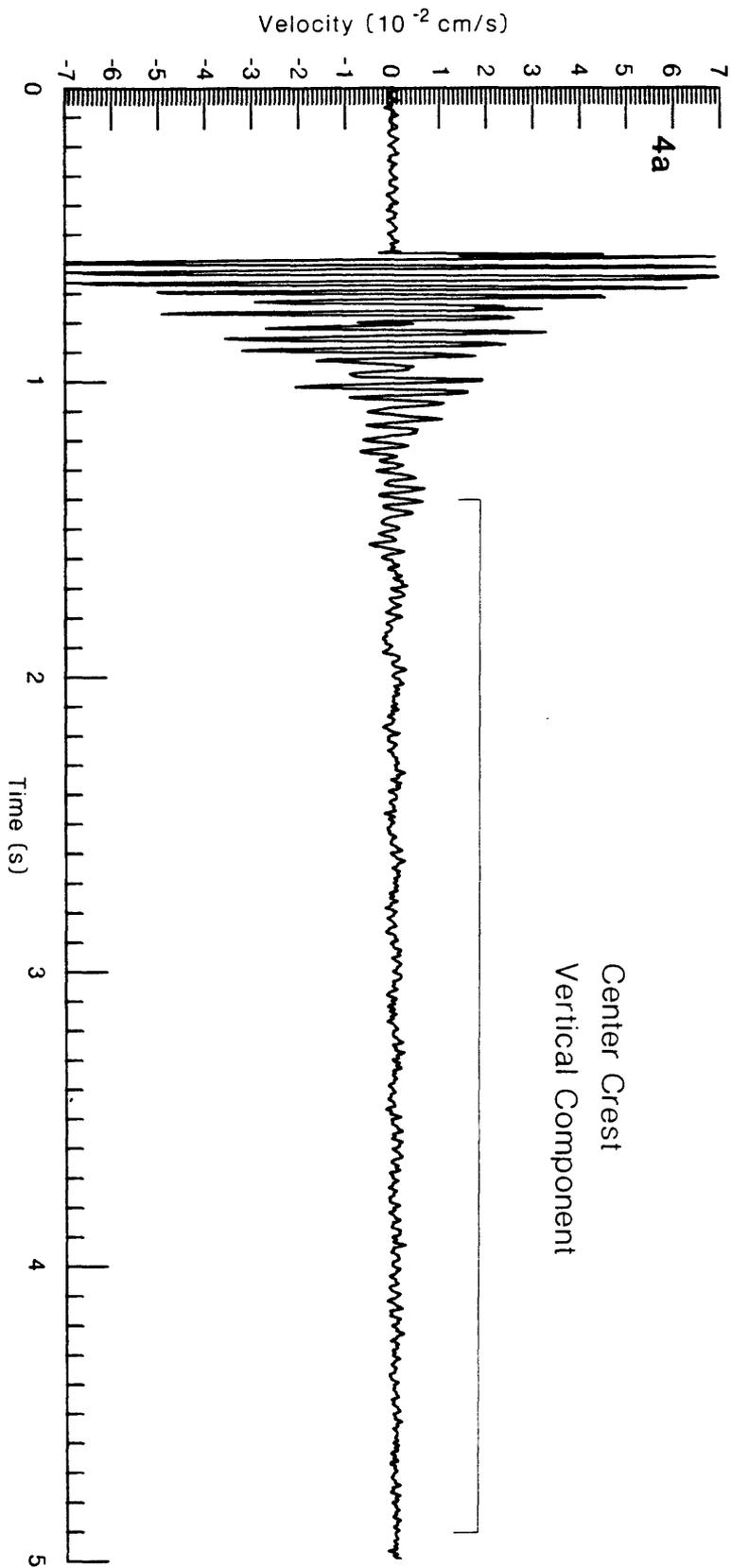


Fig. 4a. The vertical motions excited by the air gun and recorded at the Center Crest. The bracketed section of the free vibration part of the record is the section used for Fourier spectrum computation.

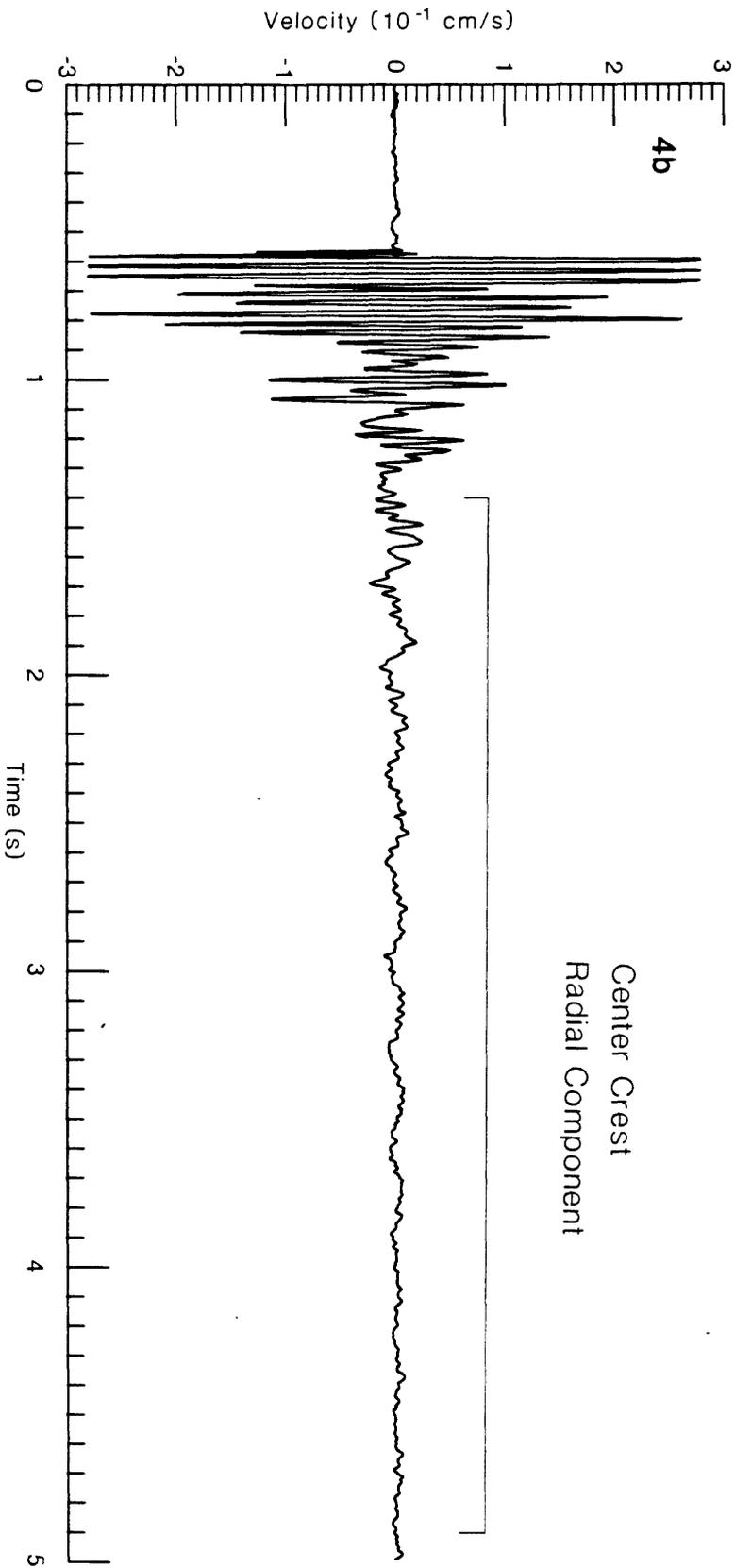


Fig. 4b. The radial motions excited by the air gun and recorded at the Center Crest. The bracketed section of the free vibration part of the record is the section used for Fourier spectrum computation.

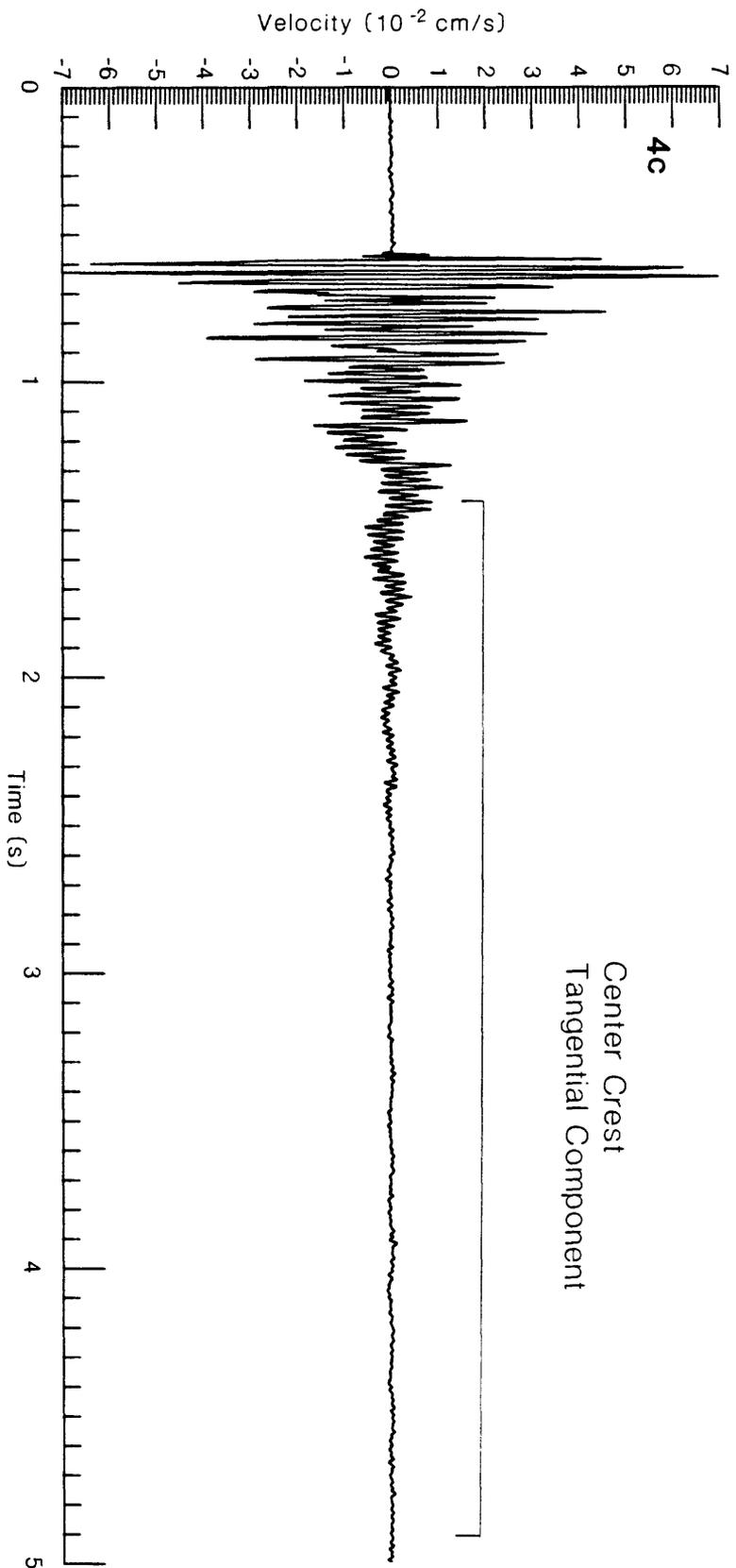


Fig. 4c. The tangential motions excited by the air gun and recorded at the Center Crest. The bracketed section of the free vibration part of the record is the section used for Fourier spectrum computation.

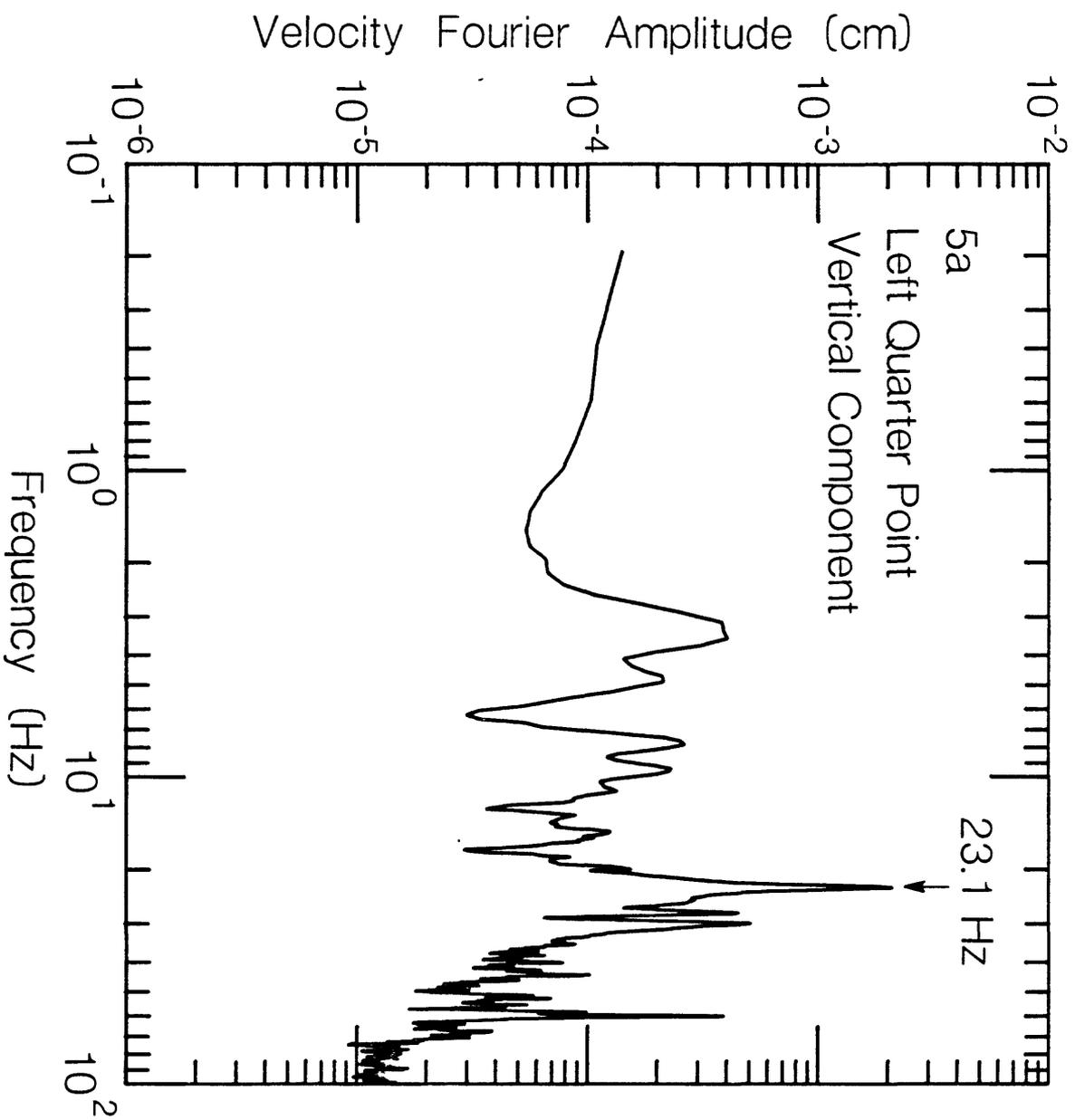


Fig. 5a. Fourier spectrum of the vertical motions recorded at the Left Quarter Point. The spectrum is computed from the bracketed section of the time record shown in Fig. 2a.

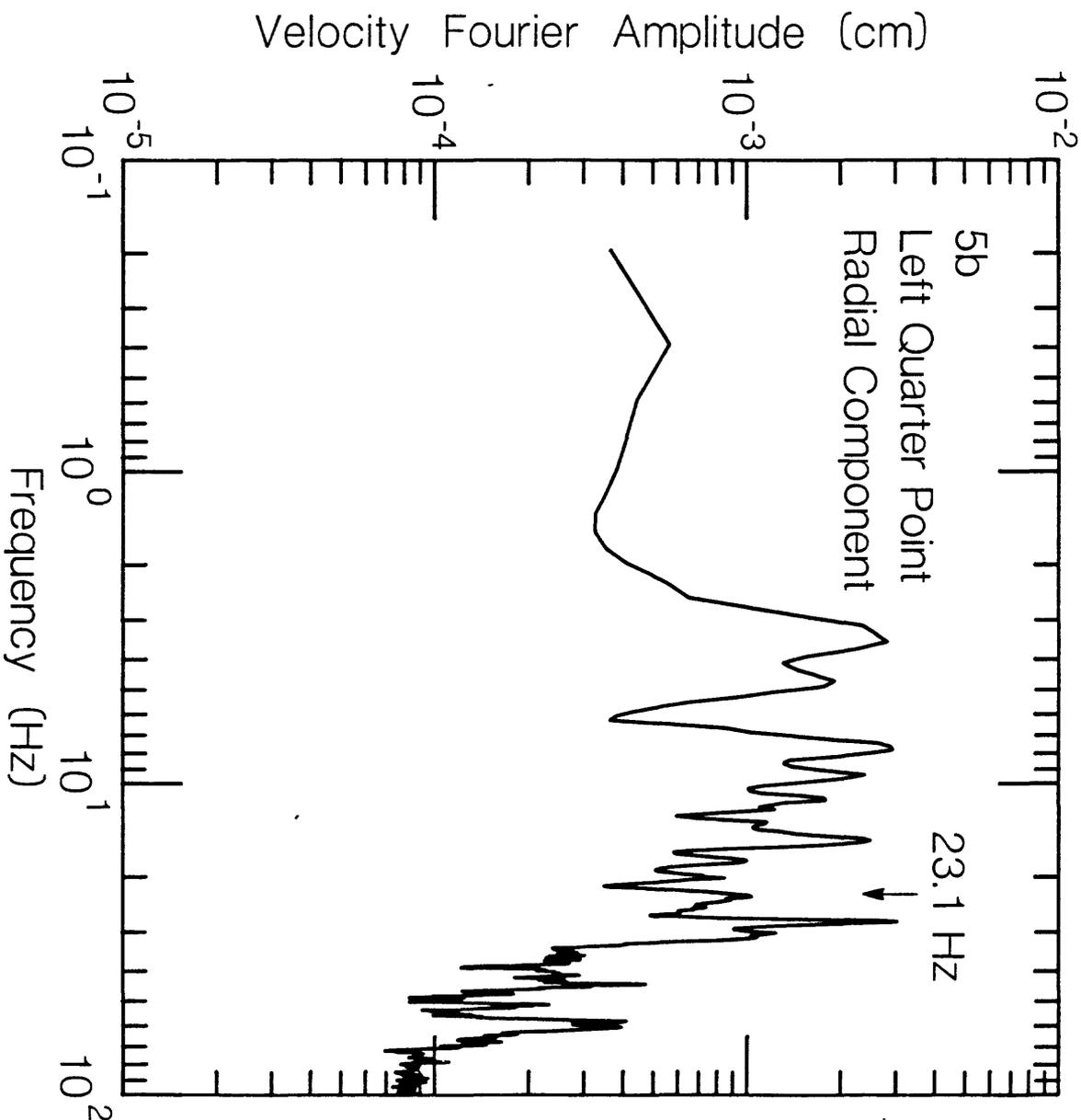


Fig. 5b. Fourier spectrum of the radial motions recorded at the Left Quarter Point. The spectrum is computed from the bracketed section of the time record shown in Fig. 2b.

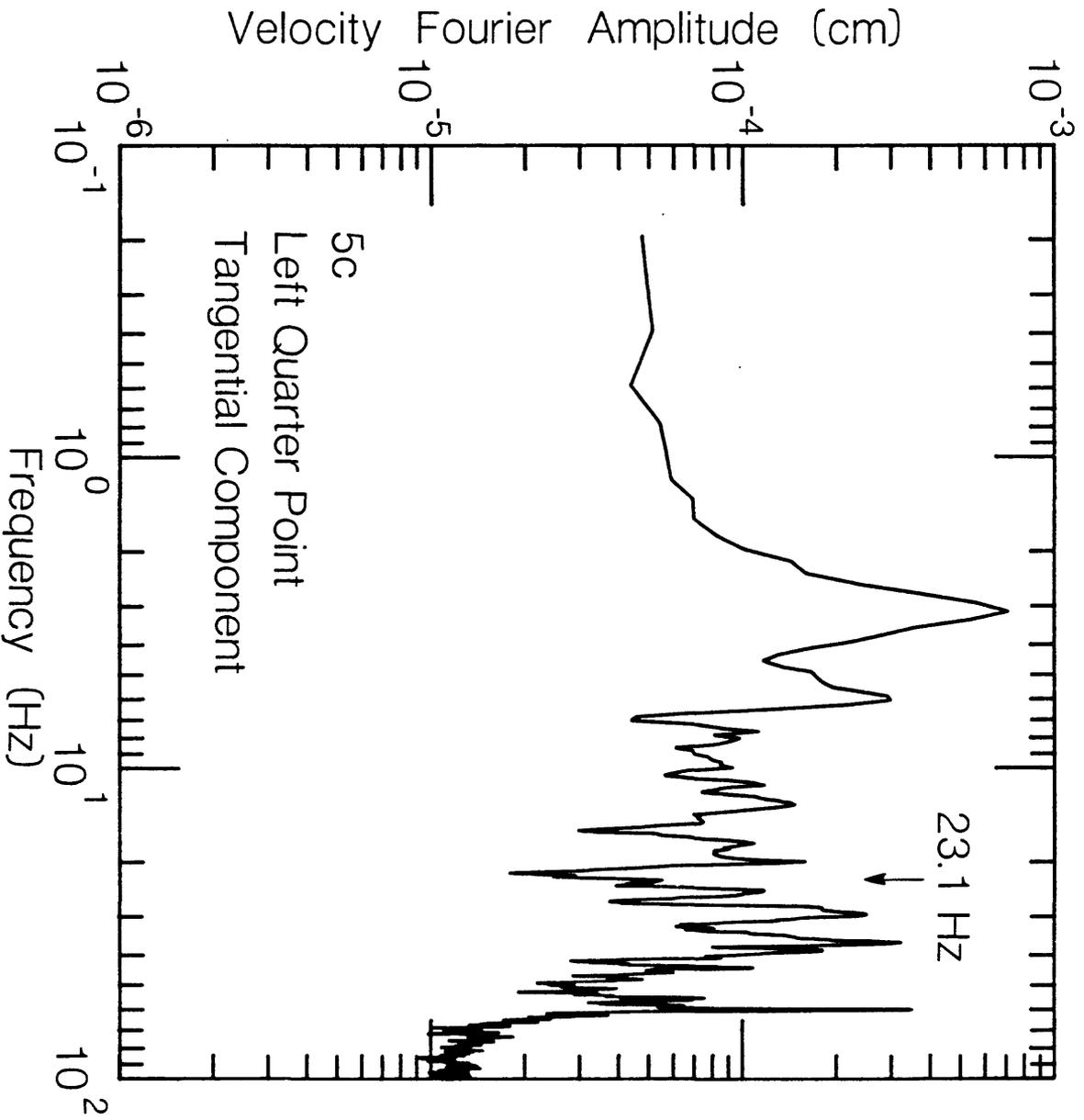


Fig. 5c. Fourier spectrum of the tangential motions recorded at the Left Quarter Point. The spectrum is computed from the bracketed section of the time record shown in Fig. 2c.

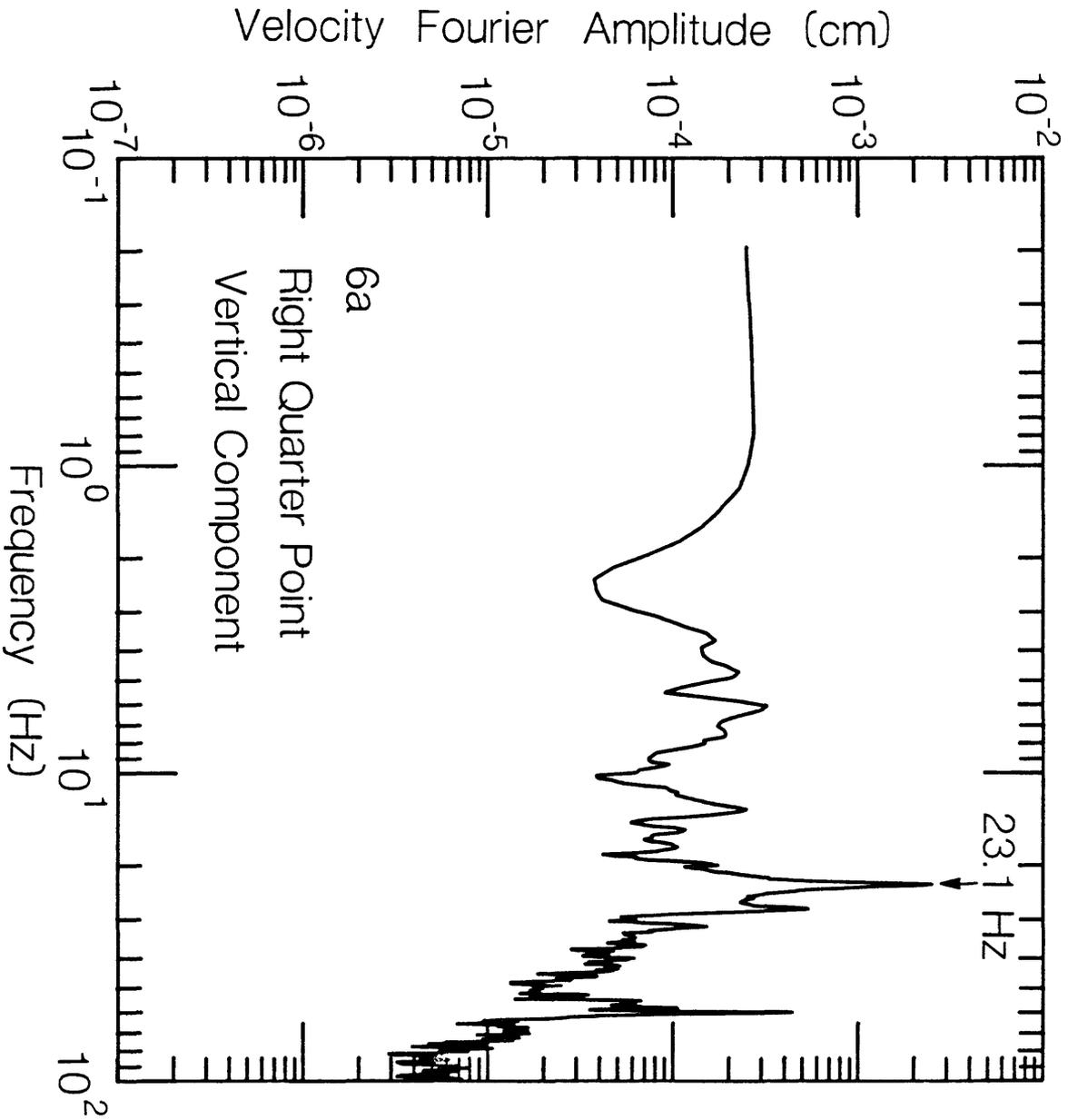


Fig. 6a. Fourier spectrum of the vertical motions recorded at the Right Quarter Point. The spectrum is computed from the bracketed section of the time record shown in Fig. 3a.

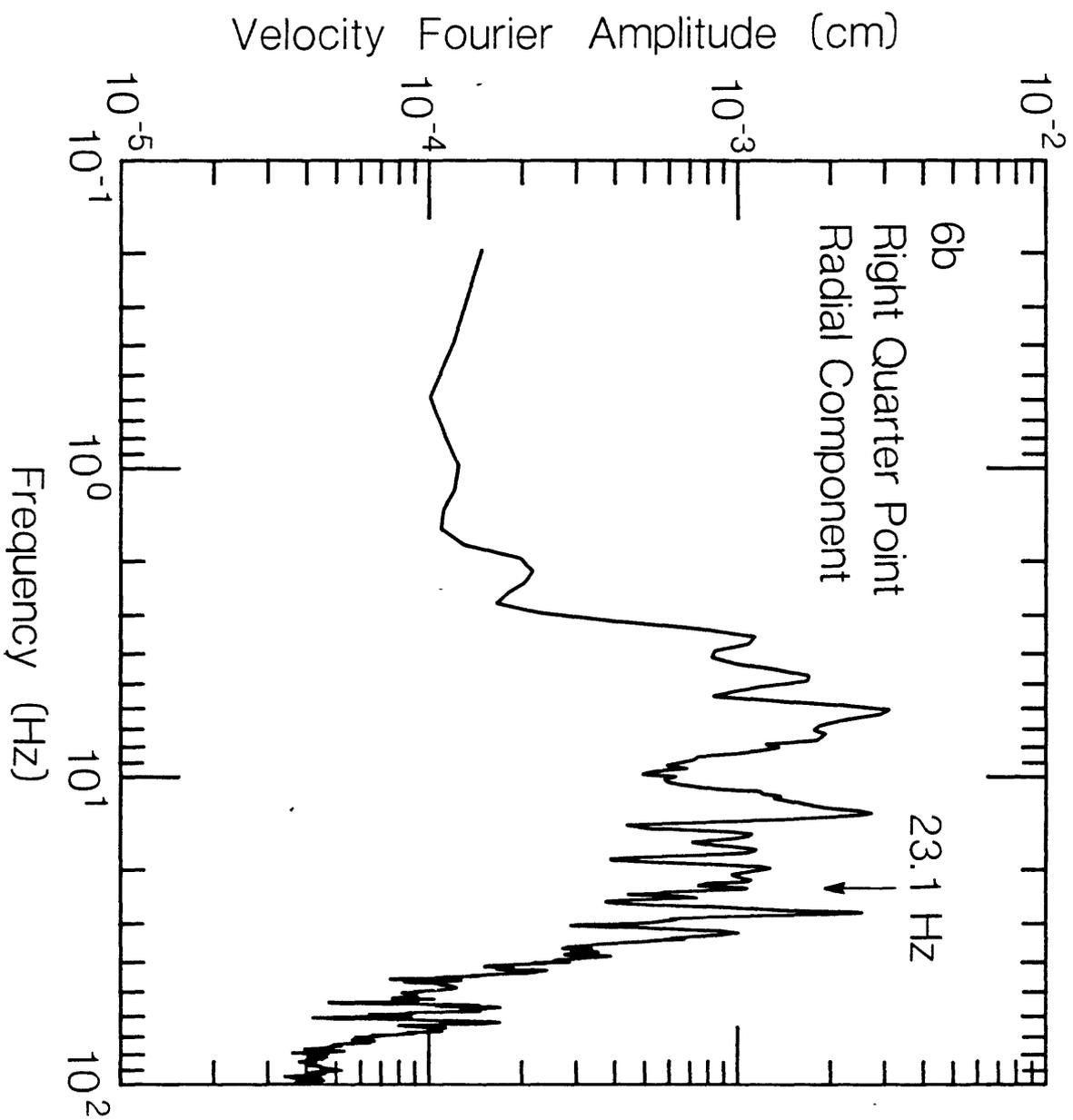


Fig. 6b. Fourier spectrum of the radial motions recorded at the Right Quarter Point. The spectrum is computed from the bracketed section of the time record shown in Fig. 3b.

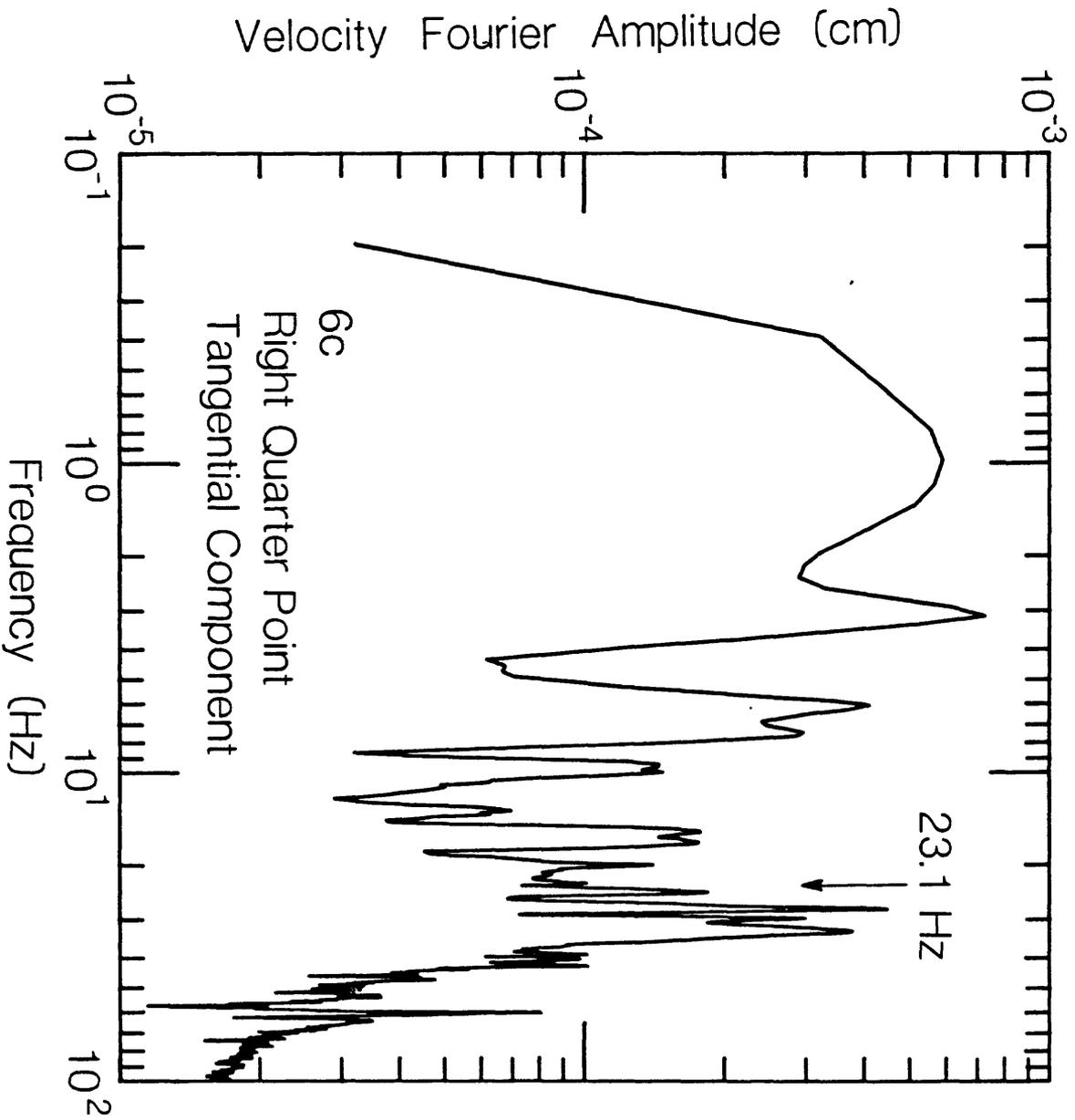


Fig. 6c. Fourier spectrum of the tangential motions recorded at the Right Quarter Point. The spectrum is computed from the bracketed section of the time record shown in Fig. 3c.

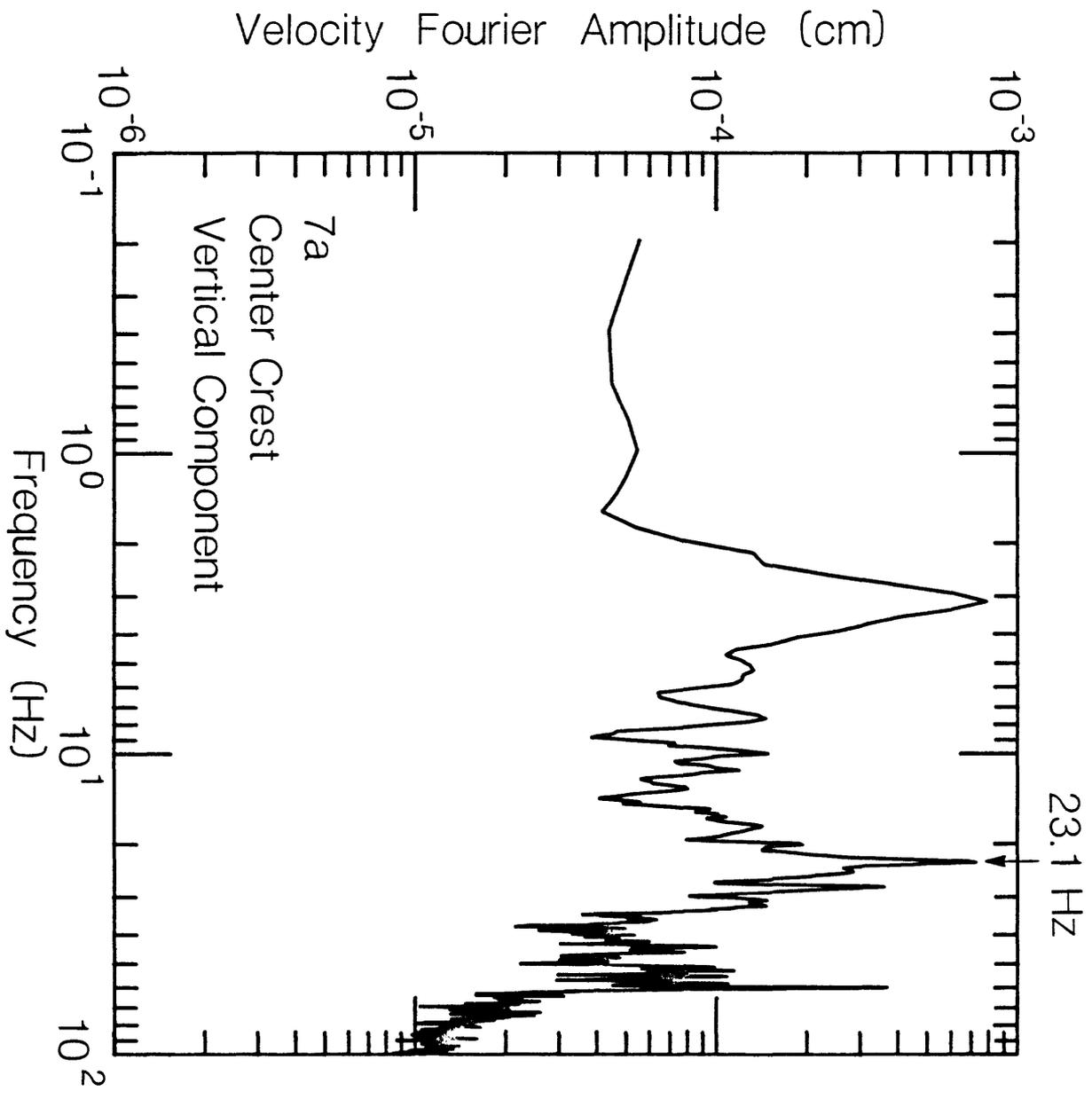


Fig. 7a. Fourier spectrum of the vertical motions recorded at the Center Crest. The spectrum is computed from the bracketed section of the time record shown in Fig. 4a.

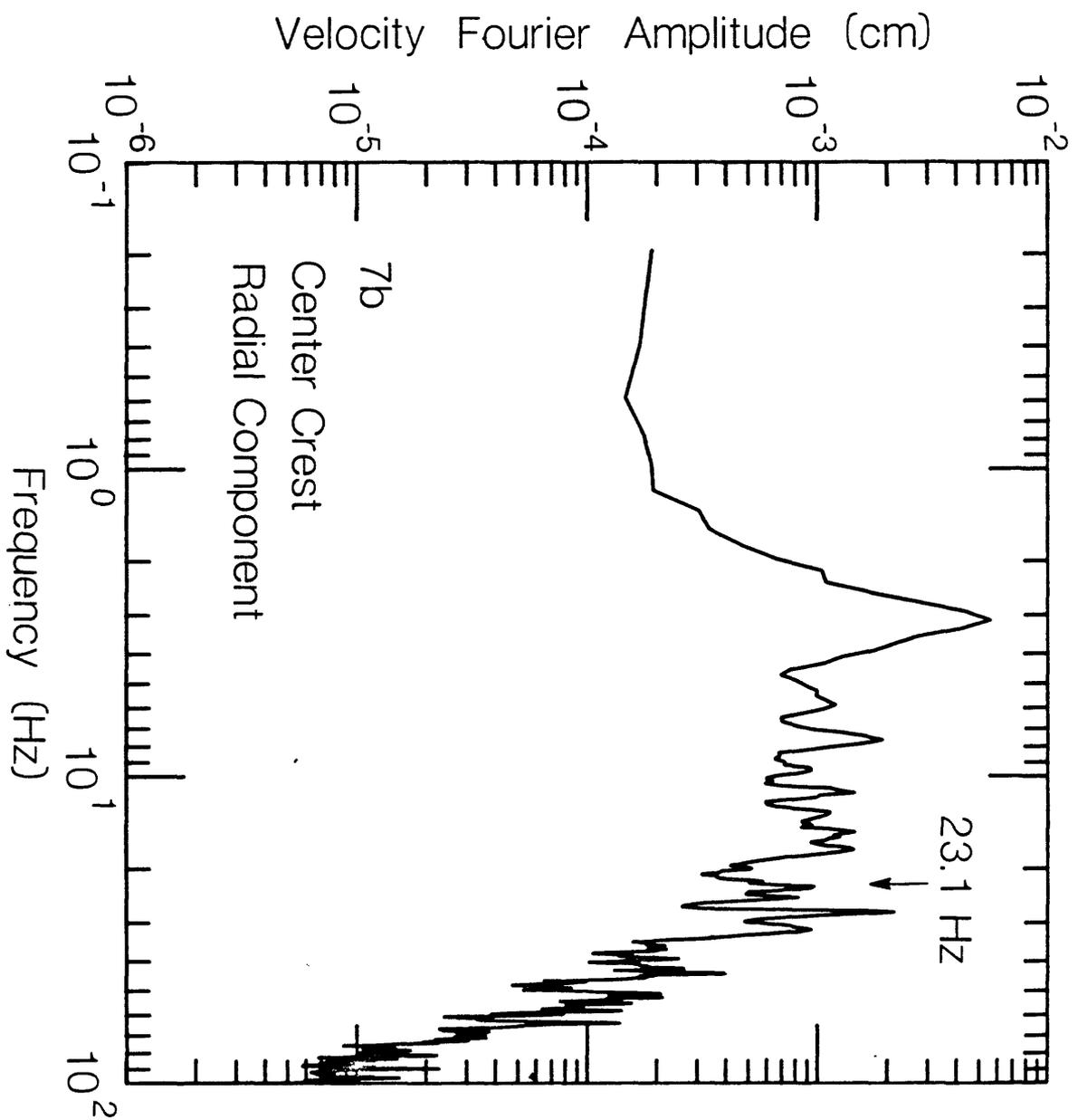


Fig. 7b. Fourier spectrum of the radial motions recorded at the Center Crest. The spectrum is computed from the bracketed section of the time record shown in Fig. 4b.

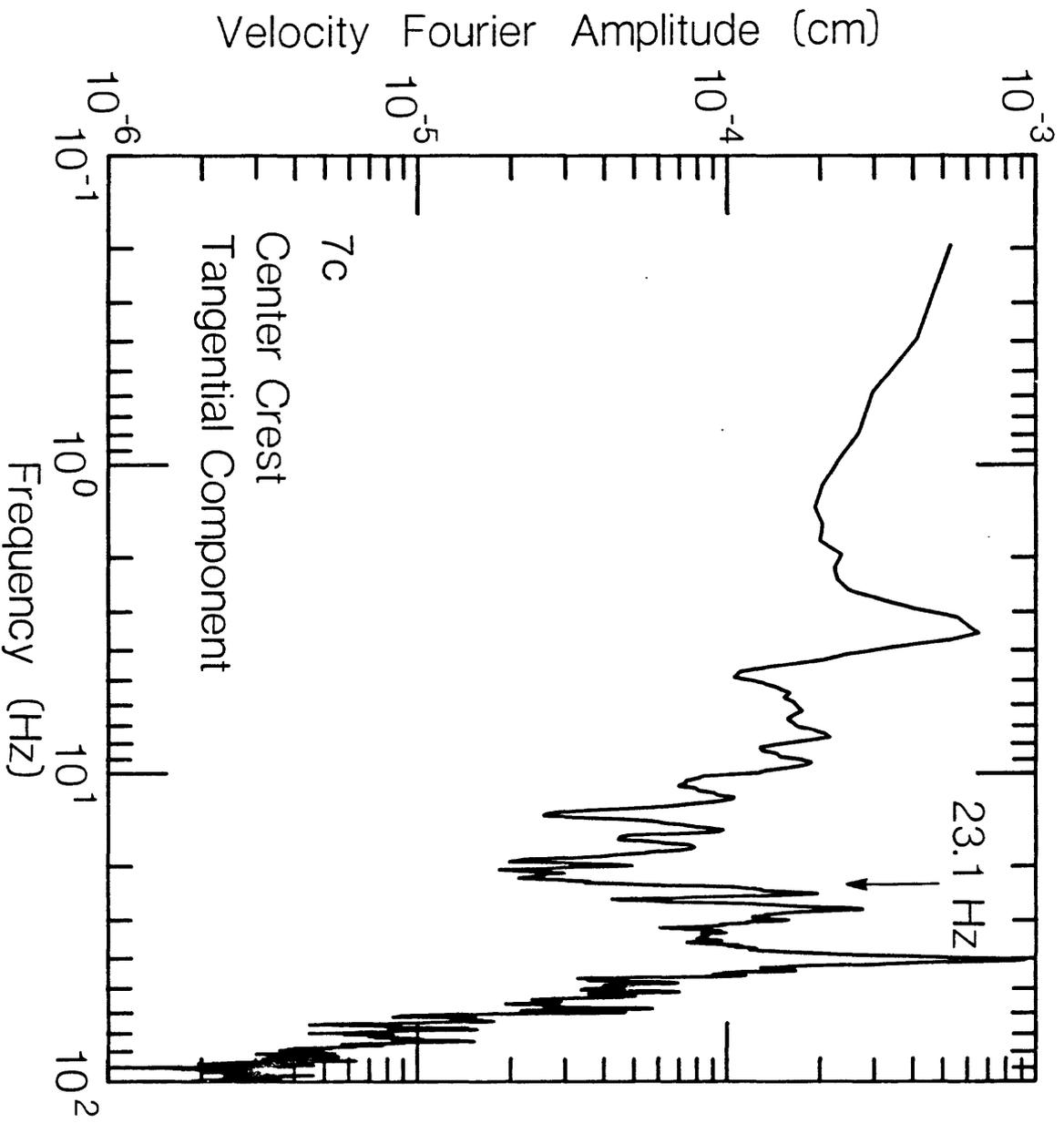


Fig. 7c. Fourier spectrum of the tangential motions recorded at the Center Crest. The spectrum is computed from the bracketed section of the time record shown in Fig. 4c.

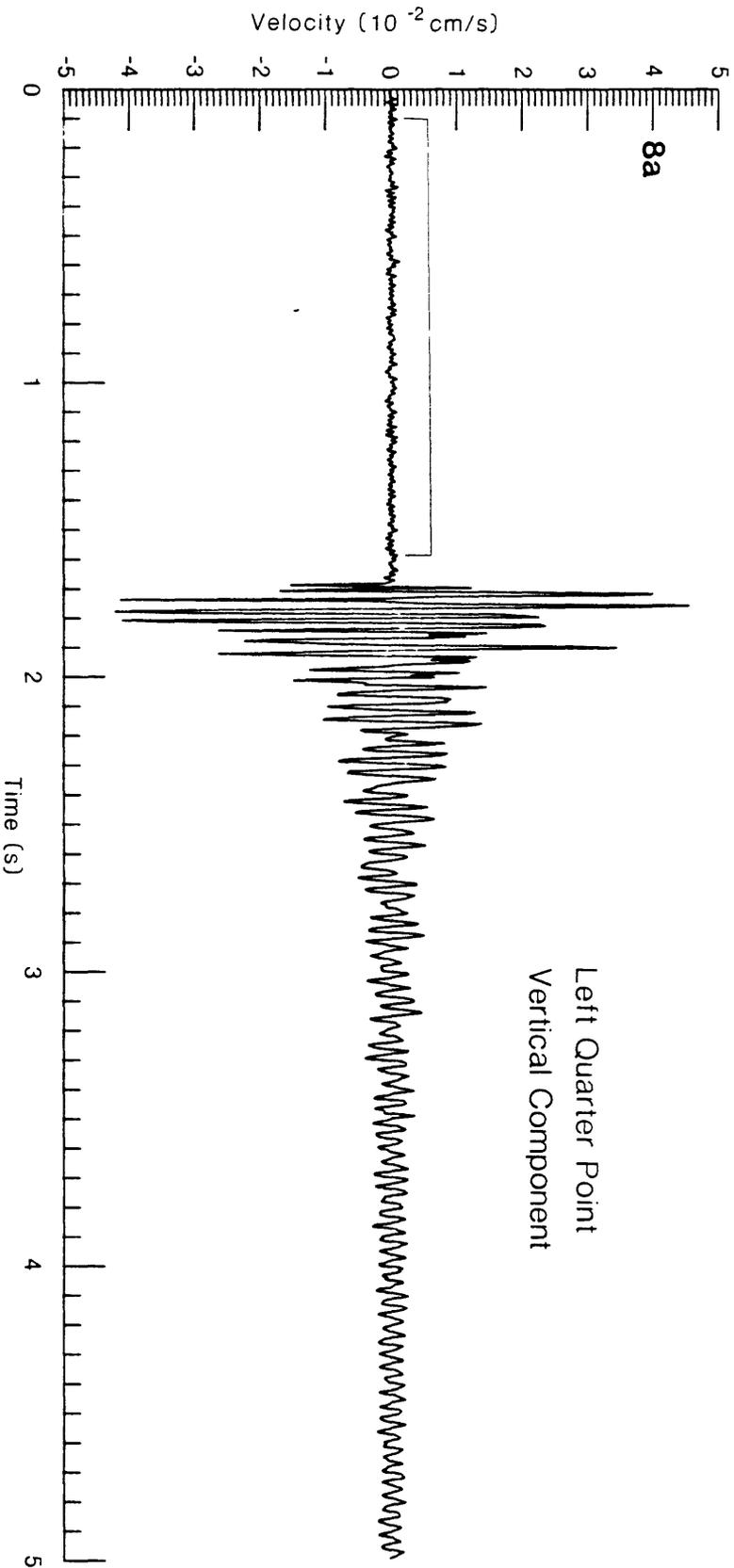


Fig. 8a. The vertical ambient vibrations at the Left Quarter Point immediately before firing the air gun. The bracketed section of the time record is the section used for Fourier spectrum computation.

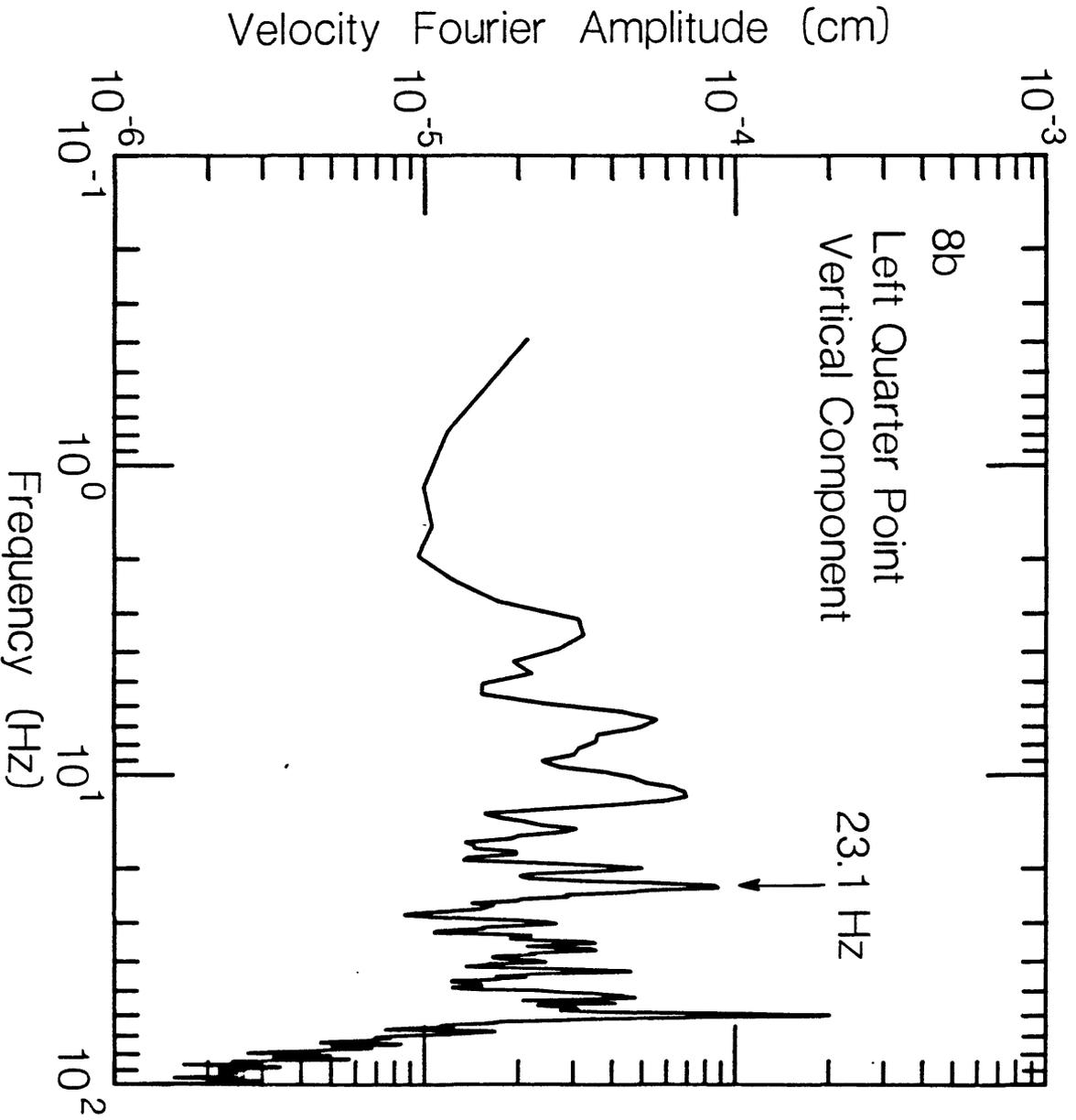


Fig. 8b. Fourier spectrum of the vertical ambient vibrations at the Left Quarter Point immediately before firing the air gun. The spectrum is computed from the bracketed section of the time record shown in Fig. 8a.

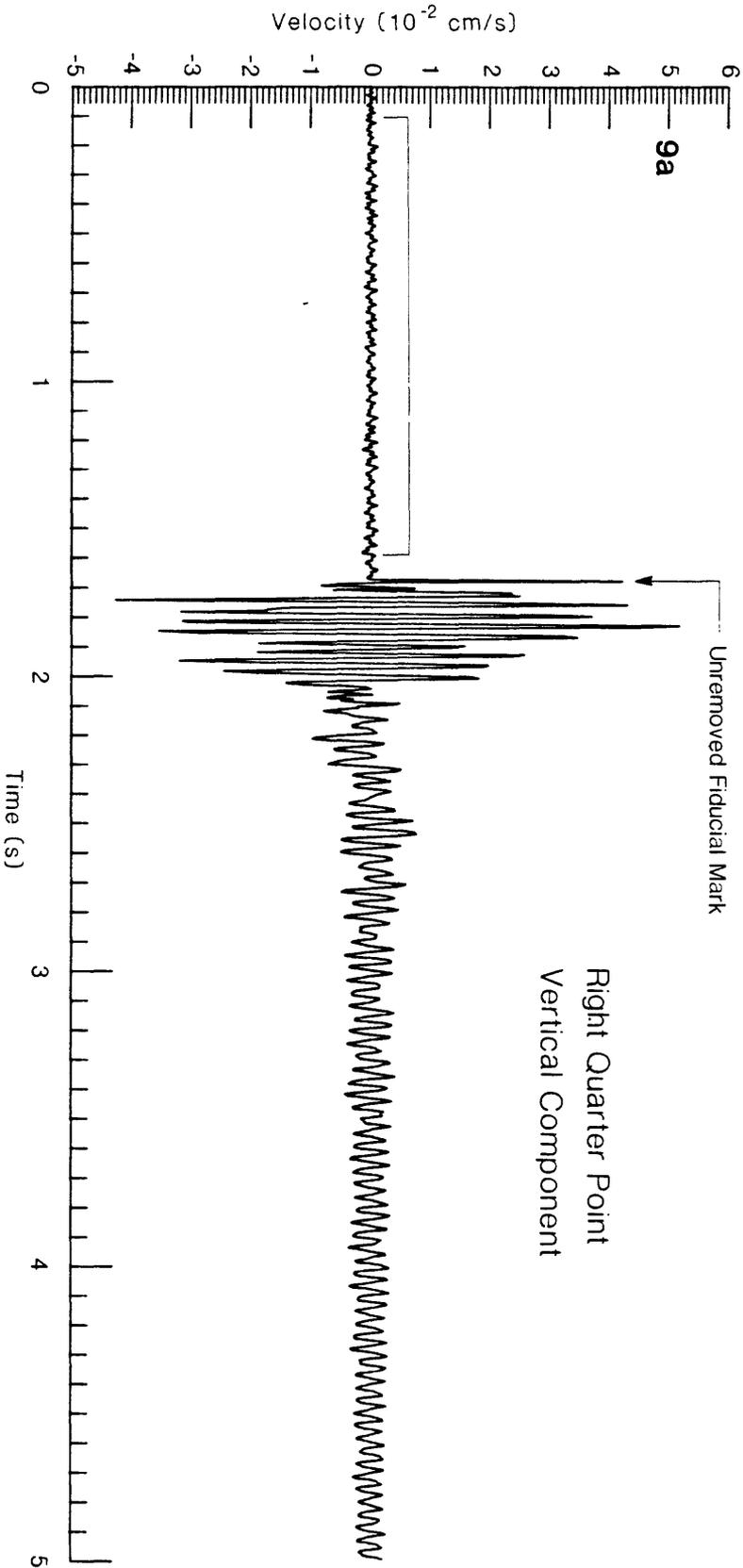


Fig. 9a. The vertical ambient vibrations at the Right Quarter Point immediately before firing the air gun. An unremoved fiducial time mark is also indicated. The bracketed section of the time record is the section used for Fourier spectrum computation.

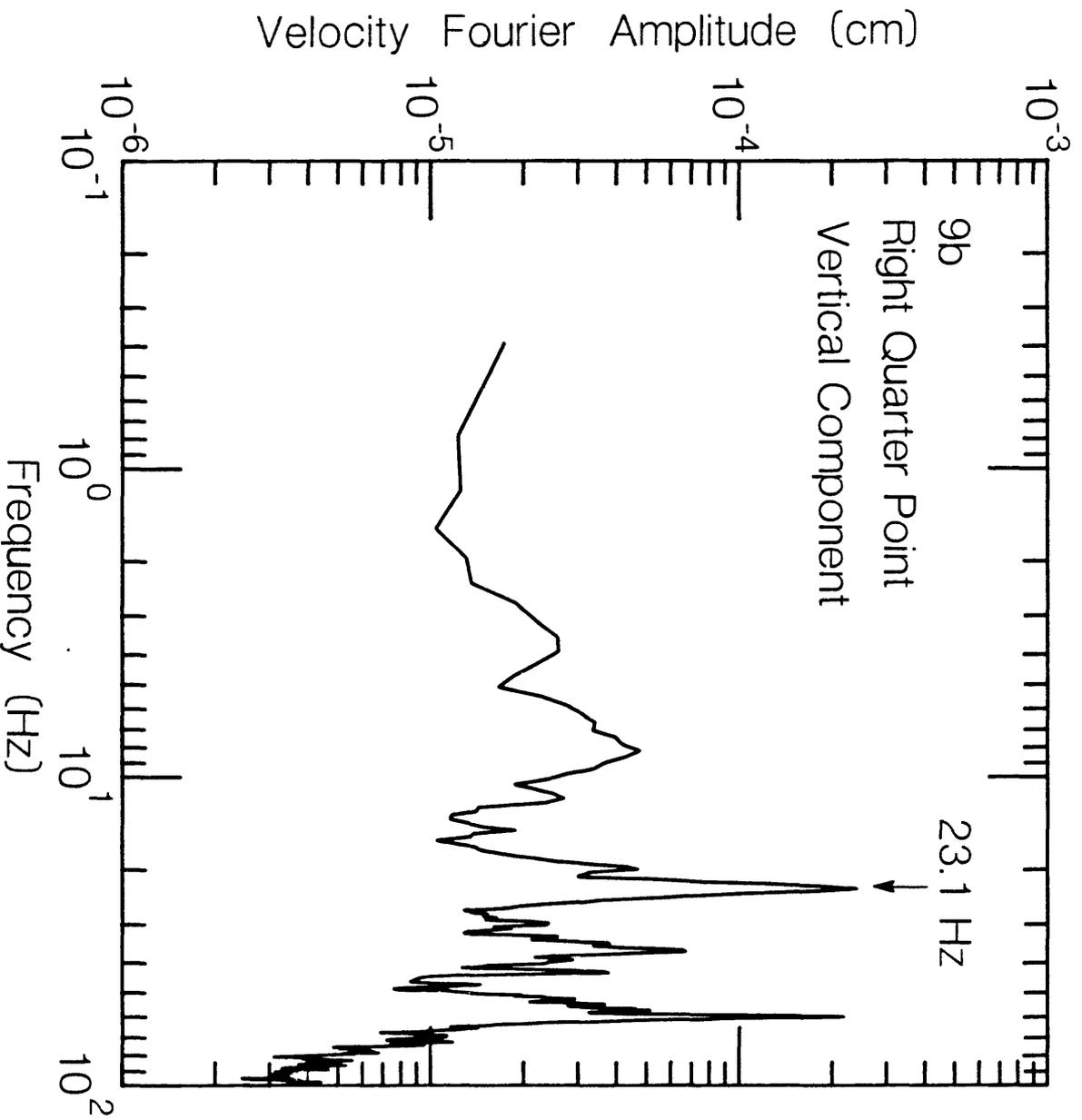


Fig. 9b. Fourier spectrum of the vertical ambient vibrations at the Right Quarter Point immediately before firing the air gun. The spectrum is computed from the bracketed section of the time record shown in Fig. 9a.

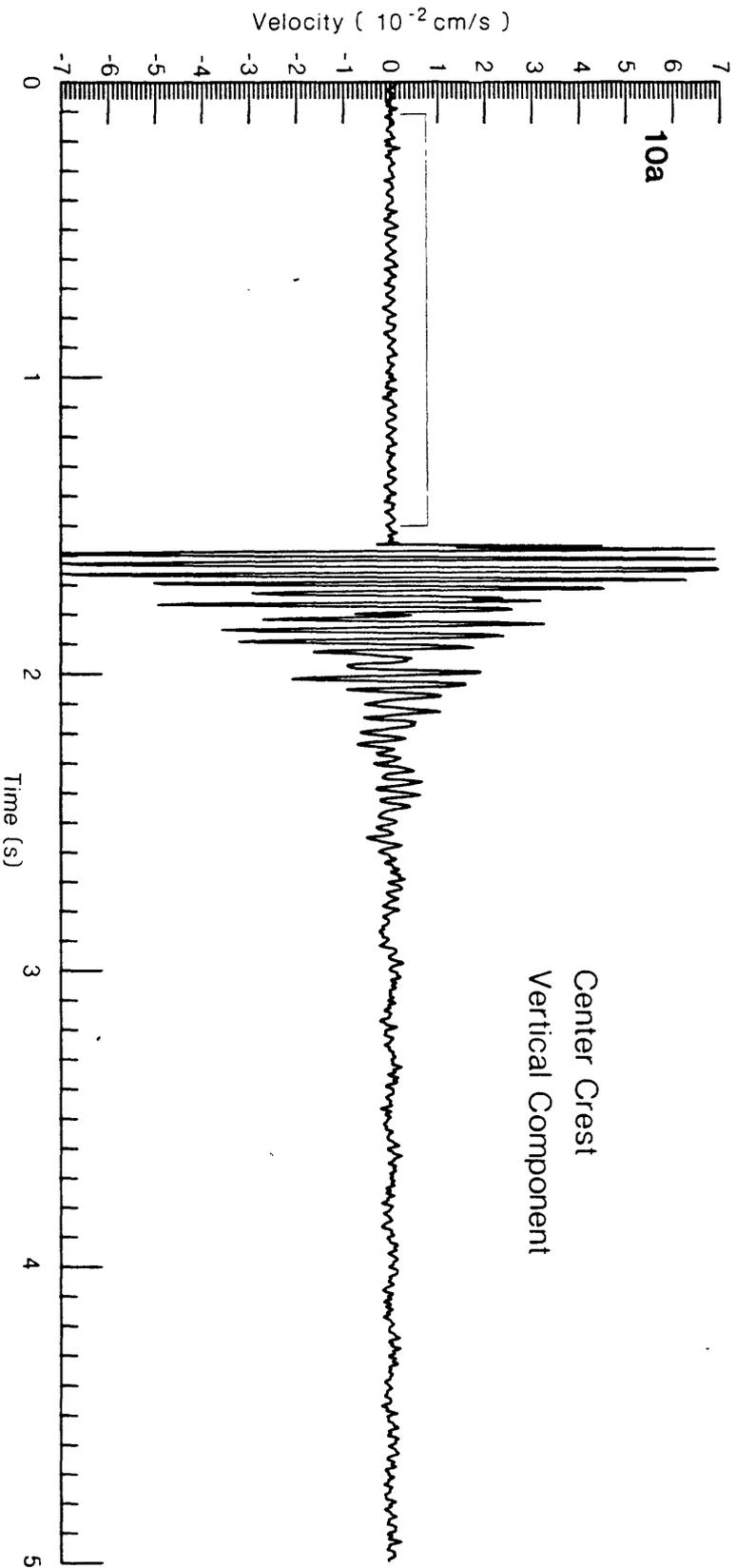


Fig. 10a. The vertical ambient vibrations at the Center Crest immediately before firing the air gun. The bracketed section of the time record is the section used for Fourier spectrum computation.

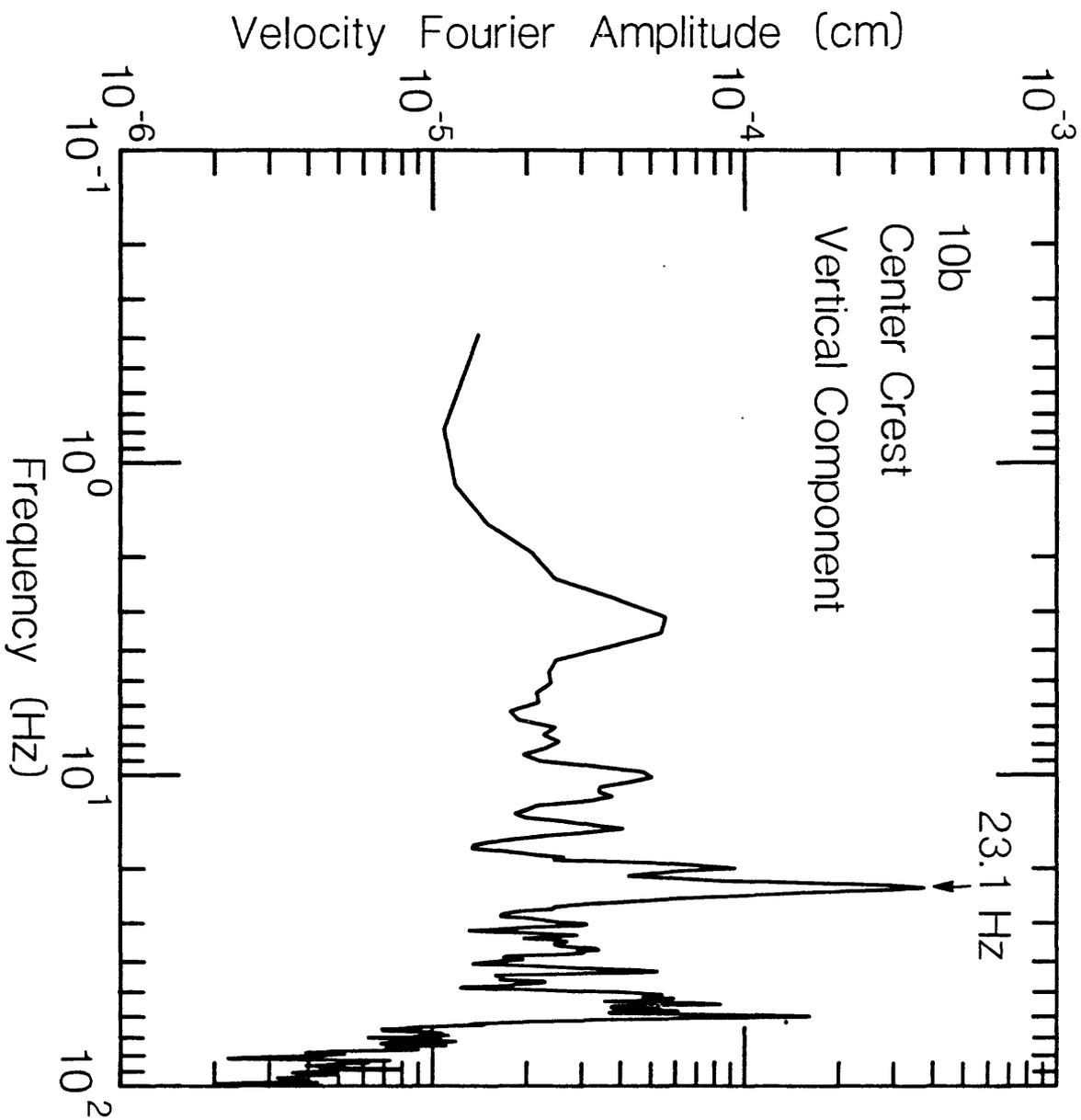


Fig. 10b. Fourier spectrum of the vertical ambient vibrations at the Center Crest immediately before firing the air gun. The spectrum is computed from the bracketed section of the time record shown in Fig. 10a.

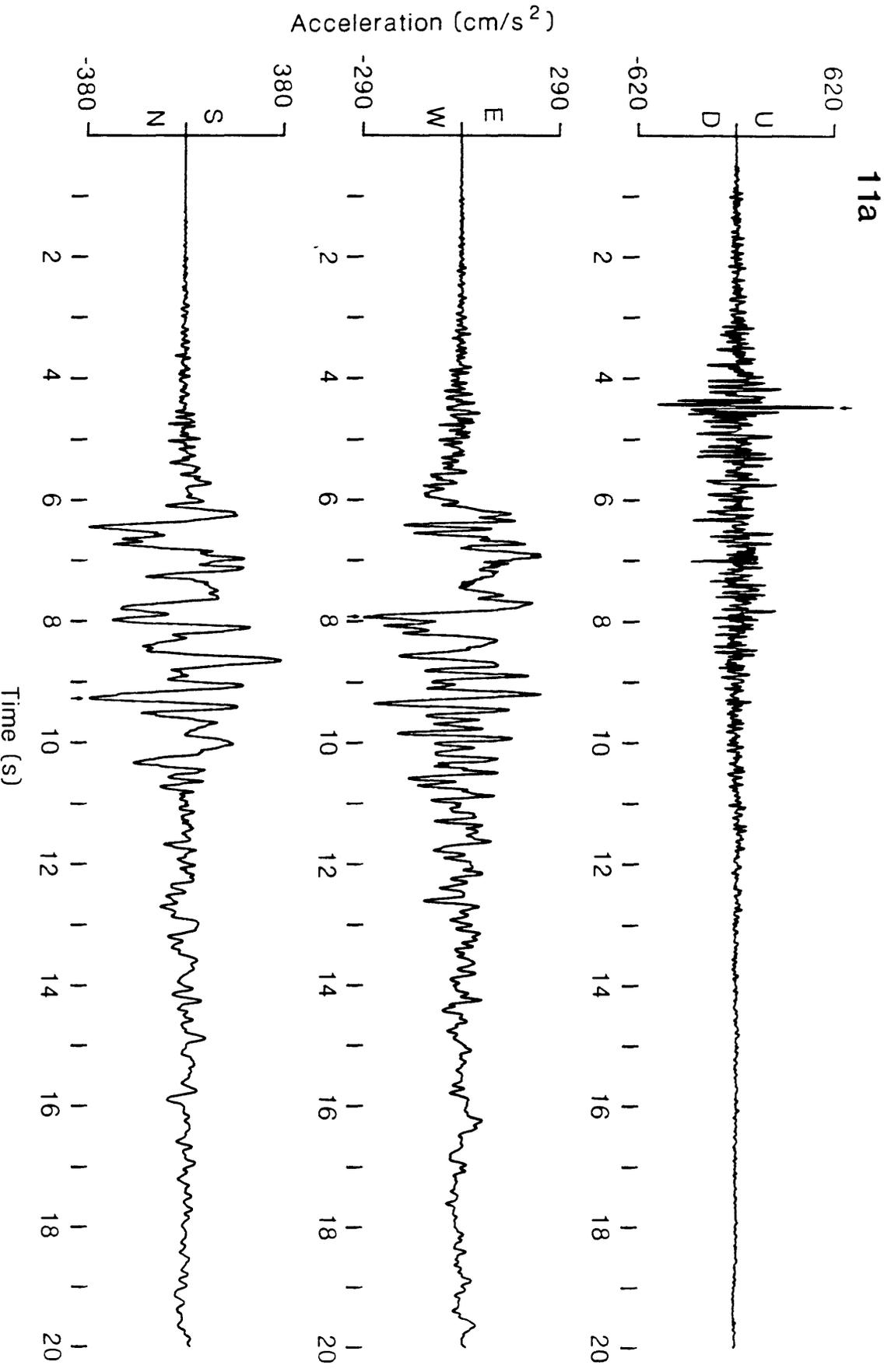


Fig. 11a. Three components of acceleration recorded at a distance of 6 km (3.73 mi) from the ruptured Imperial fault, Imperial valley earthquake, 1979.

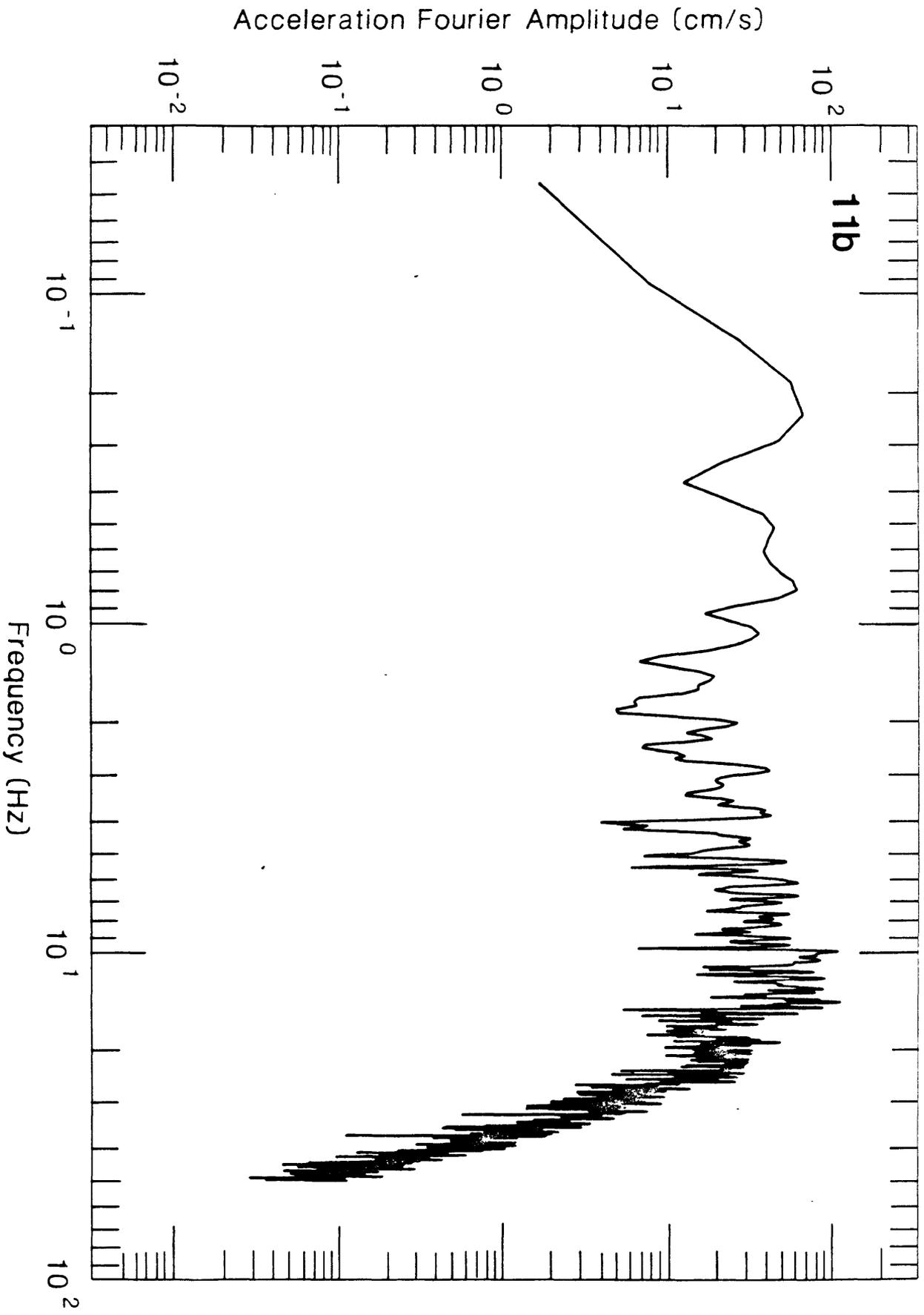


Fig. 11b. Fourier spectrum of the vertical acceleration shown in Fig. 11a. The cut-off at 25 Hz corresponds to the cut-off frequency of the electronic filter of the force-balance accelerometer.