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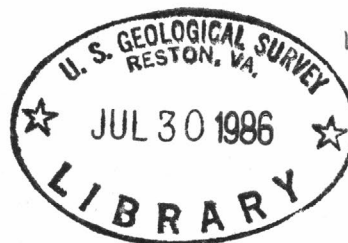
U.S. GEOLOGICAL SURVEY

A Borehole Geophone Leveling Device

by

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ABSTRACT

Horizontal electromagnetic geophones of natural period greater than 0.5 s need to be leveled to better than 1.5° . This requirement demands a leveling device for using such geophones in a borehole when the axis of the geophone package deviates from the vertical by more than 1.5° after emplacement. Using Bendix flexural pivots as rotational axes, a gimbal leveling device has been constructed which levels two orthogonally-oriented horizontal geophones to 0.1° from an initial maximum tilt of 10.5° . This leveling device is designed to fit into a borehole-geophone package 12.7 cm (5 in) in outside diameter.

A Borehole-Geophone Leveling Device

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INTRODUCTION

When a horizontal electromagnetic geophone is tilted from level, the coil equilibrium position moves away from the centered position as a result of the gravitational force. The natural period of the geophone changes slightly because the spring constant of a diaphragm spring depends on the initial static flexure. More seriously, the mass will hit its end-stop when the tilt exceeds a certain angle. For geophones with natural period greater than 0.5 s, this angle is typically 3° . The leveling requirement is more stringent if in-situ calibration by the geophone release test needs to be carried out; the tilt angle then cannot exceed a typical value of 1.5° for a reasonable coil movement.

These leveling requirements are met by using gimbals in ocean bottom seismometers (Moore et al., 1981). The seismometer assembly consists of a pendulum whose convex spherical bottom normally rests on a matching concave spherical seat; the center of curvature of these spheres is the point of intersection of the gimbal axes. When leveling, the seismometer assembly is suspended at the gimbal center by means of a solenoid.

This method of leveling has not been adapted for use in borehole-geophone assemblies because of the size requirement of the ball bearings which serve as the gimbal rotational axes in the ocean bottom seismometer. A gas bearing is used in the Teledyne Geotech Model 38600 borehole seismometer (Teledyne Geotech, 1975). Leveling is accomplished by forcing a gas pressure pulse between the convex spherical bottom of the geophone assembly and its matching concave spherical seat, allowing the assembly to float momentarily. The geophone assembly reaches level after a series of gas pulses. The use of a gas bearing requires a pump being installed in the seismometer package. Comparing the energizing elements in the two leveling methods, the solenoid is a simpler device than the gas pump.

Using free-flex flexural pivots as rotational axes, a considerable reduction in size has been achieved in the gimbal leveling method and a geophone leveling device has been constructed which levels two orthogonally-oriented horizontal geophones to 0.1° from an initial tilt of 10.5° . This leveling device can be fit into a geophone package designed for a 15.24 cm (6 in)-diameter borehole.

THE LEVELING DEVICE

The Bendix Flexural Pivot

Miniaturization of the gimbals is made possible by a flexural pivot, manufactured and patented by the Bendix Corporation. The pivot is made of flat, crossed springs supporting two rotating sleeves (Fig. 1). Because the pivot rotates by the torsional elastic deformation of the springs, the motion is frictionless. The pivot selected for the present leveling device has the Bendix catalog number 5008-800; its size is 6.35 mm diameter x 10.16 mm long

(0.250 in diameter x 0.400 in long). Under conditions designed for the present leveling device, it can be used for an indefinite number of cycles at a maximum deflection angle of 10° . The torsion constant is 0.0045 m-N/rad (0.04 in-lb/rad).

Design Requirements

The leveling device is to house two Mark Products L-22D 2.0 Hz horizontal geophones. It is to be fit into a borehole package 13.97 cm (5.5 in) in diameter. The geophones should be leveled to 0.1° after emplacement of the borehole package. The axis of the cylindrical borehole package can deviate from vertical by 10° and be within the range of correction.

Design

A sketch of the apparatus is shown in Fig. 2. The two sets of flexural pivots defining the two rotational axes are shown in the top view, Fig. 2a. The pendulum P containing the two horizontal geophones G is shown in the cross section view, Fig. 2b. The pendulum normally rests on a spherical seat (SE) having the same radius of curvature as the pendulum bottom surface. When energized, the solenoid (SO) lifts the pendulum from the spherical seat, allowing it to swing on the gimbals. The case of the leveling device, C, limits the pendulum swing to 10.5° .

The weight of the pendulum is $m = 2.65 \text{ kg}$ (5.83 lb). The torsion constant per axis is $k = 0.009 \text{ m-N/rad}$ (0.08 in-lb/rad). Fig. 3 shows the initial tilt angle of the pendulum from the vertical, θ_0 , when it rests on the spherical seat and its final tilt angle in the lifted position θ . Taking moment about the rotational axis O,

$$\begin{aligned} mgl\theta &= k (\theta_0 - \theta) & \text{or} \\ \theta &= k\theta_0 / (Mgl + k) \end{aligned} \quad (1)$$

where g is the gravitational acceleration, and l is the distance between O and the center of mass of the pendulum. Take $l = 6.88 \text{ cm}$ (2.71 in), half the length of the pendulum and $\theta_0 = 10^\circ$, $\theta = 0.05^\circ$ from Eq. 1. The result shows that the Bendix pivot chosen has a sufficiently small torsion constant that its influence on the leveling operation is less than 0.05° .

The geophones can be shifted laterally in the pendulum in order to change the center-of-mass position of the pendulum-and-geophones combination. After the device has been assembled, the geophones are shifted laterally until the pendulum's geometric axis suspends in plumb. The level of geophones is checked by using the geophone release test (Asten, 1977) as follows: A direct current is passed through the geophone coil until the mass is forced against its mechanical stop. When the external current is removed, the motion of the mass, $x_1(t)$, can be monitored at the geophone output by an oscilloscope. On reversing the direction of the current flow, the resulting motion will have the same peak amplitude as $x_1(t)$ only if the equilibrium position of the mass is exactly halfway between the two stops (assuming a symmetric magnetic flux and a symmetric coil winding). The condition that the rest position of

the mass is halfway between the two stops is used as a practical criterion for leveling the geophone. The precision of leveling by the geophone release test is 0.05° for the Mark Products L-22D geophones.

Operation

Operation of the leveling device is straightforward. The pendulum is lifted from its initial rest position by energizing the solenoid. Its ensuing motion is monitored by displaying the geophone output on an oscilloscope. When the swinging motion of the pendulum has been damped out, the current is removed from the solenoid. The geophones should now be level. Dithering of the pendulum motion in order to overcome static friction, a method commonly employed in gimbals using ball bearings as rotational axes, is not necessary as the Bendix flexural pivot is a frictionless device.

TESTS AND RESULTS

Initial Adjustment

With the case leveled by a spirit bubble, the geophones are shifted laterally until the pendulum's geometric axis suspends in plumb.

Effect of Tilt on Voltage Output from Geophone Release Test (Mark Products L-22D Horizontal Geophone)

This change is determined by tilting the case of the leveling device by a known angle while the pendulum rests on its seat. Voltage output of the geophone release transients in both directions are then measured. The results are shown in Table 1. A tilt angle of 0.1° can be readily resolved.

Leveling Capability of the Geophone Package

After the initial adjustment as described above, the case is tilted by a known angle as large as 10.5° . The solenoid is then energized, suspending the pendulum on the gimbals. The pendulum is let down after its motion has been damped out. The deviation from level of the geophones is determined by the geophone release test. The test results are listed in Table 2. Leveling to 0.1° with an initial tilt of 10° was consistently achieved during the tests.

Coupling to Ground via the Spherical Seat

The geophones are clamped to the pendulum after the initial center-of-mass adjustment. The pendulum is coupled to the spherical seat by its weight (Fig. 2b). The frictional contact between the pendulum and the spherical seat and the curvature of the spherical surfaces are sufficient to prevent relative sliding between the pendulum and the spherical seat from horizontal ground motions up to at least an acceleration of 1.03 g at 10 Hz .

The seismic response of the leveling device containing two horizontal geophones is compared with a Mark Products L-22 3D-geophone package by placing them side-by-side in an open field at St. Patrick's Seminary in Menlo Park, California. The two orthogonally-oriented horizontal geophones in the

leveling device are aligned parallel to the two horizontal geophone elements in the L-22 3D-package. Traffic noise generated outside of the seminary and motions generated by a person jumping at about 9.14 m (30 ft) away from the geophones were recorded by two USGS GEOS digital recorders (Borcherdt et al., 1985). The traffic noise record is shown in Fig. 4a; the recorded jumping motions are shown in Fig. 5a. The seismic records of the two geophone packages are very similar, except those recorded by the L-22 3D-geophone package show higher frequency content. This observation is borne out by the coherence calculation shown in Figs. 4b and 5b. The coherence is nearly 1 for traffic noise from 0 to 40 Hz (Fig. 4b). The jumping test gives better results; the coherence is nearly 1 from 0 to 60 Hz (Fig. 5b). The higher frequency motions recorded by the Mark Products 3D-geophone package could be caused by differences in the sensor-to-earth coupling between the two sensor packages.

CONCLUSION

Using Bendix flexural pivots as rotational axes, a gimbal leveling device has been constructed which levels two orthogonally-oriented horizontal geophones to 0.1° from an initial maximum tilt of 10.5° . The leveling device can fit inside a borehole package 5 in (12.7 cm) in diameter.

ACKNOWLEDGMENTS

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Table 1. Effect of Tilt on Voltage Output from
Geophone Release Test (Mark Products L-22 Horizontal Geophone)

Tilt Angle (°)	Peak Voltage of Release Transient (V)	
	Initial Coil Position Against High Stop	Initial Coil Position Against Low Stop
0	2.10	2.05
0.1	2.15	2.00
0.2	2.25	1.90
0.4	2.45	1.70

Table 2. Leveling Capability of the Gimballed
Geophone Package

Case Tilt Angle (°)	Peak Voltage of Release Transient after Leveling (V)			
	Top Geophone		Bottom Geophone	
	Initial Coil Position Against High Stop	Initial Coil Position Against Low Stop	Initial Coil Position Against High Stop	Initial Coil Position Against Low Stop
7.8	2.1	2.05	2.1	2.05
9.2	2.1	2.05	2.15	2.0
10.5	2.1	2.05	2.1	2.05

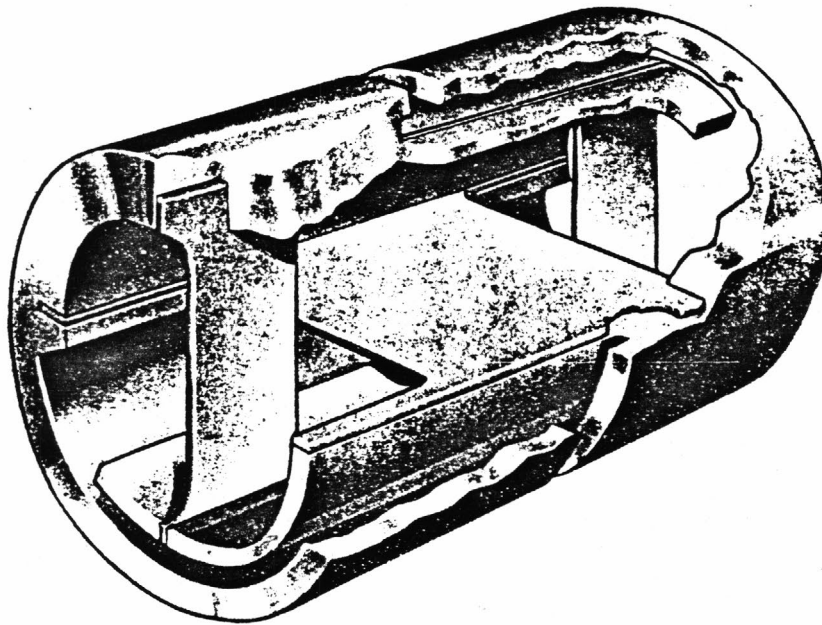


Figure 1. Sketch of a Bendix flexural pivot showing the flat, crossed springs supporting two rotating sleeves.

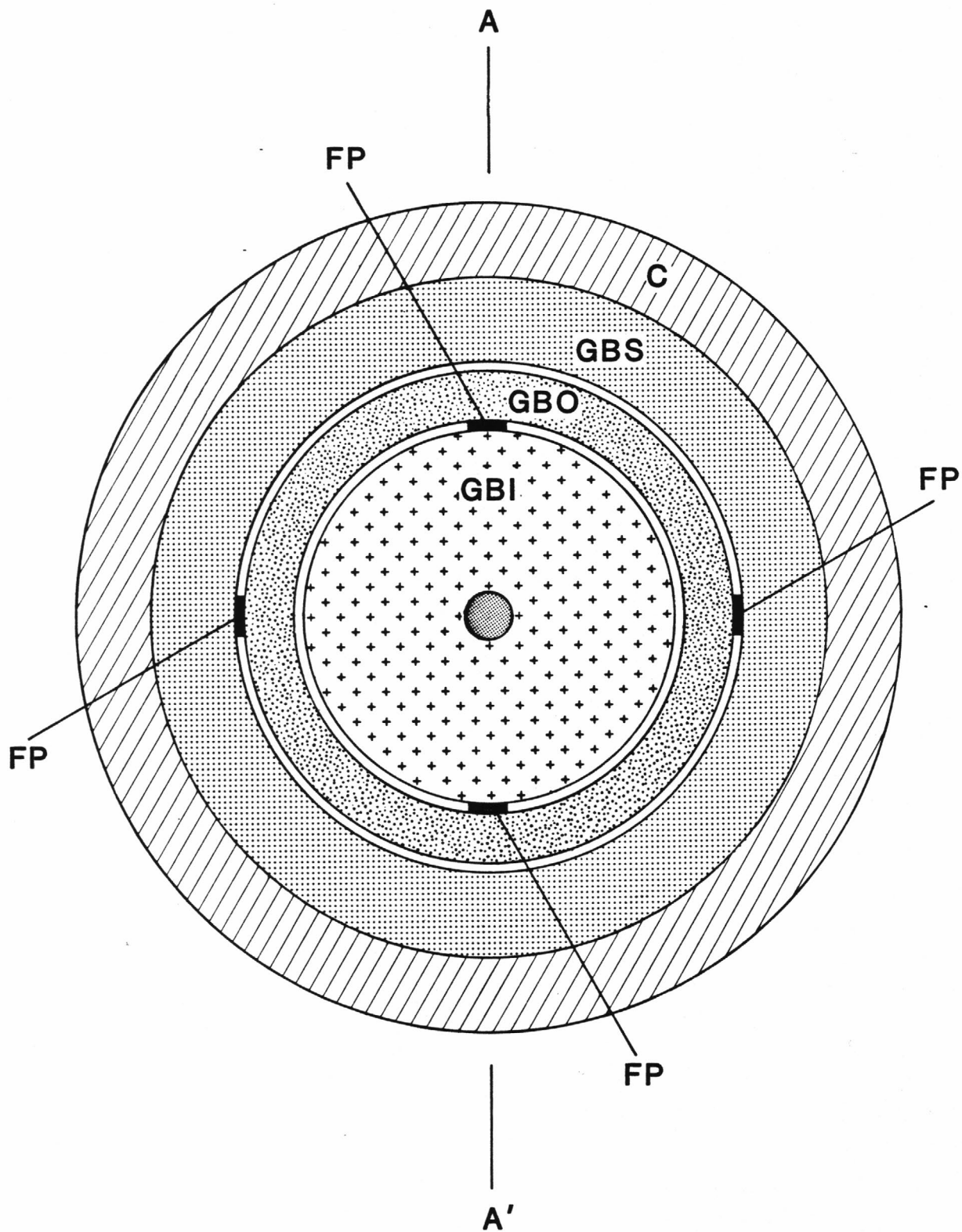


Figure 2a. Sketch of the borehole geophone leveling device, top view. FP: flexural pivot, GBI: inner gimballed ring, GBO: outer gimballed ring, GBS: gimballing support, C: case.

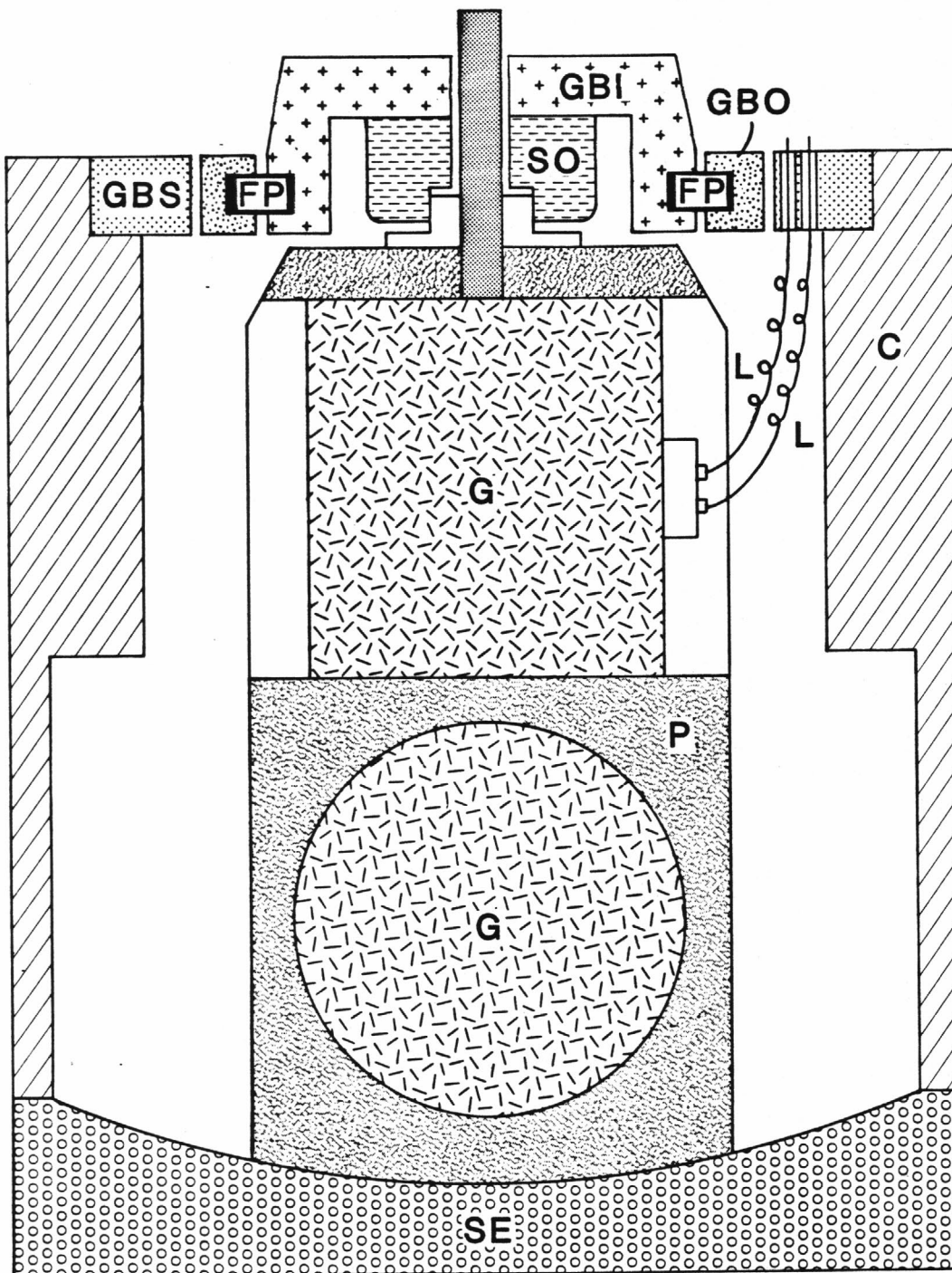


Figure 2b. Sketch of the borehole geophone leveling device, cross section view through line A-A' in Fig. 2a. FP: flexural pivot, GBI: inner gimbal ring, GBO: outer gimbal ring, GBS: gimballing support, C: case, G: geophone, L: electrical signal leads, P: pendulum, SE: spherical seat, and SO: solenoid.

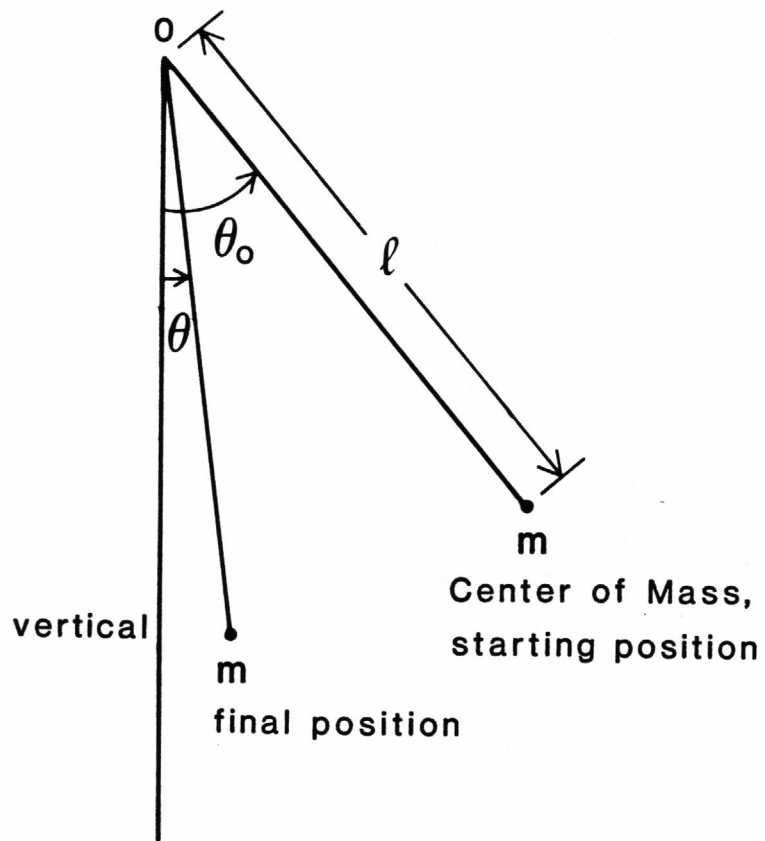


Figure 3. Schematic diagram showing the initial tilt angle, θ_0 , and the final tilt angle of the pendulum in the lifted position, θ .

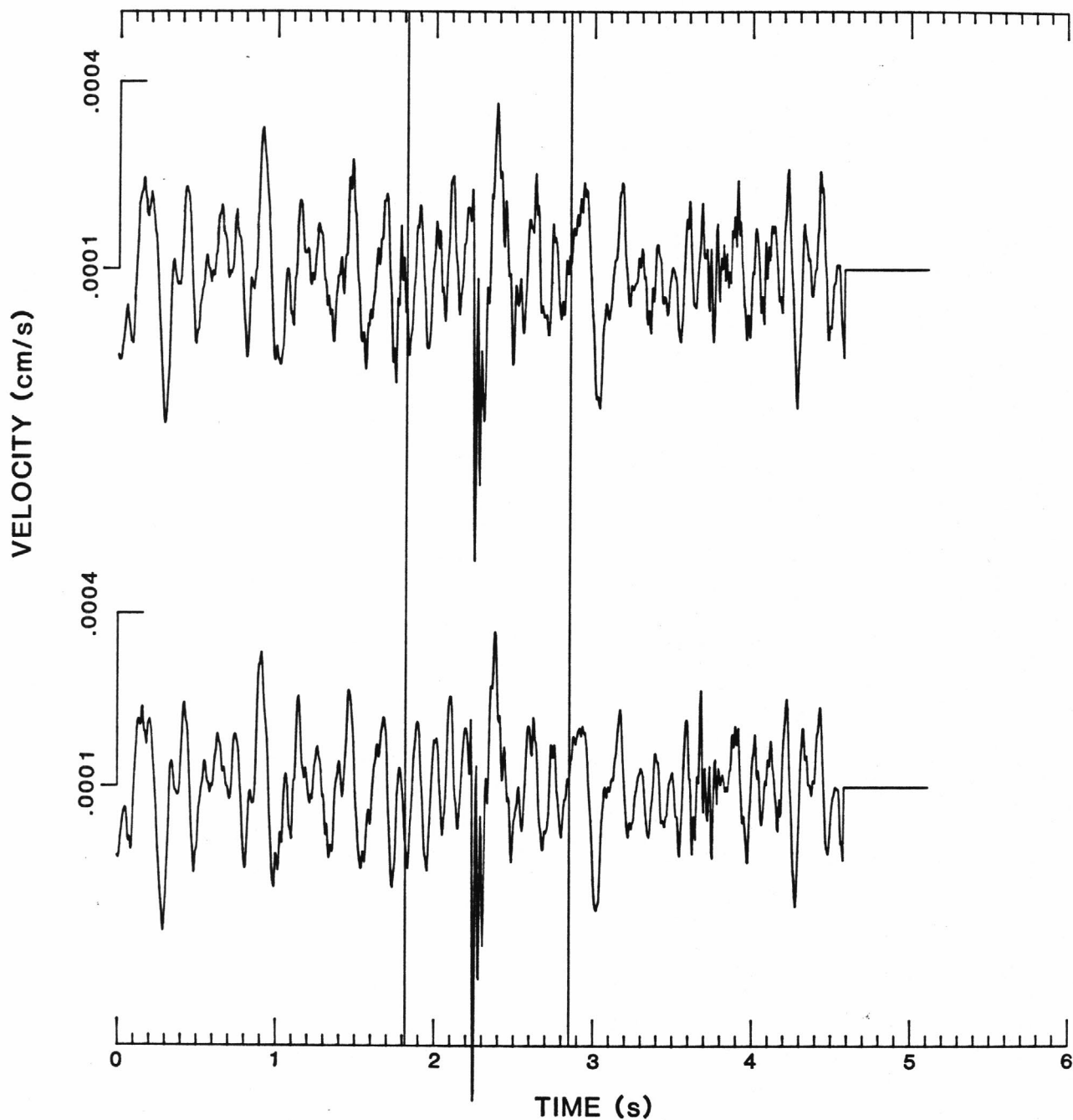


Figure 4a. Traffic noise recorded by a horizontal component of a Mark Products L-22 3D-geophone package (upper trace) and by a parallel horizontal geophone element in the pendulum (lower trace). The two geophone packages were placed side-by-side.

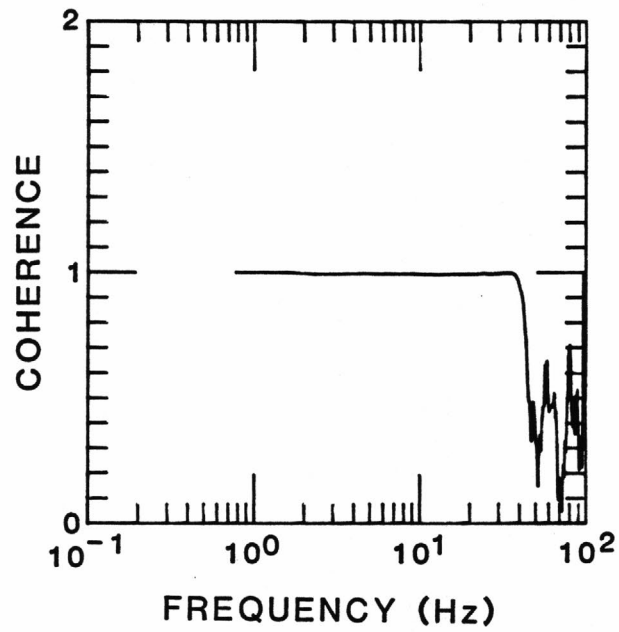


Figure 4b. Coherency calculated from the upper trace and lower trace between the vertical lines in Fig. 4a.

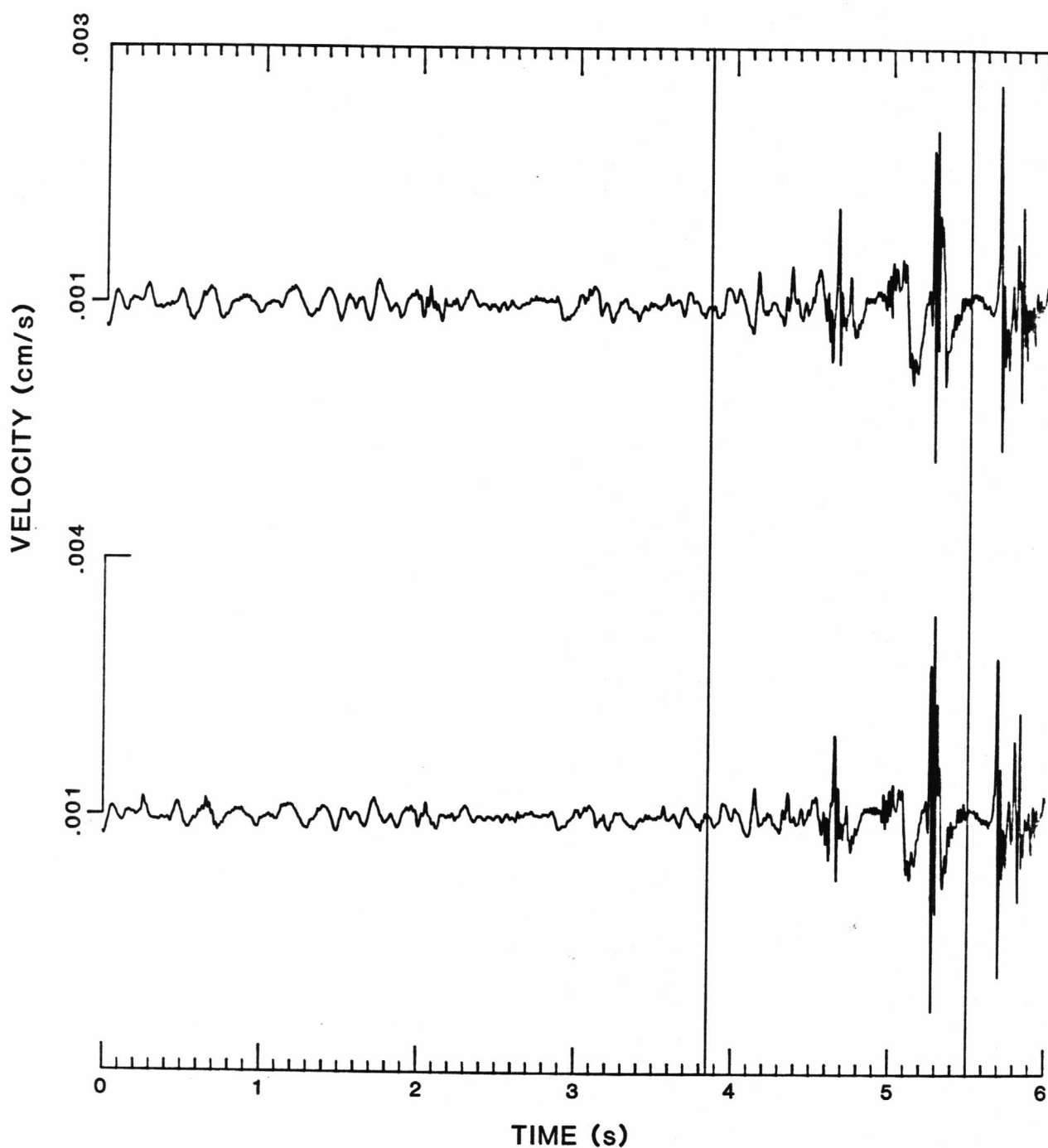


Figure 5a. Motions generated by a person jumping at about 30 ft (9.14 m) away and recorded by a horizontal component of a Mark Products L-22 3D-geophone package (upper trace) and by a parallel horizontal geophone element in the pendulum (lower trace).

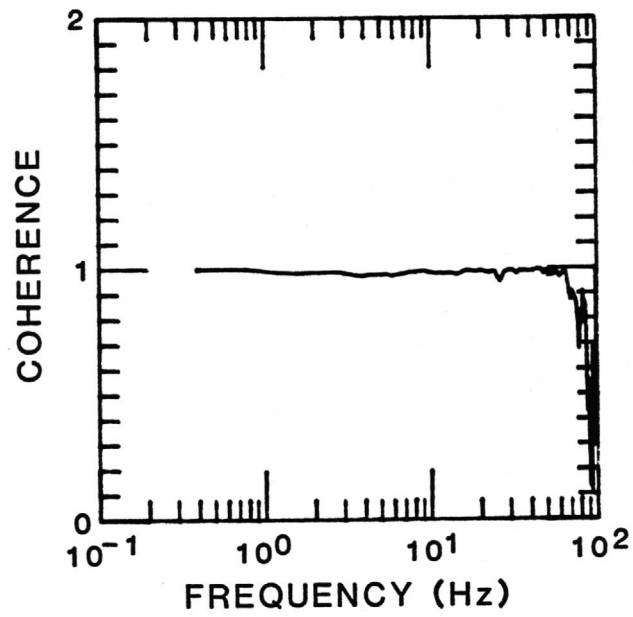


Figure 5b. Coherency calculated from the two traces between the vertical lines in Fig. 5a.