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Measurement of Ambient Relative Test Mass Motion in the 40 M Prototype

LIGO-T950038–00–R

Lisa Sievers 6/14/95

1 Introduction

This report provides information on different aspects of the ambient relative motion between the two suspended test masses in the second arm of the 40 m prototype interferometer. It should prove useful as a resource for developing requirements for different aspects of servo and actuator designs for the 40 m, 5 m and LIGO interferometers.

In our effort to understand lock acquisition of the second arm (see LIGO P950005–00–R) we found it critical to gain an understanding of the ambient relative motion of the test masses. The method used to gain this understanding was to measure the force that drives the end test mass (this force causes the end test mass to track the input test mass) while the interferometer is locked. This force is equivalent to the relative ambient force driving the test masses and can be used to calculate the relative ambient displacement, velocity, and acceleration of the test masses. Initially we had considered using the shark sensors for this measurement but found that the sharks were inadequate since they measure velocity relative to a moving reference frame (i.e. the seismic isolation stack).

2 System Description

Figure 1 defines a local coordinate system that can be used to describe the dynamics of the test mass motion in the second arm of the 40 m interferometer. The relative position of the two test masses is set to an integer number of half wavelengths when the interferometer is locked. The variables x_{s1} and x_{s2} are the displacements from equilibrium of the two mirrors. The variable Δx_{sdc} is the DC offset from equilibrium that is set when the interferometer is locked. F_{s1} and F_{s2} are the forces driving the test masses due to seismic disturbances. Equations 1–3 transform the local coordinate system defined in Figure 1 to a relative coordinate system (in terms of relative displacement and force). This relative coordinate system is used to describe the closed loop dynamics of the length control system when the cavity is on resonance. A block diagram of the length control system for a single cavity is shown in Figure 2.

$$y_s = x_{s1} - x_{s2} + \Delta x_{sdc} \tag{1}$$

$$F_{seis} = F_{s1} - F_{s2} \tag{2}$$

$$F_{dc} = m\omega_o^2 \Delta x_{sdc} \tag{3}$$

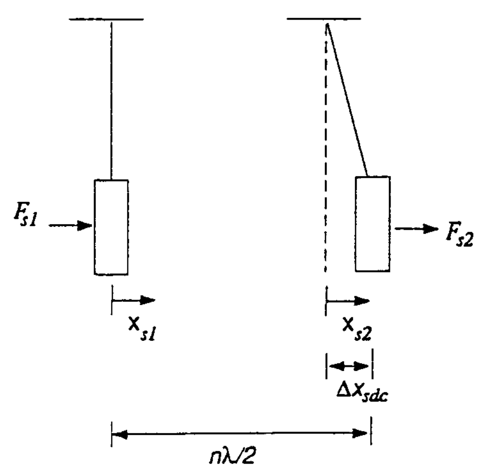


Figure 1: Local Coordinate System for Describing Test Mass Dynamics.

G(s) is the transfer function of the feedback system that keeps the second arm locked. At low frequencies (i.e. below 200 Hz) G(s) is essentially infinite so $F_c = F_{seis} + F_{dc}$. This implies that the relative seismic driving force on the test masses, F_{seis}, can be obtained by subtracting the DC offset, F_{dc}, from the calibrated control force, F_c, applied to the test mass. The calibrated control force can be calculated from a measurement of the coil driver output voltage when the interferometer is in lock. This measurement is discussed in the following section. F_{seis} can then be used to obtain both the relative displacement of the test masses as well as the relative velocity of the two test masses by filtering the relative seismic driving force through the pendulum transfer function.

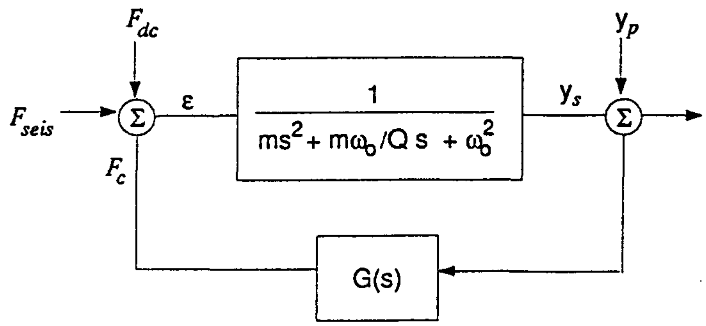


Figure 2: Block Diagram showing closed loop transfer functions of length control system in the second arm. The Q of the pendulum is assumed to be 5, the mass m is 1.54 kg, and the frequency of the pendulum is ω_o=2π.

The above analysis is accurate if the frequency of the light entering the cavity is fixed. This is not precisely the case given the control system configuration of the interferometer at the time the data was taken. At frequencies below about 3 Hz, the frequency of light entering the interferometer tracks the fixed-mass mode cleaner length. The mode cleaner length is an extremely stable reference at these frequencies; consequently, the frequency of the light is essentially fixed. However at frequencies above 3 Hz, the frequency of the light tracks the length of the primary arm cavity. To model this effect, a summing junction can be added to the output of the pendulum transfer function in Figure 2. Its inputs are length change of the second arm cavity, y_s, and length change of the primary arm cavity, y_p.

$$y_p = x_{p1} - x_{p2} + \Delta x_{pdc} \quad (4)$$

where x_{p1} and x_{p2} are the displacements from equilibrium of the two mirrors of the primary cavity and Δx_{pdc} is the DC offset from equilibrium that is set when the primary is locked. At frequencies above 3 Hz, the inputs to the other summing junction F_{seis} and F_{dc} become:

$$F_{seis} = (F_{s1} - F_{s2}) \pm (F_{p1} - F_{p2}) \tag{5}$$

$$F_{dc} = m\omega_o^2 \Delta x_{sdc} \pm m\omega_o^2 \Delta x_{pdc} \tag{6}$$

where F_{p1} and F_{p2} are the forces driving the test masses due to seismic disturbances in the primary.

In the 40 m laboratory, the seismic driving force for test mass motion has its signal strength mainly below 3 Hz. For this reason, the model used for calculating the relative test mass motion of the second arm is to assume that the light entering the cavity is essentially fixed.

3 Evening Data

A 2 minute data run was taken using the second arm of the 40 m interferometer on a Sunday evening, 11/18/94. The interferometer was locked during this stretch of time. The coil driver output voltage was recorded with a sampling frequency of 1 kilohertz. The data was recorded with a 16 bit resolution over a +/- 10 volt range. The calibration constant was .022 newtons/amp (the series resistor was 30 ohms at the time). As described previously, different aspects of the open loop test mass motion (due to the background seismic noise in the lab) can be inferred from the coil driver output data. Figures 3–10 show plots of relative seismic force and relative test mass displacement and velocity in the second arm that were generated from the data run.

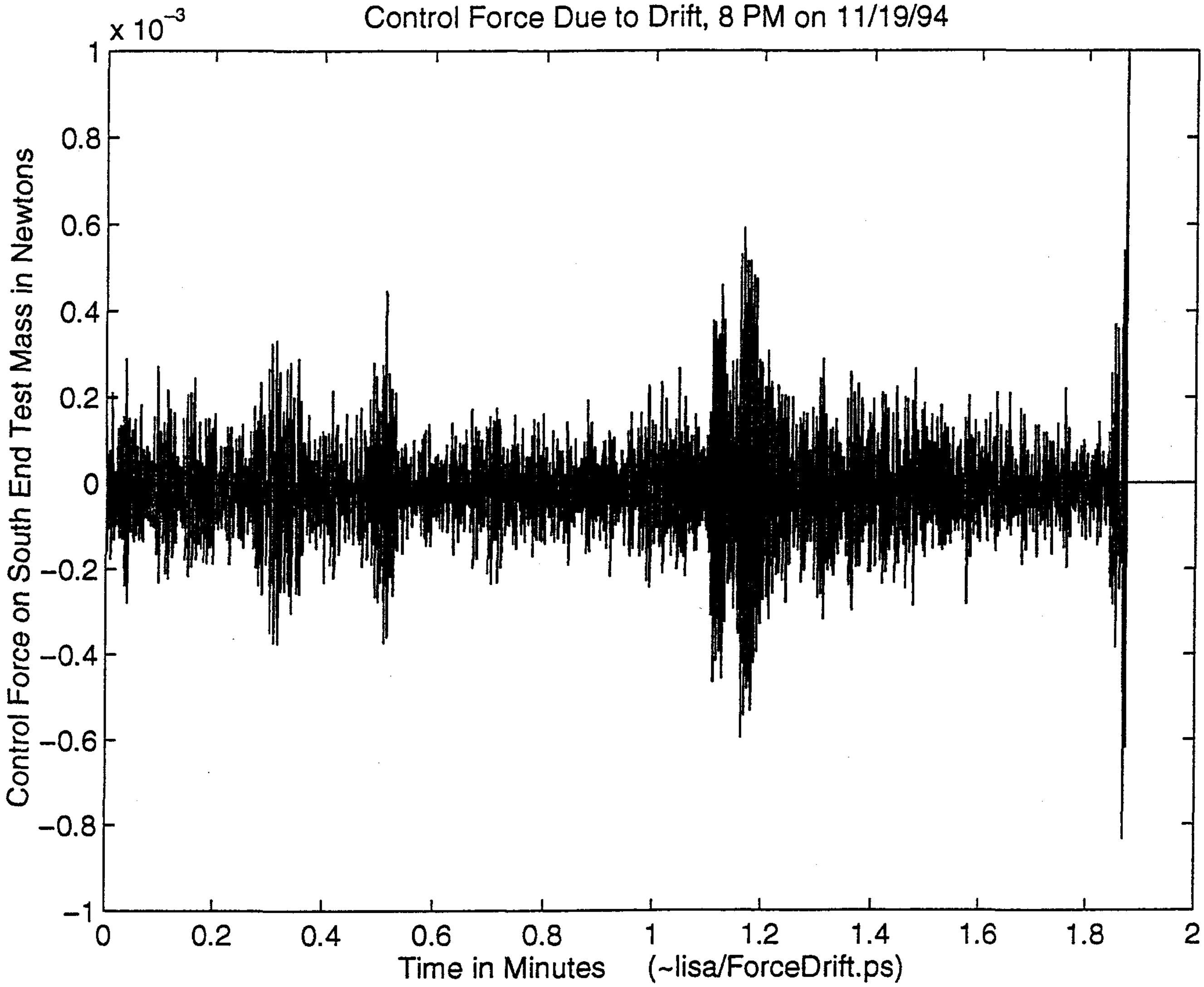


Figure 3: Calibrated force output of the coil driver taken in the evening. This is equivalent to the **relative seismic force driving the test masses**. The data shows no apparent drifts during the 2 minute data run.

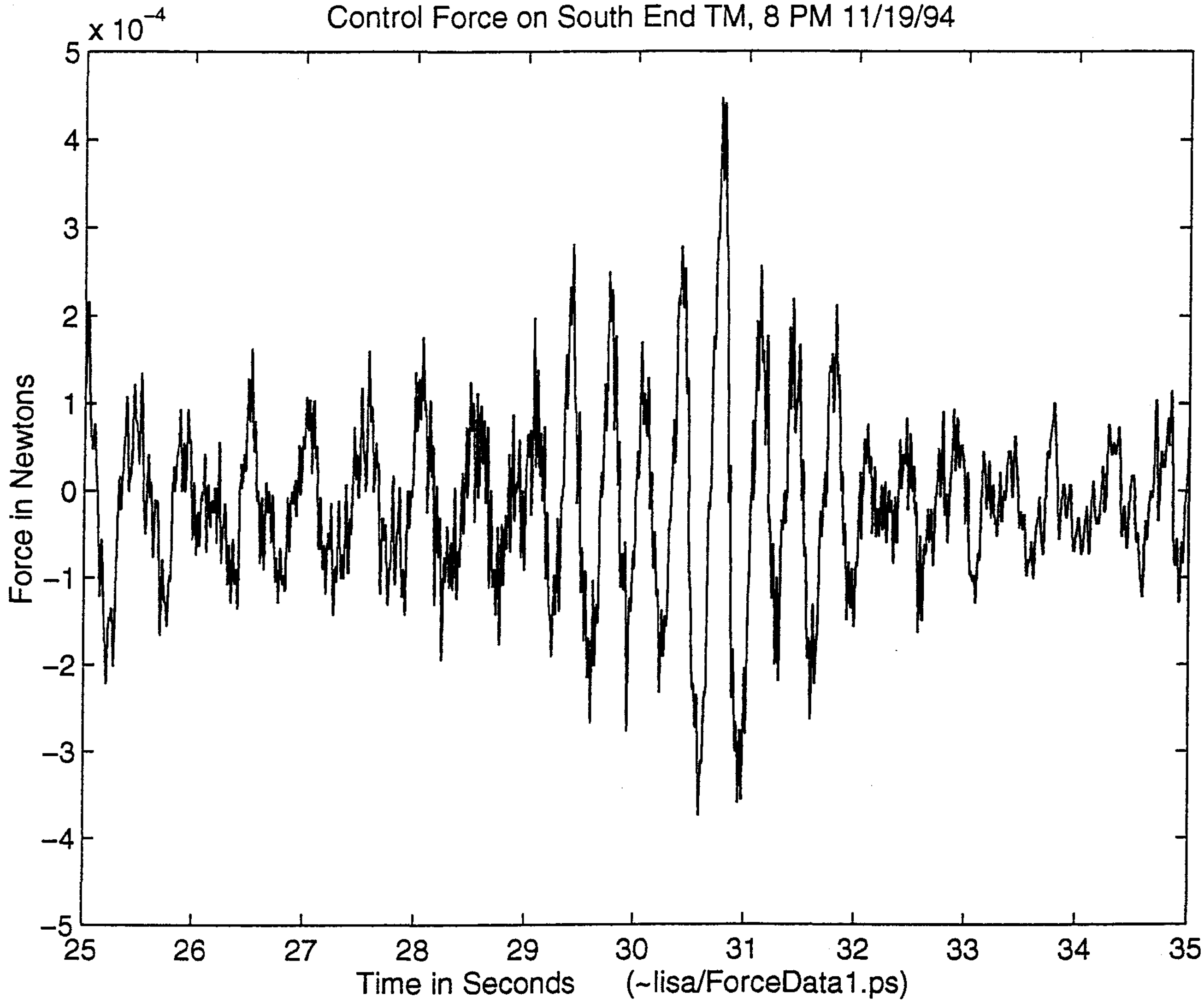


Figure 4: Calibrated force output of the coil driver taken in the evening. This is equivalent to the **relative seismic force driving the test masses.** Shows one of the largest amplitude signals during the 2 minute data run.

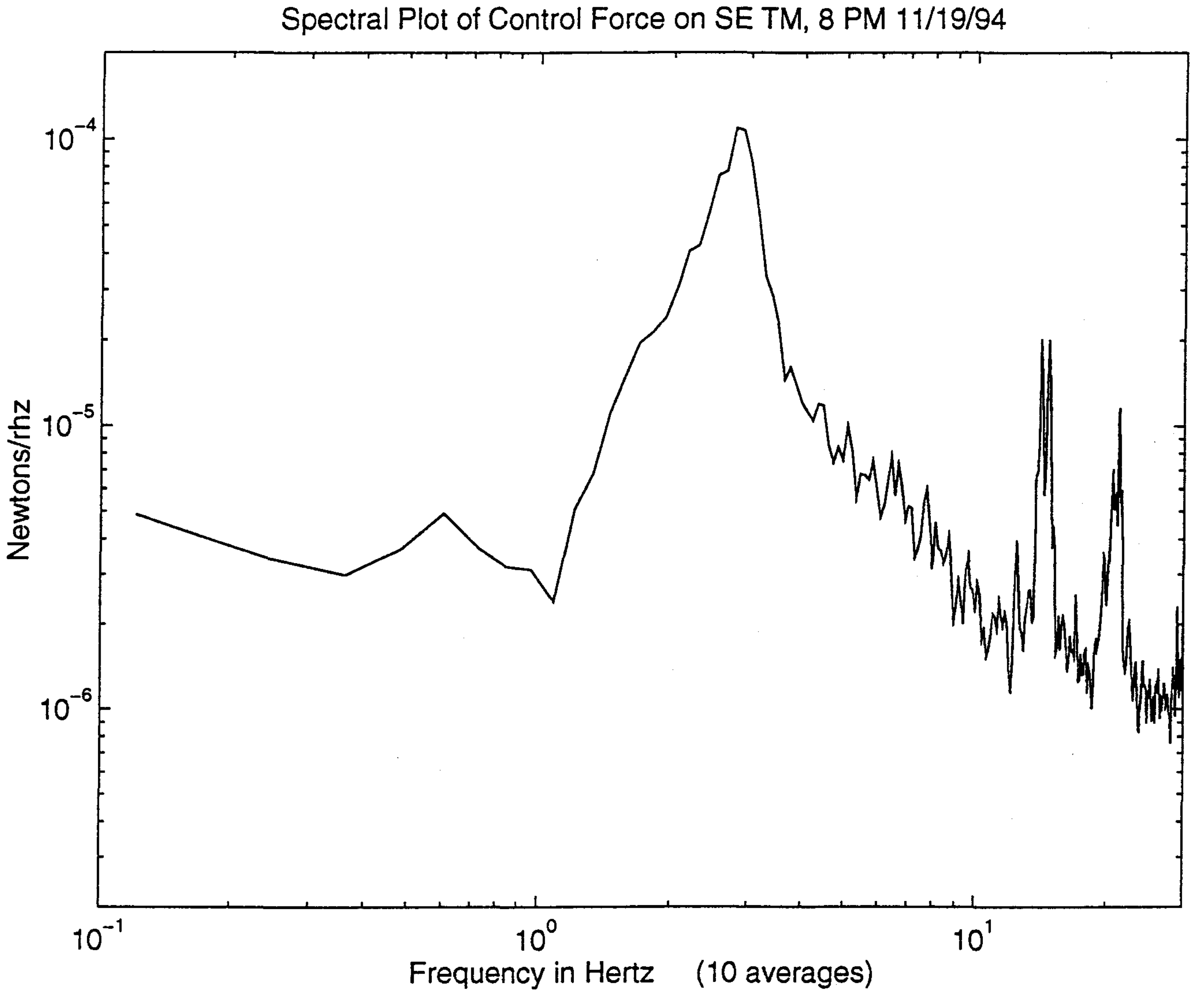


Figure 5: Spectral plot of the calibrated force output of the coil driver (equivalent to **relative seismic force driving the test masses**) taken in the evening. Peak at about 3Hz is the first stack horizontal resonance.

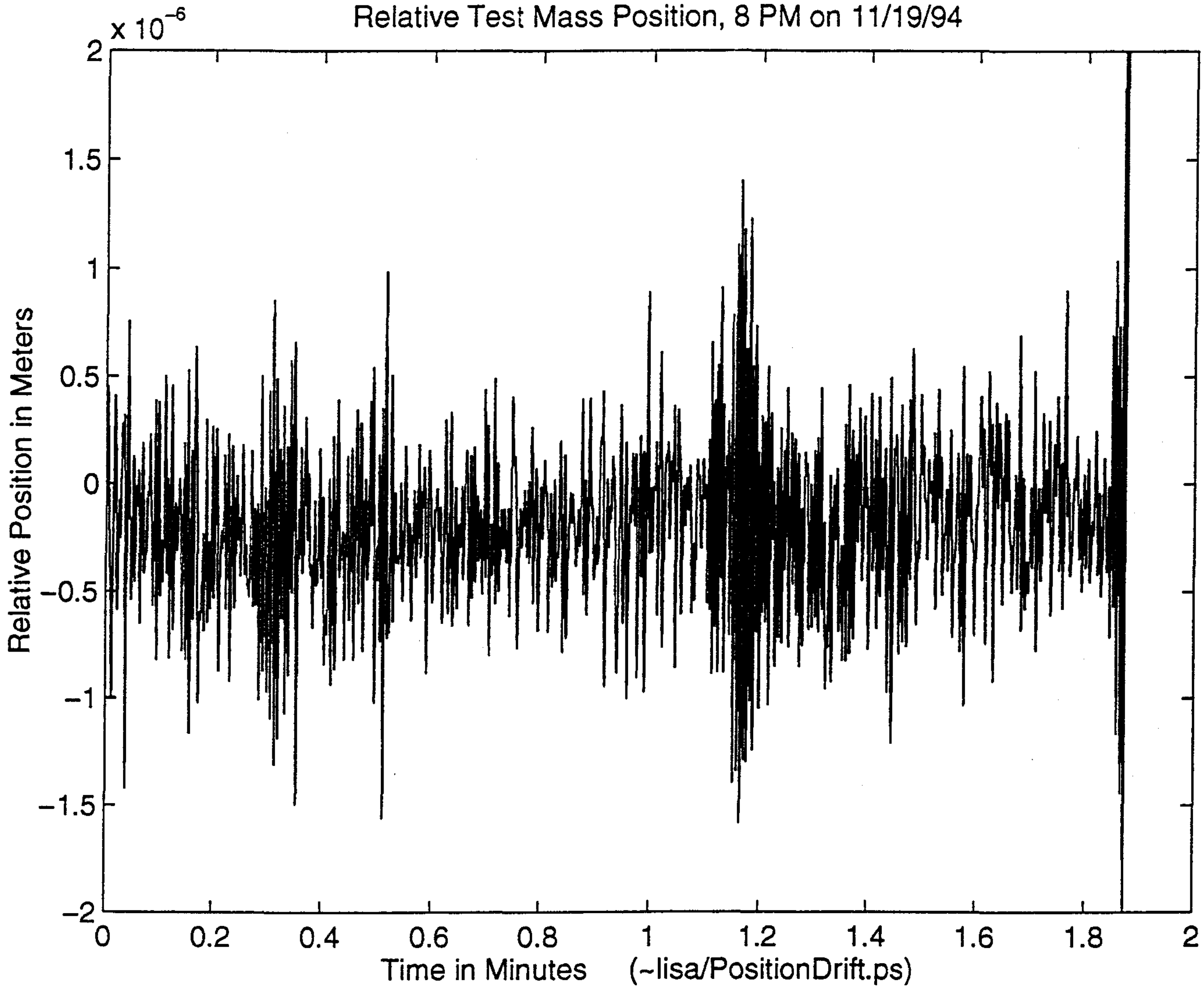


Figure 6: Calibrated force output of the coil driver filtered through the pendulum transfer function. This is equivalent to the seismically driven **relative test mass displacement**. There appears to be no drift in the data.

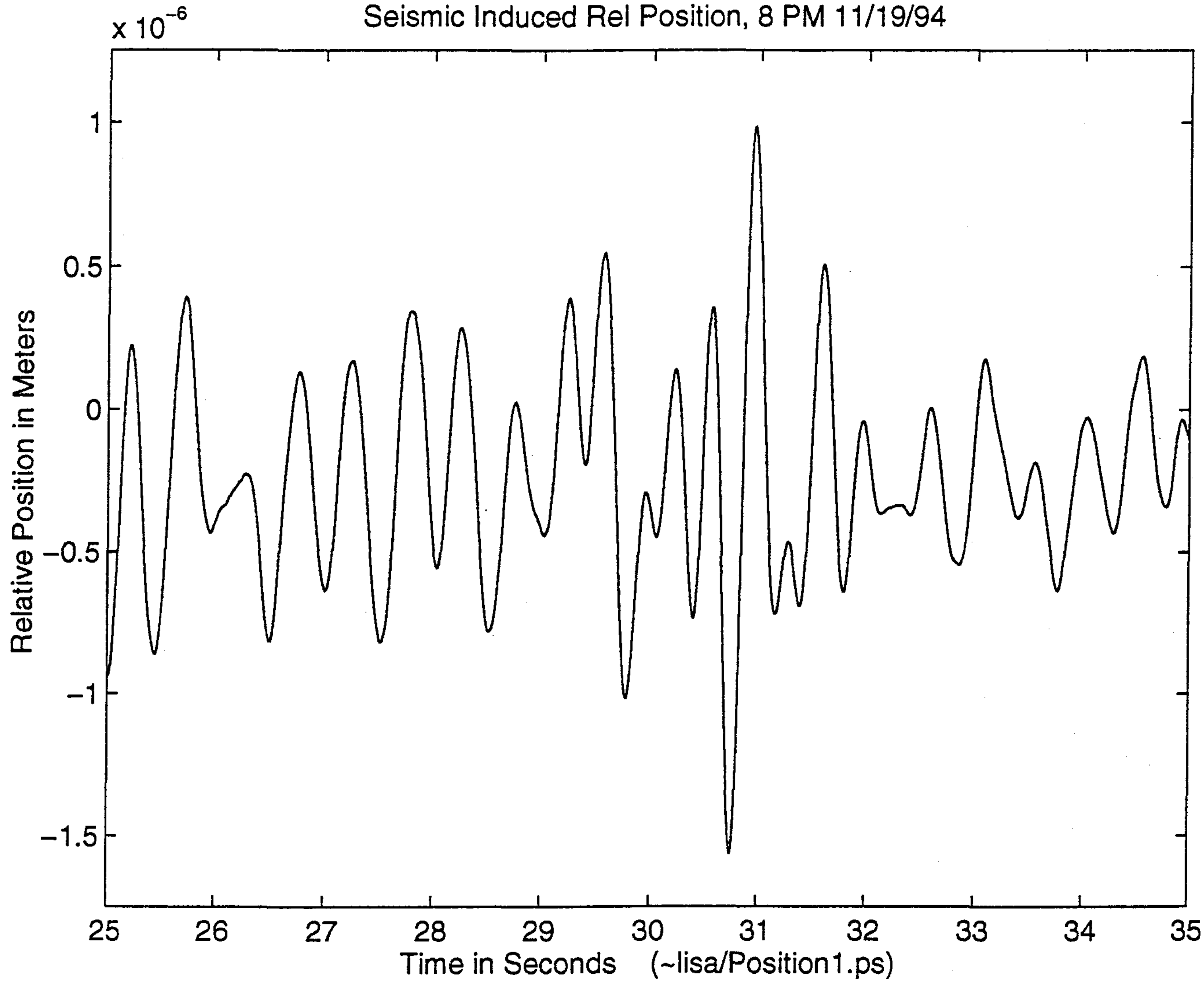


Figure 7: Calibrated force output of the coil driver filtered through the pendulum transfer function. This is equivalent to the seismically driven **relative test mass displacement**. Shows one of the largest amplitude signals during the 2 minute data run, approximately 2.5 microns p-p.

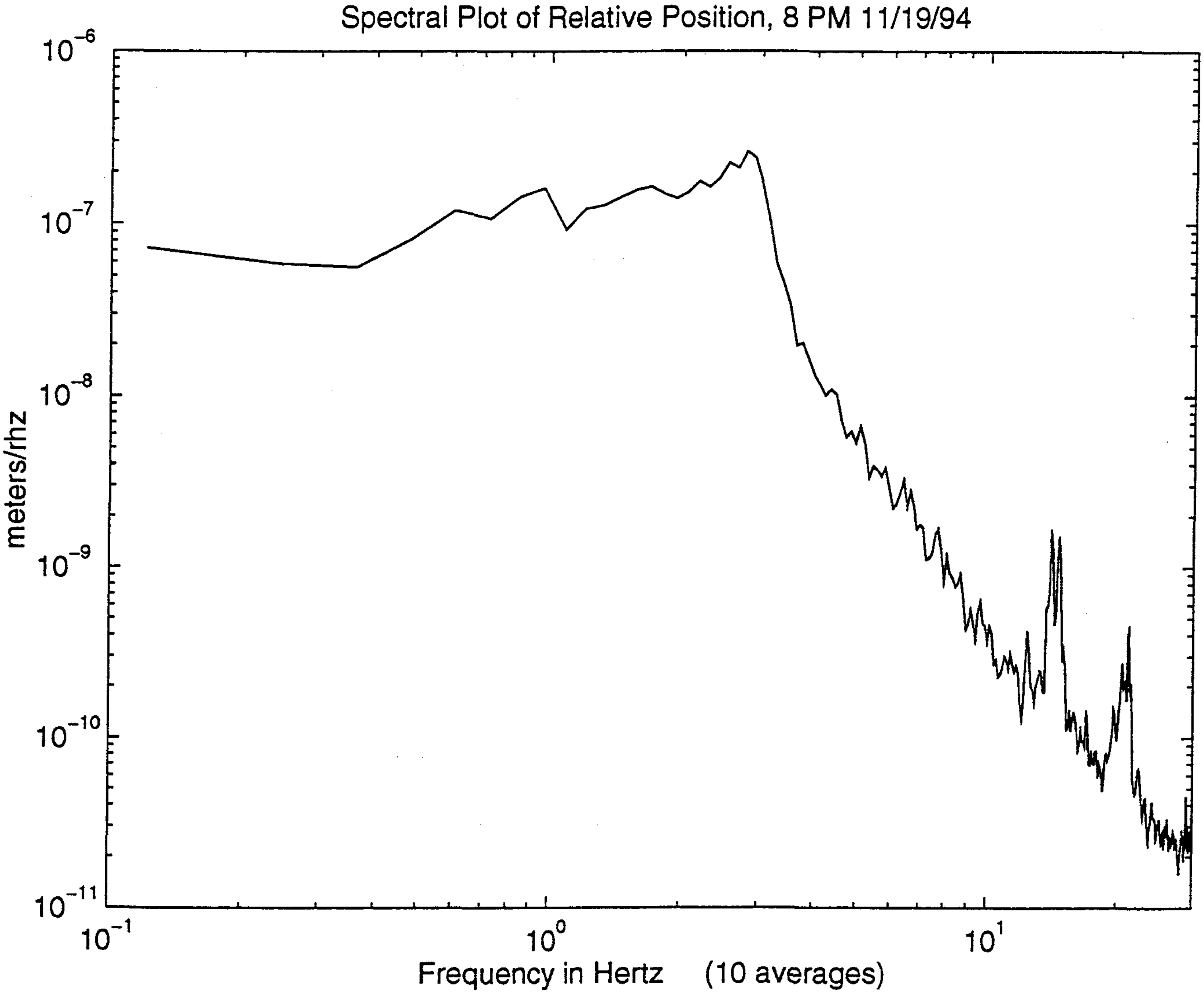


Figure 8: Spectral plot of the calibrated force output of the coil driver filtered through the pendulum transfer function (equivalent to seismically driven **relative test mass displacement**). Small peak at about 3Hz is the first stack horizontal resonance.

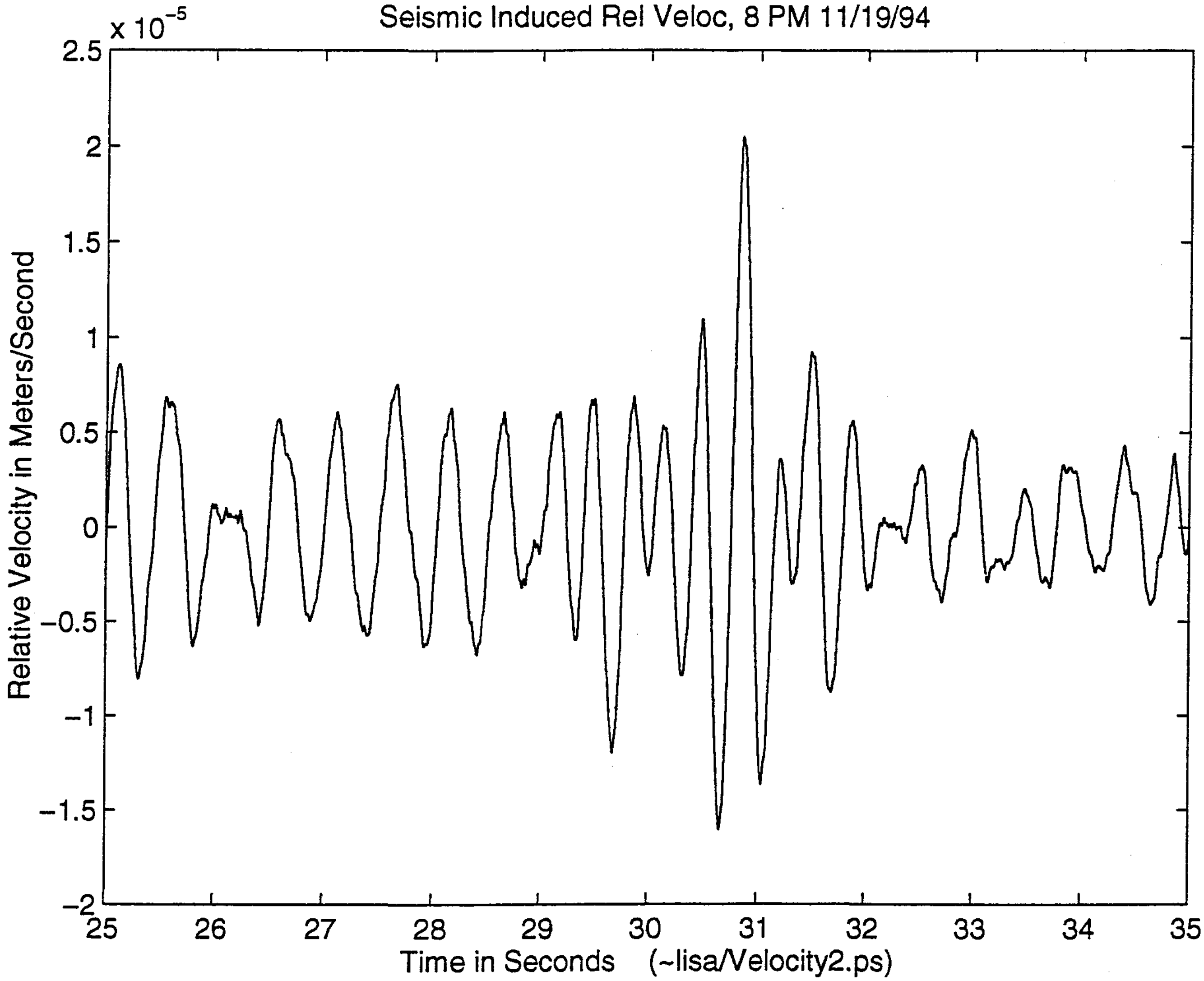


Figure 9: Calibrated force output of the coil driver filtered through the pendulum velocity transfer function. This is equivalent to the seismically driven **relative test mass velocity**. Shows one of the largest amplitude signals during the 2 minute data run. Note that the average relative velocity is around 5 microns/sec (the lock acquisition setup showed a lower average velocity due to the threshold feature built into the acquisition control system).

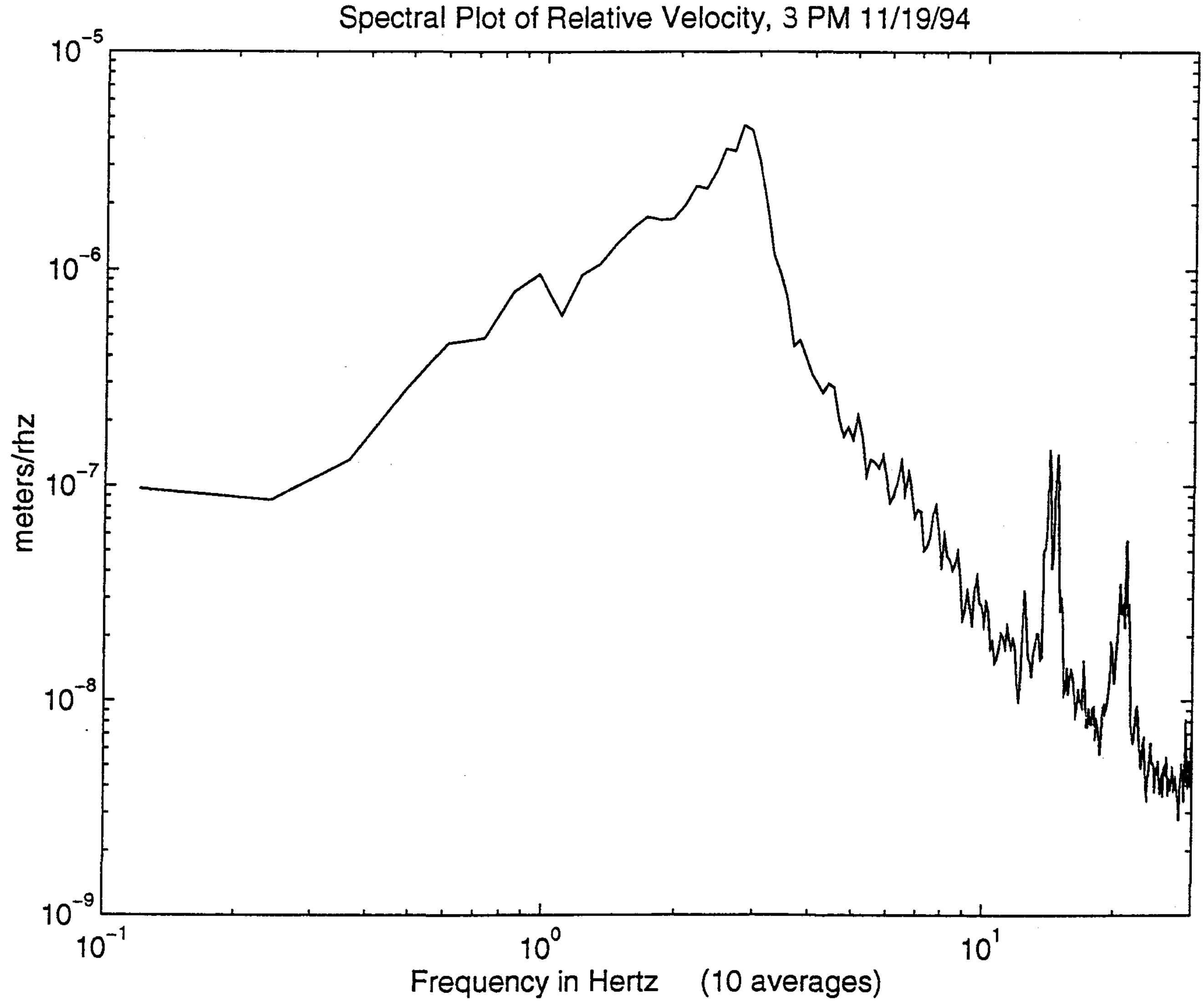


Figure 10: Spectral plot of the calibrated force output of the coil driver filtered through the pendulum velocity transfer function (equivalent to seismically driven **relative test mass velocity**). Note peak at about 3Hz is the first stack horizontal resonance

4 Daytime Data

A longer stretch of data was taken earlier in the day on 11/18/94. The interferometer stayed locked for about 10 minutes around 10:30 AM. As described previously, different aspects of the open loop test mass motion (due to the background seismic noise in the lab) can be inferred from the coil driver output data. Figures 11–18 show example plots of relative seismic force and relative test mass displacement and velocity that were generated from the data run.

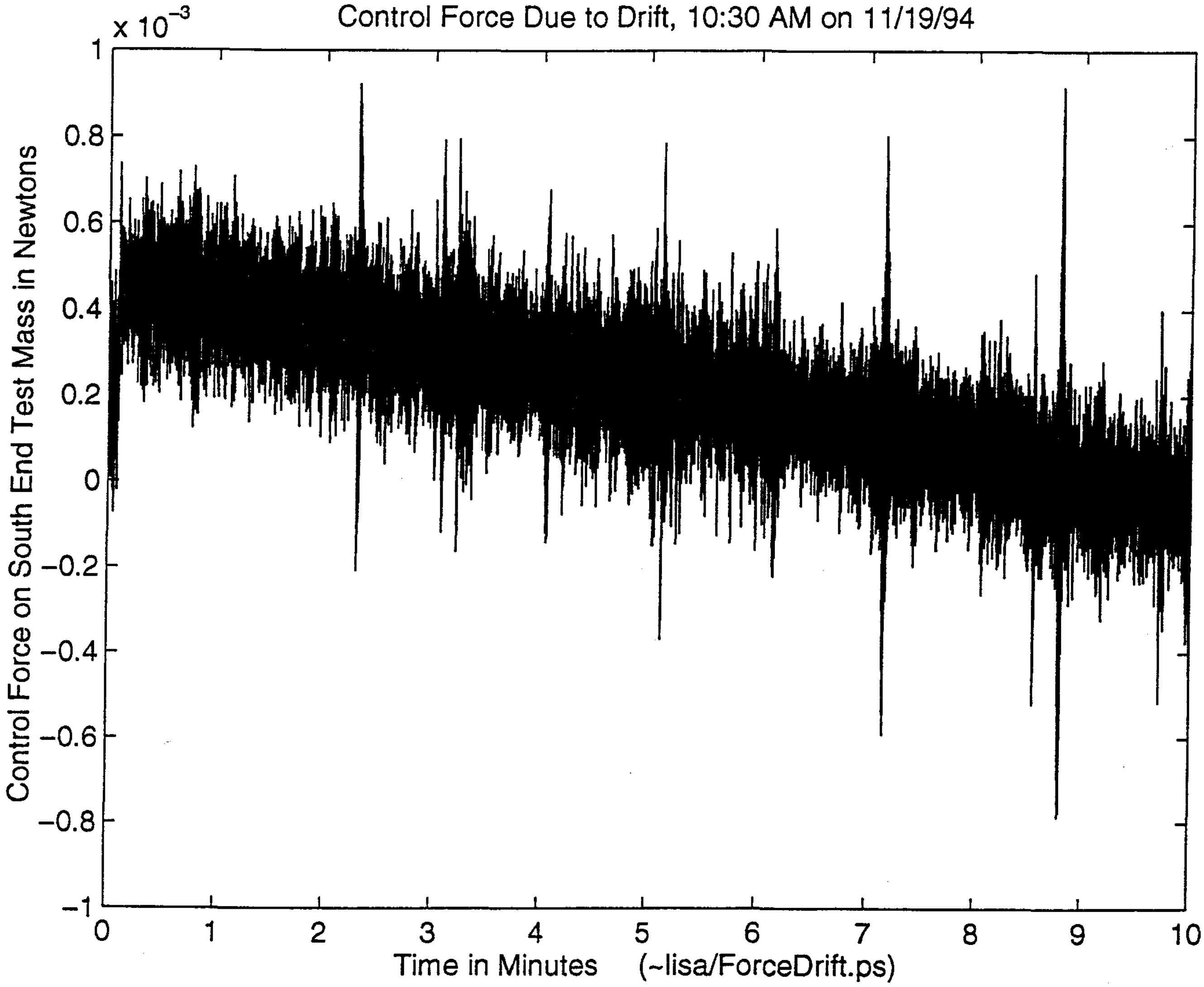


Figure 11: Calibrated force output of the coil driver taken in the morning. This is equivalent to the **relative seismic force driving the test masses**. The data shows a low frequency drift. A fringe hop is apparent in the first few seconds of the data run.

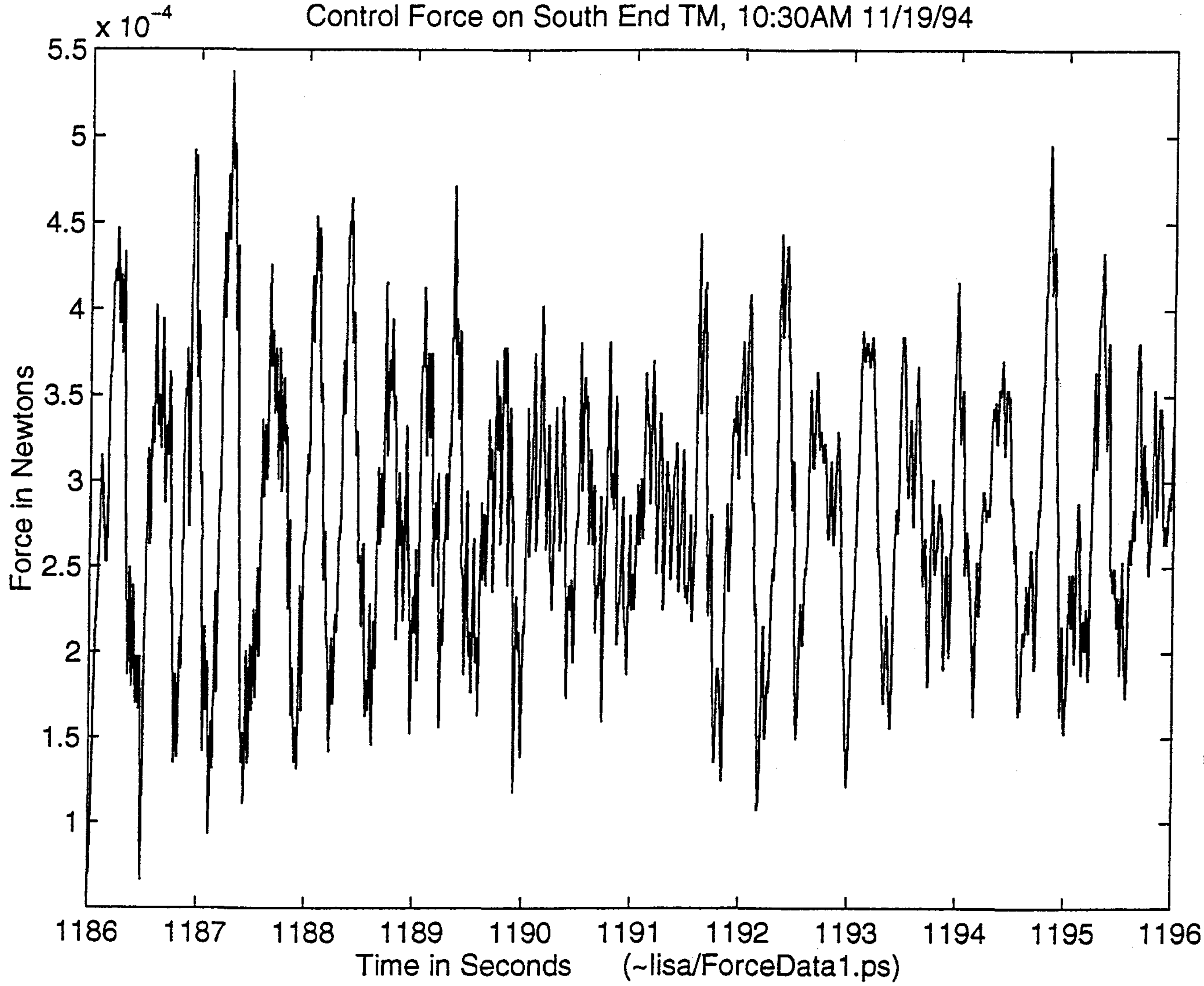


Figure 12: Calibrated force output of the coil driver taken in the morning. This is equivalent to the **relative seismic force driving the test masses.** One of the largest amplitude signals during the 10 minute data run is shown in this plot.

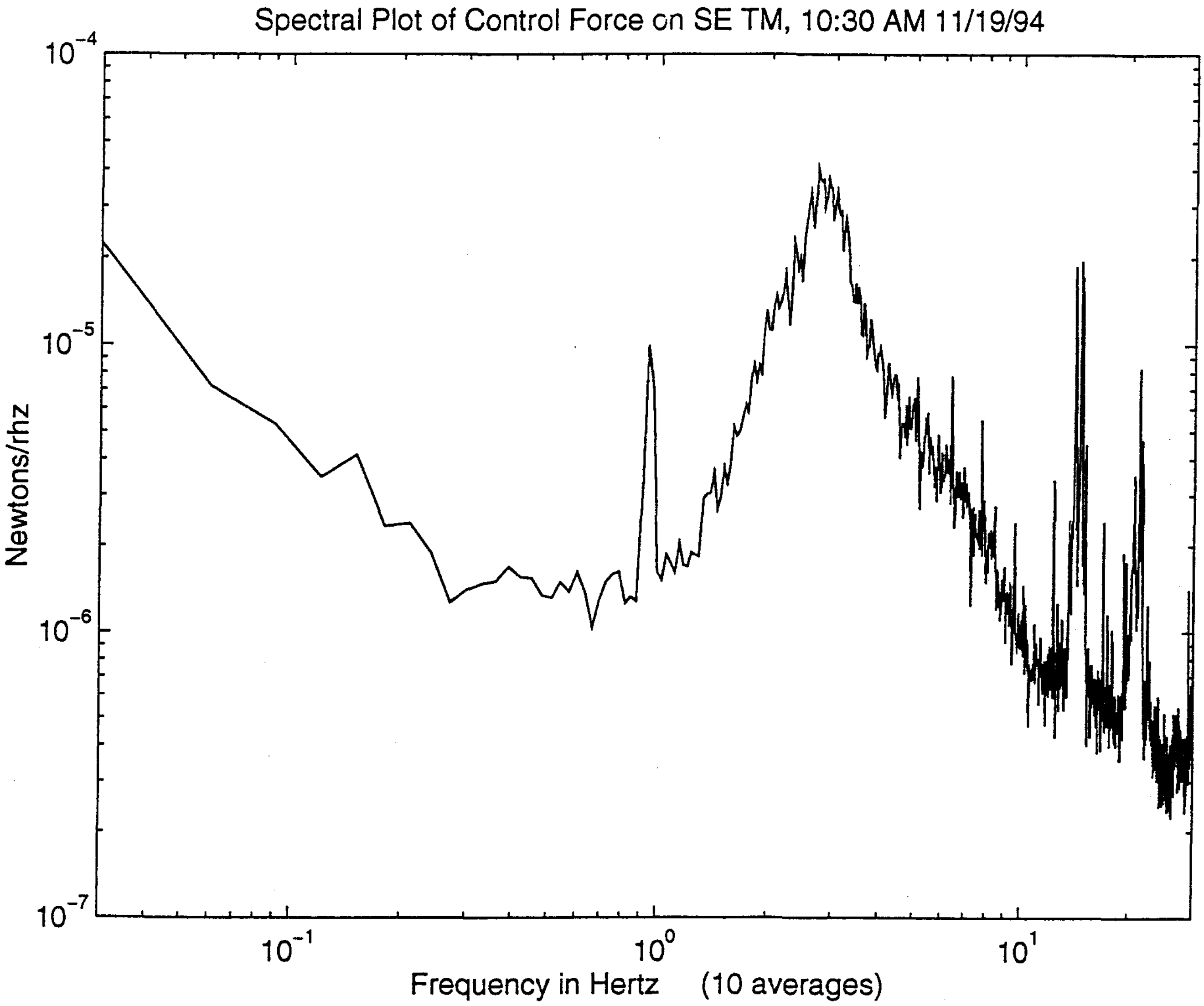


Figure 13: Spectral plot of the calibrated force output of the coil driver (equivalent to **relative seismic force driving the test masses**). The peak at about 3Hz is the first stack horizontal resonance. Also note the sharp peak at 1 Hz due to the pendulum resonance; interestingly enough this is not a feature that shows up in the evening data.

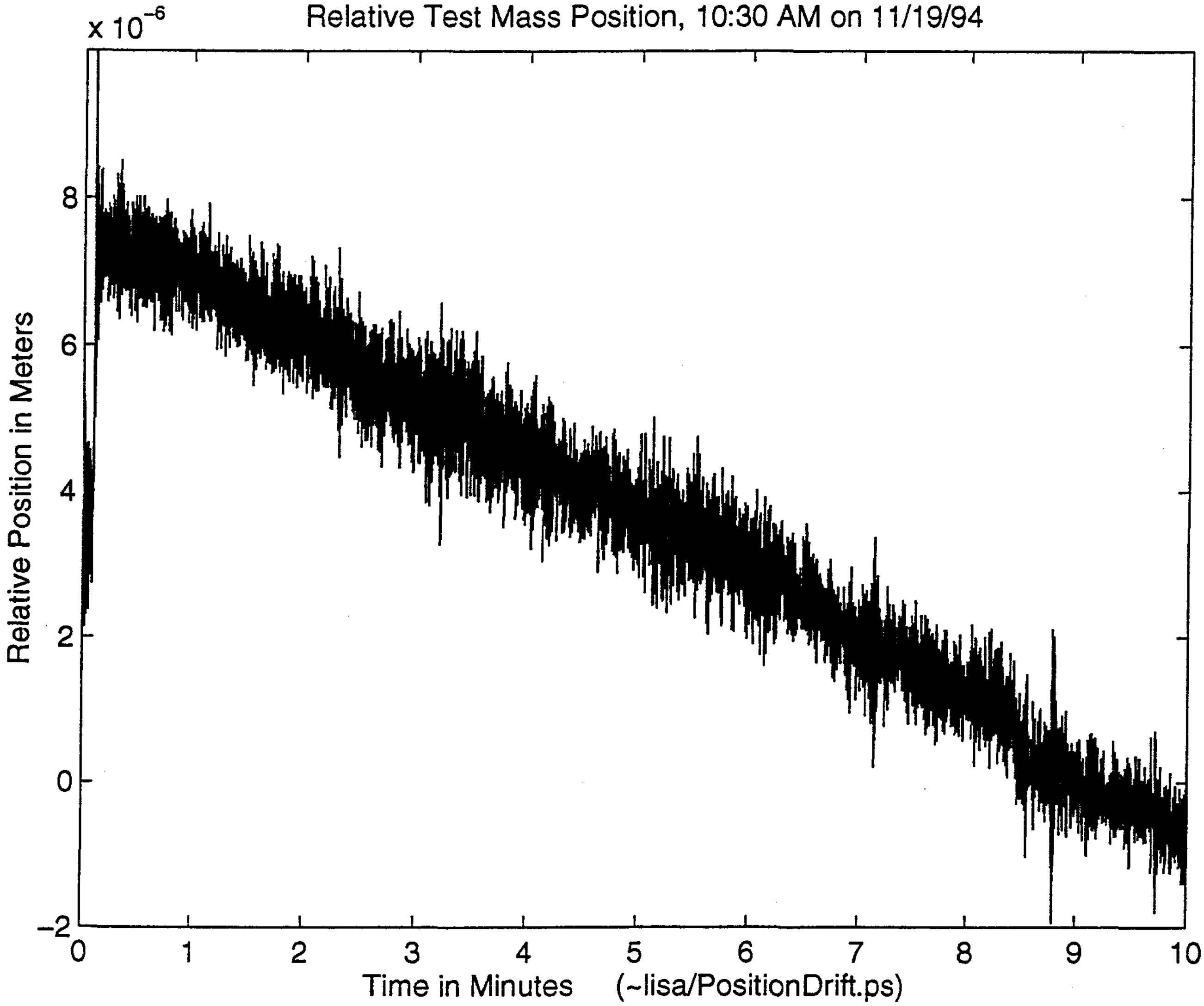


Figure 14: Calibrated force output of the coil driver filtered through the pendulum transfer function. This is equivalent to the seismically driven **relative test mass displacement.** The data shows a low frequency drift; this was not apparent in the evening data.

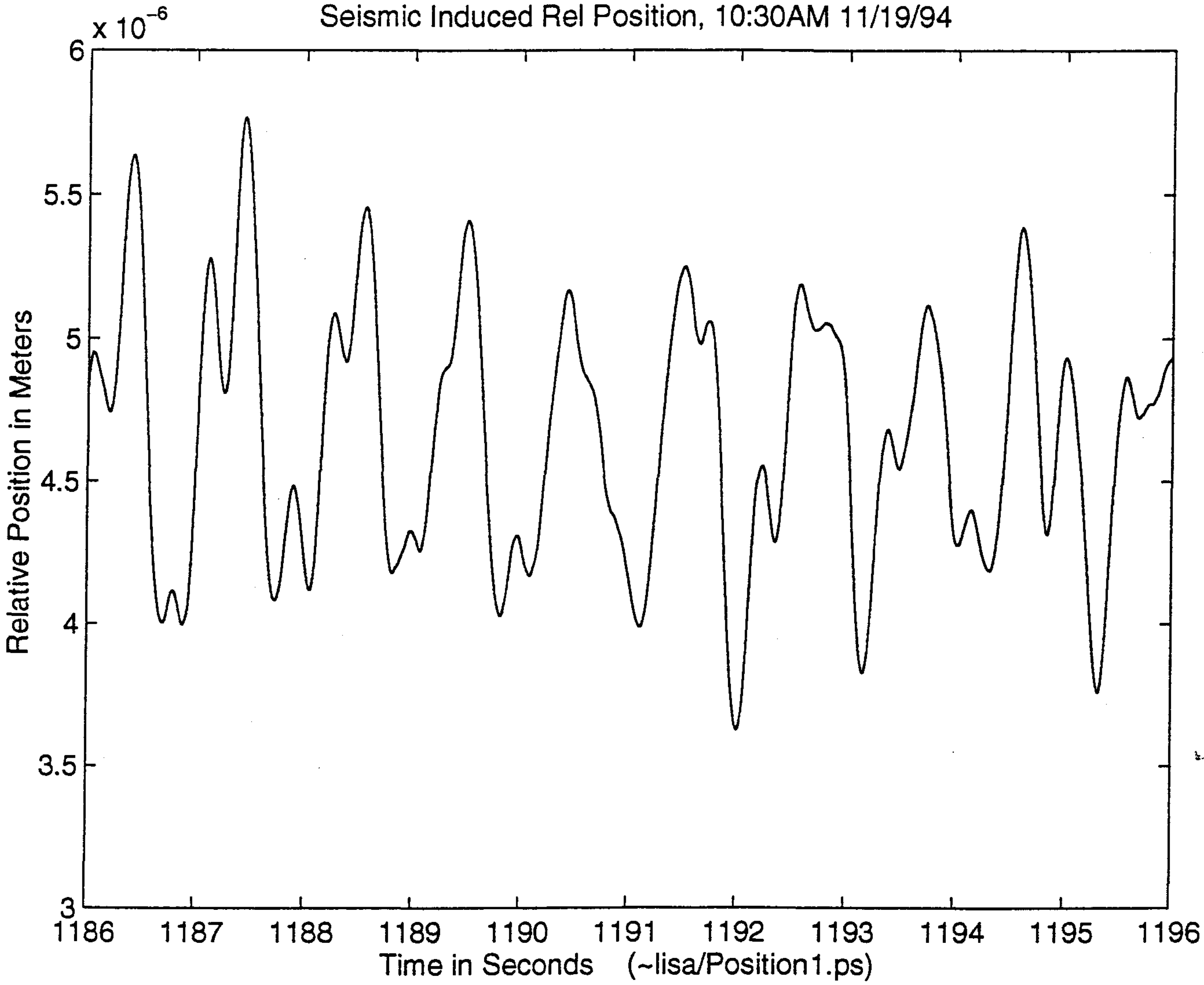


Figure 15: Calibrated force output of the coil driver filtered through the pendulum transfer function. This is equivalent to the seismically driven **relative test mass displacement**. This plot shows one of the largest amplitude signals during the 10 minute data run. Note the 1 second period of the motion due to the pendulum.

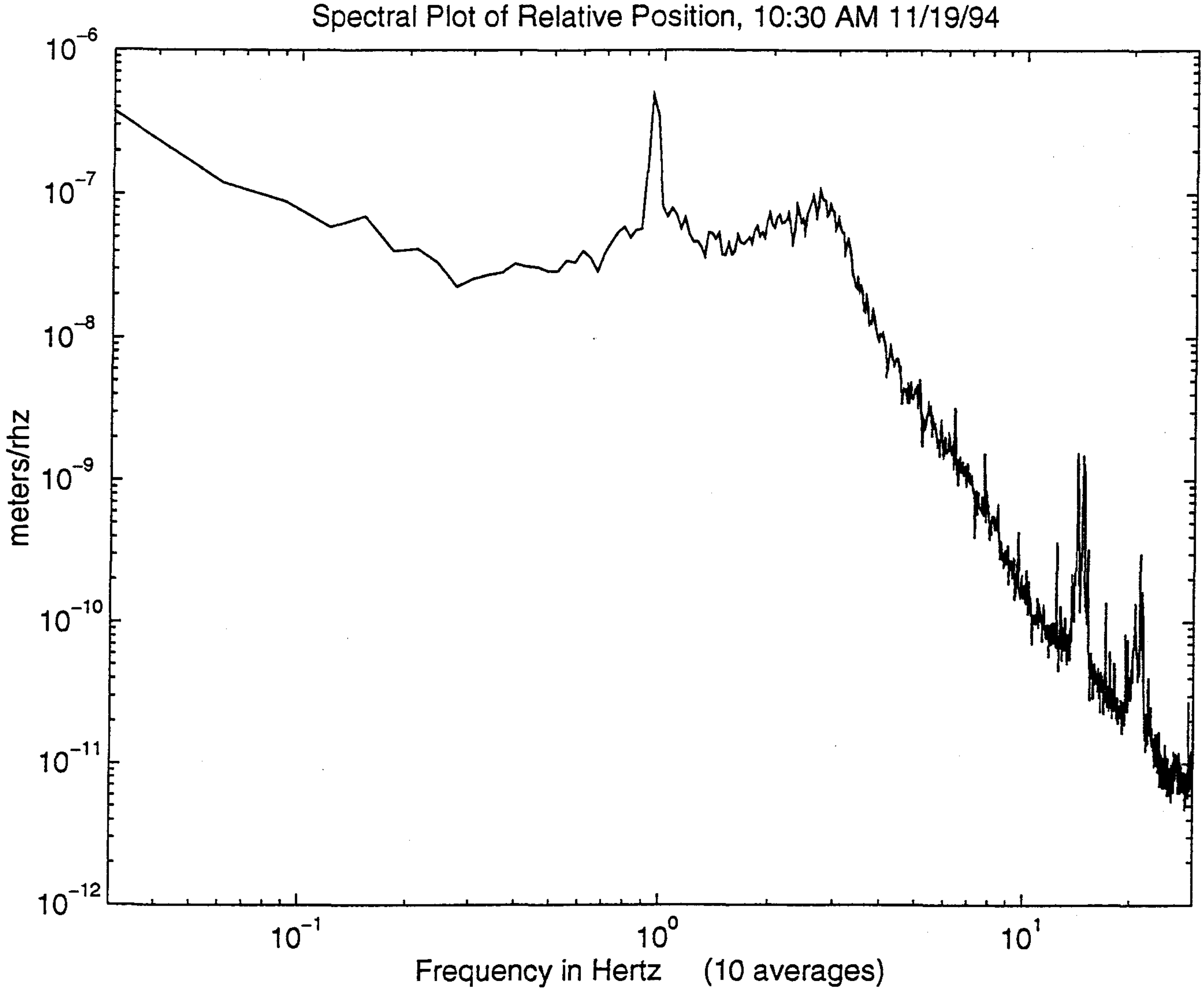


Figure 16: Spectral plot of the calibrated force output of the coil driver filtered through the pendulum transfer function (equivalent to seismically driven **relative test mass displacement**). The small peak at about 3Hz is the first stack horizontal resonance while the large peak at 1 Hertz is due to the pendulum resonance.

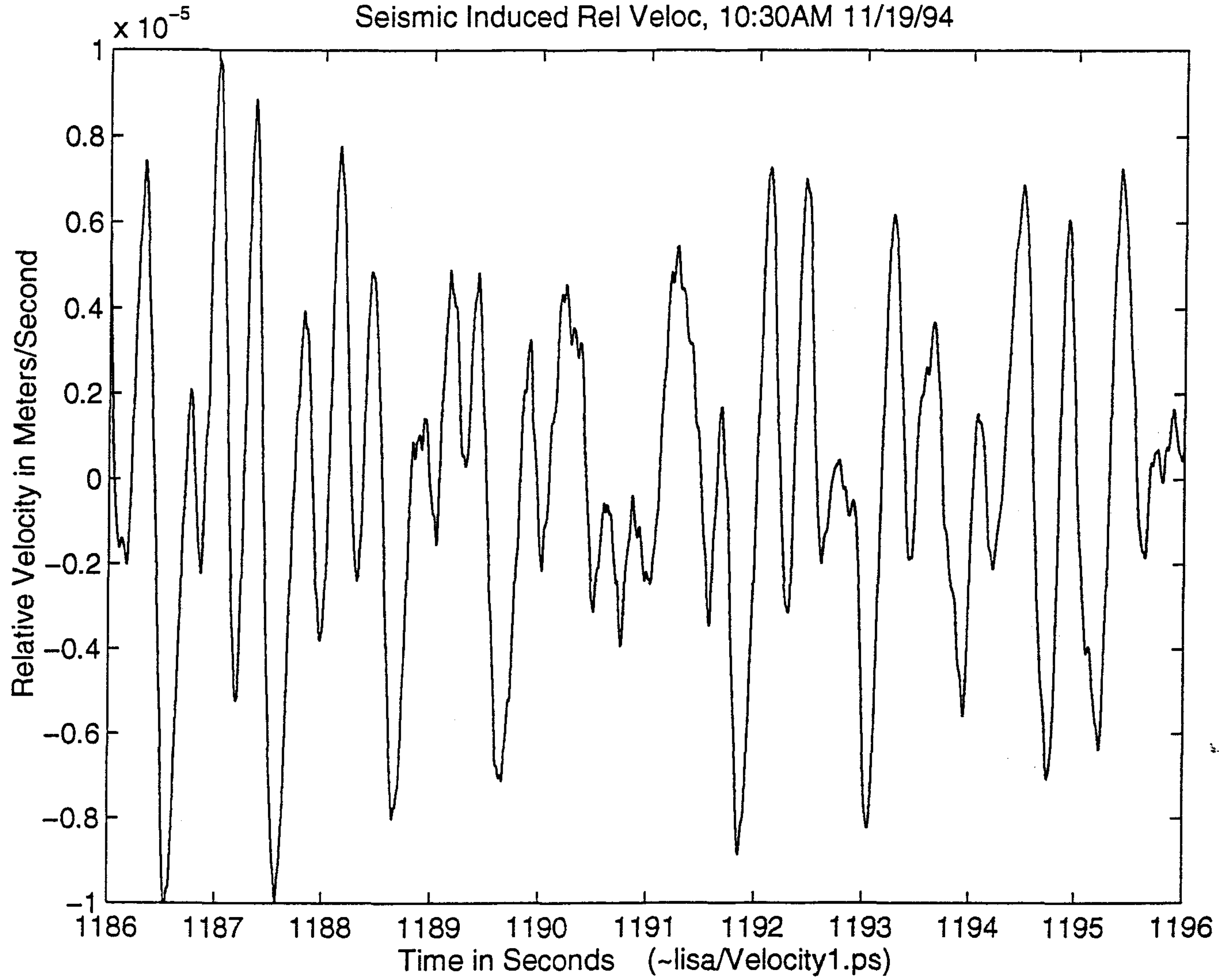


Figure 17: Calibrated force output of the coil driver filtered through the pendulum velocity transfer function. This is equivalent to the seismically driven **relative test mass velocity**. This plot shows one of the largest amplitude signals during the 10 minute data run. Note that the average relative velocity is around 7 microns/sec (the lock acquisition setup showed a lower average velocity due to the threshold feature built into the electronics). The 1 hertz pendulum motion is also apparent in the velocity signal.

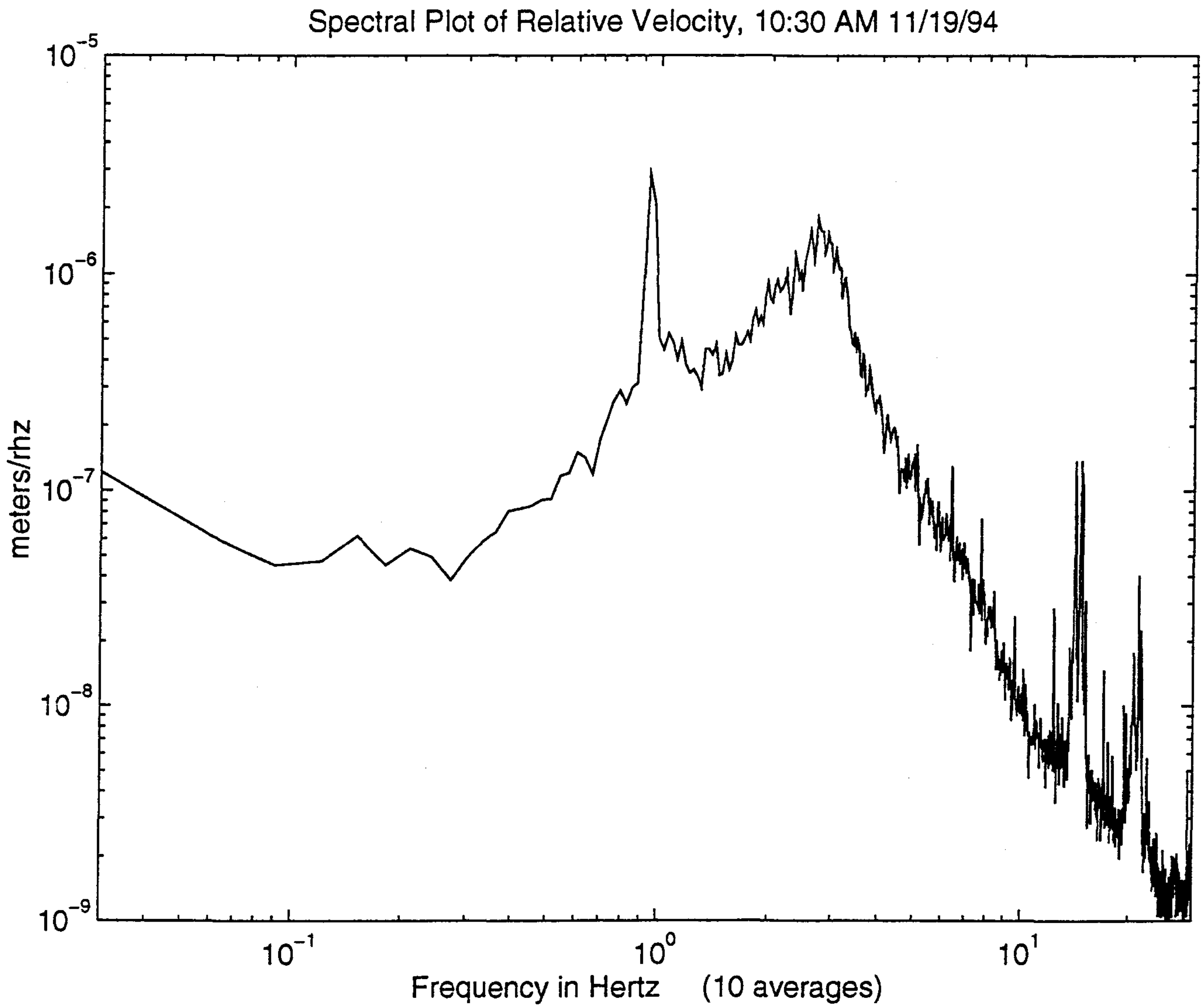


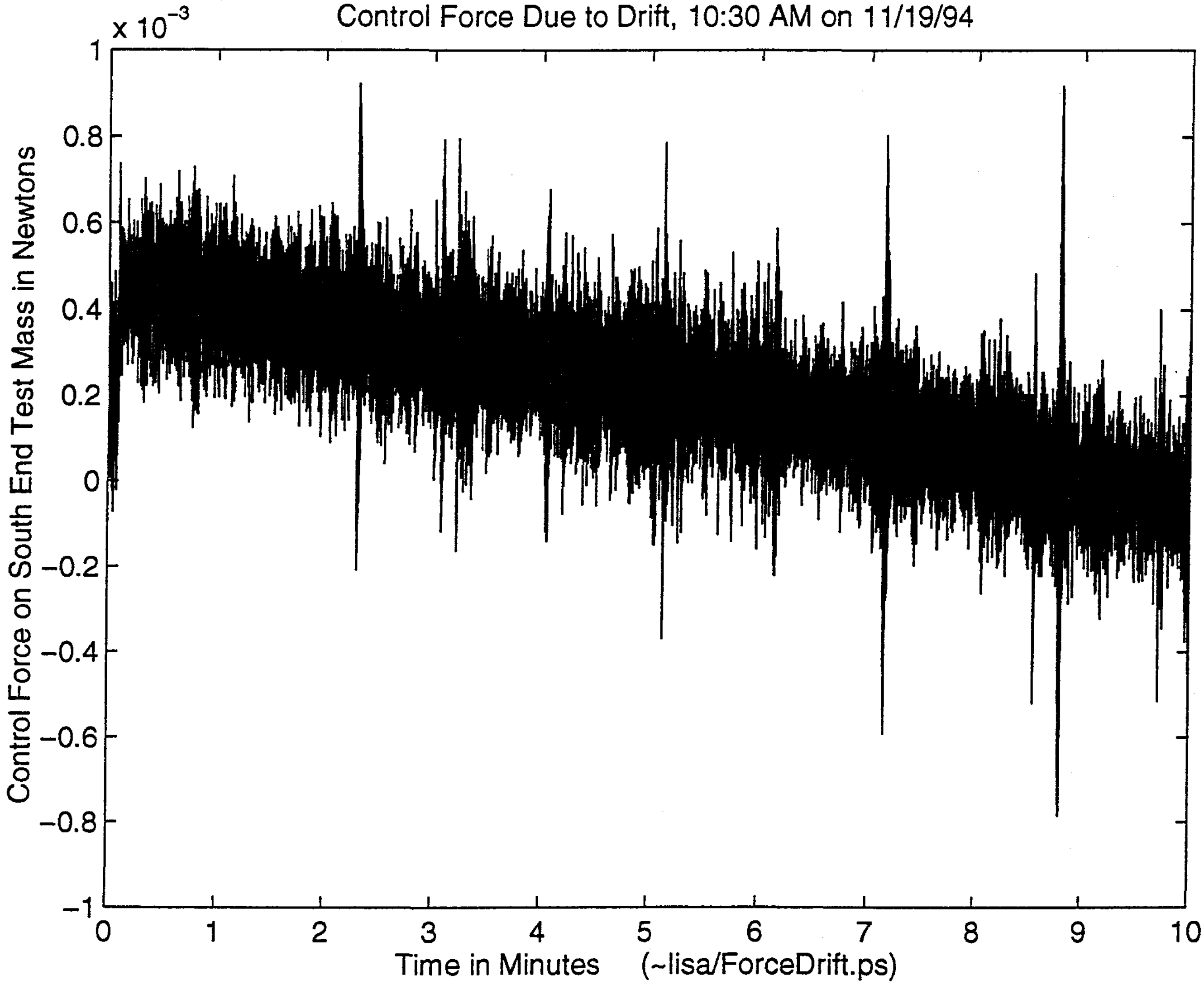
Figure 18: Spectral plot of the calibrated force output of the coil driver filtered through the pendulum velocity transfer function (equivalent to seismically driven **relative test mass velocity**). Note peak at about 3Hz is the first stack horizontal resonance while the sharp feature at 1 Hertz is the pendulum resonance.

5 Observations

There were a number of notable features in the data shown in Sections 3 and 4. The data taken during the evening had no drifts while the data taken during the day showed a significant drifting behavior. This could be due to drift in the mechanical structure supporting the 2 test masses (e.g. stacks, slab) or it could be drift in the frequency of the light entering the cavity (i.e. drift in mode cleaner length). Both of these effects would be thermally induced.

Another difference in the day and evening data was the appearance of the high Q 1 hertz peak in the daytime data (I don't think there is any correlation between day and night here). I don't have an explanation for the appearance and disappearance of the peak; a guess might be that the damping servo for one of the test masses was misbehaving in the morning but was properly tuned during the evening data run.

My expectation was that the data taken in the evening would be significantly lower in amplitude than the data taken during the day. A possible explanation is that since the data was taken on a weekend, the difference in the seismic background between day and night is not very significant (the ambient noise on the floor of the lab changes by about a factor of 10 from day to night during the work week).



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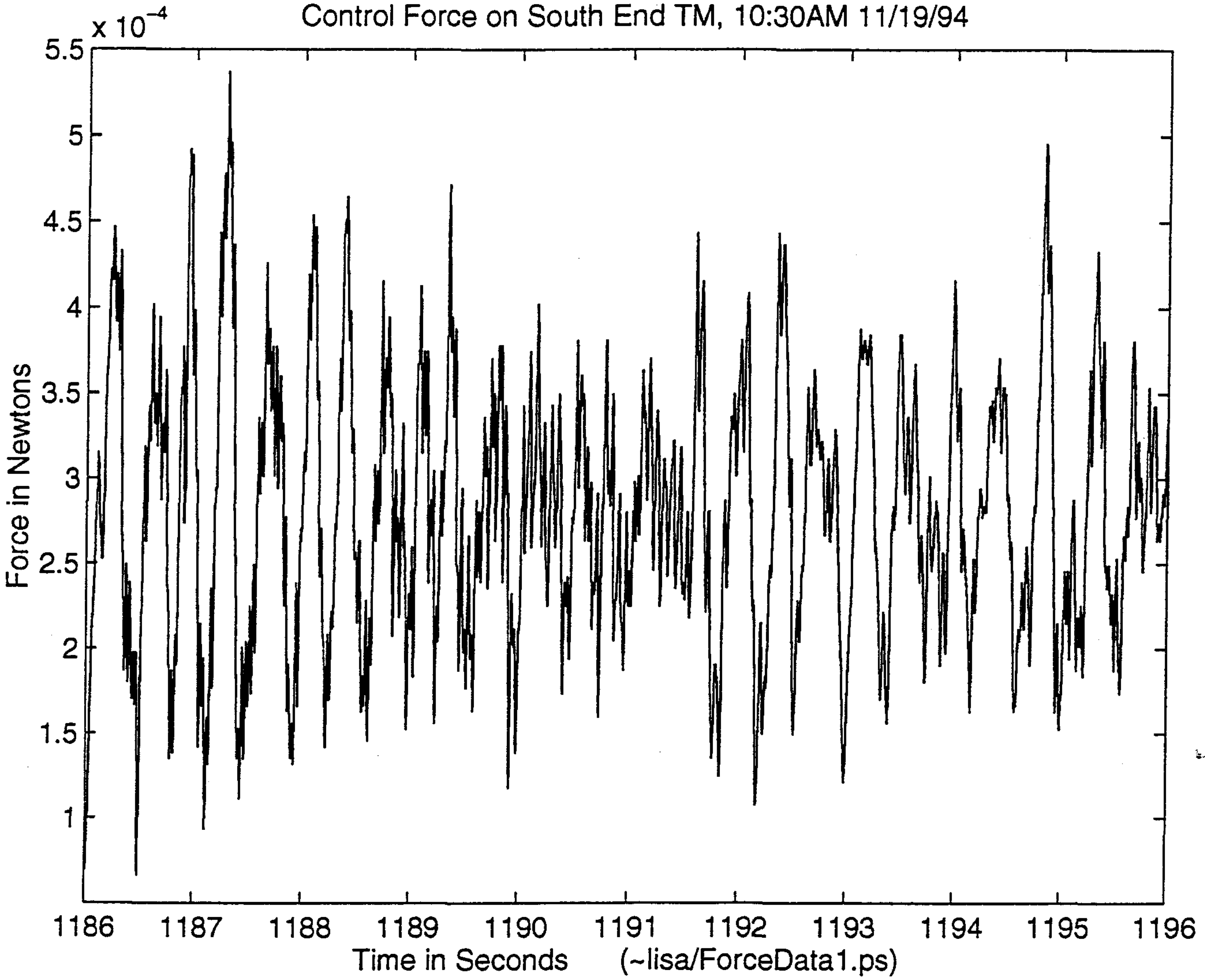

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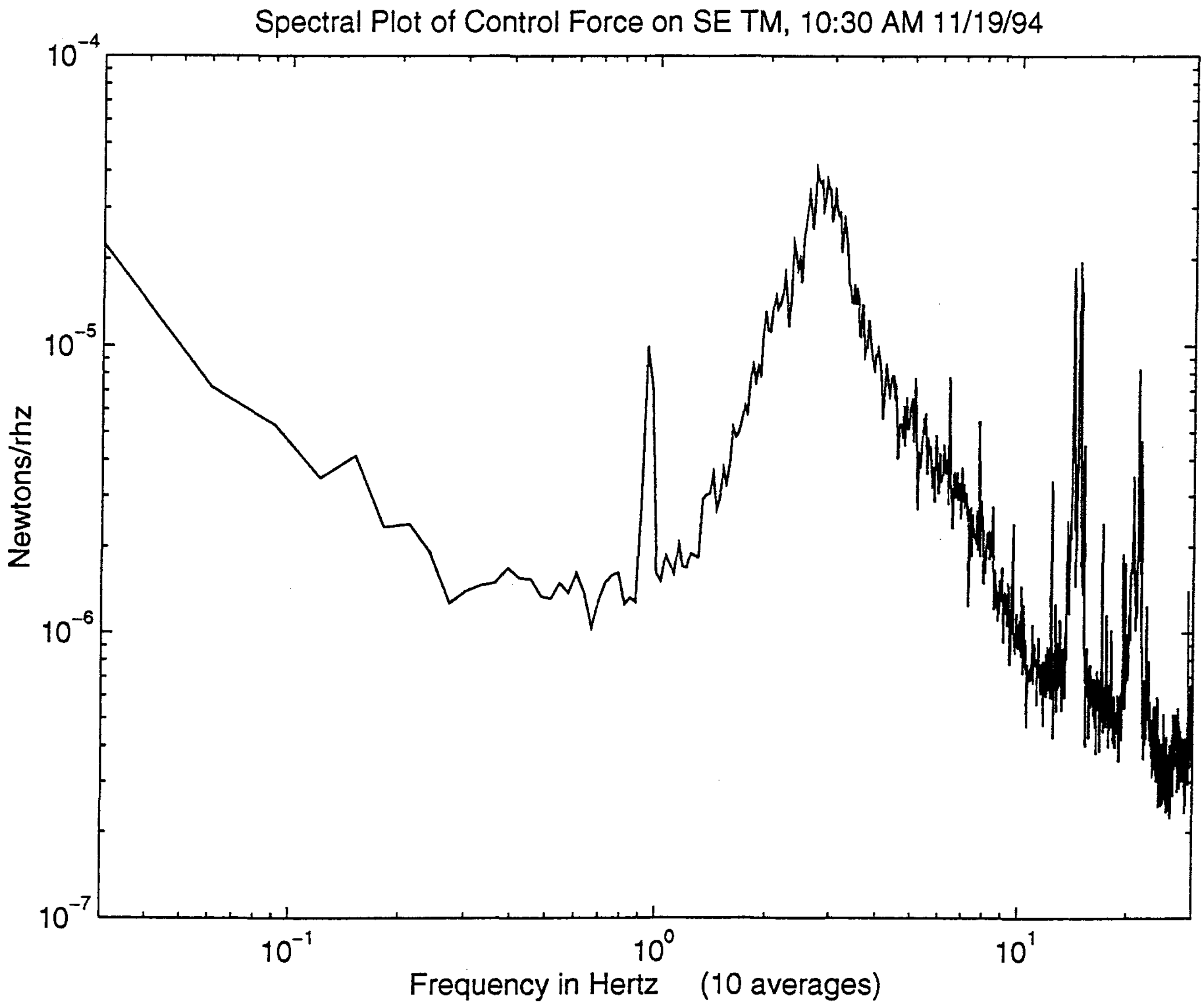

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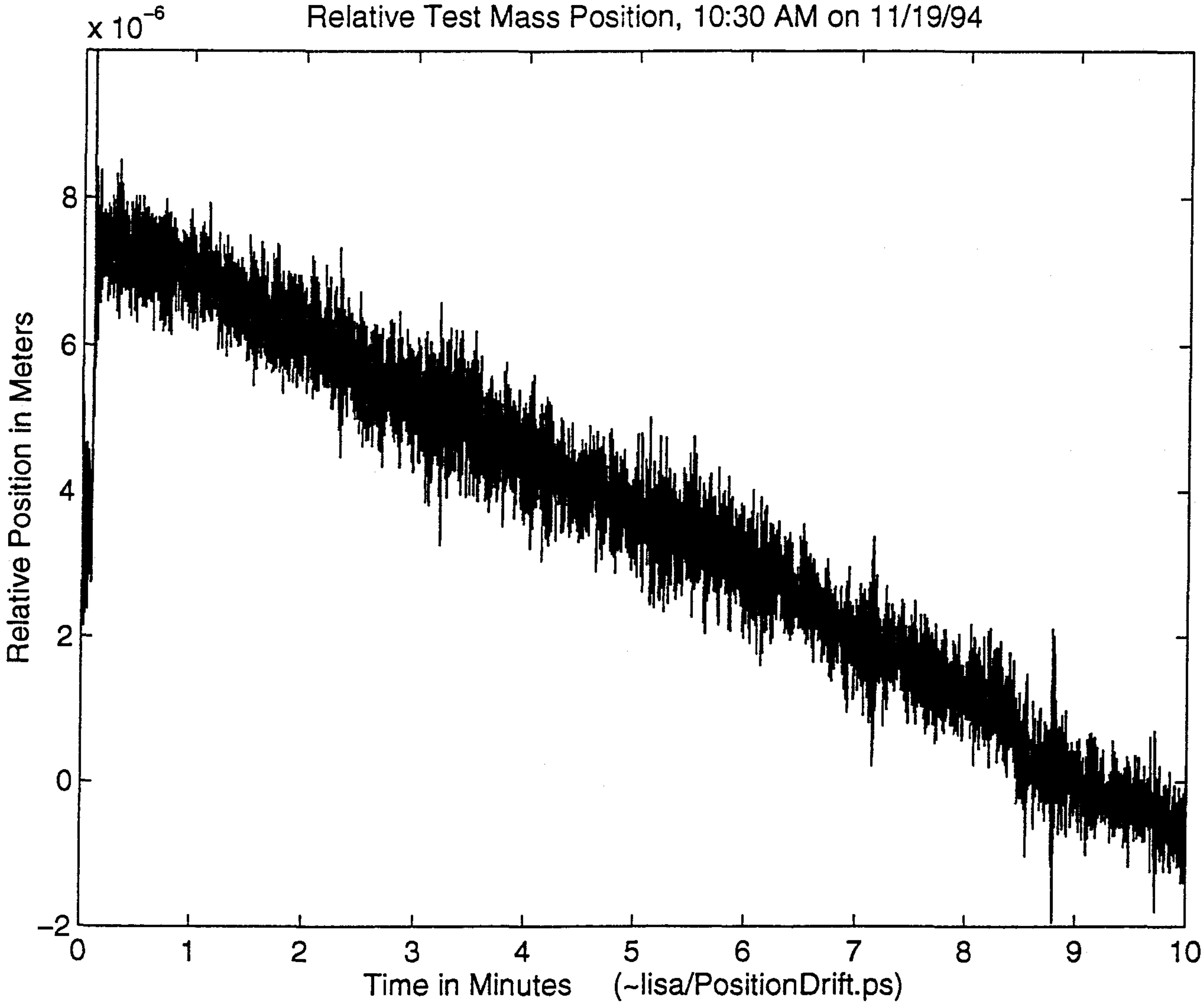

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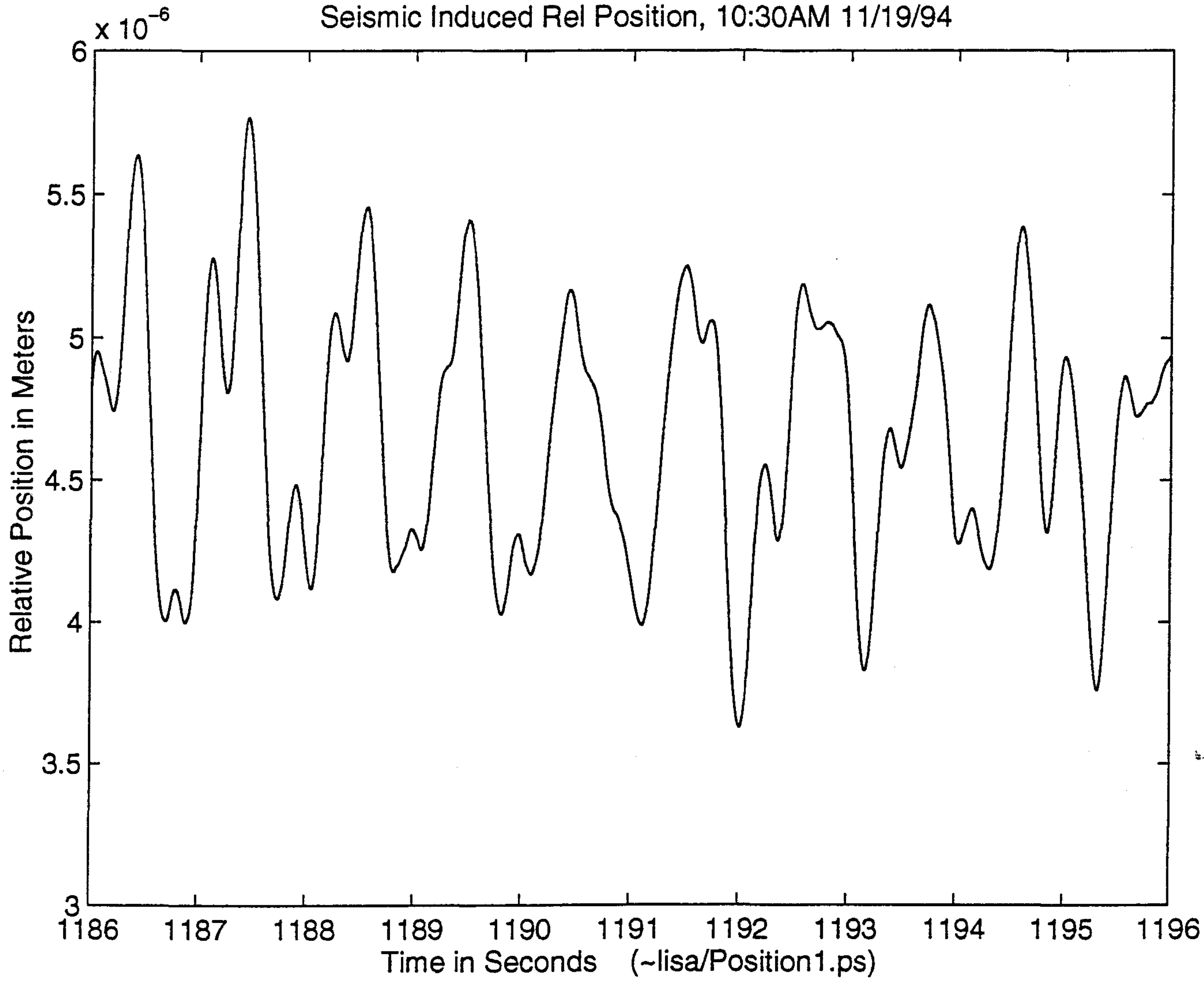

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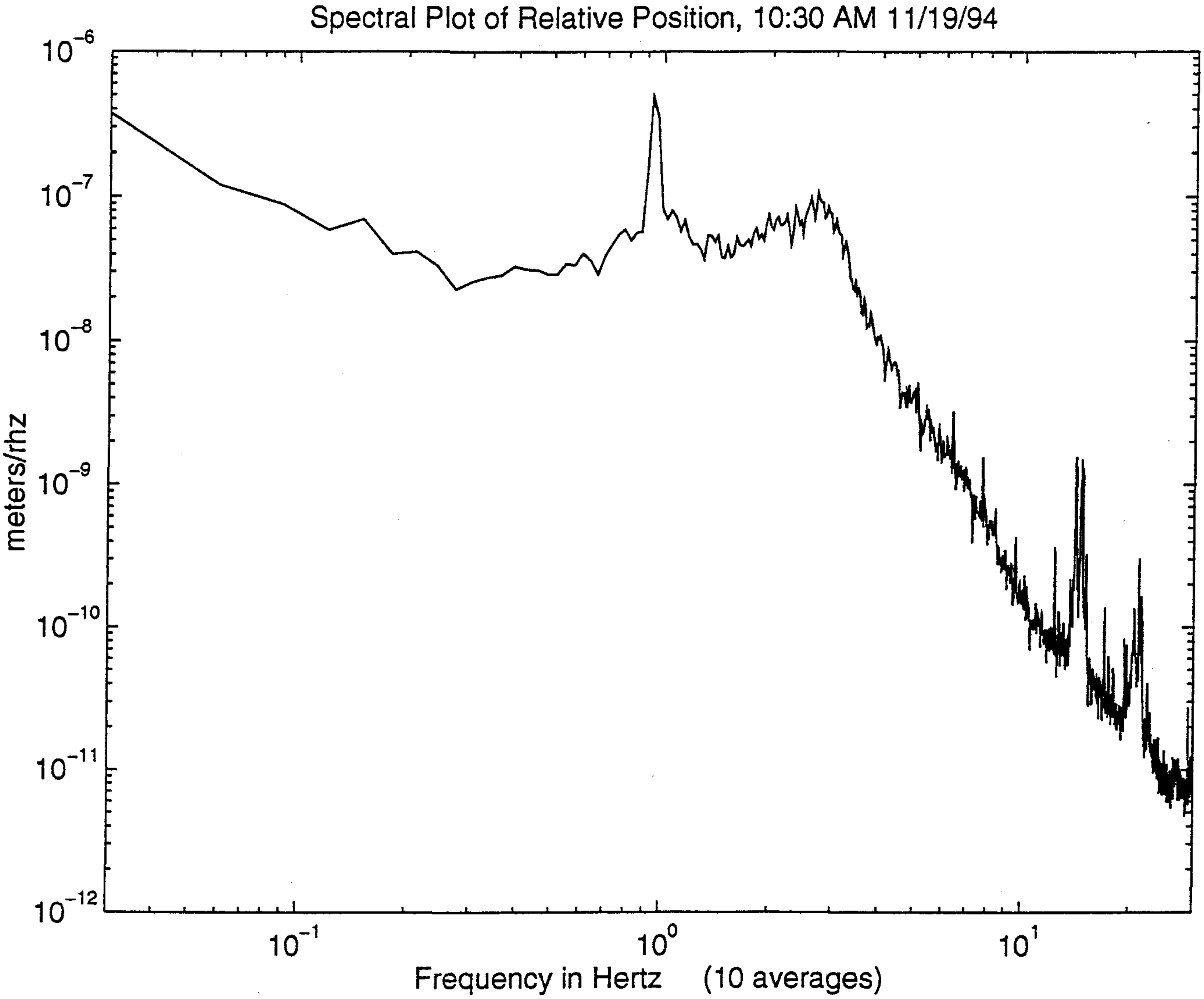

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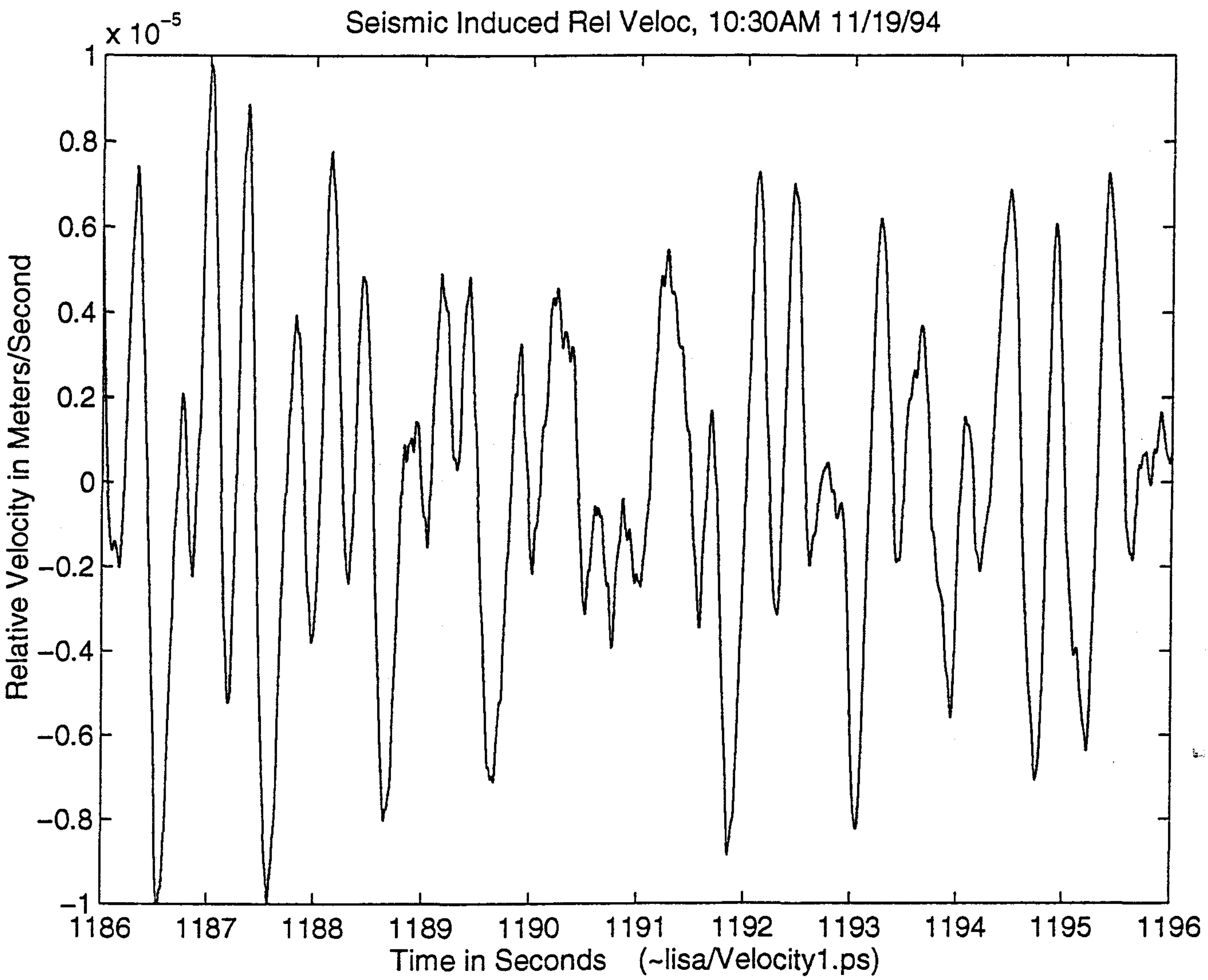

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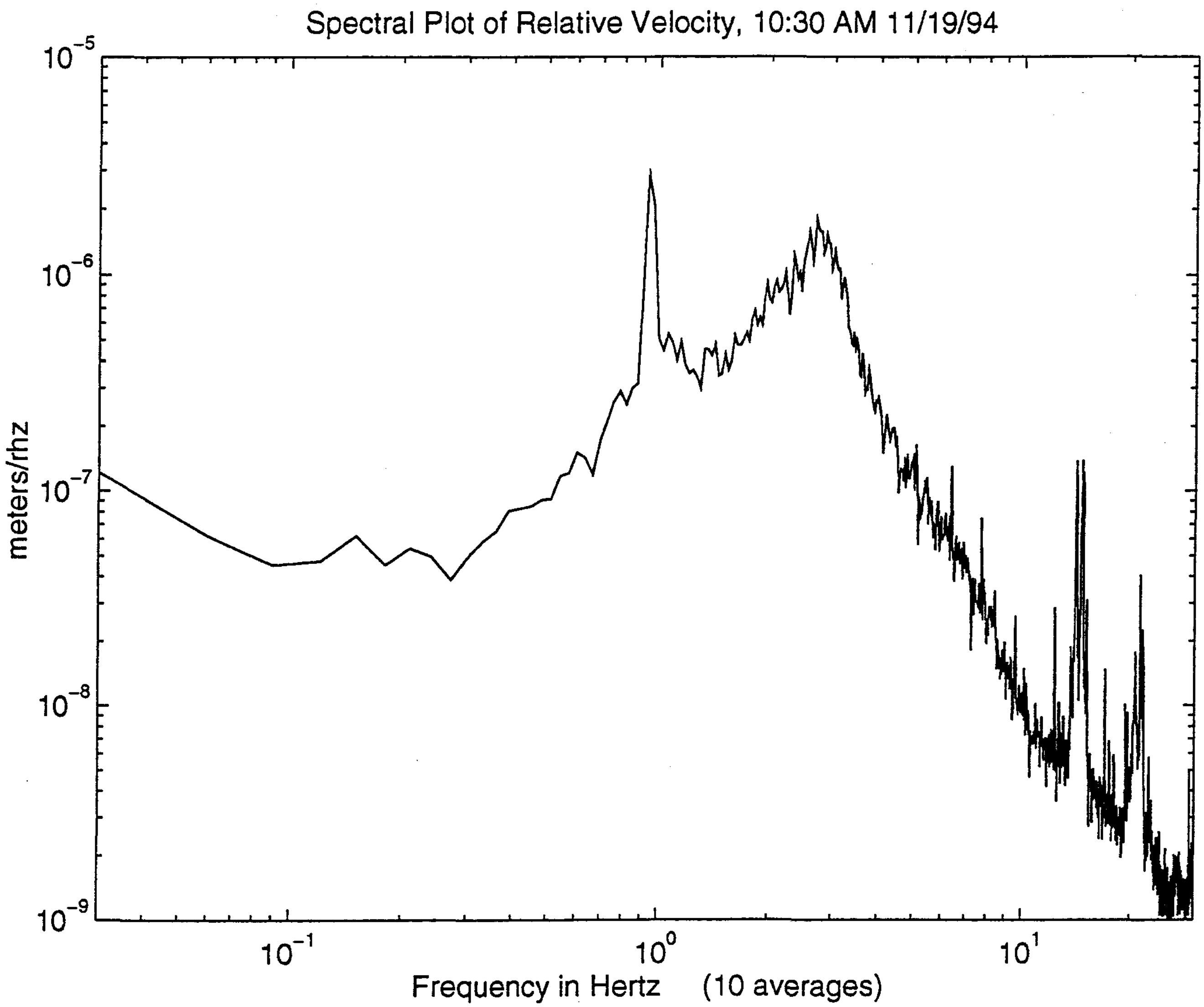

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