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Author
Mast, Terry S.

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Terry S. Mast, Jerry E. Nelson, John Saarloos
Lawrence Berkeley Laboratory, Berkeley, California
Richard A. Muller
University of California Space Sciences Laboratory,
Berkeley, California
Bruce A. Bolt
University of California Seismographic Stations,
Berkeley, California

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Theoretical estimates of the seismic response of the earth to gravitational radiation near 1 Hz have been made by Weber (1968)[1] and Dyson (1969).[2] Their estimates indicate that the surface displacement of the earth should be about 10^{-7} cm in response to a source of gravitational waves with energy flux equal to that of a star of bolometric magnitude zero. Since microseisms at an optimally quiet seismic station will produce ground motions of 10^{-8} cm or more (for a 10 Hz bandwidth) the noise is nine orders of magnitude greater than the expected signal. Nonetheless Dyson suggested that a search for such signals would be worthwhile since the estimates involved several assumptions that could be wrong by several orders of magnitude. Motivated by Dyson's suggestion, Wiggins and Press[3] analyzed 20.5 hours of data from a large seismic array in Montana, U.S.A. They searched for signals from four nearby pulsars and concluded that if such signals exist the earth's response must be less than 10^{-9} cm in amplitude.

A great deal of excitement has been generated recently by the announcement by Sadeh, Ben-Menahem, and Meidav[4] regarding the possible detection of a seismic response of the earth to gravitational waves from the pulsar CP1133. Using an autocorrelation analysis of about five months of seismic data, they conclude that they have observed signals emanating from a position in the sky that agrees with the known position of CP1133. They estimate the signal to correspond to a ground displacement of 10^{-10} cm. They also performed a signal-average at the known pulsar period of 1.18791 seconds; they interpret the appearance in a 2048 period signal-average curve of peaks at half the pulsar period to be a verification that the signal they observe is synchronous with the pulsar to four decimal places.

We report here on an analysis of seismic signals from a seismometer located near Jamestown, California. Motivated by the work of Sadeh ét al., we have limited our initial effort to a search for CP1133. We used a 14 kg Benioff vertical seismometer (Geotech model 4681) located in a tunnel in the foothills of the Sierra Nevada mountains. The signal was amplified at the site with a photo-tube amplifier (10 Hz bandpass), frequency modulated, and sent over telephone lines to our analysis station in Berkeley, California. There the signal was demodulated, amplified, and filtered, reducing the bandwidth to approximately 5 Hz. Figure 1 shows the relative gain of the entire system as a function of frequency. The seismometer calibration was checked several times each day with a magnetically induced impulse to the inertial section; no change in calibration was observed during the running period.

Throughout our analysis we have used signal-averaging to search for signals at the apparent frequency of the pulsar. Signal-averaging is a sensitive technique for extracting from noise a signal of arbitrary shape but known period. The averaging was done with a 1024 channel multiscaler (Hewlett-Packard 5401A modified). Its sweep was triggered by a frequency synthesizer (Hewlett-Packard 5103A) set at half the pulsar frequency. The multi-scaler adds the records of consecutive sweeps; signals at the pulsar frequency and its harmonics add coherently while signals at other frequencies add incoherently. Thus the signal-to-noise ratio increases in proportion to the square root of the number of sweeps. Because of the quadrupole nature of gravitational radiation, the period observed should be half that seen in the electromagnetic spectrum, i.e., about 0.59 seconds. Each sweep of the multi-scaler was 2 seconds in duration.

(At the end of a sweep there was a dead-time of approximately 0.38 seconds before the next trigger pulse arrived.) One would expect the pulsar signal to repeat itself about 3.4 times within one sweep. The pulsar frequency used was calculated from the intrinsic pulsar frequency by correcting for the Doppler shift due to the motion of the seismic station relative to the center of mass of the solar system.[5] The average earth noise was measured before, during, and after signal-averaging runs, using a pulse height analyzer. The earth noise was approximately Gaussian with a half-width at half-maximum that varied from 3×10^{-8} cm/$\sqrt{\text{Hz}}$ during the day to about 1×10^{-8} cm/$\sqrt{\text{Hz}}$ at night and on weekends. In order to reduce fluctuations due to earthquakes, the signal into the multi-scaler was limited at about three times the average noise level. (Although ground motion in excess of this limit occurs less than 1% of the time, such motion, if not limited, can greatly increase the average noise.)

Figure 2 shows the average ground motion for 30,333 sweeps synchronized to half the pulsar frequency. This represents our quietest and longest running period of approximately 16 hours (April 15 - 16) when the earth noise was approximately 1×10^{-8} cm/$\sqrt{\text{Hz}}$. A true signal from CP1133 would appear in this signal average as three peaks about 0.59 second apart. No such set of three peaks is observed. The vertical bar indicates the expected rms deviation for the entire curve based on the measured noise. The deviations observed are consistent with those expected from noise; no pulsar signal is detected.

Figure 3 shows an average signal from 31,850 sweeps taken during a noisier period. Once again the observed fluctuations are no greater than expected from earth noise. It is interesting to note that if a signal were present, it should appear with the same shape in both

Figs. 2 and 3. No such similarity is seen. Figure 4 shows the average signal for 23,050 sweeps when the frequency synthesizer was set approximately 1% different from the known pulsar frequency in order to check our understanding of the earth noise. Again the rms deviation is consistent with that expected.

More than 35 signal-averaging runs have been made (most of them for fewer sweeps than the data in Figs. 2-4). For these runs, precedence was given to those times of day when the signal from the pulsar was expected to be at maximum, i.e., when the pulsar was on the horizon as seen from Jamestown. In all of our runs the observed fluctuations are attributable to noise. If there is a seismic signal due to pulsar CP1133 its rms amplitude at our seismometer must be less than 10^{-10} cm.

The results of our experiment conflict with those of Sadeh et al. We think that their signal estimate of 10^{-10} cm is too small to be consistent with their reported noise level, their technique of analysis, and the data shown in their figures. During a quiet period their ground noise was as low as[4,6] 10^{-8} cm. (3×10^{-9} cm/$\sqrt{\text{Hz}}$). From this value we can calculate the sensitivity of their experiment.

In their autocorrelation runs, they operated with a bandwidth of 0.2 Hz.[7] Their earth noise in this bandwidth would be $(3 \times 10^{-9}\ \text{cm}/\sqrt{\text{Hz}}) \times (0.2\ \text{Hz})^{\frac{1}{2}} = 1.3 \times 10^{-9}$ cm. By using the autocorrelation technique, one would be able to see signals six times smaller than this[8], thus the minimum detectable signal (signal-to-noise = 1:1) would be 2.2×10^{-10} cm. The criterion for accepting a signal as significant was that the amplitude in the pulsar channel in the Fourier spectrum "had to be at least twice as high as the total sum of the rest of the channels (which corresponds to all the other periods between 0.1 sec and 10 sec)."[4,6] In the autocorrelation plot the signal stands out strongly. Thus it must be far above their minimum detectable signal of 2×10^{-10} cm, and therefore much greater than our limit of 10^{-10} cm.

From signal-averaging runs Sadeh et al. report a strong signal after 2048 sweeps (2048 pulsar periods, since their sweep time was 1 sec, followed by 0.19 seconds dead time). Because their earth noise may have been as low as half our earth noise[9] we need approximately four times as many sweeps for equal sensitivity. In the present experiment runs with more than 30,000 sweeps (60,000 pulsar periods) show no signal above noise. It is incorrect to conclude, as was done by Sadeh et al. that the appearance of peaks in a signal-average plot, separated by half a pulsar period, is either a verification of the detection of a pulsar signal or an accurate measurement of the pulsar frequency. Both figures 2 and 4 in this paper have peaks separated by approximately half the pulsar period, but in neither case may we accept these peaks as evidence of pulsar signal. In figure 2 the expected third peak does not appear, and all fluctuations are consistent with noise. Figure 4 was taken from a run whose synchronization was not at the pulsar frequency.

We are grateful to Russell Sell for his assistance with the seismometer and related equipment. This work was supported by the National Aeronautics and Space Administration and the U.S. Atomic Energy Commission.

FOOTNOTES AND REFERENCES

1. Weber, J., Phys. Rev. Letters, <u>21</u>, 395 (1968).
2. Dyson, F.J., Astrophys. J., <u>156</u>, 529 (1969).
3. Wiggins, R.A., and Press, F., J. Geophys. Res. <u>74</u>, 5351 (1960).
4. Sadeh, D., Ben-Menahem, A., and Meidav, M., "Possible Detection of Gravitational Waves from Pulsars," University of Tel-Aviv Preprint TAUP-270-72 (to be published).
5. The intrinsic pulsar frequency was taken from R.N. Manchester and J.H. Taylor, Astrophys. J. Letters, <u>10</u>, 67 (1972). The doppler shift was calculated by using the Jet Propulsion Laboratory Ephemeris, using the technique described in J. Nelson, R. Hills, D. Cudaback, J. Wampler, Astrophys. J., <u>161</u>, L235 (1970).
6. Ben-Menahem, A., and Sadeh, D., private communication.
7. In the Fourier analysis of their autocorrelation data, Sadeh et al. have a bin width of 0.53 - 0.60 seconds. Thus they cannot distinguish frequencies within a bandwidth of $1/0.53 - 1/0.60 = 0.2$ Hz.
8. Sadeh et al., in effect, superimpose 1310 ten second autocorrelation plots, and then take the Fourier transform of this superposition to derive the power spectrum of the earth. The ratio of signal power to random fluctuations in earth noise power would be improved by a factor of $\sqrt{1310} = 36$, and the ratio of signal amplitude to random fluctuations in earth noise amplitude would be improved by a factor of $\sqrt{36} = 6$.
9. Their noise per $\sqrt{\mathrm{Hz}}$ was a factor of 3 lower, but we operated with a narrower bandwidth (5 Hz vs. 10 Hz).

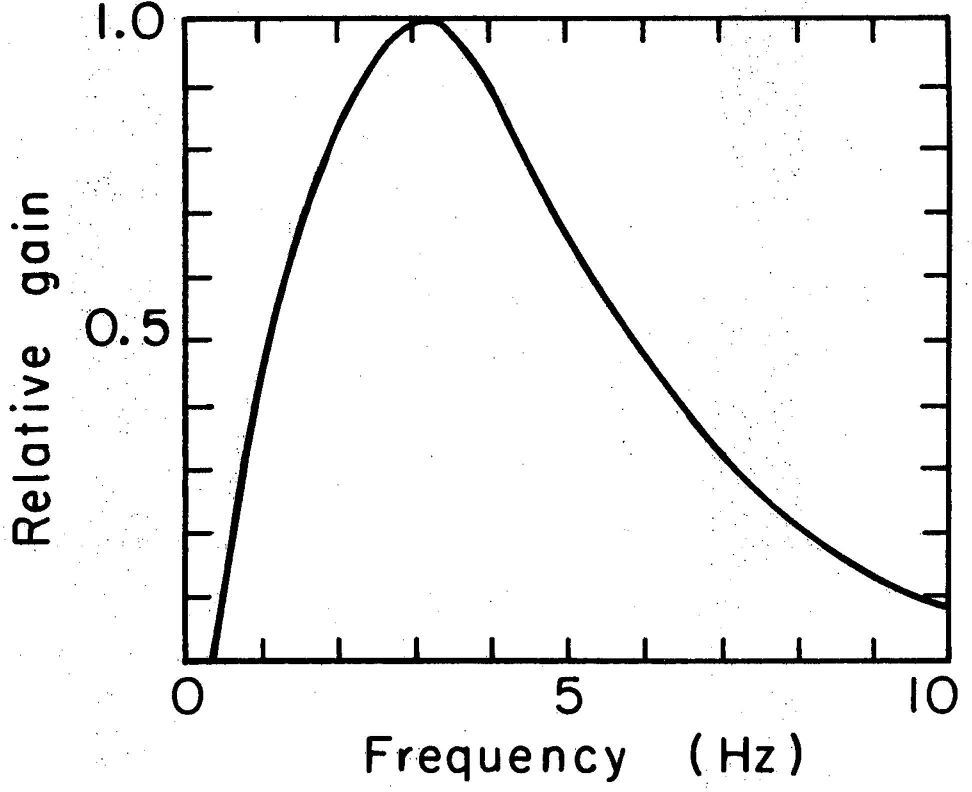
FIGURE CAPTIONS

Fig. 1. The relative gain of the seismographic, amplification, and filter system as a function of frequency.

Fig. 2. Ground displacement averaged for 30,333 two-second periods, synchronized at half the frequency of pulsar CP 1133. The apparent pulsar period, corrected for the motion of the earth, is indicated. The vertical bar indicates the expected rms of the entire curve, calculated by dividing the average noise by the square root of the number of sweeps. The vertical scale is calculated from the known gain of the system at 2 Hz.

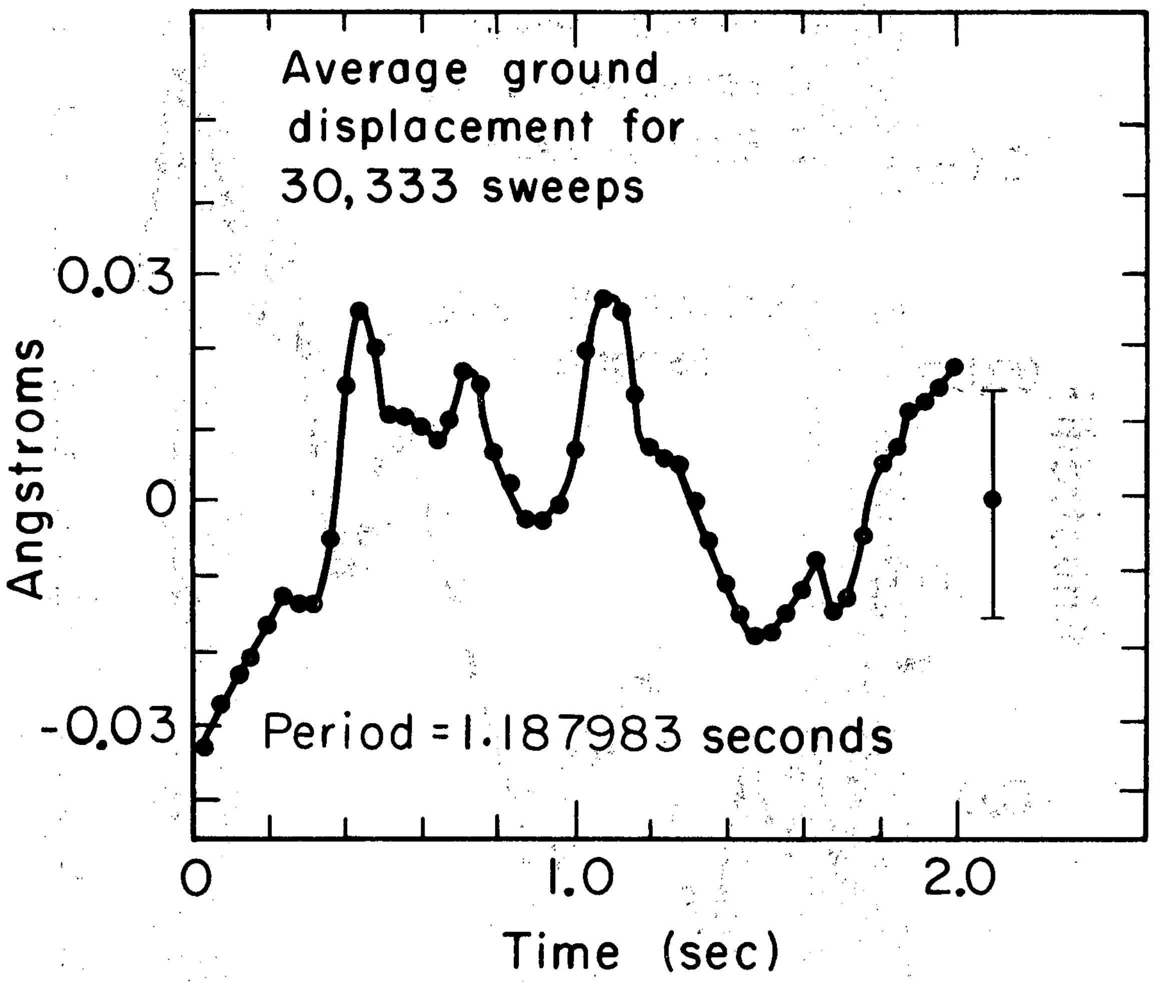
Fig. 3. Ground displacement average, similar to that in Fig. 2, but during a noisier period.

Fig. 4. Ground displacement average, similar to that in Figs. 2 and 3, but synchronized at a frequency approximately 1% different from the half-frequency of pulsar CP1133. Any true pulsar signal would therefore be washed out.



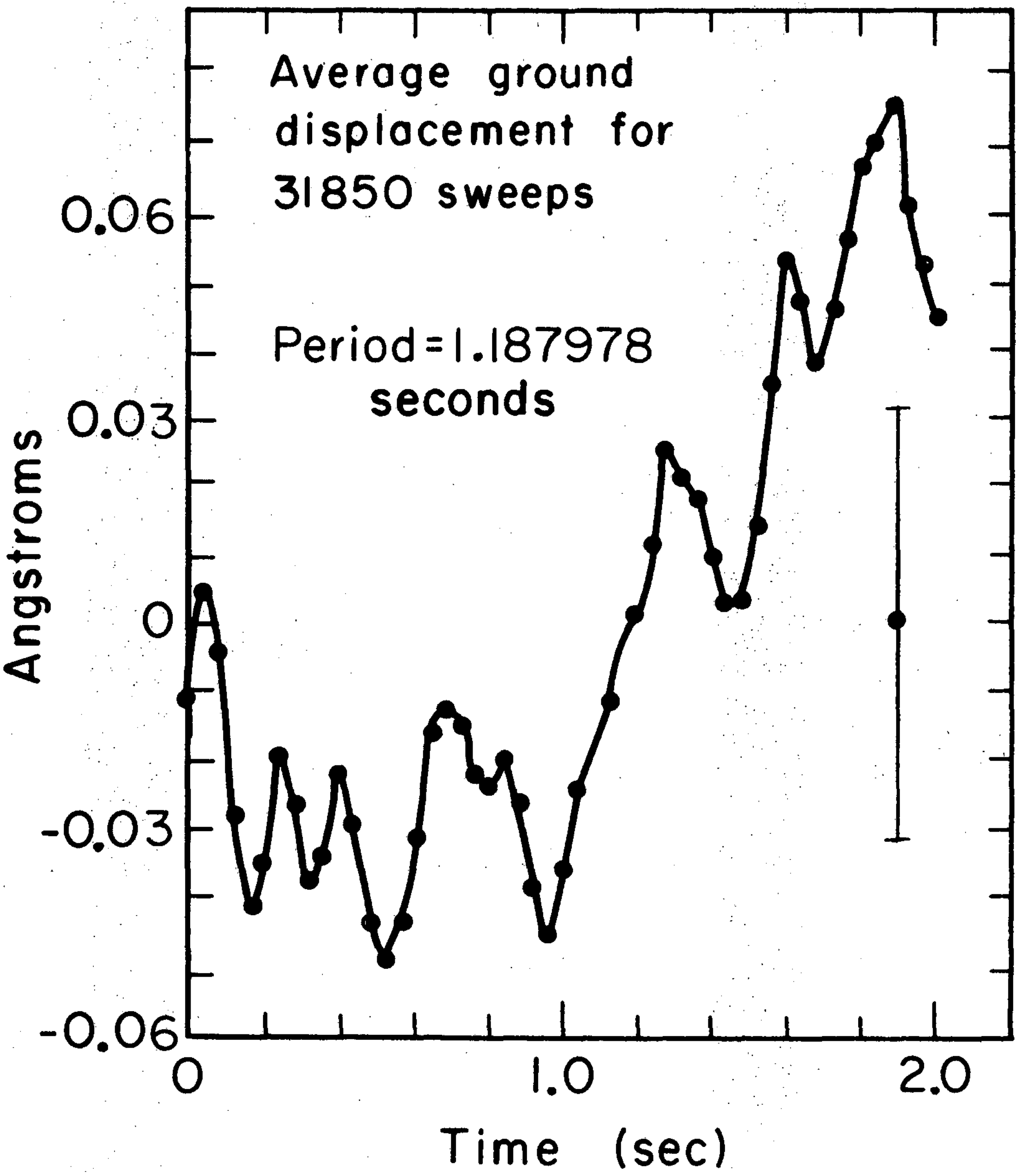
XBL725-3000

Fig. 1



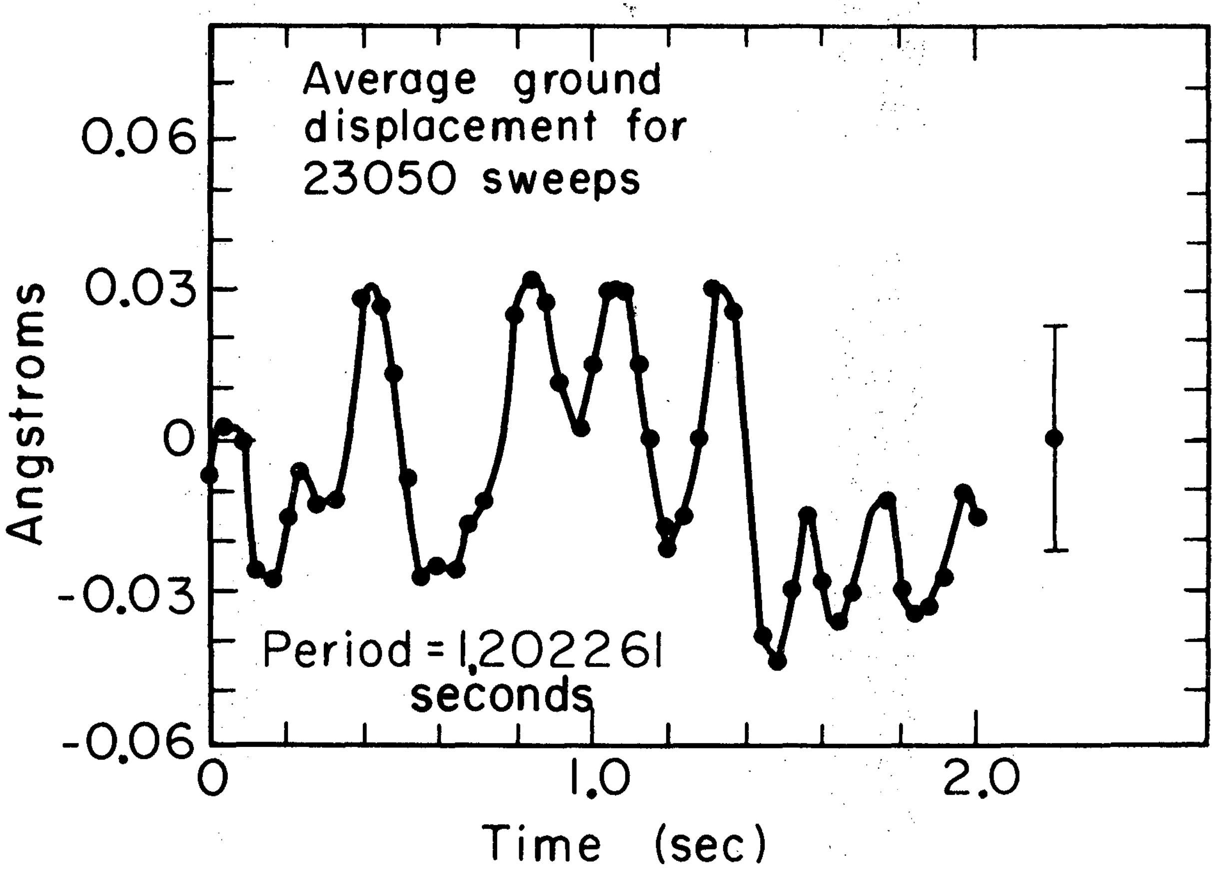
XBL 724-2829

Fig. 2



XBL724-2830

Fig. 3



XBL724-2831

Fig. 4

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LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720