S35-74
37220

RESOLVING HIGH AMPLITUDE SURFACE MOTION WITH DIFFUSING LIGHT

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W.Wright, R. Budakian & S. J. Putterman
Physics Department, University of California, Los Angeles, CA 90095

Abstract: A new technique has been developed for the purpose of imaging high amplitude surface motion. With this method one can quantitatively measure the transition to ripple wave turbulence. In addition one can measure the phase of the turbulent state. These experiments reveal strong coherent structures in the turbulent range of motion.

The high amplitude motion of a fluid surface exhibits a remarkable range of broken symmetries ranging from quasi-crystals to quantum scars to ripple turbulence[1)]. Key to a quantitative investigation of these states is a means of measuring the surface height as a function of location.

Figure 1 shows the apparatus that we have used to excite and measure the large amplitude distortions of a fluid surface[2)]. A vibration exciter oscillates a container of fluid in the vertical direction at sufficient amplitude that instabilities determined by the Matthieu equation come into play. The resulting surface motion is made visible by suspending into the water a .04% solution of polyballs. This concentration is sufficiently dense that light traveling through the water is so strongly scattered that it diffuses. A charge coupled device (CCD) records the light to exit the fluid. Typically the surface is broken up into one million pixels [1024x1024] where each pixel is capable of recording a dynamic range of 65,000 gray scales [or 16 bits]. This image is converted into the surface height with the help of a calibration plot shown in Figure 2. This plot shows the amount of light to exit the surface as a function of fluid depth. The deeper the fluid the smaller is the amount of light to make it to the surface at that location. An example of a photo and its rendition as obtained with the use of the calibration plot is shown in Figure 3.

The surface height as a function of time at a single point in the fluid can be obtained by reading out the calibrated signal from a single pixel as a function of time. From this measurement one can obtain the power spectrum of surface motion as shown in Figure 4. At low amplitudes of excitation the motion is sinusoidal at half the frequency of the drive. Harmonics of this frequency are also present. But as the amplitude of sinusoidal excitation is increased the fluid motion shows a transition to a broad band response. We claim that this is the state of wave turbulence of propagating ripples[3)]. When plotted on a log-log scale the slope which we find is -3.2 which is close to the value of -17/6 predicted by the Kolmogorov scaling law[4)] for interacting ripples[3)]. The small deviation which we find can be due to a) the finite size of the container, b) the limited range of the broad band distribution that can be obtained with our apparatus, and c) mistakes in the physical assumptions[5,6)] that underlie the theoretical analysis of turbulence in propagating capillary waves. Problems a) and b) are of experimental origin and can be addressed by carrying out this experiment in microgravity.

Theories which are based upon a random phase approximation yield a power spectrum in agreement with the Kolmogorov dimensional analysis and of course also yield a description of turbulence that is devoid of intermittency. Since phase is a physical quantity of importance equal to power [or amplitude squared] we have used the instantaneous photos [e.g. Figure 3] to investigate the phase coherence, if any, of the turbulent state. To do this we digitally filtered the photo to include only the contributions from a range of wavelengths. In this case those wavelengths corresponding to the frequency range 373Hz to 429Hz. From this filtered photo we then constructed the dissipation function which is proportional to the square of the Laplacian of the surface height. A rendition of this data is shown in Figure 5. Note that the turbulence is localized onto surfaces. It is not uniformly spread out. According to these experiments the turbulent state is filled with structures or so-called "intermittency".

It will be interesting to see of these effects persist when the turbulence cascades over a wider range of frequencies and the effects of boundaries are eliminated. This will be achieved in those arrangements where one images ripples that interact on the surface of a large drop of liquid such as can be achieved in microgravity. Mathematically, it is essential to determine the appropriate way to analyze and quantify the structures shown in Figure 5.

THE SUPPORT OF NASA MICROGRAVITY IS ACKNOWLEDGED

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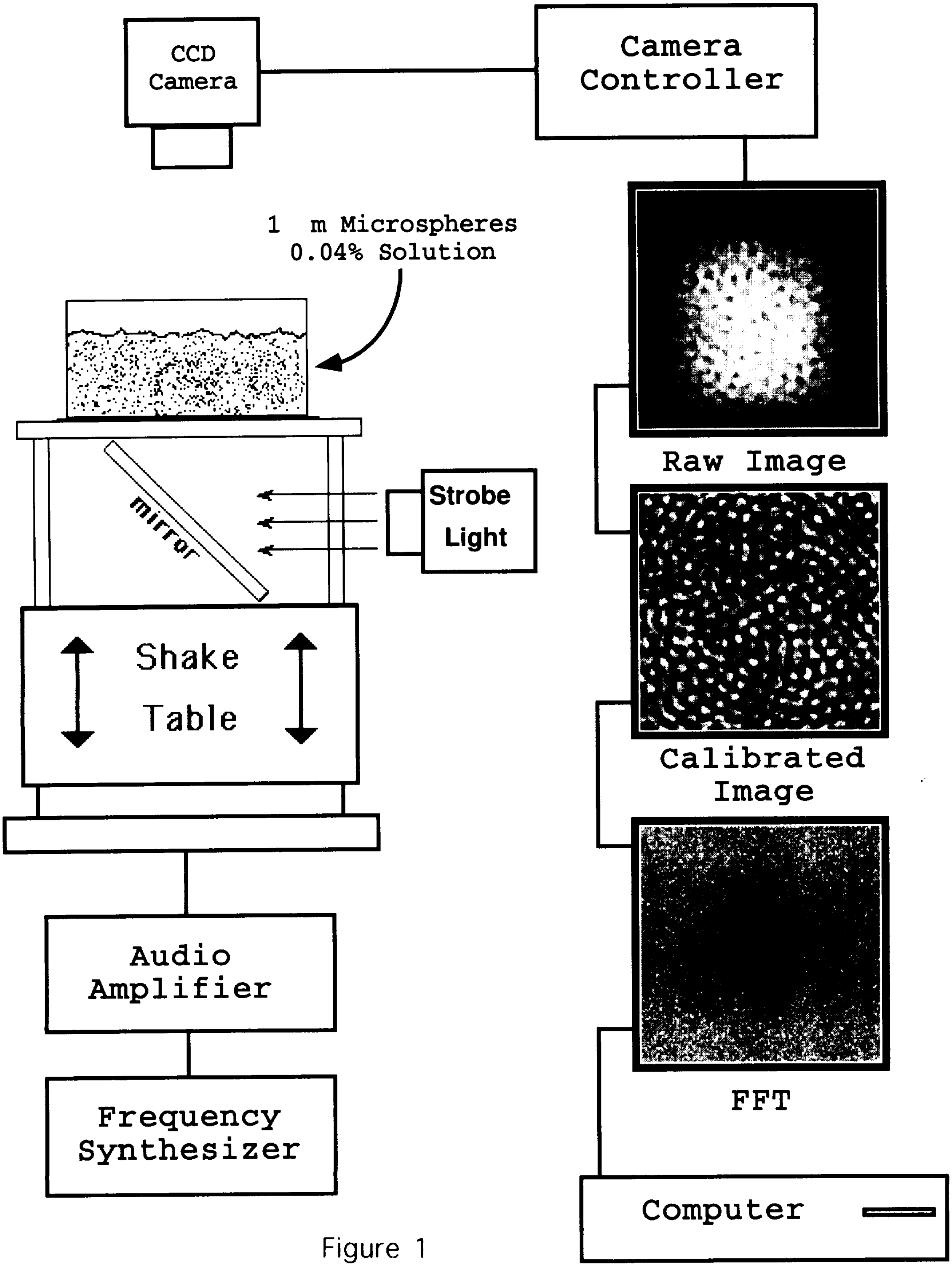
FIGURES

Figure 1; Apparatus for imaging the instantaneous high amplitude displacement of a fluid surface. A flash from a strobe diffuses through the fluid and exits the top surface where it is imaged onto a CCD. Higher regions are darker. The fluid is sinusoidally excitied by a shake table. Above a critical threshold the surface motion sets in. The light diffuses as a result of multiple scattering by a .04% concentration of polyballs suspension in the water.
Figure 2 ; Relative intensity of light to exit fluid surface as a function of depth. Each of the one million pixels of the CCD is calibrated. From this calibration the local height is determined.
Figure 3; An actual photo of the turbulent state and its scaled and calibrated rendition as obtained from use of Figure 2.
Figure 4; Power spectrum of surface motion. Displayed is the Fourier Transform of the time dependent motion as recorded at a single pixel. At high drive levels the harmonic response [characteristic of low drive] turns into a broad band spectrum. The solid line has a slope of -3.2. The threshold for turbulence [reference 2] is indicated by the dashed line.
Figure 5; Digitally filtered photo of the motion in the turbulent state. The photo shown in Figure 3 is first filtered in the range 373Hz-429Hz. Then the dissipation function is calculated [this is the square of the Laplacian and gives the local dissipation of ripple motion due to viscosity. The structure shown in this photo is indicative of intermittency. This is data, not simulation!


CCD
Camera
Camera
Controller
1 m Microspheres
0.04% Solution
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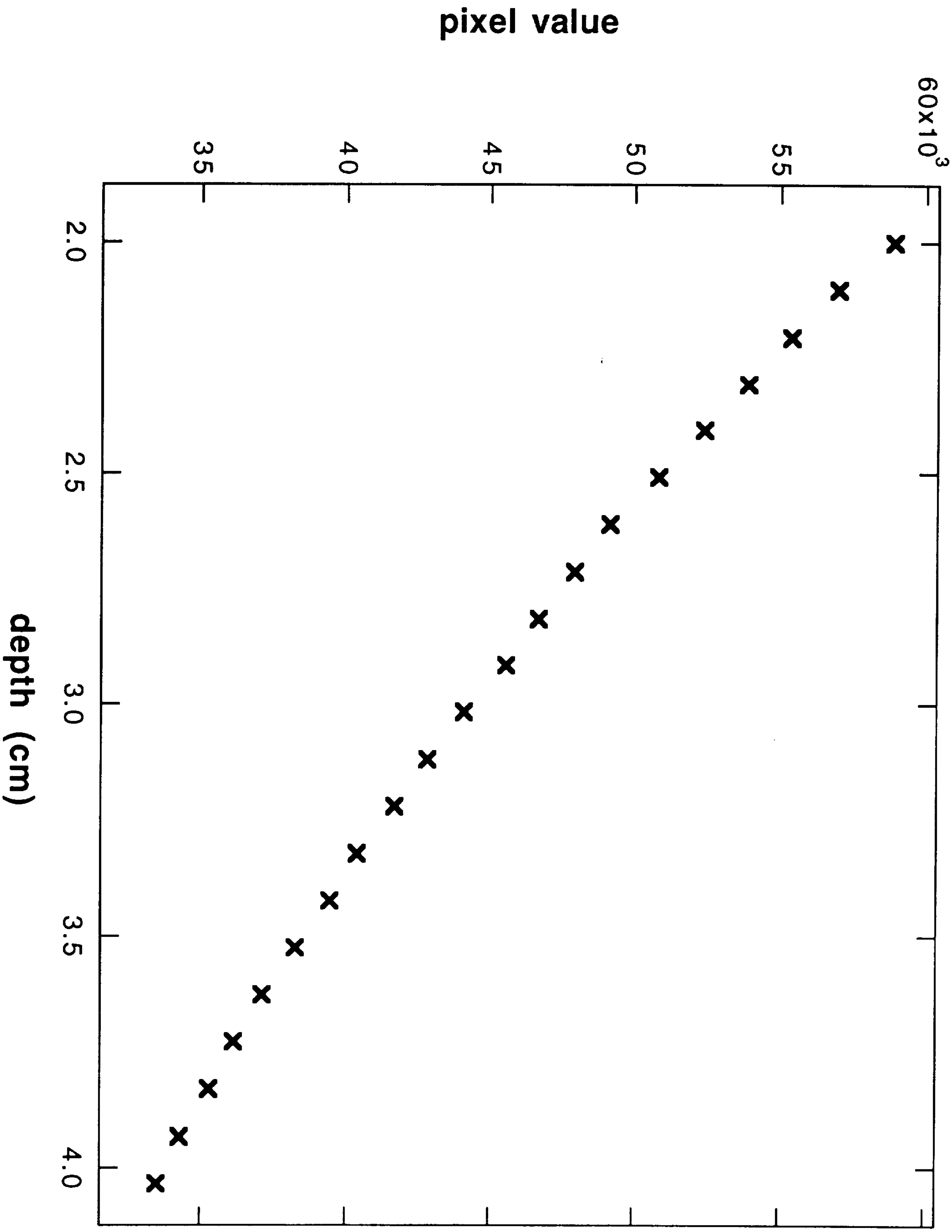
Strobe
Light
mirror
Shake
Table
Calibrated
Image
FFT
Audio
Amplifier
Frequency
Synthesizer
Computer

Figure 1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50
45
40
35
2.0
2.5
3.0
3.5
4.0
depth (cm)

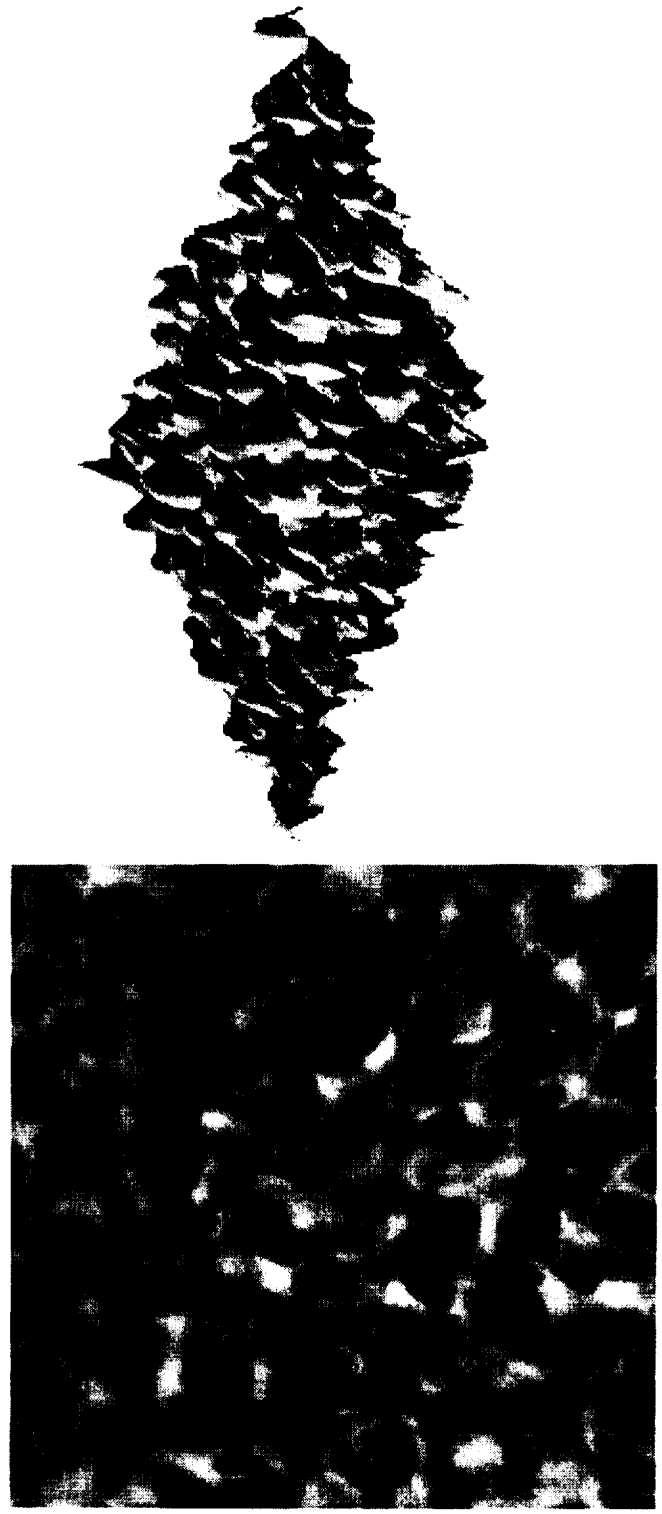

Figure 3

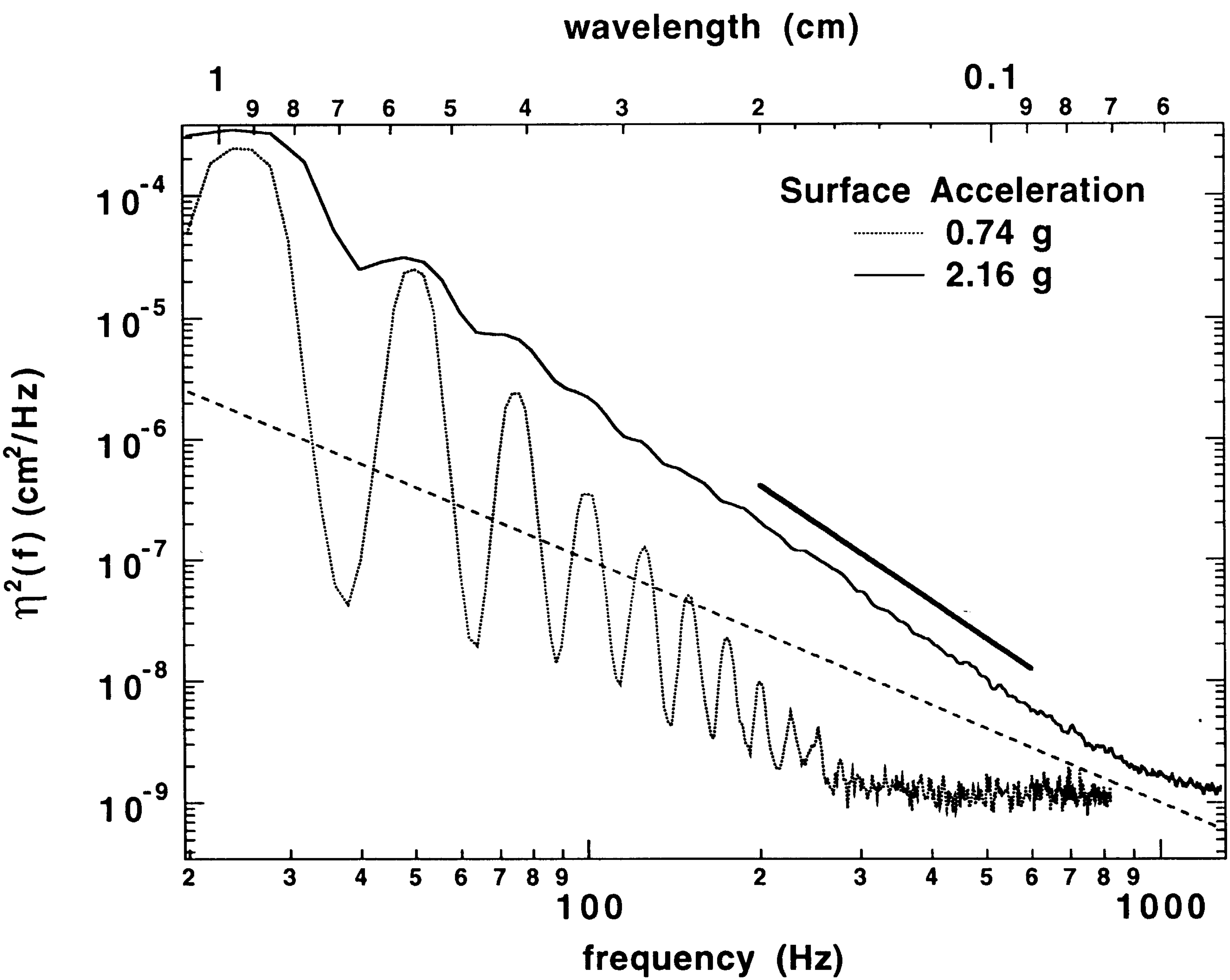
wavelength (cm)
1
0.1
9 8 7 6 5 4 3 2
9 8 7 6
Surface Acceleration
0.74 g
2.16 g
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
$\eta^2(f)$ (cm^2/Hz)
2 3 4 5 6 7 8 9
100
2 3 4 5 6 7 8 9
1000
frequency (Hz)

Figure 5