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**LASER INTERFEROMETER STRAIN SEISMOGRAPH:
DESCRIPTION AND DISCUSSION OF THE
FEASIBILITY DEMONSTRATION EXPERIMENT**

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by

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INTRODUCTION

This report describes a feasibility demonstration of a laser strain seismograph, its unique characteristics, and its potential uses.

The availability of stable single frequency lasers makes possible the construction of an interferometer suitable for use as a strain seismograph having a sensitivity of 1×10^{-9} or better. Such an instrument could supplement the Benioff strain seismographs now in use and may have some advantages over them in the study of such long period phenomena as earth tides, continental drift, and free oscillations of the earth. An experiment has been performed to demonstrate the feasibility of such a seismograph and to gain knowledge of how it should be built.

FEASIBILITY DEMONSTRATION EXPERIMENT

The feasibility demonstration experiment was carried out at an abandoned military site where a 6 in. diameter, 37 m long, steel pipe was installed between two concrete chambers. The chambers are about 20 ft underground and anchored to bedrock. The variations in the distance between these two chambers resulting from earth strains were the phenomena to be observed. Figure 1 is a schematic drawing of this structure showing the arrangement of the equipment used in this experiment.

A single frequency laser was not available for this experiment. A multimode helium-neon laser with output at $6328 \text{ \AA}$ was used. The laser beam was split as in a Michelson interferometer. One beam was directed down the pipe connecting the two chambers. The reference beam had to be folded by multiple reflection over a short distance to achieve a path length nearly equal to that of the beam directed down the pipe. Because the path lengths for the two beams are nearly equal, the equipment was equally sensitive to strain in both legs of the interferometer. The two beams were recombined at the beam splitter to produce circular interference fringes shown in Figure 2.

LASER SEISMOGRAPH SITE

FIGURE 1

Pictorial view of laser seismograph site
showing interferometer layout.

INTERFERENCE FRINGE PATTERNS

EARTH STRAIN RECORDING

FIGURE 2

Interferometer fringe patterns showing the portion of the pattern monitored. Below are typical output signals from the photomultiplier detectors.

The center of the interference fringe pattern varied from minimum to maximum light intensity for a distance change between the two chambers of one quarter wavelength, or 1.58×10^{-5} cm. For the 37 m distance between the chambers used in this experiment, the earth strain corresponding to this maximum light intensity change would be 4×10^{-9} cm/cm.

The intensity of the center area of the fringe pattern was monitored with a photomultiplier tube. A second photomultiplier tube was used to monitor a section of the pattern where the intensity was such that it generated a signal approximately 90° out of phase with that of the central light. The portion of the fringe pattern observed by each photomultiplier is shown in Figure 2. Two signals with this phase difference are required to determine the direction and magnitude of the fringe pattern changes.

The electrical signals from the photomultiplier tubes were amplified and applied to a Sanborn 650 light beam recorder. These chart recordings provided the data from which the amplitude and direction of the earth strain were determined. Although this was done manually in this experiment, an automatic system employing standard counters and data processing equipment could be used. Fringe counting techniques and suitable methods of obtaining these phase shifted signals have been described by Peck and Obetz.⁽¹⁾

Figure 2 also shows recordings of the photomultiplier output signals obtained while observing small earth strains due to microseismic activity. These traces are typical of the type of earth strains detected by this method under quiescent conditions. The strain amplitudes were observed to be of the order of a few fringes, or about 10^{-8} cm/cm. The periods of the observed strains were from a fraction of a second to several seconds.

During the course of this experiment, a quarry blast of 30,000 lb of nitro-carbonitrate was detonated 4 miles from the site. The ground waves from this seismic disturbance provided a test of the laser seismograph. The map in Figure 3 shows the location of the quarry and the relative position of the laser seismograph.

Traces of the equipment response to this disturbance are shown in Figure 4 along with a corresponding plot of the strain waves derived from the trace and

FIGURE 3

Map of the Hanford area showing the location of the seismic detectors and the quarry blast.

FIGURE 4

The upper trace is the detector signal shortly after the quarry blast. The center curve is derived from this trace. Below is a recording from a geophone seismic detector shortly after the blast.

a portion of the record of a geophone seismic detector located near Gable Mountain (Figure 3). The amplitude and period information is derived from the interferometer seismograph trace by counting the number of fringes between fringe reversals. Fringe reversals are observed as changes in the direction of the trace before full fringe amplitude is reached. In general, it can be seen that the two recordings are quite similar even though the laser seismograph is sensitive to horizontal earth strains and the geophone detects vertical earth motion.

A STABLE SEISMOGRAPH INSTALLATION

The experience gained from this feasibility demonstration suggests that a complete and operational seismograph installation would consist of three mutually perpendicular interferometers. Each interferometer would have the following characteristics.

The light source would be a single frequency, continuous wave, helium-neon laser with a coherence distance of 100 m or more. Such a light source will permit the use of an interferometer with a sensitive leg of 10 to 50 m long and with a reference leg a fraction of a meter in length. The reflector at the end of the sensitive leg can be either a corner cube, for freedom from sensitivity to rotation of the reflector and for ease and stability of alignment, or a flat mirror. Fringe counts due to changes in temperature and pressure of the air in the light paths of the interferometer would be minimized by using a tube evacuated to less than 0.1 mm Hg in the sensitive leg. The air space between the window of the tube and the reflector would be kept as small as possible, probably about 1 mm. The reflector would be mounted on a rigid pier firmly attached to bedrock and not directly connected to the evacuated tube. The air path in the sensitive leg of the interferometer would be made equal to the air path in the reference leg. With this arrangement, any change in air temperature or pressure would affect both legs and no net fringe counts would be recorded.

The return beams from each leg are recombined at the beam splitter, producing two fringe patterns with a 90° phase shift between them. One fringe pattern lies on the laser side of the beam splitter, and the other lies on the

side opposite the reference leg. Separate photomultipliers would monitor the center of the respective patterns to provide the signals necessary for reversible fringe counting. Digital readout with each digit representing a change of $\lambda/4$ or approximately 1.6×10^{-5} cm in the length of the sensitive leg would be derived from the counter. Monitoring the signal magnitude from one photomultiplier would permit interpolation to at least 1/10 of a fringe so that a strain sensitivity of 1×10^{-9} would be achieved with a 16 m long interferometer leg. This compares very well with the Benioff strain seismograph, one version of which provides a trace amplitude of 1.0 mm for a strain of 4.15×10^{-9} .⁽²⁾

INSTRUMENT CHARACTERISTICS

The important characteristic of the light source used in an interferometer seismograph is its coherence distance. The coherence distance is the difference in distance between the light paths in the two legs of the interferometer which exists when the fringe contrast has dropped to zero. This distance is given by

$$D = k\lambda' = (k + 1)\lambda$$

where λ' is the longest wavelength in the light beam, λ is the medium or average wavelength, and k is the number of wavelengths. From the above equation

$$k = \left| \frac{\lambda'}{\lambda - \lambda'} \right| = \left| \frac{\lambda}{\Delta\lambda} \right|$$

In terms of frequency, ν ,

$$k = \left| \frac{\nu}{\Delta\nu} \right| = \frac{C}{\lambda |\Delta\nu|}$$

thus,

$$D = \frac{C}{\Delta\nu} + \lambda$$

where C is the velocity of light.

The multimode helium-neon laser described by Herriot⁽³⁾ has a beam spread, $\Delta\nu$, of about 1 Gc. For such a laser the coherence distance, D , is 30 cm. Thus, the sensitive leg of the seismograph could be not much greater than 30 cm longer than the reference leg.

A single frequency laser has a beam spread of about 10 kc, yielding a coherence distance, D , of 3×10^6 cm, which is more than adequate for this application. No light source other than a single frequency laser has the required coherence distance.

Sensitivity to temperature changes should be negligible in an interferometer seismograph built as described above. Without the evacuated tube in the sensitive leg, however, the sensitivity to changes in temperature is very great. The optical path length of the sensitive leg is nL , where n is the index of refraction of air and L is the geometrical length. Let λ_0 be the wavelength when the index of refraction is then n_0 , then

$$nL = nk\lambda_0 \quad .$$

Taking $L = 16$ m and $\lambda_0 = 0.63 \times 10^{-6}$ m yields

$$k = L/\lambda_0 = 25.4 \times 10^6$$

so a change in index of refraction, Δn , means a change in optical path length of $(\Delta n)(k)$ wavelengths or $(4)(\Delta n)(k)$ fringes.

The variation of index of refraction with temperature and with pressure is given by

$$n_t - 1 = \left(\frac{n_0 - 1}{1 + t/273} \right) \left(\frac{p}{760} \right)$$

where n_t is the index of refraction for temperature t , n_0 is the index of refraction for 0°C , and P the pressure of the gas in millimeters mercury. At atmospheric pressure and near 0°C , the change in index of refraction per degree change in temperature is

$$-\frac{\Delta n}{\Delta t} = \frac{n_0 - 1}{273} \approx 10^{-6}$$

and the corresponding fringe count is

$$(4)(\Delta n)(k) = 102 \text{ fringes.}$$

This large fringe count shows the necessity of using the evacuated tube.

Fringe counts due to pressure changes may be derived from the equation

$$dn = \left(\frac{n_o - 1}{1 + t/273} \right) \left(\frac{dp}{760} \right) .$$

At $t = 0^\circ\text{C}$

$$dn = 4 \times 10^{-7} dp$$

and the fringe count due to a 1 mm Hg change in pressure would be

$$(4)(\Delta n)(k) \approx 41 \text{ fringes.}$$

The interferometer strain seismograph would have a band width with nearly flat response extending from zero frequency to several hundred cycles per second. At the high frequency end the response would oscillate between zero and maximum, depending upon the wavelength of the disturbance. Zero response would correspond to seismic waves with wavelength some multiple of twice the length of the sensitive leg. If the sensitive leg were 16 m long, uniform response would be obtained for all seismic waves having periods greater than about 0.005 sec; this adequately covers the range of interest.

It is interesting to calculate the effect on the interferometer seismograph of a change in radius of the earth such as might occur when the earth is vibrating in its fundamental mode. The calculation assumes that the sensitive leg of the interferometer lies in a horizontal plane. Let the length of the sensitive leg be L and the radius of the earth be R . Then

$$L = R\alpha$$

where α is the angle between the two radius vectors touching the ends of the interferometer leg. Thus,

$$\frac{\Delta L}{L} = \frac{\Delta R}{R} .$$

Taking the strain sensitivity of the seismograph (10^{-9}) for $\Delta L/L$ and 6.3×10^8 cm for the radius of the earth, calculations yield 6.3 mm for the minimum detectable change, ΔR , in the radius of the earth.

POSSIBLE APPLICATIONS FOR THE LASER SEISMOGRAPH

The Benioff strain seismographs have yielded unique and valuable information about the free oscillations of the earth,⁽⁴⁻⁶⁾ earth tides, and other geophysical phenomena. It is believed that the sensitivity, relative compactness, and uniform frequency response of the laser interferometer strain seismograph would supplement and perhaps improve upon the Benioff instruments in these studies. In particular, there may be applications for this instrument in the study of strain buildup as a function of time such as occurs near earthquake fault lines.

An instrument of this type is also readily adaptable to a variety of other measurements. For example, such a device could be used to lay out accurate standard base lines for use in geodetic surveys and would be similar to the Väisälä comparator discussed by Honkasalo.⁽⁷⁾ By compensating for temperature variations, an ultrasensitive barometer could be made or compensation for pressure would yield a sensitive thermometer. Also, by introducing transparent gases into the tube a very accurate determination of their index of refraction could be made.

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