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High Resolution Laser Strainmeter

A new type of laser strainmeter is now operating in a disused railway tunnel at Queensbury, Yorkshire¹. It uses two helium-neon lasers operating at 633 nm, and has extremely high resolution and linearity. The frequency of one laser, called the slave laser, is locked to the length of a Michelson interferometer attached to the ground. The other laser, used as a reference standard, is stabilised by saturated absorption in iodine vapour²⁻⁵. A similar system has been reported by Levine and Hall⁶ using helium-neon lasers operating at the infrared 3.39 μm wavelength. For practical reasons it is easier to use visible light.

The evacuated Michelson interferometer has a long arm of 55 m, a short arm of 10 cm, and is illuminated by the slave laser. The mechanical and optical details of the interferometer have been described^{7,8}. The slave laser frequency is locked to the length of the interferometer by holding one fringe at the output of the interferometer through the application of a correction voltage to the piezoelectric transducer on which one laser mirror is mounted. The relationship between the frequency ν of the laser and the strain ϵ in the Michelson interferometer is

$$\nu = \nu_0(1/\epsilon) = \nu_0(1 - \epsilon + \epsilon^2 - \epsilon^3 + \dots)$$

where ν_0 is the laser frequency when the strain is zero.

Fig. 1 Earth tides recorded by the laser strainmeter using an iodine absorption stabilised laser.

The light output from the slave laser is optically mixed with light from a frequency-stabilised reference laser to give a beat frequency equal to the difference in frequency between the two lasers. This is recorded digitally and on an analogue chart recorder. In the recording system the beat frequency is divided by 10^4 , and then enters a frequency counter which counts for 100 s every 2 min. Timing is provided by a crystal clock, and the least count corresponds to 2×10^{-13} strain. The resolution could clearly be increased to 2×10^{-17} strain, without altering the counting period, by omitting the divider and feeding the beat frequency directly into the counter. Increasing the length of the interferometer long arm would not change the resolution, although it would reduce the effect of errors introduced by poor coupling of the strainmeter mounts to the ground. Either of these changes could easily be made if required.

The beat frequency is constrained to remain between 10 and 90 MHz, which corresponds to a strain range of approximately

1.7×10^{-7} . When the beat frequency reaches either end of the range the slave laser frequency is stepped to bring the beat frequency back to the middle of the range. This extends the measurable range of strain even up to values which would mechanically damage the instrument. Theoretically, then, the relationship between laser frequency and strain is linear to less than 3×10^{-14} strain. This corresponds to a percentage non-linearity of $1.5 \times 10^{-5}\%$, which is much superior to that provided by any analogue system. In our instrument the linearity is, in practice, limited by the finite gain round the servo loop locking the slave laser frequency to the interferometer length. In principle this non-linearity could be reduced below the theoretical level.

The reference laser used in the system is one stabilised by saturated absorption in iodine vapour. Its frequency stability is better than 8×10^{-12} for the 100 s averaging time used in the beat frequency measurement^{4,5}.

A tidal record for two days is shown in Fig. 1 and there seems to be a relatively small amount of drift. Figure 2 shows a section of the record at high resolution. The record contains frequencies characteristic of microseisms at a reasonable amplitude.

Fig. 2 Record at high resolution using the iodine absorption stabilised laser. Traced from the original chart recording.

This laser strainmeter will be used to study Earth tides and free oscillations of the Earth. The important features of the instrument are the high digital resolution and its exceedingly good linearity. These are very important when studying small signals in the presence of large signals of different frequencies. For example, the cusping of tidal peaks in frequency spectra^{1,9-11} may be due to real Earth effects, but it could equally be attributed to non-linearities in tide-measuring instruments.

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N. R. GOULTY
G. C. P. KING

Department of Geodesy and Geophysics,
University of Cambridge

A. J. WALLARD

Division of Quantum Metrology,
National Physical Laboratory,
Teddington, Middlesex

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