A laser walk-off sensor for high-precision low-frequency rotation measurements

Cite as: Rev. Sci. Instrum. 90, 045005 (2019); https://doi.org/10.1063/1.5088733
Submitted: 14 January 2019 . Accepted: 09 April 2019 . Published Online: 25 April 2019

J. J. McCann, J. Winterflood, L. Ju, and C. Zhao

ARTICLES YOU MAY BE INTERESTED IN

A 4-channel, vector network analyzer microwave imaging prototype based on software defined radio technology
Review of Scientific Instruments 90, 044708 (2019); https://doi.org/10.1063/1.5083842

An open and flexible digital phase-locked loop for optical metrology
Review of Scientific Instruments 89, 093103 (2018); https://doi.org/10.1063/1.5039344

A pressure-tuned Fabry Pérot interferometer for laser frequency stabilization and tuning
Review of Scientific Instruments 89, 093107 (2018); https://doi.org/10.1063/1.5045475
A laser walk-off sensor for high-precision low-frequency rotation measurements

Cite as: Rev. Sci. Instrum. 90, 045005 (2019); doi: 10.1063/1.5088733
Submitted: 14 January 2019 • Accepted: 9 April 2019 • Published Online: 25 April 2019

J. J. McCann, a) J. Winterflood, L. Ju, and C. Zhao

AFFILIATIONS
ARC Centre of Excellence OzGrav, UWA Node, The University of Western Australia, Perth, WA 6009, Australia

a)mccannj@iinet.net.au

ABSTRACT
We present an optical walk-off sensor with an angular sensitivity of a few nrad/√Hz above 1 mHz and 0.4 nrad/√Hz above 100 mHz. This experiment furthers previous research into the walk-off sensor capabilities through an improved input laser, reduction in air optical travel length, and position control on photo-diodes. The angle change measured in this walk-off scheme features a knife edge to split the beam into two separate fiber coupled photo-diodes to minimize power dissipation in the thermally sensitive region. Using this photo-diode power differential as an error signal, a simple control scheme is used to maintain the balance position, increasing common mode rejection and improving dynamic range by mitigating thermal drift. The in-vacuum component of the optical readout takes up a volume less than $100 \text{ mm} \times 100 \text{ mm} \times 50 \text{ mm}$. This experiment shows that the walk-off sensor provides a simple and compact readout scheme with nanoradian sensitivity for angle sensing at low frequencies.

Published under license by AIP Publishing. https://doi.org/10.1063/1.5088733

I. INTRODUCTION
The need for low-frequency high-precision angle sensing became apparent when low frequency ground rotation was identified as a contributing noise source at the two advanced laser interferometer gravitational wave observatories (LIGO) located in Hanford and Louisiana, USA. Scientists of the LIGO Scientific Collaboration (LSC) developed requirements for ground rotation sensing needed to help improve the LIGO isolation systems. This spurred international research into instruments capable of measuring ground rotation at or below the specified requirements. These instruments are known as ground rotation sensors or tiltmeters.

One of the more common designs of a tiltmeter/ground rotation sensor is in the form of a beam balance. The beam balance is designed such that the beam does not follow the ground excitation above its resonant frequency. This allows the rotation to be measured between the bar and the rotating ground. To measure this angle change, various readout setups have been designed. Angle readout schemes used in the past include capacitive, inductive, and optical sensing. It has been noted that capacitive sensing has three major difficulties: nonlinearity and capacitive drift between conductive surfaces and strong spurious forces which can pollute actuation. Inductive sensing is performed through the use of linear variable differential transformers (LVDTs). While providing high precision measurements the LVDT can be susceptible to thermal drift at low frequencies.

One of the simplest forms of optical angle sensing is the optical lever which dates back to 1826. Since its discovery, much progress has been made to improve angle sensing using the principles of the optical lever. The recently developed ground rotation sensor known as the Beam Rotation Sensor (BRS) by the University of Washington utilises one such device referred to as an autocollimator. The autocollimator readout design achieved nrad/√Hz sensitivity above 5 mHz but at 60 cm in length is less suitable for more compact tiltmeters. Interferometer style optical readouts are also being researched, while they provide a more compact readout, the scheme comes with the difficulty of measuring the distance change at either end of the bars which could be subject to large common mode motion. In contrast to the interferometer, both the walk-off sensor (WOS) and auto collimator have no large common mode motion effect that must be carefully rejected making them somewhat simpler.

The WOS is a unique readout scheme which has previously been demonstrated for higher frequencies in a tiltmeter developed at The University of Western Australia (UWA) producing a sensitivity of 10 nrad/√Hz above 1 Hz. Similar to the autocollimator,
the WOS is an extension of the optical lever and utilises multiple bounces to improve sensitivity. It was noted in a previous paper by UWA regarding the tiltmeter that the WOS is a trade-off between sensitivity and dynamic range. The sensitivity is inversely proportional to the dynamic range. Additionally, it has been suggested that further improvements could be made to the WOS sensitivity by improving laser jitter noise.

This paper focuses on results achieved by an experiment conducted to improve the WOS sensitivity, dynamic range, and overall design. The focus is on its sensitivity at lower frequencies while aiming to meet the requirements set by the LSC for advanced LIGO. The requirements for ground rotation sensing are given in Table I. Section II describes the theory of the optical lever improvements made through the WOS design. Section III describes the experimental setup and method used to achieve the results detailed in Sec. IV. A noise budget for the sensor is shown in Secs. V and VI, which gives future recommendations for improvements and uses of the sensor. This WOS is being designed for use in a new low frequency ground rotation sensor (tiltmeter) under development at UWA.

II. BACKGROUND / THEORY

As previously mentioned, the WOS scheme acts similar to a simple optical lever, with a laser reflecting to a split photodiode (PD) in which the angle change can be measured from the laser position change in the split PD. The difference is that instead of one mirror there are two mirrors used. The light bounces between the two mirrors N times in a parabolic path before exiting to the split PD, see Figs. 1 and 2. These N bounces amplify the angle and in turn the position change of the outgoing beam. In order to achieve the parabolic path shown and desired number of bounces, the mirrors must have an initial angle offset, Fig. 3, and the incident angle of the incoming laser must be set to the slope of the parabola desired. An angle change in one of the mirrors is seen as a position change of the outgoing beam. This position and in turn angle change is measured by the power difference in each side of the split PD. In this experiment, the split PD is replaced by a knife edge as detailed in Sec. III but the concept and calculations remain the same.

In order to compare the optical lever to the WOS, the sensitivity calculation can be split into two components: the optical lever component and the WOS amplification component. These can then be multiplied to produce the final sensitivity of the setup.

A. Optical lever

To calculate the optical lever sensitivity, the length of beam travel and beam diameter must first be calculated. To calculate the beam diameter, it is necessary to take the beam waist, Rayleigh length, and maximum waist length into account since this setup utilizes fiber lasers and collimators as detailed in Sec. III. The length of the beam travel is approximately

\[ L \approx 2Nh + L_o + L_i, \]

where \( h \) represents the distance between mirrors, \( L_o \) is the input laser distance, and \( L_i \) is the output laser distance, see Fig. 3.

Assuming a Gaussian intensity distribution, the angle sensitivity of the optical lever, illustrated in Fig. 4, is then calculated as

\[ \frac{\Delta V}{\alpha} = \frac{\sqrt{2} \pi P_i LR(\lambda)G}{w(L)}, \]

TABLE I. Ground rotation requirements set by the LSC to improve isolation of advanced LIGO.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Angular displacement (rad/√Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>( 3 \times 10^{-10} )</td>
</tr>
<tr>
<td>0.2</td>
<td>( 6 \times 10^{-9} )</td>
</tr>
<tr>
<td>0.5</td>
<td>( 1 \times 10^{-10} )</td>
</tr>
</tbody>
</table>
where $\alpha$ represents the angle change, $P_{\text{L}}$ represents the power of the laser at the knife edge, $R(\lambda)$ represents the responsivity of the PDs used after the knife edge, $G$ represents the transimpedance gain of the photodetector differential output, and $w(L)$ represents the beam radius at the distance $L$.

**B. Walk-off sensor**

The advantage of the WOS over the optical lever is that the change in distance on the PD caused by an angle change is amplified due to the bounces between the two mirrors. Increasing the number of bounces increases this amplification but is an optimization problem limited by the reflectivity of the mirrors as shown in Fig. 5.

![FIG. 4. Simple optical lever showing change in laser position on a PD, where $L$ is the length of the laser travel, $\Delta x$ is the position change on the PD, and $\alpha$ is the angle change of the laser.](image)

At a certain number of bounces, the power loss due to reflectivity of the mirrors causes a drop in amplification. The change in displacement on the PD is calculated using basic geometry as shown in Fig. 6 and is given by

$$H = 2\alpha(N + 1)(hN + L).$$

The amplification of angular sensitivity of the WOS provided on the optical lever is then calculated to be

$$\frac{\Delta V_{\alpha}}{\alpha} = \frac{2(N + 1)(hN + L)_L}{\gamma} \frac{\Delta V_{\alpha}}{\alpha},$$

where $\gamma$ represents the reflectivity of the mirrors.

**III. EXPERIMENTAL DESCRIPTION**

The experimental setup of the WOS is shown in Fig. 7. The light source is a 635 nm fiber coupled laser with a single mode fiber cable feeding to the input collimator. A fiber laser reduces laser jitter noise, a possible limiting factor in the previous WOS.
The beam travels in free air taking the parabolic path as it bounces between the two mirrors. The mirrors used are fused silica broadband dielectric with a reflectivity of 99.43% at 635 nm. In this experiment, the outgoing laser is directed at a knife edge prism mirror which splits the light into two separate collimators. This is an alteration of the previously mentioned split PD. The angle change in the mirrors moves the beam across the knife edge changing the power split to each collimator. Each collimator directs the laser down a multimode fiber cable to a PD. The use of a knife edge as opposed to a split PD is to reduce the heat dissipation of the PDs which could increase thermal drift in the tiltmeter. The knife edge allows the light to be directed away from the setup through the collimators and fiber cables before hitting the PDs. The PDs are packaged with a balanced differential amplifier (PDB450A by thorlabs) which amplifies the differential between the two diodes by a selected gain. The output power of the laser was 1 mW which resulted in approximately 0.25 mW at the knife edge due to losses in the single mode fiber and the reflectivity of the mirrors. Based on the reflectivity specified for the mirrors used, the optimum number of bounces, as shown in Fig. 5, is 76. Since this was challenging to achieve using traditional mirror holders, the highest number of bounces used was 30. The parameters of the experimental setup are found in Table II.

There are two feedback control loops utilized to improve the WOS. The first is laser intensity feedback in which the two PDs are summed, and using an amplifier with low pass filter as an approximate integral controller, the laser intensity is stabilized by feeding the control signal back into a modulation input on the fiber laser. The second control loop was used to keep the differential PDs balanced at all times. This was achieved using a galvanometer. The position control not only allows a large dynamic range since the beam cannot walk-off the knife edge but also provides a simple means of balancing the two PDs to produce the best possible common mode rejection. To find the optimum balance point, a 3 Hz disturbance signal was at its lowest indicating that common mode rejection was then measured, and the setpoint altered until the integral was introduced into the laser modulation. The spectrum of the disturbance signal was obtained using the experimental parameters given in Table II with Eqs. (3) and (4) and found to be 2.39 × 10⁻⁵ V/Hz. Additional measurements and calculations were conducted to quantify the noise budget of the sensor.

### Angle sensitivity

The angular sensitivity of the 30 bounce setup was measured as a change in voltage seen at the PD differential, divided by the angle change in radians. The voltage change to a 4.9 × 10⁻⁵ rad angle change was 0.74 V. This resulted in an angle sensitivity of 1.6 × 10⁻⁵ V/rad. The theoretical angle sensitivity was calculated using the experimental parameters given in Table II with Eqs. (2) and (4) and found to be 2.39 × 10⁻⁵ V/Hz. The experimental result is approximately 3.5 dB lower than the theoretical calculation. The incoming power to the WOS mirrors was measured along with the power before the knife edge. The reflectivity of the mirrors was checked through the power loss and found to be 99.43% which was in turn used in the theory calculation. Therefore, the loss in sensitivity is presumed to be from power loss at or after the knife edge.

### Noise floor

The noise floor of the WOS was then measured over a period of 5 h with multiple averages. Using this result and the angle sensitivity measured above, the noise floor in rad/√Hz was plotted, see Fig. 8. A sensitivity of a few nrad/√Hz above 1 mHz and 0.4 nrad/√Hz above 100 mHz was achieved. However, the use of position control extends the dynamic range since the beam cannot walk-off the knife edge.

### V. NOISE BUDGET

A number of noise sources affect the WOS. As mentioned in the previous WOS experiment, jitter noise was a limiting noise source.¹

---

### TABLE II. Parameters used in the WOS experiment.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>30</td>
</tr>
<tr>
<td>h (m)</td>
<td>0.0045</td>
</tr>
<tr>
<td>L₀ (m)</td>
<td>0.03</td>
</tr>
<tr>
<td>L₁ (m)</td>
<td>0.1</td>
</tr>
<tr>
<td>w(L) (m)</td>
<td>0.00036</td>
</tr>
<tr>
<td>R (A/W)</td>
<td>0.4</td>
</tr>
<tr>
<td>G (V/A)</td>
<td>10⁵</td>
</tr>
<tr>
<td>λ (nm)</td>
<td>635</td>
</tr>
<tr>
<td>y (%)</td>
<td>99.43</td>
</tr>
<tr>
<td>P₁ (mW)</td>
<td>0.259</td>
</tr>
</tbody>
</table>

---

### FIG. 8

Sensitivity of the WOS with 30 bounces and in air shown with the averaged sensitivity of the results in comparison to the rotational sensing requirements for advanced LIGO.
This was mitigated by using a fiber coupled laser and collimators. However, the use of fiber comes with the additional noise source of cladding modes. This was mitigated by the standard technique of coiling the fiber cables to disperse the cladding modes before they reach the output.

Intensity noise was also seen in the WOS and as detailed earlier was somewhat reduced by a simple feedback control. The calculated effect of the remaining intensity noise is shown in Fig. 9. The effect of the intensity noise was calculated by first measuring the intensity noise of the laser with both control loops on. Since the position control keeps the common mode rejection ratio CMRR at its maximum, the effect of the intensity noise according to the specifications of the PDB450A should be reduced by approximately −55 dB. It can be seen that the intensity noise may still be affecting the sensitivity around 15 mHz and below, and this will be addressed in Sec. VI. Some of the more difficult noise sources to distinguish include air currents, air pressure, and thermal effects. An attempt to minimize these effects was made by the use of a thermal insulation box which was placed over the experiment. However, no noticeable improvement was seen, and as expected the most suitable option to reduce these noise sources requires the WOS to be installed in a vacuum. This will be discussed further in Sec. VI. The electronic noise was also measured by blocking light to the PDs. This and the calculated shot noise are also shown in Fig. 9.

VI. FUTURE WORK

The first improvement necessary for sensitivity improvement is to put the sensor and the tiltmeter into a vacuum. This would remove air current and air pressure noise while significantly decreasing thermal drift noise. As stated in Sec. III, the sensitivity of the WOS is affected by the reflectivity of the mirrors and the number of bounces. The purchase of higher reflectivity mirrors and optimizing the number of bounces would both help to improve the sensitivity. The intensity noise shown in Fig. 9 is currently an issue below 15 mHz and will most likely become an issue at higher frequencies once the setup is in a vacuum. This noise can be further reduced by increasing the feedback gain through alternative servo electronics. This noise could also be mitigated by purchasing a laser with lower intensity noise, although this option is less cost effective. As the noisefloor is reduced further by the methods detailed above, the
electronic noise may come into view. The electronic noise is currently set by the photodetector amplifier used but a lower noise PD amplification circuit could be designed if necessary. While the WOS is not currently below the requirements set for advanced LIGO at all frequencies, the improvements listed above will make the sensor capable of measuring at or below these requirements. A mechanical design for a compact version with dimensions less than 100 mm × 100 mm × 50 mm has been drawn and will be manufactured along with components for the UWA tiltmeter. One difficulty of this design was ensuring the correct adjustment of appropriate degrees of freedom for the mirrors and collimators to keep alignment simple. An additional improvement in the mechanical design is the ability to increase to the optimum number of bounces which will improve the sensitivity slightly. A drawing of the mechanical design of the sensor is shown in Fig. 10.

VII. CONCLUSION

An experiment was conducted on the walk-off sensor to quantify its sensitivity at low frequencies and in turn its potential use as a ground rotation readout scheme in a tiltmeter. It was shown that by using a fiber coupled laser to decrease jitter noise, laser intensity noise control, and position control for improved common mode rejection, the walk-off sensor achieved sensitivities of a few nrad/√Hz above 1 mHz and 0.4 nrad/√Hz above 100 mHz. The use of the position control has also shown to mitigate thermal drift effects which would have previously caused the setup to go beyond its range. The walk-off sensor has been shown to provide high sensitivity angle measurement at low frequencies with a simple and compact design.

ACKNOWLEDGMENTS

The authors of this paper would like to thank Bram Slagmolen, Australian National University, and David Blair, UWA, for many helpful discussions around possible noise sources and the overall experiment. The authors would also like to thank Masters students: Corey Berryman and Yan Liu for their assistance in the experiment. This project was conducted at the University of Western Australia and funded by the ARC Center for Excellence for Gravitational Wave Discovery (Grant No. CE170100004).

REFERENCES