

Water Resources Research



RESEARCH ARTICLE

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Key Points:

- We describe a new noncontact lidar prototype to measure river water level
- The prototype can take measurements under a range of environmental conditions, to ~35 m range, and to inclinations of ~40°
- Lidar has the potential to enrich the observational database in data-scarce regions globally

Supporting Information:

- Supporting Information S1

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A Technical Evaluation of Lidar-Based Measurement of River Water Levels

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Abstract Measuring river water level (stage) is key for a variety of applications including discharge estimation and flood prediction. Although a variety of in situ and noncontact methods are available, there is an urgent need for new and more cost-efficient methods. Rapid technological progress has accelerated the use of noncontact methods and development of time-of-flight distance sensors. Among available techniques, the use of lidar for distance measurement is promising because of its low cost, high energy efficiency, and small measurement footprint. However, lidar has rarely been used to measure water levels. Here we test a near-infrared (905 nm) lidar sensor to determine its suitability for stage measurements under a range of environmental conditions. Using different laboratory and field setups, we assess sensor performance as a function of measurement distance, surface roughness, air temperature, water turbidity, and measurement angle. Despite the low reflectivity of water for infrared radiation, we find that the tested sensor is able to take measurements under all tested conditions, up to an incidence angle of ~40°. The accuracy of the sensor is within the technical specifications of the device and is characterized by a relative error of around 0.1%. We find a strong dependence of the accuracy on sensor temperature, which we attribute to suboptimal internal compensation of the electronics. The precision of the sensor decreases with increasing measured distance and increases with surface roughness of the water body. We did not find any significant impact of water turbidity on the measurements.

1. Introduction

1.1. Noncontact Methods to Measure River Stage

Accurate monitoring of water levels is an essential component of hydrological practice, informing, for instance, flood-risk management systems, groundwater resource planning, and irrigation control systems. However, despite the wide range of available methods, the global density of river gauging stations is still well below the operational optimum, even in densely gauged countries. Many existing records are fragmentary, and inconsistent formats and a lack of metadata are a recurring problem in many places (Hannah et al., 2011). Although bottlenecks to river gauging are manifold, technical innovations may help to reduce the required resources to obtain accurate measurements and therefore to increase the density of the river gauging network. This is particularly relevant in data-scarce regions where increases in the affordability, access, and automation of monitoring technology has the potential to create a step change in data collection (Alabyan et al., 2016; Hund et al., 2016; Paul et al., 2018).

Noncontact methods for river level (stage) monitoring are increasingly deployed. Whereas in situ methods such as pressure transducers are prone to fouling and damage from extreme events, noncontact methods provide greater flexibility for installation in safe and more convenient locations. Various technologies are used for such ground-based water level sensing, but the majority of current operational systems are based on measuring the time of flight of ultrasound and radar wave pulses, reflected on the water surface. While ultrasonic systems emit acoustic waves (typically 20–200 kHz) from a transducer that also measures the reflections, radar sensors typically emit a stream of pulses in the microwave spectrum (1–100 GHz). In both setups, the recorded transmission time is converted into a distance that is precise to a few millimeters (e.g., Boon & Brubaker, 2008). Currently, approximately 5% of the U.K. Environment Agency's National River Flow Archive stations employ ultrasonic or, more recently, radar sensors to measure river levels at 15-min intervals (Environment Agency (UK), 2018).

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1.2. Lidar Distance Sensing (ranging)

Lidar-based distance sensing is a commonly applied method, for instance, in the context of digital terrain mapping (Höfle et al., 2009; Liu et al., 2005; Özcan & Ünsalan, 2017). The principle of lidar ranging relies on the rugosity of the reflective surface to generate nonspecular reflection (i.e., scattering) of the incipient laser beam. As with radar, lidar ranging measures time of flight, but it uses higher frequency waves for greater pulse intensities. Near-infrared (NIR) light is most commonly used for this purpose, typically over wavelengths of 900–1,100 nm (270–330 THz) due to the low cost of lasers operating in this wavelength range and lower energy density than the visible spectrum (Fernandez-Diaz et al., 2014; Smart et al., 2009).

The accuracy of lidar distance sensing is determined by two technical characteristics: the pulse width and the accuracy of the method that measures the time of flight. Narrowing the pulse width improves the accuracy but requires a higher pulse power and therefore a more powerful laser. Currently available systems use pulse widths of 0.5 μ s in a 50% duty cycle (i.e., when the system is active 50% of the time: Laser Technology Inc. (LTI), 2014; Garmin, 2016). Similarly, measurement precision can be improved through increasing pulse power, narrowing the pulse width, and widening the bandwidth of the receiver, which ensure that the receiver channel is able to react to the laser pulse with full amplitude and lower noise levels.

The precision of the time-of-flight measurement is determined by the internal timer, which measures the time delay between emitted and received laser pulses (Kilpela et al., 2001). Timer precision is improving rapidly with advances in the sophistication of micro-oscillators and time-to-digital converters, from an order of 10 ns in 2001 to picoseconds more recently (i.e., an improvement of up to 10^4 : Coddington et al., 2009; Kilpela et al., 2001). In state-of-the-art time-of-flight ranging systems, atomic clocks of well-defined radiofrequency standards, for example rubidium, offering femtosecond precision, are commonly used (e.g., Lee et al., 2010).

However, the application of lidar as a static, in situ method to observe water level is little explored. A proof-of-concept is reported by Tamari and Guerrero-Meza (2016), but they provide few technical details. The major difference with terrestrial lidar applications is the lower reflectivity of water surfaces for infrared radiation compared to solid objects. A calm water surface may behave as a purely specular surface, which produces reflections instead of dispersing incipient energy. This means that the reflected beams often miss the receiver altogether, especially in longer distance airborne surveys, unless viewed from normal incidence (Allouis et al., 2007; Fernandez-Diaz et al., 2014; Liu et al., 2005). In practice, a flat and mirror-like river surface still reflects ~ 2 –3% of an incident beam of infrared radiation, while the remainder is transmitted through the water (Figure 1a; Guenther, 1986; Milan et al., 2010). Additionally, in most conditions the reflectivity of a water surface will be higher because of the rugosity. This may open the possibility to using lidar as a method to measure water levels and their variations.

The laser power received from the water surface as a function of time t , $P_s(t)$, is as follows (Allouis et al., 2007; Pfeifer et al., 2008):

$$P_s(t) = \frac{\rho P_r(t) T_{atm}^2 \eta_r \eta_t A_r \cos^2(\theta_0)}{\pi t^2}, \quad (1)$$

where ρ is the reflectance at the air/water interface; $P_r(t)$ is the power of the transmitted laser pulse; T_{atm}^2 is the transmission coefficient of the atmosphere; η_t and η_r are the optical transmission and reception efficiencies, respectively; A_r is the area of the receptor; θ_0 is the incidence angle of the sensor; and L is the distance of the sensor from the water surface. Based on equation (1), the water surface reflectance ρ can be calculated (Pfeifer et al., 2008). Milan et al. (2010) followed this procedure to produce reflectance curves as a function of laser light wavelength for different concentrations of suspended sediment (Figure 1b). At 905 nm, which is the wavelength of many commercially available rangefinders, reflectance is below 10% but increases as a function of suspended sediment concentration.

Here we report on laboratory and field tests to determine the performance of lidar to assess its potential as a hydrometric technique under different environmental conditions. We use a commercially available system operating in the NIR spectrum (905 nm), which is representative of currently available systems (section 2). In section 3, we outline the results of laboratory testing, as well as field experiments on the River Thames and other water courses around London, UK. Section 4 contains conclusions and a brief statement of future work.

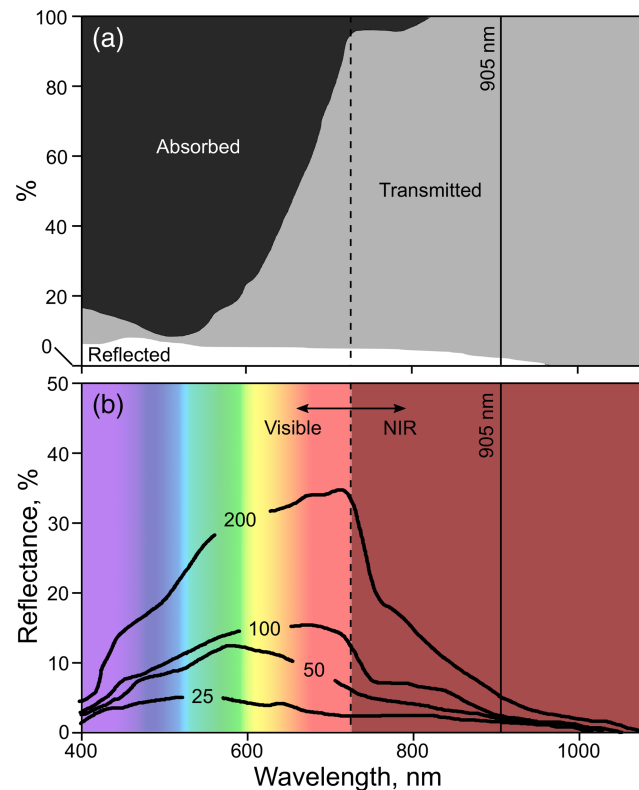


Figure 1. (a) Spectral character of clear still water as a function of laser wavelength (Lednev et al., 2013; Milan et al., 2010). (b) Influence of suspended sediment concentration (curves: units of mg L^{-1}) in river upon reflectance (after Milan et al., 2010).

2. Methodology

We conducted our tests with a Garmin Lidar Lite rangefinder sensor (Garmin, 2016), operating at 905 nm, which was connected to a self-built data logger. The rangefinder has an internal measurement frequency of 10–20 kHz; peak laser power is 1.3 W, and the energy per measurement pulse is <280 nJ. Full specifications are given in Table 1. At the time of writing the rangefinder sensor is available for ~£120 (US\$130). The sensor uses the time-of-flight principle described above: it sends out pulses with a coded signature and searches for matching signature in the returned pulses. The time measurement is carried out using an integrated time-to-digital converter with a resolution of 50 ps. The sensor then performs internal averaging over all signature-matching acquisitions until the signal peak in the correlation record reaches a maximum value. If this does not happen or the signal peak is below a threshold (calculated from the level of ambient noise), then the sensor does not return a measurement (Garmin, 2016). These measurements can be repeated with a typical frequency of 50 and up to 500 Hz. We connected the sensor to an Arduino-based datalogger (for further details see supporting information).

Table 1 Specifications of Garmin Lidar Lite laser (Garmin, 2016)	
Specification	Measurement
Wavelength	905 nm
Total laser power (peak)	1.3 W
Energy per pulse	<280 nJ
Mode of operation	Pulsed (256 pulses per train)
Pulse width	0.5 μs (50% duty cycle)
Pulse train repetition frequency	10–20 kHz
Beam divergence	8 mRad ($\sim 0.46^\circ$)

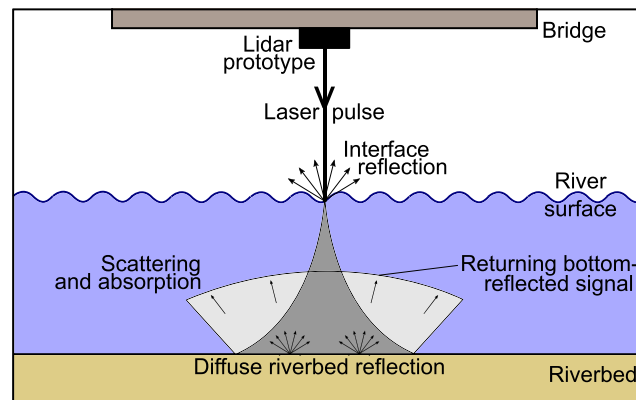


Figure 2. Schematic of lidar prototype experiment, where it is clamped to the underside of a bridge to measure river stage.

We programmed the logger to take 10 consecutive readings over a period of 5 ms. These were repeated every second to construct time series, which were averaged to evaluate the impact of varying environmental conditions. Measurements were stored on an SD card. The lidar and logger were housed in a waterproof box with a clear polycarbonate lid. Polycarbonate is largely transparent to NIR (transmission coefficient of 905 nm light ~ 0.90 ; Wydeven, 1977); our setup did not enable us to quantify absorption of NIR light. Figure 2 shows a typical outdoor experimental setup.

We performed the following tests:

- Effect of sample size. To eliminate the potential influence of measurement autocorrelation, we first determined the number of measurements required to take an average with minimum bias. For this test, we ran the sensor at a frequency of 250 Hz to measure a distance of 2 m.
- Effect of distance from water. We moved the sensor vertically along a metal pole above a tank with a smooth water surface relative to outdoor conditions (rugosity estimated by eye of < 1 cm) and measured at 1-m intervals for the range of 0–10 and 5-m intervals for the range of 10–40 m.
- Effect of water turbidity. We added quantities of kaolin and montmorillonite clay to the water (per Bhargava & Mariam, 1990). Although laser reflectance was not measured quantitatively, we calculated the standard deviation and measurement bias between the actual and measured distance (e.g., Bhargava & Mariam, 1991).
- Effect of inclination. We measured the bias and data variance by varying the angle at which the sensor was clamped in steps of 10° increments from 0° (i.e., normal incidence) to a maximum of 60° . Again, measurements were taken, at each inclination, for 1 hr. This test was implemented both in laboratory and in field conditions. In the laboratory, the vertical distance to the water surface was 2 m. In the field test, the distance between sensor and water surface was held constant at 6.3 m as sensor inclination was varied.
- Effect of ambient temperature. We conducted a series of tests in laboratory conditions, in which the sensor was alternately heated by hot air from an industrial welding unit and cooled in a refrigerator or freezer and allowed to return to room temperature. We heated the sensor with hot air to temperatures of $\sim 90^\circ\text{C}$ (greater than the maximum operational temperature of most electronic components of 85°C) and cooled it down to -20°C in a freezer. We recorded both the measured distance and temperature while the logger adjusted back to room temperature, in order to cover the full temperature range.
- Effect of water surface rugosity. The sensor was tested at four outdoor locations in Greater London (i.e., the River Lea at Tottenham, the Serpentine Lake in Hyde Park, and the River Thames at Battersea and Teddington Lock). In each location rugosity (i.e., surface wave amplitude) was estimated by eye.

3. Results and Discussion

3.1. Sample Size and Autocorrelation

First, we determined the required sample size to eliminate the effect of autocorrelation in the measurement bias. The deployed sensor has a built-in receiver bias correction mode, which results in slower

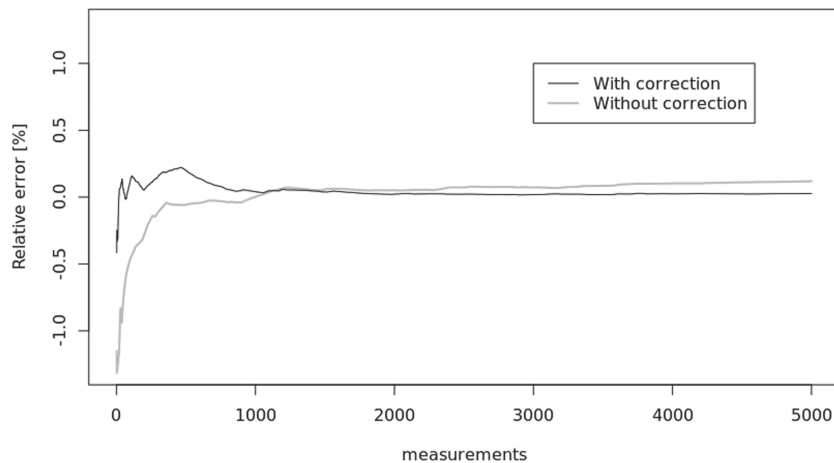


Figure 3. Variation of relative measurement error with number of measurements in sample. The distance from the sensor to target was 2.00 m; measurement frequency ~ 250 Hz.

measurements. When the receiver bias correction mode is enabled, we find that the bias rapidly converges to a value within the specification of the sensor (i.e., 1%; Figure 3). Without bias correction, the convergence takes longer but is also within the specifications for all but the smallest number of measurements. These results suggest a lack of instrumental drift over the course of the test. They also imply that, with bias correction, a sample size of far fewer than 100 measurements is acceptable for operational practice, yielding a relative measurement error of $<0.3\%$.

3.2. Measured Distance

We find that the absolute measurement bias of the tested sensor increases with distance (especially beyond 15–20 m), but the percentage error remains roughly constant, which suggests a proportional error of 0.1% (i.e., between the mean measurement and the real distance: Figure 4). This implies that there is very little inherent systematic bias in the device.

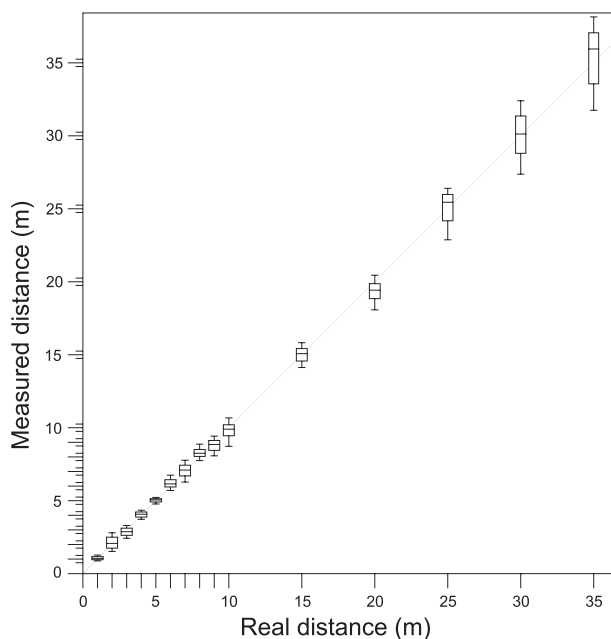


Figure 4. Measured versus actual distance. Minor ticks either side of each y-axis major tick = ± 1 cm measured distance, corresponding to vertical scale of box plots. Whiskers span entire range of dataset. Each box plot represents 500 readings.

Our results fall within the sensor specifications, which state that the accuracy is ± 2.5 cm for measurements of less than 5 m, and ± 10 cm for measurements of more than 5 m (Garmin, 2016). No measurements were returned (i.e., no reflections received) at 40-m distance; accuracy is ~ 1 cm for measurement distances <10 m and no greater than 3 cm for distances of up to 30 m (i.e., relative error $<0.1\%$).

3.3. Turbidity

Bhargava and Mariam (1990) and (1991) studied the relationship between reflectance and water turbidity using kaolin and montmorillonite clay, showing that reflectance increases linearly with turbidity for both materials within an incident light wavelength range of 500–1,000 nm. However, we do not find an impact of water turbidity on the bias and variance of the measurements (Figure 5). This suggests that the receptor is sufficiently sensitive to take adequate measurements under conditions of low reflectance and that a higher reflectance does not improve the reading.

3.4. Rugosity

The water surface roughness (rugosity) also has a theoretical impact on the intensity and number of lidar returns from the air-water interface (e.g., Allouis et al., 2007; Bhargava & Mariam, 1990). We chose four field sites with different surface rugosity, which was estimated by eye to test the impact of rugosity in field conditions. Our installations were temporary (<12 -hr measurement); potential issues arising from extended or permanent installations (e.g., interference from dust, vegetation, insects or meteorological effects like fog or high winds) are not considered here.

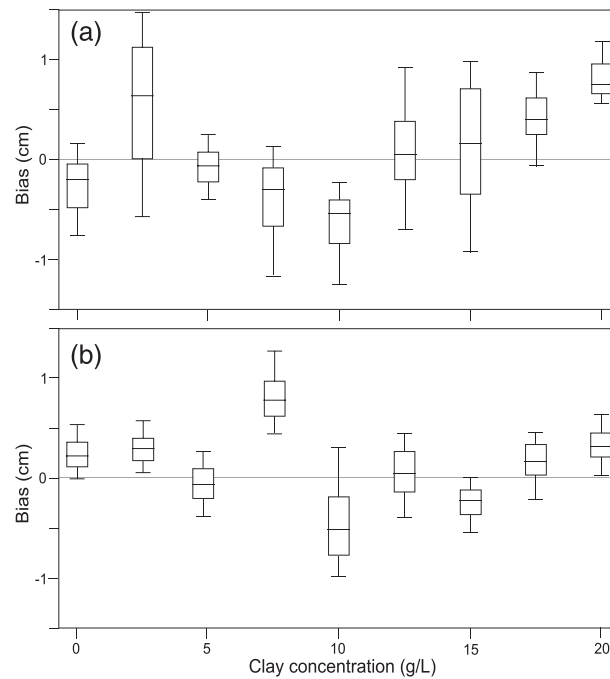


Figure 5. Results of turbidity tests using (a) montmorillonite and (b) kaolin. Box plots show measurement bias (from a vertical distance of 2 m) as a function of clay concentration. Whiskers span entire range of dataset.

Our test results show that a higher water surface rugosity decreases the variance of the measurements (Figure 6). The variance obtained at the River Lea (rugosity of <1 cm) is 8.2 cm (Figure 6a), which reduces to 1.7 cm at the more turbulent River Thames (rugosity of ~ 5 cm). When the sensor is inclined, a diffuse surface will cause incipient laser energy to disperse uniformly, while a smooth, specular surface will mainly reflect energy. However, in this case, the laser beam is perpendicular to the water surface. It is therefore more probable that, for more specular water surfaces, a greater proportion of incident radiation will be absorbed by (and transmitted through) the water (as opposed to being reflected back to the sensor: Figure 2a).

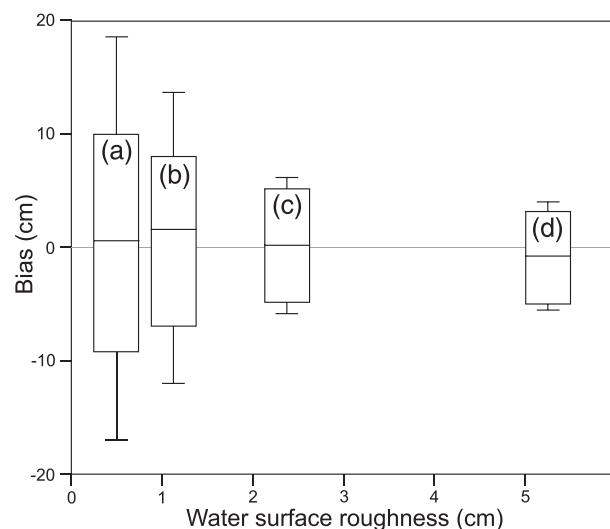


Figure 6. Effect of water surface rugosity on measurement bias at four locations in Greater London, UK: (a) River Lea, Tottenham (distance from sensor to water surface = 3.6 m; rugosity = ~ 0.5 cm); (b) Teddington Lock, River Thames (distance = 4.2–8.3 m; rugosity = ~ 1 –1.5 cm); (c) Serpentine Lake, Hyde Park (distance = 6.2 m; rugosity = ~ 2.5 cm); (d) River Thames, Battersea (distance = 5.4–10.2 m; rugosity = ~ 5 –5.5 cm). Note clear relationship between data variance and rugosity and low measurement bias in all tests. Whiskers of box plots span entire range of dataset.

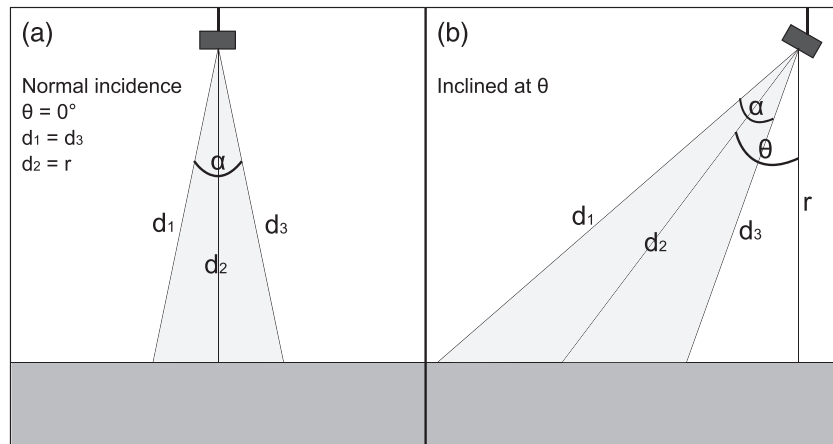


Figure 7. Cartoon of lidar tests (a) at normal incidence ($\theta = 0^\circ$) and (b) when inclined ($\theta > 0^\circ$). For this lidar sensor, beam dispersion $\alpha = 8$ mRad ($\sim 0.46^\circ$; Table 1; Garmin, 2016). r = normal distance from sensor to water surface.

Therefore, more dispersed radiation is received by the sensor under conditions of rougher water surfaces. In all four field deployments, the median value of measurement bias, averaged over the recording time, is <1.5 cm (Figure 6).

3.5. Inclination

The path difference between the outer edges of the laser cone, $d_1 - d_3$, is a proxy for beam divergence α and is a function of inclination angle θ as follows (Figure 7):

$$d_1 - d_3 = \frac{r}{\cos(\theta + \frac{\alpha}{2})} - \frac{r}{\cos(\theta - \frac{\alpha}{2})}, \quad (2)$$

where r is the normal distance from sensor to water surface and d_1 , d_3 , and d_2 are the distances traveled by the outer edges and midpoint of the laser cone, respectively. Theoretical measurement bias and variance increase with incidence angle, as a result of the beam divergence (i.e., $d_1 - d_3$). Figure 8 demonstrates such theoretical and calculated relationships, which show close agreement. The increase is larger in conditions of higher surface roughness, which is to be expected as divergence and wave movement reinforce each other (variations in path length due to water surface waves are not considered here). However, in all conditions, the increase is limited to a few centimeters, which may be acceptable in many operational conditions.

This opens up new perspectives for the use of lidar in situations where vertical measurement is not feasible, for instance, for rivers with a seasonally varying width or an unstable river bank that does not allow installation of a sensor above the water.

Guenther (1986) underlines the importance of water surface rugosity for dispersion when imaging at non-normal incidence (“off-nadir geometry”). This rugosity is manifest as small wavelets or capillary waves containing tiny facets that are perpendicular to the inclined laser beam, allowing energy to be reflected and an interface return to reach the transceiver. However, increasing the incidence angle has the opposite effect to increasing surface rugosity, as laser beam dispersion must be taken into account.

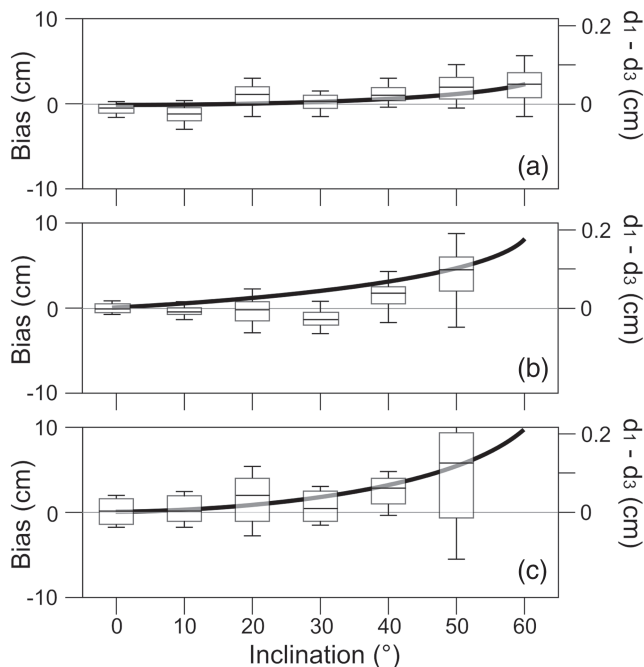


Figure 8. Effect of incidence angle on measurement bias and variance (0° = vertical). Box plots = lidar data (left-hand axis); thick black line = predicted beam divergence (i.e., $d_1 - d_3$ on Figure 7: right-hand axis). (a) Laboratory test: initial vertical distance from sensor to water surface = 2.0 m. (b) Outdoor test: distance = 6.3 m. (c) Test on River Thames at Battersea: initial distance = 8.0 m. Whiskers of box plots span entire range of dataset.

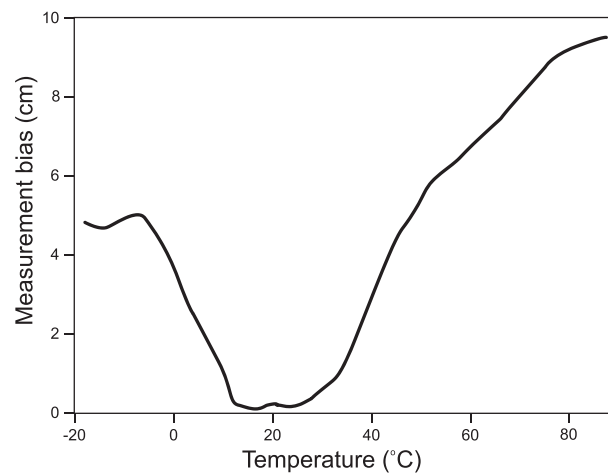


Figure 9. Effect of temperature on measurement bias. Actual distance = 2.5 m; graph shows the average bias for 100 tests.

3.6. Temperature

The effect of air temperature on the time of flight of the laser is negligible. However, various electronic components may be affected by variations in ambient temperature, including the clock and the laser emitter. Light intensity and the wavelength of any lidar sensor increase with temperature because of the resultant slight increase in injection current to the laser diode; however, slow temperature variations do not seriously affect the measured distance value (Jensen et al., 2009). Typical rates of increase have been reported as ~ 0.04 and ~ 0.09 nm/°C for lasers nominally operating at 1,062.3 (NIR) and 531 nm (green), respectively (Jensen et al., 2009; Kikuta et al., 1986). These values are slightly different for different lasers.

We find that both heating and cooling produced a positive measurement bias of maximum magnitude of up to ~ 9 cm (Figure 9). This strong dependence of accuracy upon ambient temperature may be a consequence of inadequate internal temperature compensation of the electronics. Alhashimi et al. (2015) note that changes in temperature increase the degree of oscillation between different wavelength modes of laser light. This effect has the greatest impact on the accuracy of time-of-flight ranging systems: at extreme temperatures, the actual wavelength of the laser pulse is substantially different to the nominal value (Alhashimi et al., 2015). These results suggest that in field conditions, the sensor should be installed in locations that avoid high temperature fluctuations such as direct sunshine.

4. Conclusions

Our results show that time-of-flight lidar can be used to measure water level at high temporal resolution. Areas where establishing a monitoring network is precluded by cost and/or accessibility could benefit from devices that use this technique. Our experiments suggest that, to improve current hydrometric practice, lidar could work especially well when applied to stage measurement, for instance, as part of a flood early-warning system. Sensors could potentially be mounted under bridges or inclined and attached to the bank. We did not find any evidence of instrumental drift over the course of our tests, and, with the application of a suitable correction algorithm, as few as ~ 10 measurements may be sufficient from which a representative average distance may be calculated.

We have demonstrated that, in spite of the low reflectivity of the air-water interface to NIR radiation, a lidar prototype is able to take measurements under a range of environmental conditions, as well as when inclined at angles no greater than $\sim 40^\circ$. The accuracy of the sensor is ~ 1 cm for measurement distances less than ~ 10 m, while the maximum detectable range is 30–35 m, which is far greater than that of existing ultrasonic sensors that measure water level. The precision of the sensor decreases with increasing measured distance and increases with surface roughness. We do not find a significant impact of water turbidity on measurements. Lastly, measurement bias increases systematically as a consequence of temperature excursions outside typical operational conditions (i.e., 10–30 °C).

Our findings suggest that lidar may be a practical method for water level sensing, which has broad and important implications for hydrometry. Lidar has the potential to be used in data-scarce regions where accurate measurements of water level (e.g., river stage and groundwater) are crucial for, for example, flood risk management. It would be useful to investigate whether our findings could be generalized beyond our specific sensor (e.g., lasers of different wavelengths, power, and pulse width). The technique is cost efficient and has a high energy efficiency and small measurement footprint (relative to ultrasound systems; Figure 7); it could be exploited to increase the global density of river gauging stations, which at present is still suboptimal.

Acknowledgments

Experimental data reported here are available from the British Geological Survey's (BGS) National Geoscience Data Archive (NGDC) under <https://doi.org/10.5285/5454f41e-9934-4f80-9db6-0d3d16cf3455>. We acknowledge funding from the U.K. Natural Environment Research Council (NERC) and Department for International Development (DfID) (Contract NE/P000452/1). The assistance of Chris Swan and Dave de Ruyter in the Fluid Mechanics Laboratory at Imperial College London is gratefully acknowledged. Alexander Babulevich, Dimitrios Charemis, Milani Chatterji-Len, Wai-Tong Chung, Vivi Li, and Simon Moulds all provided invaluable assistance with the tests. The comments of two anonymous reviewers greatly strengthened the manuscript.

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