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ACCURACY AND PRECISION OF SMARTPHONES IN MEASUREMENTS OF ILLUMINANCE AND LIQUID TURBIDITY

EXACTITUD Y PRECISIÓN DE TELÉFONOS INTELIGENTES EN MEDICIONES DE ILUMINACIÓN Y TURBIDEZ LÍQUIDA

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Smartphones have demonstrated being attractive tools for illuminance and liquid turbidity measurements. The ambient light sensor and its corresponding mobile application can measure the reduction in illuminance with the distance away from a light source. The indirect measurement of turbidity is performed via the light passing through a solution. The illuminance linearly decreases with the increase in molar concentration of solution and a linear conversion equation to the turbidity can be obtained. By repeating the experiment, the uncertainty in direct measurements of illuminance is less than 1 %, ensuring an appropriate precision for educational and professional uses.

Los teléfonos inteligentes han demostrado ser herramientas atractivas para las mediciones de iluminación y turbidez. El sensor de luz ambiental y su aplicación para móvil son capaces de medir la reducción en la iluminación con la distancia desde la fuente de luz. La medición indirecta de la turbidez se hace mediante la luz a través de la solución. La iluminación decrece linealmente con el incremento en la concentración molar de una solución, de modo que se puede obtener una ecuación de conversión lineal a la turbidez. Repitiendo el experimento, la incertidumbre en mediciones de iluminación es menor que el 1 %, lo que asegura una precisión suficiente para usos educacionales y profesionales.

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I. INTRODUCTION

In addition to their conventional uses in communication and multimedia access, smartphones have increasingly been under research and development as measurement tools in physics education. The challenge for the lecturers is to fully utilize high accuracy sensors included in smartphones. Oprea and Miron comprehensively explored and explained a variety of examples based on physical measurements made by smartphones [1]. The angle and acceleration sensors can be effectively utilized in the teaching of mechanics [1–4]. Quantitative experiments have been also set up for teaching magnetic field and waves [1,5,6].

For recent experiments in acoustics and optics, ambient sound has been analyzed by smartphones [7] and ambient light sensors have been used to verify the inverse-square law with the distance [8–10]. In addition, Diaz-Melián *et al.* also analysed the illuminance in diffraction and polarization experiments by using a smartphone [8]. The Malus' law has been demonstrated with smartphones by Monteiro *et al.* [11] as well as by Çolak and Erol [12]. Light absorption of materials has been studied according to the Beer–Lambert law [13,14]. Furthermore, oscillations can be detected by ambient light sensors [15].

Countryman suggested that students can be engaged in learning several aspects of physics and engineering from the installations and functions of these inbuilt sensors [16]. The mobile applications for the experiments mentioned above are widely available for free or commercial download. Moreover, some lessons can be arranged without downloading additional programs, as demonstrated by Lincoln [17].

Beyond science education purposes, there there are several reports on simple measurements in smart farming, healthcare, engineering and geology using smartphones. Colorimetry by a smartphone was used in the determination of fruit ripeness [18,19], cholophyl contents [20] and ancient pottery classifications [21]. Examples of healthcare applications include the measurements of blood pressure [22] and heart rate [23] by smartphones. Smartphone sensors are conveniently used by geologist in the field survey [24]. For engineering applications, the vibration of machines has been successfully monitored by the inbuilt accelerometer [25]. In additions, smartphones have been increasingly employed as data acquisition devices in other professional uses [24,25].

Of particular relevance to this report is the use of a smartphone as a light meter. The ambient light sensor, normally used for adjusting the brightness of the screen according to environmental lighting, is capable of measuring the illuminance. With a freely downloadable mobile application, the reading from a smartphone's light sensor can be calibrated with standard instruments in the unit of Lux. In addition to the obvious implementation in physics classes, the development is also beneficial for professional uses, including occupational health.

Interestingly, the potential use of smartphones in measuring the turbidity of liquids has also been explored. Determinations of turbidity –a decrease in transparency of a liquid caused by the inclusion of suspended particles– are in demand for environmental monitoring and manufacturing processes. The traditional Secchi disk and Jackson candle turbidity meter relies on visual observations which are not easily standardized. Therefore, most commercial turbidity meters utilize the nephelometric 90° light scattering measurement and the unit of turbidity is defined in NTU (Nephelometric Turbidity Unit). The light from Mie scattering, depending on the liquid turbidity, is measured at right angle respect to the incident light. Based on this method, Hussain *et al.* devised a smartphone- based turbidity meter and tested it with formazin standard solutions [26].

In this report, the measurement of illumination associated to light passing through a liquid is demonstrated as a route to determine the turbidity. The configuration somewhat resembles the Jackson candle turbidity meter, but replaces the eye inspection with the smartphone opposing the light source.

II. EXPERIMENTAL SETUPS

Two different Android smartphones (Phone 1: Samsung Galaxy S7 and Phone 2: Vivo Y85) and two mobile applications (App 1: Lux Light Meter Free by Doggo Apps and App 2: Lux Light Meter Pro by Elena Polyanskaya) were firstly compared. Two incandescent bulbs were used as light sources. Defined by the Commission Internationale de l'Eclarage (CIE), such light sources correspond to the standard "illuminant A" with a relative power distribution of the Planck radiation around 2856 K [27]. This spectral range is effectively detected by the smartphone ambient light sensor [26]. In the first experiment, the illuminance was measured at varying distances (d) by aligning the ambient light sensor directly in front of a light bulb. Plots of illuminance from a 100 W light bulb as a function of $1/d^2$ was then calibrated with an Extech 407026 Light Meter. The turbidity was indirectly determined from the illuminance through the solution, prepared by dissolving sugar in water to obtain a molar concentration within the range 0.1-0.6. The solution of varying turbidity was poured into an acrylic box of dimensions $15\times15\times20$ cm^3. The light bulb and the ambient light sensor were directly located on opposite sides of the container. By measuring the same solutions with an ECTN10IR Portable Turbidity Meter, the illuminance in Lux could be converted to the turbidity in NTU. All measurements were repeated three times for each data point.

III. RESULTS AND DISCUSSION

III.1. Smartphone as light meter

The measurements using three different combinations of smartphone devices and mobile applications were compared. All three plots in Fig. 1 similarly exhibit a linear trend of the inverse-square law in which the illuminance is inversely proportional to the distance squared (d^2) from the light bulb, approximated as a point source. The standard deviation from each measurement is minimal and the values of R^2 from three linear fits are comparable, ranging from 0.9924-0.9944. The difference in equations describing the straight three lines in Fig. 1 suggests that the changes in smartphone, and mobile application affect the illuminance reading and each combination needs a calibration with a standard instrument. Interestingly, the slope is significantly reduced by changing the smartphone, which reveals the characteristics of each ambient light sensor, but they are less sensitive to the mobile application used in this experiment.

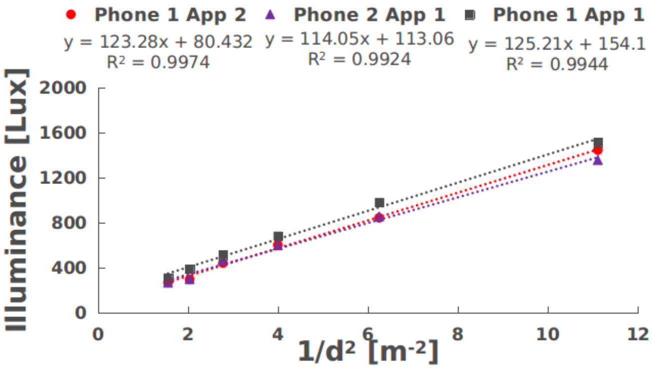

Figure 1. Variation of illuminance from with the distance (d) from the light source measured by using three different combinations of smartphone devices and mobile applications.

The illuminance reading by Phone 1 (Samsung Galaxy S7) and App 1 (Lux Light Meter Free by Doggo Apps) can be calibrated with the standard light meter as shown in Fig. 2. The straight line with $R^2 = 0.9996$ indicates very good agreement between the smartphone and the standard instrument. Error bars are not visible since the uncertainty from three repeated measurements are less than 1 %. The accuracy of the smartphone reading can be assessed by the slope of this calibration plot. The slope of 1.3289 from Fig. 2 means that the reading by the ambient light sensor and mobile application in smartphone is higher than the illuminance measured by the standard instrument. The difference is likely attributed to the infrared contribution from the light source. Because the illuminance is luminous flux per unit area incident on a surface perpendicular to it [27], the detection by the smartphone reading includes both visible light and infrared radiation from the incandescent light source. On the other hand, the Extech 407026 Light Meter is designed to eliminate this frequency range [28].

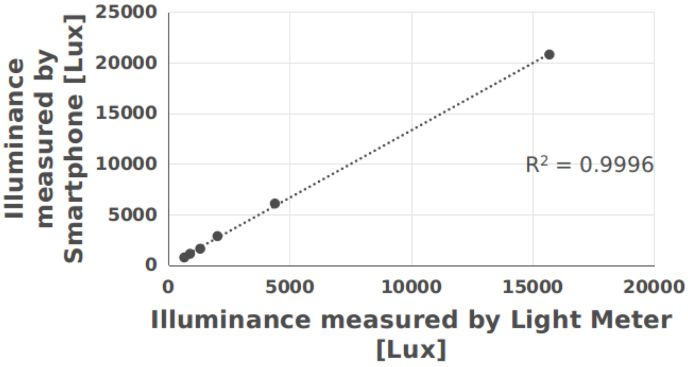

Figure 2. Linear relationship between illuminance measured by a smartphone and a light meter (Phone 1 and App1; see text).

III.2. *Smartphone as turbidity meter*

The results from the solutions of different concentrations, firstly measured by the turbidity meter, are shown in Fig. 3. The turbidity within the range of 4-20 NTU is directly proportional to the concentration of the solution from 0.1 to 0.6 Molar. Likewise, the illuminance of the light passing through the solution is also reduced with increasing molar concentration of the solution. This is consistent with the enhanced light absorption and scattering with increasing number of particles in solution.

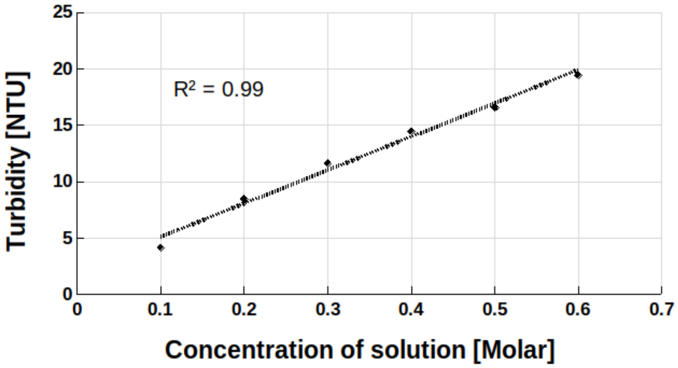

Figure 3. Variation of the turbidity measured by the turbidity meter as a function of the molar concentration of solutions.

By comparing the measurement by a smartphone with the turbidity meter reading, a straight line is obtained with $R^2 = 0.9958$ as shown in Fig. 4. Error bars indicate that the uncertainty in measurements by the smartphone is 1.77 %, higher than those made by the turbidity meter. This linear variation can be represented by a conversion equation;

$$\text{Turbidity} = -0.0092(\text{Illuminance}) + 35.462. \qquad (1)$$

Certainly, the reproducibility of this measurement is highly influenced by the type of light source. Fluorescent lamps have a large variation of spectral distributions. Fluorescent light sources likely lower the sensitivity of this measurement set-up. Furthermore, the ambient light sensor may not be sufficiently sensitive to the light passing through very turbid water and the measurement of illumination by an opposing smartphone is therefore not effective in the case of waste water. With a different configuration, Hussain *et al.* demonstrated that the turbidity up to 400 NTU could be measured [26]. Their smartphone-based turbidity meter deployed an IR LED as a light source and measured the scattered infrared light at 90° using a proximity sensor.

The results in this section underline the versatility and precision of the ambient light sensors contained in smart phones. Besides the direct measurement of light, they can be used in the indirect measurement of other physical quantities by calibrating with standard instruments. As illustrated in the case of turbidity, the repeatability and linearity in an extended range are appropriate for educational and other professional applications.

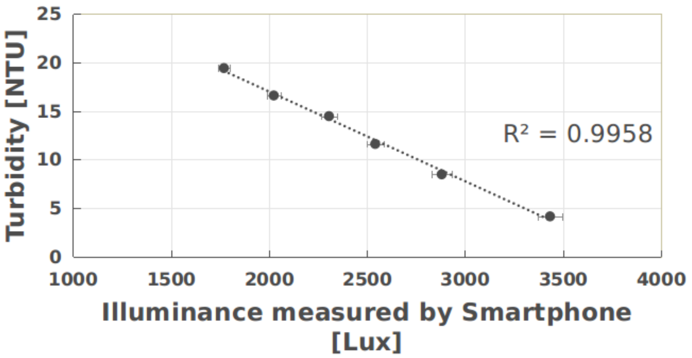

Figure 4. Linear relationship between the illuminance measured by the turbidity meter and the smartphone. (Phone 1 and App1; see text).

IV. CONCLUSION

The smartphone's ambient light sensors can measure light illuminance in a way comparable to a standard light meter. The study of three different combinations of smartphones and mobile applications confirms that the illuminance is inversely proportional to the distance squared from the light source. When increasing the concentration and the turbidity of the solution, the light sensor from the smartphone detects a linear reduction in the illuminance of the light passing through the solution. That makes smartphones useful for both educational and professional applications related to the quantification of turbidity.

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