Measuring Ultraviolet Radiation Underwater: A Practical Application of the Beer-Lambert-Bouguer Law for High School Physics

INTRODUCTION

The precise measurement of solar UV on the surface of the Earth is not a simple process. Instruments such as spectroradiometers, spectrometers, radiometers and basic handheld UV meters must be adequately calibrated to appropriate standards, maintained fastidiously and employed correctly within their operational limitations in order to obtain accurate data that is of the quality necessary for scientific research. Other factors such as atmospheric parameters like column ozone, trace gases and aerosols and their influence upon instrument response must also be taken into account during measurements or else critical errors may become apparent in the measured data. These issues are also in effect with solar UV measurements made underwater, except that in the underwater environment the difficulty of obtaining useable data becomes greatly amplified due to the optically complex and at times unpredictable nature of water itself. The instrumentation employed to take the solar UV measurements must not only be calibrated to proper standards and prepared for changes in the dynamic atmosphere, but they also must be completely sealed and waterproofed in readiness for the harsh surrounds of the underwater environment and also corrected for the optical phenomenon known as the immersion effect.

The difficulties of making solar UV irradiance measurements in real-world underwater environments brought on as a result of cumbersome spectroradiometric and radiometric measurement equipment, poor instrument response with changes in depth, unpredictable changes in water quality and transparency as a result of both natural and anthropogenic activity, shading caused by nearby trees and plants along with the presence of surface waves have made recording reliable estimates for optical properties of water bodies an extremely difficult proposition (Morrow & Booth, 1997). Additionally, Morrow and Booth (1997) have made the point that underwater UV measurements can also be complicated by the fact that the total UV becomes a very small signal that has to be measured alongside the much more pronounced visible waveband coupled with unpredictable features at the surface of the water including wave focusing effects like those reported by Deckert & Michael (2006) and also changes in water line elevation caused by evaporation and tidal changes.

From an optical perspective, three main factors influence underwater UV measurements made with all types of UV measuring instrumentation. The first is that the field of view as seen by any sensor is reduced and hence a smaller amount of radiation is intercepted by the sensor. Secondly the change in the local refractive index between the open-air environment where the sensor was calibrated in comparison to the underwater environment where the sensor is employed (Ohde & Siegel, 2003). The third factor is that during a water-based measurement, a greater amount of light is scattered out of the sensor in comparison to a similar air-based measurement, which is caused by the difference between the refractive indices for air and water at the sensor interface (Hooker & Zibordi, 2005; Zibordi, 2005; Zibordi *et al*, 2004). This is known as the immersion effect. In order for reliable solar UV measurements to be made underwater, wavelength dependent immersion factors must be calculated and applied using a strict methodology. However, for the practical exercise presented in this article, it is not necessary to calculate the immersion factor for the recommended UV meter as only relative measurements will need to be obtained and analysed in order to investigate the Beer-Lambert-Bouguer law.

Electromagnetic radiation moving within a natural body of water is subject to both absorption and scattering processes initiated by the constituent materials held within the water body. These absorption and scattering processes have the potential to change the original distribution of UV energy existing above the surface of the water. The extent of this change is of course limited by the type and amount of materials propagating inside the water body. One way to distinctively quantify the optical properties of a particular type of water is to calculate two interconnected mathematical parameters known as the attenuation coefficient and the 1% attenuation depth value respectively. The attenuation coefficient is derived using real-world data in combination with a modified version of the Beer-Lambert-Bouguer Law, which is an exponential function employed to describe the propagation of light for a variety of optical Physics applications in many different types of media. The 1% attenuation depth value is then found simply by multiplying the attenuation coefficient by a factor of 4.605 (Bukata *et al*, 1995). For most cases in the literature the attenuation coefficient is referred to in short as the K_d value and the 1% attenuation depth is known as the $z_{1\%}$ value. These two parameters will be referred to as such in this article. The calculation of both K_d and $z_{1\%}$ values are of extreme importance to marine scientists as they allow for estimations to be made on how much biologically damaging solar UV radiation can enter and propagate throughout a particular body of water. The following practical exercise aims to provide the Year 11 and Year 12 Physics students with a step by step appreciation into how the Beer-Lambert-Bouguer Law can be applied underwater and how handheld solar UV measurement instrumentation can be employed to provide rapid estimations for both K_d and $z_{1\%}$ values in conjunction with a modified version of the Beer-Lambert-Bouguer Law in order to correctly evaluate the optical properties of any given sample of water in a partially controlled environment, such as a water tank and in turn provide a basic assessment of the level of risk for aquatic life forms to solar UV associated damage. Most scientific research dealing with underwater light measurements work with K_d and $z_{1\%}$ values with respect to single wavelengths. Also, in general K_d and $z_{1\%}$ calculations performed in actual aquatic locations are made from the collation of sizeable amounts of data taken over a long period of time over a wide range of different depths. As spectral irradiance measurement instrumentation is extremely cost prohibitive and due to the fact that there is only a limited amount of time in which the teacher has to deliver these concepts and limited space to run a complete practical class, only a simple inexpensive broadband UV meter will be employed in this exercise that requires no more than an hour to run. Additionally, a reasonably sized durable water tank which will double as a microcosm to an idealised real-world aquatic environment and water sourced from the tap, a tank or from a local natural water body will be needed.

The proposed technique identifies and extends concepts of physical optics studied in high school physical courses, adding to the familiar physical mechanisms of reflection, refraction and diffraction, new mechanisms including scattering and material absorption characteristics. Extension of optical absorbance caused by scattering of water and particulate mater in a water column is investigated in this activity in the UV waveband, whereby the radiometric unit of irradiance ($W\ m^{-2}$) has been introduced. This relates directly to studies of radiation as a form of energy. The practical work outline presented by the authors of this paper is significant as it offers an entirely new, relevant and engaging way of introducing Year 11 and Year 12 physics students to various optical physics concepts in an environment different to air, which is the medium generally used for high schools optics experiments.

Calculation and comparison of measured K_d values for different bodies of water provide students with the opportunity to engage in active practical and sufficiently detailed experimental project techniques, including for example extended experimental investigations outlined in the current Queensland Physics senior syllabus. This activity provides students with the opportunity to practice physics measurements and make comparisons with the work presented by other researchers. The presented activity provides further opportunity to develop cross-curricular links to biological studies by understanding UV radiative transfer processes in the underwater environment and linking the radiation present with its influence in the natural environment. Extension of the results found by completing the proposed activity may consider for example the ability of underwater UV radiation to cause a sunburning reaction at depth or detail what effect underwater UV radiation has on living marine and freshwater organisms, including for example consideration of the influence of UV radiation in coral bleaching episodes.

The practical work outlined in this paper could also form the basis for an EEI (Extended Experimental Investigation) by linking the basic theory of underwater electromagnetic radiation propagation theory into real world marine problems such as coral bleaching. After completing this practical, students will gain an appreciation of how deep solar UV radiation can travel within a given sample of water and as a result see the potential that solar UV radiation has to cause damage to aquatic organisms.

METHOD AND IMPLEMENTATION

Basic Principles

In basic terms K_d is an expression of the fractional decrease in radiation beam intensity per unit length (Tett, 2005). As an example, a K_d value measured as 0.02 cm^{-1} equates to approximately 2% of the total intensity of a beam of radiation being removed with every 1 cm increase in depth. Generally, clear waters with minimal levels of turbidity caused by buoyant particulate materials, such as glacial streams, have smaller characteristic K_d values in comparison to turbid waters such as stagnant dams inhabited by various forms of animal and plant life where the K_d values can be increased by the existence of numerous forms of particulate and dissolved elements floating in the water, for example dissolved organic matter or phytoplankton (Williamson, 2005).

Real-world K_d estimations can be made using measured data taken using an actual sample of water in a partially controlled environment together with a modified version of the Beer-Lambert-Bouguer Law. The Beer-Lambert-Bouguer Law describing the decay of irradiance with depth in water can be converted into the following logarithmic form:

$$\ln\left(\frac{E(z,\lambda)}{E(0,\lambda)}\right) = -K_d z \qquad \textbf{1.}$$

For irradiance measurements with a broadband UV meter, the irradiance does not depend on wavelength and the equation becomes:

$$\ln\left(\frac{E(z)}{E(0)}\right) = -K_d z \qquad \textbf{2.}$$

From this equation K_d can be found graphically by plotting $\ln\left(\frac{E(z)}{E(0)}\right)$ data obtained from a real-world aquatic environment using UV measurements against z and subsequently calculating the absolute of the gradient of the resulting straight line of best fit.

After calculating the K_d for a particular water type the 1% attenuation depth can then be determined using the algebraic function as mentioned in the introduction:

$$z_{1\%} = 4.605 K_d \qquad \textbf{3.}$$

where $z_{1\%}$ is the depth to which 1% of the incident surface light penetrates through the water column (Bukata *et al*, 1995). When an evaluation is made for $z_{1\%}$, only water types where the K_d value is known to be relatively constant over a large depth range can be analysed in order to minimise the uncertainties resulting from extrapolation into depths where attenuation properties become variable (Williamson, 2005). Interestingly, the $z_{1\%}$ for any water type cannot be regarded as an annual constant value. One example study carried out by Kuwahara *et al* (2000) has shown that the $z_{1\%}$ for relatively optically clear coastal waters off the shores of Japan can vary by as much as 5.7 m at a wavelength of 305 nm and 17.6 m at a wavelength of 380 nm over the space of a year.

Equipment

Water Tank

Before measurements begin a tank is to be filled up with clean water. Water taken straight from the tap can be used, however it is best to use distilled water if it is at all possible. The teacher running the practical may also choose to use as many different types of water as possible, such as water sourced from local creeks, dams or even sea water taken directly from the ocean in order to provide comparative sets of data. Any kind of durable storage tank may be used to hold the water. In a trial run performed by the authors of this article a large water container purchased from a discount shop was employed. This water container was a storage container made out of tinted plastic and had a length of 66 cm, a width of 46 cm and a depth of 35 cm. This plastic was measured to be almost completely opaque to the UV waveband, so any UV wavelengths hitting the sides of the tank during the measurement series would not have any influence upon the UV measurements being performed on the inside of the tank. During the trial run any pieces of debris landing in the tank were removed in order the keep the water as close to its original state as possible. Also, if any water was split from the container, water levels were immediately topped up in order to maintain a constant water depth.

UV Meter and Water Proofing

A personal handheld UV meter (Edison, UV checker) supplied by Jaycar Electronics (2009) was used to measure the underwater UV in the trial run and is recommended for use in this exercise as it is capable of providing UV irradiance measurements instantaneously in units of W m^{-2}. A picture of an Edison handheld solar UV meter is shown in Figure 1. Currently the cost of one of these meters is approximately 25 Australian dollars. Unfortunately, despite their usefulness these meters are susceptible to water logging after prolonged underwater use. In order to overcome this problem a square sheet of glad wrap no more than 20 cm x 20 cm was used as a water proofing shield by wrapping and securing it around the UV meter with the help of a rubber band. A front and back picture of this water proofing set up is depicted in Figure 2 (A) and Figure 2 (B) respectively.

Figure 1: The Edison handheld solar UV meter.

A)

B)

Figure 2: The Edison handheld solar UV meter covered in glad wrap front view (A) and back view (B).

Figure 3 shows the spectral transmission and absorption properties for the glad wrap filter as measured by a spectrophotometer system (model 1601, Shimadzu Co., Kyoto, Japan). Across the UV waveband from 280 nm through to 400 nm the average UV transmission and absorption values measured through the filter were found to be 84% and 0.08 respectively. This is reasonable proof that the glad wrap is close to being reasonably transparent to UV wavelengths. It can also be seen that the filter maintains a relatively flat transmission and absorption distribution across the solar UV waveband from 290 to 400 nm. This particular characteristic of the glad wrap was advantageous as it allowed for equal amounts of solar energy at each wavelength to be filtered through the glad wrap to the personal handheld UV meter, which greatly helps to minimise measurement uncertainty that could come into play caused by changes in the spectral properties of the incoming solar UV.

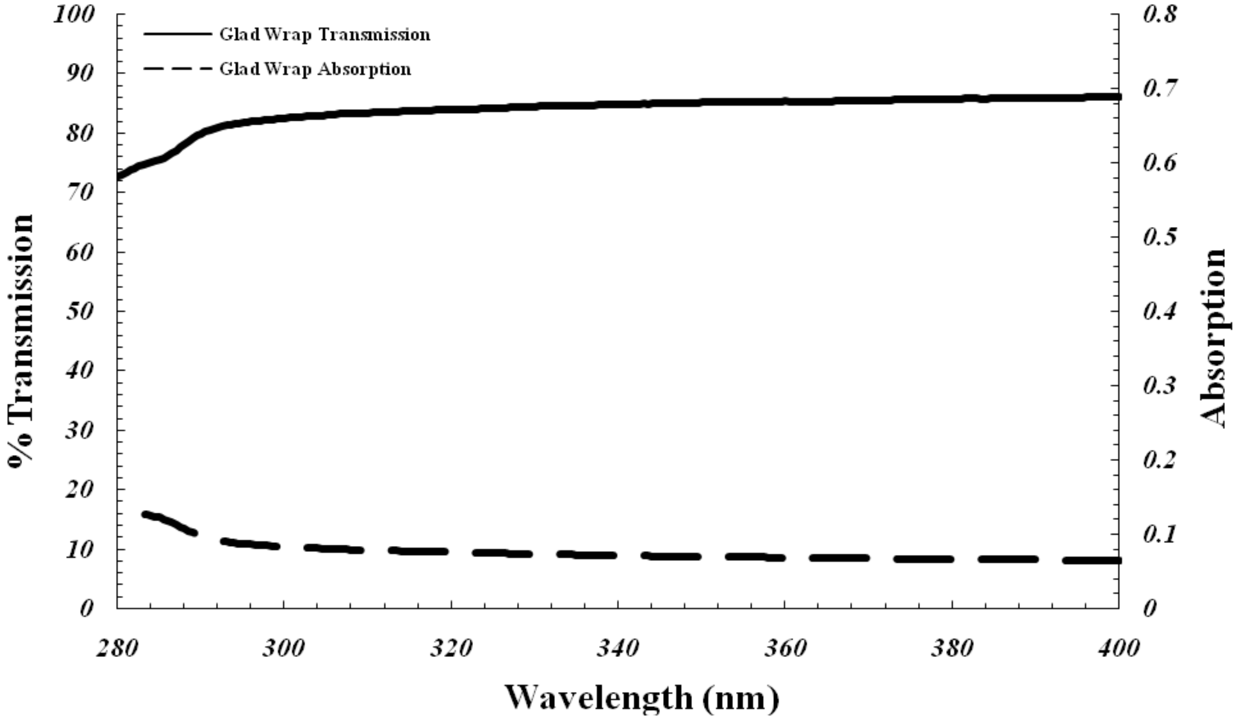

Figure 3: Spectral transmission and absorption properties for the glad wrap filter used with the Edison handheld solar UV meter.

Measuring Solar UV Underwater

This practical should only be carried out during the months of summer, early autumn or late spring so that the UV meter can detect reasonable amounts of solar UV. It could also be possible to run this practical on completely cloud free winter days. It is also recommended that the UV measurements be made sometime between 11 am and 1 pm to ensure that absolute peak level UV irradiances are measured. Cloud cover during the measurements should be minimal at best. If cloud cover does become a problem, time should be taken to wait for the clouds to pass away from the solar disc during each consecutive measurement so that measurements in full sunlight can be taken. If this is not possible the practical should be abandoned and left for another day when there is minimal cloud. As the students will be outdoors in direct sunlight all UV preventative measures must be enforced. This includes the wearing of full brimmed hats, long sleeve shirts preferably with collars, sunglasses and an appropriate SPF 30+ sunscreen. The measurement of the solar UV underwater should be carried out using the following series of steps:

1. Ensure that the water tank sits on a level surface. Check this by using a bubble level. If the water tank does not sit level choc wedges can be used to reposition it so that it sits as close to the horizontal plane as possible.
2. Measure and record the depth of the water from the top water line to the bottom of the tank using a ruler making sure to work in units of cm.
3. Take and record a UV irradiance measurement just below the surface of the water ensuring that the meter is aligned directly parallel with respect to the horizontal plane. This measurement will serve as the E(0) data point. The UV irradiance can be seen in the bottom right hand corner of the UV meter display screen. Just beneath this display screen is a green click button. A new UV measurement is provided each time this click button is held down for more than a second.

NOTE: If the irradiance value is too small or does not change from depth to depth try pointing the UV meter towards the exact direction of the solar disc while avoiding to point its field of view into the sides of the water tank. This should help to increase the measured UV irradiance values. After doing this it is important to make sure that the angle the UV meter is pointed towards the sun remains the same throughout each successive measurement during the practical.

4. Take a series of measurements in 2 cm increments from the water surface until the bottom of the tank is reached. Care must be taken not to shade the UV meter during these measurements or the quality of the data will be severely diminished. Students should also not touch the top sensor of the UV meter as

oils and dirt can attach to the clear outer sensor casing and in turn reduce measured UV irradiance values. Additionally, if a water type with a higher level of turbidity than tap or distilled water is being analysed the entire UV meter should be cleaned with a tissue between each successive measurement. Try to take each measurement as quickly as possible so that the angle of the sun does not change too drastically throughout the exercise.

5. Repeat steps 3 and 4 two more times in order to obtain three separate UV irradiance values for each particular depth. For these measurements the students must ensure that the position of the top water level remains constant at all times.

The total amount of working time required to complete these measurements should be no longer than 45 minutes to 1 hour.

Data Analysis

Students may choose to complete the graphical work required for this exercise on paper or by using Microsoft Excel. However, it is probably best to use Microsoft Excel as it allows for the rapid determination of gradient and R^2 information. The data analysis phase is completed in the following order:

1. After averaging the three sets of data at each of the depths, graph the underwater UV irradiance as measured by the UV meter in W m^{-2} versus depth in cm. By fitting an exponential trend function to this data a good R^2 value of above 0.9 should hopefully be seen. If not the students should be asked why the distribution of underwater UV irradiance did not turn out to be as expected. One reason for this could be variable amounts of shading caused by the sides of the tank, cloud coverage, changes in the solar angle or

accidental shading by the students themselves influencing the response of the UV meter over the duration of the practical. Another reason for a low level of accuracy in the exponential model could be an uneven distribution of turbid matter throughout the water if it was sourced from a location such as a dam or a creek. Figure 4 provides a graph of underwater UV irradiance versus depth taken from the trial run for clean tap water with an exponential trend line fitted to the data series. Note the high R^2 of 0.97.

2. The data now has to be normalised with respect to the UV irradiance measured at the position just below the surface of the water. To do this divide the UV irradiance measured at each depth by the UV irradiance measured at the E(0) data point.
3. Apply the natural logarithm to all of the now dimensionless normalised measurements.
4. Graph the normalised data against depth following the application of the natural logarithm. The y-intercept should be set to zero for simplicity. Figure 5 provides a graph of the normalised underwater UV irradiance versus depth as calculated from the trial run for clean tap water with a straight trend line fitted to the data series. Again note the high R^2 of 0.94. The gradient of the line of best fit should be negative. If the gradient is not negative something has gone wrong with the calculations and they should be checked for any errors.
5. It can clearly be seen that equation **2** is basically the formula for a straight line of best fit which is given as y = mx + c, where y is $\ln\left(\frac{E(z)}{E(0)}\right)$, x is z and m is K_d. The c value disappears as the y-intercept was initially set to zero. As a

result the K_d value can be easily discerned by taking the absolute value of the gradient.

6. Compare this K_d value to other example K_d values previously calculated by the author which are as follows:

   Tap Water: 0.03 cm^{-1}.

   Sea Water: 0.028 cm^{-1}.

   Stagnant Dam Water: 0.1 cm^{-1}.

   Running Creek Water: 0.036 cm^{-1}.

   The following percentage error equation should be used to detail a quantitative estimate on the disparities between the author's K_d values and the student's own K_d values:

$$\%Error = \left| \left(\frac{(K_d)^{STUDENT} - (K_d)^{AUTHOR}}{(K_d)^{AUTHOR}} \right) \right| \times 100\%$$

   Keep in mind that water taken from natural sources may turn out to have lower K_d values in comparison to tap water. A good question would be to ask the students why this is possible. Students could also perform a literature search using Google to find refereed academic articles that have included other K_d value estimations and they could then compare their results to those found in these articles.

7. Use the calculated K_d value to evaluate the $z_{1\%}$ value characteristic to the water type under analysis by using equation **3**.

8. For their practical exercise write up students should have to provide ideas as to why the K_d and $z_{1\%}$ would vary between different water types. Also, students should provide a full step by step quantitative error analysis detailing what

environmental and measurement based factors could have influenced a reduction in overall data accuracy.

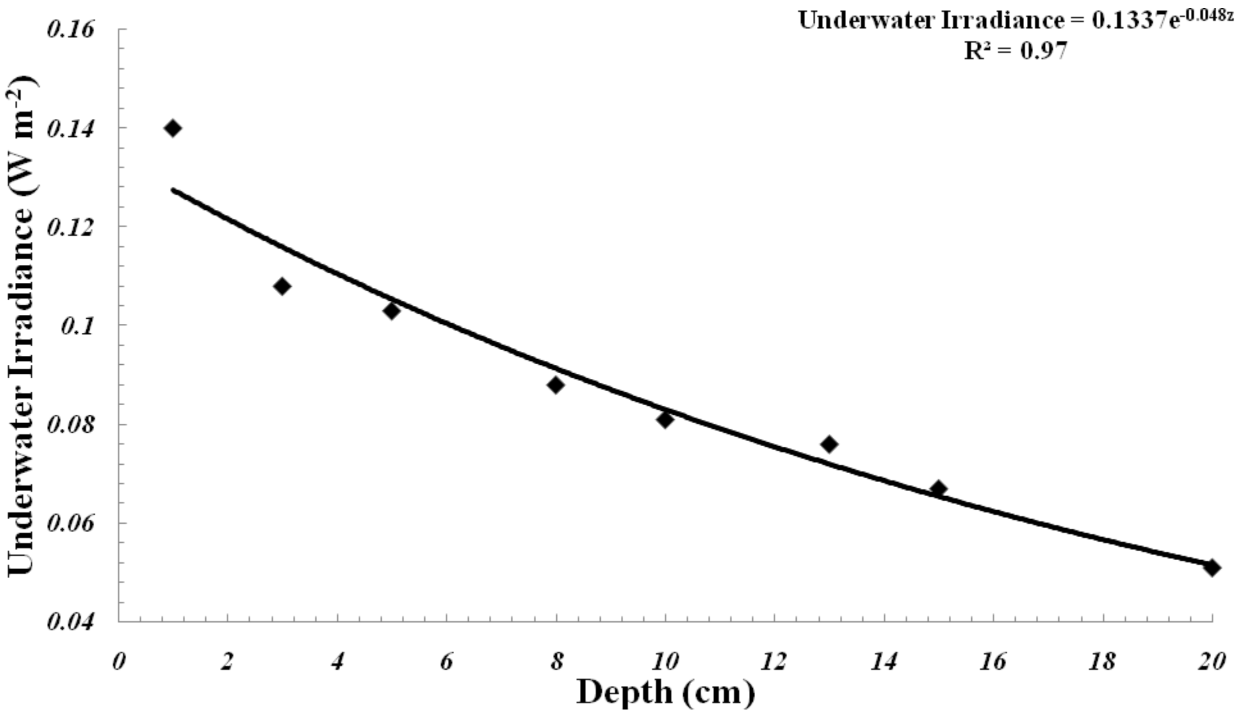

Figure 4: An example underwater irradiance depth profile measured using the Edison handheld solar UV meter.

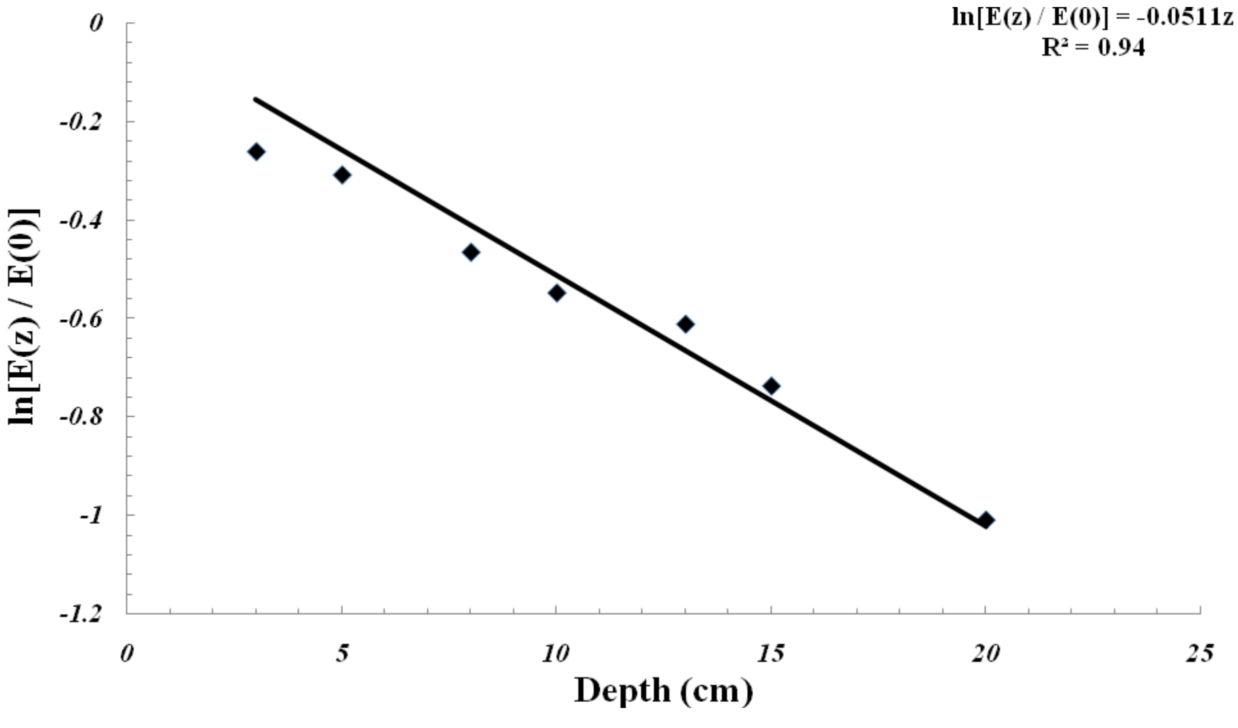

Figure 5: The underwater irradiance depth profile data from Figure 4 converted to a normalised series of measurements relative to E(0). The absolute gradient gives the K_d value.

As the data analysis work required to adequately complete this practical is extensive, it is recommended that students work on it as a homework task. It should take an estimated 1 to 3 hours to complete depending upon the ability of the student.

CONCLUSION

This article has provided Year 11 and Year 12 Physics teachers a simple and quick practical exercise from which they can provide students with a real-world example of how the Beer-Lambert-Bouguer Law can be used as an analytical tool in the estimation of various optical properties such as K_d and $z_{1\%}$ values characteristic for a variety of water types. In doing this the students gain an appreciation in how solar UV measurements are made underwater and how progressively changing atmospheric factors such as solar angle and cloud coverage can have a drastic effect on the amount of UV that we see here on the Earth’s surface. Students are also given a brief insight into concepts such as spectral transmission and absorption distributions and the practical application of exponential and logarithmic functions. Additionally, from this exercise students are able to develop their numerical and algebraic ability and scientific literacy along with developing skills in Microsoft Excel based data analysis and graphing.

The teacher may wish to extend this exercise beyond a day and run further trials over several days for each season of the year in order to collect a larger database of K_d and

$z_{1\%}$ values. For this field trips may be arranged in which solar UV measurements could be made at deeper depths within actual local water bodies. From the long-term enhanced analysis resulting from this work the teacher can show that seasonal changes in atmospheric parameters such as solar angle and column ozone can modulate K_d and $z_{1\%}$ values and hence show that the relationship between the penetrative ability of solar UV and water is not a static one. Daily column ozone values can be sourced from the NASA OMI website located at http://jwocky.gsfc.nasa.gov/ozone/ozone_v8.html.

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