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Predicting Underwater Visibility in Tourist Beaches

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Abstract

Aiming towards supporting recreational snorkelling in tourist beaches, we have investigated the relationship between underwater visibility range and backscattering coefficient. A series of field experiments involving simultaneous monitoring of beam transmission, backscattering and underwater horizontal black disk sighting have been conducted in various locations. The first results indicate that monitoring backscattering, even in the red part of the spectrum, can provide a useful proxy for visibility determination with an estimated accuracy of 20%.

Introduction

Greece is ranked amongst the 20 top touristic destinations with most of the growth associated with beach destinations. Tourism has, over recent decades, become synonymous to beach recreational activities. Within the framework of the project "Synergy for the Sustainable Development and Safety of the Hellenistic Tourist

Beaches – BEACHTOUR", a low cost Beach Environmental Monitoring System-(BEMS) is being developed. The system incorporates sensors for obtaining air temperature and humidity, solar and UV radiation, wind speed/direction, atmospheric pressure, shallow water temperature, salinity, wave height and turbidity. This information is processed, stored, and communicated in a quasi-real time mode to an LCD screen to be available to the beach users.

The intention of turbidity (backscattering) monitoring in this system, is to be used in prediction of underwater visibility range which is handy piece of information for recreational snorkelling. Existing analytical algorithms relate contrast reduction and visibility range to the photopic beam attenuation coefficient α (Preisendorfer, 1986). However, photopic attenuation meters do not exist and in practice are substituted by single wavelength transmissometers which measure the attenuation coefficient $c(\lambda)$, the sum of absorption $a(\lambda)$ and scattering $b(\lambda)$ coefficients. Zaneveld and Pegau (2003) have demonstrated that such instruments operating in green (where human vision is most sensitive), blue or even red can provide sufficient information needed to estimate the visibility range with certain accuracy. Nonetheless they are expensive and bulky and they are mainly used for scientific tasks. A turbidity meter on the other hand measures only the backscattering coefficient $b_b(\lambda)$, usually at the red part of the spectrum, but is cheaper and compact. Backscattering in general is not linearly related to beam attenuation and is directly related to the scattering coefficient. For this reason, a series of field experiments aiming towards associating the backscattering coefficient with underwater visibility were recently undertaken and preliminary results are reported here.

Materials and Methods

The general problem of visibility refers to contrast attenuation of an object and is defined as:

$$C_0 = \frac{N - N_b}{N_b} \qquad (1)$$

where N is the luminance (photometric equivalent of radiance) of the object and N_b the luminance of the background. Visibility theory applied underwater (e.g. Preisendorfer, 1986) predicts that at a distance r, the apparent contrast when the object is viewed horizontally is:

$$C_r = C_0 \exp(-\alpha r), \qquad \alpha = \frac{\int_{400}^{700} N_b(\lambda)\,\bar{y}(\lambda)\,c(\lambda)\,\mathrm{d}\lambda}{\int_{400}^{700} N_b(\lambda)\,\bar{y}(\lambda)\,\mathrm{d}\lambda} \ (\mathrm{m}^{-1}) \qquad (2)$$

Here α is the photopic beam attenuation coefficient, $c(\lambda)$ the spectral beam attenuation coefficient and $\bar{y}(\lambda)$ the photopic luminosity function. Blackwell (1946) found that there was an almost constant limiting contrast C_L for all emmetrope humans provided that both ambient adaptive lighting and angular observation size are sufficient. Moreover if the object is black (e.g. a black disk), then the inherent contrast C_0 is simply -1 and the visibility range simplifies to:

$$y = \frac{\ln\left(C_0/C_L\right)}{\alpha} = \frac{\ln\left(-1/C_L\right)}{\alpha} = \frac{\Psi}{\alpha} = \frac{\Psi}{\alpha_c + \alpha_w} \approx \frac{\Psi}{kc(\lambda_o) + \alpha_w} \qquad (3)$$

where Ψ is a coupling constant that for most circumstances is approximately 4.8 (i.e. Davies-Colley, 1988; Hou et al., 2007). The photopic attenuation coefficient can be separated in two major parts: α_c due to scattering of particulate matter (SPM) and absorption of dissolved substances (mainly CDOM –coloured dissolved organic matter); and α_w resulting from water itself. It turns out that α_c can be substituted successfully by the attenuation coefficient at a particular wavelength, properly scaled by a factor of k ((Zaneveld and Pegau, 2003).

In tourist beaches during summer, a period with no phytoplankton blooms and plenty of sunlight which leads to loss of CDOM through photobleaching, beam attenuation is expected to be dominated by particulate scattering. This is especially true for the red edge of the spectrum where CDOM absorption in any case is minimal. The backscattering ratio, $b_b(\lambda)/b(\lambda)$, although spectrally constant it does depend on the size of the scatterers (Whitemire et al., 2007). Retrieval of the scattering coefficient from the backscattering one has been obtained empirically elsewhere (e.g. Doron et al., 2007). Following this practice, in the present work we chose to engage a simple power law.

Five tourist beaches located at diverse environments have been investigated so far during the period June – July 2015 (Fig. 1). The beach at Paralia Katerinis (South Thermaikos Gulf), with shallow waters mainly influenced by riverine outflows. The beach of Gerakas located at the southeast tip of island of Zakynthos, a well-protected area being one of the largest Caretta Caretta sea turtles nesting ground. The beach at Gournes (Northern Crete) and the beach at Agia Pelagia again at Northen Crete but this one sheltered from the Etesian winds. Finally, the long stretching Koutsounari beach, located at Levantine (Southern Crete) and characterized by deep waters.

All the experiments were held during noon time to ensure plenty underwater lighting, at 2 meters depth. Instrumentation chosen was a $c(660)$ beam transmissometer (C-star), and an Eco-Triplet (Wetlabs) which monitors backscattering (turbidity) at 660nm, CDOM and chlorophyll-a concentrations (by means of fluorescence). Both instruments were calibrated prior to deployment. The matte black disk monitored had a standard diameter of 0.2 m. The protocol followed was: After all instruments where temperature stabilized, collection of time series all parameters was initiated. Meanwhile, two divers performed the visibility experiment simultaneously with the parameter monitoring procedure. One diver held the black disk at his side 2 m away from him by means of a black pole while the second one started moving away until the disk just disappeared from his sight. A measurement of the distance was recorded and this procedure was repeated at least two more times with the divers changing places. Finally, another set of measurements was held at the same beach but under different environmental conditions.

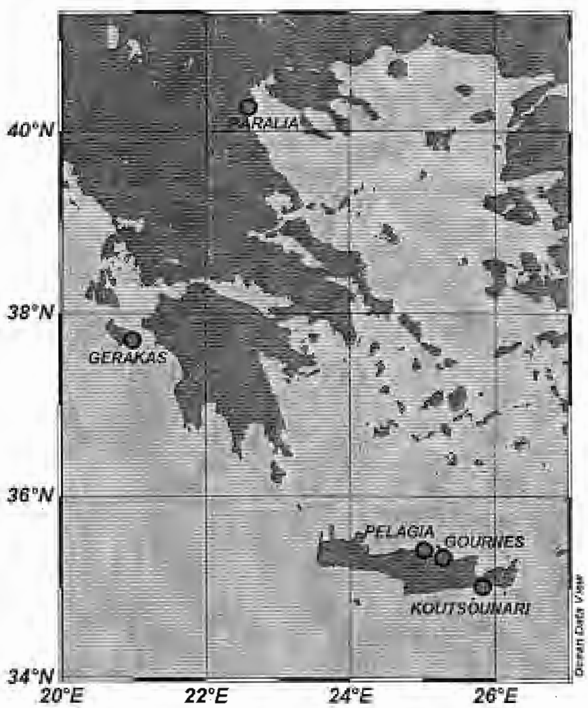

Fig. 1: The five beaches investigated in Ionian, NW Aegean, Cretan and Levantine Seas.

The time series data were cut in segments corresponding to the exact period of the divers' measurement procedure and then averaged. In order to estimate the resulting error of the entire procedure we evaluated APD, a measure of percentage error. It is the difference between the algorithm estimate and the measurement, weighted on the measured visibility range value. APD was computed as:

$$\mathrm{APD} = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{y_{fit.}(i) - y(i)}{y(i)}\right| \times 100 \tag{4}$$

where $y_{\mathrm{fit}}(i)$ are the modelled visibility ranges and $y(i)$ the observed.

Results and Discussion

The empirical relationship that best fitted our field data of $c(660)$ and $b_b(660)$ was:

$$c(660) = 36 b_b(660)^{0.89} \tag{5}$$

The goodness of fit (R-square) was 0.94 and the results are shown in Fig. 2. It can be seen that scatter of the data and thus uncertainty increases at very clear waters (low c and b_b coefficients). This happens because the instruments reach their lower monitoring range limits and meanwhile the absorption term becomes more important.

In order to model the visibility range, initially the photopic beam attenuation coefficient of pure water was estimated by evaluating the integral of Eq. (2). Under typical background radiance profile at 2 meters depth during summer noon hours, it was found to be approximately 0.08 m^{-1}. Then, following Eq. (3), the empirical relation that best described the covariance of visibility range and $c(660)$ was:

$$y = \frac{\Psi}{\alpha} = \frac{3.7}{1.35c(660) + 0.08} \tag{6}$$

The goodness of fit (R-square) was 0.97. It is interesting to note that although the numerator was set as a free parameter in the fitting procedure, it attained the same value obtained in Zaneveld and Pegau (2003).

Finally the visibility range was estimated by combining the two equations and the results can be seen in Fig. 3. Evaluation of (APD) gave an estimated error of 20%. In Fig. 4 the predicted and actual ranges are plotted along with the 20% error lines.

A potential source of error is the omission of the absorption term. CDOM concentration ranged from 0.81 to 2.96 ppb (QSU) whereas chlorophyll concentration from 0.08 to 0.37 mg/m^3. For both parameters the highest values were observed in the waters of Paralia Katerinis beach. This happens due to the prevailing southward flow in

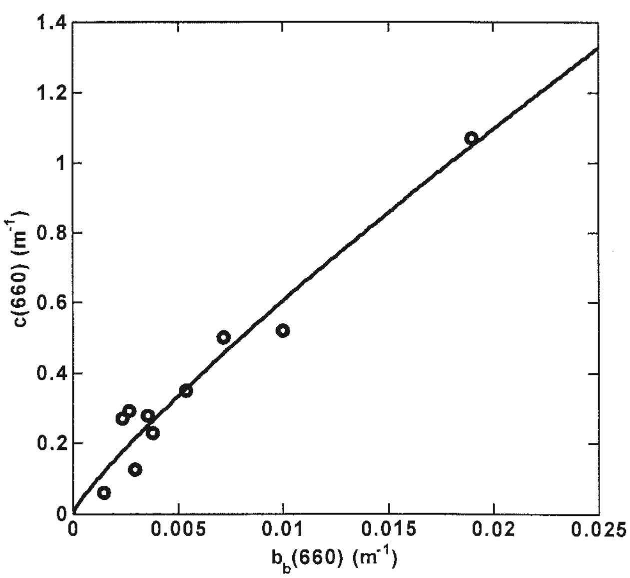

Fig. 2: Covariance of backscattering and attenuation coefficients at 660nm as observed in situ (circles) and fitted with a power law (solid line).

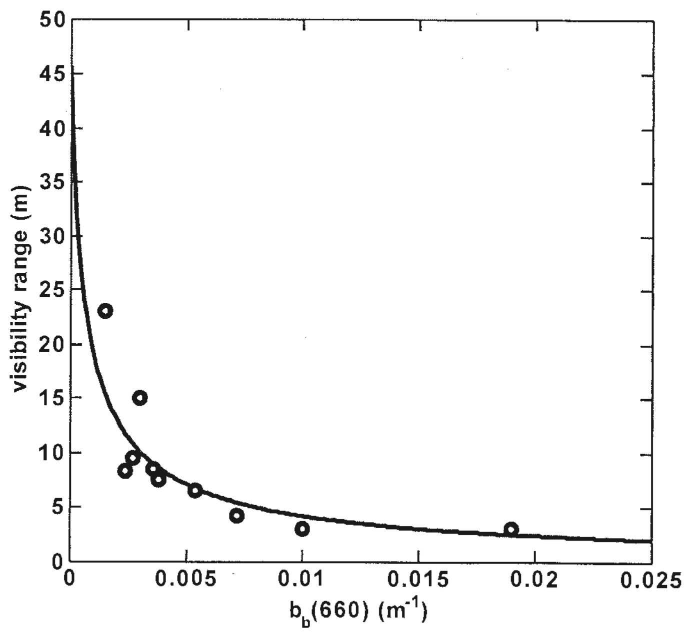

Fig. 3: Covariance of backscattering coefficient at 660nm and horizontal visibility range as observed in situ (circles) and fitted according to equations 5 & 6 (solid line).

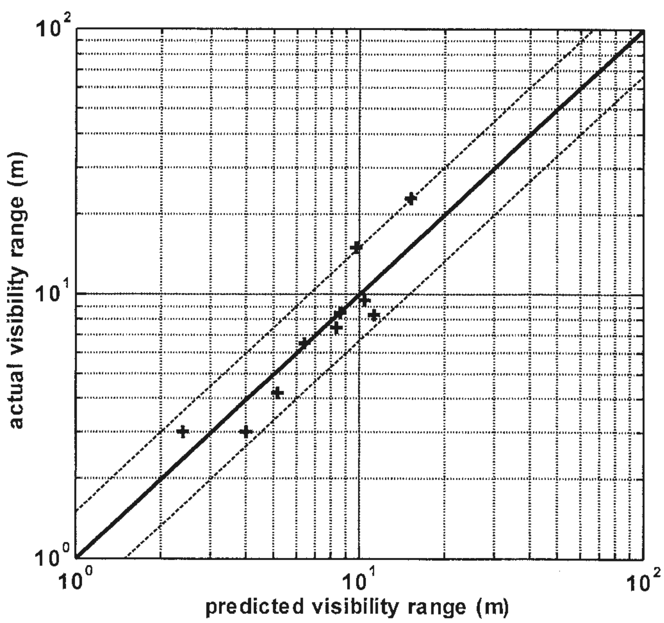

Fig. 4: Predicted and actual horizontal visibility range in all five beach environments. The solid line is the 1:1 line and the dashed are the +/- 20 % lines.

the area which feeds it with the eutrophic and riverine outflow waters of north Thermaikos Gulf. This flow clearly carries large quantities of suspended particles as was recorded by both the attenuation and backscattering meters and is reflected in the observed horizontal visibility. This balances the fact that although CDOM absorption influence in the peak of photopic eye response (555 nm) is small, at the red wavelengths is even smaller. Moreover, there is a tendency also to underestimate the predicted range in waters of high clarity. This is due to the fact that instruments reach their lower limit sensitivity as mentioned earlier.

Conclusions

This is a first attempt to derive an algorithm connecting water turbidity to a more end-user realizable underwater visibility range, an aid to recreational snorkeling in tourist beaches. Returns from all beaches visited, were treated as a common data pool giving encouraging results. Nevertheless, we expect that further collection of regional data will lead to local algorithms having higher accuracy. The final product will provide for each beach management structure that incorporates BEMS, a dedicated algorithm tuned to the local inherent optical properties and the specific turbidity meter used.

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