Light and the Behavior of Pelagic Animals during Night and Crepuscular Periods

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Summary

Light plays an important role in ecological processes in the ocean both day and night. While relatively inexpensive, off the shelf instruments are available to measure Photosynthetically Active Radiation or PAR during the day, efforts to quantify light levels at night have proven more difficult. The goal of this work was to quantify nighttime light levels while simultaneously examining the movement of pelagic animals to explore correlations between light levels and the vertical movement of these animals during crepuscular periods and during the rise and set of the moon.

This study explores two hypotheses about the role of light with respect to the vertical migration of animals in water. The first is that at a constant depth, light levels correlate with the scattering volume, or abundance, of animals in the water column. The experiment failed to prove this hypothesis; therefore, it is concluded that light is not a significant predictor of the amount of animal scattering volume at a constant depth. The second hypothesis tested is that pelagic animals follow an isolume up and down the water column as light levels change. Experiments showed a wide variance in animal scattering volume along an isolume instead of being relatively constant as would be expected if animals followed an isolume. Additional analysis showed no relationship between volume backscatter and depth. Therefore it is concluded that animals do not follow an isolume up and down the water column as light levels vary.

The development of methods to monitor nocturnal behavior of pelagic animals has implications for marine resource management. This study was performed in the Monterey Bay National Marine Sanctuary and provides previously unavailable data to Sanctuary Managers about
important nocturnal marine processes. Sanctuary Managers are mandated to use Ecosystem-Based Management principles in managing the Sanctuary. This is a complex marine ecosystem in which the interaction of small scale components can have large influences in macrosystem dynamics which can feed back to influence smaller scale systems again. To assist them, Sanctuary Managers have developed Resource Preservation and Research plans that require data of many types. Experiments incorporating techniques using acoustical instruments to measure abundance and migration patterns of pelagic animals can help Sanctuary Managers better understand the complex linkages of the marine ecosystem in the Monterey Bay National Marine Sanctuary.
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Introduction

Managers of marine and coastal resources are facing serious challenges. Examples of some of these challenges include the over-exploitation of many marine species, the destruction of important marine habitats, ocean pollution, introduction of invasive species, and global warming and climate change. On top of this, managers must meet multiple and even conflicting legal and societal mandates for the sustainable use of ocean and coastal resources (Link 2002; Link et al. 2002; Slocombe 1998). Focusing on just one or two aspects or uses of the marine environment is not enough (Francis et al. 2007). The complexity of marine ecosystems necessitates a much broader approach to ocean management such as Ecosystem Based Management (EBM) which has become a high priority for managers (Link 2002; Pikitch et al. 2004).

There have been a number of reports from commissions published that embrace EBM as a viable approach for managing our marine resources (PEW Oceans Commission, 2003. US Commission on Ocean Policy, 2004; National Research Council, 1999; West Coast Governor’s Agreement on Ocean Health, 2008). For example, the West Coast Governors’ Agreement on Ocean Health suggests that ecosystem approaches to marine management go beyond single species or single issue management. EBM for the oceans is the application of ecological principles to manage key activities affecting the marine environment. EBM considers the interdependence of all ecosystem components and the environments they live in (Levin and Lubchenco 2008). An EBM approach provides a comprehensive understanding of the ecosystem and is needed to support complex and difficult management systems (Slocombe 1998).
Meeting the goals and objectives outlined for EBM poses serious challenges for marine resource managers. Application of EBM principles to marine resource management requires an understanding of the interactions of organisms in a marine ecosystem and their surrounding environment. They are complex, adaptive systems in which the interactions of small scale components can have large influences in macrosystem dynamics which then feeds back to influence the small scale systems (Levin 1998; Levin 2003; Levin and Lubchenco 2008). Understanding the linkage among these scales and incorporating that knowledge into management actions and policy decisions is paramount (Levin and Lubchenco 2008).

Developing an understanding of these linkages requires an immense amount of new information. Experiments incorporating techniques such as the use of acoustical instruments to measure abundance and migration patterns of pelagic animals can help scientists better understand these complex linkages (Hewitt and Demer 2000; Holliday and Pieper 1995; Warren et al. 2001). The research outlined in this study provides additional information about animal behavior that has previously been unavailable. This study helps reveal more about the function and structure of the marine ecosystem under conditions of low-light and at nighttime. This information can help marine resource managers more clearly understand the role light plays in influencing the nocturnal behavior of pelagic animals and provides data that has heretofore been missing.

Light plays an important role in a number of ecological processes in the ocean. For example, light contributes to the oceans’ temperature regime because light photons are absorbed by water molecules and converted into heat (Lalli and Parsons 1993). More than one-half of the oxygen in our air is generated by the photosynthesis process in the ocean (Reynolds 2006). Animal behavior in the ocean can also be dependent on light. Vision is the primary means of prey
detection and feeding for many animals making foraging at low light levels difficult, necessitating other adaptations for finding food. Prey often moves to lower light levels which can be an active predator avoidance tactic (Abrahams and Kattenfeld 1997). Finally, light can serve as a physiological cue for processes such as Diel Vertical Migration (Lalli and Parsons 1993).

Measurement of light levels in the ocean has focused primarily on Photosynthetically Active Radiation or PAR. PAR is the amount of light available for photosynthesis (Hall 1999). Because light is scattered and absorbed as it penetrates the ocean, there is an exponential decrease in light intensity with increasing water depth, decreasing phytoplankton photosynthetic ability as well. Consequently the maximum depth distribution of phytoplankton is controlled largely by the intensity of light at depth or PAR (Lalli and Parsons 1993). Measurement of PAR during the day is useful to develop a thorough understanding of the photosynthetic processes in the ocean and their effects on our environment.

At night, instead of light being primarily used for photosynthesis, what little light is available from the stars and moon is used for vision. Animals use the available light for predator detection and avoidance as well as feeding (Han and Strakraba 2001). In many parts of the world ocean, a migration of marine animals occurs towards the surface each night. This movement of animals both large and small, called Diel Vertical Migration (DVM) (Gabriel 1988), is hypothesized to be a response to the changing light levels after sunset which allows them to feed in rich surface waters while avoiding predation by visual predators. Figure 1 is a cartoon showing the concept of Diel Vertical Migration. The vertical axis represents depth in the ocean and the horizontal axis represents different light periods of a day. Under daylight conditions, animals suspend
themselves in deeper water where light levels are low enough to avoid predation (Lampert 1989). As the sun sets, surface light levels decrease and animals begin to move up towards the surface to feed on food particles in the shallower depths (Han and Strakraba 2001; Van Gool and Ringelberg 1997). They stay near the surface to feed during the night and if there is a moon rise, they might drop down a little as surface light levels increase. Finally, as the sun rises the next morning, the animals drop down to deeper water where light levels are low to avoid their predators again.

![Diel Vertical Migration](image)

*Figure 1 – Mechanics of Diel Vertical Migration*
Some researchers have suggested that animals accomplish this balance of minimizing the risk of detection by predators while maximizing their opportunities for feeding by remaining at a constant light level, or isolume (Roe 1983; Widder and Frank 2001). As light levels vary during the night, the depth of the isolume moves up and down. Animals are hypothesized to adjust their location in the water column accordingly to maintain optimal benefits. However, little work has been done to test this theory. Widder and Frank (2001) used a low light auto-radiometer (LoLAR) in a submersible to gather light level readings at different depths. The depth of the submersible was adjusted to keep the light input into the LoLAR as constant as possible. Their primary goal was to measure the speed of the isolume as it moves vertically in the water. No real analysis of animal abundance along the isolume was done. They made estimates of animal distribution by running visual transects during the day but were not able to gather abundance data at night. Therefore, no conclusion of the relationship of animal movement and light levels were made (Widder and Frank 2001).

While relatively inexpensive, off the shelf instruments are available to measure PAR during the day, efforts to quantify light levels at night have proven more difficult. This is primarily because the light levels at night are too low to be detected by standard radiometers. The goal of this work was to quantify nighttime light levels while simultaneously examining the movement of pelagic animals to explore the role light plays in the vertical movement of these animals during crepuscular periods and during the rise and set of the moon. There have been few studies to explore animal movement as light conditions change and none have involved using bioacoustical measurement of animal abundance and in-situ light level readings. For example, Nelson, et al. acoustically tracked the movement of a megamouth shark off the coast of California in 1990 during crepuscular periods. Acoustical transmitters were used to track the shark. Their light
data were not taken real-time. Isolume data were constructed from twilight illumination profiles and then adjusted for depth using a seawater light extinction coefficient (Nelson 1997). However, Widder and Frank (2001) point out that to do accurate analysis of the relationship of animal movement in the water and isolumes, in-situ light data is essential. Hernandez, et al. (2001) looked at zooplankton abundance in subtropical waters and tried to correlate those data to lunar cycles. Their abundance information came from historical zooplankton abundance data taken from bi-monthly samples at an oceanic station. Animal samples were taken from oblique tows from 200 m up to the surface. This experiment did not collect any light data for analysis of any relationship between abundance or movement of animals and changing light conditions. They only looked at data from phase changes of the moon (Hernández-León 2001). Finally, Ashjian, et al. (2002) looked at the distribution, annual cycles, and vertical migration of acoustically derived biomass in the Arabian Sea. Estimates of biomass were made using data from deployment of an acoustic Doppler current profiler (ADCP) made over a period of ten cruises along a 1000 km transect. No real-time acoustical biomass data were collected. This experiment also did not collect any in-situ light level data or attempt to correlate distribution or movement of animals in the water to light (Ashjian 2002).

The difference between these few studies and the work presented here is that in this study, light levels are quantified at the surface and down through the water column while simultaneously measuring the vertical movement of mysids and zooplankton using acoustical instruments. This study was performed in shallow water in Monterey Bay, California during May 2008. Of particular interest was analysis of Diel Vertical Migration of zooplankton and mysids due to benthic emergence. Using the quantified light and animal movement data two hypotheses are tested:
1. At a constant depth, light can be used to predict animal abundance.

2. Animals follow an isolume as it moves vertically in the water column.
Methods

Field Site

Data for this analysis was collected during a scientific cruise in May 2008 in the Monterey Bay National Marine Sanctuary (MBNMS) in Northern California. The MBNMS is the nation’s largest Marine Sanctuary, encompassing approximately 350 miles of California coastline extending from San Francisco Bay in the north to approximately 100 miles south of Monterey Bay. The sanctuary waters host a variety of diverse habitats from lush kelp forests to productive coastal lagoons to deep sea communities in water over 3000 meters deep. A combination of geological and oceanographic characteristics in the sanctuary contributes to providing highly nutrient rich waters within the sanctuary boundaries. Because of the high concentration of nutrients in the water this area is rich with animal life and contains some of the greatest biodiversity in the temperate regions of the earth. Other habitats outside the sanctuary boundaries are also linked to the MBNMS and are critical for migrating species that frequent the area (http://montereybay.noaa.gov/).

During the period from May 17 to May 27, 2008 a scientific cruise on the 16 m R/V Shana Rae was undertaken in Monterey Bay National Marine Sanctuary (MBNMS) to collect data on light levels and acoustical backscatter from pelagic animals. The general data collection area was chosen because of the high water column productivity observed during previous experiments (Benoit-Bird, unpublished data) and was somewhat protected from strong winds from the northwest. Sampling occurred between 2 and 6 km from shore in shallow water from 15 to 25 meters deep. Figure 2 is a site map of the experiment area in the Monterey Bay National Marine
Sanctuary. Stationary experiment sites are labeled as Sun-Moon Stations 1-6 and are shown as orange dots on the site map. Transect grids were followed from stations A1-A5 and G5-G1. The individual station sites shown are CTD sampling sites performed on the transect grids.

Figure 2 - Site map of project experiment area in Monterey Bay, California. Stationary stations are labeled as Sun-moon Stations 1-6 and shown as orange dots. Transect grids were performed from stations A1-A5 and G5-G1. CTD sampling was performed at individual station sampling sites.

**Data Collection**

Data were collected from approximately two hours before sunset until about 6 hours after sunset each day. During 6 nights, data were collected at one of the four stationary sites shown by the orange dots. On 2 other nights, sampling was conducted over a predefined transect grid. During all sampling, a SBE19 plus CTD was deployed at half hour intervals to gather temperature, salinity, and depth data. The CTD was also equipped with a WetLabs C-Star transmissometer (25 cm path length, 530 nm wavelength), to gather information on light transmissivity in the
water column. Every hour, a vertical plankton net tow with a 0.75 m diameter, 333 µm mesh net equipped with a General Oceanics flowmeter was made to gather samples of animals.

**Acoustic Measurements**

The movement of pelagic animals up and down the water column was tracked by recording the acoustical backscatter of the animals using a calibrated, split-beam, four-frequency echosounder system (SIMRAD EK 60 at 38, 70, 120 and 200 kHz). The echosounder transducers were mounted 1 m below the surface on a flat plate attached to a rigid vertical pole secured to the side of the ship. The 38 kHz echosounder had a 12º conical beam. The 70 kHz echosounder had a 7º conical beam. The 120 and 200 kHz echosounders each had a 7º conical beam. All four frequencies used a 256 µs pulse resulting in a vertical resolution of 10 cm. The echosounders were calibrated in the field following the procedures outlined by Foote et al. (1987).

**Acoustic Data Analysis**

Acoustic backscatter data collected on the echosounder system were processed with Myriax’s Echoview software. Shown in Figure 3 is a plot of the data collected by the 120 kHz Echosounder on May 21, 2008. This plot, or echogram, shows the depth of the water column on the vertical axis ranging from the surface to the bottom which was 15 meters at this site. The horizontal axis displays the time span of this echogram which is 6 hours. The colors shown on the echogram are indicative of the strength of the backscatter signal received by the echosounder from animals in the water. The color bar on the right of the figure shows the relative differences in signal strength with the browns and reds having the highest backscatter levels and the blue and gray colors showing weaker backscatter signal strength. The metric used on the color bar is Scattering Volume, or $S_v$. It is a logarithmic measure of volume backscatter. The metric used in this analysis is Nautical Area Scattering Coefficient or NASC. NASC is a linear measure of
backscatter and is proportional to animal abundance. NASC is measured in units of m²/nmi².

See Maclennan et al. (2002) for more details on the derivation and measurement of NASC.

Further examination of Figure 3 shows strong signal returns in the surface waters. These signals, indicated by brown color, are caused by noise bubbles and/or fish near the surface. Because of this strong noise layer, analysis of animal movement in this experiment was done starting at depths below 2 meters. The blue patches (circled in red) are signal returns from zooplankton. Note that there are areas of marked vertical movement towards the surface as indicated by the arrows on the echogram. Near the far lower right of the echogram we can see emergence of benthic animals (circled in green) that have emerged from the sediment layer.

Figure 3 – Echogram of 120 kHz Echosounder data taken on May 21, 2008
Data collected during these six nights were analyzed to explore what relationship there might be between volume backscattering and light levels. Backscatter data analysis was done by creating 1 meter vertical by 1 minute horizontal bins and integrating the NASC within each bin. The integrated values are proportional to the animal abundance in each bin area. Data were separated into discrete depth levels ranging from 2 to 15 meters below the echosounders. The light and volume backscatter data collected were used to test two separate hypotheses:

1. At a constant depth, the total acoustic backscatter, which is a measure of animal biomass in the water, would be inversely proportional to light level.

2. Animal biomass will remain constant at a constant light level or isolume, even as the isolume moves vertically in the water column.

To analyze relationships between illumination levels and animal abundance at constant depths, NASC was examined as a function of illumination to determine if animal abundance varied inversely with light levels. To test for significance in the correlation between light levels and volume backscatter over the sampling period, data were scaled to a percentage of maximum NASC and percentage of maximum illumination from a specific depth. Scaling of the data was done to eliminate differences in magnitudes of NASC and light level between days and depths. A regression analysis was performed on the data.

To see if animals follow an isolume vertically in the water column, a band of +/- one meter depth around the isolume was established. Averaged values of volume backscatter within the +/- one meter band were calculated and plotted as a function of time along with the isolume to see how the volume backscatter varied along that isolume. Scatter plots were also generated to explore
the relation between NASC and depth of an isolume and the relation between NASC and depth without regard to any isolume. Scaled percentages of maximum NASC and percentages of minimum depth were used to eliminate differences in the magnitudes of NASC and depth between days. In each case, regression analysis was then performed.

**Light Level Measurements**
The measurement of surface light level intensity and changes was done using custom, very sensitive light sensors. These measurements were coupled with profiles of light attenuation down through the water column from the transmissometer to develop a profile of light level in the water column.

**Light Measurement**
A custom light sensor, called the Nightlight, was developed for recording extremely low light levels during the night (Wisdom and Benoit-Bird 2008 (in review) Appendix 1). Four Nightlight sensors were used during this cruise and were mounted in the “crow’s nest” or top of the mast of the R/V Shana Rae. The top of the mast location was used because it provided a mounting location that was minimally affected by the operation and running lights of the ship. A previous deployment of the Nightlight sensors where there was interaction with ship operation lights showed the critical importance of proper Nightlight sensor placement (Wisdom and Benoit-Bird 2008 (in review) Appendix 1). The Nightlight sensor contains a datalogger and stores the output of a photodiode that measures the light level. These instruments were calibrated by Wisdom and Benoit-Bird (in review) to provide absolute light levels at the surface of the ocean. The dataloggers were programmed to start recording light level data approximately two hours before
sunset and to stop recording data two hours after sunrise the next morning.

To determine light levels down through the water column, measurements of the transmission of light through the water column were needed. The transmissometer used here measured light attenuation at 530 nm, the peak sensitivity of the light measured by the Nightlight and near a peak of the spectrum of nocturnal light (Johnsen 2006). Integrated into the CTD, the transmissometer was lowered down into the water every one-half hour during each evening of the cruise, providing data on the transmissivity and depth 8 times a second as it transversed from the surface to near the bottom and back.

**Light Data Analysis**

To explore what correlation there might be between light and vertical movement of pelagic animals in the ocean, one must be able to measure the levels of light intensity during sampling periods. Measurement of light during the day is relatively easy. A radiometer is used to make daytime light measurements. It measures irradiance in standard wavelengths from 400 to 865 nm. Sensitivity for this type of instrument ranges from 300 to 2.5 E-03 µwatts/cm².

Unfortunately, radiometers intended for use during the day are not sensitive enough for measurement of light levels during crepuscular periods or nighttime. Kaul, et al.(1994) measured the available light on a cloudless, moonless night to be as small as 9.6 *10^-5 µwatts/cm². To overcome this problem, a custom, very sensitive light sensor was developed called the Nightlight (Wisdom, Benoit-Bird 2008 (in review) Appendix 1). This sensor is simple, inexpensive, easy to operate, and is very sensitive. The measured sensitivity range of a typical Nightlight sensor is from 12 to 1.7 x10^-9 µwatts/cm².
Figure 4 shows the calibrated data from a typical Nightlight sensor collected in Monterey Bay on May 21, 2008 over the time period from 1800 to 0030 local time the following morning. Sunset was around 2120 and moonrise was around 2215 local time as shown by the red lines in the plot.

Figure 4 – Typical plot of Nightlight Sensor output (µwatts/cm²)

Figure 5 is the same data but with the Y axis converted to a log scale to show the variability of the light sensor output more clearly.
Figure 5 – Log Plot of Nightlight Sensor output illustrating the variability of Nightlight Sensor output

Using the surface light levels recorded by the Nightlight sensor at the exact times the transmissometer was deployed, profiles of the light levels down the water column can be developed. Figure 6 shows plots of transmissivity data and light levels down the water column for data collected on May 21. The left plot shows light transmission as a percentage and the right plot is illumination versus depth in meters. Transmissivity is measured as a percent and represents the amount of light penetration down through the water column. Illumination is measured as $\mu$watts/cm$^2$. The surface light level recorded by the Nightlight sensor can then be applied to the transmissivity data and the result is a plot of the decay of light levels as water depth increases. As can be seen, the illumination levels drop off quickly from the surface to
approximately three meters in depth and more slowly as depth increases as shown by the right plot in Figure 6.

![Figure 6 - Plots of transmissivity percentage and light levels in water column vs. depth. Light levels drop off dramatically from the surface to approximately 3 meters in depth.](image)

To see how the depth of constant light level varies over time, depth data throughout an experiment period for a constant light level were plotted. Figure 7 shows the variance of the depth of a constant light level of 0.01 µwatt/cm² throughout the night of May 20, 2008. This plot of constant illumination varying over time and/or depth is called an isolume. The vertical axis shows the depth of the isolume in meters and the horizontal axis is the time the transmissivity readings were taken that evening. On this day, sunset was at 2012 local time and moon rise was at 2121 local time as indicated by the vertical red lines in Figure 7. Looking at the plot we can see how the isolume depth decreases as the sun sets and it increases as light levels increase with
the moonrise. Note that it takes a few minutes for the isolume to begin moving into deeper water. The reason is that the moon has to rise above the horizon somewhat to begin having an effect on the isolume.

![Diagram](image)

**Figure 7** - Plot of 0.01 µwatt/cm² isolume on 20 May, 2008. The vertical red lines indicate the time of sunset and moonrise. Note the lag time before the depth of the isolume increases due to the time required for the moon to raise high enough to have an effect on surface light levels.
Results and Discussion

Hamner describes Diel Vertical Migration or DVM as perhaps the most massive animal migration on the planet (Hamner 1988). It has been suggested that animal distribution patterns in the ocean can be affected by light (Widder and Frank 2001). There are two popular hypotheses about the role light may play in vertical migration of animals in the ocean. One is the “rate of change” theory. It suggests that animal migration might be affected by light intensity change and/or direction of change (Clarke 1930; Ringelberg 1964). The other is the “preference” theory. It suggests that animals prefer certain light levels or zones and will follow those zones up and down the water column as the amount of light available varies with depth (Russell 1926; Roe 1983; Widder and Frank 2001).

The first hypothesis tested in this experiment is that at a constant depth, the total acoustic backscattering, a measure of the biomass of animals in the water, would be inversely proportional to light level. To test this hypothesis, volume scattering and light level data were collected during a scientific cruise in Monterey Bay National Marine Sanctuary in May, 2008. Contrary to our expectations, we found no predictable pattern in the relationship between light level and acoustic backscatter signal. Figure 8 is an example of data collected during the evening of May 19. Plotted on the vertical axis is Nautical Area Scattering Coefficient or NASC in units of \text{m}^{2}/\text{nmi}^{2} at a depth of three meters. The dots on the plot are estimates of animal abundance derived by integrating data from the echosounder in 1 meter depth by 1 minute time bins. The resultant value is the estimated animal abundance in that area or NASC. Plotted on
the horizontal axis is the light level present at a depth of 3 meters at various times during the night when transmissivity data were collected from CTD deployment. The illumination values were calculated using data from the Nightlight sensor coupled with measures of the water column transmissivity. In this case, as light levels decrease, volume scatter *increases* which would be expected if animals do migrate upwards towards the surface as light levels decrease.

**Figure 8** – Nautical Area Scattering Coefficient (NASC (m$^2$/nmi$^2$)) vs. Illumination (µwatts/cm$^2$) at a depth of 3 meters on May 19. The dots on the plot are estimates of animal abundance derived by integrating data from the echosounder in 1 meter depth by 1 minute time bins. The plot shows NASC or volume scattering increasing as light levels decrease.

Figure 9 is a plot of data taken at three meters depth on May 20. Interestingly, this plot shows the volume scattering *decreasing* as the light levels decrease. This pattern is contrary to what the
prevailing theory suggests: that animals should migrate upwards at low light levels, resulting in
an increase in volume scattering at shallow depths as light levels decrease.

Figure 9 - Nautical Area Scattering Coefficient (NASC (m$^2$/nmi$^2$)) vs. Illumination (µwatts/cm$^2$) at a depth of 3 meters on May 20. The dots on the plot are estimates of animal abundance derived by integrating data from the echosounder in 1 meter depth by 1 minute time bins. The plot shows NASC or volume scattering decreasing as light levels decrease.

The same analysis was done for a depth of fifteen meters. Figure 10 is a plot of volume scattering versus light levels at a constant depth of fifteen meters for data collected on May 26. Volume scattering decreases as light levels decrease which seems logical if animals migrate to
the surface as light levels decrease. If animals migrate towards the surface the abundance should decrease in deeper water levels.

Figure 10 - Nautical Area Scattering Coefficient (NASC (m\(^2\)/nmi\(^2\))) vs. Illumination (µwatts/cm\(^2\)) at a depth of 15 meters on May 26. The dots on the plot are estimates of animal abundance derived by integrating data from the echosounder in 1 meter depth by 1 minute time bins. The plot shows NASC or volume scattering decreasing as light levels decrease.

On the other hand, data shown in Figure 11 for a fifteen meter depth on May 17 illustrates just the opposite: In this case we can see an *increasing* trend in volume scattering as light levels *decrease* which is again contrary to what one would expect.
Figure 11 - Nautical Area Scattering Coefficient (NASC (m²/nmi²)) vs. Illumination (µwatts/cm²) at a depth of 15 meters on May 17. The dots on the plot are estimates of animal abundance derived by integrating data from the echosounder in 1 meter depth by 1 minute time bins. The plot shows NASC or volume scattering increasing as light levels decrease.

Examination of the rest of the data from other days and other depths showed these same contradictions. On a given day, some depths showed increases in volume scattering as light levels decreased and other depths showed decreases in volume scattering.

To determine if there was any significant relationship between the light levels and volume scattering over the sampling period, the data from each day were scaled into percent of maximum NASC and percent of maximum illumination from that depth during that day in order to eliminate differences in the magnitudes of NASC and light levels between days and depths. Figures 12 and 13 are scatter plots of data taken for all six days at a constant depth of three
meters and fifteen meters, respectively. Linear Analysis indicates that there is no significant relationship between light levels and volume scattering at constant depth. Based on this data set, we can conclude that light alone is not a significant predictor of the volume scattering, a measure of animal biomass, present at a constant depth in this area of Monterey Bay. The migration patterns recorded for a particular depth were not consistent. Some days showed an upward movement, some depicted downward movement and others showed no dramatic movement at all. This suggests that this particular area experiences some upward vertical migration, some downward or reverse vertical migration, and perhaps some horizontal migration or advection of animals during each evening.

Figure 12 – Scatterplot of % Maximum NASC vs. % Maximum Illumination at constant 3 meters depth for data collected on all six days of the experiment. Low $R^2$ value indicates that there is no significant relationship between volume scattering and light levels at a constant depth.
Figure 13 - Scatterplot of % Maximum NASC vs. % Maximum Illumination at constant 15 meters depth for data collected on all six days of the experiment. Low $R^2$ value indicates that there is no significant relationship between volume scattering and light levels at a constant depth.

The second hypothesis tested in this experiment is that animals follow an isolume. If the theory that animals attempt to remain at a constant light level is true, it can be hypothesized that animal biomass measured as NASC will remain constant at a constant light level or isolume, even as this isolume moves vertically in the water column. Contrary to our predictions, we found that animals do not simply follow isolumes and that there is no significant relationship between animal volume scattering and depth. Figure 14 shows the variability of the depth of the 0.1 µwatt/cm² isolume over time taken on May 17, 2008. In this instance, light data were collected
starting two hours before sunset and continued throughout the night. On this evening sunset was at 2012 local time. The plot shows the movement of this isolume towards the surface as surface light levels diminish. Around 2130 we see the direction of the isolumes vertical movement change as a result of the rise of a nearly full moon at 2121 local time.

![Plot of 0.1 µwatt/cm² isolume on 17 May, 2008](image)

**Figure 14 – Plot of 0.1 µwatt/cm² isolume on 17 May, 2008**

To test the hypothesis that animals follow an isolume, a +/- 1 m band around the isolume was created as shown in Figure 15. Average values of volume backscatter within the +/- 1 meter band were calculated and plotted as a function of time to estimate the variance of volume scattering about the 0.1 µwatt/cm² isolume. If the animals prefer to remain at an isolume as hypothesized, one would expect a relatively constant amount of volume backscatter over the
entire evening. Figure 16 shows two curves; a constant level of animal abundance (solid black line) as would be expected if animals follow an isolume and the actual animal abundance (dashed red line) calculated by averaging the NASC values within the +/- 1 meter band around the isolume. The plot shows that there is wide variation of animal abundance around the isolume instead of being constant as predicted. Individual isolume plots along with volume scattering data were made for a number of light levels and days. Each plot showed the same wide variation in animal abundance we see in Figure 16. The results indicate that the amount of volume backscatter varies considerably along an isolume rather than being relatively constant so it is concluded that animals are not simply following an isolume up and down the water column.

Figure 15 - Plot of +/- 1 meter band around the 0.01 µwatt/cm² isolume of May 17, 2008
Figure 16 – Plot of predicted constant level of animal abundance (black) and actual averaged volume backscatter or NASC (dashed red) calculated +/- 1 meter about the isolume. Plot shows considerable variability of volume scattering along an isolume instead of being relatively constant.

While there does not appear to be any relationship between volume backscatter and the isolume, there might be a relationship between volume backscatter and the depth of isolumes. To test this, the percent of maximum NASC was plotted as a function of the percent of minimum isolume depth for all data collected for the following isolumes: 1, 0.1, 0.01, 0.001, 0.0001, $1 \times 10^{-5}$, and $1 \times 10^{-6}$ μwatt/cm². The NASC and depth numbers were scaled to a percentage of the maximum NASC and minimum depth values recorded for each day to eliminate differences of variances of NASC and depths between different isolumes and days. The results are shown in Figure 17. A linear trend line and the $R^2$ value are shown on the plot. The $R^2$ value of 0.242 indicates that there might be a relationship between volume backscatter and the depth of the isolume. An
exponential curve was also fitted to the data and an $R^2$ value of .311 was calculated. The relative difference in goodness of fit ($R^2$ values) did not change significantly using exponential regression compared to linear regression, suggesting that the pattern shown in the figure is robust.

To test if this effect was simply related to the depth rather than the depth of the isolumes, the relationship between the percentage of maximum NASC each night as a function depth for data taken at 2,3,4,5,7,10, and 15 meters. The results are shown in Figure 18. The small $R^2$ value of 0.057 indicates that there is no significant relationship between volume backscatter and depth. An exponential curve was also fitted to the data and an $R^2$ value of .147 was calculated. The relative difference in goodness of fit ($R^2$ values) did not change significantly using exponential regression compared to linear regression, suggesting that the pattern shown in the figure is robust. The relationship observed in Figure 18 is not simply a response of the acoustic scatterers to depth, but to the interaction of in-situ light levels and depth.
Figure 17 – Scatterplot of % Maximum NASC vs. % Minimum Depth along isolume depths. The $R^2$ value indicates there might be a relationship between volume scattering and depth of an isolume.
Figure 18 - Scatterplot of % Maximum NASC vs. Depth without regard to any particular isolume. The R² value indicates no significant relationship between volume scattering and depth.

Discussion

Two theories on the role light has with respect to the vertical migration of animals in the water are explored in this experiment. The first is that at constant depth, as light level decreases, acoustic scattering, a measure of animal abundance, is inversely proportional to light levels. Therefore, at shallower depths, it is expected that there will be an increase in volume scattering as light levels decrease and at deeper depths, the volume scattering should decrease. However, our experiments failed to support this hypothesis. At all depths, we noted both increases and decreases of volume scattering from day to day and from depth to depth with no discernable pattern forming. Therefore we conclude that animals do not seem to use light alone to determine...
their position in the water column and that light is not a significant predictor of the amount of volume backscattering at constant depth.

The second theory is that animals follow an isolume up and down the water column as light levels change. Individual isolume plots along with volume scattering data showed scatter volume varying widely along an isolume rather than being fairly constant as one would expect if animals followed an isolume. Additional analysis showed that there may be a relationship between volume backscattering and depth along a specific isolume but no relationship between volume backscatter and depth in general. The implication of these findings is that animals do not simply follow an isolume up and down the water column as light levels vary. There is no significant relationship between depth and animal volume scattering and that vertical migration of pelagic animals is a much more complex relationship that involves the interaction of both light and depth.

There are some things that should be pointed out that may impact the results of this study. First, there is some inherent heterogeneity in the data. One cause is the result of a long sampling period of transmissivity data. The transmissivity data were collected on ½ hour intervals. Consequently, illumination data used in the analysis were not continuous over time. The effect of this is that we are looking at light level changes at ½ hour increments instead of being continuous. Also, the animal abundance data used were those values recorded at the time the transmissivity data were collected. This results in fewer data points being available for analysis. An alternative to this approach would be to analyze all transmissivity data collected during one night time series and see how much the transmissivity varies. If there is not much variation during the evening, then a general profile of transmissivity down the water column for that night
could be derived and applied throughout the night resulting in having many more data points available for analysis. Another potential cause of data heterogeneity is animal patchiness in the water. The boat was drifting with the current and wind and could move over a patch of zooplankton quickly which may affect animal volume scattering numbers. In addition, horizontal advection of zooplankton may affect volume scattering as the animals move through the study area.

A second issue is the effect of ship running/operation lights at night. One problem is that bright lights around a boat do attract many marine animals towards the surface. Care must be taken to remove the effects of extraneous light as much as possible during nighttime studies to avoid artificial increases of animals in water near the surface. During this study, extreme care was taken to eliminate all effects of ship operation/running lights during data collection periods.

Another issue is that the Nightlight Sensors are extremely sensitive and recorded light data can be affected adversely by even the slightest addition of artificial light. In this study, the sensors were mounted on the mast of the ship inside the “crow’s nest” to eliminate any affects ship lights might have. In addition, only flashlights were used on deck while collecting data. These precautions insured that light data recorded by Nightlight Sensors were only from nocturnal light and not from the ship.

Finally, this was a shallow water study to analyze vertical migration of mysids and zooplankton due to benthic emergence. The results presented in this study are specific to the shallow waters in this ecosystem. It is not known how these results might be transferred to marine ecosystems in other parts of the world.
Implications for Monterey Bay National Marine Sanctuary Managers

The West Coast Governors’ Agreement on Ocean Health, the US Commission on Ocean Policy and the PEW Oceans Commission recommend the principles of Ecosystem Based Management (EBM) be used as guidelines for managers of marine resources (PEW Oceans Commission, 2003; US Commission on Ocean Policy, 2004; West Coast Governor’s Agreement on Ocean Health, 2008). Marine resource managers other than those responsible for marine sanctuaries are not yet mandated to use EBM principles but many are integrating them into their management strategies. Managers of marine sanctuaries such as the Monterey Bay National Marine Sanctuary, however, are mandated to use EBM principles in managing the nation’s marine sanctuaries by the National Marine Sanctuary Act (NMSA) (16 U.S.C. 1431) (http://sanctuaries.noaa.gov/about/legislation/). Two important goals of the NMSA include:

1. Maintain the biological communities in national marine sanctuaries, to protect and restore and enhance habitats, population and ecological habitats.

2. Support, promote, and coordinate scientific research on, and long-term monitoring of, the resources of the marine areas.

In response to the EBM mandate the managers of the Monterey Bay National Marine Sanctuary (MBNMS) adopted a Sanctuary Action/Management Plan and Environmental Impact Statement (http://sanctuaries.noaa.gov/jointplan/fmp/101408mbnmsfmp.pdf). Two key areas of emphasis for Sanctuary Managers are the protection of Sanctuary resources and marine research. The
Sanctuary Action/Management Plan identifies a number of key strategies to be implemented to address these areas (http://montereybay.noaa.gov/intro/mbnms_eis/). A scientific research framework has been established outlining three types of scientific studies that are essential to implementing the Action/Management Plan strategies (http://montereybay.noaa.gov/intro/mbnms_eis/):

- **Baseline Studies** – Studies that are designed to obtain an understanding of the ecology of the Sanctuary at present.

- **Monitoring Studies** – Monitor Sanctuary data over longer periods and use this data to make adjustments to management policies and/or adapt to changing conditions as they occur.

- **Predictive Studies** – Analysis of causes and consequences of ecosystem changes that are more short-term in nature and are intended to address immediate management issues.

The stated highest priority of the Sanctuary is to “protect its marine environment, resources and qualities”. A key part of this objective is to ensure that research results and scientific data collected from the marine sanctuary are utilized by appropriate management agencies in their resource protection strategies. Managers realize that scientific investigations and research into Monterey Bay ecosystem structures and functions are essential.

The acoustical study collecting data on pelagic animal abundance and behavior presented here can help Sanctuary Managers meet these goals. While light has been identified as playing a role in the behavior of marine animals at nighttime (Widder and Frank 2001), no data has been available that correlates nocturnal behavior of pelagic animals with changing
low-light conditions. Integrating information about the structure and function of the marine ecosystem under conditions of low-light and at nighttime, as outlined here, provides information about ecosystem processes which has been largely unavailable. Following are some specific examples of how MBNMS managers can be informed by the data presented.

*Predator/prey interaction* – Monterey Bay is an important stop-over for migrating Grey Whales (Pelagic Working Group 2002; Forney 2007). They rely on mysids, a type of zooplankton, and herring/sardine populations for food (Pauly et al. 1998, Darling 1998). Typically, mysids, sardines, and herring congregate and feed on plankton in surface waters at night (Nilsson 2003, Mackinson 1999). A fluctuation in the abundance of prey animals or a change in prey migration patterns could impact the distribution and residence patterns of migrating whales in the Sanctuary as well as their overall health. Our results show that in the Northeast corner of Monterey Bay, there is no clear diel benthic emergence pattern of mysids. Our data suggest a much more complicated pattern of near bottom scatterers in response to time of day, depth, and light. This provides baseline data describing the nocturnal behavior of mysids and other pelagic animals in this part of Monterey Bay. Using the techniques outlined in this project, baseline data for other areas of Monterey Bay could also be obtained and compared with periodic monitoring studies to look for changes or alterations of nocturnal prey behavior that might affect the health of the prey populations and ultimately the health of the migrating whales. This knowledge could enable managers to adjust their Grey Whale management plans in the Sanctuary accordingly, for example reducing boat traffic or limiting fishing effort in key prey areas during grey whale residence.
Schooling Pelagic Fishery – The night fishery for pelagic schooling fish (sardines, anchovies, and herring) in Monterey and San Francisco Bays are the northernmost sardine fishing centers in California. Schools of Pacific Herring that move into the state's northern bays to spawn provide an important food source for other animals including invertebrates, fish, birds and mammals [http://www.dfg.ca.gov/marine/herring/oc_article.asp]. Herring in California have been harvested primarily for their roe, with small amounts of whole herring marketed for human consumption, aquarium food, and bait [http://www.dfg.ca.gov/marine/status/pacific_herring.pdf]. These fish feed on plankton that resides in the bay (Cascorbi 2004). During nighttime, small animals typically migrate towards the surface to feed. The herring and sardine schools follow and congregate near the surface, feeding on the plankton and other small animals. This congregation of sardine, anchovy, and herring schools makes the fish more catchable at night. Having access to data on the nocturnal behavior of these small animals can help managers develop an understanding of the location and distribution of these schooling pelagic fish at night and obtain an estimate of the abundance of the food sources for these fish. Shifts in abundance or migration patterns of the plankton food source could be an indicator of pending problems or changes with this fishery. Using this information, managers can make predictions about the effects on this fishery and can alter their management strategies as necessary.

Changes in relative distribution – Changes in animal density or distribution can be an indicator of some sort of perturbation in the marine ecosystem. Natural phenomena such as Sea Surface Temperature change or an ENSO (El Niño – Southern Oscillation) event are known to alter oceanic characteristics and can affect the behavior of animals in the water (Crocker et al. 2006; Ottersen et al. 2001; Trillmich and Limberger 1985). Changes in the nocturnal migration pattern or distribution/abundance shifts can alert Sanctuary managers of potential problems.
This data can help them determine the locale and extent of the perturbation and provide valuable data for modeling the effects to Sanctuary waters.

*Studies of the health of whales, pinnepeds and seabirds in the Sanctuary* – The health of these animals is of primary concern for Sanctuary Managers. Prey abundance and distribution studies can help managers understand population changes in a particular sea mammal or sea bird. Fluctuating abundance or changes in migration patterns of food sources could be essential information to managers monitoring and protecting the health of these species providing explanations for observed patterns or ruling out potential impacts. Nocturnal behavior studies of the prey of animals like murres and sea lions that are known to feed at night on resources that are often unavailable during the day would be especially invaluable by providing insight into night predator/prey interaction that has not been available until now.

*Marine Protected Areas (MPAs)* - In addition to protecting Sanctuary resources and conducting marine research, MBNMS managers must also manage the Sanctuary as a Marine Protected Area (MPA). MPAs are an important conservation tool for marine resource managers. The World Conservation Union (ICUN 1988) formally defines a MPA as “any area of inter-tidal or sub-tidal terrain, together with its overlying water and associated flora, fauna, historical and cultural features, which has been reserved by law or other effective means to protect part or all of the enclosed environment” ([http://cmsdata.iucn.org/downloads/wpamarinepoaen.pdf](http://cmsdata.iucn.org/downloads/wpamarinepoaen.pdf)). Over the years the term MPA has emerged as a commonly used term implying conservation of species and communities (Allison et al. 1998). In 1999 the State of California approved the Marine Life Protection Act ([http://www.dfg.ca.gov/mlpa/](http://www.dfg.ca.gov/mlpa/)) that mandates the state design and manage an improved network of marine protected areas in state waters. The MBNMS responded to this
mandate by considering the addition of more MPAs within Sanctuary boundaries as a priority issue to be addressed in its Marine Protected Areas Action Plan (http://montereybay.noaa.gov/resourcepro/resmanissues/mpa.html). The overall goal of the Sanctuary managers is to determine if the addition of more MPAs can play a role in conservation and management of the marine resources in Sanctuary waters. To effectively do this, important biological data will be critical in the design and location of additional MPAs in the Sanctuary. For example, knowledge of consistent migration patterns could help define MPA boundaries. Data collected in low-light conditions or at nighttime might reveal hot spots or areas where animals are congregating and feeding at night but may not be in during the day. Those areas could be important habitats for pelagic animals and should be considered for inclusion into the boundaries of the MPA.
Conclusion

The purpose of this project was to quantify nighttime light levels while simultaneously examining the movement of pelagic animals to explore the role light plays in the vertical movement of these animals during crepuscular periods and during moon rise and setting events. The quantization of extremely low levels of light at night was done using a custom, very sensitive light sensor called the Nightlight. Surface light level data from Nightlight sensors were used along with water column transmissivity data to develop profiles of light levels down the water column for each day of the experiment. These light profiles along with animal volume scattering or abundance data were then used to explore two hypotheses about the role light plays in the vertical movement of pelagic animals.

The first hypothesis tested was that at constant depths, light levels can be used to predict the amount of volume scattering or abundance of animals in the water. Analysis of volume backscatter data versus illumination levels at constant depth revealed that there is no significant relationship between light levels and volume scattering at constant depths, contrary to the hypothesis. The second hypothesis tested was that animals follow an isolume up and down the water column as light levels change. Individual isolume plots along with volume scattering data showed the amount of scattering varying widely along an isolume instead of being fairly constant as was expected if animals follow an isolume. Instead, a complex relationship between volume scattering, light levels, and depth of isolumes exists. Additional analysis of volume scattering and depth without regard to specific isolumes showed no significant relation between scattering volume and depth.
Managers of Monterey Bay National Marine Sanctuary face many challenges. They are mandated by the National Marine Sanctuary Act to manage the Sanctuary using Ecosystem-Based Management principles. They must address multiple and even conflicting societal mandates for the sustainable use of ocean and coastal resources. The complexity of marine ecosystems necessitates a much broader approach to ocean management.

The response to these challenges was a Sanctuary Management and Action Plan by which managers manage the MBNMS. Two key strategies of the Management/Action Plan are data collection on oceanographic parameters of the Sanctuary and establishment of a monitoring program to assess environmental changes as they occur due to natural and human causes. A scientific research framework was developed to implement these important strategies. It consists of three different types of studies: Baseline, Monitoring, and Predictive. All three studies will require an immense amount of data from numerous sources. One key source could be acoustical instruments that can provide information on the behavior and abundance of pelagic animals in the Sanctuary. The work done on this project specifically provides additional information about nocturnal animal behavior that has previously been unavailable in Monterey Bay and elsewhere. The research helps reveal more about the function and structures of the marine ecosystem under conditions of low-light and at nighttime. Having access to animal behavior and movement in low-light conditions and at nighttime provides sanctuary managers with new data that can be used to help determine if there are differences in animal distribution between day and nighttime and if so, how those differences affect other animals in the Sanctuary. This information also helps managers in MBNMS more clearly understand the role light plays in influencing the nocturnal behavior of pelagic animals in Sanctuary waters.
References


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Appendix 1
An inexpensive sensor for nocturnal measurement of light
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Running head: Nocturnal light sensor
Acknowledgments

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Abstract

Light during crepuscular periods and at night plays an important role in the behavior of many animals in the ocean, most notably in diel vertical migration. Commercially available instruments are not sensitive enough to measure the low light levels found at night. A simple, easy to deploy, inexpensive custom instrument was developed to provide measurements of irradiance during these periods. A calibration technique using polyethylene sheets to attenuate light from a constant light source was developed to compare the custom instrument to a calibrated radiometer that had a much different sensitivity range. The custom instrument was shown to be robust and to provide stable measurements. Calibrated values show the custom instrument has a sensitivity range of $1.7 \times 10^{-9}$ to $12.3 \mu$watts/cm$^2$; suitable for measurements to be made on the darkest nights. Preliminary at-sea tests combined with acoustic sampling of the movements of scattering layers illustrate the importance of quantifying light levels found at crepuscular periods and at night in order to understand changes in the behavior of pelagic animals in the ocean.

Introduction

Light plays a significant role in many ecological processes of the ocean including heating, (Lalli and Parsons 1993) photosynthesis and oxygen production, (Reynolds 2006) animal behavior, (Abrahams and Kattenfeld 1997) and control of physiological rhythms (Lalli and Parsons 1993). Studies of light levels have focused mainly on daytime measurements of Photosynthetically Active Radiation or PAR, the amount of light available for photosynthesis
Hall 1999). As light penetrates through the water column, it is both scattered and absorbed; resulting in a roughly exponential decrease in light intensity with depth (Clarke 1970). As light intensity diminishes, photosynthesis usually decreases as well, controlling the maximum depth distribution of plants and some animals (Lalli and Parsons 1993). Measurement of PAR during the day is useful for understanding of the photosynthetic processes in the ocean and their ecological effects.

The role of light in the ocean changes after sunset. Instead of being primarily used for photosynthesis, what little light is available is used for vision; the primary means of predator detection and feeding for many animals (Han and Strakraba 2001; Kaartvedt et al. 1996; Loose 1994). In many areas, animals undergo diel vertical migrations, moving towards the surface at sunset to feed on primary productivity in surface waters (Gabriel 1988). This migration often includes tiny zooplankton that are followed by larger organisms that feed on them and each other (Salvanes 2001). This feeding occurs throughout the night until the light levels begin to increase with the coming sunrise and the organisms begin to move deeper to maintain themselves at light levels sufficiently low to offer protection from their visual predators (Han and Strakraba 2001; Lampert 1989; Van Gool and Ringelberg 1997). Diel vertical migration has been hypothesized to not only be an evolutionary response to light, but also a proximate one with animals following light isolumes to minimize their predation risk while maximizing their feeding intake (Roe 1983; Widder and Frank 2001). During dawn, dusk, and night, light level measurements can be useful to help understand the mechanisms of diel vertical migration and the interactions between marine organisms.
Daylight measurement of PAR can be made using standard, relatively inexpensive, off-the-shelf radiometers. However, measuring light levels during crepuscular periods and at night is more difficult because of the sensitivity required to detect the low flux of available photons. Commercially available instruments surveyed for measurements of light at night are not sensitive enough to detect low light levels. For example, typical irradiance levels at night range from \((9.6 \times 10^{-5} – 0.75) \mu\text{watts/cm}^2\) over the wavelength interval 310 – 560 nm (Kaul et al. 1994). The sensitivity ranges for various sensors are shown in Table 1. The table shows that none of these commercially available sensors is capable of measuring light at the low levels needed to satisfy our requirements. Consequently, we developed a custom instrument that is inexpensive but has the sensitivity to measure extremely low light levels during our periods of interest and calibrated this instrument against a commercially available sensor to provide quantitative measurements of crepuscular and nighttime measurements of light. Some examples of field measurements of light and coincident measures of zooplankton and fish behavior are presented to illustrate the importance of these measurements for understanding diel migration and other nocturnal behaviors.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Model Number</th>
<th>Sensitivity Range (\mu\text{watts/cm}^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>International Light Tech.</td>
<td>IL 1700 w/ SED033 Sensor</td>
<td>2.14 – 2.41(\times)10^{3}</td>
</tr>
<tr>
<td>International Light Tech.</td>
<td>IL 1400 w/ SED033 Sensor</td>
<td>1.2(\times)10^{2} – 4.22(\times)10^{4}</td>
</tr>
<tr>
<td>International Light Tech.</td>
<td>IL 1700 w/ SHD240 Sensor</td>
<td>1(\times)10^{3} – 5(\times)10^{2}</td>
</tr>
<tr>
<td>International Light Tech.</td>
<td>IL 1400 w/ SHD240 Sensor</td>
<td>5(\times)10^{2} – 5(\times)10^{4}</td>
</tr>
<tr>
<td>Satlantic Inc.</td>
<td>OCR – 507</td>
<td>2.5(\times)10^{3} – 3(\times)10^{2}</td>
</tr>
<tr>
<td>Manufacturer</td>
<td>Sensor Type</td>
<td>Sensitivity Range</td>
</tr>
<tr>
<td>------------------------------------</td>
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</tr>
<tr>
<td>LI-COR Biosciences</td>
<td>LI-192 Upwelling</td>
<td>$2.175 \times 10^1$ – $4.35 \times 10^2$</td>
</tr>
<tr>
<td>LI-COR Biosciences</td>
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</tr>
<tr>
<td>Chelsea Technologies Group</td>
<td>PAR Sensor</td>
<td>$4 \times 10^{-2}$ – $4.357 \times 10^4$</td>
</tr>
</tbody>
</table>

Table 1 - Sensitivity ranges of various light sensors according to their manufacturers. The sensitivity necessary for measurements of nocturnal light is at least $9.6 \times 10^{-5} \mu$watts/cm$^2$.

**Materials and Procedures**

A custom instrument called the Nightlight was designed to measure the low levels of light present just above the ocean’s surface during nighttime hours. It consisted of an 8-bit data logger (HOBO® H8 4 External Channel Data Logger, Onset Computer, Bourne, MA USA), a photodiode (CL705HL, Clairex Electronics, Plano, TX, USA) and a 10 meg-ohm resistor to scale the output range of the diode. The data logger provided power to the photodiode and digitized and stored the output voltage from the diode. The logger and small circuit board were housed in a waterproof box with a clear, polycarbonate lid (Otter Box, TM, Fort Collins, CO, USA). The photodiode was held securely against the inside of the lid with custom shaped black foam. A small area surrounding the photodiode in the lid was left clear but the surrounding area was painted flat black to minimize reflections. The measured dynamic range of the sensor setup was 120 mV, corresponding to complete darkness, and 2.485 V, the saturation value which occurred during all daylight hours until approximately 30 minutes after sunset.
Assessment

Calibration

A radiometer (OCR-507-1CSA, Satlantic, Inc., Halifax, Nova Scotia, Canada) was used to measure the light intensity in $\mu$watts/cm$^2$ at seven wavelengths from 412.1 nm to 683.7 nm. The sensitivity range of the radiometer, stated by the manufacturer as $3 \times 10^2$ to $2.5 \times 10^3$ $\mu$watts/cm$^2$, was not sufficient to measure twilight and nighttime illumination levels. In fact, the output values dropped dramatically as the sun set and after approximately 45 minutes, the output values from each channel were essentially below the noise level of the instrument. The goal of this effort was to be able to utilize the Nightlight to quantify low light levels. However, the output from the Nightlight is in volts which we needed to convert to $\mu$watts/cm$^2$. A simple calibration procedure was developed to compare the output of the Nightlight and that of the factory calibrated radiometer to allow this conversion. Because of the differing sensitivities of each instrument used, there was only a very short time period, about 15 minutes at dusk and 15 minutes at dawn where there was any overlap between the radiometer and the Nightlight; not enough common data points to obtain a good fit between the two instruments.

A tungsten-bulb flashlight powered by fresh batteries was used as a standard light source on the darkest nights during the study. The flashlight was rigidly mounted 17.8 cm above the sensor of the Nightlight or the radiometer. We used various numbers of 2 mm thick sheets of gray polyethylene to vary the light levels from the flashlight. The polyethylene sheets were held firmly against the head of the flashlight in a way that no wrinkles were introduced into them.
Readings for the radiometer ranged from no plastic sheet to 4 sheets. This resulted in a distinct set of known light levels that corresponded to the number of sheets over the sensor. The same procedure was applied to each data logger. The final outcome was five distinct input light levels on the radiometer that could be used to generate a relationship between attenuation sheets and measured light that could then be used to convert five distinct voltage levels on each Nightlight to units of $\mu$watts/cm$^2$. The spectral response curve of the flashlight measured by the radiometer was very similar to the response curve obtained for sunlight with a peak near 500 nm with a slow, linear descent in light levels at longer wavelengths. The application of plastic sheets over the flashlight did not change the shape of the radiometer’s spectral response curve appreciably from that of sunlight, though it decreased the amplitude of the measured flux.

The radiometer was measured first. When it was completely dark, the flashlight was turned on and data were recorded from the radiometer for 1 minute, sampling the channel inputs every 2 seconds. The light was then turned off, a single polyethylene sheet added, and after 1 minute of darkness, the light was turned on again for one minute and so on. This process continued for 4 sheets of polyethylene when the radiometer measurements were below the noise floor of the instrument. A similar process was performed for each of the four Nightlight sensors. Since they were so much more sensitive, 10 sheets of polyethylene were needed to attenuate the light down to their lowest detectable levels.
The radiometer data logged over seven discrete wavelengths for each 1 minute session were averaged over time. Even though the radiometer measures 7 distinct wavelength bands, we chose to use data from only the 554.4 nm band for a calibration standard for two reasons: 1) it lies above the sharp peak of the spectral response curve for sunlight and our light source where there is a nearly linear change in light intensity as wavelength changes and 2) it is approximately the peak sensitivity of the photodiode used in the Nightlights. The data from each 1 minute session from each Nightlight were also averaged. As a result single mean values and their 95% confidence intervals were obtained for the 554.4 nm band of the radiometer and each Nightlight. A series of regression models were fit to the average measured values versus the number of sheets of polyethylene plus 1 (to eliminate a zero value) for each instrument. The best fit regression in each case was chosen using the adjusted R\(^2\) values. The overlapping data points and extrapolation of the equation for the radiometer to lower illumination levels in increments of polyethylene sheets permitted the output voltage from the Nightlights to be converted to the radiometer output of µwatts/cm\(^2\).

Figure 1 shows the output of a typical Nightlight sensor versus the number of polyethylene sheets + 1 used to attenuate the light source and Figure 2 shows the output of the 554.4 nm band of the radiometer versus the number of polyethylene attenuation sheets + 1.
Figure 1 - Output of a typical Nightlight data logger as a function of the number of polyethylene sheets plus 1 used to attenuate the light source. The dashed line represents the best-fit regression line, a power function. Error bars indicate the 95% confidence interval about the mean of 1 minute of data (30 values). These values are extremely small and are thus not visible on all the points. The equation for the regression relationship is also shown.

\[ \text{volts} = (\# \text{ sheets} + 1) \times 1.4797^{2.0724} \]

\[ R^2 = 0.97 \]
\[ \mu\text{watts/cm}^2 = 98.32 \times e^{-2.6646 \times (#\text{ Sheets} + 1)} \]

\[ R^2 = 0.99 \]

Figure 2 - Output of the 554.4 nm band of the radiometer as a function of the number of polyethylene sheets used to attenuate the light source. The dashed line represents the best-fit regression line, an exponential function. Error bars indicate the 95\% confidence interval about the mean of 1 minute of data (30 values). These values are extremely small and are thus not visible on all the points. The equation for the regression relationship is also shown.

The two regression equations can be used to develop a single equation that relates \( \mu\text{watts/cm}^2 \) to volts.

\[ \mu\text{watts/cm}^2 = e^\left[ \left( \frac{1.20813175}{\text{volt}^{0.1825}} \right) - 1.72191979 \right] \times 2.6646 \]

Equation 1
Equation 1 can be used to convert voltage outputs from a Nightlight to values of irradiance in μwatts/cm². The high goodness of fit values ($R^2$) and very small 95% confidence intervals for measurements at each discrete light level support the application of this combined equation.

**Field deployment**

Between June 24 and July 9, 2007, two Nightlight sensors were secured to the railing of the 01 deck and two more were secured to a railing on the top deck of the R/V Hugh R. Sharp as nearly level as possible in locations that minimized the amount of light they received from nighttime ship operations as well as obstruction of natural illumination by the ship’s superstructure. The two different locations were chosen because there was a light on the operations deck of the ship that illuminated portions of the 01 deck. The top deck of the ship was not directly exposed to the same direct light so we could get different light readings at the two locations if the ship’s deck lights were turned on. The top deck, unfortunately, was subject to illumination by the ship’s forward lights. We could find no location on the ship where ship night lights had no effect at all times on the light levels we were trying to measure. However, this impact was mitigated by awareness of this problem through minimal use of the problematic lights. The Nightlight sensors were programmed to start recording at 1900 h local time each night and continued to record until mid-morning the next day at a sampling rate of 0.5 Hz.

During the deployment of the Nightlight sensors, observations of acoustic scatterers beneath the vessel were recorded using a calibrated, four-frequency, split-beam echosounder
system (Simrad EK60 at 38, 70, 120, and 200 kHz). During several crepuscular periods, the vessel remained stationary to record temporal changes in the vertical distribution of scatterers in relation to changes in light. For comparison to the light data, volume backscattering data from a calibrated 70 kHz split-beam scientific echosounder (Simrad EK60) were thresholded at -75 dB and averaged over 5 minutes horizontally and 5 m vertically. A 25 m vertical running mean was then calculated from the resulting volume scattering curves to provide local mean measures of volume scattering. Volume scattering values in the original 5 m vertical bins that were at least 3 decibels greater than the local mean were determined to be significant scattering layers. The depths of the identified layers were then plotted as a function of time.

A profile of Nightlight sensor data collected during a last quarter phase of the moon on a night with moonrise near midnight but cloud cover during the entire evening is shown in Figure 3 while Figure 4 shows the same data during a new moon. In both figures, the data are plotted in both the original voltage units of the logger output and in units of µwatts/cm² calculated using Equation 1. Note that the left vertical axis is on a log scale. Data logging was started before sundown and stopped after sunrise. Also note the small increase in light level around 3:00 AM in Figure 3. This is due to the forward ship lights being turned on momentarily during the night. Two important things are shown by the comparison of these data: the relatively high levels of light from nighttime sources other than the moon, probably stars, and the magnitude of light level decrease caused by cloud cover. The irradiance measured during a quarter-moon with clouds was four orders of magnitude less than the irradiance on a moonless night without clouds.
Figure 3 - Nightlight data from just before sunset to after sunrise for the last quarter phase of the moon on a night with moonrise near midnight but cloud cover during the entire evening as a function of local time. The solid black line shows the Nightlight output in μwatts/cm² (left axis, note the logarithmic scale). The grey line shows the output in volts (right axis). Note the detection of ship operation lights at around 0300 h local time.
Figure 4 - Nightlight data from just before sunset to after sunrise for a new moon on a clear night as a function of local time. The solid black line shows the Nightlight output in μwatts/cm² (left axis, note the logarithmic scale). The grey line shows the output in volts (right axis).

A plot of Nightlight sensor data taken during a last quarter moon phase night when the moon rose well after sunset is shown in Figure 5. Superimposed on this plot is simultaneously collected volume backscatter data from a 70 kHz split-beam echosounder. As the light level falls off from 20:30 to 21:30 local time, we see a dramatic decrease in the depth of backscatter layers. After the moon rises at 22:41, an increase in the depth of some of the backscatter layers is observed. Also of interest is a thin backscatter layer with a distinct frequency response that is
observed at a depth of 50 m at the start of the time series. This feature is indicated by light grey dots and is a separate scattering layer that was not observed after sunset. This example highlights the need for measurements of the low levels of light found at crepuscular and nighttime periods for understanding diel migration and other nocturnal behaviors. It also shows the capability of this instrument to detect the changes in light levels found not only during sunset and sunrise, but also more subtle changes in light such as moonrise.

![Graph showing depth of volume scattering layers detected with a 70 kHz split-beam echosounder (points) along with a plot on a log scale of light from a Nightlight (solid line) as a function of local time. The main scattering layers are indicated by the black points. A thin backscatter layer with a distinct frequency response that was not observed after sunset is indicated by light grey points.]

**Figure 5** - The depth of volume scattering layers detected with a 70 kHz split-beam echosounder (points) along with a plot on a log scale of light from a Nightlight (solid line) as a function of local time. The main scattering layers are indicated by the black points. A thin backscatter layer with a distinct frequency response that was not observed after sunset is indicated by light grey points.


**Discussion**

Measurements of nocturnal light levels is important for the analysis of animal behavior in the ocean during nocturnal conditions. These measurements have been difficult because of the low irradiance levels. Typical commercially available radiometers do not have the sensitivity necessary to measure these low radiance levels. We have been able to develop an instrument, the Nightlight, which can be used in extremely low light conditions and is easy to operate. Our calibration conversions show that the Nightlight has a sensitivity range of $1.7 \times 10^{-9}$ to $12.3 \, \mu\text{watts/cm}^2$ allowing the detection of nocturnal light levels, even on the cloudiest nights and those with no moon. The instrument is very inexpensive to build; parts costs are less than $100 USD and each requires less than one hour to fabricate. Programming and operation of the data logger is simple. The data stored by the logger are easily downloaded into a computer for analysis using a standard computer communication port. The limited number of components in the Nightlight helps make the design robust and reliable. And finally, because of the low build cost, a number of instruments can be built and deployed simultaneously to gather much more data than could be obtained with just a single sensor.

There are, however, some disadvantages to our design. As with any sensor, the Nightlight must be calibrated to a known standard. Because there are no commercial instruments available that measure light at directly comparable levels and calibrated light sources are not readily available, a fairly cumbersome calibration scheme was needed to match Nightlight sensor outputs to the calibrated output of an easily accessed radiometer. Note that calibration must be conducted on each Nightlight sensor used because the response of individual photodiodes varies
slightly. Based on our selection of photodiode, the Nightlight, unlike most radiometers, has a relatively broad sensitivity covering 400-600 nm with a peak at 510 nm. This broad coverage is ideal for detecting light available to visual animals that typically have a broad sensitivity response but would need to be changed for other applications requiring information on specific wavelengths of light. Finally, the extreme sensitivity of the instrument presents a problem for instrument deployment because any unnatural light, i.e. ship operations lights, is easily detected. Consequently, care must be taken to place sensors in locations that will not be affected by extraneous light sources. In our field tests, we found this to be an issue we could not completely resolve.

There are a few modifications that could be made to improve the Nightlight's design. First, developments in easily deployed data loggers could be exploited, increasing the resolution of the digitization from 8-bits which provides 256 levels of data to 10 or 12 bits which would provide 1024 and 4096 values respectively. This finer resolution would be valuable for the extremely small light levels detected. Second, the logger was programmed to record data every 2 seconds. The main reason for the longer period between samples was the memory limitations of the data logger used. Newer loggers have much more memory available for data storage allowing an increase in the sample rate of the data logger and thus improving the temporal resolution of the sensor. This would have been an advantage in our field test when we were experiencing heavy seas and rolling of the ship. More frequent samples of light levels would allow us to filter out variances of light caused by rolling of the ship. Other changes could be made to customize
the sensor to the application, for example, choosing a different photodiode and/or scale resistor to change the range of light sensitivity or the spectral response of the meter.

Preliminary field tests of the Nightlight on the deck of a research vessel showed that local measurements of irradiance near the surface of the ocean can be made. Light measurements were combined with simultaneous acoustic observations of the movements of scattering layers. In the representative example shown here, there appears to be a strong correlation between the decrease in light at sunset and the vertical migration of a deep scattering layer. Perhaps even more interestingly, a change in behavior with a decrease in layer depth and an increase in the number of layers through disaggregation is observed when light levels increase due to the moonrise. This sample of data illustrates the importance of quantifying light levels found at crepuscular periods and at night in order to understand the behavior of pelagic animals in the ocean.
References


