Design and Development of an Autocalibrating Radiometer for Deep Sea Biooptical Studies

Edith A. Widder
Bioluminescence Department

Frank M. Caimi
Lawrence D. Taylor
Robert F. Tusting
Department of Electrical Engineering

Harbor Branch Oceanographic Institution, Inc.
5600 Old Dixie Highway
Ft. Pierce, Florida 34946

Abstract - Measurements of light underwater are critical to research investigations involving a wide range of aquatic photo processes. Solid state detectors used in modern underwater irradiance meters are excellent detectors of bright sunlight in surface waters. However, these detectors are not sensitive enough to measure light over the intensity and temporal response range which are characteristic of the photic reactions of many marine organisms. Solar radiation below the epipelagic zone, lunar radiation and bioluminescence all exert a powerful influence on the population dynamics of the marine environment and therefore require accurate quantification. Photomultiplier tubes (PMTs), which have the sensitivity to measure such low intensities are not commonly used in radiometric instruments because they cannot match the accuracy and reliability of solid state detectors in field deployment. The Low Light Auto-Radiometer (LoLAR) was developed to extend the lower limit of contemporary underwater irradiance detectors. The system uses a PMT but circumvents the temperature sensitivity and poor stability of the tube with an internal calibration circuit.

LoLAR, which was designed for use on the Johnson-Sea-Link submersible, has a 1000 m depth capability and includes additional sensors for measurement of depth, temperature, and orientation from vertical. Data collection is achieved via laptop computer or from graphics overlay on the submersible video. Instrument sensitivity extends from 10^{-2} to 10^{-8} $\mu W/cm^2$ with sample rate of 275 Hz. Input optics consist of a cosine irradiance collector, a computer controlled shutter, and a two position filter wheel.

Data collected with LoLAR include measurements of downwelling irradiance to depths of 500 m, vertical profiles of stimulated bioluminescence, horizontal transects of stimulated bioluminescence, and bioluminescence intensity and kinetics measurements from individual, identified zooplankton.

This paper includes a detailed system description, including elements of the optical and electronic design which allow for the cosinusiodal azimuthal response, wide dynamic range, and autocalibration feature. Calibration data will be presented and performance in the field will be reviewed.

INTRODUCTION

Optical instrumentation has become a cornerstone of oceanographic research. Instruments such as the beam transmissometer, fluorometer, and radiometer are commonly used in undersea studies, as a result of design improvements that permit intercomparison of data collected by different investigators. The improvements are primarily attributable to advancements in solid state electronics that allow the manufacture of low-cost, high stability designs.

In those photometric applications where relatively few photons are available, and where high speed of response is mandated, photomultiplier tube detectors are usually employed in preference to solid-state photodiodes. The superiority of PMTs over solid-state detectors at low light intensities is well known [1] and results from their inherent high gain and low thermal noise. Good quantum efficiency in the blue-green region of the optical spectrum is another advantage for undersea work. However, PMT detectors require high-voltage power supplies and are subject to gain variations as a function of temperature. These effects, in addition to poor stability as a result of mechanical shock or exposure history, mandate frequent calibration. As a result, PMTs have not gained acceptance for use in commercially available oceanographic irradiance meters.

The Low Light Auto-Radiometer (LoLAR) described here, was designed to circumvent the inaccuracy and instability associated with PMT-based systems, while providing an underwater irradiance detector 5 orders of magnitude more sensitive than any commercially available unit. The

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need for improved sensitivity exists in at least three different areas of investigation--hydrological optics, photophysiology, and bioluminescence.

The utility of the LoLAR in hydrologic optics relates to verification of models of the maximum penetration of radiant energy in natural waters [2,3]. Measurements of the space-time variance of optical properties of the world's oceans are critical to models of oceanic processes. In this regard, LoLAR was designed for easy integration into existing vertical profiling systems as well as for use on untethered submersibles where corrections for perturbation of the in-water light field by ship shadow are not necessary [4].

Effects of light on the population dynamics of the ocean extend over an enormous dynamic range, from surface irradiance levels of almost 10^5 μw cm^{-2} [5] down to the thresholds of sensitivity of the eyes of deep sea organisms, estimated to be as low as 10^{-10} μw cm^{-2} [6]. The benefit of the extended sensitivity provided by the LoLAR lies in being able to make direct correlations of environmentally and physiologically relevant irradiance levels with organism distribution, orientation and vertical migration.

The large number of marine organisms which are bioluminescent [7] and the presence of eyes in so many animals living below the photic zone [8] attests to the obvious importance of bioluminescence in the marine environment. In-situ measurements of absolute intensity and kinetics of bioluminescence from identified organisms in response to defined mechanical and photic stimuli are critical to studies of the effects of bioluminescence on population dynamics. A photomultiplier tube, like that used in the LoLAR, is the detector of choice for such measurements due to its sensitivity and fast response times [9].

SYSTEM OVERVIEW

The LoLAR system has been designed with several features that are particularly useful for undersea research. A dual functionality has been built-in to provide measurement of bioluminescent flash intensity, and to allow measurement of downwelling irradiance--a parameter of interest for photophysiology and hydrologic optics studies. Both functions use identical light collection optics. For bioluminescent measurements, the instrument has been designed to act as an integrator with an integration period of 1/ 275 Hz or about 3 milliseconds. With this response time, bioluminescent flashes can be recorded for study of their temporal characteristics. For measurement of irradiance, temporal response is traded for dynamic range covering approximately 6 orders of magnitude. The system also incorporates autocalibration features, in addition to a unique optical design which preserves coupling efficiency while providing a cosinusoidal azimuthal response.

With an instrument capable of a large dynamic measurement range, electrical system design features such as automatic shutter closure and high voltage shutdown are required for protection from large, transient light intensities. A block diagram of the entire system is shown in Figure 1.

OPTICAL DESIGN

A. Calibration

The internal calibrator for the LoLAR is a radio phosphorescent source. The source is a 25 mm diameter Betalight®(Saunders-Roe Development Ltd.) glass sphere and serves as a secondary radiometric standard in which phosphor excitation is provided by tritium gas. The phosphor emission is isotropic, centered about λ_{max}=450 nm (FWHM=50 nm), and is a close match to the spectral distribution of bioluminescence and downwelling irradiance in the epipelagic zone. The total quantum flux available from the source is approximately 1.7 X 10^{13} quanta s^{-1}. A fiber optic waveguide, coupled to the radiophosphorescent surface, conducts approximately 4.1 X 10^8 quanta s^{-1} to the photocathode of the PMT. This flux constitutes a stable source to calculate the responsivity of the PMT and thereby correct for any changes in sensitivity of the tube. The effects of any variations in quantum flux from the radiophosphorescent source due to aging or temperature are reduced through the use of a correction factor derived from an auxiliary flux monitor. The monitor utilizes a high stability silicon diode to directly observe the emission from the phosphorescent source. Therefore, the stability and reliability of the LoLAR are based on the known temperature independence and excellent long-term stability of the SPD.

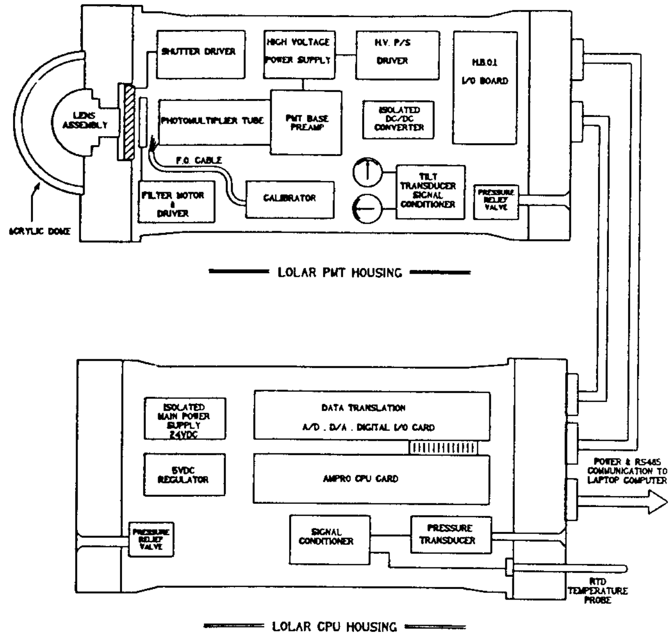

Figure 1. Mechanical configuration and system block diagram of the low light autoranging radiometer.

Initial calibration of the LoLAR was accomplished with an NBS referenced standard (Optronic Laboratory Model 310 multi-spectral calibration source). Calibration is maintained by referencing the PMT output to the known quantum flux from the radiophosphorescent source.

In operation, the LoLAR can periodically perform an internal calibration sequence. A standard sequence consists of the following steps: 1) command PMT shutter open and fiber optic shutter closed; 2) obtain background reading; 3) obtain SPD reading; 4) implement software correction of phosphor calibration factor; 5) command fiber optic shutter open; 6) obtain PMT reading; and 7) perform software calculation and storage of PMT responsivity. The PMT responsivity calibration factor is applied to all PMT readings until the next calibration sequence. The internal calibration sequence is applied anytime PMT gain is changed or temperature has changed by more than 1° C.

The radiophosphorescent emitter is superior to other commonly available sources for a number of reasons. Light emitting diodes (LEDs) are subject to thermally induced variations in output intensity, as well as shifts in output spectrum. Incandescent standards operate with high power budgets, require warm up, and exhibit short lifetimes. In contrast, the phosphorescent source exhibits a tritium half-life of 12.3 years and maintains stability of approximately 80% over 10,000 hours. These variations are compensated by the SPD monitor circuit, which ultimately limits the instrument calibration accuracy. Excluding effects from contamination of the optical surfaces, stability is expected to be equivalent to that of the SPD, or about 1% per year.

B. Angular response

The measurement of underwater light fields has been adequately described elsewhere[10]. Optical oceanographers measure the quantities called "vector" or "scalar" irradiance, depending upon the objectives of the particular experiment. Vector irradiance is measured with a classical cosine collector that integrates the arriving flux over a 2 π steradian solid angle with a cosine weighting factor determined by the azimuthal direction of the arriving photons. A similar measurement is often conducted by photobiologists wishing to characterize the absorption of quanta by plants. Cosinusoidal response weighting allows measurements to be made which are indicative of the flux hypothetically falling onto a flat surface with an area equivalent to that of the radiometer aperture.

The objective of the LoLAR optical design process was to produce a cosinusoidal weighting factor while preserving the detector efficiency. The conventional approach, employing an optical diffuser, was abandoned due to the poor flux transfer efficiency commonly obtained (less than one percent). Instead, an alternate correction method was developed using an r-θ lens and an apodizing mask.

The r-θ lens is designed to map light rays arriving from different angles at the lens face into concentric rings in the focal plane. The lens focal length and position relative to the detector is chosen to match the radial dimension of the photocathode to the outermost ring corresponding to ± 90 degrees from boresight. The lens and detector combination produce a response which is not necessarily cosinusoidal, but which can be modified by placing an apodizing filter over the detector surface. The present design closely matches the desired cosine response as shown in Figure 2. Error between the measured and ideal response is less than 18 percent average from 0 to 80 degrees.

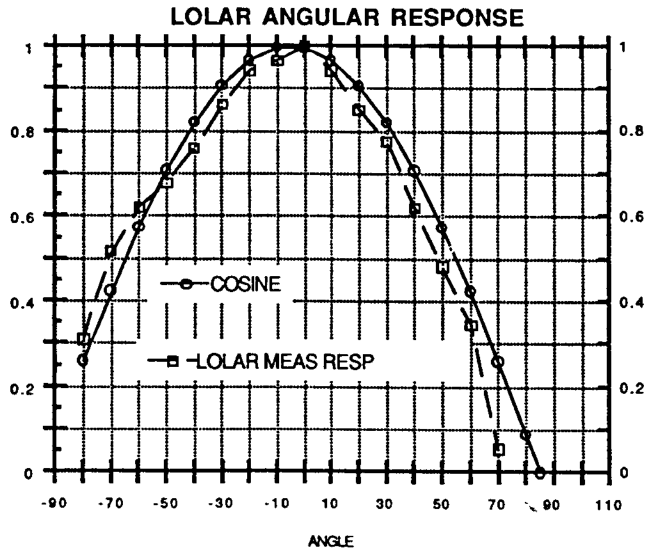

Figure 2. Normalized theoretical (solid line) vs. Measured (dashed line) angular response of LoLAR light collection system.

ELECTRICAL DESIGN

A. Detector

The detector is an 11 stage photomultiplier tube powered by an EMI Model H3-15 high-voltage power supply. The dynode structure employs a venetian blind configuration which is noted for low noise at the expense of bandwidth and output current.

The photocathode is a bialkali type with a peak Q.E. (quantum efficiency) of approximately 25% at 370 nanometers. The Q.E. drops to less than 2% for wavelengths longer than 600 nanometers. Poor red response generally provides low thermally-induced dark current, which is a major source of noise in a photomultiplier tube. The venetian blind dynode configuration results in low noise by reducing optical feedback from the last few dynodes and anode to the photocathode. The PMT is outfitted with a computer selective spectral filter as shown in Figure 1. The typical spectral response of the PMT is shown in Figure 3.

B. Analog Electronics

The analog electronics amplifies the signal from the photomultiplier and provides high level signal output, gain switching for the ranging circuit, and several control functions which include over-range shutter closure, high voltage shutdown, and input to the digital processor for range switching. The input stage consists of a low noise integrating amplifier which is reset at a 275 Hz rate. The rate is chosen to provide an optimal trade-off between response time and S/N ratio at the lowest response range.

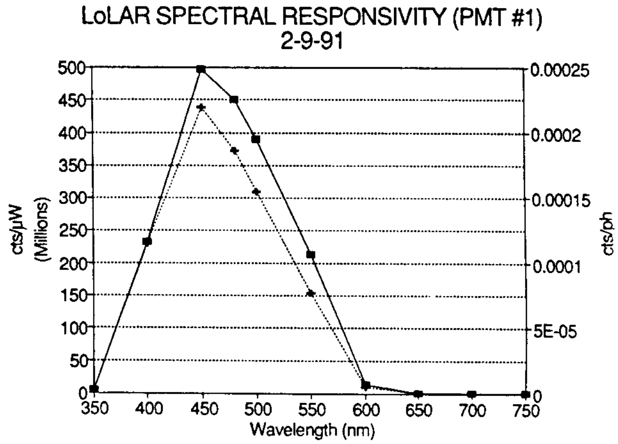

Figure 3. Measured spectral response of LoLAR photomultiplier tube under typical operating conditions.

The PMT signal is held at virtual ground at the input of a conventional op-amp integrator. Range switching is accomplished with custom-designed low capacitance, low leakage relays. The integrator is reset with an ultra low leakage field effect transistor switch. The switch was designed for low charge injection while maintaining small enough "on"-resistance to provide a fast discharge function of the integrating capacitor used on the lowest sensitivity range.

A rate-of-change circuit monitors the integrator output to provide an indication of a possible over-range condition. This output is used to provide a control signal to a fast acting shutter installed between the lens and the PMT faceplate. The time constants associated with this circuit are chosen to allow proper range selection while minimizing the chance of overload to the PMT.

An additional protection circuit is provided for manual closure of the PMT shutter, as well as PMT high voltage shutdown and control.

C. Digital Electronics

The LoLAR operation is controlled by an AMPRO

286 CPU using software written in Turbo C 2.0. An interactive graphical display, resident on the 386SX laptop computer, provides user control of PMT voltage, amplifier gain, filter selection, and shutter control. In the run mode, data is displayed graphically as irradiance and/or temperature vs. time or depth. A status screen is displayed simultaneously and provides numerical readout of irradiance, depth, temperature, descent rate, pitch, internal housing temperature, calibrator flux level, and current PMT responsivity value. Selection of real-time display output as irradiance and/or temperature and depth is independent of data storage. All data is stored in raw form and may be read back into the display screen at any time in either format.

PERFORMANCE

A. Field Results

During field tests LoLAR was mounted on a pan and tilt head on the upper work bar of the JOHNSON-SEA-LINK submersible (Fig. 5). Four different protocols were possible from this location: 1) For vertical profiles of downwelling irradiance LoLAR was tilted straight up, as indicated by a zero reading of the tilt indicator. 2) For vertical profiles of bioluminescence potential, LoLAR was tilted to 90° and panned to measure stimulated bioluminescence from the vertical thruster exhaust. 3) For horizontal transects of bioluminescence potential, as the submersible moved through the water at a forward speed of 0.6 kts., luminescence was mechanically stimulated from organisms striking an 1800 μm mesh NITEX screen stretched across the end of a Plexiglas tube (24.5 cm I.D.). During these transects LoLAR was pointed at the screen, on-axis with the stimulation tube, and 40.6 cm from the screen. 4) The same configuration was used to record bioluminescent displays from individual organisms which were maneuvered into the end of the stimulation tube. When the organism contacted the screen at the end of the tube, LoLAR recorded the kinetics and intensity of the stimulated bioluminescence, while an underwater SIT video camera, mounted next to LoLAR, recorded the spatial characteristics of the display. Following each such recording the animal was collected into a container on the lower work platform for definitive taxonomic identification.

LoLAR has been used on two oceanographic cruises to date. Data collection has included downwelling irradiance measurements to depths of 500 m, vertical profiles of stimulated bioluminescence, horizontal transects of stimulated bioluminescence, and bioluminescence intensity and kinetics measurements from gelatinous zooplankton too fragile for laboratory studies. An example of an *in situ* recording of a bioluminescent flash from the cydippid ctenophore *Euplokamis stationis* is shown in Figure 4.

ACKNOWLEDGMENTS

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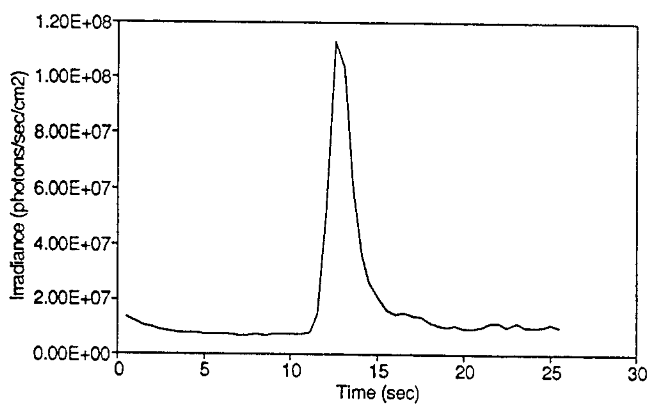

Figure 4. In-situ recording of stimulated bioluminescence from Euplokamis stasionis.

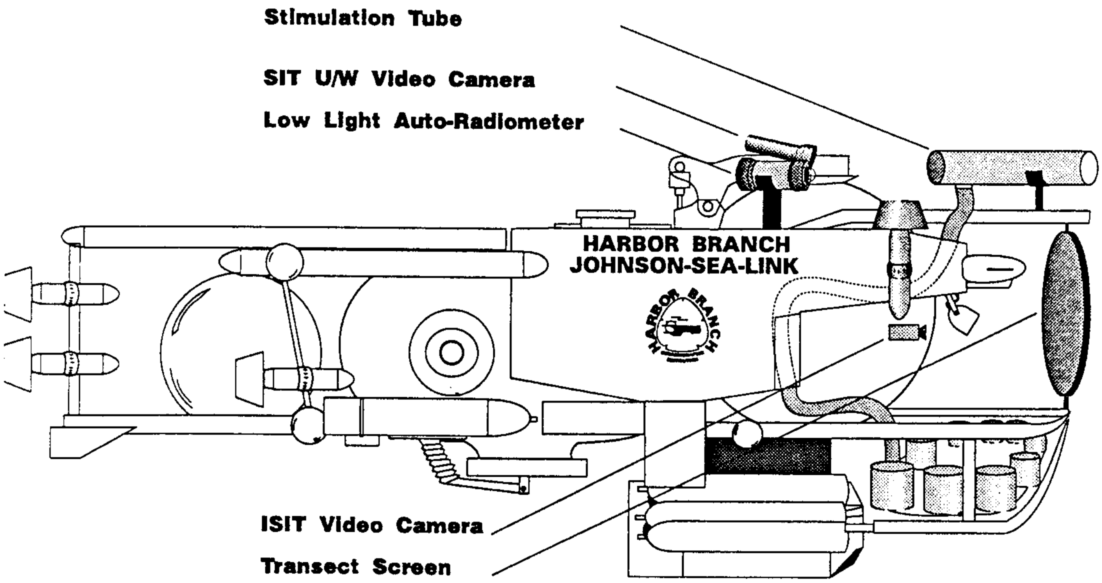

Figure 5. Field test configuration of LoLAR on the JOHNSON-SEA-LINK submersible.

REFERENCES

[1] Thorn EMI Electron Tubes LTD, 1984. A comparison of the performance of photomultiplier tubes and silicon photodiodes. Technical Report.

[2] Smith, R.C. and K.S. Baker. 1986. Analysis of ocean optical data II. SPIE 637 Ocean Optics VIII: 95-107.

[3] Smith, R. C. Personal communication.

[4] Spinrad, R. W. and E. A. Widder, 1992. Ship Shadow Measurements obtained from a manned submersible. SPIE Proceedings 1750: 35-46

[5] Clarke, G.L. and G.K. Wertheim, 1956. Measurements of illumination at great depths and at night in the Atlantic Ocean by means of a new bathyphotometer. Deep Sea Research 3: 189-205.

[6] Denton, E.J. and F.J. Warren, 1957. The photosensitive pigments in the retinae of deep sea fish. J. Mar. Biol. Assoc. U.K. 36:651-662.

[7] Herring, P.J. 1987. Systematic distribution of bioluminescence in living organisms. J. Biolum. Chemilum. 1:147-163.

[8] Locket, N.A. 1977. Adaptations to the deep sea environment. In: Handbook of sensory physiology. Vol. VII. No. 5. F. Crescitelli, Ed. Springer Verlag, Berlin, Heidelberg, New York, p.68-192.

[9] Wampler, J.E. 1985. Instrumentation: Seeing the light and measuring it. In: Chemi- and Bioluminescence. J.G. Burr, Ed. Marcel Dekkar, Inc. New York. pp.1-44.

[10] Blizard, M. 1986. Ocean Optics: Introduction and Overview. SPIE 637 Ocean Optics VIII: 2-17.