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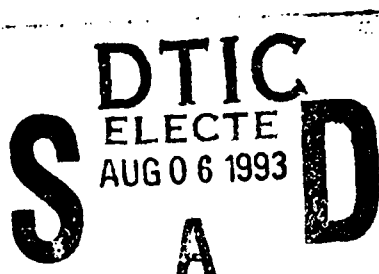
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Ship shadow measurements obtained from a manned submersible

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1. ABSTRACT

Measurements of ship shadow were made from a manned submersible, equipped with a downwelling PAR irradiance sensor. These measurements were made as transects under the surface ship during clear sky conditions and three separate profiles (on the shady side, under the ship and on the sunny side) during overcast conditions. Results from the clear sky measurements agree with previous numerical simulations, indicating only small errors due to ship shadow. During overcast conditions, the profiles indicate the shadow effects are detectable to considerable depth, but not at a distance of one optical depth from the ship rail on the sunny side. These measurements also demonstrate the effectiveness of manned submersibles for optical oceanographic studies.

2. INTRODUCTION & BACKGROUND

Ever since optical data have been acquired *in situ* from oceanographic research vessels the problem of avoiding interfering effects of the shadow and reflections from the research platform has been daunting. As Jerlov has written, "... the meter cannot be lowered more than 5-7m outboard, and therefore shading due to the ship may influence the results"[1]. Aas[2] adds that "... the effect of reflected light from the ship is more difficult to estimate." All researchers have agreed that from theory and experimentation it is true that the effect is much more significant under overcast skies than under clear sunny conditions.

Early work began to quantify the magnitude of the errors induced by ship shadow in measurements of irradiance and radiance at sea. Poole[3] estimated shading errors (in downward radiance measurements) for overcast skies to be of order 10% in the surface waters (< 5 meters). Jerlov[1] analyzed the results of Aas[2] and concluded that the reduction in downward irradiance due to ship shadow (measurements made 5 meters abeam of the ship rail, on a ship of length 52 meters) was less than 10% for all depths under clear skies, but as much as 22% (at 20 meters depth) under overcast skies.

Later experimental studies confirmed the general trends observed by earlier researchers, but found even larger potential errors due to ship shadow effects. Voss et al.[4] measured, among other parameters, downwelling spectral irradiance at two distances (0 meters and 9 meters) from the ship rail under overcast and sunny conditions. Again, their results show that in the surface waters there is less than a 5% reduction (comparing the 0 meters reading to the 9 meters reading) in

downwelling irradiance, E_d, in the clear sky case (for all wavelengths), but this error was at least 40% under overcast skies. The diffuse attenuation coefficient for downwelling irradiance at 488nm in the surface waters was approximately 0.06 m^{-1}. Smith and Baker[5] approached the same problem in a different manner. In their study the above-water spectral irradiance data were used to develop a correction to ship shadowing. Important components of their study were the estimation of the air-sea interface transmittance characteristics, and the determination of the relative components of direct and diffuse (i.e. sun and sky, respectively) downward irradiance. Their conclusions were that, uncorrected, measurements of downwelling irradiance just under the sea surface were in error by "only a few percent" for clear skies, but by as much as 30% for overcast conditions.

Theoretical studies have generally been in agreement with observations, and have provided some of the insight needed to improve experimental design. Using Monte Carlo simulations Gordon[6] studied the roles of many optical parameters (e.g. solar elevation, solar azimuth, single scattering albedo, etc.) in affecting the irradiance error, which, for downwelling irradiance is defined as:

$$[(E_{d_t} - E_{d_m})/E_{d_t}]$$

(1)

where t and m designate *true* and *measured*, respectively. Gordon concluded that with the sun within 45° of the ship beam, and with measurements made by an irradiance meter some 1.5 meters off the ship rail on the sun side, typical mid-day irradiance errors induced by ship shadow will be of order 2-5% for direct sun (i.e. similar to clear conditions) and of order 20% for sky illumination (i.e. similar to overcast conditions), depending, of course on the beam attenuation coefficient. Gordon adds that in the case of diffuse illumination error reduction would most adequately be addressed by floating a small sensor package a "considerable distance" from the ship. Responding to this suggestion, Waters et al.[7] designed and tested an optical free fall instrument for obtaining standoff vertical profiles of spectral downwelling irradiance. Initial trials with this package, as corroborated by simultaneous measurements of inherent optical properties indicate its success in avoiding influences of ship shadow on irradiance measurements near the sea surface. An additional combined theoretical and experimental study was conducted by Helliwell et al.[8]. In this study 1-dimensional and 3-dimensional finite difference solutions to the radiative transfer equation were used to model the effect of ship shadow on downwelling and upwelling radiance distributions at several depths under the sunny side and the shade side of a research vessel. Measurements were made with the RADS radiance distribution camera, described by Voss[9]. Qualitative agreement between the model and the measurements to depths of 55 meters was quite good. The contour plots of the diffuse attenuation coefficients in Helliwell et al.[8] can be used as a prediction of what distances from the ship are appropriate for sensing irradiance without interference from the ship shadow.

All of these theoretical and experimental treatments argue for better understanding of the nature of the ship shadow effects. The use of manned submersibles was identified as a mechanism for performing the next generation of studies. Manned submersibles have already proven quite effective in a wide range of biological, geological and biogeochemical studies. Data from a submersible could serve hydrological optical studies well with continuous, or near-continuous

transects of irradiance at fixed depths on either side of and within the ship shadow. Since a manned submersible is a very stable platform, orientation of the irradiance sensor could be assured, and, of course, by placing the sensor well above the plane of the submersible, influences of the submersible itself could be minimized. Navigational systems of current manned submersibles lend themselves to very accurate positioning and orientation relative to the shadowing surface vessel. For these reasons an experiment was conducted in February, 1991 in waters off the Bahamas, using the Johnson Sea Link manned submersible, deployed off the R/V Edwin Link of the Harbor Branch Oceanographic Institution. The intent of this study was to obtain an accurate set of data describing the 3-dimensional variability of the irradiance distribution underneath and surrounding the surface research vessel.

3. EXPERIMENTAL SETUP

Geometric relationships between the manned submersible, Johnson Sea Link (JSL) and the surface vessel, R/V Edwin Link are shown in Figure 1a. Two dives were conducted in the JSL. Dive 2900 (21 February 1991, under clear skies) was centered at 26°31.38'N, 78°05.53'W. The pattern of transects run under the R/V Edwin Link is shown in Figure 1b. Dive 2909 (25 February 1991, under overcast skies) was centered at 26°31.57'N, 78°02.96'W and its transect pattern is shown in Figure 1c.
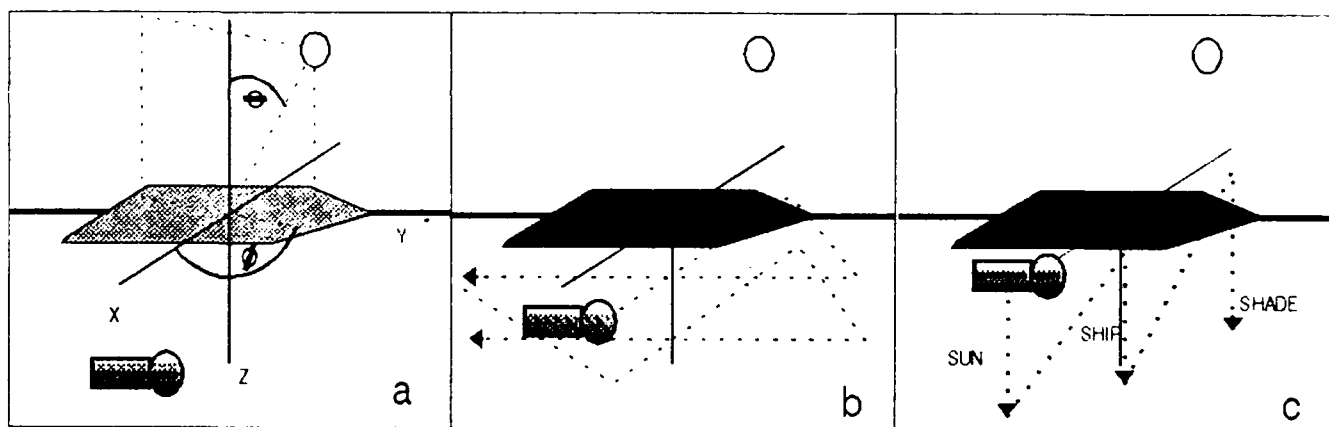
Figure 1. a) General geometry of measurements; b) transects of dive 2900; c) profiles of dive 2909.

The JSL was equipped with a LI-COR. Model LI-192SA underwater cosine response quantum sensor. Spectral response for this instrument is shown in Figure 2.
The sensor was placed aboard the JSL in a location to minimize influences from the submersible, and to allow vertical orientation. During dive 2900 data were recorded as one minute averages of readings taken approximately every three seconds. For dive 2909 data were obtained as

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approximately one-minute averages every 5 meters of depth below approximately 20 meters, with several measurements closer to the surface for the two casts on either side of the ship.

In addition, an intercalibrated, gimbal-mounted 5-channel irradiance collector was placed unobstructed on the 02 deck of the R/V Edwin Link, but this sensor malfunctioned prior to and during Dive 2909. Positioning of the surface ship and the JSL was monitored with 0.1 meter resolution using the Track-Point◦ acoustic navigation system.

Additional optical data were collected at other times during this research cruise. Dr. Jim Case obtained profiles of beam attenuation (660nm) using the HIDEX bathyphotometer. Measurements of ship hull reflectance were obtained at three wavelengths using a Gardner-/Neotec Colorgard II◦ reflectometer.
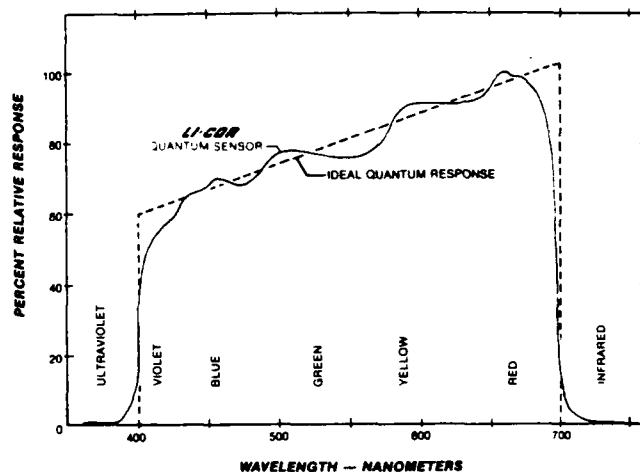
Figure 2. Typical spectral response of LI-COR Quantum sensor and the ideal quantum response.

## 4. RESULTS

The results of dive 2900 are shown in Figure 3.
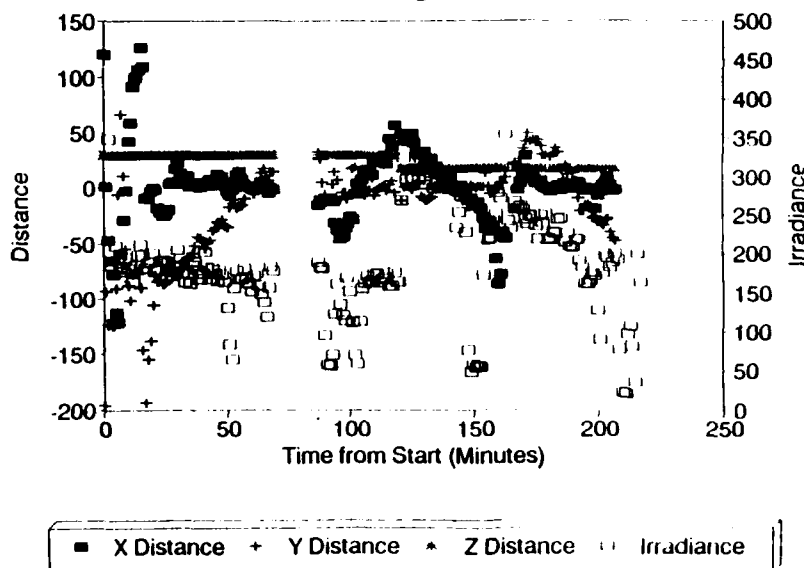
Figure 3. Relative position of the submersible and irradiance measurements during dive 2900.

All of the position-related data and the downwelling irradiance are shown in this composite figure. By way of reference to Figure 1a, the solar zenith angle, Θ, varied from 36° to 61°, over the 3.5 hour duration of the dive (start time was 1211 local), and the relative azimuth, $\varnothing$, was

approximately 83°. This value of ø is rather large, but given the large zenith angle, this ensured that the starboard side of the ship was fully in sun, and the port side shaded. Consequently, negative values of X correspond to the port, or shade side of the ship. Transects are shown as collected at 30 meters and 20 meters depth. Beam transects are shown by highly sloped X values; major axis transects are indicated by highly sloped Y values.

An arbitrary discriminator of 150 micromoles irradiance was used to define the spatial distribution of light levels for dive 2900. Figure 4a shows the spatial distribution of all points where the irradiance value was less than this value, regardless of depth. Figures 4b and 4c show the same data as Figure 4a, but for the depths of 20 meters and 30 meters, respectively.

a   b   c
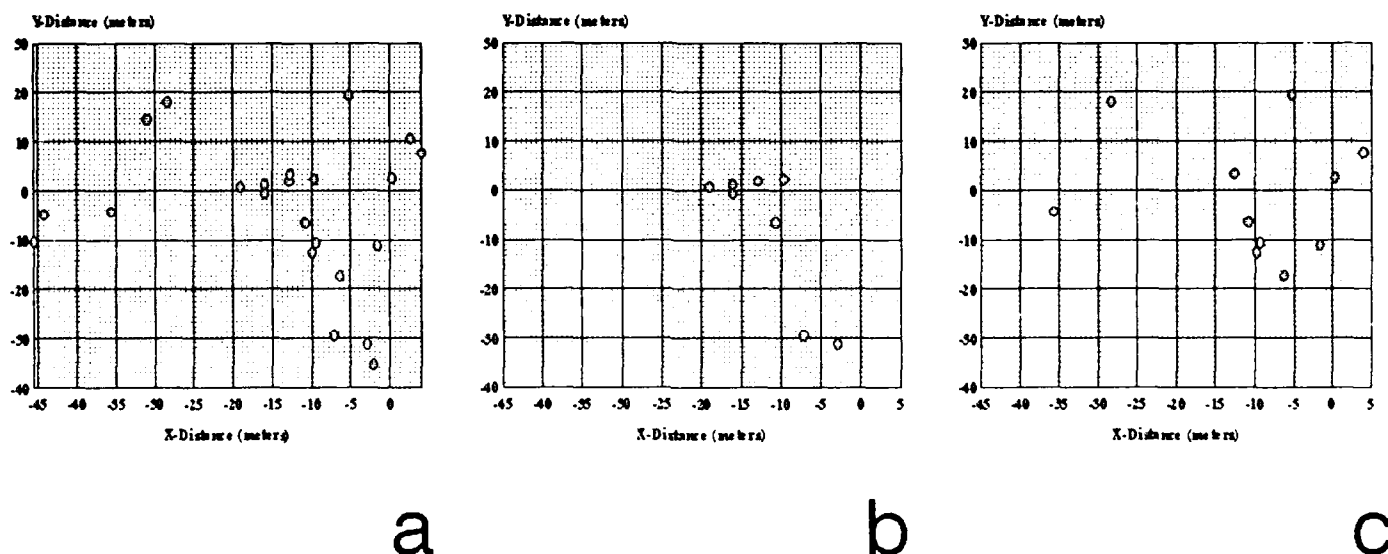
Figure 4. Relative positions of irradiance readings: a) less than 150 micromoles at both depths; b) less than 150 micromoles at 20 meters; c) less than 117 micromoles at 30 meters.

In the case of the 30 meters depth, the irradiance cutoff was 117 micromoles, since that corresponds to approximately the same light value as 150 micromoles at 20 meters for the downwelling diffuse attenuation coefficient as measured during the submersible dive.

Dive 2909 was comprised of three vertical profiles, each separated some 30 meters, and centered on the center of the R/V Edwin Link as shown in Figure 1c. The dive was begun on the shady side (-X) at 1054 local time, and ended at 1234 local. While skies were virtually completely overcast, the solar zenith was recorded as 46° at the start and 36° at the finish. Figure 5 shows the log-linear plots of irradiance versus depth for each of the three profiles.

The profile directly under the surface ship was limited to a minimum depth of 15 meters. Some variation in the vertical profiles may be attributed to variations in $E_d(0^+)$, the downwelling irradiance just above the sea surface. Since the deck irradiance meter malfunctioned during this dive it is not possible to correct the values in Figure 5 for atmospheric variations.

E$_d$ profiles
Dive 2909 (Overcast)

Irradiance (micromoles)
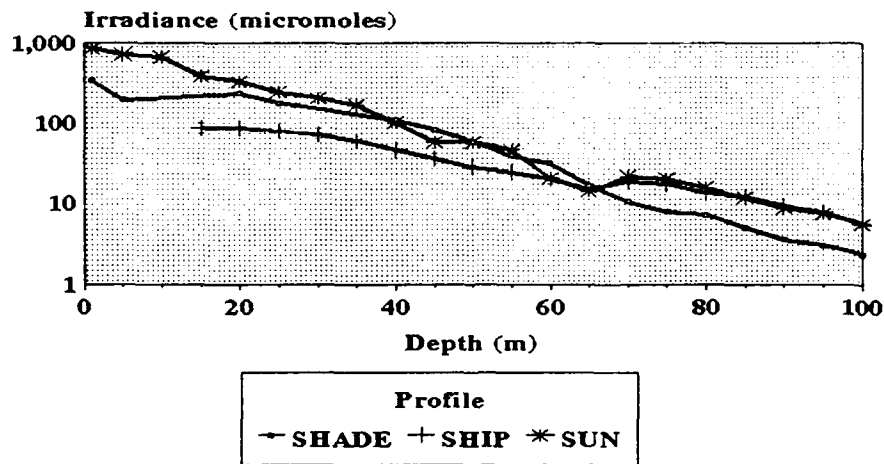
Figure 5. Profiles of irradiance 30 meters from the ship on the shady side (SHADE), under the ship (SHIP) and 30 meters from the ship on the sunny side (SUN) during dive 2909.

5. DISCUSSION

In the case of dive 2900 it is clear from Figures 4a,b and c, that the relatively low values of irradiance were detected in the quadrants identified by -X and +/- Y, as expected with the sun on the +X side. Figures 4b and 4c suggest that the maximum shadow effect would show up in the beam transects, rather than the axis transects. When equation (1) is used to quantify the shadow effect in terms of errors in E$_d$, the difference between the beam and axis transects (Figures 6 & 7) is obvious.

For the purposes of these two figures, the term E$_{true}$ was estimated as the mean value of all measurements greater than 150 micromoles at 20 meters depth and greater than 117 micromoles at 30 meters depth.

Figure 6 shows the error in E$_d$ at both depths in the axis transect (the ordinate of the figure has been chosen to allow comparison with the same ordinate in Figure 7). Typically, the error at 20 meters (60 feet) was less than 30%, with some change from positive to negative, going from astern of the surface ship to forward of the surface ship. This is consistent with a slightly brighter irradiance field in the forward region. This forward brightening is not as evident in the deeper axis transect (Figure 6b), but, again, the error is typically less than 20%. Trends of shadow effects are difficult to discern from the axis transect.

Figure 7, plotted on the same axis for errors, as Figure 6, shows the extreme signal change associated with the shadow of the ship at both depths. In the case of the 20 meter transect the error increases from roughly 20% to over 400% within 30 meters of the center of the ship. At the
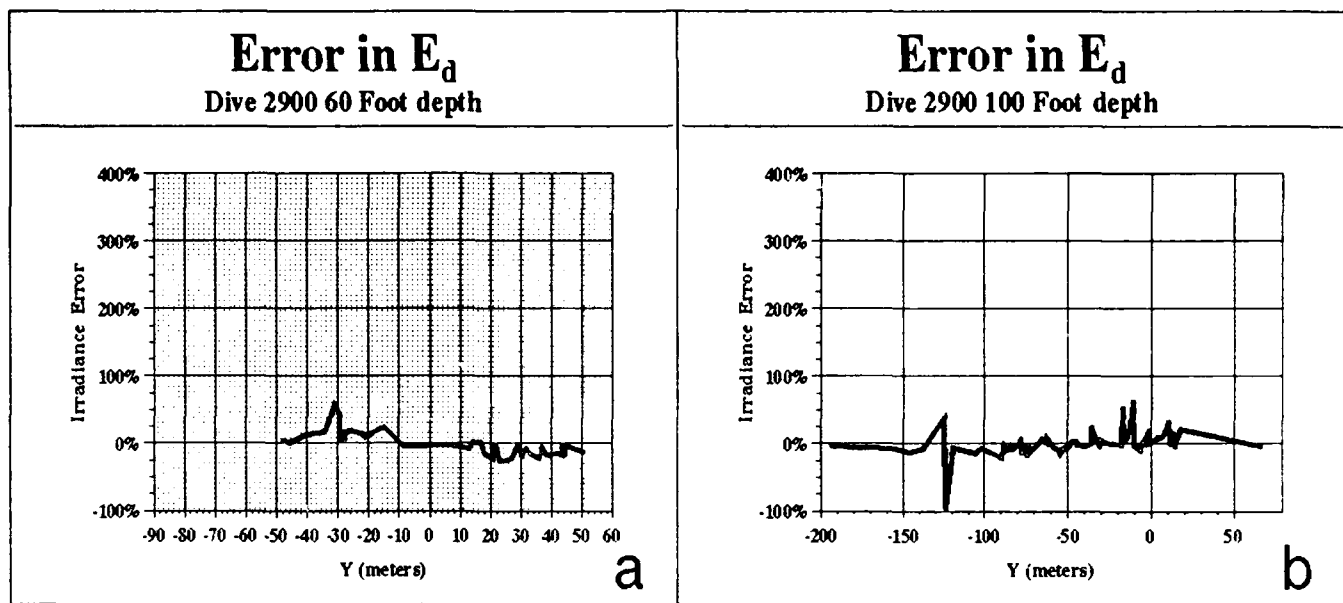
Figure 6. Errors in downwelling irradiance on transect taken under ship length (axis) at: a) 20 meters and; b) 30 meters on dive 2900.

30 meter depth a similar pattern is detected, but the error is only about 180% (still quite large compared with the axis transect).

At both depths the shadow is clearly skewed to the -X side, as one should expect with the sun located on the +X side. Also shown in Figure 7a, and plotted in enhanced scale in Figure 8, are the results of the simulations done by Gordon[6] at 20 meters depth, for a different shadowing geometry. Nonetheless, Figure 8 shows that in the range of 5 to 15 meters from the ship rail, the measured errors are consistent with errors one would predict for a clear sky (i.e. predominantly sun illumination). Gordon's predictions are shown for two different values of the beam attenuation coefficient. Figure 9 shows that the results obtained here are closest to predictions for waters having a beam attenuation coefficient, c_{par} of 0.3 m^{-1}. Measurements of c_{par} were not made in this study, but values of order 0.3 m^{-1} are not inconsistent with the water quality of this region (measurements of c at 660nm taken at this station were typically approximately 0.4m^{-1}).

Concluding, for the clear sky case, the data show that the most significant effect of ship shadow is seen in the transect performed along the beam of the ship, when the ship bearing was such that the sun was abeam. At a depth of 20 meters (i.e. approximately one optical depth), the ship shadow was still quite evident at distances of 35 meters on the shady side of the ship. Errors on the sunny side were consistent with predictions from Monte Carlo simulations.

The data for the overcast profiles, as shown in Figure 5 demonstrate, as predicted qualitatively, that the shadow effect is much more extensive in this case. Several features in Figure 5 are notable. Measurements of irradiance were lowest directly under the ship. The shady side and sunny side had nearly equal irradiance values near the surface. At a depth between 40 and 65 meters there is a "crossover" point at which the shade side irradiance values become the lowest. Below this crossover point the profiles on the sunny side and directly under the ship are nearly
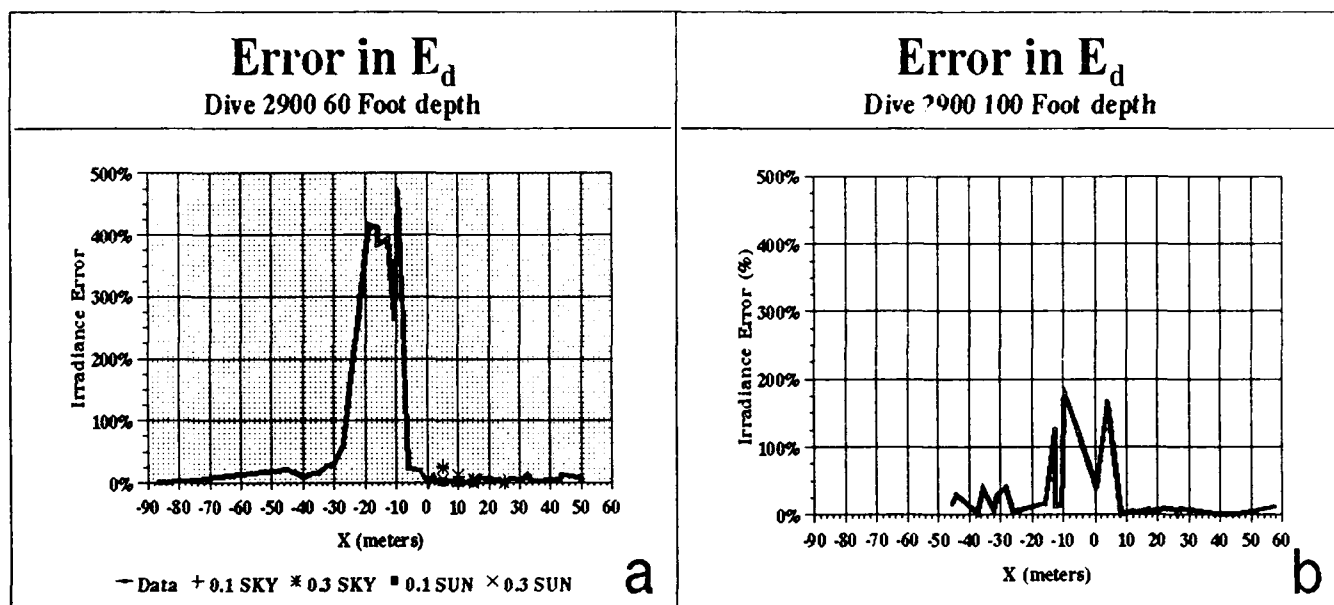
Figure 7. Error in irradiance measured during transect taken under beam of ship at: a) 20 meters and; b) 30 meters depth in dive 2900. Also shown are the errors predicted from Gordon[6].
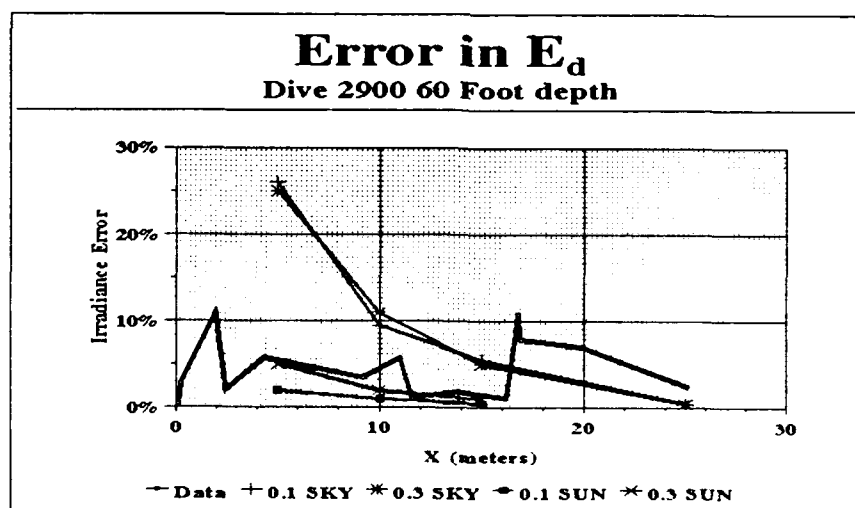

Figure 8. Same as Figure 7a on expanded scale.

equal. This pattern is as one would expect for a shadow that is projected under the ship at some angle consistent with the sun location. The shady side profile should be essentially unaffected until some depth where the vertical profile intercepts the top edge of the shadow. By the same token,

the vertical profile directly under the ship should eventually be outside of the shadow. These results suggest that the ship shadow appears at a depth of approximately 40 meters some 30 meters abeam of the ship on the side opposite the sun. The results also suggest that the shadow disappears from directly under the ship at a depth of approximately 65 meters. For the solar zenith angle of 46°, and a ship beam of approximately 8 m, Snell's law suggests that the shadow at 30 meters abeam of the ship should first appear at 40 meters depth. These results are entirely consistent with the geometric prediction of ship shadow. Similar analysis of the disappearance of the shadow under the ship suggests a dispersion of the shadow by approximately 26° (i.e. the shadow is not collimated, but actually subtends an angle of 26°).

Figure 9 shows the discrete and integrated values for the diffuse attenuation coefficient, K_d, defined as:

$$K_d(discrete) = \frac{\ln E_d(z_2) - \ln E_d(z_1)}{z_1 - z_2}$$

$$K_d(integrated) = \frac{\ln E_d(z_2) - \ln E_d(z_{ref})}{z_{ref} - z_2}$$

(2)

and reference values for the integrated diffuse attenuation coefficient were 1 m, 15 m, and 1 m, respectively for the shade, ship and sun profiles.
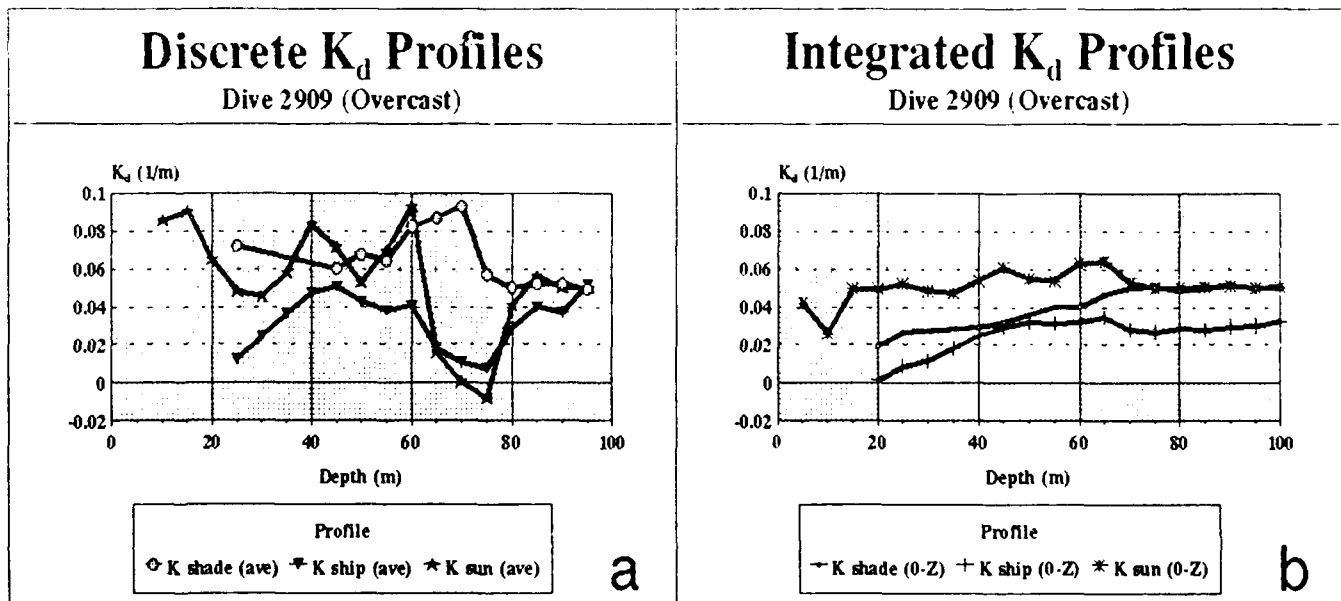

Figure 9. Profiles of the diffuse irradiance attenuation coefficient during dive 2909: a) three point running average of discrete 5 meter values; b) integrated (relative to 1, 15, and 1 meter for shade, ship and sun, respectively) values.

In the case of the discrete coefficients (Figure 9a) a boxcar average of three depths was used to smooth the profiles. The results, shown in Figure 9a show considerable variability in K_d. The

integrated values in Figure 9b serve better to highlight the features of the shadow. For example, neglecting the two shallowest values in the sun profile, the integrated K_d stays within 0.01 m^{-1} of 0.055 m^{-1}. On the other hand, the overall change in both the ship and shade profiles is of order 0.03 m^{-1}. In addition, the 65 meter depth at which the shadow disappears under the ship is quite evident as a sudden drop in K_d; the appearance of the shadow at about 40 meters in the shade profile is not so evident, but may be manifested in the slightly increased slope in the K_d profile at that depth. A peculiarity is the fact that the sunny and shady profiles reach the same values of K_d at about 70 meters, but the ship profile K_d does not appear to have reached an asymptote, even at 100 meters. This may be a manifestation of the use of a shadowed irradiance as a reference in the calculation of the integrated irradiance.

Ratios of the discrete values of K_d are shown in Figures 10a and b. In Figure 10a values greater than 1.0 imply enhanced attenuation compared with the control (i.e. sun side) profile. The Figure shows that the shade profile is similar to the sun profile near the surface and at the bottom of the cast. By comparison, the profile under the ship does not begin to come to full agreement (i.e. K_ds within 20%) with the sunny side profile until a depth of approximately 80 meters. The drastic decrease in the ship:sun ratio at 75 meters arguably corresponds with the bottom of the shadow. This is also shown in Figure 10b, where the shade and ship profiles are compared. In essence this Figure shows the full three dimensional character of the ship shadow, with its appearance at 45 meters, its disappearance under the ship at about 75 meters, and its complete disappearance, even from the shady side profile between 95 and 100 meters.
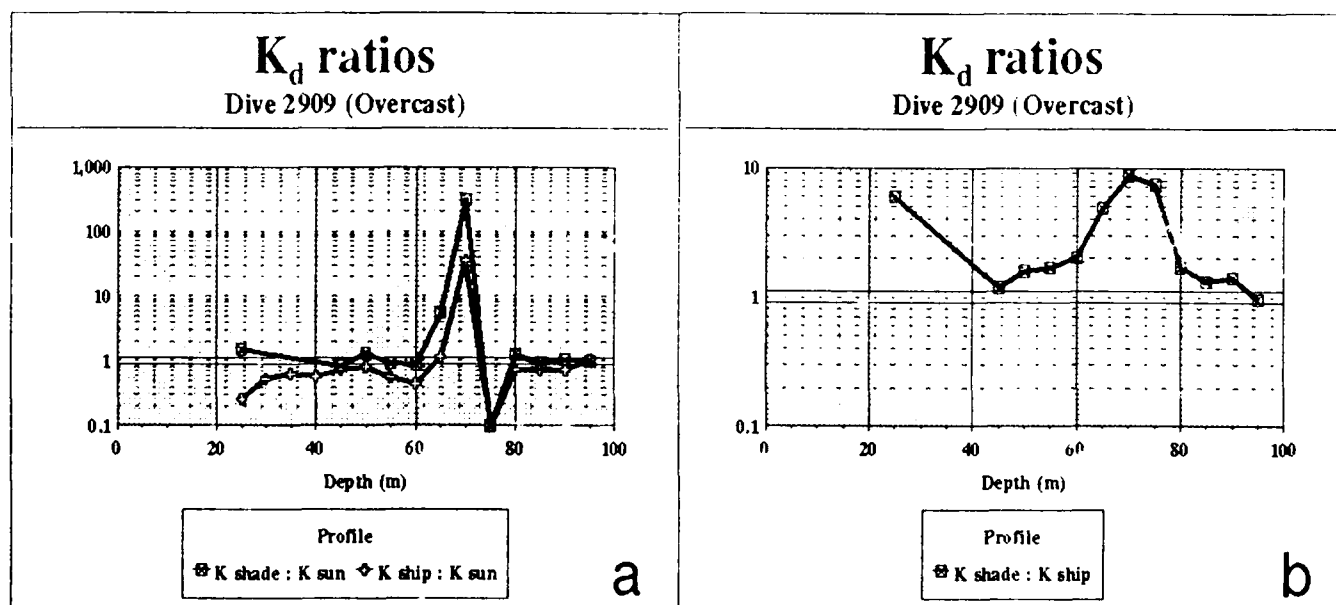
Figure 10. Ratios of the discrete values of K_d.

These results demonstrate that the ship shadow is a noticeably large effect, especially under overcast skies. It also demonstrates that the shadow under such conditions behaves not as a collimated pencil of reduced illumination, but rather as a spreading center of darkness: a function

of the diffuse irradiance from the sky. The effect is still detectable to depths of order four optical depths at distances of approximately one optical depth from the ship on the shady side.

6. CONCLUSIONS

Ship shadow cannot be avoided from large surface vessels, but these measurements have provided the first nearly continuous set of transects under the vessel to define the shape and extent of the shadow. Results under sunny conditions are consistent with numerical models, suggesting errors of order 5% within 10 meters of the ship at 20 meters depth, for waters with an optical depth of approximately 20 meters at the surface. Under overcast conditions, the ship shadow was not evident at a distance of 1½ optical lengths from the ship on the sunny side, but at the same distance on the shady side the shadow was quite evident between 2 and 4 optical depths. Directly under the ship at 1 optical depth the shadow amounted to decrease in downwelling irradiance of approximately 80%.

These results would benefit from further theoretical comparisons. The data of ship reflectance, in conjunction with the geometric considerations of the experimental design could be used to test existing models of ship shadow.

This research also demonstrated very effectively the power of manned submersibles for optical research. The ease of positioning, navigation, stability and measurement all proved essential to obtaining optical measurements of reasonably high accuracy and repeatability.

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