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SUBMARINE VISIBILITY AND RELATED AMBIENT LIGHT STUDIES

(FINAL REPORT)

by
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FOREWORD

This is the final report on work performed by the Visibility Laboratory of the Scripps Institution of Oceanography under Contract N62306-1034 (FBM) between the U.S. Naval Oceanographic Office and the Regents of the University of California. The contract called for effort by the Visibility Laboratory to assist the Naval Oceanographic Office in the analysis of ambient light data and related problems as described in the Visibility Laboratory's proposal UCSD 1073, dated 15 May 1962, which was in response to USNHO, RFQ No. 280519, dated 20 April 1962, and USNHO Specification 3525-62-10, dated 30 March 1962.

The authors wish particularly to acknowledge the assistance of Dr. S. Q. Duntley and J. E. Tyler for their guidance and contribution to the studies which were performed under this contract and which are reported here.

SUMMARY

This report describes the activities of the Visibility Laboratory of the Scripps Institution of Oceanography on behalf of the U.S. Naval Oceanographic Office under contract No. N62306-1034 (FBM)

The major effort which was undertaken during the one-year period of the contract was to provide requested support for two field operations whose purpose was the study of the visibility of submarines from aircraft. Neither of these operations were successful in providing the primary information which was being sought due mostly to the vagaries of the weather and the Cuban blockade. Recommendations are given for a plan for a future operation with more carefully controlled conditions and more restricted and specific objectives.

Data was submitted for examination which had been obtained on several cruises of the USS REDFIN to various areas in the Atlantic Ocean. Within the limitations imposed by the lack of adequate documentation on many of the records these data were reduced and analyzed. Recommendations are made for uses of the data obtained, for improved methods and instrumentation to be used to obtain data in the future.

It is suggested that further data be obtained with careful documentation followed by additional study and analysis. Such a program should be able to provide a methodology for the use of ambient light measuring equipment to assist submarine commanders in the accomplishment of their operational mission.

1.0 INTRODUCTION

Since its formation over a decade ago, the Visibility Laboratory has worked with many problems involving the detection of submerged submarines from aircraft, the measurement of ambient light in the sea, and the development of equipment for this latter purpose. Through contracts with the Bureau of Ships, notably NObs-43356 and NObs-72092, the Laboratory has on numerous occasions worked with the Hydrographic Office on various instrumentation systems and in giving assistance with underwater optics problems. For example, the water clarity measuring equipment which was installed on the USS REDFIN (SS-272) in 1959 was provided by this Laboratory under the second of the above contracts. In April 1962, the Laboratory was approached by the Hydrographic Office with a request to submit a proposal for a level-of-effort type contract in accordance with Specification 3525-62-10.

Contract N62306-1034 (FBM) which resulted from these negotiations provided that the Visibility Laboratory make available its research and development personnel and facilities to analyze the ambient light data obtained from fleet submarines on patrol to determine their applicability to submarine detection; to evaluate the accuracy and reliability of photo-sensors as used by the submarines; to suggest new equipment, modifications to existing equipment and/or new methods of application of existing equipment which would result in obtaining the Submarine Visibility Detection Program objectives with improved accuracy, in a reduced time, or with greater simplicity or reliability. Provision was also made for the possibility of photometric calibration of sensors and instrument design recommendations. It was not expected, however, that major instrumentation or data acquisition system development would be accomplished. Details of the work to be performed were determined by mutual agreement between the Oceanographic Office personnel and the principal investigators within the scope outlined above.

During the period of the contract, assistance was given to the Oceanographic Office by the Laboratory in planning and carrying out two field experiments whose purpose was to obtain information on the sighting ranges of submerged submarines with documentation of the optical and meteorological conditions which existed during the test. In Section 2 of this report these two field experiments are described along with their preparation and the results or lack of results which were obtained. This information was included for the purposes of record and to establish the basis on which the recommendations for a future experiment are made. As Appendix A there is included a verbatim transcription from a voice tape recorder carried by Dr. Taylor on the operation with the USS REDFIN in the Norfolk area in April 1963. By the inclusion of this it is hoped that additional insight may be obtained into the problems which occur when undertaking an operational exercise of this type.

Section 3 briefly describes the analyses which were made of some of the data provided to the Laboratory in the form of records from earlier cruises of the USS REDFIN. More detailed comment on the records of Cruise 2 and their analysis is included in Appendix B. Section 3 also includes a brief description of the work which was done on the analyses of fluctuations of ambient light underwater and the correlation which exists with wave measurements made simultaneously.

2.0 FIELD OPERATIONS

2.1 Bermuda-Argus Island Field Experiment

The first Visibility Laboratory effort under the contract was preparation for, and participation in the Hydrographic Office operation involving the USS REDFIN (SS272), the Argus Island, and a Navy P5M aircraft in the vicinity of Bermuda. The Laboratory was requested to give support to the TEST ITEM in the Oceanographic plan for this exercise. The purpose of "ITEM" was to collect operational data on the visibility of submarines from aircraft and to establish a relationship between ambient light measurements made aboard the submarine and its visual detectability. The proposed plan was submitted to the Laboratory and a number of recommendations were made for modifications to TEST ITEM which it was felt would provide more meaningful data on submarine detectability.

2.1.1 Instrumentation

It was intended that the sightings which were to have been made from the P5M aircraft during the Bermuda exercise would be documented by various measurements made from the air, from the submarine, and from the Argus Island contemporaneously with the visual observations. For this purpose, the following instruments were prepared and calibrated for the specific objectives described:

Telephotometer - A modified Spectra Brightness Spot Meter with a half-degree acceptance angle and with its spectral sensitivity made to approximate that of the light-adapted human eye was to be used to measure the apparent luminance of the ocean surface along the path of sight used on each pass. The aircraft was to proceed without change of altitude or heading until this measurement was made. A second Spectra Brightness Spot Meter with a one and one-half degree field and similarly calibrated was taken along as a back-up for the first instrument and for possible use on Argus Island.

<u>Abney Level</u> - It was planned to ascertain the angle of the path of sight used for each observation by use of an Abney level. The angles so estimated, together with altitude information, would enable an additional estimate of sighting range to be made which would supplement that made by the pilot, based upon ground speed and time.

<u>Photometric Camera</u> - a 35 mm camera was calibrated in the Laboratory, using a film-and-filter combination which approximates human photopic sensitivity. A calibrated polarizing filter was to be used in order to quantify the gain in target contrast which might be achieved if the observers were equipped with polarizing glasses. Densitometric analysis of the films would yield absolute values of apparent luminance of the scene as determined by lighting conditions, sea state, windscreen, glare, heading, and the like.

<u>Illuminometer</u> - A modified Macbeth illuminometer equipped with specially designed and calibrated filters and itself calibrated against Bureau of Standards reference lamps was provided for the purpose of establishing and maintaining the calibration of the telephotometer and the photometric camera so that absolute luminance values could be ascertained.

Gray Scale - A gray scale consisting of neutral patches of known reflectance, covering the range from 0.04 to 1.72 (reflection density values) in approximately equal steps, was prepared for use in calibrating the individual films.

Underwater Illuminometers - Five illuminometers belonging to the Oceanographic Office were submitted to the Laboratory for calibration. One of these was to be used on the Argus Island for a study of correlations between surface waves and fluctuations in the ambient light. The remaining four were to be installed on the REDFIN for measurement of the downwelling illuminance at the stations and for measurement of the illuminance incident on the submarine from the port and starboard sides. A special electrical attenuator panel was constructed consisting of four 11-step shunts which could be individually used to control the sensitivity of the four illuminometers on the submarine. The illuminometers were calibrated against standard lamps maintained at the Laboratory and against daylight illumination levels measured by a calibrated Macbeth illuminometer. The calibration factors for the illuminometers are given in the table below.

ILLUMINOMETER CALIBRATION FACTORS

Nominal Full Scale Range (ft-c)	Multiplying Factors (To obtain actual ft-c from attenuator output in MV)				
	Cell No. 1 Atten.No.1	Cell No. 2 Atten.No.2	Cell No. 3 Atten.No.3	Cell No. 4 Atten.No.4	Cell No. 5 Atten.No.4
5	0.495	0.500	0.480	0.480	0.400
10	0.880	0.870	0.860	0.890	0.730
25	2.06	2.06	2.05	2.05	1.75
50	4.06	4.04	4.00	4.12	3.50
100	7.90	8.05	8.12	8.15	6.95
250	19.6	20.2	20.1	20.1	17.3
500	39.3	41.2	41.2	41.4	35.2
1,000	80.0	82.0	82.5	83.5	72.0
2,500	200.0	230.	216.	211.	184.
5,000	420.	520.*	448.	434.	376.
10,000	1160.	1330.*	1490.*	1110.	960.

By multiplying the voltage appearing across the terminals of the attenuator in millivolts by the factor in the table for the appropriate range setting of the attenuator, the illumination incident on a particular photocell may be obtained in the units of foot-candles (lumens per square foot). These factors are adequate for data reduction except in the case of cells 2 and 3 on the higher scales, as marked with a *. For these ranges more accurate data reduction can be obtained by using the curves which were supplied to the Oceanographic Office personnel in Bermuda.

Other equipment taken to Bermuda consisted of a calibrated deck-type photo-voltaic illuminometer for use on the Argus Island, and a special Visibility Laboratory logarithmic telephotometer which was to be used for measuring sea surface luminances from the Argus Island.

2.1.2 Field Experience

Through the use of the instruments noted above plus other sensors located on the REDFIN and Argus Island it was expected that adequate documentation of the environmental conditions could be obtained to permit a correlation to be developed between the observed sighting ranges of the submarine from the aircraft and optical parameters which could be measured on the submarine.

Equipment difficulties on the submarine and extremely high winds caused by a hurricane in the vicinity of Bermuda prevented the acquisition of any data pertinent to the objectives of TEST ITEM during the first week of scheduled operation. On Monday of the second week the blockade of Cuba was announced resulting in a complete lack of availability of the ASW type aircraft which had been scheduled for TEST ITEM. Thus no data were obtained during the two-week interval which was pertinent to the primary objective of the Bermuda operation insofar as the Visibility Laboratory's participation was concerned. However, with the instrumentation on the Argus Island data were obtained which were pertinent to a secondary objective of the operation, namely that of obtaining correlations between the fluctuations in the ambient light records and the records of wave height as obtained by the wave staff.

During the first week the underwater illuminometer calibrated at the Visibility Laboratory and an EDO transducer were mounted together and lowered on the instrumentation support cables which the Oceanographic Office had mounted on the south side of the Argus Island tower. A preliminary check was run on the instrumentation, and it was determined that it was operating satisfactorily. However, certain equipment spares on Argus Island were needed to repair the inoperative equipment on the REDFIN and as there was no possibility of operating with the REDFIN until the following Monday, the Argus Island personnel concerned with the Oceanographic Office operation returned to Bermuda on Friday. Over the week end the nearby hurricane caused seas of 30 to 40 feet and winds up to 50 knots. The violence of this storm completely removed the underwater illuminometer and the EDO Transducer from the instrumentation cables. This was not discovered until personnel returned to Argus Island Monday morning. Arrangements were made to borrow an underwater photocell housing from the Bermuda

Biological Station. The housing was modified to accept a spare photocell which had been brought to Bermuda, and this assembly was calibrated against the "deck cell" illuminometer which the Visibility Laboratory had on Argus Island. By Wednesday evening the equipment had been received and calibrated and was lowered into the water for a preliminary operating checkout. On Thursday the equipment was lowered by hand from the "Hydro platform" area. Because of the large surface current the wire angle was extreme and there was considerable uncertainty as to the orientation of the collector surface and as to the exact depth of the sensor. On Friday the Biological Station photo-housing was suspended below an instrument fixture and lowered on the instrumentation support cables. However, owing to the large surge and current it became obvious that the orientation of the collector surface was neither fixed nor horizontal, and therefore it was not possible to separate the fluctuations due to the motion of the illuminometer and those due to changes in the light field caused by surface waves. The record showed an unexpectedly large fluctuation apparently correlated with the wave action despite the fact that the sky was completely overcast. This fluctuation decreased when the cell was lowered and it was hypothesized that the surge was less and that consequently the swaying of the photocell diminished at greater depths.

On Saturday an auxiliary fixture was fabricated for holding the cell to the top of the instrument fixture, thereby essentially eliminating motion of the cell. Using this arrangement, data were obtained on Saturday and on Sunday morning which proved to be adequate for the purpose of determining the desired correlations. Data were reduced from a sample lowering to demonstrate the procedure to be used to obtain K, the diffuse attenuation coefficient. The profiles of the ambient light versus depth showed a rapid decay of the light field in the first 20 feet or so. Below this level a uniform, less rapid decay was found, indicating a well mixed water mass down to 100 feet with a value of K of 0.065 per meter. Data were not taken below this depth at that time. The rapid decay near the surface was attributed to one or both of the following factors: First, the wave action on the legs of the tower and the direction of the surface current were such that there was frequent evidence of bubble clouds drifting over the location of the photocell. Massive clouds of entrapped air could have produced a rapid decrease in light flux. The second and more probable cause of the rapid decay near the surface was that the photocell was equipped with a Wratten 102 spectral filter to give the cell a photopic spectral response.* The first 20 or 30 feet of water would act to attenuate, very rapidly, the far blue and red ends of the

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* All photocells used in the field experiment were fitted with these same spectral filters which gave them a response approximating that of the light-adapted human eye. This was done because the experiment was concerned with visibility determinations, and cells so corrected will measure flux in photopic units whose size is directly proportional to the efficacy of the flux in producing a stimulus in the human observer.

spectrum. This would change the spectral quality of the light reaching the cell as it was lowered. Thus the water was acting as a natural monochromator and attenuated the spectrally-broad natural illumination near the surface at a much greater rate than the flux in the much narrower spectral region which is found at depths below the surface layers.*

A quick visual inspection of the records obtained from the ambient light recorder and the wave staff recorder showed what were apparently excellent correlations between the temporal variations in the two phenomena.

At this point it was felt that no further purpose was to be served by having Visibility Laboratory personnel remain in Bermuda, and they returned, therefore, to San Diego.

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* An insight into how the spectral transmission properties of the water quickly dominate in determining the spectral quality of light penetrating into the sea may be obtained by reading J. E. Tyler, "Natural Water as a Monochromator", Limnology and Oceanography Vol. IV, No. 1, Jan. 1959, pp 102-105.

2.2 Norfolk Field Experiment

In January 1963 the Visibility Laboratory was again requested to assist the Oceanographic Office by participating in a second exercise with objectives similar to those of the first, viz., to study the visibility of submerged submarines from aircraft and to correlate the findings with ambient light measurements made contemporaneously aboard the submarine. These tests were run on 4 April and 8 April 1963 in an operating area off Norfolk, Virginia, following, in general, TEST ITEM in the Oceanographic Plan. As there was no oceanographic tower such as the Argus Island in the Bermuda experiment from which lighting and sea conditions could be documented, all data not obtained by the submarine had to be obtained by observers on the aircraft. Although a helicopter was requested as first choice and a P5M as second choice for the observation aircraft, neither of these was available, and a standard ASW-configured P2V from Patrol Squadron VP56 at Norfolk Naval Air Station was used. Dr. J. H. Taylor of the Visibility Laboratory flew these missions and his description of the tests follows.

2.2.1 Experimental Plan

It became evident upon arrival in Norfolk that (1) only P2V aircraft were available for use in the experiment, and that (2) no opportunity existed to make dry-run orientation flights which would enable us to check out instruments and to devise an optimum flight pattern. The aircraft configuration dictated that the two observers could best occupy positions in the nose and in the aft compartment, despite the fact that these two stations were quite dissimilar in regard to the possibilities each afforded for the sighting task. As previously planned for the Bermuda operation, sighting ranges were to be obtained both from slant path angle and altitude and from direct horizontal range estimates provided by the navigator from sonobuoys. The arrangement of submarine and aircraft was intended to follow the schedule stated in the Oceanographic Plan. It soon became evident that this was unrealistic owing to the variable and unfavorable sky conditions which were encountered, and a highly simplified plan had to be adopted. The actual runs, therefore, were made with only two submarine headings (North and West), keel and periscope depth, and a variety of aircraft headings.

The personnel involved, in addition to the crew of the aircraft, were two civilian observers; one with 20/20 vision for distance, the other corrected to 20/20 by means of spectacles. Each was provided with polarizing sunglasses for use in suppressing sky reflection from the water surface, although these were not generally used (v.i.).

Instrumentation was essentially identical with that provided for the Bermuda tests already described, with the addition of a portable tape recorder used by the observer in the nose of the aircraft.

2.2.2 Résumé of the Flights

Two flights were made during the period of the Norfolk operation. The rearward observer was able to remove hatches on the side of the fuselage, and thereby to obtain a clear view of the ocean surface below and to the side, although his forward and rearward views were very limited. The forward observer was afforded excellent angular coverage, but the optical properties of the plastic nose imposed severe distortions of contrast, color, and shape. Some idea of the extent and severity of these effects may be gained by reference to Plate I, which is from a photograph taken from the forward observer's eye position. In this downward look, it is evident that:

1. Most of the field of view is veiled by stray light resulting from the reflection of the bright sky in the curved plastic surfaces of the lower section of the nose.

2. The dark central band, caused by the presence of a section of green plastic directly overhead, represents the area of best contrast rendition, but with a concomitant chromatic distortion.

When polarizing glasses were used, a very beautiful but highly irregular and distracting pattern of colored bands became visible, caused by internal stresses in the plastic. For this reason, the forward observer did not use the polarizing glasses. The rearward observer, although not troubled by intervening plastic, was unable to state with certainty whether or not they were of positive benefit. (It is known, of course, that useful elimination of the water surface reflection of the sky will occur when the sea is relatively calm and the viewing path is approximately at Brewster's angle.) The two flights will be briefly summarized below, primarily to indicate certain problems which were encountered and which will later be referred to in a section dealing with recommendations for any subsequent study. A transcript pie

of tape recordings made during the operation is contained in Appendix A. All times are Eastern Standard.

First Flight - 4 April 1963 - The takeoff from NAS NORVA was at 0648. Aircraft was on station in the northern part of Area 21 at approximately 0800. At this time the estimated sea state was 3, surface temperature 58° F., wind velocity 15 knots at 245°. The sky condition, initially clear in the direction of the sun, became progressively more cluttered by broken overcast and considerable haze. The aircraft operated at altitudes from 300 to 500 feet from the water surface, and at various headings which were intended to permit observation of both sunlit and shadowed sides of the submarine as it maintained constant 2-knot headway and depth. As may be deduced from the tapes, it was impossible to conduct the experiment as planned because of unfavorable conditions of the sky (changing, broken, overcast) and the sea surface (sea state varying from 2 to 3.) The few sightings which were made occurred when the REDFIN was operating at periscope depth and there was usually some extraneous cue, such as the antenna wake, which could be held responsible for initial location of the boat. This, of course, would not be likely to occur in the case of a real submarine hunt, especially at conventional search altitudes. The apparent luminance of the sea surface was measured as a function of azimuth, at a zenith angle of about 150°. (This was approximately the angle which the observers used during the flights.) Owing to the high resolution of the telephotometer (narrow acceptance angle) there was considerable local variation from point to point as seen by the instrument. This difficulty, which resulted from the coarse optical texture of the sea surface, produced considerable scatter in the luminance readings, especially when passing near the sun's glitter path. The data, nevertheless, are shown in Appendix A.

Second Flight - 8 April 1963 - It was thought, at the end of the first flight, that experience enough had been gained so that a somewhat simplified experimental plan would succeed, provided the weather improved sufficiently. On the basis of hour-to-hour forecasts and the five-day outlook as supplied by the squadron, no further flights were possible until 8 April. On that date the short-range forecast was for clear skies and a sea state between 0 and 2. Upon departure from NAS NORVA at 0829, however, there were winds of about 20 knots from the North, and an estimated sea state of 2.5. In the operating area the sea state seemed even higher, and there was an appreciable amount of white water. During the target runs, which occupied the period from 0930 to 1040, only a few sightings were made, and these were, again, usually due to some controlled cue. Surface winds remained at 11 - 12 knots and the sky gradually became cluttered with the high overcast which had typified the earlier mission. White-caps increased in number and persistence, and the experiment was terminated at 1040. It was felt that no gain was made on the second flight, and that it served only to underscore the necessity for conducting the test under more predictable and consistent weather conditions, in addition to the various other improvements which should be incorporated in a subsequent exercise.

2.2.3 Subjective Impressions

In the absence of quantitative data from either the Bermuda or the Norfolk expeditions, one may be permitted the space to give a brief answer to the question: "What did it look like?" Two thousand words of narrative may immediately be replaced by inclusion of Plates II and III. From Plate II it is possible to gain an impression of the appearance of the periscope wake in the absence of whitecaps of like size. The REDFIN is on a northerly heading, so that the sun is behind and to the left of the observer; that is, viewing conditions are just about the best encountered, yet the submarine cannot be seen. In Plate III the submarine is on the same heading, but now we are looking into the glitter path of the sun. The deck and hull of the boat, although immediately below the surface, are yet more difficult to discern. The patchy chromatic veiling seen in both pictures is due to reflections in the plastic of such things as the observer's orange flight suit, objects in the compartment, and sky.

3.0 STUDY AND DATA ANALYSIS

3.1 Analysis of Data from REDFIN Cruises

Data obtained from the water clarity equipment on the USS REDFIN were sent to the Visibility Laboratory for analysis. These data include strip chart recordings and notes obtained on the various cruises from October 1959 through November 1960. A complete analysis of these recordings was not possible because of the lack of appropriate documentation, i.e., annotation on the charts or other supplementary information which would be required for reduction of the data. This equipment was new and developmental in its nature, and it is presumed the personnel responsible for its operation were unfamiliar with the operating procedures to be used to obtain the optimum use of the data. We have had to piece together, in many circumstances, the necessary information for even a superficial analysis of the records. In general, however, where adequate depth, time, location, and illuminometer sensitivity range annotations have been made on the chart it has been possible to reduce the information from the illuminometer cells and obtain illuminance profiles from which values of K, the diffuse attenuation coefficient, can be obtained.

The alpha-meter proved to be a more difficult instrument to use. In fact, the data from it are suspect because the α-values obtained are unlike those which would be expected from waters of the types which were measured. The transmittance values are too low, and the cause for this is difficult to reconstruct at this late date. It is unfortunate that this instrument was not made to perform satisfactorily and that the information from it cannot, therefore, be correlated with that derived from the illuminometers. An interesting and important correlation, for example, which could have been obtained would have been that between K-values and α-values for various oceanic operating areas. Some sample determinations of alpha were made from the records of Cruise 2 and are given in Appendix B. However, they will not be repeated here because of their doubtful significance.

It is encouraging to note that the illuminance profiles obtained from the records of the three illuminometers with few exceptions produced quite reasonable answers even though the recordings were obtained in some cases fifteen months after the calibration of the illuminometers, and their treatment in the intervening period is unknown but is likely to have been severe, as is typical of field equipment. In some instances the over-all level of illuminometer sensitivity seems to be reduced, which may have been caused by dirt accumulating on the collector surfaces. This could also account for the disparity which is occasionally noted between the various cell outputs when the submarine is surfaced and all three cells presumably have the same light field.

In each case where there was a "recorder zero" shown on the chart which was not zero, this value was used to correct the apparent output of that illuminometer. For example, throughout most of the records the recorder zero was apparently one and one-half divisions up-scale. This is the equivalent of 150 microvolts of dc stray signal. It is not difficult to obtain stray signals of this magnitude in a complex electrical system such as a submarine, and the simplest and only available routine for us to follow at this juncture is to subtract such a value from the apparent output of the cell.

Some of the records had been marked with absolute illumination figures which indicated that the nominal value of the sensitivity range had been taken as the absolute value of the maximum output. Because of the zero scale correction and because of the fact that the actual full-scale sensitivity values for the various ranges are not the same as the nominal values for that range, such a procedure can only give approximate values for the illumination. In order to obtain more accurate data it is necessary to use both the appropriate calibration factors as given in the table below and the zero scale value correction. These calibration factors were obtained by the Visibility Laboratory before the system was shipped in 1959 and were supplied to the Oceanographic Office personnel at the time of installation. They are reproduced here for convenience in reference. The table on page 2-3 should be used for data taken after October 1962. The data which are presented below were reduced in this manner and assume that the resistive attenuator networks were not changed, that the cells and their optical filters were not changed, and the calibrations were in no other way disturbed.

ILLUMINOMETER CALIBRATION FACTORS (Aug 59 Calib)			
	Multiplying Factors To Convert Chart Reading (0 - 100) to Absolute ft-c		
Nominal Full Scale Range (ft-c)	Lower	Upper	Sail
5	0.0503	0.0512	0.0485
10	0.100	0.100	0.0952
25	0.254	0.256	0.251
50	0.512	0.511	0.504
100	1.05	1.04	1.03
250	2.66	2.64	2.61
500	5.38	5.32	5.28
1000	10.9	10.5	10.9
2500	26.9	26.6	26.1
5000	60.2	57.6	57.3
10000	170	151	169

3.1.1 Cruise 2, October-November 1959

As this was the first operation of the equipment in the field for which we have data and as the records were more complete than for some of the subsequent cruises, a more complete examination was made of these data than for the remaining records. The significance of the data, however, is subject to some question because of the operating procedure which was used for the illuminometers and the previously noted difficulties with the α-meter. The detailed analysis of the records for this cruise is given in Appendix B, and a brief summary of the more significant points is given here.

On 11 October 1959 the record shows a surface illumination as measured by the illuminometer on the sail of 6,000 foot-candles. This agrees exactly with the value predicted for this date, time and location by the Bureau of Ships Natural Illumination Charts*. The upper bow cell reads 5300 candles (12% low), and the lower bow cell approximately 6500 candles (8% high). Analysis of several possible causes for this discrepancy is given in the appendix. However, it should also be noted that the calibration of the cells was most difficult in this high illumination-level range, and that the discrepancy could represent merely an error in calibration or a non-linearity in cell output for this range. Closer agreement was usually noted on the lower ranges as when the cells were submerged.

At a later time on the 11th of October the sail cell showed an illumination fluctuating between 7100 and 7850 foot-candles. The horizontal illumination which would be predicted from the Natural Illumination Charts was 7220 foot-candles for a clear, sunny day. A tipping of the collector surface of 2 degrees, as might be caused by roll or pitch of the submarine, could account for the observed fluctuation and increase above the predicted value.

Again on the 27th of October the illumination on the surface as measured by the sail cell agreed well with the value predicted by the Natural Illumination Charts considering the conditions under which the measurements were made, i.e., greater than 10-foot waves and seas breaking over the bow.

These records serve to point out the requirement for having adequate chart annotation. In particular, in order to predict the

*U.S. Navy, Bureau of Ships, Natural Illumination Charts, by D. R. E. Brown, Report 374-1, Washington 25, D.C., Sept 1952 (U).

surface illuminance which would be expected for a clear, sunny day it is necessary to know 1) the latitude and longitude of the submarine at the time of the measurement (within, say, one degree), 2) the date, 3) the time (either Local Zone Time or Greenwich Mean Time, but in either case carefully noting which), and 4) the amount of roll or pitch of the submarine at the time of measurement. With this annotation it is possible to determine the solar elevation angle at the time of the measurement and consequently the surface illuminance. It is also possible to predict, by the variations in apparent solar elevation angle caused by the roll and pitch of the vessel, what the fluctuation could be expected to be in the measured illuminance.

The record for 31 October 1959 provided the first data from the illuminometers while submerged. From this data and some assumptions which were necessary due to lack of chart annotation, it was possible to compute a value of K of 0.091 m^{-1} for the 3.5 meters of water. This is a value which seems reasonable for the surface water in the assumed location of the submarine when the measurements are made with photopically corrected photocells.

Later that same day three additional determinations of K were made for discrete sections of the record. These were all made at relatively shallow depths of 4.5 to 10.5 feet of water above the cell with considerable evidence of surface wave activity. The three values of K computed were 0.082 m^{-1}, 0.076 m^{-1}, and 0.077 m^{-1}. These three, plus the value obtained earlier, are in good agreement considering the fact that they are all based on values for the surface illumination as determined by the Natural Illumination Charts (which means we are assuming a clear sky,) and measurements of ambient illumination made slightly below a wave-crested surface. There is also good agreement between these values and those which were obtained for like depths in this general area on subsequent cruises in 1960.

3.1.2 Cruise 3, January 1960 -- Virgin Islands

Cruise 3 placed the REDFIN in the Virgin Islands. The assumed location is 18° N 55° W. The record shows a run made with the sail cell from a keel depth of 255 feet to the surface. Data reduced from the recorded chart are plotted in Figure 3-1. These data plotted on semi-log paper show a straight-line curve from below 200 feet to within 50 feet of the surface. In this region the diffuse attenuation coefficient, K, is 0.061 m^{-1}. This is the clearest water that was measured in any of the records that were examined. Portions of the ascent were quite rapid, and it was possible to obtain data at only one other point between the 50-foot point and the surface. This was at a cell depth of 13.5 feet. The straight-line slope between the 50-foot point and the 13.5-foot point yields a K value of 0.084 m^{-1} and from 13.5 feet to the surface a K value of 0.157 m^{-1}. These two values are suspect for there is evidence that they are too high. Not only is it unlikely that such dense surface water would be found in this area, but there is evidence that the cell calibration on this 10,000 - foot-candle (nominal), full-scale range was in error at the time of measurement. The maximum illumination which would be expected for this location and time would have been 7200 foot-candles. The value measured by the

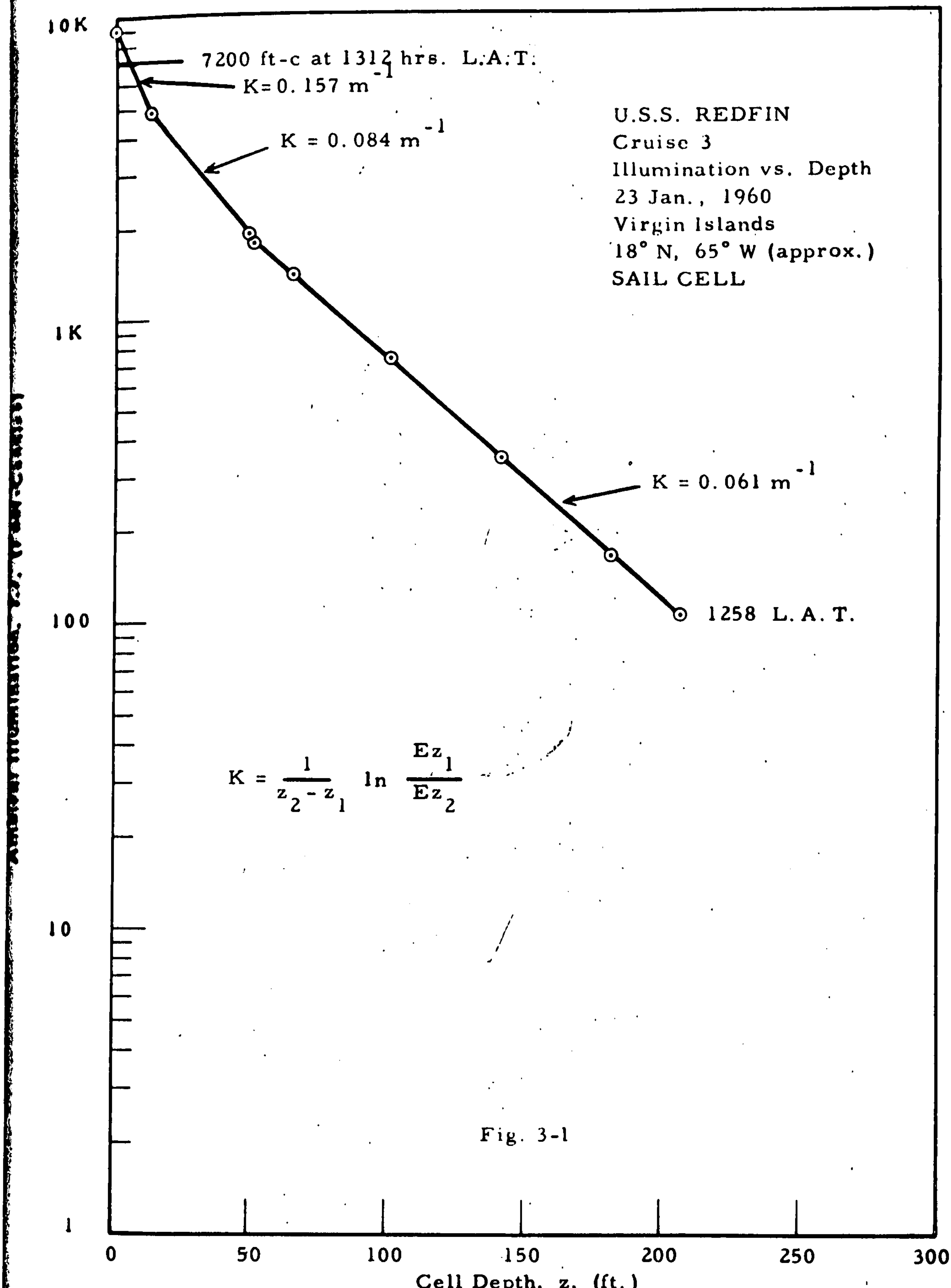

10K
1K
100
10
1
7200 ft-c at 1312 hrs. L.A.T.
K= 0. 157 m-1
K = 0. 084 m-1
U.S.S. REDFIN
Cruise 3
Illumination vs. Depth
23 Jan., 1960
Virgin Islands
18° N, 65° W (approx.)
SAIL CELL
K = 0. 061 m-1
1258 L. A. T.
K = 1/(z2 - z1) ln Ez1/Ez2
0
50
100
150
200
250
300
Cell Depth, z, (ft.)

Fig. 3-1

illuminometer on the sail was 9050 foot-candles. If the time and location were correct, it would not have been possible to obtain values of this magnitude. We must, therefore, suspect the absolute magnitude of the data. This would not, however, affect the credibility of data obtained at greater depths where the illuminometer sensitivity had been increased by switching to other ranges.

The exact location for the measurements was not given on the chart other than a pencilled notation of "Virgin Islands." If, in fact, the location was appreciably south of this, larger values of surface illuminance would have been possible. The time markings on the chart run from 1302 to 1349. There is no indication of which zonal time the clocks were keeping. There is, however, an after-the-fact notation that the time span was 1802 through 1849 GMT. This would imply that the time markings on the chart were Eastern Standard Time instead of Atlantic Standard Time, the proper zonal time for this location. Thus there is some confusion as to the solar elevation angle at the time of measurement.

3.1.3 Cruise 4, April 1960 -- Cape Hatteras Area

Data for two days, 13 April and 14 April 1960, were reduced and are presented in graphical form in Figures 3-2 and 3-3. The records on these two days are rather extensive and provide information for several ambient light profiles with depth. One dive and one ascent were reduced for each day.

On 13 April the data reduced were obtained from sail cell readings. The descent started at 0838 Local Apparent Time and lasted until 0915 LAT.

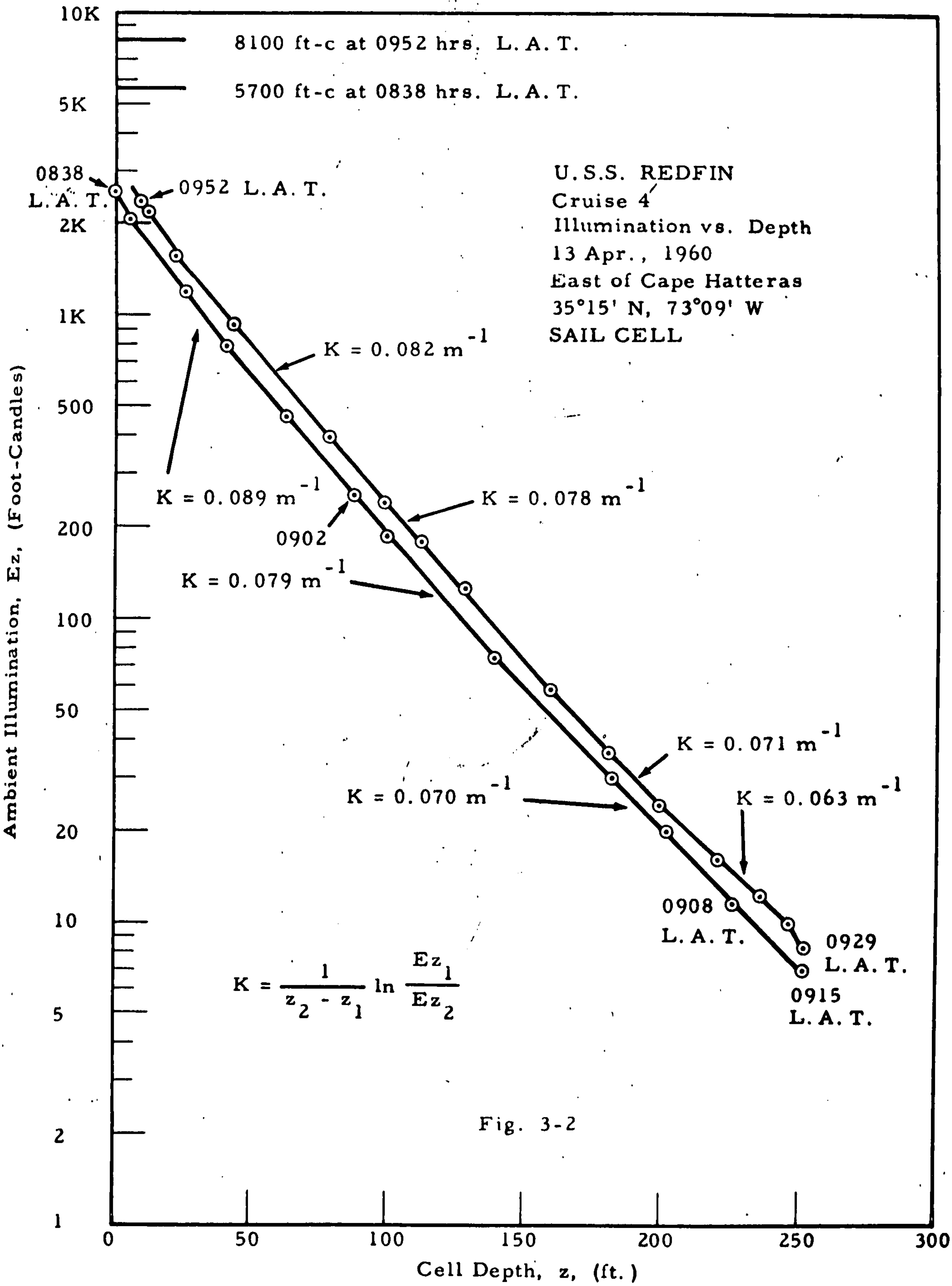

8100 ft-c at 0952 hrs. L.A.T.
5700 ft-c at 0838 hrs. L.A.T.
U.S.S. REDFIN
Cruise 4
Illumination vs. Depth
13 Apr., 1960
East of Cape Hatteras
35°15' N, 73°09' W
SAIL CELL
0838 L.A.T.
0952 L.A.T.
K = 0.082 m-1
K = 0.089 m-1
K = 0.078 m-1
0902
K = 0.079 m-1
K = 0.071 m-1
K = 0.070 m-1
K = 0.063 m-1
0908 L.A.T.
0929 L.A.T.
0915 L.A.T.
K = 1/(z2 - z1) ln Ez1/Ez2
10K
5K
2K
1K
500
200
100
50
20
10
5
2
1
0
50
100
150
200
250
300
Ambient Illumination, Ez, (Foot-Candles)
Cell Depth, z, (ft.)

Fig. 3-2

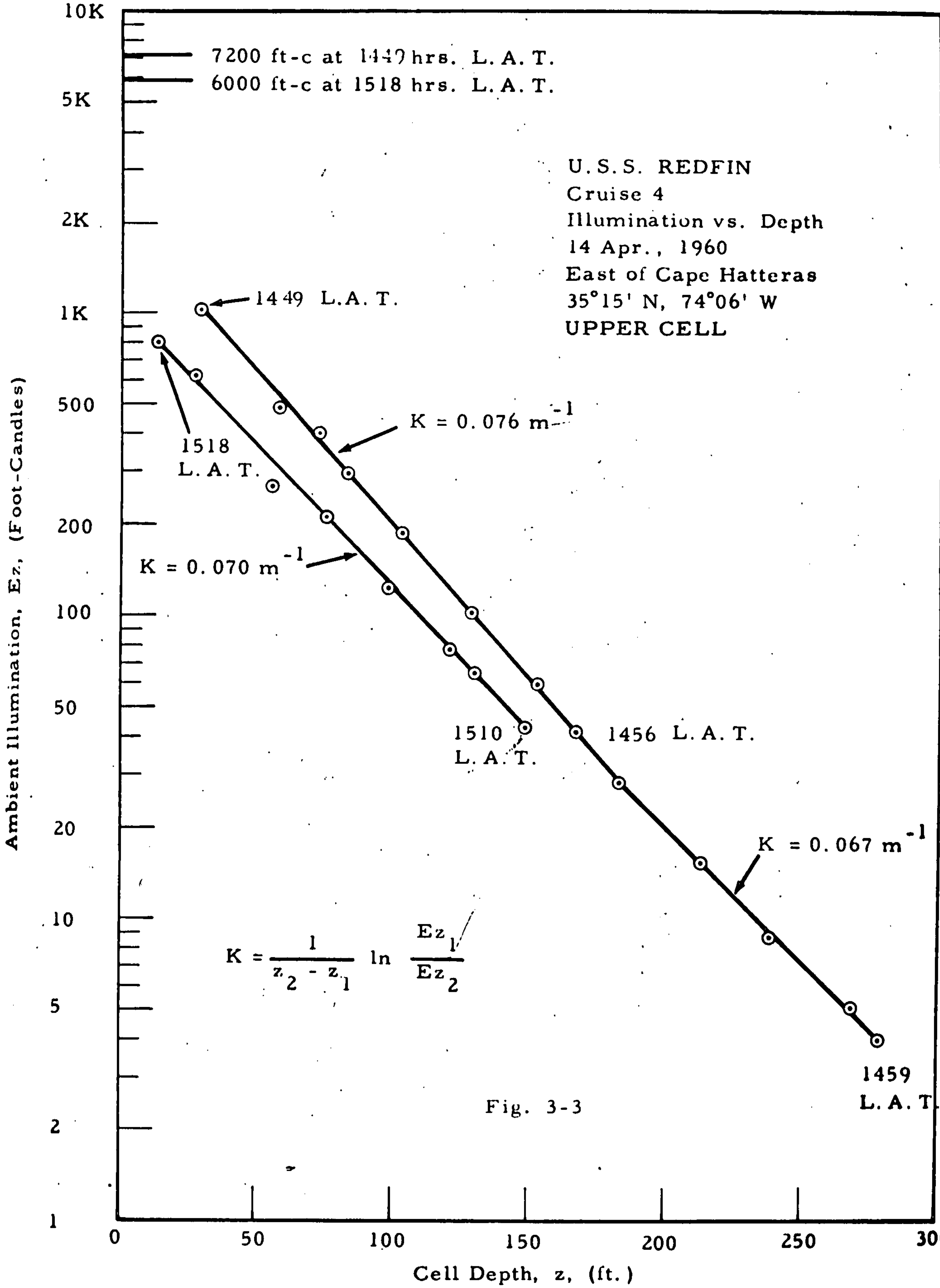

7200 ft-c at 1449 hrs. L. A. T.
6000 ft-c at 1518 hrs. L. A. T.
U. S. S. REDFIN
Cruise 4
Illumination vs. Depth
14 Apr., 1960
East of Cape Hatteras
35°15' N, 74°06' W
UPPER CELL
1449 L.A. T.
1518 L. A. T.
K = 0.076 m-1
K = 0.070 m-1
1510 L. A. T.
1456 L. A. T.
K = 0.067 m-1
1459 L. A. T
K = 1/(z2 - z1) ln Ez1/Ez2
Ambient Illumination, Ez, (Foot-Candles)
Cell Depth, z, (ft.)
10K
5K
2K
1K
500
200
100
50
20
10
5
2
1
0
50
100
150
200
250
300

Fig. 3-3

The ascent started at 0929 and lasted until 0952 LAT. The slopes of the illumination profiles on ascent and descent are very similar and indicate that the water clears as the depth increases. Diffuse attenuation coefficients near the surface are approximately .09 m^{-1} and at the greatest depths of measurement around 250 feet are 0.063 m^{-1}. There is an absolute shift in the illumination levels on descent and ascent which may be attributed to the change in time between the two runs, or it may have been due to a slight change in the attitude of the sail cell with respect to the sun on the two runs. It will be noted, at the top of Figure 3-2, that under sunny conditions the surface illuminance would have been expected to increase from 5700 foot-candles at the start of the descent to 8100 foot-candles at the end of the ascent. That neither of these values was realized is an indication of either a cloudy day or a change of the calibration of the sail cell, or perhaps both. A notation was made on the record at one point that there were "a few scattered clouds," and there were other notations as to the dive angle and heading of the submarine on descent and ascent. These latter notations might account for a change in the orientation of the cell with respect to the sun.

The diffuse attenuation coefficient data which were derived from the curves agree well with that obtained from other runs in this area.

On 14 April the descent and ascent were made later in the day between 1449 LAT and 1518 LAT. The data which were reduced on this date were obtained from the upper bow cell. Information was provided on the chart as to the dive and climb angles which were used during the two periods. This information was used, along with an assumed distance between the bow cell and the point on the submarine where the depth was measured to determine a depth correction which was applied to the data before plotting Figure 3-3.

The slopes of the illuminance profiles on this day yield diffuse attenuation coefficients very close to those noted on the previous day, as might be expected. Again, the illumination at the surface which would be obtained by extrapolating the data curves to the surface would be considerably less than that which is noted at the top of the figure for the times corresponding to the beginning and end of the run. These illumination values were obtained from the Natural Illumination Charts for the clear, sunny-day condition. The assumption, therefore, would again be made that the day was overcast or at least partially so. Indeed, there were sections of the record run at a constant depth wherein there were large, slow fluctuations in the ambient illumination which would be similar to those which would occur due to a broken overcast.

3.1.4 Cruise 6, August 1960 -- Norwegian Sea

Of the remaining cruises that were available for reduction, only one showed much hope of having different information which would be of interest. This was Cruise 6 in the Norwegian Sea in August of 1960. Unfortunately, this was very poorly annotated: there were insufficient depth marks, time marks, and no indication of trim angle. Furthermore, the operator changed the illuminometer sensitivity by factors of 5 and 10 instead of 2 and 2.5, thereby reducing the precision with which the information can be recovered. Portions of the descent and ascent were very rapid with the result that the accuracy of depth determination is very poor. However, despite these difficulties with the record, the data plotted surprisingly well as seen in Figure 3-4. The indicated diffuse attenuation coefficient is considerably higher for this area than for the other two areas in which data was reduced. K in the 200-foot region was 0.094 m^{-1} and from there upward to 50 feet the best straight-line fit gave a K of 0.110 m^{-1}. Projecting this straight line upward to the surface would give an intercept at zero depth somewhat below that which would be predicted for this time of day from the Natural Illumination Charts. This fact, together with the relatively small fluctuation that was noticed throughout the record, would seem to indicate that there was an overcast condition existing at the time of the measurement.

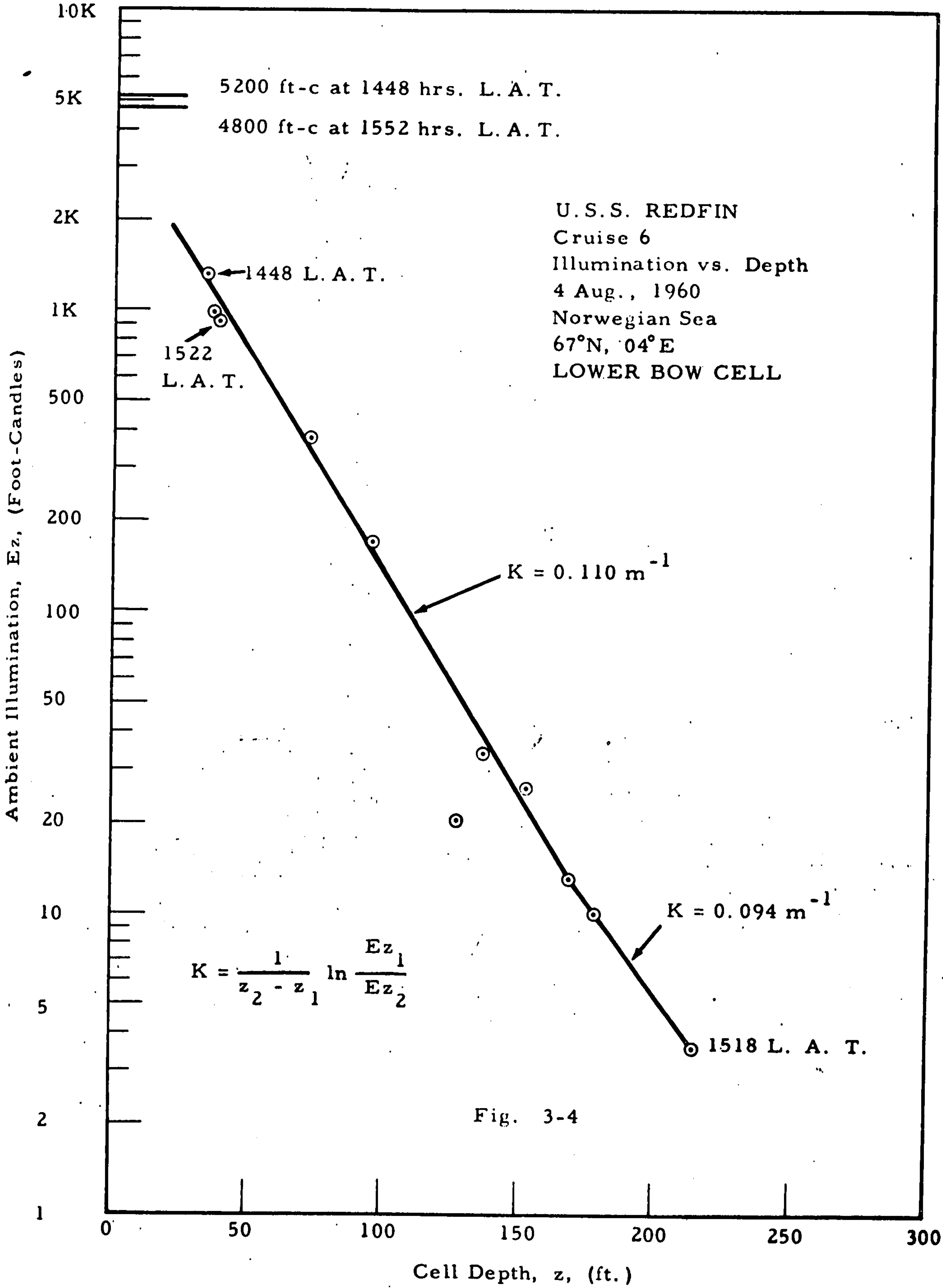

10K
5K
2K
1K
500
200
100
50
20
10
5
2
1
5200 ft-c at 1448 hrs. L. A. T.
4800 ft-c at 1552 hrs. L. A. T.
U.S.S. REDFIN
Cruise 6
Illumination vs. Depth
4 Aug., 1960
Norwegian Sea
67°N, 04°E
LOWER BOW CELL
1448 L. A. T.
1522 L. A. T.
K = 0.110 m-1
K = 0.094 m-1
1518 L. A. T.
K = 1/(z2 - z1) ln Ez1/Ez2
Ambient Illumination, Ez, (Foot-Candles)
0
50
100
150
200
250
300
Cell Depth, z, (ft.)

Fig. 3-4

3.2 Fluctuations of Ambient Underwater Illumination

Flux reaching any depth below the surface of the ocean may be treated as the linear summation of two components. The first is the collimated light field due to refracted, unscattered flux passing from the sky and sun through the water surface to the depth of observation. The second component is the diffuse light field due to that flux which has been scattered out of the collimated field. The amount of energy existing as collimated light decreases monotonically as the depth increases, for it loses energy by absorption and to the diffuse light field by scattering. The energy existing in the diffuse light field is small at the surface and increases with depth until the losses by absorption exceed the flux scattered into it from the collimated field.

Practically speaking, it is not possible, in the general case, to distinguish between the two components by a single measurement. Any observation or measurement technique responds to the total flux from the two components falling within its angular field and area of sensitivity. In certain particular situations, however, it is possible to infer from a series of measurements that an observed phenomenon is due to one or the other of these components.

The collimated light field contains the image-carrying flux, F_c, and is attenuated at a rate determined by α, the attenuation coefficient for collimated light, according to the usual expression.

$$F_{c_z} = F_{c_o} e^{-\alpha z}.$$

where z is the distance along the path which the flux is following and F_{c_o} is the flux at the point where z is zero. The distinguishing characteristics of this field are 1) the attenuation coefficient, α, is greater than that for the diffuse light field, 2) all the collimated flux in a flat-surfaced, source-free, optically deep ocean flows downward in a cone having a half-vertex angle equal to the critical angle for an air-water interface (about 48.5°), and 3) any images of the surface, sky, or sun which are apparent to the sensor are due to -- hence, are evidence of -- the presence of this field.

The diffuse light field contains only scattered flux, F_D, which has been perturbed by at least one scattering since entering the water surface with consequent loss of image information and is attenuated at a rate very nearly equal to K, the attenuation coefficient for the natural light field. The distinguishing characteristics of this field are that it is attenuated at a lesser rate than the collimated light field and that, except for the special case of observations made right at the surface, flux flows from all directions toward the point of observation.

As the usual methods of measurement do not permit the separation of the two fields, it is not possible to measure directly the accretion of flux in the diffuse field. The illuminometers used on the REDFIN, for example, measure the total combined flux in the two fields and the attenuation coefficient, K, obtained from an ambient illumination profile is actually a hybrid coefficient which tends to approach α near the surface and become asymptotic to the true diffuse attenuation coefficient as the contribution of the collimated flux to the total decreases with depth. This effect is most noticeable when direct sunlight contributes the majority of the flux to the light field at the surface, and the effect decreases as the ratio of sunlight to sky light decreases.

The fluctuations noticed in ambient light measurements may be attributed to fluctuations in these two component light fields. The large, rapid fluctuations which are seen near the surface when the sun is shining are due to the refractive effect of the water surface causing the flux to be focused at different depths according to the curvature of the waves. These fluctuations are attenuated at a rate probably lying between α and K due to the coupling between the two fields. The lower frequency fluctuations which persist at greater depths and are noticed even on overcast days near the surface are due to the change in water depth over the detector as waves pass overhead. These fluctuations decrease with depth at the same rate as the average ambient light field and therefore do not at first appear to decrease when measured as a percentage of the average value. However, as the transducer depth is increased, it integrates the flux received from a surface area including more than one ocean wavelength, and the fluctuation tends to reduce due to this factor as will be shown.

3.2.1 Fluctuations in the Collimated Light Field

Direct sunlight is the major source of collimated flux in the sea. The flux as it passes through the surface is refracted according to Snell's law, $n \sin i = n' \sin r$, where n and n' are the indices of refraction of air and water respectively, i is the angle the incident ray makes with the normal to the surface, and r is the angle between the refracted ray and the normal. If the ocean surface is flat the flux entering the water remains collimated but its direction of flow is bent toward the normal. Two special cases should be noted. The first is when the sun is close to the horizon. In this instance most of the flux is reflected by the water surface, but that direct sunlight which penetrates into the ocean travels downward at an angle of 48.5 degrees from the vertical. The second case is when the sun is directly overhead, in which case the flux is undeviated in its downward travel.

If there are waves on the ocean surface the curvature of the wave surface will cause a bending of the rays toward the surface normal. This will have the effect of causing a concentration of flux in regions where the rays are bent toward each other when the center of curvature of the wave lies below the surface, and a decrease in flux density in regions where the rays are divergent as when the center of curvature lies above the surface. This, for example, accounts for the patterns of changing light intensity which are seen on a shallow bottom when the sun is shining on a wave-disturbed water surface.

As the ocean surface cannot be described by simple analytic expressions, it is not possible to make a simple, rigorous description of the light field and its variations with time. We can make some observations and put bounds on the problem as a result of some simplifications and assumptions.

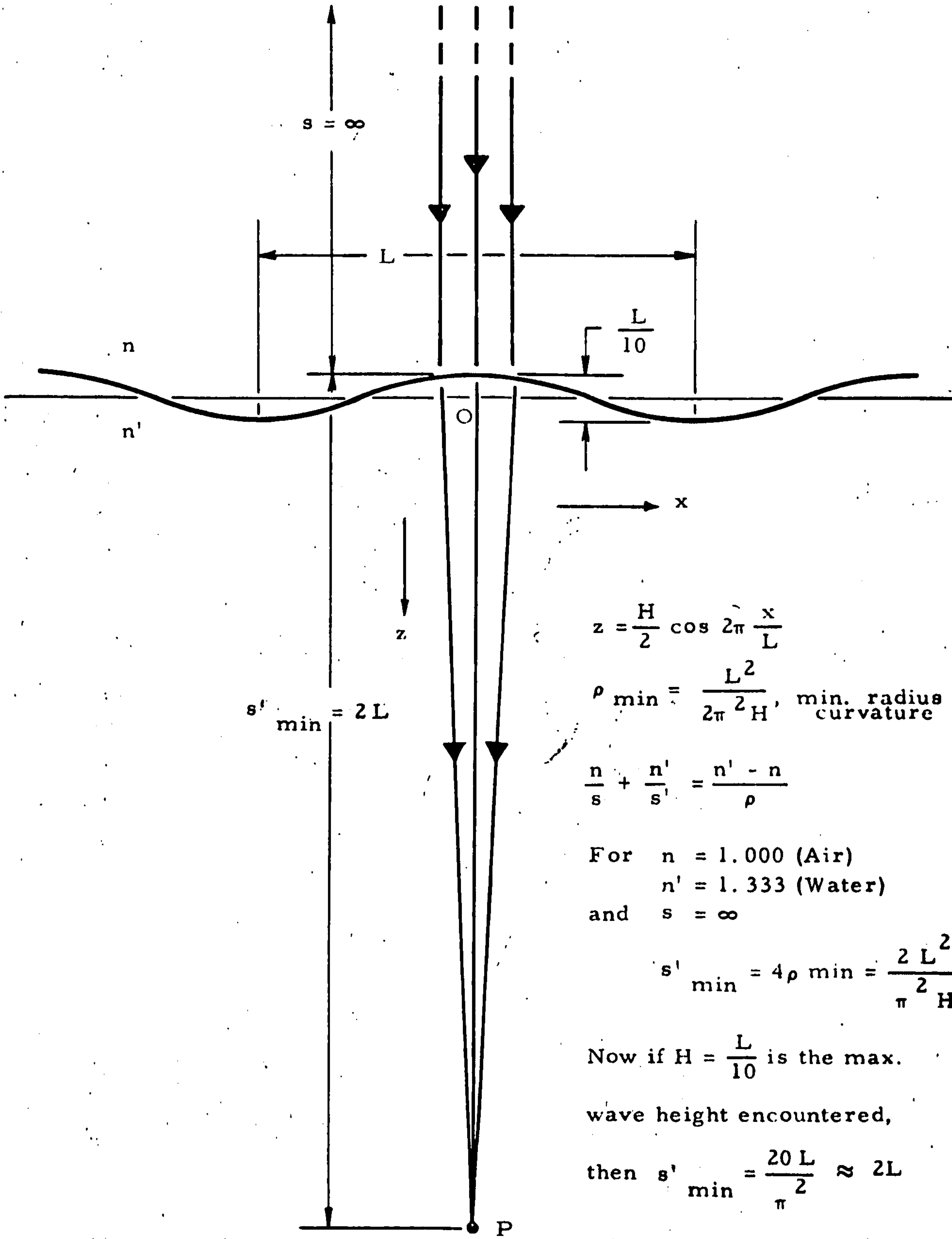
By the concepts of Fourier analysis the complex ocean surface can be portrayed as composed of a linear superposition of an infinitude of two-dimensional sinusoidal surfaces whose amplitude and phase spectra uniquely describe the particular surface. In the case of low amplitude ocean swells with no locally generated wind waves, the surface approaches closely a one-dimensional single sinusoid. As the amplitude of the wave increases, it departs from the single sinusoid, and higher order harmonics are present. When several wave systems are superimposed, the spectrum in general becomes two-dimensional and is the sum of two or more harmonic series. In case there are locally generated wind waves and capillaries, the surface becomes more chaotic and indeed the most powerful way of handling problems involving a description of the surface involves the use of stochastic processes. The concepts of Fourier analysis may still be helpful here in picturing the mechanism of flux variations, however.

Consider the single, one-dimensional sinusoidal component shown in Fig. 3-5 as describing the ocean surface. The flux from the sun will be "focused" at different depths below the surface depending upon the position of the sun and the curvature of the wave surface. The condition for maximum curvature (minimum radius of curvature) occurs when the sun is directly overhead. For this case, if we describe the wave by

$$z = \frac{H}{2} \cos 2\pi \frac{x}{L}$$

where the symbols have the meanings shown in the figure, the minimum radius of curvature is

$$\rho_{min} = \frac{L^2}{2\pi^2 H} .$$



$$z = \frac{H}{2} \cos 2\pi \frac{x}{L}$$

$$\rho_{min} = \frac{L^2}{2\pi^2 H}, \text{ min. radius of curvature}$$

$$\frac{n}{s} + \frac{n'}{s'} = \frac{n' - n}{\rho}$$

For $n = 1.000$ (Air)
$n' = 1.333$ (Water)
and $s = \infty$

$$s'_{min} = 4\rho_{min} = \frac{2L^2}{\pi^2 H}$$

Now if $H = \frac{L}{10}$ is the max. wave height encountered, then $s'_{min} = \frac{20\,L}{\pi^2} \approx 2L$

Fig. 3 - 5

From simple Gaussian geometrical optics the distance s' to the focal point (or line, for this one-dimensional case), if the index of refraction of water is taken to be 4/3, is 4ρ. Hence the minimum distance below the surface that the flux will be focused is,

$$s'_{min} = \frac{2L^2}{\pi^2 H} .$$

Above and below this depth the flux will show less spatial or temporal variation due to this particular wave. However, above this depth waves of shorter wavelength, L, or larger amplitude, H, will have their maximum effect on the flux concentration, and below this depth the wave components with longer wavelength and/or smaller amplitude will be most important in contributing to the fluctuations. Overlaying these observations is the general decrease of the collimated light field by absorption and by scattering into the diffuse light field. The attenuation coefficient α determines the rate of exponential decay of this collimated flux.

We can now, by well known hydrodynamic formulae and some empirical observations, arrive at values which may be helpful in orienting our thinking about the source and magnitude of the fluctuations.

From Barber and Tucker's discussion on the kinematics of wind waves, Eqs. 2 and 3 and Table I, page 665 of The Sea*, we can obtain the following.

*M. N. Hill, ed. The Sea, Vol. I, New York, Interscience Publishers, 1962.

$$L = \frac{2\pi C^2}{g} = \frac{gT^2}{2\pi}$$

$$C = \frac{gT}{2\pi}$$

where L is the wavelength

C is the velocity of advance of the wave

T is the period

and g is the acceleration due to gravity.

Typical Sea Waves

Type	Period, T sec	Wavelength, L ft	Velocity, C ft/sec
Ground Swell	15	1150	73.5
Swell	10	510	51
Ocean Waves	7	245	35.8
In Anchorages	3	46	15.4

Barber and Tucker further state that the height of waves cannot exceed about one-seventh of their length, and in practice it is unusual to meet waves the height of which exceeds one-tenth of their wavelength. Using this latter figure as a practical upper limit, we obtain the following approximate relation for s'_{min}.

$$s'_{min} = \frac{2L^2}{\pi^2 H} = \frac{2L^2}{\pi^2 \frac{L}{10}} \approx 2L = \frac{gT^2}{\pi}$$

from which the table below was prepared. Also included is the transmission of the water to the depth s'_{min} for collimated and diffuse flux based on the expressions $t_c = e^{-\alpha s'_{min}}$, and $t_d = e^{-Ks'_{min}}$. Alpha was chosen to be 0.2 m^{-1} (0.061 ft^{-1}). This choice was based on an empirically observed relationship that α is between two-to-three times K for most natural waters, and a typical value of K of 0.075 m^{-1} (.023 ft^{-1}) obtained from data taken on Cruise 4 of the REDFIN.

Flux Focusing Depth and Attenuation Functions

Period Secs	s'_{min} feet	Collimated Transmission, tc	Diffuse Transmission, td
15	2300	---	---
10	1020	---	---
7	490	---	---
5	256	3×10^{-7}	2.8×10^{-3}
3	92	0.0037	0.12
2	41	0.082	0.39
1	10.2	0.54	0.78
0.5	2.56	0.85	0.94

Several things become immediately obvious from a study of the table. First, the refractive or focusing effects of the waves having periods over, say, 5 or 6 seconds are not likely to be significant at any depth.

For example, a wave having a period of 5 seconds and an amplitude of 12.8 feet (a purposely large amplitude for this period) would refract the rays from the sun when directly overhead to a line-focus at a depth of 256 feet. But at this depth the flux in the collimated field is four orders of magnitude below that which will be found in the diffuse field! Obviously at this depth the contribution to fluctuations by the collimated light are insignificant. Even at 90 feet, where the increase in flux density by refraction from a 5-second-period wave will be small, the collimated flux will amount to only about 3 per cent of the diffuse light field. At this depth (90 feet) temporal variations in ambient light having a 5-second period would be essentially due to changes in water depth over the transducer. A lesser wave height or a lower sun would make these statements even stronger.

A second observation which may be made from an inspection of the table is that the 1-, 2-, and some of the 3-second-period fluctuations which were so frequently seen on the records from just below the surface to cell depths of 40 to 60 feet are due to refracted collimated light. Their attenuation is due to both the exponential decay of the collimated field and the fact that beyond the focusing depth the rays are diverging and the spatial (hence temporal) variation in flux density becomes less pronounced.

Third, the presence of fluctuations having periods less than two seconds and amplitudes amounting to more than a few per cent of the average value is almost certain to indicate that there is a strong source of collimated flux in the sky. The fluctuation of the diffuse light field due to these shorter period, lower amplitude waves would not be more than a few per cent in any but the most turbid waters.

3.2.2 Fluctuations in the Diffuse Light Field

According to our hypothesis given in the introductory discussion in section 3.2 the diffuse light field provides a very small portion of the total ambient flux near the surface, and its percentage of the total increases with depth. Due to the large preponderance of fluctuation attributed to the collimated field near the surface, it is difficult to measure the effect of variations in the diffuse field at very shallow depths unless there is a completely uniform overcast sky. However, on a sunny day by the time the natural light field has penetrated a depth equal to one reciprocal K only about 20 per cent of the flux is contributed by the collimated field, and the diffuse light field rapidly becomes completely dominant as the depth increases beyond this point.

The following expression can be used to describe approximately the variation in the diffuse field with time when the depth is small compared to a wavelength, L, but of the order of, or larger than, 1/K:

$$F_{Dz}(t) = F_0 \exp\left[- K\left(z + \frac{H}{2} \sin \frac{2\pi t}{T}\right) \right].$$

where F_{Dz} is the diffuse flux at depth z

F_0 is the total flux in the natural light field at zero depth.

Because of the nature of the exponent we see that the flux at a depth z has a fixed value given by $F_0 e^{-Kz}$ modulated by a time-varying function

$\exp\left[-\frac{KH}{2}\sin\frac{2\pi t}{T}\right]$. This latter function is independent of depth and accounts for the fluctuation in the diffuse light field due to changes in water height over the point of observation. As the depth increases and becomes comparable with and then greater than the wavelength of the surface disturbance, the time-varying function will decrease due to the fact that the greater surface area contributing to the flux at the observation depth contains all portions of the wave. The rate at which this factor becomes significant will depend on the angular collecting properties of the transducer used in the measurement, but eventually the mechanism of multiple scattering will eliminate the temporal fluctuations even when the measurement is made with a vertically oriented narrow angle radiometer.

The over-all rate of decrease in the observed fluctuations with depth is, of course, the combined result of all the factors that have been pointed out. They will combine in different ways depending upon the lighting situation at the surface, the existing wave condition, and the attenuation properties of the water. By making a series of records with time at different depths we can deduce a great deal about the environment from the nature of these fluctuations. Further observations and study are needed to determine the optimum procedure for obtaining information of operational value.

4.0 CONCLUSIONS

4.1 Operational Uses for Submarine Ambient Light Measurements

Through the use of ambient light measurements made from submerged submarines, the submarine Commander has an additional contact with his environment which may permit him to obtain information not obtainable from other instrumentation and, in addition, to obtain corroboration of information obtained through other sensors. One advantage of using the ambient light system for obtaining information about the underwater environment is that it is completely passive, a factor which may be of prime importance under some operational situations.

From a study of the data which has been obtained from the several cruises of the USS REDFIN, we find that illuminometers on submarines, such as those currently on the FBM class units for ambient light measurements, or perhaps a modification of this installation as recommended in section 5.2 below, could yield information which would be helpful to the accomplishment of the mission of the submarine. However, much as the sonar operator is required to develop skills for interpreting the seemingly uninformative sounds and scope presentations in order to obtain the maximum output from his sophisticated sonar equipment, so in this case a methodology would have to be developed whereby the trained operator, equipped with graphical and analog (slide-rule) computation aids, would be able to provide valuable information about the environmental conditions which exist on the surface above the submarine, such as weather, sea-state, ice conditions, etc., as well as the ocean environment surrounding the submarine, all while submerged.

4.1.1 Sea Surface Conditions

For example, it is possible to determine a great deal about the sea surface conditions existing over the submarine from an examination of the fluctuations in ambient light data with time. Records which have been examined from REDFIN cruises show for overcast days a definite long-period fluctuation correlated with the change in depth due to the passage of waves over the submarine. The nature of this fluctuation varies with depth of observation and the attenuating properties of water. However, it should be possible by the examination of properly documented ambient light records to develop relatively simple, passive methods of determining wave heights. On sunny days the fluctuation in ambient light has superimposed on the previously mentioned variation a more rapid fluctuation caused by the refraction of the sun's rays by the surface waves. The amplitude and frequency of these fluctuations will be more highly dependent on depth of observation than are the previously noted fluctuations. Again, in this case, it should be possible through a study of properly documented ambient light records to develop techniques for ascertaining the amplitude and period of the shorter period waves about which information could not be determined by the previous method.

4.1.2 Surface Ice Conditions

A second use for the illuminometers and the information which they can provide is in the operation of submarines in the Arctic below ice. This is an area wherein we understand the Oceanographic Office has first-hand information of the value of ambient light measurements for locating holes or thin ice above the submarine.

4.1.3 Visual Detectability from Above While Submerged

A third use for the ambient light data is to provide the submarine commander with information regarding his visual detectability from aircraft. If we know the reflectance of the paints used on the submarine and have equipment which will measure and record as a function of time, the illumination incident on the submerged hull and the diffuse attenuation coefficient of the water above the submarine, we should be able to compute as a function of depth the likelihood of visual detection from aircraft. We believe that comparatively simple methods could be devised for performing these calculations on the basis of a "worst-case" situation whereby the submarine commander would be able to determine the minimum depth which he could safely maintain and have no part of his hull visually detectable from the air.

In order to make these calculations, it is necessary to have certain information or to make certain assumptions. First, it is necessary to know how the target submarine is illuminated and how this illumination is reflected back toward the aircraft. This information is obtained from the illuminometers and from knowledge of the submerged reflectance of the submarine's paints. From this one can obtain an estimate of the inherent optical signal.

Secondly, the transmission loss which the optical signal incurs in traveling from the submarine to the surface can be determined by a knowledge of the diffuse attenuation coefficient K, and the attenuation coefficient for collimated light α, for some assumed angles of observation. The equipment on the submarine does not measure α directly, and the calculation would be based on the measurement of K and an empirically found coupling between observed α and K measurements over the past years.

Thirdly, the deterioration of the optical signal by passage through the air-water surface must be computed. This depends upon the sea-surface condition, i.e., the capillary wave slope distribution, and the sky conditions, i.e., the amount of cloud cover existing at the time of observation. The sea-surface condition can be inferred from the high-frequency fluctuation in the illuminance record with time. A study would have to be made to determine the degree of correlation, if any, which exists between the surface wind conditions (hence the capillary wave condition) and the rapid small-scale fluctuations which are noticed and are presumably caused by the short-period wind-generated gravity waves. The cloud cover can be inferred from the long-time fluctuations in the ambient light record and from the general level of the ambient light data compared with the value which would be predicted based on a knowledge of solar elevation angle, the diffuse attenuation coefficient and depth of the submarine.

With this information of the inherent optical signal generated under water by the submarine against its water background, the transmission factor for this signal through the water to the surface, and the contrast reduction caused by the reflection of sky andsun by the ruffled water surface, one can compute the apparent contrast of the submarine and determine whether or not it would be visible. The detailed procedures for this, as well as the underlying physical principles, have been known for some time. They were reported by Duntley in 1952.* The procedure recommended here would be a much simplified and abbreviated one which would necessarily require conservative assumptions. The simpler the computation and the greater the number of assumptions, the more conservative the final answer will be, but the more readily it may be arrived at. It would, for example, be possible as a limiting case to provide for a particular submarine painting scheme a curve of illuminance versus depth so arranged that if the illuminance observed on the submarine fell below the value shown on the curve for the depth of observation, the submarine could not be seen from the air under any circumstances. If it was desired to cruise closer to the surface, further information could be introduced such as solar elevation angle, K, fluctuations in illumination, etc., to permit a more accurate determination of the minimum depth.

4.1.4 Visual Detectability from Above After Surfacing

Information could be determined from the ambient light records which may be operationally important under certain situations wherein

*Massachusetts Institute of Technology, Visibility Laboratory, The Visibility of Submerged Objects, by S. Q. Duntley, Cambridge, Massachusetts, 31 August 1952.

the submarine is about to surface in an area which may be hostile. This information would be the degree of cloud cover, illumination level, and sea-surface conditions. These are all items which, as can be seen from the previous paragraphs, could be readily inferred from the ambient light records by a person trained in their interpretation and would be important factors in assaying the likelihood of visual detection from aircraft after surfacing.

4.2 Visibility Studies - Field Experiments

The major outstanding feature of the two field experiments was their singular lack of quantitative conclusions relative to the primary objectives of the mission. An understanding of the magnitude of the problems involved in the conduct of such field experiments was definitely obtained. A major conclusion was the futility of conducting such an experiment unless the conditions for the experiment can be controlled in a manner such as is recommended in section 5.1 below.

4.3 Correlation of Surface Wave Phenomena with Ambient Light Fluctuation

The data from the REDFIN cruises and the observations made from the Argus Island show, very convincingly, the connection between the temporal fluctuations which are seen in the ambient light records and the surface wave phenomena. Unfortunately, neither the data which were made available to the Laboratory nor the time which it was possible to spend on the study of the problem permitted more than a rather superficial investigation of the detailed nature of this connection.

5.0 RECOMMENDATIONS

5.1 A Program for Obtaining Sighting Ranges on Submerged Submarines

After giving due consideration to the two field experiments which were run in Bermuda and Norfolk during the period of the contract, the Visibility Laboratory recommends an experiment which would attempt to put a bound on the problem of submarine detection ranges. After a study of the results of this more limited experiment, it would be possible to determine the operational and economic desirability of obtaining additional information under other conditions. This first experiment, then, would be designed to provide the maximum useful data with a minimum of effort and operational complexity.

It will be assumed that the first case that is of interest is the worst possible situation for the submarine. This will involve the clearest water, a calm sea, a clear blue sky, and a high sun. Under these conditions a submarine will be visible to the greatest depths. Performing the tests under these conditions will provide the submariner with a minimum depth below the surface at which he can cruise and remain undetected visually from aircraft under these adverse circumstances. This, then, is the bound referred to in the paragraph above. The particular minimum depth obtained from such an experiment would be a function of the painting configuration which was used on the submarine during the test and would also assume that there is no significant bottom reflection. It would, of course, be possible to obtain other minimum depths for other painting configurations and for the case where the submarine is over the reflective bottom by a relatively simple extension of the first phase of the operation. The conditions listed above dictate that the experiment should be run in the lower latitudes in the spring or summer months in an area where clear oceanic water is found and the probability is high of obtaining clear skies with calm seas.

The best vehicle for the observers would be an HSS-2 helicopter. It has good endurance, will permit a much better control of range and direction than fixed-wing aircraft, the visibility from its open hatch should be satisfactory, and sufficient time should be available to the observers to make their sightings, measurements, and photographs. The use of the helicopter would place further restrictions on the location as the operating area must be close to an air station with facilities for servicing helicopters and still provide a reasonably long observing time over the submarine. For this experiment the use of fixed-wing aircraft should be avoided if at all possible for the reasons noted above.

If the experiment is to involve the REDFIN it would seem desirable to perform the tests in the area around Florida, perhaps in the vicinity of Key West where there is normally a complement of HSS-2 in an ASW helicopter squadron, and the Key West Test and Evaluation Detachment would be available for handling the operational problems. There is also a submarine operating area immediately offshore from Key West with a satisfactory range of depths available. It would seem, therefore, that most of the required conditions could be met from this location providing suitable weather conditions can be obtained in a reasonable period of time.

In addition to the necessity of having enough time to obtain the desired weather, sufficient time should be available for training "dry runs" which may indicate the necessity for reformulation of some of the details of the operation as well as providing for the training of personnel. It would also be desirable to have sufficient slack time to take care of instrumental difficulties which might arise. It is estimated that a period of two weeks should be available for the exercise with more time, if possible, for contingencies. Other unrelated tests could be scheduled for the same period to obtain full utilization of the submarine providing the visibility tests could take precedence when the conditions were suitable. Three or four days of actual operation including the training period should prove sufficient for this "worst case". Should the conditions seem propitious, runs could be made to obtain maximum sighting ranges as a function of depth with other factors as parameters such as sea state, cloud cover, and bottom reflectance. It is felt, however, that the emphasis should be on obtaining the measurements on the "worst case" situation under documented conditions.

Two experienced observers would be needed in the aircraft who are also skilled in the use of photometric and photographic equipment and in the determination of range by stadiometric or other procedures. Additional methods for obtaining ranges on the submarine would be required. These methods may be by means of sonobuoys, dunking sonar, MAD gear location plus velocity and time interval information, or some optical ranging system which may be devised. Two cameras would be needed on the aircraft for taking wide-angle shots of the sky and sea surface conditions which exist at the time of the operation and for normal or telephoto shots of the submarine as the observers saw it from the air. In addition, the observers in the aircraft should be equipped with a lightweight portable telephotometer having various fields of view and attachments which would be used to measure sea surface luminance as a function of observing angle, illuminances, target reflectances, etc.

The submarine would be equipped as at present to measure and record the ambient light and diffuse attenuation coefficient by means of the several photocells mounted on it. As a result of our study of the earlier REDFIN data, as reported in Section 3.1 above, it would seem desirable to install two forward-looking cells for the measurement of K as recommended in Section 5.2 below. The upward-looking sail cell and the port- and starboard-looking sail cells should be retained. It may also be necessary to paint special areas of the submarine in a particular manner for measurement or detection purposes.

The program of measurement presented above should result in quantitative information on the visibility of submarines from aircraft under documented conditions. The conditions would hopefully be chosen to represent a single important limiting case. The information obtained from this experiment could be of considerable significance in itself, and the experience gained by the experiment would indicate the desirability of running additional tests of this nature in the future and the direction which such future studies should take.

5.2 Improvements in Ambient Light Instrumentation for Submarines

The type of ambient light instrumentation to be recommended depends, of course, upon the mission of the submarine and the uses to which it is anticipated the data will be put. In general, however, the study of the data obtained from the REDFIN installation suggests changes in future installations which would be desirable for both investigational and operational purposes.

Because of (a) the large temporal fluctuation in photocell output caused by wave phenomena, (b) the clarity of the water in most operating areas, and (c) the difficulty of obtaining and maintaining adequate calibrations of the photocells, it has become manifestly obvious that a 1-meter vertical separation between the cell surfaces, as currently exists on the REDFIN bow cells, is not adequate to provide the precision necessary for a determination of the attenuation coefficient K. Furthermore, the large horizontal separation between the bow cells and the sail cells makes this arrangement undesirable because their vertical separation becomes very dependent on the trim of submarine, making this angle a necessary bit of information to incorporate into the data reduction process. This horizontal separation also means cells in the two locations will, in general, be in a different light field due to wave and cloud phenomena, thus reducing the usefulness of any measurement system that requires a comparison of the simultaneous output of cells so separated.

We, therefore, recommend that the installation of photocells on the REDFIN be changed as discussed below with the objectives of developing an ambient light measuring system which can be used on FBM submarines and devising operational procedures for immediate use by submarine commanders of the data so obtained.

Two types of measurements should be made. The first is the absolute value of the ambient light at the depth of the submarine and the character of the temporal variations of this light field. A simple illuminometer located on the sail so that it has an unobstructed view of the upper hemisphere should be a suitable sensor for this measurement. It is recommended that the output be recorded on a recording potentiometer with a two-speed chart drive to permit the use of a fast chart speed for a detailed examination of the higher frequency fluctuations when this is necessary, and a slow speed, more economical of paper, for continuous monitoring. It is also recommended that the recorder be fitted with "event marker" pens to permit the accurate location of time and depth notations on the chart. A two-pen recorder with the second channel devoted to recording the sail cell depth would be even more desirable. This first measurement entails little change over the present system except for improvements in the recording system to assist in providing more adequate annotation and a more suitable time base for analysis of the fluctuations.

The second type of measurement recommended is a direct measurement of the attenuation coefficient for diffuse light, K. This would be accomplished by automatically taking the ratio of the output from two photocells oriented to look horizontally and located on the sail, one directly over the other. These cells would have an identical field of view which would be restricted vertically so that no direct collimated flux from the surface would be received by the cells and no portion of the submarine hull would be in the field of view. The vertical separation would be as large as could be conveniently arranged in order to maximize the precision of the K measurement. A separation of from 3 to 5 meters should be possible on both the REDFIN and the FBM class submarines. A three-meter separation, for example, would give a ratio of 0.625 for $K=0.157\ m^{-1}$, the highest K-value in the REDFIN data reduced and a ratio of 0.833 for $K = 0.061\ m^{-1}$, the lowest K-value obtained. If the separation could be increased to 5 meters, the corresponding ratios would be 0.455 and 0.737 respectively. In the clearer waters (low K's) the requirement that the two photocells have the same sensitivity becomes more critical as the separation between the cells is reduced. The placement of the cells around sail is not important except that one should be directly over the other and they should be placed where the solid angle of flux acceptance could be the maximum in order to increase the total flux available for the measurement. The K obtained by such a measurement procedure should be closer to the true diffuse attenuation coefficient than that obtained by the present procedure because the collimated flux field is not included in the measurement and the K-value obtained near the surface would not, therefore, be a hybrid coefficient contaminated by the attenuation of the collimated field.

As the true K value will not normally change rapidly as compared with the ambient light fluctuation caused by waves, the ratio-taking circuit or device could be slowed down in its response to average over a period of time, long compared to that of the longest waves. Furthermore, because the two cells will not see any of the rapidly varying collimated field, the fluctuations present in the outputs of the cells should be due only to the variations in the diffuse field. These latter variations in the two cell outputs should have approximately the same time phase due to the fact that the cells are located one over the other and fluctuations in the ratio therefore will be further reduced.

The ratio could be taken by an electro-mechanical servo system such as a modified recording potentiometer or by a digital ratiometer if the information is suitably filtered (averaged) before sampling. The output could be recorded if this is desirable, but a simple indicating system with periodic entries in a log and on the ambient light record might prove sufficient.

The flux available to all three sensors will vary over a wide range with time, location, and especially with depth. The cell outputs should have sufficient amplification to permit useful ambient light records and ratios down to illumination levels of one foot-candle or less. The wide range of values to be handled would require sensitivity changing either manually or automatically to assure that the maximum accuracy was obtained at all levels of ambient illumination and that the ratio-taking servo system did not lack sensitivity at low light levels nor become unstable at the higher levels.

These two measurements, ambient illumination as a function of time and diffuse attenuation coefficient would provide the data from which a great deal of useful information about the submarine environment can be determined, even at the present state of knowledge, providing adequate use is made of the other necessary facts which are available to the observer. These facts are location, date, time, depth, weather, illuminometer sensitivity, etc., which should always be carefully noted on the records.

Because additional information should be obtained on the correlation between K and α we also recommend that the α-meter supplied to the REDFIN as part of the original water clarity equipment be updated and placed back into service. Simultaneous K and α data obtained in this way would quickly determine the necessity or desirability of having separate measurements of these two water properties for visibility determinations of the type suggested in Section 4.1.3. Furthermore, if this equipment system consisting of an illuminometer, a K-meter, and an α-meter can be installed on the REDFIN, maintained in good calibration and operating condition, and operated by personnel familiar with its operation and the use of the data, the Oceanographic Office will have a unique opportunity to perform much needed research in optical oceanography. We strongly recommend such a program of research be undertaken and staffed with oceanographers who can take a permanent professional interest in this work.

Appendix A

LOG OF FLIGHTS OFF NORFOLK, VIRGINIA, APRIL 1963

OPERATION WITH U.S.S. REDFIN

(Transcribed from voice tape recorder)
Dr. John H. Taylor

4 April 1963 - 0648

We took off on schedule from the Naval Air Station and had a very smooth take-off. The weather in Norfolk was overcast but now as we approach the operating area we seem to be restricted to some high cirrus near the horizon. The overhead sun looks pretty good. The view from the nose is excellent. We have a very low sea state out here; a few white caps, but by and large the sea state looks pretty low. The plastic in the nose is exceptionally clear. There is, however, a certain amount of sun reflected from the plastic, and I notice wearing the Polaroids looking directly into the glitter path that there is a chromatic pattern from strains in the plastic of the nose.

0800

It is now 0800, we have the REDFIN in sight expecting to dive in about five minutes. The estimated sea state at this moment is three, the air is hazy, and the REDFIN is taking up a northerly heading. We will fly parallel off its starboard beam at 700 yards range.

0810

It is now 0810, and we are making passes over the REDFIN at periscope depth. They are fairly visible, of course; however, it seems doubtful that we will be able to see them at any depth much greater than periscope depth, particularly out at 700 yards.

. . . .

We have made a number of passes over the REDFIN at this point, and it is pretty clear that unless they remain near the surface we aren't going to see much. The hull becomes invisible just as the tail goes under, and that's flying directly over the sub. As soon as we get off to the side a little bit, I don't think we are going to see anything at all below periscope depth. We've been running this operation with the submarine at periscope depth and then having them retract the scope at various times when making a pass. Flying over the sub at this time it appears that we are not able to see any part of the hull. The pilot has spotted the sail on one occasion. So far, all of our aircraft headings have been north. The pilot caught the sub, once after the scopes were down; I missed it. We were practically directly overhead, flying at 375-400' altitude.

0917

It is now 0917. We are going to make a pass with a south heading. The submarine is going to stay at periscope depth with the scope retracted. We have a little bit of cloud cover on the southern horizon. . . . . . .

Now we just made a southbound run over the sub. We had it going right under the nose. It is possible to see the upper part of the sail. The top of the sail appears as a dark target. We will change the sub heading for the second part of the exercise.

0923

We just missed it completely on our northbound pass at 0923. We are coming out again for another southbound pass. We will try once more, if we can contact him before he resurfaces. . . . . . .

We are coming in on a southbound pass now. The glare situation on the forward plastic is a little better; we don't have quite as much sun coming up from the bottom part of the plastic, or at least so it seems. I haven't made any photometric measurements of this so far. We are perhaps a mile out now. We had no difficulty seeing the sub on that pass. We did have a little white water behind the sail, so it was hard to tell whether we were seeing part of the sail or not. The antenna was up, and the pipe was still up a little bit.

We just talked to Tidrick on the radio, and he agrees to take up a westerly heading and we'll finish up the operation today. Then we will wait for a different sea state on Friday or Monday. The westerly heading is advantageous for us on the passes, because we will get a slightly lower ground speed this way. We will try passes both north of the sub, that is to say, on the shaded side, also on the sunlit side.

0940

It is 9:40 A.M., and our sky condition is getting a little bad now. We have a broken overcast, a lot of haze, and some high cirrus.

This could mean that we are going to have a grand average of the weather conditions here; very few passes with any single sky condition.

0947

It is 9:47 A.M.,and we are making a run just to the south of the submarine. The sky is very generally fouled up here, and the visibility is poor. The last pass we made near the submarine we were unable to see it. The pilot missed, and I missed it in the nose. I think we are just about aced out on this operation for today. The sea state is simply too high. The Polaroid glasses don't seem to help too much, possibly because of the defects in the plastic in the nose. We are coming over the submarine now . . . .

0958

We just made a pass a little bit north of the submarine. We were able to see the top of the sail,which was exposed momentarily, but there is nothing visible below the sail even with the Polaroid glasses. We're going to come around now and approach the sub on the south side. The pilot estimates horizontal visibility to be 3 - 4 miles.

1005

We just made a pass at 10:05 A.M., and we got the impression that we could just barely make out the forward part of the hull; that is, at periscope depth and looking straight down. There was relatively little glare from the water surface. I was using Polaroids, and I believe the co-pilot spotted it also. I don't know if he was wearing Polaroids also, but I think that Polaroids at this angle wouldn't have mattered much.

1007

Just made another pass at 10:07 A.M. We were able to see the side of the sail that time in addition to the bubbles aft of the sail. We are going to request that the REDFIN lower their pipes at this point and see if we have any chance of picking them up at periscope depth. We will make three or four passes to see if we can pick them up, and then maybe they will go to 100 feet, although I doubt very much if we will see anything.

1018

We just made a pass at 10:18 A.M., 300 feet altitude. Pilot spotted the submarine with its pipes down. Everyone else missed it. We were practically right over it, and I think that the pilot had a better position than any of us. So if there had been any search involved he certainly would have had a hard time to find it. This is only at periscope depth.

1024

We just made a pass at 10:24 A.M., and we were able to spot the submarine by the fact that the antenna was above the surface. We saw the side of the sail loud and clear. There was no search problem, and that is probably why we saw it. Whether we could make out the hull or not is a question. We could easily see the little wake made by the antenna mast.

Anyway, we did see the sail, from about 500 feet which was nearly a straight down look, so we didn't have much of a glare problem, since we had some fairly blue sky above us.

We have the submarine dead ahead, not yet in sight, making a pass east to west now. The submarine is still at periscope depth with the periscope retracted, but with the antenna up. I do not yet have them in sight. They should be off the starboard wing. No one reports contact so far. I don't see a thing off the starboard side of the airplane. I'll see now if anyone else saw it.

1037

We just made a pass at approximately 10:37 A.M., with no pick-up. The sun is very hazy at this point, practically no sharp shadows cast at all. It is very nearly overcast; you can see a bright spot where the sun is, but very little in the way of sunlight at this time.

We are coming around again for another pass. Heading east to west should bring the submarine off our starboard wing. No smoke in sight. I'll follow this one on down, and I'll leave the tape recorder going while we come into the turn. We're still in the turn. We're leveling out in a westerly course -- a mile or so out yet and coming straight down to the new smoke. The sun is still obscured pretty much by the high overcast, and we are just coming over the tail part of one of the old smokes and right down the slot. The pilot tells me we should have the sub in sight, dead ahead. So far I can see nothing;

there is too much white water out here to pick up the antenna. I don't see it -- we're approaching the smoke, ten seconds and we will be over the submarine. We just spotted them off the starboard beam here because the pipes were up and also, because of the high sea state, we had part of the sail exposed. I don't think that at this azimuth we would have a chance to see a thing.

We're going to make a couple .. passes, and then we're going to secure and leave the area. Just before we do, however, we'll make a 360° turn at which time I will monitor the apparent brightness of the sea surface, looking down at the angle at which we have been making these observations. I'll call out headings and brightnesses as rapidly as I can around the full 360°.

1040

The pilot is going to begin a 360° turn. We'll read out every ten degrees and I will try to get a reading from the Spectra meter. These are going to be quite approximate because the local sea surface structure causes a needle-jump owing to the narrow acceptance angle. I'll leave the tape recorder going and try to maintain the Spectra meter at the same angle that we were doing the previous observing.

070° is 176, 060° is 175, 050° is 130, 040° is 125, 030° is 140, 020° is 120, 010° is 100, 360° is 95, 350° is 95, 330° is 110, 320° is 140, 310° is 150, 300° is 160, 290° is 160, 280° is 160, 270° is 165, 260° is 170, 250° is 170, 240° is 175, 230° is 175, 220° is 200, (a little bit of glare in here now, kind of a wavy needle) 210° is 250, 200° is 350, 190° is 500, 180° is 500, (very much oscillation, reaching up to nearly a 1000 down here) 170° is 700 (average), 160° is 800 (average), 150° is approximately 850-900, 140° is 600, 130° is 160, 120° is 150 to 170, 110° is 150, 100° is 135, 090° is 130 to 135, 080° is 130, 070° is 120, 060° is 110.

1046

That completed the azimuth sweep before leaving the station on 4 April 1963. The time of departure from the station was 1047. At that point we cancelled out and returned to Norfolk and had wheels down at approximately 1200 local time.

I will use the remaining tape for comments which there was no time to make in the airplane:

The visibility of the submarine was extremely dependent on azimuth; it being nearly impossible to see any part of the submarine from the northerly quarter even on the east-west heading. It was possible to see it during the first part of the operation by reason of the upper part of the sail presenting a light target to the observers. Bear in mind, however, that we were flying nearly directly over the submarine. Until we see Selkirk's numbers on this, we won't know exactly what the zenith angles were. Toward the end of the operation the sky overcast became more solid and we were less and less able to see the submarine. The combination of specular reflection off the wavelets with a large diffuse component of high brightness and with a considerable number of whitecaps, meant that there was a great deal of breaking up of water surface as far as its luminance went. It would be very difficult to detect the submarine had we not known its exact location. On several passes, even knowing exactly where the submarine was, plus or minus (let us say within a 10^{o} cone), we were still unable to spot it. The co-pilot made the most successful spottings, and even he missed them on a few runs although we were going directly over the sub.

1320

The present plan, as of this moment (1320 Thursday), in view of the weather forecast which is for approximately the same sea state that we had today, is to wait until Monday, at which time we will have a weather check from the REDFIN to SUBRON 6 at 7:00 Monday morning. This, we are told by the squadron, is plenty of warning for them to take us off at 10:00 A.M. If we do not have a flat calm or sea state less than 1 on Monday, we will wait until Tuesday or Wednesday, at which time, I believe, unless the weather forecast looks extremely favorable, we will then scrub the mission. It think it is evident from our experience this morning that one is never going to see this submarine unless the sea is extremely calm; unless perhaps with a very blue sky, and a medium sun angle with the sun at the observer's back. This might help things quite a lot. We suffered a great deal by having high overcast and hazy conditions so that not only did we have a little bit of attenuation (bear in mind we were flying these at 500 feet or lower,) but also the reflection from the sea surface was quite high, owing to the bright overcast. This was especially true, in fact disablingly so, when we were passing north of the submarine when the submarine was on a westerly course. If we do find a flat calm, or if we find extremely clear conditions with a blue sky essentially horizon-to-horizon, or a combination of both of these, we will proceed on Monday morning with another run. At the moment we have no way of forecasting that far ahead, so we will simply have to wait until the conditions are right. We will wait this out until Wednesday and decide at that time whether to wait any further if we have not made a successful run by that time.

(End of record for 4 April 1963.)

7 April 1963

Note added Sunday night. We have a forecast which indicates very good weather coming up. . . . . . . Everything so far looks very good for an operation tomorrow. We have no doubt that the squadron will have the equipment necessary as promised, and it is my intention to call up Chief Hennessey at SUBRON 6 the first thing in the morning to find out what their transmission has been from the REDFIN. If everything looks good then we will proceed to the squadron headquarters and try to run this operation tomorrow, April 8. One other item of interest which should be added to this tape is that Chuck Selkirk now tells me that the submarine plans, if possible, to be back into Norfolk by the conclusion of work tomorrow. This changes the previous plan a little bit because if we get bad weather tomorrow and if they come in, this essentially ends the operation. We will see, however, what tomorrow's weather looks like and whether in fact we can encourage the submarine to stay out one or two more days if the weather does not seem ideal for tomorrow.

8 April 1963

This is a transmission for 8 April 1963. We were off at 0829, and we're approaching areas 20-A and -B. We have estimated 12-knot winds, and there are scattered whitecaps although they are becoming less as we approach the operating area.

0915

It is now 9:15 A.M., and we are approaching the operating area. The sea surface has occasional whitecaps, but it is much better than last Thursday. Sky is clear except for a few thin, high cirrus clouds.

0920

We have the REDFIN now in sight at 9:20 and are orbiting while they prepare to dive to periscope depth and retract their pipes. We have occasional whitecaps as before but we might be able to do some good. They are going to take a westerly heading, and we are going to fly both north and south.

1045

We have just secured this operation, and the time is now 10:45 A.M. We finally encountered, during the latter part of the operation, sea states and skies very similar to Thursday's, so we concluded that there was no point in pursuing the mission. As before, when we were exactly on top we were able to see part of the sail on the sunlit side. It was very difficult to acquire the submarine while it was at periscope depth with the pipes down and only the antenna mast protruding. I spoke with Tidrick on the horn, and they are going to secure their operation and return to Norfolk, and I will meet them when I arrive in Norfolk.

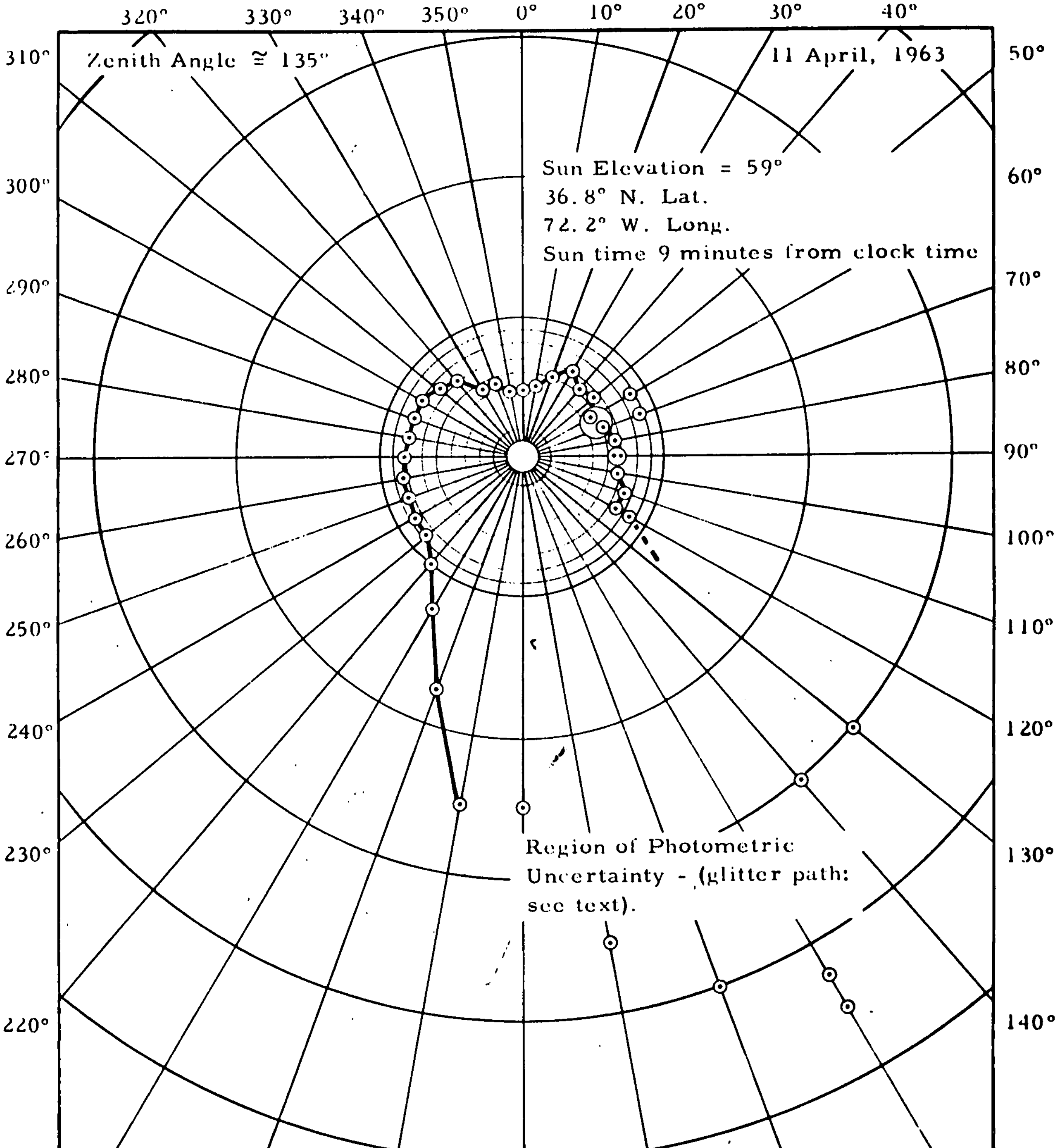

Zenith Angle ≅ 135°
11 April, 1963
Sun Elevation = 59°
36.8° N. Lat.
72.2° W. Long.
Sun time 9 minutes from clock time
Region of Photometric Uncertainty - (glitter path: see text).
320°
330°
340°
350°
0°
10°
20°
30°
40°
310°
300°
290°
280°
270°
260°
250°
240°
230°
220°
50°
60°
70°
80°
90°
100°
110°
120°
130°
140°
210°
200°
190°
180°
170°
160°
150°

Fig. A-1

Appendix B

CRUISE 2, OCTOBER, NOVEMBER 1959

The data available from this cruise consists of strip chart records from the Leeds and Northrup recorder containing information from the three illuminometers and the alpha-meter. These records are numbered 1 through 6, each covering a different day or series of runs. Also included are excerpts from shipboard notes.

Record 1, 11 October 1959.

This record starts at 10:10 Eastern Standard Time and the location is the entrance of Chesapeake Bay. All the data on this record were taken with the submarine surfaced. There are no transcribed shipboard notes as there are for some of the other records. The Leeds and Northrup chart does not carry explicit annotations as to the weather and sea conditions which existed at the time. Using the calibration information which the Visibility Laboratory has in its files on the particular photocells in use on the REDFIN, three different values may be obtained for the illumination on the ocean surface at that time. The value measured by the sail cell was 6000 foot-candles, by the upper bow cell 5300 foot-candles, and by the lower bow cell approximately 6500 foot-candles. Referring to the Bureau of Ships Natural Illumination Charts (U.S. Navy Bureau of Ships Report 374-1, September 1952), one can compute that the expected illumination under a clear sky condition for the solar elevation which existed at the time of measurement would be expected to be 6000 foot-candles. Thus the reading obtained from the sail cell is in excellent agreement with the expected value. One should expect a better agreement between the two bow cells than was found, however. It is, of course, difficult to establish at this time what the causes may have been for the observed errors. It is possible to postulate several possible causes. First, the upper and lower bow cells may have been inadvertently interchanged. Second, the upper cell may have had dirt on its white collecting surface. Third, the lower cell may have had the color correcting filter, which is placed between the white diffuse collector plate and the photocell, slightly misaligned causing some of the flux to bypass the filter and thereby cause an apparent increase in sensitivity. Fourth, the record on the chart shows a variability in lower cell reading; this was noted on the chart as possibly caused by shadows. We would suggest that this might more probably have been caused by water puddling on the top of the cell collector surface, thereby refracting more of the sun's flux into the cell. Fifth, the discrepancy may simply indicate a need for more frequent calibration in the field.

At 12:25 Eastern Standard Time (12:32 Local Apparent Time) the sail cell indicated an illumination fluctuating between 7100 foot-candles and 7850 foot-candles. The solar elevation at this time was 46 degrees which would produce an illumination of 7220 foot-candles on a clear, sunny day. A ship's roll or pitch of plus or minus two degrees could account for the observed fluctuation.

Record 1 for this date shows no alpha-meter records which can be reduced due either to a failure of the instrument or improper calibration of operation of the instrument.

Record 2, 13 October 1959 and Record 3, 14 October 1959

Records 2 and 3 and the corresponding shipboard notes contain no data of significance.

Record 4, 16 October 1959

The record and the shipboard notes for 16 October indicate difficulty with the operation of the alpha-meter. This difficulty may have resulted from a misunderstanding of the instructions for the calibration of the instrument. The record indicates that the instrument was adjusted to read one hundred divisions in air, but due to an instrumental difficulty it was not possible to carry out the suggested procedure for making the instrument direct reading in transmittance per meter, i.e. increase the sensitivity in air by a factor of 1.1 to account for window losses when the water tube is in place. This did not affect the accuracy of the instrument provided the proper data-reduction procedure is followed. The indicated reading from the chart varied from approximately 5.8 divisions at 250 feet to 8.8 divisions at snorkeling depth. Multiplying these readings by the factor 1.1 (which accounts for reflection and transmission losses at the windows of the water tube when the instrument is in the measurement position,) transmission values are obtained of 6.5 per cent per meter and 9.7 per cent per meter, respectively. These values are extremely low but are typical of those that might be expected in estuaries, muddy harbors, etc. Again, there were no indications on the chart of the precise location of this particular operation, and therefore it is impossible to determine whether or not such low values are to be expected or whether they indicate an instrumental problem.

The shipboard notes for 17 October express a doubt as to the adequacy of the sensitivity of photocells. It is our understanding from subsequent discussions with the operating personnel that, to this point, the illuminometer range switch had been kept on the "10K" position. This was apparently due to a misunderstanding that this position provided the maximum sensitivity, whereas just the opposite was true. That is, the labeling of the switch was meant to indicate the nominal range of the photometers in foot-candles. Thus, the 10K position represented a full-scale sensitivity of 10,000 foot-candles and the 5 position represented a full-scale sensitivity of 5 foot-candles.

Record 5, 27 and 28 October 1959.

This chart is much more adequately annotated. The 27 October section has both alpha-meter and illuminometer records for the submarine on the surface. Unfortunately, there is no alpha-meter air reading, and there was no record of a previous calibration which can be used in conjunction with the alpha flux-monitor information to determine the full-scale sensitivity of the alpha-meter. If we make the assumption that the instrument was adjusted to give a full-scale reading in air of 100 per cent then the indication for this date is that the water had a transmittance of 48.5 per cent per meter. This would correspond to an alpha of 0.72 per meter. One might expect the water 170 miles off Cape Hatteras (the location for this reading) to be clearer than this would indicate. However, as noted above, the instrument was apparently not in calibration nor was there any notation that the windows had been recently cleaned. This would have been an important factor in obtaining proper values of transmittance.

The illuminometers show large variations in incident flux which would be expected under the conditions noted on the chart, namely, greater than 10-foot waves and seas breaking over the bow. The illumination recorded by the sail cell varied between 4300 and 5000 foot-candles. The illumination which would be expected by examination of the Natural Illumination Charts would have been 4200 foot-candles. The discrepancy between the value given in the Charts and the value observed is trivial under the circumstances which existed at the time of the measurement. For example, it is possible under certain meteorological conditions wherein there is a thin cloud formation near the sun, that forward scattering may provide sufficient augmentation of the flux from the sun to increase the observed values over those found in the Natural Illumination Charts. Furthermore, a slight variation in the trim of the submarine, a slight tipping of the surface of the photocell from the horizontal in its mounting, or some water on the top of the light-collecting surface of the cell could have increased the indicated output, because at the low solar elevation of 29 degrees which existed at this time the amount of flux collected by the cell is highly dependent on the orientation of the cell with respect to the normal.

The remainder of Record 5 covering the dates of 27 and 28 October were obtained during the late evening hours and therefore have only information from the alpha-meter. Again, these records are not particularly significant because of the lack of calibration information shown on the chart. However, if we assume the instrument to have been in the same condition as previously noted, i.e., adjusted to read 100 divisions in the calibrate position but not adjusted to be direct reading in transmittance, we find the measured alpha to be approximately the same as noted on the 27th of October, viz., 0.72 per meter.

Record 6, 31 October 1959

The alpha-meter reads 88.5 divisions in air, 50 divisions in water (after correction for 0.5 divisions displacement of zero on recorder.) The water transmittance is, therefore,

$$T = \frac{50}{88.5} \times 1.10 = 0.62.$$

Now $$T = e^{-\alpha x}$$

and as x, the path length, is in this instance 1 meter

$$\alpha = \ln \frac{1}{T} = 0.48 \ m^{-1}$$

A 6- or 7-minute record was made of the sail cell output. The keel depth was 52 to 58 feet; thus the cell was 4.5 to 11.5 feet below the surface. No information was available regarding the heights of waves, the heading of the submarine or the location of the sun relative to the periscopes nor the weather. A number of things may, however, be inferred from the record. The sensitivity switch was on the 10K position (it would probably have been better to have it on the 5K position to obtain greater accuracy), and the average reading was approximately 21 divisions. This corresponds to an ambient light value of 21 x 169 or 3500 foot-candles. The minima and maxima were usually between 10 and 30 divisions or 1690 to 5070 foot-candles. There seems to be a period between successive maxima or minima of 7 to 9 seconds. There is, superimposed on this system, a number of faster fluctuations with periods of two seconds and less. There are occasional minima where the record goes well below 10 divisions which may have been caused by shadows of periscopes or antennas on the sail. It is also quite probable that the cell occasionally broke water and was exposed to direct sunlight. Assuming the location was the same as on the 27th of October, 34° 48' N by 72° 47' W (obviously incorrect, but no coordinates are given) we can say that the local apparent time was 26 minutes later than the Eastern Standard Time indicated on the record, or about 0945. Entering the Natural Illumination Charts for 35° latitude at 0945 Local Apparent Time and 14° contrary declination (31 October) we find the illumination on a horizontal surface would have an expected value of 4700 foot-candles. The maximum readings of 5070 are reasonable as we can state quite definitely by the nature of the fluctuations of the trace that the sun was out, and with the wave action the cell was likely to break water or at least to get very close to the surface. In either situation refraction of the water above or puddled on the collector surface could increase the apparent luminance, or a tipping of the collector surface two degrees toward the sun by pitch or roll of the submarine would account for the observed value being greater than that obtained from the charts. The average ambient light is 75% of the predicted surface illuminance, and if we assume the cell depth during the period to be 10.5 feet (3.5 meters) the value of K would be 0.091 m^{-1}. This is very crude because of the many assumptions made here which would not have to be made if the data were being reduced concurrently with its taking. However, we can state with some confidence from the level of illumination and the period and magnitude of the fluctuations in the record that the sun was out, that there was an 8-second period major wave system with a shorter period system superimposed, and with somewhat less confidence that the water was not as clear as Gulf Stream water but was similar to off-shore surface water. We would expect with additional study of records of this nature and simultaneous records of wave heights obtained by some other means that a simple passive method could be devised that would permit one to quickly estimate amplitudes and periods of the surface waves with sufficient accuracy for operational purposes.

The next section of the record taken about 10 minutes later has another alpha-meter reading which, after corrections for change in the monitor cell reading, shows the transmittance to be essentially unchanged at 61 per cent.

The remainder of this record covers a period from 1520 to 1627 EST or 1546 to 1654 Local Apparent Time (assumed). The keel depth was slowly increased from 50 feet at 1537 EST to 195 feet at 1627. Data from the alpha-meter show little change from 50-feet to 70-feet keel depth, the range over which this instrument was in operation. However, no "α-flux monitor" data were taken during the afternoon run, so the values obtained, (transmittance of 56.3 per cent and α of 0.575 m^{-1}) cannot be confidently compared with the values obtained six hours earlier.

The illuminometer records in this afternoon run were again taken with the sensitivity switch set at "10K" instead of setting the switch at the lowest full-scale foot-candle value that would keep the instrument on scale. For this run, where the trace seldom got over 10 divisions, the sacrifice in accuracy was considerable. The surface illumination would have had a maximum value for clear sun conditions of 2200 foot-candles at 1546 Local Apparent Time and 430 foot-candles at 1654 L.A.T. From the appearance of the record it is obvious that the sky had broken cloud cover. There is a marked difference in the per cent fluctuation in the illumination record as the average magnitude indicates a change from cloudy to clear sun.

Examples below show the data reduction for discrete sections of the record.

Example 1. Date: 31 October 1959

Zone time: 1520 EST

Location (assumed): 35° N by 72° 47' W

Keel depth: 58 feet

Sail cell output: 10 div, 10K scale

Local Apparent Time calculation

Zone time	1520 hrs
Latitude correction $75^{\circ} - 72^{\circ}47' = 2^{\circ}13'$ at 4 min/degree	+0009
Equation of time correction for 31 Oct.	+0016
	1545 hrs LAT

Declination of sun 31 Oct: 14° contrary

Surface illumination, E_o, from Nat. Ill. Charts, Plate 6 for 35° latitude, 1545 hrs and 14° declination: 2200 ft-c

Sail illuminometer cell depth, z

Keel depth	58 ft
Sail cell above keel	47.5
	10.5

Sail cell factor for 10K scale: 169 ft-c/div

Sail cell output: 10 div

Sail cell illuminance, $E_{10.5}$ = 1690 ft-c

Transmittance of 10.5 feet of water

$$T = e^{-Kz} = \frac{E_z}{E_o} = \frac{1690}{2200} = 0.77$$

$$K = \frac{1}{z} \ln \frac{1}{T} = \frac{0.262}{10.5} = 0.025 \text{ ft}^{-1} = 0.082 \text{ m}^{-1}$$

Observations: Sky apparently broken clouds as factor of two change in illuminance noted over period of one minute. Above calculation based on interval when sun apparently unobscured based on level of illuminance and magnitude of rapid fluctuation.

Example 2. Date: 31 October 1959

Zone time: 1543 EST

Location: 35° N by 72°47' W

Keel depth: 52 ft

Sail cell output 8 div, 10K scale

LAT calculation

Zone time	1543
Latitude and Eq of Time Corr.	+0025
	1608 LAT

Sail illuminometer cell depth, z, 52 - 47.5 = 4.5 ft

Doclination 31 October: 14° contrary

Surface illuminance, E_0: 1500 ft-c max

Sail cell illuminance, E_z, 8 div x 169: 1350 ft-c

Transmittance of 4.5 ft of water $T = \frac{1350}{1500} = 0.90$

$K = .0232\ ft^{-1} = 0.076\ m^{-1}$

Example 3. Date: 31 October 1959

Zone time: 1550 EST

Location: 35° N by 72°47' W

Keel depth: 54'

Sail cell output: 6.1 div, 10 K scale

LAT calculation

Zone time	1550
Latitude and Eq of time corr.	+ 25
	1615 LAT

Sail illuminometer cell depth, z, 54 - 47.5 = 6.5 ft

Declination 31 Oct: 14° contrary

Surface Illuminance, E_0: 1200 ft-c max

Sail cell illuminance, E_z, 6.1 div x 169: 1030 ft-c

Transmittance of 6.5 ft water $T = \frac{1030}{1500} = 0.86$

$K = 0.0235\ ft^{-1} = 0.077\ m^{-1}$