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Technical Report 1553
September 1992

**Oceanic In Situ
Fraunhofer-Line
Characteristics
(Fraunhofer-Line
Underwater eXperiment:
FLUX)**

M. G. Lovern
M. W. Roberts
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ADMINISTRATIVE INFORMATION

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1. INTRODUCTION

Daytime performance of underwater optical communications in the upper ocean is limited by solar background. To enhance performance, numerous researchers have proposed using signal wavelengths within the reduced solar background provided by Fraunhofer lines. The performance improvement (references 1 and 2) gained by operating in a Fraunhofer line can be significant and, at some wavelengths, approaches an order of magnitude in signal-to-noise ratio. However, recent work in optical oceanography suggests the presence of an "additional" light field (references 3-7) in the upper ocean. The effect of an increased light field could significantly reduce (potentially eliminate) the absorption depth of Fraunhofer lines and reduce their solar-rejection benefits to optical communications.

For a number of years, optical oceanographers have measured abnormally low values for oceanic diffuse attenuation coefficients (K); and in certain cases, these values have been lower (references 8-12) than those for molecular water. These abnormally low values of K indicate the presence of more light at depth than for the case of molecular water. The increased light level has been suggested to result from internal-radiant emission caused by an inelastic (Raman) scattering process. This action produces a wavelength-shifted band of light (references 3-7) with a mean frequency shift of 3357 cm^{-1} . In other words, Raman scattering causes solar irradiance from shorter wavelengths to be wavelength-shifted to longer wavelengths, thus increasing ambient light at the longer wavelengths. The result of this process should be more apparent in the "green" spectral region (reference 13) due to the transmission characteristics of seawater.

The Naval Oceanographic and Atmospheric Research Laboratory (NOARL) has recently developed a model (references 3 and 4) that accounts for the additional light field induced by Raman scattering. Their optical model is a Monte Carlo solution of the radiative-transfer equation. Model results indicate the underwater light field becomes increasingly dominated by the Raman-scattered light component as depth increases. The largest unknown in the model (references 3, 4, and 6) is the value of the Raman-scattering coefficient. A range of values for the Raman-scattering coefficient has been determined by using experimental data from both field measurements and laboratory observations. The Raman-scattering coefficient values are bounded by a high estimate and a low estimate. Application of the high estimate in the NOARL model (at 520 nm) indicates that at a depth of 110 m, 50 percent of the total amount of light present is due to direct solar irradiance, and the other 50 percent is due to Raman scattering. However, when the low estimate is used, this same condition occurs at a depth of 160 m. As the depth is increased beyond this point, the underwater light field becomes dominated by the Raman-scattered light.

Since the Raman-scattering process produces a band shift, the total Raman contribution to any narrow wavelength interval should be homogeneous. This would suggest that as the Raman-scattered contribution to the underwater light field increases as depth increases, the Fraunhofer lines would become less defined: The lines would appear to "fill-in" to the continuum level as depth increases.

2. AT-SEA MEASUREMENTS

To investigate the potential effect of reducing the Fraunhofer absorption, an experiment was conducted at sea in August 1989. This experiment, the Fraunhofer Line Underwater eXperiment (FLUX), was conducted approximately 100 miles north of Oahu, Hawaii. FLUX was conducted on the Semi-Submerged Platform (SSP) Kaimalino, operated by the NCCOSC RDT&E Division (Hawaii). The objective of the experiment was to characterize Fraunhofer lines as a function of ocean depth.

Table 1 lists the five Fraunhofer lines characterized. As illustrated in figure 1, the fine structure inherent in the Fraunhofer lines (reference 14) requires narrowband spectral scanning and a high degree of wavelength accuracy. This was accomplished by using a 0.75-m double monochromator with an optical bandwidth of 0.01–0.02 nm. In addition to the five Fraunhofer-line scans, a continuous scan (0.1-nm resolution) from 450 to 550 nm was made at a depth of 73 m.

Table 1. Fraunhofer-lines investigated.

Center Wavelength (nm)	Scan Parameters (nm)		Scan Width (nm)
	Start	End	
420.18 (Fe)	420.03	420.33	0.30
440.47 (Fe)	440.20	440.70	0.50
486.13 (H)	485.28	487.00	1.72
518.30 (Mg)	517.80	519.00	1.20
532.42 (Fe)	532.15	533.15	2.00

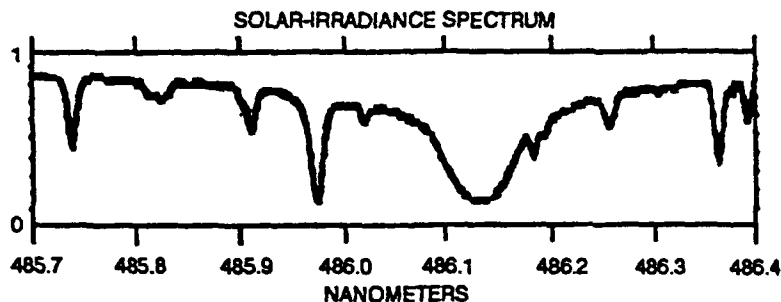


Figure 1. 486-nm Fraunhofer line.

Figure 2 shows the FLUX experimental setup. A custom-built fiber-optic bundle was used to couple the underwater light into the shipborne monochromator. A fiber-optic cable was chosen, since it is difficult to find a high-resolution monochromator capable of being submerged and remotely operated. The fiber-optic bundle was 120 m long and consisted of one-hundred, 210-micron fibers optimized for the visible region. The bundle was carefully shielded to prevent light from leaking into and out of the cable. The fibers were arranged in a circular pattern at the collection end and a 1-by-100 linear array at the exit end. The linear array of fibers at the exit

end was designed to be compatible with the linear input slit of the monochromator. To increase the coupling efficiency of the fiber-to-monochromator interface, a relay lens system was used to image the output of the fiber array onto the input slit of the monochromator. The monochromator had a linear drive motor attached to the wavelength scanner to scan the wavelength at a constant speed. A photomultiplier tube (PMT) was attached to the output slit of the monochromator with the anode connected to a photon counter. The spectral scans were recorded by interfacing a computer to the photon counter. The computer recorded the number of photoelectron counts as a function of time which in turn translates to counts versus wavelength.

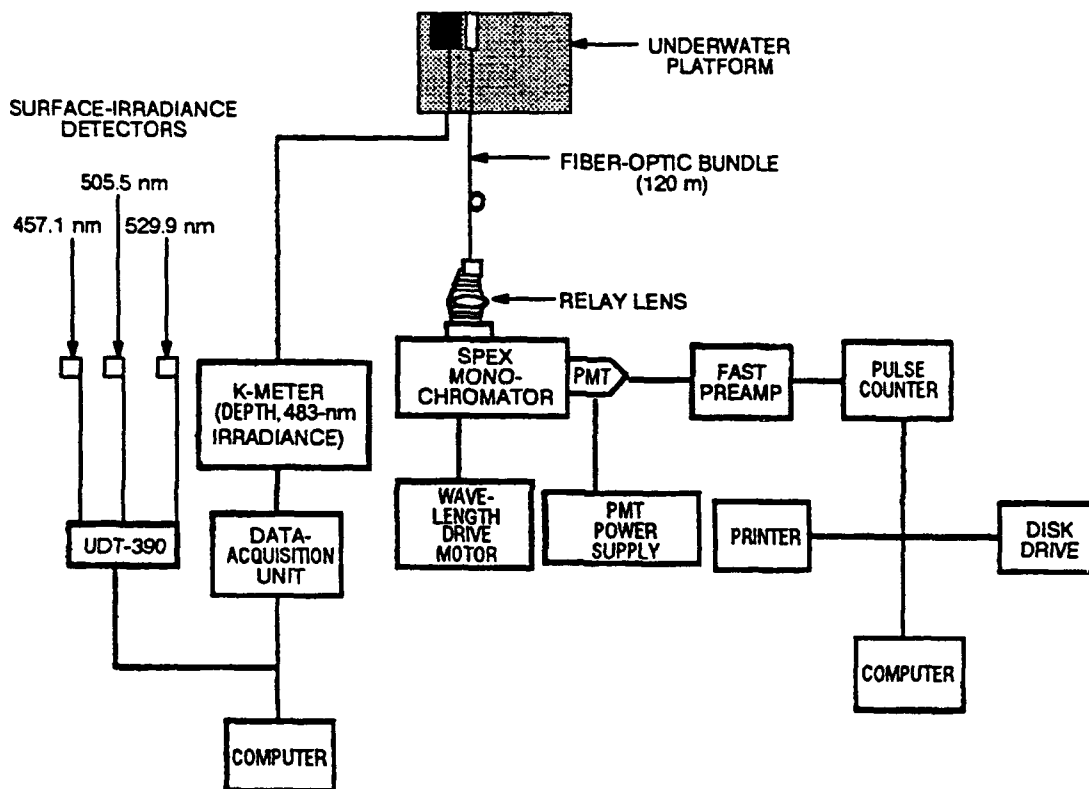


Figure 2. FLUX system, block diagram.

The wavelength of each of the five Fraunhofer lines was scanned at four discrete depths: 25, 50, 73, and 90 m. Scans were also conducted at the surface, both to check the system and to serve as a reference. Figure 3 shows a comparison between a textbook scan and one the FLUX equipment recorded for the 486-nm Fraunhofer line. (Note: the rough appearance of the two figures is caused by the optical scanner used to read them into the computer for this report.) The scans are vertically offset to allow a better comparison, with the textbook scan positioned on the top. The strong similarity indicates no statistically significant differences and ensured that the in-situ characterizations are correct. During the final day, we added a broadband spectral scan from 450 nm to 550 nm (0.1-nm resolution).

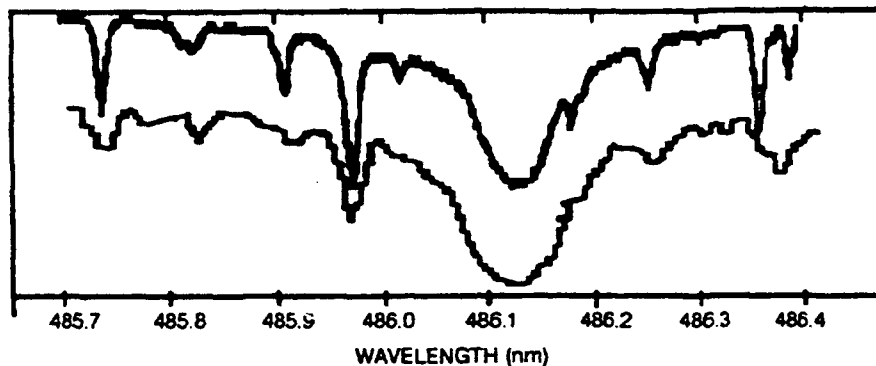


Figure 3. Fraunhofer-line comparison—FLUX versus textbook.

Concurrent irradiance measurements were made during the FLUX scans to normalize solar-irradiance fluctuations due to the presence of clouds, wave focusing, and other underwater optical disturbances. These irradiance measurements were made simultaneously at the surface and underwater (when possible). Underwater irradiance measurements were made with an irradiance meter (K-meter) included in the underwater sensor package as illustrated in figure 4. The K-meter contains a PMT that was spectrally filtered at 483.5 nm with a 10-nm bandpass and a depth sensor. Cable length limited the K-meter to a maximum depth of 73 m. For scans at depths greater than 73 m, the K-meter was removed from the underwater sensor package, and irradiance normalizations were obtained using the surface irradiance data. The fiber-optic bundle was marked at regular intervals (from the 73-m point at 5-m increments), and depth was then determined from these physical markings.

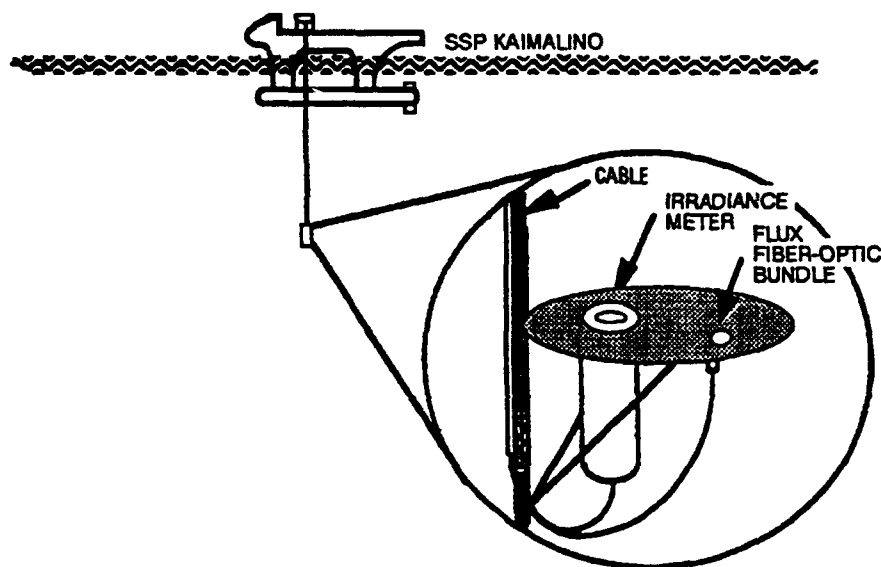


Figure 4. Underwater sensor package.

The K-meter was also used for measuring the diffuse attenuation coefficient (K) before and after each FLUX sensor deployment. A measurement of K was made by recording the irradiance

as a function of depth. Once these data were plotted, integrated K was determined by calculating the slope of a linear fit to the data. Figure 5 is a typical example of a K measurement from the FLUX experiment

$$K = \frac{-\text{Ln}\left[\frac{E_z}{E_0}\right]}{z}$$

where K is the diffuse attenuation coefficient (m^{-1}), z is the depth in meters, E_z is the irradiance at depth, and E_0 is the surface irradiance.

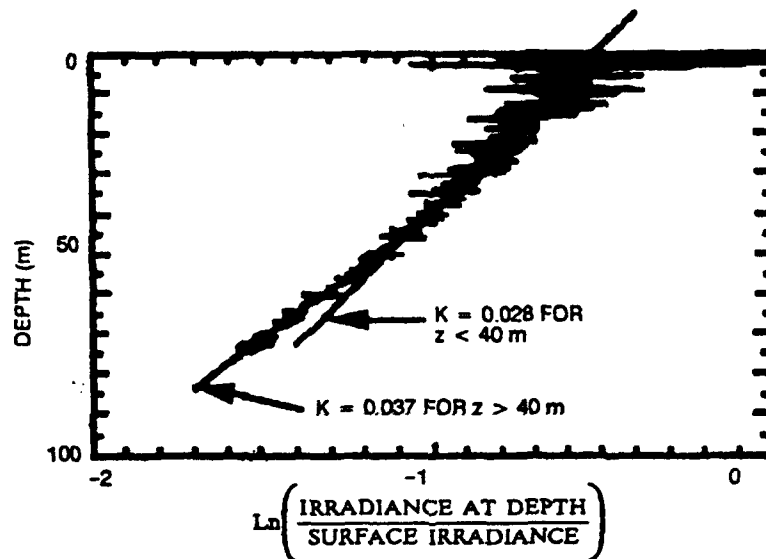


Figure 5. Typical example of K measurement.

The FLUX K profiles had two distinctive slopes intersecting at an approximate depth of 40–50 m and were concurrent with the location of a thermocline. These multiple slopes have the effect of creating a change in the value of integrated K used, depending upon the operating-depth zone. Table 2 is a summary of the FLUX K measurements.

Table 2. FLUX K data summary.

Date	Time	Depth Range (m)	K (483.5 nm)
8/7/89	1437	60-73	0.025
8/7/89	1643	30-73	0.048
8/7/89	1643	0-50	0.040
8/8/89	1138	40-70	0.037
8/8/89	1138	0-40	0.028
8/8/89	1309	50-70	0.029
8/8/89	1413	22-45	0.043
8/9/89	1008	0-55	0.031
8/9/89	1008	55-71	0.042
8/9/89	1200	50-73	0.040
8/9/89	1300	25-40	0.032
8/9/89	1400	0-25	0.034
8/10/89	0910	38-73	0.041
8/10/89	0910	0-38	0.033
8/10/89	1101	47-73	0.037
8/10/89	1101	0-47	0.027

3. ANALYSIS

The majority of the individual spectral scans—referred to as “short scans”—encompassed a wavelength range of approximately 1 nanometer. The start and end wavelengths of each scan were selected so the primary Fraunhofer line was centered within the scan. Additional criteria were that the scan should contain an adequate “continuum” level as well as nearby secondary lines. The continuum level is defined as the level at which the solar irradiance is at maximum. For the short scans, each data point is the photoelectron count accumulated during a 2.5-second integration time. The wavelength scan rate was set for 0.1 nm per minute, and the spectral resolution was approximately 0.01 nm.

Two submerged “long” scans were also performed over the continuous wavelength range from 450 to 550 nm. The scan rate during the “long” scans was 0.6 nm per minute, integration time was 0.6 seconds, and spectral resolution was approximately 0.1 nm.

During each scan, the operator periodically entered wavelength-counter readings. These counter readings were automatically “time-tagged” by the computer and stored with the data. The settings of all pertinent equipment parameters were also stored in the data file during the scan.

Each scan contained “zero-level” measurements made prior to starting the scan and also at the end of the scan. These are measurements of the dark-noise count and were obtained by blocking the entrance slit of the monochromator and recording several data points at the same sample rate as for the spectral scans. The shutter located between the exit slit and the PMT was left open during these zero-level measurements. Zero-level measurements quantified both the PMT dark noise and any ambient light entering the monochromator.

Two principal “noise” sources producing irradiance fluctuations were noted during the experiment. The sources were caused by wave-focusing and clouds passing overhead. Wave-focusing produced significant fluctuations at 25- and 50-m depths, but had little effect at 73 and 90 m. Irradiance dropout due to clouds was occasionally quite large and was noticeable at all depths.

Since the purpose of the experiment was to determine to what extent various Fraunhofer lines “filled-in,” the analysis centered on comparing the Fraunhofer spectra collected at depth against the same Fraunhofer spectra collected at the surface. Each data scan was zero-level corrected and then normalized. The submerged scans were also corrected for gross-temporal irradiance fluctuations by using data from the underwater irradiance meter. Minor higher frequency random noise observed in the raw data was removed by spectral processing (treating the scan as a time series) by using a discrete fast fourier transform (FFT) algorithm.

Comparisons between submerged and surface “short” spectral scans are shown in figures 6 and 7. These figures contain examples of the spectral plots for all five of the Fraunhofer lines that were investigated at depths of 73 and 90 m respectively. For each wavelength, the plot of the underwater scan (solid line) has been normalized and processed using the techniques just described. Along with the underwater plot is a normalized plot of the associated surface scan (dotted line). To within experimental accuracy, the line shapes and the ratios between line depth and continuum level remained constant for all observed wavelength ranges at all depths.

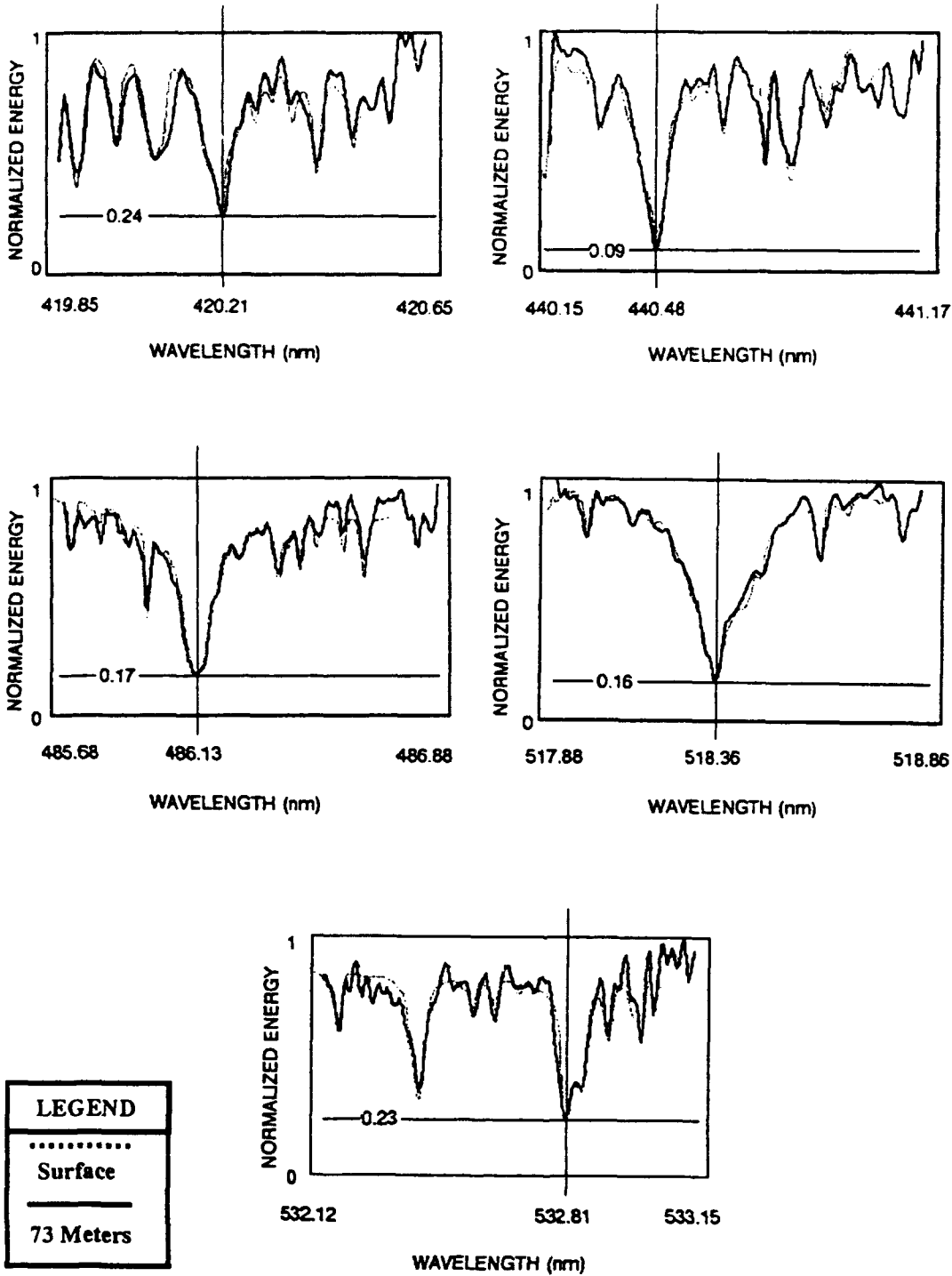


Figure 6. Comparison of submerged (73-m depth) and surface Fraunhofer-line scans.

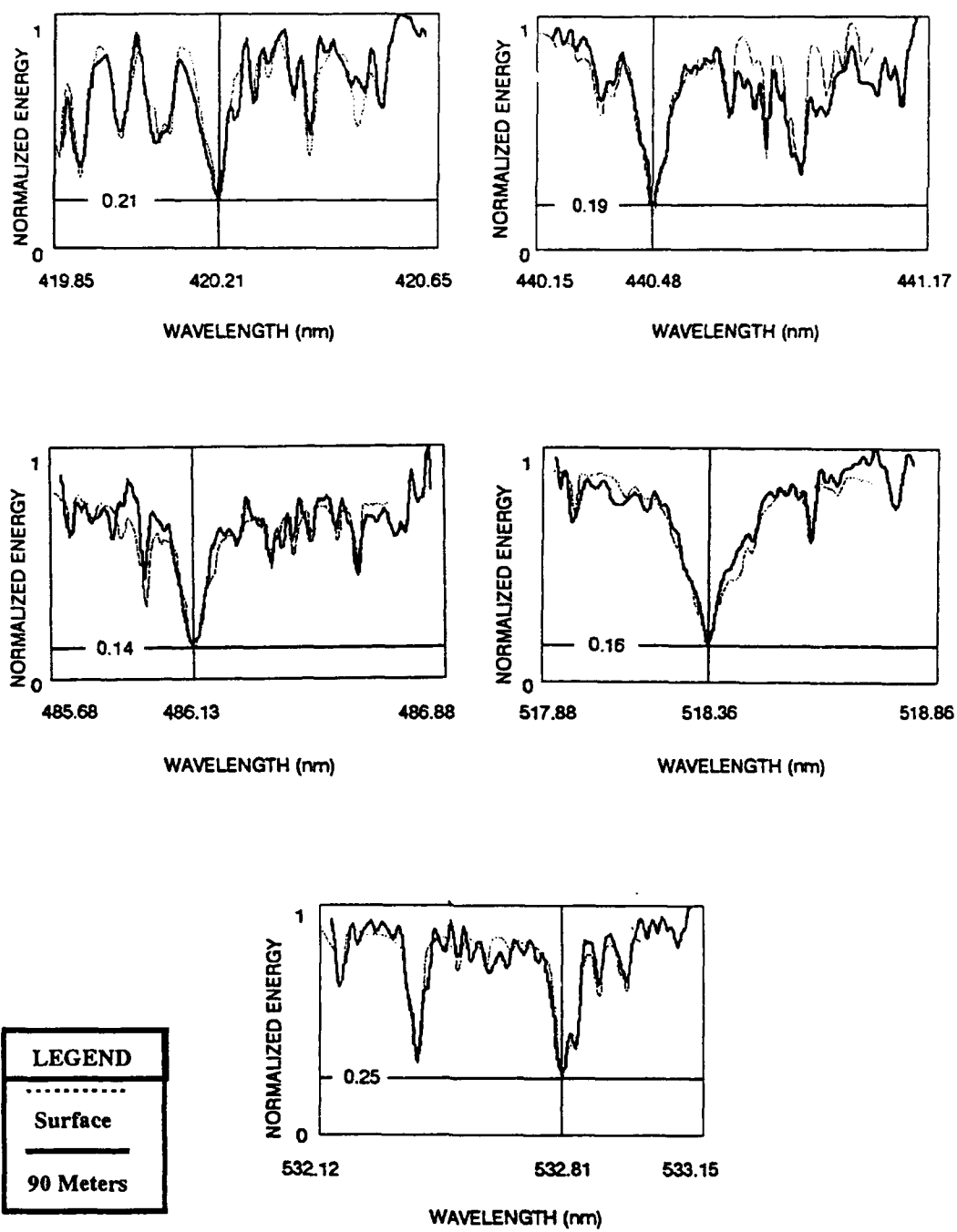
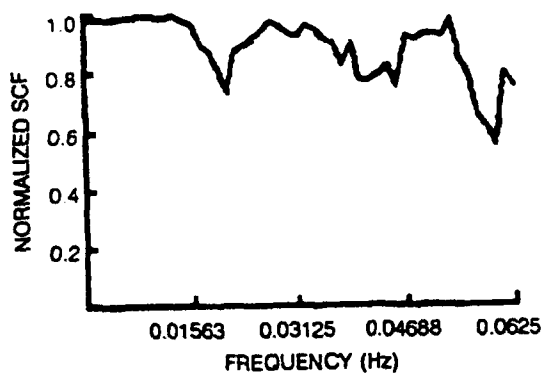


Figure 7. Comparison of submerged (90-m depth) and surface Fraunhofer-line scans.

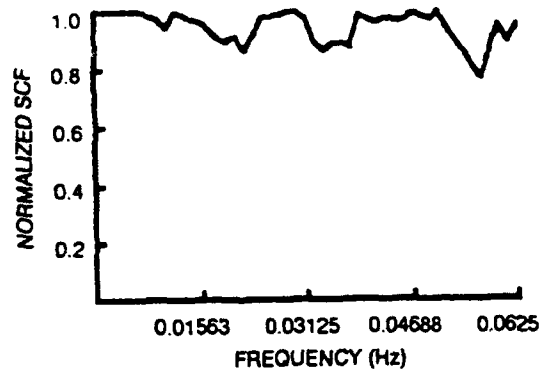
Some minor differences in the wavelength scale may be seen; however, this can be attributed to the slight variability in the wavelength drive motor for the monochromator. The much narrower absorption lines surrounding the main Fraunhofer line have not, in any of the scans, degraded in absorption depth or width. If interwavelength scattering had occurred, the narrowest lines would simply have disappeared and the absorption peak for the main line would have been reduced in depth. Further, a comparison between the 73- and 90-m scans reveals no detectable difference. Had there been interwavelength scattering, a noticeable difference should have occurred between the scans of different depths, particularly at 518 and 532 nm. Thus, these observations reveal no obvious reduction ("filling-in") of the Fraunhofer-line structure.

Conclusions based upon the observations just made were further corroborated by calculations of the squared coherence function (SCF) for the surface and underwater data. Figure 8 is a plot of the SCF between the surface and underwater data for the scans shown in figure 6. The value of the SCF never falls below 0.6 and is usually close to 1.0 for the frequency region between 0 and 0.03125 Hz, which contains nearly all of the energy in each scan. This strongly indicates the level of agreement between the surface and underwater scans. Had any interwavelength scattering occurred, the SCF value would have been much lower, particularly at the higher frequencies. Higher frequencies represent the narrower Fraunhofer lines, which are more susceptible to change due to interwavelength scattering. (Since they are narrow in line width, a smaller increase in light level within the absorption band is more readily detected.) Therefore, if the underwater light level had increased and the Fraunhofer line had begun to "fill-in," one would expect the SCF values to fall off toward 0 at higher spatial frequencies. However, this clearly does not occur.

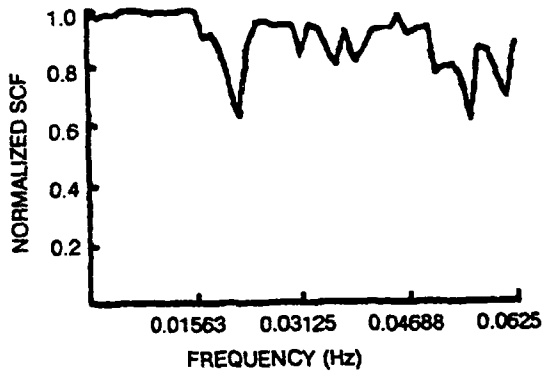
A comparison between submerged and surface "long" scans is presented in figure 9. Figure 9(a) is the complete scan from 450 to 550 nm, whereas figures 9(b) and (c) are expanded views of the 486- and 518-nm Fraunhofer lines taken from the "long" scans. Both scans have been zero-level corrected and normalized. Additionally, each scan was corrected for the dispersion in the fiber-optic bundle using post-field spectral calibration data. The underwater scan was also corrected for temporal irradiance fluctuations.



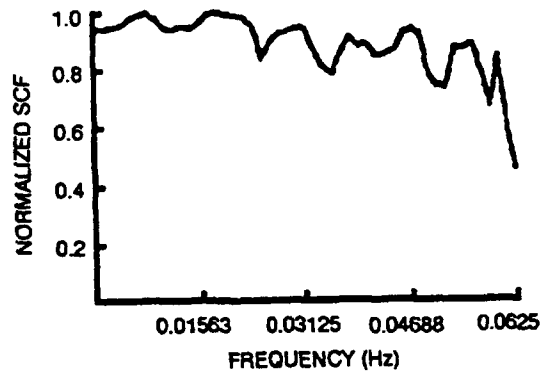
a. 486.13-nm FRAUNHOFER LINE



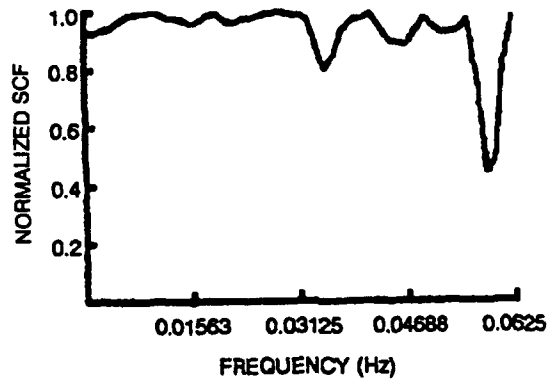
b. 518.36-nm FRAUNHOFER LINE



c. 532.42-nm FRAUNHOFER LINE

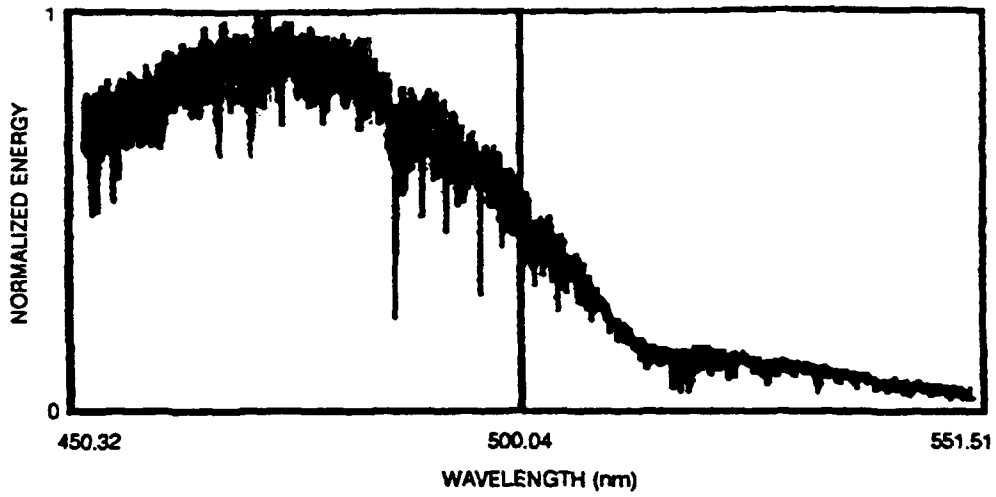


d. 440.48-nm FRAUNHOFER LINE

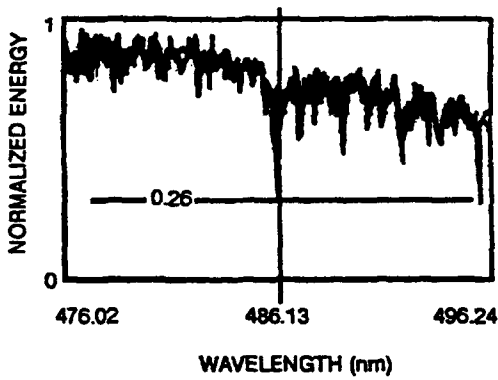


e. 420.18-nm FRAUNHOFER LINE

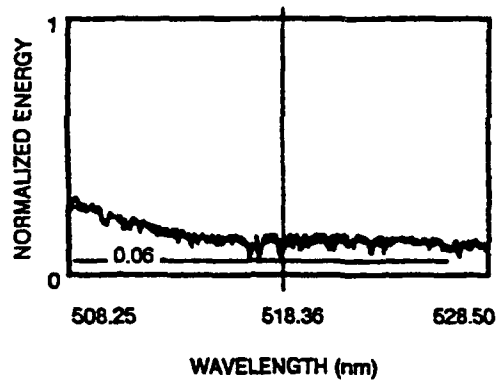
Figure 8. Squared coherence function comparisons for 73-m Fraunhofer-line spectral scans.



a. "LONG SCAN" FROM 450 TO 554 nm



b. EXPANDED VIEW AROUND
486.13-nm FRAUNHOFER LINE



c. EXPANDED VIEW AROUND
518.36-nm FRAUNHOFER LINE

Figure 9. Comparison of submerged (73-m depth) and surface "long" scans.

The surface "long" scan has been altered to appear as it would at a depth of 73 m. This was done by applying the Austin/Petzold water model (reference 15). Using this model, knowing the value of the diffuse attenuation coefficient at any wavelength in the range from 400 to 700 nm allows calculation of K at any other wavelength within the range. During the experiment, measurements of K (483.5 nm) were made at the beginning and end of a FLUX sensor deployment. The mean of these measurements was 0.035. This value was used in the water model to correct the surface "long" scan data for the relative dispersive attenuation of the ocean to a depth of 73 m. Although distinguishing between the two curves in figure 9 is difficult, they illustrate how much agreement exists between the surface and underwater scans. Had there been interwavelength scattering, the underwater scan would have fallen away from the surface scan as wavelength increased from 450 to 550 nm. Furthermore, the fine structure in the underwater scan would have disappeared. The expanded views of the 486- and 518-nm lines clearly indicate the level of agreement between the two scans.

4. CONCLUSIONS

The ONR-sponsored Fraunhofer-Line Underwater eXperiment (FLUX) was successfully conducted off the coast of Hawaii in August 1989. This experiment obtained the first-known characterizations of Fraunhofer lines underwater. These characterizations verified the presence of the blue-green spectrum Fraunhofer lines to a depth of 90 m with no measurable change in the line structure.

According to the current Raman scattering model, use of the high-estimate scattering coefficient yields a prediction that a significant amount of Raman scattered light should have been present at the FLUX measurement depth of 90 m. The model predicts the Raman scattered contribution in the "blue" (420, 440, and 486 nm) Fraunhofer lines was potentially too small to resolve. It also predicts that an observable change should have occurred in the "green" (518 and 532 nm) Fraunhofer lines. The Raman scattering effect should also have been observable in the "long" scan. The results of the FLUX experiment indicate that the high estimate of the Raman scattering coefficient may be discontinued.

These results demonstrate the need for additional experimental investigation to quantify the Raman scattering coefficient. While, clearly, Fraunhofer lines may be used in an SLC system down to 90 m without degrading their solar rejection characteristics, further experiments should be conducted at depths greater than those achieved during FLUX. These experiments should include upwelling and side-looking irradiance measurements, since these measurements would contain dominating amounts of scattered light.

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