Journal of Tokyo University of Fisheries, Vol. 87, pp. 13–21, 2001

Spatial Resolution of a New Micro-optical Probe for Chlorophyll and Turbidity

Fabian Wolk*1, Laurent Seuront*2 and Hidekatsu Yamazaki*2

(Received August 30, 2000)

Abstract: A newly developed bio-optical sensor enables us to perform high-resolution measurements of *in situ* chlorophyll and turbidity. The sensitivity and the spatial resolution of the probe are tested in several laboratory experiments. Analysis of the test data shows that this probe is capable of resolving spatial distributions of chlorophyll as small as 0.02 m. Evaluation of the spectral characteristics of chlorophyll and turbidity signals recorded in field tests corroborate the laboratory results.

***Key words*:** *Phytoplankton*, *Bio-optical sensors*, *Microstructure*

Introduction

Recent technological advancements have made it possible to make *in situ* observations of small-scale distributions of marine organisms. For example, Davis *et al.*[1] developed a video image system (Video-Plankton Recorder, VPR) and observed that actively swimming zooplankton exhibit a patchiness on spatial scales as small as 10 cm. It is also becoming clear that the phytoplankton layers often show the formation of layers as thin as 10 cm[2]. At this scale, the most important fluid dynamic processes are mixing and stirring due to turbulence.

During the last decade, many researchers began to focus on the coupling between turbulence and planktonic ecosystem[3,4]. Desiderio *et al.*[5] were the first to successfully measure the high-resolution chlorophyll field while simultaneously measuring the associated turbulence. Unfortunately, no subsequent report has since appeared in the literature, apparently because of technical difficulties in operating the high resolution optical probe with turbulence probes.

In order to address the above questions in more detail, we developed a new micro-scale optical probe that measures both chlorophyll and turbidity. The non-intrusive character of the probe, as well as its high spatial resolution allows us to sample the bio-optical properties of undisturbed water. The probe is designed to be deployed alongside sensors that measure microstructure turbulence. The concurrently developed free-falling instrument TurboMAP (Turbulence Ocean Microstructure Acquisition Profiler, Wolk *et al.*[6]) will serve as a platform that carries the new probe.

The new probe was tested extensively in laboratory experiments to determine (*i*) its sensitivity to artificial and naturally occurring fluorescent sources and (*ii*) its spatial resolution. This paper describes the basic operating principle of the probe and the experimental setup and procedure for determining the probe's sensitivity and spatial resolution. The results of these laboratory tests will be presented along with an example of field data collected with the new probe.

Operating Principle

Fluorescence is the radiation produced by certain biological and chemical substances in response to incident radiation of a shorter wavelength. The combined chlorophyll/turbidity sensor (hereafter CTS, Figure 1) uses the fluorescent property to determine the *in situ* concentration of oceanic phytoplankton. Simultaneously, the backscatter of the incident light is used to measure the turbidity of the water.

As an excitation source, the CTS uses an array of six light emitting diodes (LEDs), which emit light in the waveband of 400–480 nm. The LEDs are arranged on a circumference of 20 mm diameter and canted in such a way that their collimated beams are mutually orthogonal. The beams intersect in one focal point located 15 mm above the center of the LED circle, in front of the receiver diode. The spatial extent of the focal point defines the sampling volume of the probe. The re-emitted light from fluorescent material that passes through the sampling volume is collected by the receiver diode, which has an optical pass-band of 640–720 nm. A second re-

*1 System Division, Alec Electronics Co. Ltd., 7–2–3, Ibukidai-higashi, Nishi-ku, Kobe 651–2242, Japan.
*2 Ocean Ecosystem Dynamics Laboratory, Department of Ocean Sciences, Tokyo University of Fisheries, 5–7, Konan 4-chome, Minato-ku, Tokyo, 108–8477, Japan.

ceiver diode has an optical pass-band identical to the excitation light. This receiver measures the intensity of backscatter of light from suspended particles, which is a measure of the turbidity. The sensor output voltage for both channels is a linear function of the received light intensity.

The overall design and data acquisition of the CTS probe differ from other commercially available *in situ* fluorometers. The conventional systems typically have large cylindrical pressure cases measuring approximately 0.1–0.15 m in diameter and 0.2–0.3 m in length, and they sometimes employ a pump system to bring the water into the sampling volume. Because of their shape and low sampling frequencies (typically 0.2–2 Hz), these standard fluorometers are unable to resolve the centimeter-scale structures we seek to measure. In contrast, the CTS probe is deployed on a free-falling instrument that moves vertically through the water at a constant speed. The small size and rounded shape of the probe minimize the influence of the probe on the surrounding flow, so that the small scale structures of fluorescence and turbidity are not destroyed by flow deformation. In addition, the probe "looks sideways" into the free flow.

The signals of both channels of the CTS probe are passed through an analog low-pass filter (with a cut-off frequency of 128 Hz), then sampled at a rate of 256 Hz, and digitized with a 16-bit A/D converter. At the nominal fall speed of the instrument of $0.5\,\mathrm{m\,s^{-1}}$, the bandwidth of the data acquisition system (128 Hz) gives one data point every 4 mm.

Experimental Setup and Procedure

A series of laboratory experiments are conducted to establish the performance of the CTS probe. The objectives of the tests are to estimate the size of the sampling volume to establish the spatial resolution of the probe, and to determine the response of the probe to naturally occurring fluorescent sources, such as algae and pure chlorophyll *a* solutions.

Sensitivity and Dynamic Range

The CTS probe is initially calibrated against sodium fluorescein solutions of various concentrations. The preset range of detection is approximately 0 to 300 ppb (parts per billion) and the sensor output is a linear function of concentration with a slope of 1V per 100 ppb of sodium fluorescein. From the noise floor of measured *in situ* chlorophyll spectra, the resolution of the probe in terms of chlorophyll is estimated to be 5×10^{-3} ppb.

The sensitivity, linearity, and dynamic range of the CTS probe are investigated by recording the probe output voltage for various concentrations of (*i*) a strong fluorescent chemical reagent (sodium fluorescein), (*ii*) pure chlorophyll *a* solutions, and (*iii*) natural phytoplankton species. Chlorophyll *a* and natural phytoplankton are considered both in terms of biomass (i.e., chlorophyll *a* concentration) and fluorescence (i.e., *in vivo* fluorescence) using standard laboratory determination techniques. The concentrations are chosen in such a way as to represent reasonable oceanic values of these fluorescent materials. The pure chlorophyll *a* is extracted from *Anacystis nidulans* (Sigma Chemicals). The concentrations of chlorophyll *a* in the different diluted solutions used in the experiment are estimated from small samples (5 ml), which are stored in the dark at 0°C for the duration of the whole experiment (ca. 2 hours) and are subsequently quantified directly in a Turner fluorometer (10R) following Strickland and Parsons[7].

Marine diatoms (*Skeletonema costatum*), isolated from natural phytoplankton assemblages sampled in Tokyo Bay on February 4, 2000, were grown in the M_1 medium of Ogata *et al*.[8] at 15°C. Illumination was supplied with fluorescent light ($130\,\mu\mathrm{E\,m^{-2}\,s^{-1}}$), and cells at the late exponential growth phase are used for the calibration experiments. In addition, a natural phytoplankton assemblage sample is collected from the surface water of Tokyo Bay off the pier of the Tokyo University of Fisheries on April 27, 2000.

For each dilution of the initial algal solution, as for natural phytoplankton population sample, algal cells are collected on a Whatman GF/F glass micro fiber filter by filtration of a 30 ml water sample. Chlorophyll pigments are extracted by direct immersion of the filter in *N*,*N*-dimethylformamide following Suzuki and Ishimaru[9]. Chlorophyll *a* concentration is estimated from the extract using a Turner fluorometer (10R) following Strickland and Parsons[7]. In addition, 30 ml water samples are taken for *in vivo* fluorescence determination using a Turner fluorometer (10R).

Fluorescence measurements with the CTS are carefully performed under exactly the same conditions for all solutions (i.e., chlorophyll or algal solutions). The test solutions are placed into a 1-liter beaker that is lined with black tape in order to prevent noise and bias from ambient light sources. To reduce bias further, the test is conducted in a dark room illuminated with a 25 W desk light. The sensor head is placed at mid-depth into the beaker, so that the back of the sensor touches the beaker wall. For each realization of the test, the operator places the sensor head into the beaker in the same way, in order to reduce systematic errors. Systematic errors can occur from residual excitation light that is reflected off the inside beaker walls. Due to spectral leakage[10] of the CTS's

receiver filter and the high intensity of the reflected light, a fraction of the reflected light can bias the measurement. This bias is a constant offset and is easily estimated in a control measurement with clear water.

Spatial Resolution

The dimensions of the sampling volume determine the spatial resolution of the CTS probe. The probe's sampling volume is established by finding its spatial resolution in the tangential direction relative to the sensor face (see Figure 1), and its sensitivity as a function of distance in the normal direction (i.e., to determine how far the probe can "see"). During deployment with TurboMAP, water moves in front of the sensor in the tangential direction as indicated in Figure 1. Therefore, the spatial resolution in the tangential direction ultimately determines the smallest scales resolved by the probe.

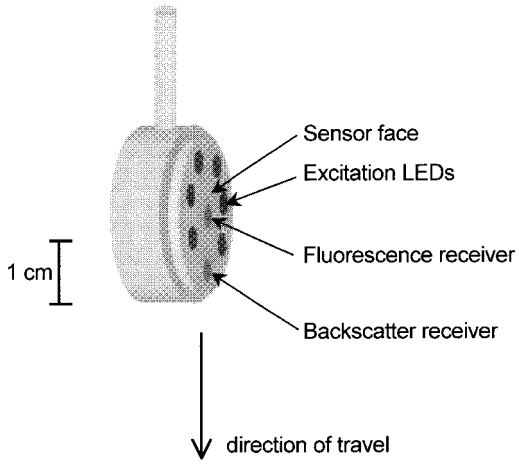

Figure 1. Sketch of the CTS probe showing the arrangement of the excitation LEDs and receiver LEDs. The probe head is 2.2 cm thick and the sensor face is 2.5 cm in diameter. The windows of the excitation LEDs and the receivers are 0.6 cm in diameter.

To determine the tangential resolution, strips of paper are dyed with fluorescent ink (text highlighter) and pasted in pairs onto a black cardboard surface (Figure 2). Individual paper strips are 1 mm wide and 100 mm long. The pairs are separated by 10 mm, 20 mm, 30 mm, 40 mm, and 50 mm, and the distance between each pair is approximately 100 mm. The cardboard is mounted onto a motor-driven carriage and moved at constant speed parallel to the sensor surface (Figure 2). This is done for carriage speeds between 0.2 and 0.7 $m\,s^{-1}$ and for three distances between the sensor surface and the board (5 mm, 10 mm, and 25 mm). The range of carriage speeds is chosen to cover the expected fall speeds of TurboMAP (nominally 0.5 $m\,s^{-1}$). The passing of a fluorescent strip in front of the probe shows up as a peak in the sensor output. The probe output voltage is sampled 256 times per second, which is the sampling rate of TurboMAP.

The sensitivity as a function of distance in the normal direction is established by placing a glass pipette filled with fluorescent material in front of the sensor at various

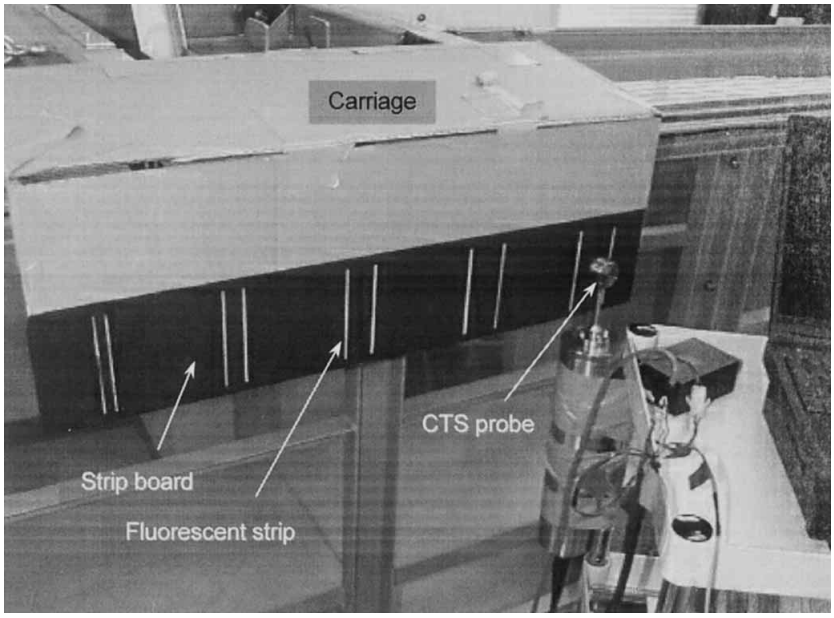

Figure 2. Experimental setup for the tangential spatial resolution test. The CTS probe is visible in the foreground.

distances along the normal axis and measuring the sensor output. The pipette has an inner diameter of approximately 5 mm, and thus represents a point source of fluorescent material as may be encountered in the ocean (such as an algae aggregate or a blob of plankton). The pipette test is conducted in a dark room, where some background light is provided by either a 25 W desk light or a 20 W neon tube. The sensor is placed 0.1 m above the bottom of an aquarium measuring 0.44 m×0.29 m×0.3 m (L×W×H). The aquarium is filled with tap water to a level of approximately 0.22 m, and the sensor head is placed at mid-depth into the aquarium.

A ruler taped to the bottom of the aquarium is used to measure the distance between the probe and the pipette. The pipette tip is placed onto the ruler and held perpendicular to the aquarium bottom. A 20-second time series of the probe output is recorded from which the mean and standard deviations are computed. For this test, the following fluorescent substances are used:

1. Sodium fluorescein solution, equivalent to 250 $\mu g\,l^{-1}$ chlorophyll *a*;
2. Tap water, taken from the test tank;
3. Live algae (*Skeletonema costatum*), 51.54 $\mu g\,l^{-1}$;
4. Live algae (*Skeletonema costatum*), 26.72 $\mu g\,l^{-1}$;
5. Bucket sample from Tokyo Bay collected at the pier of Tokyo University of Fisheries, 8.8 $\mu g\,l^{-1}$ chlorophyll *a*;
6. Chlorophyll *a*, 10.5 $\mu g\,l^{-1}$.

The tests involving solutions 1 and 2 were conducted on March 31, 2000; those involving solutions 3 through 6 were conducted on April 28, 2000.

Results and Discussion

Sensitivity and Dynamic Range

For pure solutions of chlorophyll *a*, the sensor output is clearly linear for concentrations ranging from 0.05 to 25 $\mu g\,l^{-1}$ (Figure 3), with a highly significant regression coefficient ($p<0.01$). The change of behavior observed at high concentration can be attributed to light attenuation by chlorophyll *a* over the optical path; it is indeed observed visually that for concentrations higher than 35 $\mu g\,l^{-1}$ the light transmission is effectively blocked (filled circles in Figure 3).

For *Skeletonema costatum* solutions, the response of the sensor is significantly linear ($p<0.01$), with chlorophyll *a* concentration ranging from 4 to 52 $\mu g\,l^{-1}$ (Figure 4a) and *in vivo* fluorescence ranging from 0.9 to 42 IVF relative units (Figure 4b). Moreover, the slopes of the two regression lines are statistically identical (*t*-test, $p<0.05$)[11]. This result shows a very similar static response of this fluorescence sensor for both phytoplankton biomass and phytoplankton fluorescent activity. Thus, the sensor can be used with confidence to estimate chlorophyll *a* concentrations. It is noteworthy that the results obtained from the natural phytoplankton sample in terms

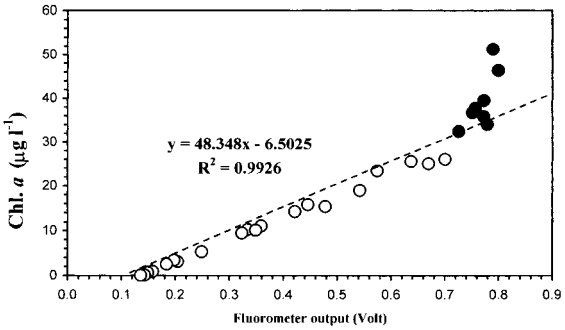

Figure 3. Output of the chlorophyll sensor obtained in well-stirred pure chlorophyll *a* solutions (open circles). Filled circles indicate the range of chlorophyll *a* concentrations over which the sensor has been influenced by light attenuation from chlorophyll *a*.

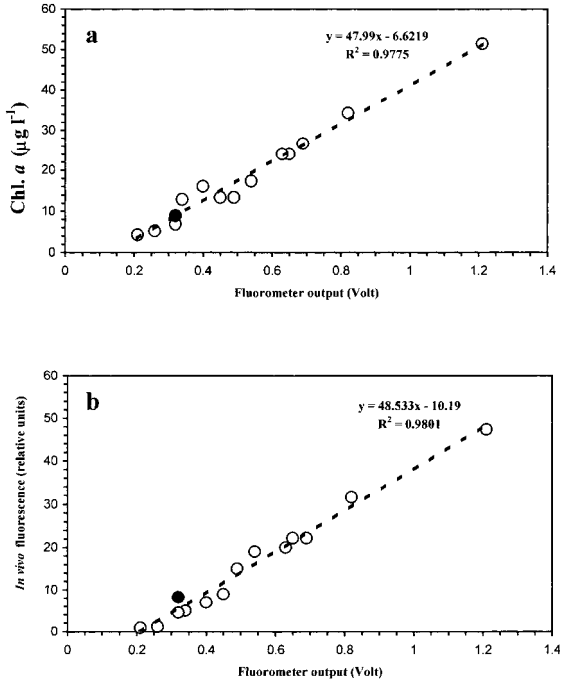

Figure 4. Output of the chlorophyll sensor obtained in well-stirred solutions of the diatoms *Skeletonema costatum* (open circles), shown together with the best regression lines obtained from chlorophyll *a* concentrations (a) and *in vivo* fluorescence (b) estimated from algal cells. Filled circles represent the results obtained with natural phytoplankton assemblage, and have not been taken into account in the regression.

of both biomass and fluorescence, plotted as additional data on Figure 4a and Figure 4b (filled circles), are fully congruent with our previous observations, suggesting a relevant behavior of the sensor for both monospecific and plurispecific phytoplankton assemblages.

Finally, the non-significant difference observed between the slopes of the regression lines estimated from the experiments conduced on pure chlorophyll *a* and *Skeletonema costatum* cells ($p<0.05$) for overlapping ranges of chlorophyll *a* concentrations demonstrates the ability of the CTS probe to detect chlorophyll *a* concentrations over a wide range of values encountered in the ocean, from oligotrophic[12] to highly productive marine waters[13].

We note that the probe output never exceeds 1.3 V, even for the test solutions that have a high fluorescent concentration, i.e., approximately 50 $\mu g\,l^{-1}$, which represents an extraordinarily high oceanic value. This means that only about 30% of the dynamic range of the sensor is used, which ultimately limits the probes ability to resolve small variations in concentration levels. For future deployments, we need to adjust the sensor's dynamic range to better match the common oceanic range.

Spatial Resolution in the Normal Direction

The results of the range sensitivity for the different fluorescent solutions are given in Table 1. The sensor output voltage is listed for various distances along the normal direction from the sensor face. Values in parenthesis are the standard deviations of the recorded 20-second time series. The listed values include a constant instrument bias of 0.11 V, which is caused by an offset voltage in the sensor circuitry plus the offset produced by the background lighting in the laboratory. The background lighting also adds broadband noise to the measured signal, which is reflected in the standard deviation of the measured time series. The background light is a 25 W light bulb for solutions 1 and 2, and a 20 W neon tube for solutions 3 through 6. The results for solutions 3 through 6 show a significantly greater standard deviation than the results for solutions 1 and 2, as well as a residual offset of about 0.01 V. We assume that the increased measurement uncertainty is introduced by the brighter background light. The residual offset cannot be explained, however. The results from the water sample show that there is an additional small bias introduced by the glass of the pipette. Some of the excitation light is reflected back to the receiver when the pipette is very close to the sensor. This causes a small offset signal due to spectral leakage of the optical filter (as discussed above).

The values of Table 1 are summarized in Figure 5. For all solutions except sodium fluorescein, we observed an exponential decrease in output voltage as a function of distance. The sodium fluorescein solution has a concentration equivalent to 250 $\mu g\,l^{-1}$, which represents an unrealistically high oceanic concentration of fluorescent material, and this curve is shown for reference only. For all natural solutions, the probe output voltage, $V(r)$, follows an exponential curve

$$V(r)=\lambda e^{-r}, \tag{1}$$

where r is the distance from the probe (in cm) and λ is a coefficient that depends on the concentration of the solution. In Figure 5, the response function is shown for $\lambda=0.2$, which agrees well with the curve for the live algae solution with a concentration of 51.54 $\mu g\,l^{-1}$. Such a concentration of algae represents an upper limit of the oceanic range, and therefore we consider the response function $V(r)$ for $\lambda=0.2$ to be a "worst-case scenario" in terms of the spatial averaging in the normal direction. The resolution of the CTS in terms of measured fluorescence is 5×10^{-3} ppb, which corresponds to an output voltage of 5×10^{-5} V. For $\lambda=0.2$, the response $V(r)$ equals 5×10^{-5} at $r=8.3$ cm, and so we regard that value of r as the maximum detection range of the probe. Thus, in the normal direction the probe performs a weighted average with a negative exponential weighting function given by (1).

The response of the probe for $r<0.5$ cm is not known because the experimental setup does not allow us to place a test solution closer than 0.5 cm to the sensor. We assume that the response (1) is constant for $r<0.5$ cm, i.e., $V(r)=$V (0.5) for $r<0.5$. This curve is shown as the thin line in Figure 6. The cumulative integral of the model response curve (shown as the thick line) reveals that 90% of the contribution of the measured signal comes from the first 2.4 cm in front of probe. Thus, we regard 2.4 cm to be the characteristic spatial response in the normal direction.

Spatial Resolution in the Tangential Direction

Figure 7 shows the data from the spatial resolution experiment with the fluorescent strip board. In panels (a)–(f), the probe output is plotted versus the distance which the probe has traveled relative to the leading edge of the board. The passing of a fluorescent strip in front of the sensor shows up as a peak in the output signal. In the figure, the signal is normalized by the maximum probe output voltage (2.5 V). Each panel shows the output of three runs (offset by unity) for three different distances D between the probe and the strip board: the bottom line is for $D=5$ mm, the middle line is for $D=10$ mm, and the top line is for $D=25$ mm. As the probe moves relative to the strip board (from left to right), it first encounters the strip

Table 1. Results of the range sensitivity test. LED sensor output in Volts and standard deviation (in parentheses) are shown as a function of normal distance for six solutions

Distance [cm]	Sol. 1	Sol. 2	Sol. 3	Sol. 4	Sol. 5	Sol. 6
0.5			0.207 (0.012)	0.133 (0.011)	0.132 (0.012)	0.147 (0.009)
1.0	1.918 (0.038)	0.120 (0.003)	0.168 (0.010)	0.127 (0.011)	0.122 (0.012)	0.134 (0.009)
1.5						0.118 (0.009)
2.0	0.819 (0.054)	0.110 (0.001)	0.126 (0.011)	0.115 (0.011)	0.112 (0.012)	
2.5						0.111 (0.009)
3.0	0.770 (0.060)	0.110 (0.001)	0.110 (0.012)		0.110 (0.012)	0.107 (0.009)
3.5						0.105 (0.009)
4.0	0.430 (0.007)	0.110 (0.001)				0.104 (0.009)
4.5						0.104 (0.009)
5.0	0.242 (0.002)	0.110 (0.001)				0.103 (0.009)
5.5						0.104 (0.009)
6.0	0.185 (0.002)	0.110 (0.001)				0.103 (0.009)
7.0	0.156 (0.001)	0.110 (0.001)				
8.0	0.146 (0.001)					
9.0	0.139 (0.001)					

Remarks:
Sol 1: Sodium Fluorescein solution, equivalent to 250 $\mu g\,l^{-1}$ chlorophyll *a*
Sol 2: Tap water, taken from the test tank
Sol 3: Live algae (Skeletonema costatum), 51.54 $\mu g\,l^{-1}$
Sol 4: Live algae (Skeletonema costatum), 26.72 $\mu g\,l^{-1}$
Sol 5: Bucket sample from Tokyo Bay collected at the pier of Tokyo University of Fisheries, 8.8 $\mu g\,l^{-1}$ chlorophyll *a*
Sol 6: Chlorophyll *a*, 10.5 $\mu g\,l^{-1}$

pair with the 10 mm spacing, followed by the strip pairs with a spacing of 20 mm, 30 mm, 40 mm, and 50 mm. The separation of the strips is indicated at the top of the figure. Those strips that are separated by more than 20 mm produce two distinguishable changes in amplitude (peaks) in the sensor output for all traveling speeds and for all values of D. For the strip pair separated by 10 mm, the output of the sensor is seen as a single peak for $D=5$ and 25 mm. For $D=10$ mm, the sensor output shows two peaks, but the output does not return to zero in between the peaks.

These results indicate that the sampling volume is lo-

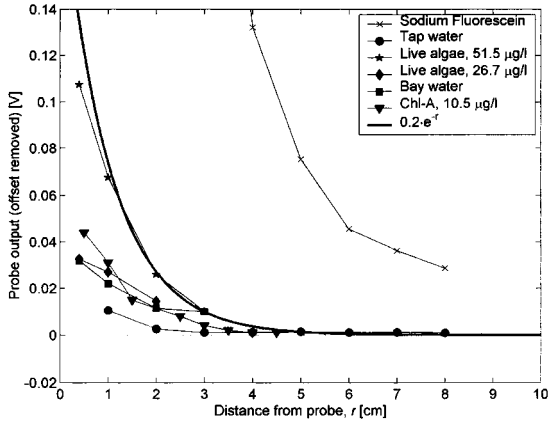

Figure 5. Range sensitivity of the chlorophyll sensor for different solutions as indicated in the inset. Values correspond to those in Table 1. For clarity of the figure, error bars are omitted. An instrument offset of 0.11 V is removed. The heavy line is the empirically determined response model of the sensor for $\lambda=0.2$.

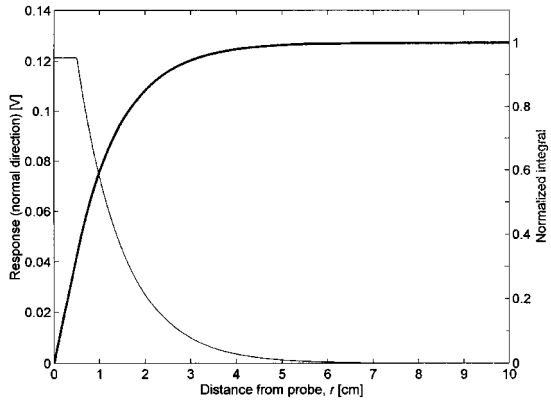

Figure 6. Model of the range sensitivity of the chlorophyll sensor (thin line) based on the experimental data. The shape of the curve corresponds to model curve shown in Figure 5 for $r\geq 0.5$, for $r<0.5$ the shape is assumed. The cumulative integral of the model (thick line) shows that 90% of the measured fluorescence comes from the first 2.4 cm in front of the probe.

cated approximately 10 mm in front of the sensor. At this distance, the probe clearly distinguishes fluorescent strips that are separated by 20 mm or more. Thus, if the signal source is approximately 10 mm in front of the probe, the probe is able to resolve spatial scales equal to or longer than 20 mm. This is true for sensor velocities up to 0.7 m s^{-1} relative to the signal source.

We conclude for the tangential direction that the probe performs a running average over a window with a total

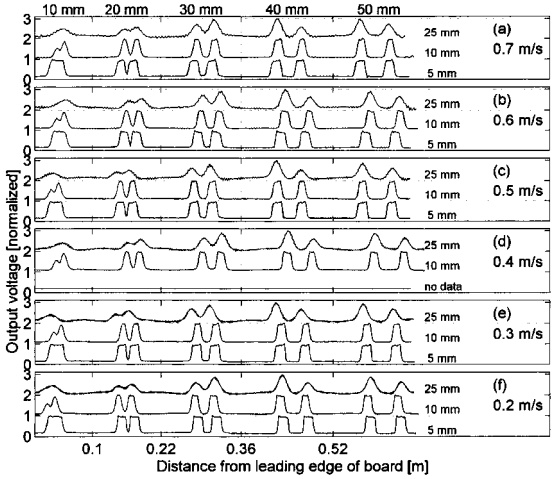

Figure 7. Panels (a)–(f) show the probe output versus distance that the probe head has moved relative to the leading edge of the fluorescent strip board (shown in Figure 2). The probe output is normalized by the maximum probe output voltage (2.5 V); the carriage speed is indicated in each panel. Each panel shows the output of three runs (offset by unity) with different distance D of the probe from the board ($D=5$, 10, and 25 mm; bottom, middle, and top line, respectively). No data are available for $V=0.4$ m s^{-1} and $D=5$ mm. Further explanation is given in the text.

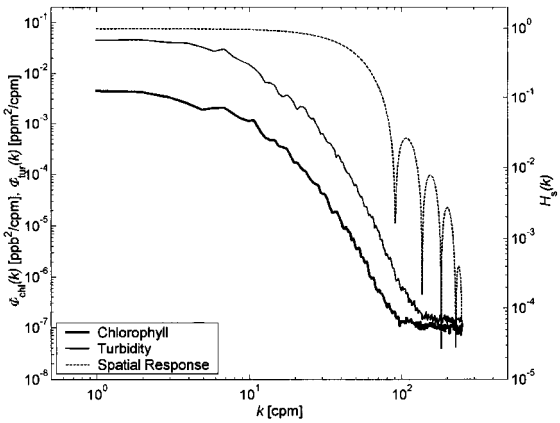

Figure 8. Spectra of chlorophyll and turbidity ($\Phi_{chl}(k)$ and $\Phi_{tur}(k)$, solid heavy and thin lines, respectively) and response function representing the spatial averaging in the tangential direction (dashed line).

width of 20 mm. Since the light intensity must decrease gradually away from the focal point of the excitation beams, we assume that the averaging window has tapered edges, and choose a cosine window as a model for the window function. This agrees well with observed spectra characteristics of measured field data (see below). The

exact shape of the taper is ultimately not important.

Field Test

During a field test carried out in a tidal channel in the Seto Inlet in Hiroshima, Japan, the CTS probe is mounted on the free-falling instrument TurboMAP. The probe's output voltage is sampled at 256 Hz and digitized using a 16-bit A/D converter. Shown in Figure 8 are the spectra of chlorophyll (heavy solid line) and turbidity (thin solid line) of a single profile of the water column between 5 and 45 m depth. The spectra are computed by averaging the power spectra of 81 half-overlapping, 2-second segments, and so they represent the average over the 40-m depth range.

Both spectra clearly roll-off towards higher wavenumbers and the slope of the roll-off increases with increasing wavenumber until the spectra reach a clearly defined noise floor. The dashed line in Figure 8 represents the wavenumber response of a running average filter for a cosine window of width of 20 mm, which we take as a model of the spatial response function of the probe. Clearly, the roll-off of the chlorophyll and turbidity spectra begins before the spatial averaging affects the signal. In addition, for wavenumbers smaller than approximately 60 cpm, the spectral slope is steeper than that of the response function, which shows that the spectral roll-off is not caused by attenuation due to spatial averaging of the probe.

Summary

From the described laboratory experiments, we were able to establish that the underlying principle of the CTS probe is suitable to detect chemical as well as naturally occurring fluorescent sources and to accurately measure their concentrations. This was demonstrated for both chemical and biological fluorescent sources at varying concentrations.

The probe performs a weighted average over a normal distance of maximal 83 mm, where 90% of the signal contribution comes from the first 24 mm. This was shown for a live algae solution with a concentration of $51.54\,\mu g\,l^{-1}$. Furthermore, it was shown that the probe could distinguish two fluorescent sources that are separated by 20 mm or more, moving past the sensor tangentially. Thus, in the tangential direction, the probe performs a moving average over a 20 mm cosine window. The sampling volume of the probe can be imagined as a cylinder of radius 10 mm and length 24 mm.

In summary, we conclude that the presented sensor is able to accurately quantify in situ concentration levels of chlorophyll and turbidity over the oceanic range, and to resolve spatial variations of these parameters on scales as small as 20 mm.

Acknowledgements

This study was supported by a Grant-in-Aid for Scientific Research C (10640421) and Alec Electronics Co., Ltd. The authors are indebted to Dr. Y. Tanaka and Dr. T. Ishimaru for stimulating discussions and for letting us to use their lab facilities; to Mr. Takuo Omura who managed the phytoplankton culture; and to Mr. Tsuyoshi Matsumura and Ms. Naho Horimoto for useful advice and technical assistance. Thanks are also extended to Prof. Y. Yamaguchi who provided the chlorophyll *a* extract, and to two anonymous reviewers for constructive comments and advices on an earlier version of the manuscript. We also thank Dr. T. Cowles (Oregon State University) for his useful comments during the development of the probe. L. Seuront is supported by a postdoctoral fellowship from the Japan Society for the Promotion of Science and a Monbu-sho Grant-in-Aid for JSPS Fellows (99756).

References

1) C. S. Davis, G. R. Flierl, P. H. Wiebe, and P. J. S. Franks: Micropatchiness, turbulence and recruitment in plankton. *J. Mar. Res*., 49, 109–151 (1991).
2) T. J. Cowles, R. A. Desiderio, and M. E. Carr: Small-scale planktonic structure: persistence and trophic consequences. *Oceanography*, 11, 4–9 (1998).
3) C. Marrase, E. Saiz, and J. M. Redondo: Lectures on plankton and turbulence. *Sci. Mar.*, 61, 1997, 238 p.
4) H. Yamazaki, D. L. Mackas, and K. L. Denman: Coupling small-scale turbulent processes with biology, in 「The Sea, Biological-Physical Interactions in the Ocean」 (ed. By A. R. Robinson, J. J. McCarthy, and B. J. Rothschild), Vol. 11, in press.
5) R. A. Desiderio, T. J. Cowles, and J. N. Moum: Microstructure profiles of laser-induced chlorophyll fluorescence spectra: evaluation of backscatter and forward-scatter fiber-optic sensors. *J. Atmos. Oceanic Tech.*, 10, 209–224 (1993).
6) F. Wolk, H. Yamazaki, L. Seuront, and R. G. Lueck: A new free-fall profiler for measuring biophysical microstructure. *J. Atmos. Ocean. Tech*. (submitted).
7) J. D. H. Strickland and T. R. Parsons: A practical handbook of seawater analysis. *Bull. Fish. Res. Bd. Can*., 167, 1972, 310 p.
8) T. Ogata, T. Ishimaru, and M. Kodama: Effects of water temperature and light intensity on growth rate and toxicity change in Protogonyaulax tamarensis. *Mar. Biol*., 95, 217–220 (1987).
9) R. Suzuki and T. Ishimaru: An improved method for the

determination of phytoplankton chlorophyll using *N*,*N*-Dimethylformamide. *J. Oceanogr. Soc. Japan*, 46, 190–194 (1990).
10) G. M. Jenkins and D. G. Watts: Spectral analysis and its applications. Holden-Day, San Francisco, 1968, 525 pp.
11) J. H. Zar: Biostatistical analysis. Prentice-Hall International, Englewood Cliffs, 1996, 662 pp.
12) F. P. Chavez, K. R. Buck, S. K. Service, J. Newton, and R. T. Barber: Phytoplankton variability in the central and eastern tropical Pacific. *Deep-Sea Res. II*, 43, 835–870 (1996).
13) J. M. Brylinski, C. Brunet, D. Benley, G. Thoumelin, and D. Hilde: Hydrography and phytoplankton biomass in the eastern English Channel in spring 1992. *Estuar. Coast. Shelf Sci*., 43, 507–519 (1996).

小型クロロフィル・濁度計の空間解像度について

ファビアン ヴォルク [*1] ・ローレン ソーロン [*2] ・山崎秀勝 [*2]

([*1] アレック電子株式会社
[*2] 東京水産大学海洋環境学科)

我々は高解像度の蛍光光度および濁度を測定することのできる光学センサーを開発し，空間解像度がどの程度であるのか明らかにするため室内実験を行った。このセンサーはサンプル空間を乱すことなく，自由落下型の乱流観測装置などに搭載することが出来ることが特徴である。実験水槽における検定によりセンサーの解像度は 0.02 m であることが判明した。この論文では海洋の濁度と蛍光光度のスペクトルの実測値も紹介する。

キーワード：植物プランクトン，生物光学センサー，微細構造