ANALYSIS OF ALOPE DATA FROM SUPERFLUX

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SUMMARY

Remote sensing data collected with the Airborne Lidar Oceanographic Probing Experiment (ALOPE) laser fluorosensor during the Superflux I (March 17, 1980) and Superflux II (June 23, 1980) experiments have been analyzed using two techniques. A qualitative technique which requires no supplementary data has provided a near-real-time estimate of relative abundance of the golden-brown and green phytoplankton color groups. Contour plots developed for the June 23, 1980 mission are used to demonstrate the utility of this technique. A quantitative technique which requires supplementary data to define the attenuation coefficient provides chlorophyll *a* concentration by color group. The sum of the golden-brown and green chlorophyll *a* data yields total chlorophyll *a* values which may be compared with in situ data.

Maximum values of chlorophyll *a* concentration for the golden-brown population were 0.08 g/m^3 in the vicinity of Newport News Point for the March 17, 1980 mission. Maximum values of chlorophyll *a* concentration for the green population were 0.03 g/m^3 in the vicinity of Fort Monroe and again offshore in the region of the "Green River." As expected, the golden-brown population was dominant in the Chesapeake Bay and the Bay plume whereas the green population was dominant in shelf waters.

INTRODUCTION

The Airborne Lidar Oceanographic Probing Experiment (ALOPE) remote laser fluorosensor was used in Superflux I and II to collect data on the relative abundance and chlorophyll *a* concentrations of phytoplankton species of the golden-brown and green color groups. Two analysis techniques were used in this study. The first provides a qualitative distribution of phytoplankton between the two color groups of interest (golden-brown and green) without the need for either chlorophyll *a* sea truth or measurement of attenuation coefficient. The second provides a quantitative distribution of chlorophyll *a* by color group but requires some in situ data on attenuation coefficient to define the depth of penetration of the laser beam into the water. This paper presents both qualitative and quantitative data on chlorophyll *a* concentrations and species diversity for the Superflux missions of March 17 and June 23, 1980.

Classification errors are not discussed; however, the potential for such errors is discussed by Farmer (ref. 1). In addition, correlations between

the remote fluorosensor data and in situ cell counts have not been attempted to date. The data of Marshall (ref. 2) will provide the necessary data base for such comparisons.

SENSOR AND MISSION DESCRIPTION

The ALOPE remote laser fluorosensor, originally configured for four excitation wavelengths (see ref. 3) was modified for the Superflux missions to use only two excitation wavelengths. The dominance of the golden-brown and green phytoplankton color groups in Chesapeake Bay and adjacent continental shelf waters eliminates the need for consideration of the blue-green and red color groups. For this study, excitation wavelengths of 454 and 539 nm were selected as near optimum for discrimination between the two color groups of interest. Alternating pulses of laser light at the 454 and 539 nm wavelengths are emitted with a time separation of 1.9 seconds. Laser power varies from 2 to 5 mJ with a pulse duration of 400 n sec. Laser-induced fluorescence at 685 nm is collected through a telescope-optical filter (9-nm-bandwidth) photomultiplier tube system. Laser-off data are also collected to determine background radiance.

The ALOPE sensor was mounted in the NASA-Wallops P-3 aircraft and flown at 152-meter altitude at a nominal airspeed of 350 km/hour. The data presented here are for the James/shelf mission of March 17, 1980 (identical to the mission of June 20, 1980 as presented in fig. 2 of ref. 4) and the mapping mission of June 23, 1980 (see fig. 3 of ref. 4).

The fundamental equation defining laser-induced fluorescence (as developed in ref. 5) is:

$$F(\lambda) = K(\alpha_\lambda + \alpha_F) \frac{P_{r_\lambda}}{P_{o_\lambda}} \qquad (1)$$

where $F(\lambda)$ is the chlorophyll a fluorescence at 685 nm produced by laser excitation at wavelength λ

α_λ is the water attenuation coefficient at the excitation wavelength

α_F is the water attenuation coefficient at the fluorescence wavelength (685 nm)

P_{r_λ} is the energy received by the PMT at 685 nm

P_{o_λ} is the output energy of the laser at the excitation wavelength

K is the collected geometrical and optical terms which are constant for a given flight altitude and system

Fluorescence can be related to chlorophyll a concentration by the expression

$$F(\lambda) = \sum_i n_i \sigma_{i\lambda} \tag{2}$$

where n_i is the chlorophyll a concentration, or density of a given phytoplankton color group

and $\sigma_{i\lambda}$ is the fluorescence cross-section of a given phytoplankton color group at excitation wavelength λ

Thus, for Chesapeake Bay and adjacent shelf waters where there are two dominant phytoplankton color groups, equation (2) becomes

$$F(\lambda_1) = n_1 \sigma_{1\lambda_1} + n_2 \sigma_{2\lambda_1} \tag{3}$$

Then for the two excitation wavelengths used for the Superflux experiments

$$F(454) = n_1 \sigma_{1,454} + n_2 \sigma_{2,454} \tag{4a}$$

and

$$F(539) = n_1 \sigma_{1,539} + n_2 \sigma_{2,539} \tag{4b}$$

If σ is known, then chlorophyll a concentration can be determined from equations (4a) and (4b).

The fluorescence cross-sections of a number of phytoplankton species have been measured in the laboratory by flowing well-mixed samples through a fluorescence spectrophotometer (see ref. 5). Typical values of σ for the golden-brown and green color groups as a function of excitation wavelength are shown in figure 1. Also indicated are the two excitation wavelengths selected for the Superflux experiments. Note that the two curves are significantly different in shape, thereby permitting differentiation between the two color groups through data obtained at the two indicated excitation wavelengths.

Although environmental factors are known to effect the value of σ, the shape of the $\sigma - \lambda$ curve is not significantly affected. Thus, use of laboratory-derived cross-sections with remotely sensed data can provide an estimate of the chlorophyll a concentration by color group and a qualitative determination of the relative distribution of phytoplankton between color

groups. Limited in situ data can be used to correct the laboratory-derived cross-sections for environmental effects to provide quantitative data on chlorophyll a density by color group.

Qualitative analysis.- The qualitative approach to phytoplankton color group discrimination without the need for definition of α or sea-truth data to correct laboratory-derived cross-sections is derived from examination of the fluorescence ratio

$$R = \frac{F_{539}}{F_{454}} \tag{5}$$

Substitution of equation (1) yields

$$R = \frac{\alpha_{539} + \alpha_{685}}{\alpha_{454} + \alpha_{685}} \frac{P_{r539}}{P_{o539}} \Big/ \frac{P_{r454}}{P_{o454}} \tag{6}$$

Elimination of the α dependency of equation (6) requires examination of the α term in equation (6) over a variety of conditions. Figure 2 presents measured values of the α ratio from 20 in situ samples with α values ranging from 0.43 m^{-1} to 36.9 m^{-1} (at λ = 633 nm, ref. 3) as a function of α_{633}. The α ratio is seen to be essentially constant at a value of 0.929. Those data of figure 2 for which in situ chlorophyll measurements were available are plotted in figure 3 to demonstrate that there is no significant variability of α with chlorophyll a. Thus, equation (6) can be rewritten as:

$$R \simeq 0.929 \frac{P_{r539}}{P_{o539}} \Big/ \frac{P_{r454}}{P_{o454}} \equiv 0.929\ R^* \tag{7}$$

Remotely sensed data can then be input to equation (7) to determine fluorescence ratio.

From figure 1 (and ref. 3) it can be seen that for values of R of approximately unity, the phytoplankton are essentially all golden-browns, while for values of R of approximately 0.3, the phytoplankton are all members of the green color group. Values of R between 1.0 and 0.3 would indicate mixtures of phytoplankton of the two color groups.

Quantitative Analysis.- Quantitative determination of chlorophyll a by color group is obtained by substitution of equations (4a) and (4b) into equation (1) to obtain

$$n_1\sigma_{1,454} + n_2\sigma_{2,454} = K(\alpha_{454} + \alpha_{685}) \frac{P_{r454}}{P_{o454}} \tag{8a}$$

$$n_1\sigma_{1,539} + n_2\sigma_{2,539} = K(\alpha_{539} + \alpha_{685}) \frac{P_{r539}}{P_{o539}} \tag{8b}$$

Solution of equations (8a) and (8b) for n_1 and n_2 requires measured values of α and corrections to laboratory-derived values of σ. (In these calculations, laboratory-derived values for σ were used.) For the purposes of this study, values of α were obtained from a straight-line fit between background radiance at 685 nm (laser off) and the measured in situ values of α. Under clear-sky conditions, background radiance normalized by solar elevation angle correlates well with attenuation coefficient. For future studies, however, it is recommended that the laser-induced Raman peak be used to determine α as discussed by Hoge (ref. 6).

RESULTS

Qualitative Analysis

Equation 7 was used to generate the results shown in figures 4 and 5. Figure 4 presents results for the return leg of the March 17, 1980 James/shelf mission. As discussed previously, values of R of 1.0 indicate golden-brown phytoplankton, and values of 0.3 indicate green phytoplankton. Golden-browns are seen to dominate within the Chesapeake Bay with greens dominating offshore (from about 120 km to 180 km). The increase in relative abundance of golden-browns between 180 km and 195 km corresponds to the shelf break region.

Sufficient data were collected on the mapping mission of June 23, 1980 to generate the contour plot shown in figure 5. Golden-browns clearly dominate within the Bay ($R > 0.65$). The contour for $R = 0.43$ gives a good qualitative description of the Bay plume extending along the Virginia-North Carolina coast, and is in good agreement with other data collected on this mission. The wave-like structure (wavelength $\simeq$ 25 km) of the outer edge of the plume appears to be induced by tidal effects.

Data of the type shown in figures 4 and 5 could be generated in near real time for future Chesapeake Bay plume studies. Such data would be very useful in directing seaborne systems to sampling areas of high interest.

Quantitative Analysis

Quantitative plots of chlorophyll a for the March 17, 1980 mission are presented in figures 6, 7, and 8 for the golden-brown color group, the green color group, and total chlorophyll a, respectively. These data were obtained by solution of equations (8a) and (8b). Golden-browns are seen (fig. 6) to peak at a value of about 0.08 g/m^3 in the vicinity of Newport News Point. They decrease to zero in the range of 120 to 160 km and increase slightly in the expected region of the "Green River." In figure 7, greens are seen to be low in the Bay, then increasing to a peak of 0.03 g/m^3 in the vicinity of Fort Monroe.

Total chlorophyll a, shown in figure 8, indicates significant fine structure with clearly defined peaks at 10- to 15-km intervals from 20 to 110 km distance. These data also indicate a minimum between 130

and 150 km. Further analysis of these data, in combination with the data from other remote sensors and in situ investigations, will be required to assess the significance of these results. The four sea truth data points indicated on figure 8 show consistency between remote and in situ data within the accuracy of both techniques. The results presented in figures 6 to 8 were obtained using laboratory-developed fluorescence cross sections, σ. Future analyses should incorporate a correction to these values derived from in situ data.

CONCLUSIONS

Data generated by a dual-laser-excitation-wavelength, single-wavelength-detector remote airborne fluorosensor provide a near-real-time qualitative assessment of phytoplankton distribution by color group without the need for in situ data. Quantitative chlorophyll a concentrations by color group are obtained through the use of supplementary data to define the attenuation coefficient. It is recommended that the laser-induced Raman peak be used to determine attenuation coefficient in future studies.

Results from this study demonstrate the capability of remote laser fluorosensor systems to determine fine-scale structure both within the Chesapeake Bay Plume and in shelf waters.

References

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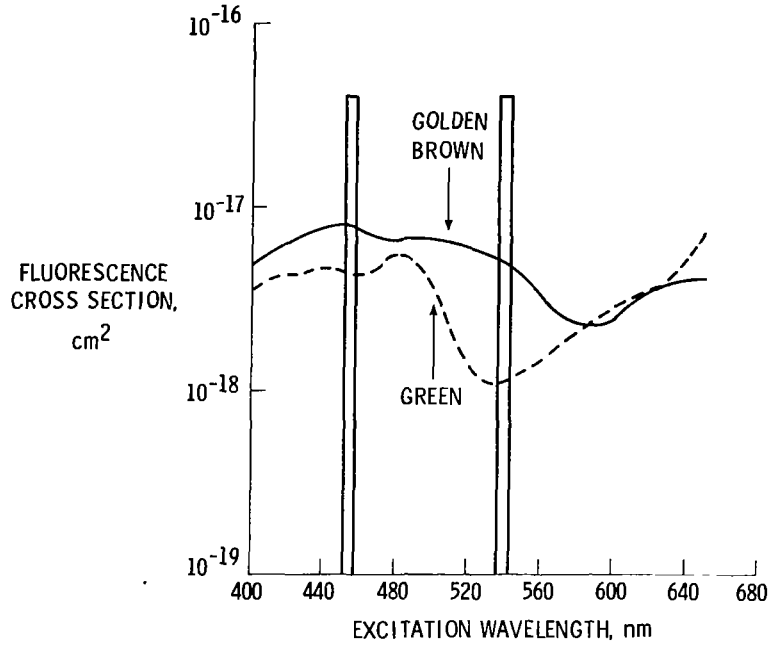

Figure 1.- Fluorescence cross-sections for single species representative of green and golden-brown phytoplankton color groups. (Vertical bars are at laser excitation wavelengths.)

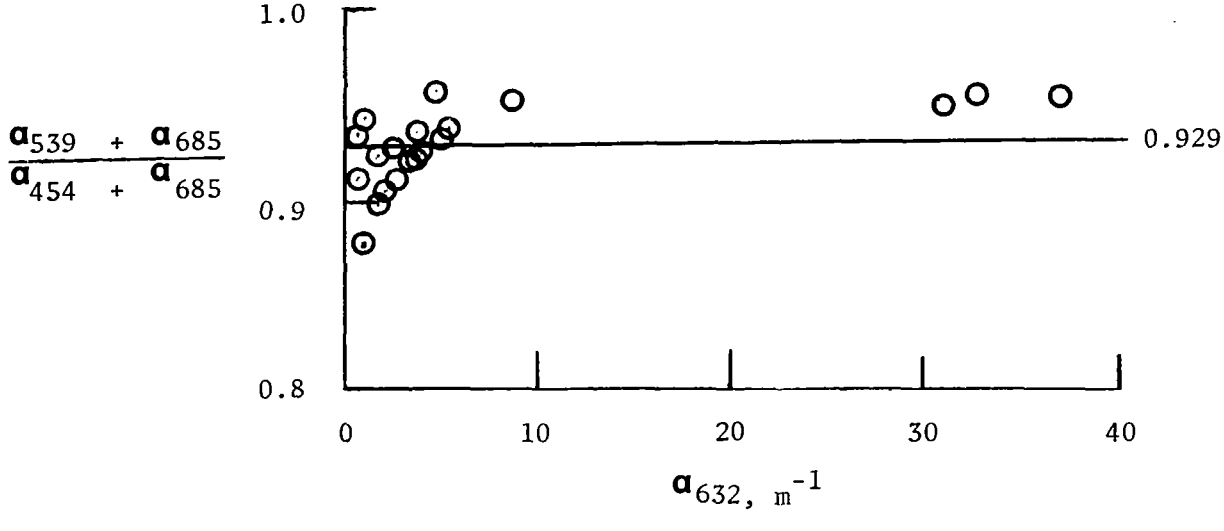

Figure 2.- In situ attenuation coefficient ratio.

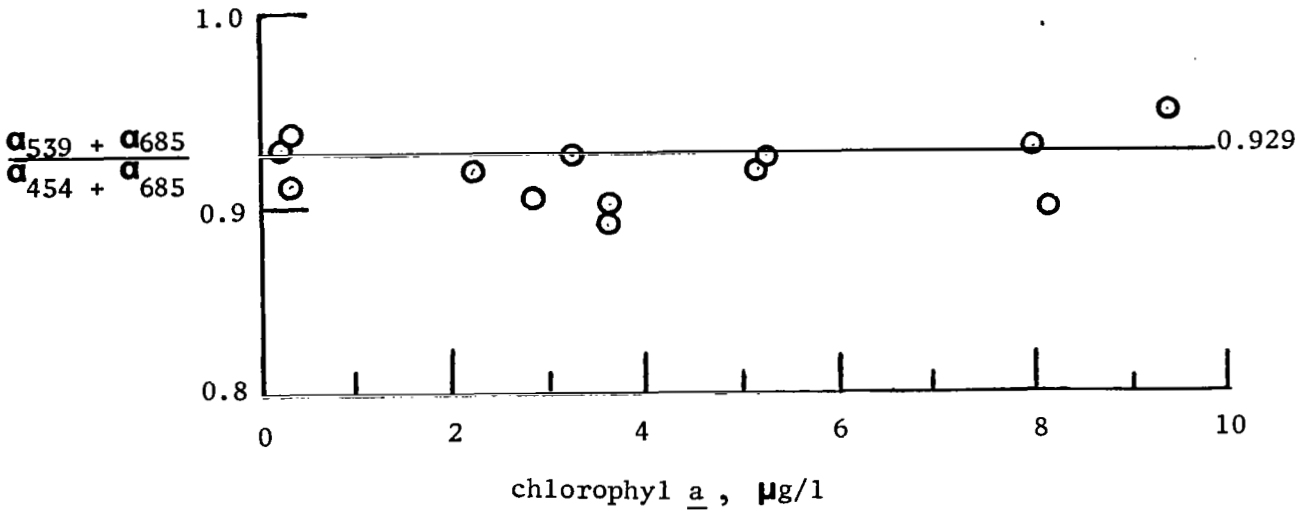

Figure 3.- In situ attenuation coefficient ratio - chlorophyll a relationship.

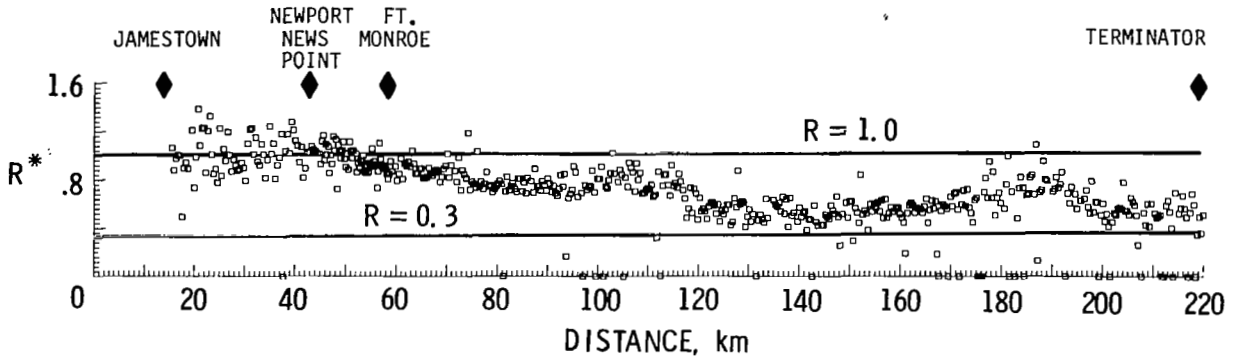

Figure 4.- Fluorescence ratio, R*, for March 17, 1980 James/shelf mission.

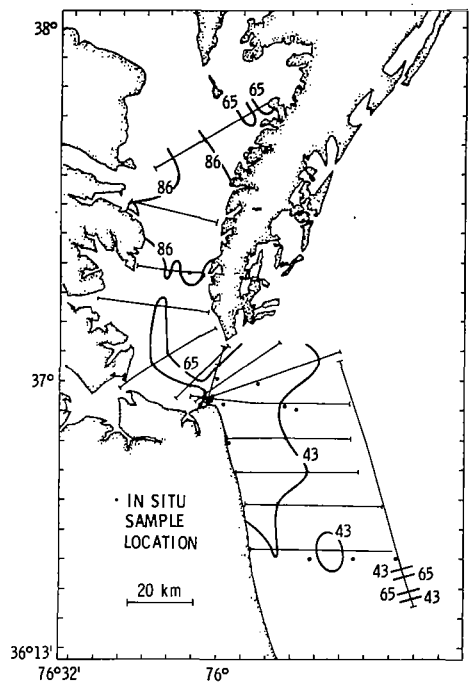

Figure 5.- Flight paths and contours from calculations of fluorescence ratios for June 23, 1980 mapping mission. (Numbers on contour lines are fluorescence ratio, R, x 10^2.)

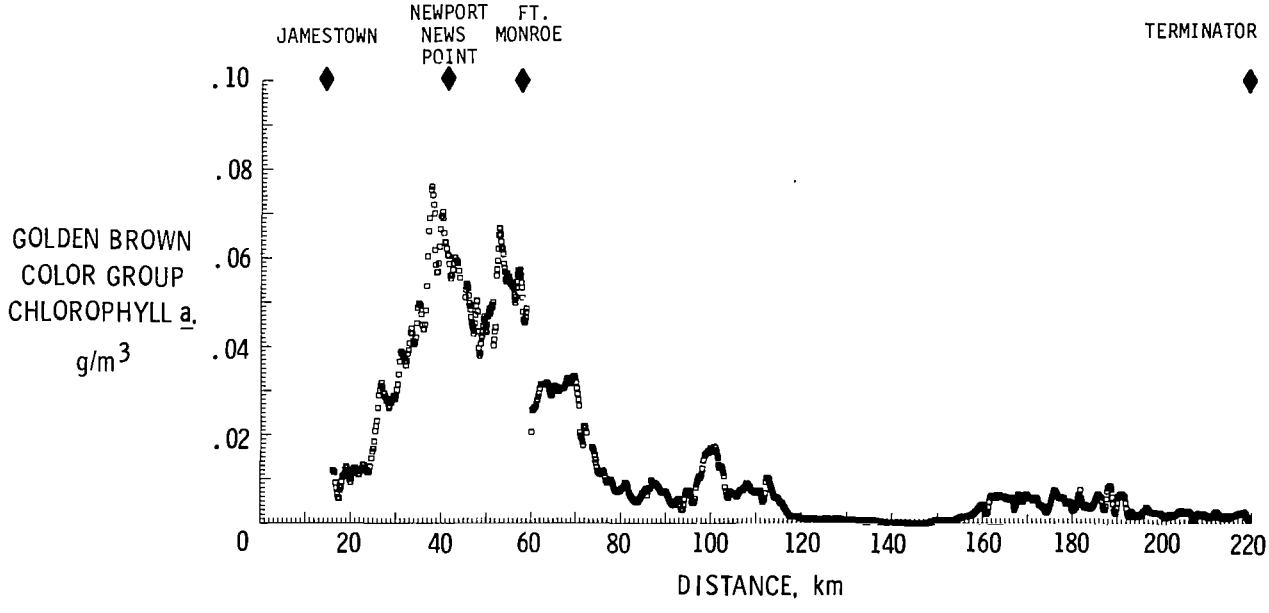

Figure 6.- Chlorophyll a density in golden-brown color group for March 17, 1980 James/shelf mission.

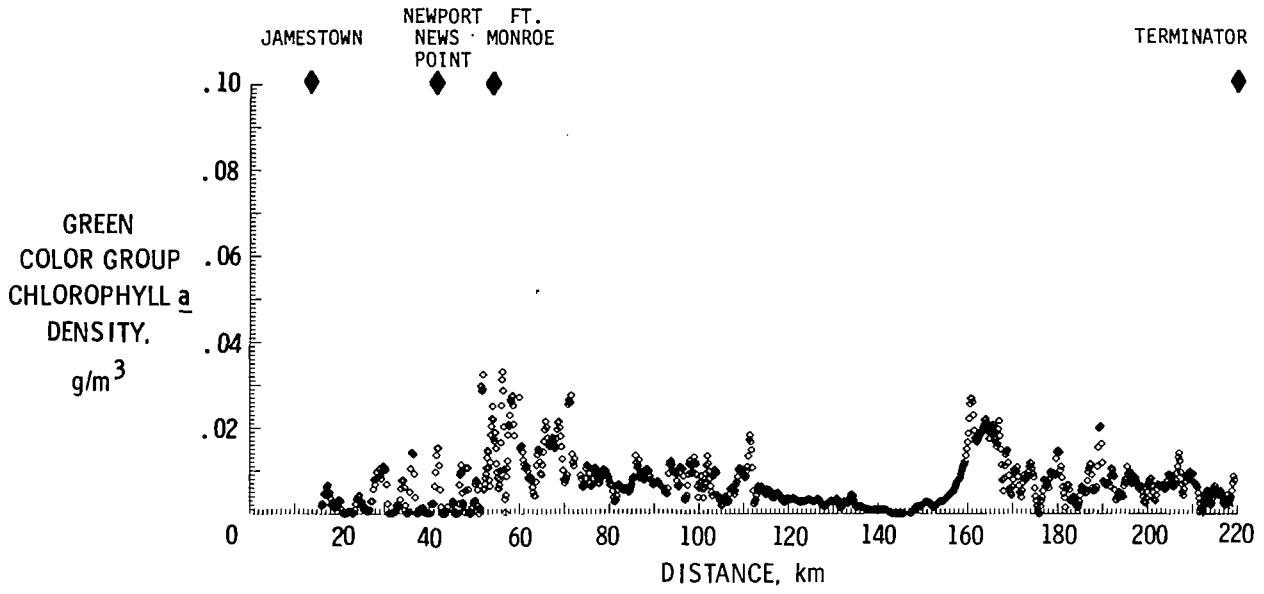

Figure 7.- Chlorophyll a density in green color group for March 17, 1980 James/shelf mission.

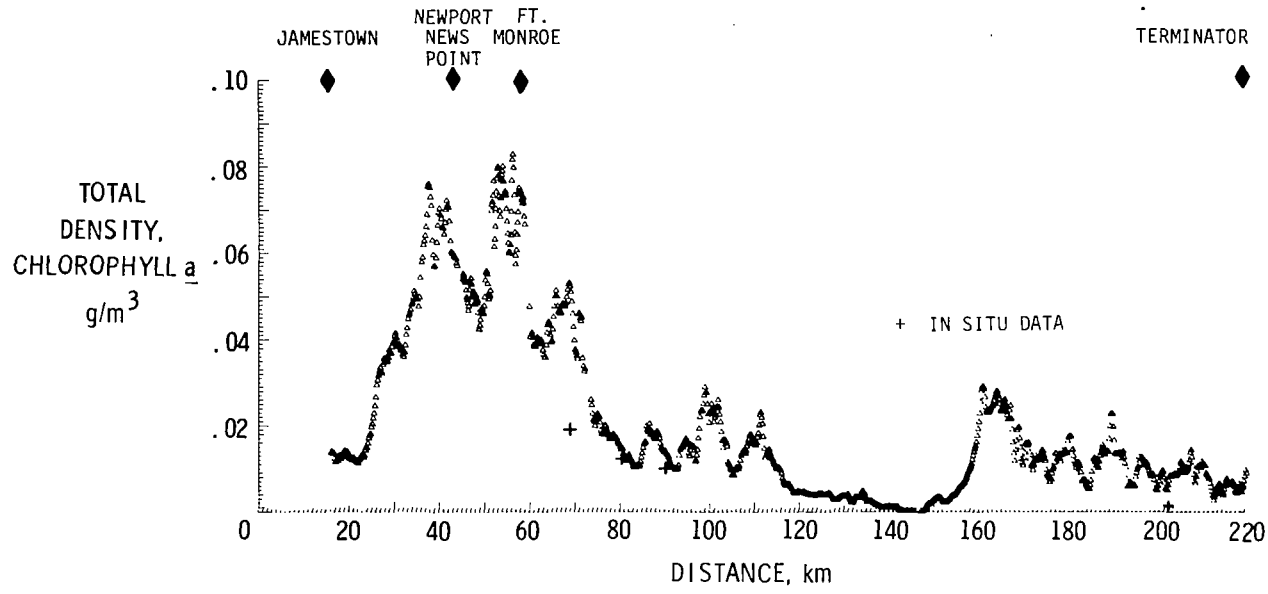

Figure 8.- Total chlorophyll a (total of data on figs. 6 and 7) for March 17, 1980 James/shelf mission.