Validation of Terra-MODIS phytoplankton chlorophyll fluorescence line height. I. Initial airborne lidar results

Frank E. Hoge, Paul E. Lyon, Robert N. Swift, James K. Yungel, Mark R. Abbott, Ricardo M. Letelier, Wayne E. Esaias

The Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Terra spacecraft contains spectral bands that allow retrieval of solar-induced phytoplankton chlorophyll fluorescence emission radiance. Concurrent airborne laser-induced (and water-Raman normalized) phytoplankton chlorophyll fluorescence data is used to successfully validate the MODIS chlorophyll fluorescence line height (FLH) retrievals within Gulf Stream, continental slope, shelf, and coastal waters of the Middle Atlantic Bight portion of the western North Atlantic Ocean for 11 March 2002. Over the entire ~480-km flight line a correlation coefficient of $r^2 = 0.85$ results from regression of the airborne laser data against the MODIS FLH. It is also shown that the MODIS FLH product is not influenced by blue-absorbing chromophoric dissolved organic matter absorption. These regional results strongly suggest that the FLH methodology is equally valid within similar oceanic provinces of the global oceans.

OCIS codes: 010.4450, 120.0280, 280.3640, 280.3420, 300.2530, 300.6360.

1. Introduction

Remote sensing of solar-induced phytoplankton chlorophyll fluorescence emission at ~683 nm has had recurring study over the past several decades.[1–8] The Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on the Terra spacecraft launched on 17 December 1999 is the first satellite realization of the chlorophyll fluorescence line height (FLH) method. The European Space Agency's Medium Resolution Imaging Spectometer, or MERIS, carries similar technology, as does NASA's MODIS, recently launched (4 May 2002) aboard the Aqua spacecraft. The satellite proliferation of solar-induced phytoplankton chlorophyll fluorescence emission spectral sensors suggests that wide-area methods be employed for their validation. It is the object of this paper to apply well-known airborne lidar methods[9–12] to validation of the Terra-MODIS phytoplankton chlorophyll fluorescence line height retrievals.

2. Instrumentation

A. Terra-MODIS

This sensor has been described.[13] The spectral bands and algorithm for retrieval of the phytoplankton chlorophyll fluorescence emission line height have been reported.[4] Chlorophyll fluorescence increases the amount of water-leaving radiance at 683 nm[14–16] that would be expected for chlorophyll-free water. The amount of this increase depends on several factors, including the specific absorption of chlorophyll, fluorescence quantum efficiency, the amount of incident sunlight, and various atmospheric effects. However, judicious choice of wavelengths tends to minimize the effects of the atmosphere. Thus the main component of the algorithm is the estimation of the increased radiance caused by fluorescence. By defining a baseline underneath the expected fluores-

F. E. Hoge (hoge@osb.wff.nasa.gov) is with the National Aeronautics and Space Administration, Goddard Space Flight Center, Wallops Flight Facility, Wallops Island, Virginia 23337. P. E. Lyon, R. N. Swift, and J. K. Yungel are with E. C. & G. Incorporated, Wallops Flight Facility, Wallops Island, Virginia 23337. M. R. Abbot and R. M. Letelier are with the College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, Oregon 97331. W. E. Esaias is with the National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, Maryland 20774.

Received 23 September 2002; revised manuscript received 29 January 2003.
0003-6935/03/152767-05$15.00/0

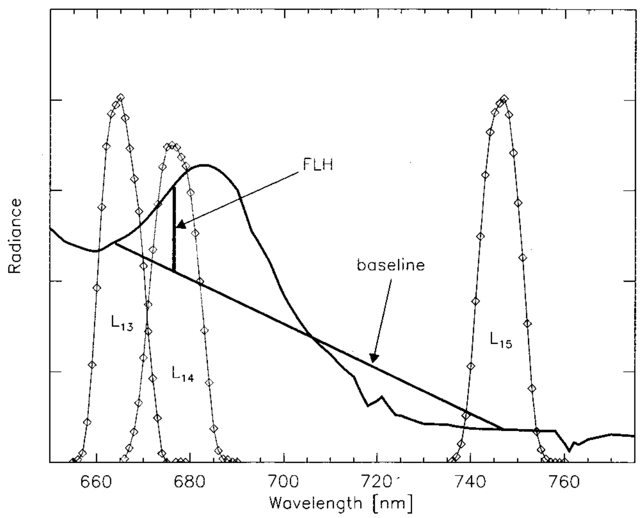

Fig. 1. Schematic of the FLH algorithm. The relative transmittance of MODIS bands 13, 14, and 15 are labeled L_{13}, L_{14}, L_{15}. The baseline for FLH measurement is established by a straight line between the radiance observed in bands 13 and 15. FLH is the radiance within band 14 that is above the baseline value. An example of FLH for a chlorophyll concentration of 10 mg/m^3 is illustrated. The fluorescence per unit chlorophyll is assumed to be 0.05 W/m^2/μm/sr per mg chlorophyll.

cence peak, one can estimate the relative contribution to the upwelled radiance field by chlorophyll fluorescence. This baseline is linear, based on MODIS channels placed on either side of the fluorescence peak. FLH is then simply the intensity of upwelled radiance in MODIS band 14 (676.7 nm) above the baseline created from bands 13 (665.1 nm) and 15 (746.3 nm). Figure 1 shows a schematic of the FLH algorithm.

B. Airborne Oceanographic Lidar (AOL)

The newest version of the AOL has been described.[12] Briefly, however, 532-nm laser pulses are transmitted vertically downward into the ocean to induce chlorophyll (and phycoerythrin pigment fluorescence emission)[17] from waterborne phytoplankton and water-Raman emission from the surrounding sea water molecules. The concurrent chlorophyll (approximately 670–690 nm) and phycoerythrin (approximately 540–595 nm) fluorescence, and water Raman spectral emissions (~645 nm) are collected by a telespectroradiometer. The pigment fluorescence signals are normalized by the water-Raman signal to remove the spatial water column variability.

Also, 355-nm laser pulses are transmitted simultaneously into an adjacent portion of the ocean to induce the broad spectrum chromophoric dissolved organic matter (CDOM) fluorescence (approximately 360–650 nm) and water Raman emission (~404 nm) from the surrounding water molecules. The CDOM fluorescence peak at ~450 nm is normalized by the water-Raman signal at ~404 nm to remove the spatial variability of the water column. The resulting CDOM fluorescence-to-Raman ratio, $F_{\mathrm{CDOM}}(450)/R(404)$, is used to calculate the CDOM absorption coefficient via a linear algorithm.[18,19]

3. Results

A. Comparison of MODIS FLH with Airborne Laser-Induced Chlorophyll Fluorescence

Figure 2 shows the MODIS solar-induced chlorophyll fluorescence line height [W/m^2/nm/sr] image of the Middle Atlantic Bight portion of the western North Atlantic Ocean for 11 March 2002. Shown is the northerly outbound flight line terminating within the northwestern portion of the Gulf Stream and the southerly inbound flight line segments returning across Gulf Stream, slope, shelf, and coastal water masses. At the time of satellite passage the airborne lidar occupied the outbound portion of the flight line. The entire airborne validation flight was conducted from 10:07 AM to 12:03 AM EST, thus some satellite–airborne disagreement is expected from water mass changes during the longer airborne mission. The annoying sensor-induced striping in the MODIS FLH image has been retained to confirm the validation under worst-case satellite data acquisition and processing conditions.

Figure 3 shows a profile plot of the MODIS FLH extracted from the image along the concatenated outbound and inbound flight track lines and plotted together with the airborne laser-induced (and water-Raman normalized) chlorophyll fluorescence. The airborne chlorophyll fluorescence regression against the MODIS FLH is shown in the rightmost panel with a correlation of $r^2 = 0.85$. Without the Terra-MODIS striping artifact the correlation would perhaps be higher. In the oligotrophic Gulf Stream at ~215 km along track location, the FLH reaches its lowest values, but the satellite–airborne agreement is still quite good albeit highly variable.

B. Performance of the MODIS FLH Algorithm in the Presence of CDOM Absorption

Figure 4 shows the MODIS FLH plotted together with the 412 nm CDOM absorption coefficient. The CDOM absorption coefficient is derived from the lidar CDOM fluorescence/water-Raman ratio.[19] The profile plot suggests that CDOM absorption produces no discernible influence on the FLH retrieval even in CDOM-laden coastal regions. This lack of CDOM influence is further corroborated by noting that (1) the FLH–CDOM correlation is only $r^2 = 0.276$ (rightmost panel) and (2) the CDOM absorption coefficient at ~683 nm is computed to be only ~1% of the 412-nm value (based on an exponential model spectral slope of 0.017/nm). The reader can further assess the general performance of the FLH algorithm by noting the typical inherent optical properties variability for the entire Middle Atlantic Bight found in published imagery.[11]

4. Discussion and Conclusions

Comparisons of Terra-MODIS chlorophyll fluorescence line height with airborne laser-induced (and

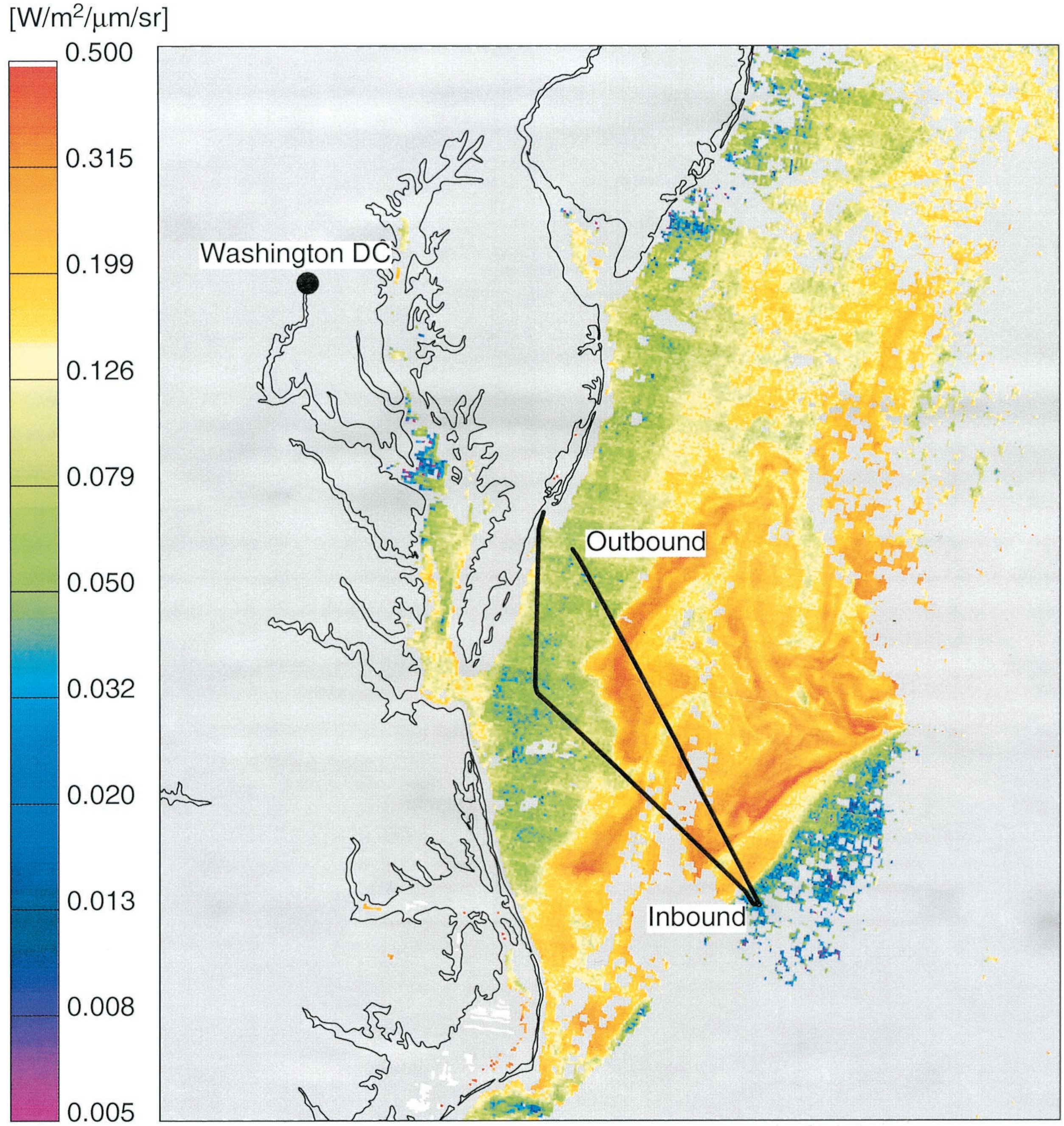

Fig. 2. Terra-MODIS fluorescence line height image of the Middle Atlantic Bight portion of the western North Atlantic Ocean for 11 March 2002. The airborne lidar occupied the northerly Outbound flight line as the satellite passed overhead. The annoying MODIS instrument artifact called "striping" is still under study but does not severely hinder the validation results presented herein. The flight lines were designed to traverse four distinct water masses: coastal, shelf, slope, and Gulf Stream.

water-Raman normalized) chlorophyll fluorescence yield very favorable correlation: $r^2 = 0.85$ in the coastal, shelf, slope, and Gulf Stream waters of the Middle Atlantic Bight portion of the western North Atlantic Ocean.

The concurrent airborne laser-induced chromophoric dissolved organic matter fluorescence comparison with MODIS FLH yields very poor correlation and suggests that CDOM absorption at 412 nm over a ~6× range of 0.03–0.19 m^{-1} has no discernible influence on the FLH retrievals in the red region. This experimental validation of the low impact by CDOM absorption at 412 nm confirms what one would theoretically expect on the basis of exponential absorption models of CDOM with a slope of 0.017/nm: ~100× less absorption at the chlorophyll emission spectral location, ~683 nm, produces little influence on the FLH retrievals.

These findings suggest that the Terra-MODIS algorithm will perform equally well in other oceanic

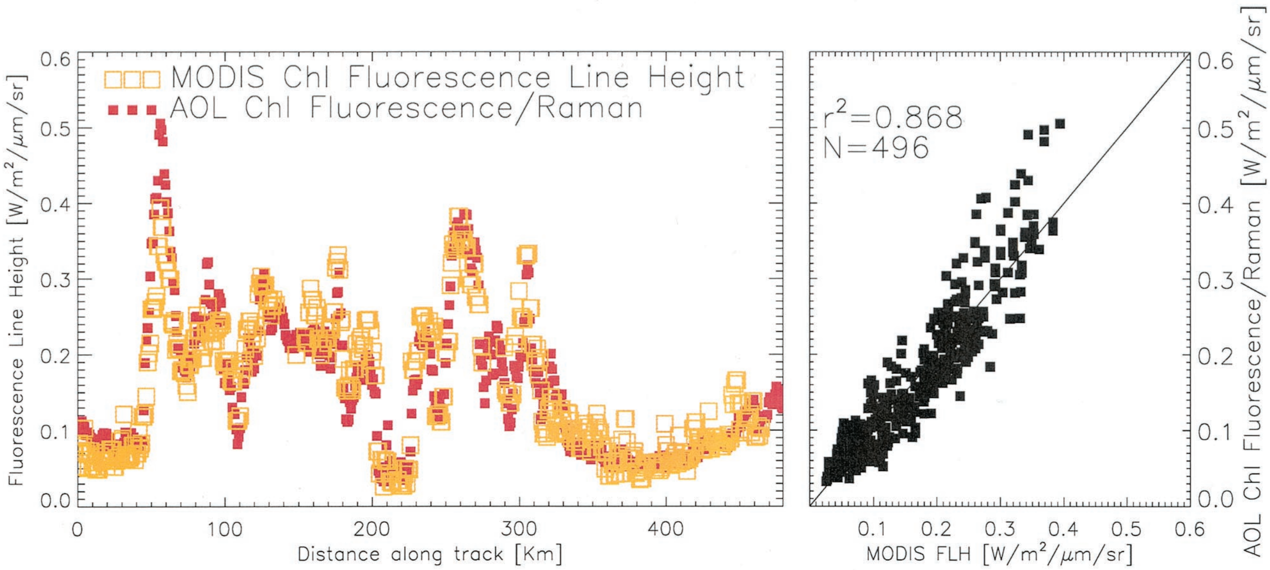

Fig. 3. MODIS chlorophyll fluorescence line height extracted from the image in Fig. 2 along the entire outbound and inbound flight track lines. The airborne laser-induced (and water Raman-normalized) chlorophyll fluorescence is also plotted for direct comparison. The regression of the MODIS FLH and airborne laser chlorophyll fluorescence in the rightmost plots yields a correlation coefficient of $r^2 = 0.85$.

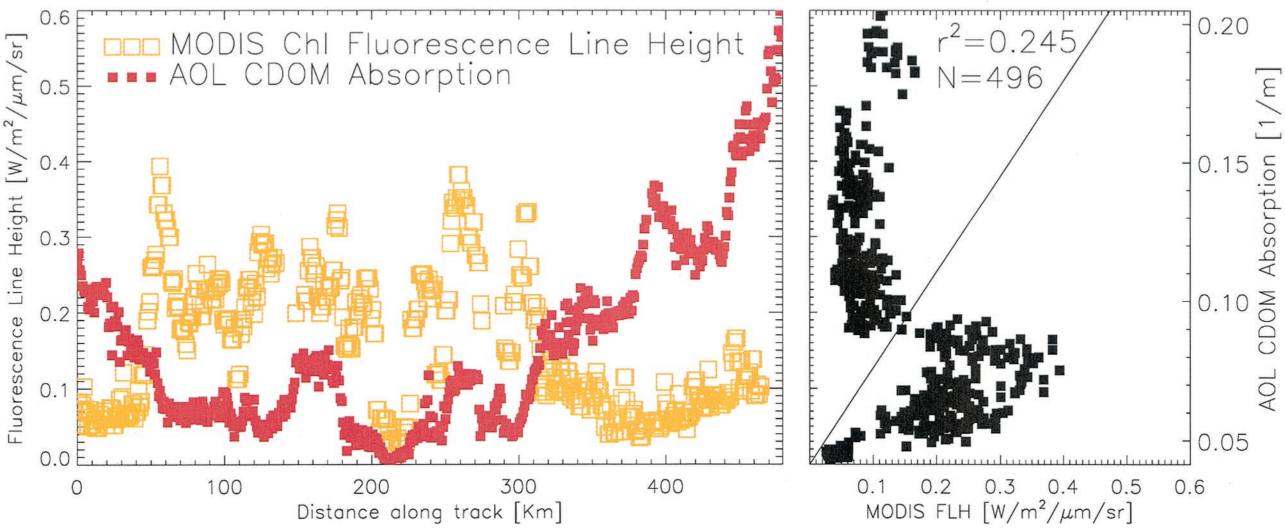

Fig. 4. Performance of the Terra-MODIS FLH algorithm in highly absorbing CDOM-laden waters. The CDOM absorption coefficient at 412 nm is derived from the lidar CDOM fluorescence/water Raman ratio.[19] The CDOM absorption coefficient at ~683 nm is ~1% of the 412-nm value and produces no discernible influence on the FLH retrievals even in the coastal region (see 460–470 Km along-track distance locations).

provinces having water types that range from coastal to oligitrophic. The results also indicate that airborne laser-induced fluorescence methods are an acceptable method for the validation of passively retrieved chlorophyll fluorescence line height. Accordingly, airborne data in other oceanic regions outside the Middle Atlantic Bight are being sought to provide additional analyses. It is also expected that future airborne underflight of Terra-MODIS contemporaneous with the newer Aqua-MODIS and MERIS satellite sensors will provide rather vibrant intercomparisons.

The continued support and encouragement of NASA's Earth Science Enterprise program is sincerely appreciated.

References

1. R. A. Neville and J. F. R. Gower, "Passive remote sensing of phytoplankton via chlorophyll-alpha fluorescence," J. Geophy. Res. **82,** 3487–3493 (1977).
2. J. F. R. Gower, "Observations of in situ fluorescence of chlorophyll a in Saanich Inlet," Boundary-Layer Meteorol. **18,** 235–245 (1980).
3. J. F. R. Gower and G. A. Borstad, "Mapping of phytoplankton

by solar-stimulated fluorescence using an imaging spectrometer," Int. J. Remote Sens. **11,** 313–320 (1990).

4. R. M. Letelier and M. R. Abbott, "An analysis of chlorophyll fluorescence algorithms for the moderate resolution imaging spectrometer (MODIS)," Remote Sens. Environ. **58,** 215–223 (1996).
5. J. F. R. Gower, R. Doerffer, and G. A. Borstad., "Interpretation of the 685 nm peak in water-leaving radiance spectra in terms of fluorescence, absorption and scattering, and its observation by MERIS," Int. J. Remote Sens. **20,** 1771–1786 (1999).
6. A. Bricaud, A. Morel, and V. Barale, "MERIS potential for ocean colour studies in the open ocean," Int. J. Remote Sens. **20,** 1757–1769 (1999).
7. J. L. Bezy, S. Delwart, and M. Rast, "MERIS-A new generation of ocean-colour sensor onboard Envisat," ESA Bull. **103,** 48–56 (2000).
8. A. M. Matthews, A. G. Duncan, and R. G. Davison, "An assessment of validation techniques for estimating chlorophyll-alpha concentration from airborne multispectral imagery," Inter. J. Remote Sens. **22,** 429–447 (2001).
9. F. E. Hoge, C. W. Wright, P. E. Lyon, R. N. Swift, and J. K. Yungel, "Satellite retrieval of inherent optical properties by inversion of an oceanic radiance model: a preliminary algorithm," Appl. Opt. **38,** 495–504 (1999).
10. F. E. Hoge, C. W. Wright, P. E. Lyon, R. N. Swift, and J. K. Yungel, "Satellite retrieval of the absorption coefficient of phytoplankton phycoerythrin pigment: theory and feasibility status," Appl. Opt. **38,** 7431–7441 (1999).
11. F. E. Hoge, C. W. Wright, P. E. Lyon, R. N. Swift, J. K. Yungel, "Inherent optical properties imagery of the western North Atlantic Ocean: horizontal spatial variability of the upper mixed layer," J. Geophys. Res. **106,** 31129–31140 (2001).
12. C. W. Wright, F. E. Hoge, R. N. Swift, J. K. Yungel, and C. R. Schirtzinger, "Next-generation NASA airborne oceanographic lidar system," Appl. Opt. **40,** 336–342 (2001).
13. W. Esaias, M. Abbott, I. Barton, O. Brown, J. Campbell, K. Carder, D. Clark, R. Evans, F. Hoge, H. Gordon, W. Balch, R. Letelier, and P. Minnett, "An overview of MODIS capabilities for ocean science observations," IEEE Trans. Geosci. Remote Sens. **36,** 1250–1265 (1998).
14. H. R. Gordon, "Diffuse reflectance of the ocean: the theory of its augmentation by chlorophyll a fluorescence at 685 nm," Appl. Opt. **18,** 1161–1166 (1979).
15. B. J. Topliss, "Optical measurements in the Sargasso Sea: solar-stimulated chlorophyll fluorescence," Oceanolgy Acta **8,** 263–270 (1985).
16. B. J. Topliss and T. Platt, "Passive fluorescence and photosynthesis in the ocean: implications for remote sensing," Deep-Sea Res. **33,** 849–864 (1986).
17. F. E. Hoge, C. W. Wright, T. M. Kana, R. N. Swift, and J. K. Yungel, "Spatial variability of oceanic phycoerythrin spectral types derived from airborne laser-induced fluorescence measurements," Appl. Opt. **37,** 4744–4749 (1998).
18. F. E. Hoge, A. Vodacek, and N. V. Blough, "Inherent optical properties of the ocean: retrieval of the absorption coefficient of chromophoric dissolved organic matter from fluorescence measurements," Limnol. Oceanogr. **38,** 1394–1402 (1993).
19. F. E. Hoge, A. Vodacek, R. N. Swift, J. Y. Yungel, N. V. Blough, "Inherent optical properties of the ocean: Retrieval of the absorption coefficient of chromophoric dissolved organic matter from airborne laser spectral fluorescence measurements," Appl. Opt. **34,** 7032–7038 (1995).