Recent advances in laser remote sensing

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ABSTRACT

Current terrestrial and hydrographic laser remote sensing research and applications are briefly reviewed. New progress in airborne oceanic lidar instrumentation and applications is then highlighted. Topics include the unique role of airborne active-passive (laser-solar) correlation spectroscopy methods in oceanic radiative transfer studies. Based on a perceived need for high resolution, improved specificity, and wider range of applicability than fluorescence methods, laser-induced resonance Raman and atomic emission spectra of oceanic constituents are suggested.

Keywords: Laser, lidar, remote sensing, airborne, satellite, oceanic, inherent optical properties, Raman

1. INTRODUCTION

Airborne laser (active) systems are presently contributing to NASA's Earth Science Enterprise (ESE) through the development and validation of satellite algorithms for the Moderate Resolution Imaging Spectroradiometer (MODIS)[1,2,3]. Such passive (solar) algorithms are used to retrieve the optical properties and constituents of the global oceans. MODIS is scheduled for launch in July 1999 aboard the Earth Observing System (EOS) AM1 platform. The EOS is the cornerstone of the observational strategy of the United States Global Change Research Program (USGCRP). In turn, the USGCRP is an integral part of the International Geosphere-Biosphere Program (IGBP) and the World Climate Research Program (WCRP).

The oceans are sinks and sources for key compounds in global biogeochemical cycles. Likewise primary production is a major factor in the global carbon cycle and a governing factor in atmospheric CO_2 balance. Ocean productivity, especially in coastal zones, fundamentally limits fish harvests and related direct societal exploitation of ocean biological resources[4].

2. GLOBAL CHANGE RESEARCH AND ACTIVE-PASSIVE (LASER-SOLAR) SPECTRAL MEASUREMENTS

2.1 Active (Laser) Spectral Measurements

Carbon cycle studies are being addressed using both shipboard laser fluorometers (SLF) and airborne oceanographic lidar (AOL) systems to develop satellite algorithms for global retrieval of optical properties and/or carbon-containing constituents (phytoplankton chlorophyll and chromophoric dissolved organic matter, CDOM)[1,2,3].

Typically a 532nm Nd:YAG laser is used to induce fluorescence emission at 683nm from the intracellular chlorophyll[5,6,7,8]. Spectra from the ship or the airborne system includes the water Raman line at ~645nm providing

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water column attenuation information[9,10]. Furthermore, the spectra include the laser-induced fluorescence of phycoerythrobilin (PEB) fluorescence at ~560nm to 585nm depending on the presence of phycourobilin (PUB) chromophores substituted at PEB chromophore sites[7]. The phytoplankton containing phycoerythrin are important since they have been shown to fix nitrogen[11], a nutrient used by phytoplankton, and can therefore limit growth.

The concurrently available 355nm UV pulsed output from the Nd:YAG laser is used to simultaneously stimulate an adjoining water parcel to yield the CDOM fluorescence whose broad peak occurs at ~450nm. This fluorescence spectral signal can be normalized by the water Raman at ~402nm. This water Raman normalized CDOM can be readily converted to the absolute absorption coefficient of CDOM, $a_{CDOM}(355)$[12,13]. Recent work[14] strongly suggests that the molar carbon can be derived from the absorption coefficient. Thus, the eventual satellite retrieval of the CDOM absorption coefficient could lead to the global satellite mapping of carbon in the upper several meters of the ocean seen by satellite. In turn the quantification of the large pool of oceanic dissolved organic carbon could lead to improved knowledge of the global carbon cycle.

2.2 Active-Passive (Laser-Solar) Spectral Measurements

Passive spectroradiometers have been flown together with airborne lidar fluorosensors to provide remarkable quantities of correlative data[2,15,16,17,18]. These data quantities are far in excess of individual-station sampling from ships[2] and allow the precise test and validation of radiative transfer models needed for passive retrieval of oceanic optical properties and/or constituents. Typically, for forward modeling, the laser chlorophyll fluorescence is converted to chlorophyll biomass and then to absorption coefficient using typical specific absorption coefficients. The water-leaving radiance is then calculated using an oceanic radiance model derived from the radiance transfer equation (RTE)[19]. Such experiments have allowed the determination of the high precision of both the RTE-based models and the airborne active-passive measurements[2]. More importantly, the passive RTE-based model can be readily inverted using matrix methods to retrieve the absorption coefficient of chlorophyll, the absorption coefficient of CDOM and the backscatter of all the constituents[20]. Using airborne water-leaving radiances, it has been recently shown that the inversions are well-conditioned and additionally can be validated by using the laser induced chorophyll fluorescence and CDOM[3]. Such passive radiance model inversions are directly applicable to satellite derived water-leaving radiances and can therefore be used to concurrently produce global maps of phytoplankton absorption and CDOM absorption both of which can be converted to molar carbon. While the algorithms for converting chlorophyll and/or CDOM to carbon are under development they are not expected to be the primary problem. The principal problem is the *accurate* removal of atmospheric radiance from the satellite measured radiances.

2.3. Metric Measurements

Global change can also be studied and potentially assessed using high accuracy short-pulse airborne lidar systems[21] to address global warming issues and the possibility of melting of polar region ice masses. Here, the ice sheet is mapped and/or profiled by airborne pulsed laser systems. The laser spot must be accurately located on the ice sheet in order to meet the necessary accuracy requirements (<20cm). Accordingly the aircraft laser system position is determined by dual frequency carrier phase Global Positioning System (GPS) receivers. A ring laser gyro inertial navigation system (INS) is used to determine and account for aircraft attitude variations. Widely separated GPS antennas further allow independent aircraft attitude information to monitor drift in INS pitch, roll, and heading. Results from flight data over the Greenland ice sheet indicate that ice surface elevations can be reliably measured to an accuracy of ~20cm and possibly ~10cm[21].

3. REGIONAL ENVIRONMENTAL CHANGE: PULSE TIME-OF-FLIGHT, SPECTRAL, AND TIME-DECAY MEASUREMENTS

3.1 Pulse-Time-of-Flight Measurements

Pulse time-of-flight measurements were among the first applications of pulsed laser systems and even today are still being applied to important environmental problems. In the 1970's and 1980's the applications to terrain mapping and bathymetry were hampered by the lack of a practical means of positioning/locating the airborne platform that carried the lidar system. Additionally, the location of the laser footprint on the surface also demanded accurate roll/pitch attitude information available then by mechanical/inertial gyroscopic systems. Today, the availability of the Global Positioning System and laser-based gyro systems has significantly improved the application of lidar systems to regional environmental problems. For example, beach erosion mapping missions over vast stretches of the California and Eastern U.S. coastlines have recently been completed[22]. Today's technology would allow past demonstrations of submerged plumes (suggestive of underwater erosion)[23] to be more accurately pinpointed and modeled. While coral reef mapping has not enjoyed the attention and success of hydrographic mapping, the threat and realities of extensive coral bleaching[24] is leading to renewed interest in establishing interagency programs to provide baseline and continuing measurement efforts as witnessed by a recent February 1999 conference in Florida[25]. The extension of pulse time-of-flight measurements to include laser-induced-fluorescence may be possible[26] but probably difficult to accomplish in the case of chlorophyll fluorescence emission at 683nm because of water-column attenuation at this wavelength. The observation of fluorescence emission at ~570nm from symbiotic phycoerythrin-containing zooxanthella may prove more viable. Finally, it is recommended that active-passive (laser-solar) methods be tested over coral reefs. Such active-passive correlation spectral correlation (APCS) methods have had considerable success in ocean color studies[2,16,17,18] most notably the development of satellite algorithm development for the retrieval of global oceanic inherent optical properties such as phytoplankton absorption coefficient, CDOM absorption coefficient, and total backscattering coefficient[3]. The application of such algorithms to satellite data is presently hindered by the lack of algorithms to accurately remove the residual atmospheric radiance contributions.

3.2. Vegetation Height Distribution and Canopy Fluorescence

The remarkable potential of airborne lidar systems to evaluate vegetation parameters such a timber volume was recognized early[27] and continues today[28]. The possibility of simultaneously assessing the health of vegetation was soon demonstrated by observing the leaf fluorescence emission together with the vegetation profile[29].

3.3 Plant Physiology

In addition to the vegetation height and leaf/canopy fluorescence, the inclusion of yet another parameter, the time decay of fluorescence[30] suggests the remote definition of plant physiology[31]. The study of these methods has led to the specification of the laser pulse energy requirements[32] and the development of leaf and canopy fluorescence models to better relate chlorophyll fluorescence and photosynthesis[33]. The instruments and techniques are undergoing more development in Europe than in the U.S.[34,35,36].

3.4 Other Spectral and Temporal Measurements

Oil spills have long been an environmental concern. Airborne lidar studies have shown that it is possible to measure the oil film thickness for thicknesses of ~4000nm[37] beyond which the laser-induced water Raman signal is too severely attenuated for reliable measurements. At that point microwave measurements are sometimes used to further infer the thickness[38]. Airborne laser-induced spectral fluorescence measurements have been used to show that the absolute oil fluorescence spectral fluorescence conversion efficiency can be retrieved from temporal decay data obtained at several wavelengths[39]. This potentially allows "fingerprinting" the type of crude using a data base of coefficients for various crude oils.

Man-made[40] and naturally occurring oceanic surface films can quite easily detected using airborne lidar systems. The detection is accomplished through the modification of the water column backscatter by the suppression of capillary/short water waves by the film[41]. Such films are also detectable by microwave radar[42].

4. ADVANCED OCEANIC LIDAR SYSTEMS

4.1 Resonance Raman Spectroscopy

The laser induced fluorescence of oceanic constituents is of course limited to those that actually fluoresce. For constituents that do not fluoresce, or are weakly fluorescent, no information is obtained by airborne laser induced spectrofluorometry. In the case of oceanic phytoplankton the carotinoids and phycocyanins are essentially inaccessible by fluorescence methods leaving only the chlorophyll and phycoerythrobilins available for study. Additionally, a very large number of oceanic constituent molecules/atoms/ions are not accessible by fluorescence methods.

Fortunately, algal carotenoids and chlorophylls have a resonance Raman spectrum[43]. Generally, resonance Raman spectroscopy (RRS) possesses[44] (1) high specificity (or molecular spectral signature), that is (2) independent of the excitation wavelength, (3) molecular signatures that are the sum of the individual components, (4) nearly independent of the state (solid, liquid, gas), (5) can be calibrated by comparison to co-existing species, (6) insensitive to water molecule quenching. RRS has been demonstrated in aqueous suspensions of marine plankton and the sensitivity and rapidity of the method suggested that it may be useful in remote sensing applications[42]. Fortunately, ground-based remote RRS systems for atmospheric research are now appearing[44] and laboratory work suggests that ground and airborne remote sensing systems may be possible for marine applications especially algal detection and identification[42]. While background fluorescence is observed in natural samples, it is not deemed a major problem[42] and methods have been suggested to mitigate the problem[45].

4.2 Laser Induced Plasma Spectroscopy

More than thirty years ago a laser-induced plasma was produced within water[46]. This phenomenon is due to electron avalanche ionization[47]. To date this method has not been applied to oceanic remote measurements. The main difficulty is that the high power densities (via small spot diameter) required to reach the breakdown threshold for ionization are proportional to the focal length of the lens[48,49]. The focal length is the remote sensing distance and the spot size rapidly grows too large to produce the needed breakdown threshold power density. New hope for airborne oceanic feasibility is provided by the recent demonstration of laser induced breakdown spectroscopy (LIBS) of terrestrial samples at distances of >25m[50]. While the ocean contains a plethora of living and dead particles and ions having a molar concentration of >1mM[51], trace elements such as iron[52] may have significant influence on global chemical cycling. Thus, the ability to measure oceanic trace elements over wide regions is of high importance. NASA's forthcoming Earth Science Enterprise Science Implementation Plan will emphasize six science areas including the Global Carbon Cycle: thus direct airborne laser sensing of elemental carbon via plasma spectroscopy may significantly assist in the development of global oceanic satellite algorithms for carbon distribution. Airborne laser-induced plasma spectroscopy offers this possibility while present laser-induced fluorescence capabilities do not.

4.3 Sound Velocity in the Ocean: Brillouin Scattering

Airborne lidar measurement of oceanic sound velocity using Brillouin scattering has not yet been announced. Recent progress in Faraday filters may provide better background noise rejection and transmission[53].

4.4 Imaging Laser Systems

Imaging laser systems are now showing more promise in underwater applications. Gated, sychronously scanned systems are already capable of ranges beyond conventional floodlight illuminated silicon intensified tube cameras[54]. The potential for retrieving 3-dimensional distributions of chlorophyll over a broad range of concentrations has also been demonstrated[55].

4.5 Earth-Orbiting Lidar

Earth-orbiting spaceborne lidars are poised to make unique contributions to earth science. The Lidar In-space Technology Experiment (LITE) has recently demonstrated the potential for measurement of stratospheric and tropospheric aerosols, multilayer clouds, planetary boundary layer, and land/water pulse return energy data[56]. A satellite-borne tree canopy lidar project[57] has recently been approved.

REFERENCES

1. Frank E. Hoge, M.E. Williams, R.N. Swift, J.K. Yungel, and A. Vodacek, Satellite retrieval of the absorption coefficient of chromphoric dissolved organic matter in continental margins, Jour. Geophys. Res. **100**, pp. 24847-24854, 1995.

2. Frank E. Hoge, Robert N. Swift, and James K. Yungel, Oceanic radiance model development and validation: Application of airborne active-passive ocean color spectral measurements, Applied Optics, **34**, pp. 3468-3476, 1995.

3. Frank E. Hoge, C. Wayne Wright, Paul E. Lyon, Robert N. Swift, James K. Yungel, Satellite retrieval of inherent optical properties by inversion of an oceanic radiance model: A preliminary algorithm, Applied Optics **38**, pp. 495-504, 1999.

4. Charles Kennel, Edward Frieman, Berrien Moore, Lisa Shaffer, NASA Earth Science Enterprise, Report of the Post 2002 Mission Planning Workshop, Easton, MD, 24-26 August 1998.

5. Frank E. Hoge and R.N. Swift, "The influence of chlorophyll pigment upon upwelling spectral radiances from the North Atlantic Ocean: An active-passive correlation spectroscopy study", Deep Sea Research **40**, pp. 265-277, 1993.

6. Frank E. Hoge and R. N. Swift, Phytoplankton accessory pigments: Evidence for the influence of phycoerythrin on the submarine light field, Remote Sensing of Environment **34**, pp. 19-25, 1990.

7. Frank E. Hoge, C. Wayne Wright, Todd M. Kana, Robert N. Swift, and James K. Yungel, Spatial variability of oceanic phycoerythrin spectral types derived from airborne laser-induced fluorescence measurements, Applied Optics **37**, pp. 4744-4749, 1998.

8. Frank E. Hoge, C. Wayne Wright, Robert N. Swift, James K. Yungel, Richard E. Berry, Richard Mitchell, Fluorescence signatures of an iron-enriched phytoplankton community in the eastern equatorial Pacific Ocean, Deep Sea Research II, **45**, pp. 1073-1082, 1998.

9. Bristow, M., D. Nielsen, D. Bundy, and F. Furtek, "Use of water-Raman emission to correct airborne laser fluorosensor data for effects of water optical attenuation", Applied Optics **20**, pp. 2889-2906, 1981.

10. Frank E. Hoge and R. N. Swift, "Airborne simultaneous spectroscopic detection of laser-induced water Raman backscatter and fluorescence from chlorophyll a and other naturally occurring pigments," Applied Optics **20**, pp. 3197-3205, 1981.

11. Douglas Capone, Jonathan P. Zehr, Hans W. Paerl, Birgitta Bergman, and Edward J. Carpenter, "*Trichodesmium*, a globally significant marine cyanobacterium," Science **276**, pp. 1221-1229, 1997.

12. Frank E. Hoge, Anthony Vodacek, Neil V. Blough, "Inherent optical properties of the ocean: Retrieval of the absorption coefficient of chromophoric dissolved organic matter from fluorescence measurements,"

Limnology and Oceanography **38**, pp. 1394-1402, 1993.

13. Frank E. Hoge, Anthony Vodacek, Robert N. Swift, James Y. Yungel, Neil V. Blough, "Inherent optical properties of the ocean: Retrieval of the absorption coefficient of chromophoric dissolved organic matter from airborne laser spectral fluorescence measurements," Applied Optics **34**, 7032-7038, 1995.

14. Anthony Vodacek, Frank E. Hoge, Robert N. Swift, James K. Yungel, Edward T. Peltzer, Neil V. Blough, "The use of in situ and airborne fluorescence measurements to determine UV absorption coefficients and DOC concentration in surface waters," Limnology and Oceanography **40**, pp. 411-415, 1995.

15. Frank E. Hoge and Robert N. Swift, "Development and validation of satellite retrieval algorithms and derived products: An emerging role for airborne active-passive (laser-solar) ocean color remote sensing," Paper 2964-06, SPIE Special Edition, Volume 2964, pp. 92-99, 1996.

16. Frank E. Hoge and R. N. Swift, "Active-passive correlation spectroscopy: A new technique for identifying ocean color algorithm spectral regions," Applied Optics **25**, pp. 2571-2583, 1986.

17. Frank E. Hoge, R. E. Berry, and R. N. Swift, "Active-passive airborne ocean color measurement: 1. instrumentation," Applied Optics **25**, pp. 39-47, 1986.

18. Frank E. Hoge, R. N. Swift, and J. K. Yungel, "Active-passive airborne ocean color measurement: 2. applications," Applied Optics **25**, pp. 48-57, 1986.

19. Howard R. Gordon, D.K. Clark, J.W. Brown, O.B. Brown, R.H. Evans and W.W. Broenkow, "Phytoplankton pigment concentrations in the Middle Atlantic Bight: Comparison between ship determinations and the coastal zone color scanner estimates", Applied Optics **22**, pp. 20-36, 1983.

20. Frank E. Hoge and Paul E. Lyon, "Satellite retrieval of inherent optical properties by linear matrix inversion of oceanic radiance models: An analysis of model and radiance measurement errors", Jour. Geophys. Res. **101**, 16,631- 16,648, 1996.

21. W. B. Krabill, R.H. Thomas, C.F. Martin, R.N. Swift, and E.B. Fredrick, "Accuracy of airborne laser altimetry over the Greenland ice sheet," Int. Jour. Remote Sensing **16**, pp. 1211-1222, 1995.

22. William Krabill, Personal communication, 1999.

23. Frank E. Hoge, C. Wayne Wright, William B. Krabill, Rodney R. Buntzen, Gary D. Gilbert, Robert N. Swift, James K. Yungel, and Richard E. Berry, "Airborne lidar detection of subsurface oceanic scattering layers," Applied Optics **27**, pp. 3969-3977, 1988.

24. J.T. Hardy, F. E. Hoge, J.K. Yungel, R.E. Dodge, "Remote detection of temperature-induced coral 'bleaching' using pulsed-laser fluorescence spectroscopy", Marine Ecology Progress Series **88**, pp. 247-255, 1992.

25. Wayne Wright, Personal Communication, 1999.

26. Mary C. Cattone, "Coral pigments: Quantification using HPLC and detection by remote sensing," NASA Contractor Report CR-97-205937, University of Western Washington, Bellingham, WA, 84pp. 1995.

27. G. A. McClean and W.B. Krabill, "Gross merchantable timber volume estimation using an airborne lidar system," Can. Jour. Remote Sensing **12**, pp. 7-8, 1986

28. Michael A. Lefsky, D. Harding, W.B. Cohen, G. Parker, and H.H. Shugart, "Surface lidar remote sensing of basal area and biomass in deciduous forests of eastern Maryland, USA," Remote Sensing of Environment

67, pp. 83-98, 1997.

29. Frank E. Hoge, R. N. Swift, and J. K. Yungel, "Feasibility of airborne detection of laser-induced fluorescence of green terrestrial plants," Applied Optics **22**, pp. 2991-3000, 1983.

30. Guido Schmuck and Ismael Moya, "Time-resolved chlorophyll fluorescence spectra of intact leaves," Remote Sensing of Environment **47**, pp. 72-76, 1994.

31. K. P. Guenther, H-G. Dahn, and W. Ludeker, "Remote sensing vegetation status by laser-induced fluorescence," Remote Sensing of Environment **47**, pp. 10-17, 1994.

32. A. Rosema and H. Zahn, "Laser pulse energy requirements for remote sensing for chlorophyll fluorescence," Remote Sensing of Environment **62**, pp. 101-108, 1997.

33. A. Rosema, W. Verhoef, J. Schroote, and J.F.H. Snel, "Simulating fluorescence light canopy interaction in support of laser-induced fluorescence measurements," Remote Sensing of Environment **37**, pp. 117-130, 1991.

34. Giovanni Cecchi, Piero Mazzinghi, Luca Pantani, Riccardo Valentini, Daniele Tirelli, and Paolo De Angelis, "Remote sensing of chlorophyll *a* fluorescence of vegetation canopies: 1. Near and far field measurement techniques," Remote Sensing of Environment **47**, pp. 18-28, 1994.

35. Riccardo Valentini, Giovanni Cecci, Piero Mazzinghi, G. Scarascia Mugnozza, G. Agati, M. Bazzani, P. De Angelis, F. Fusi, G. Matteucci, and V. Raimondi, "Remote sensing of chlorophyll *a* fluorescence of vegetation canopies: 2. Physiological significance of fluorescence signal in response to environmental stress," Remote Sensing of Environment **47**, pp. 29-35, 1994.

36. M. Methy, A. Olioso, and L. Trabaud, "Chlorophyll fluorescence as a tool for management of plant resources," Remote Sensing of Environment **47**, pp. 2-9, 1994.

37. Frank E. Hoge and R. N. Swift, "Oil film thickness measurement using airborne laser-induced water Raman backscatter," Applied Optics **19**, pp. 3269-3281 (1980).

38. William F. Croswell, J. C. Fedors, F. E. Hoge, R. N. Swift, J. C. Johnson, "Ocean experiments and remotely sensed images of chemically dispersed oil spills," IEEE, Transactions of Geoscience and Remote Sensing **GE-21**, pp. 2-9, 1983.

39. Frank E. Hoge and R. N. Swift, "Experimental feasibility of the airborne measurement of absolute oil fluorescence spectral conversion efficiency," Applied Optics **22**, pp. 37-47 1983.

40. Heinrich Huhnerfuss, W. D. Garrett, and F. E. Hoge, "The discrimination between crude oil spills and monomolecular sea slicks by an airborne lidar," Int. J. Remote Sensing **7**, pp. 137-150, 1986.

41. Frank E. Hoge, "Oceanic and Terrestrial Lidar Measurements," Chapter 6, p.472, in Laser Remote Chemical Analysis., Raymond M. Measures, Editor. John Wiley and Sons, New York 1988.

42. Heinrich Huhnerfuss, Werner Alpers, Aubrey Cross, William D. Garrett, William C. Keller, Philipp A. Lange, William J. Plant, Franz Schkude, and Dale L. Dchuler, "The modification of X and L band radar signals by monomolecular sea slicks," Journal of Geophysical Research **88**, pp. 9817-9822, 1983.

43. S. K. Brahama, P.E. Hargraves, W.F. Howard Jr., and W.H. Nelson, A resonance Raman method for the rapid detection and identification of algae in water, Applied Spectroscopy **37**, pp. 55-58, 1983.

44. A. J. Sedlacek and C. L. Chen, Remote detection of trace effluents using resonance Raman spectroscopy: Field results and evaluation," Brookhaven National Laboratory, report BNL-62155; SSN No. 95-34, under Department of Energy contract N0. DE-AC02-76ch00016, 5pp., 1995.

45. A. M. Angel, M.K. DeArmond, K.W. Hanck, and D.W. Wertz, Computer controller instrument for the recovery of resonance Raman spectrum in the presence of strong luminescence, Analytical Chemistry **56**, pp. 3000-3001, 1984.

46. R. A. Barnes and K.E. Rieckhoff, "Laser induced underwater sparks," Appl. Phys. Lett. **13**, pp. 382-384, 1968.

47. C. A. Sacchi, "Laser-induced electric breakdown in water," J.Opt. Soc. B **8**, pp. 337-345, 1991.

48. Vahid Majidi, "Laser-induced plasmas, A versatile tool for chemical analysis," Spectroscopy **8**, pp. 16-24, 1993.

49. Vahid Majidi and Martha R. Joseph, "Spectroscopic applications of laser-induced plasmas," Critical Reviews in Analytical Chemistry **23**, pp. 143-162, 1992.

50. J. D. Blasic, D.R. Pettit, and D. A. Cremers, " Laser-induced breakdown spectroscopy for remote elemental analysis of planetary surfaces," Los Alamos National Laboratory Report LA-UR-92-3940 DE93 003865, submitted to International Symposium on Spectral Sensing Research, Maui, HI, Nov. 15-20, 11pp., 1992.

51. Kenneth S. Johnson, Kenneth H. Coale, and Hans W. Jannasch, "Analytical chemistry in oceanography," Analytical Chemistry **64**, pp. 1065-1075, 1992.

52. John Martin, et al., "Testing the iron hypothesis in ecosystems of the equatorial Pacific Ocean," Nature **371**, pp. 123-129, 1994.

53. Edward S. Fry, "Lidar remote sensing of sound velocity in the ocean," Report No. 3249, Texas A&M Research Foundation, College Station, TX; sponsored by Office of Naval Research, Arlington VA, 36 pp., 1996.

54. Mike L. DeLong and Tom J. Kulp ,"Underwater laser imaging system (UWLIS)," Document UCRL-JC-120534, March 1995, Lawrence Livermore National Laboratory under U.S Department of Energy contract W-7405-ENG-48, for submittal to Symposium on Autonomous Systems in Mine Countermeasures, Monterey, CA April 4-7, 1995.

55. Jules S. Jaffe, "Underwater imaging studies," Report MPL-U-11/96, Marine Physical Laboratory, University of California San Diego, Scripps Institution of Oceanography for Office of Naval Research Grant N00014-94-1-0087, Nov 1996.

56. Dave M. Winker, "Cloud distribution statistics from LITE," Proceedings of the Nineteenth International Laser Radar Conference, Part 2, pp. 955-958, July 1998.

57. R. Dubayah, J.B. Blair, J.L. Bufton, "The vegetation canopy lidar mission," In Land Satellite Information in the Next Decade II: Sources and applications, ASPRS, Washington, DC, pp. 11-12, 1997.