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Feasibility of Airborne Detection of Laser-induced Fluorescence Emissions from Green Terrestrial Plants

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Feasibility of airborne detection of laser-induced fluorescence emissions from green terrestrial plants

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Recent experiments conducted with the NASA airborne oceanographic lidar (AOL) have shown that laser-induced fluorescence (LIF) spectral emissions from green terrestrial plants are detectable from a remote platform. A 3-MW peak power frequency-doubled Nd:YAG laser at 532 nm was used from an altitude of 150 m to induce fluorescence from trees, bushes, and grasses growing on a barrier island. A companion 422-nm XeCl excimer pumped dye laser with a controlled maximum output power of 100 kW was used separately on additional passes in order to compare its effectiveness over the same test area. Slant range measurements obtained simultaneously from each laser on-wavelength return pulse provided valuable, comparative elevational information on the heights of plants and variations in terrain along the flight lines. Samples of airborne LIF color spectra obtained with 532-nm excitation and cross sectional profiles are given together with supporting spectral measurements performed on selected plant types with a laboratory laser system. While the results to date are very encouraging, additional laboratory and field tests are required to establish the utility of the airborne LIF technique for measuring the distribution of plant pigments and biomass remotely from an airborne platform.

I. Introduction

Biomass assessment and the measurement of plant pigments associated with photosynthetic processes are important aspects to both agricultural and forestry management programs. Further, the multispectral resolution of laser-induced fluorescence (LIF) has potential for plant identification, gauging crop maturity as well as for providing early warning of plant stress. Species identification of growing plants in early stages, as well as developing stages, is important for food crop inventory reporting on a local, national, and international basis. Such cultivated crop identification and reporting are used to provide estimates of world food supply and distribution. The previsual detection of plant stress would of course allow improved productivity by prompting early corrective procedures such as application of water, fertilizer, or herbicides. Additionally, the ability to discriminate among different varieties of the same species would allow regional identification of more naturally resistant strains of different cultivated food crops. In the same way citrus tree farming as well as timber crop productivity could be improved with such species, varietal, maturity, and stress identification capabilities. The significance of these potential applications is considerable and has provided the impetus for initiating the preliminary airborne experiments reported herein.

Insofar as we have been able to determine from the literature, related investigations have to date been confined to laboratory and ground-based field situations. The reported experimental techniques and/or instrumentation can principally be categorized as (a) reflectance, (b) Fraunhofer line discrimination, (c) standard or nonlaser spectrofluorometry, (d) laser-induced fluorescence spectrometry. The spectral reflectance method is a major field of study that has produced (and continues to produce) voluminous amounts of research findings published in all the major technical journals. A Fraunhofer line discriminator (FLD) has been used in a rail-mounted trucklike configuration to investigate plant water stress in lemon trees.[1] It was shown that, in the evaluation of plant water stress, the FLD method was as sensitive as standard stomatal resistance and water potential measurements. In previous FLD work it was reported that luminescence is an indicator of geochemical stress in

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plants produced by metal toxicity.[2] In a novel ground-based field study of crop differentiation involving wheat, oats, barley, corn, and soybeans, the principal Fraunhofer absorption lines were identified within high resolution spectral reflectance curves of these plant types. It was suggested that the growth stage or maturity as well as the soil contribution are the dominant factors for proper utilization of these type high resolution spectra. Furthermore, such FLD instrumentation can be configured for operation onboard aircraft and space platforms. A study has also shown that solar stimulated fluorescence of *in vivo* chlorophyll *a* in terrestrial plants could be detected using a spaceborne FLD.[3]

Standard fluorometric techniques have shown that the fluorescence induction differences between two leaf sides are essentially comparable with those of plants grown in sun and shade conditions.[4] Additionally, fluorescence induction in intact plant leaves has been used to estimate the concentration of reaction centers of photosystem II relative to total chlorophyll.[5] Chlorophyll fluorescence induction has also been applied to assess ozone-induced injury in bean leaves before visual occurrence of leaf necrosis.[6] Fluorescence spectrometry has been utilized to demonstrate that as many as six different oat cultivars may be identified using canonical analysis of the spectra.[7,8] In fact some of this fluorescence spectroscopy effort followed an earlier pilot study aimed at automatic identification of cultivars.[9] Low temperature bioluminescence has been used to study the seeds of rye grass and barley, but no differences were found between the spectra of the seeds.[10]

The major utilization of laser-induced fluorescence in the study of intact plants has been performed in Canada. Brach[11] and co-workers used remote sensing laser spectroscopy techniques in a laboratory–greenhouse configuration. A pulsed nitrogen laser (337 nm) and a cw helium–cadmium laser (441 nm) were used to investigate the potential for recognition of both lettuce maturity and variety. While the techniques showed promise, no conclusions regarding their ultimate application were made. Subsequent LIF experiments[12] showed that the fluorescence induced by 410-nm laser excitation of a lettuce or grass crop increased as the lettuce or grass matured. However, the same experiments indicated that the laser fluorescence technique would not discriminate between different varieties of lettuce cultivars. Later experiments on grain crops[13] showed that the fluorescence quantum yield (and possibly the structure of the fluorescence spectra) could be used to differentiate between species and cultivars of a species. Additionally, the authors noted that the pigment composition determines the fluorescence yield and structure of the fluorescence spectral curve. As we shall show in this paper, similar spectral differences can be seen in the leaves from mature trees depending on the laser excitation wavelength. From their work, as well as ours, it can be seen that additional future effort must be directed toward the study of the various pigments within the plants which give rise to the observed fluorescence responses to laser excitation.

Although this paper is concerned with the study of intact leaves of higher plants, one should note that substantial progress in the investigation of phytoplankton has been made using the various techniques discussed earlier in this section. Global mapping of phytoplankton pigments in the near-surface layer of the ocean by reflectance or backscattered spectral radiance has received considerable attention.[14] Laboratory spectrometry has been used to predict the potential for success in the detection of phytoplankton luminescence with an airborne FLD.[15] Standard or nonlaser fluorometry has been used extensively to study phytoplankton.[16,17] Only recently has laser-induced fluorescence been used in phytoplankton studies. The first report of the airborne detection of phytoplankton fluorescence came about a decade ago.[18] The use of one or more lasers and multichannel detectors in the wide area mapping of fluorescence from organisms in major oceanographic features has recently been published.[19,20]

The airborne portion of this work was performed to (a) ascertain the system requirements necessary to detect laser-induced fluorescence from living terrestrial plants; (b) assess the practical acquisition of useful single-shot LIF waveforms over vegetative canopies whose effective area within the pulsed laser footprint is essentially random; (c) determine which laser system, airborne platform, and terrestrial environmental parameters are most practical; and (d) formulate a better understanding of the logistical problems associated with conducting such airborne experimental studies and ultimate routine field applications should the techniques prove feasible. The laboratory portions of these studies were performed to support the airborne investigations. In particular no published LIF spectra for 422- and 532-nm excitation could be found in the literature. Accordingly, it was necessary to select field samples along the flight line from various known trees, bushes, and grasses in order to evaluate their spectral differences. Laboratory LIF spectra of samples from water bodies encountered along the flight path were also examined to assist in the interpretation of the airborne data.

II. Instrument Descriptions

A. Airborne Oceanographic Lidar

The National Aeronautics and Space Administration (NASA) AOL is a conically scanning laser radar having a multispectral time-gated receiving capability. A number of general applications of this airborne instrument have been described for ocean surface oil detection and mapping,[21] absolute oil fluorescence spectral conversion efficiency measurement,[22] marine phytoplankton photopigment mapping experiments,[19,23] bathymetry,[24] and estuarine front delineation.[25] The two-laser configuration used in these studies has been described in a previous paper[20] and will not be repeated here. The only change in the instrument operation for these terrestrial experiments was the use of a 50-pps dye laser repetition rate on two of the flight lines that will

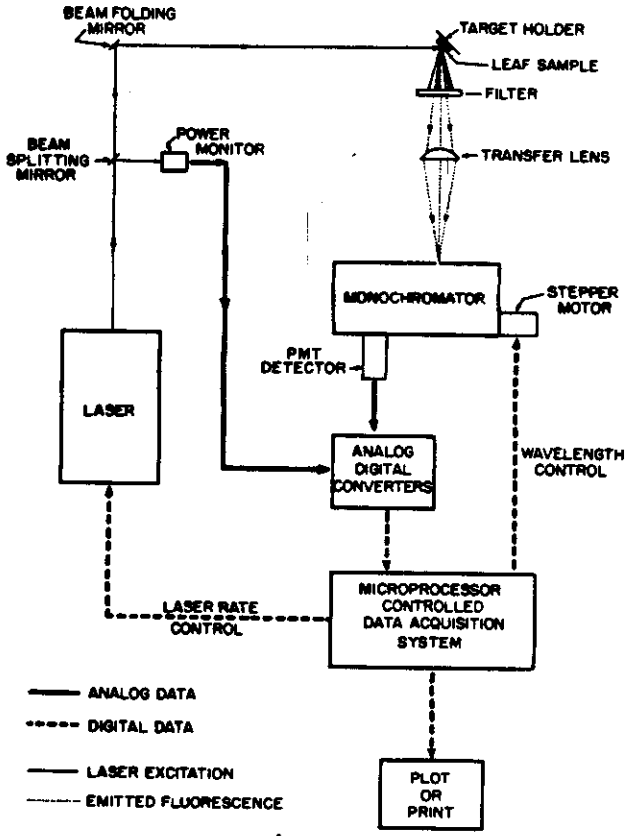

Fig. 1. Block diagram of the laboratory LIF spectrometer. The laser used in the investigations was either (a) an excimer pumped dye operating at 422 nm or (2) a frequency-doubled Nd:YAG operating at 532 nm.

be discussed. Also, we remind the reader that a Kodak 21 filter was used in front of the fluorosensor to reject the powerful 532-nm backscatter. Consequently, no fluorescence at wavelengths shorter than ~550 nm was detected with the YAG laser.

B. Laboratory Laser-Induced Spectrofluorometer

The laboratory laser spectrofluorometer is a microprocessor-controlled data acquisition system which provides fluorescence information useful in determining the feasibility of airborne experiments and also in postmission confirmation of airborne results. For the data presented in this paper, the laser spectrofluorometer was configured as shown in Fig. 1.

Two lasers were used separately during the experiments to provide excitation wavelengths which matched the excitation wavelengths used by the AOL equipment. The Lambda Physik excimer/dye laser combination was used to provide 422-nm excitation (300 kW/pulse maximum), and an International Laser Systems model NT274 frequency-doubled Nd:YAG laser provided the 532-nm excitation energy (1.0 MW/pulse maximum). The power levels were monitored throughout the experiment to ensure laser fluctuations did not adversely affect the results. Also, laser output power was adjusted with neutral density filters to ensure that the vegetation did not suffer from necrosis or burning.

The bandpass filter shown in Fig. 1 was a Schott OG550. It was used only with the 532-nm laser to reject a large portion of the on-frequency laser radiation. This filter was not needed with the 422-nm dye laser due to reduced scatter resulting in part from a smaller beam diameter. The transfer lens is an $f/3$ with a focal length of 80 mm. The monochromator is an Instruments SA model H-10 equipped with an optional microprocessor-controlled stepper motor for scanning the emission spectra. The photomultiplier housing attaches directly to the exit port of the H-10 monochromator and houses a Hamamatsu R-666S PMT. The microprocessor controls the laser repetition rate and the monochromator emission wavelength scan rate thus allowing selection of the number of laser pulses averaged over each nanometer or subnanometer interval. On each laser pulse, the microprocessor reads and records onto 20.3-cm (8-in.) floppy disks the fluorescence intensity and monochromator wavelength stepper-motor position. The data are also displayed in real time on a video monitor allowing the operator to assess data quality. Although not shown in Fig. 1, the microprocessor has a hardwired link to a minicomputer, which allows in-depth analysis of the laboratory data as well as direct comparison with the airborne spectra. Future experiments using the laboratory laser spectrofluorometer include spectral correction of the data to standards traceable to the National Bureau of Standards; investigation of reported effects of incident laser power,[26–28] repetition rate, and pulse width on chlorophyll fluorescence yield and spectral emission characteristics; and investigation of seasonal variation in terrestrial plant fluorescence.

III. Description of Laboratory Investigations

Samples of leaf vegetation from some of the more dominant species overflown by the AOL were gathered and examined using the laboratory laser spectrofluorometer described above. For additional analysis, water samples were also taken from the marsh which occupies some of the northern section of Wallops Island. Spectra from four of the plant species are shown in Fig. 2. Spectra from the marsh water is shown in Fig. 3. Figures 2(a)–(d) show to emission spectra for each plant; the uppermost spectrum was obtained using the 422-nm laser while the lowermost spectrum was obtained with the 532-nm laser. A constant bias was added to the 422-nm spectrum in order to physically separate the two plots for ease of comparison.

Two major fluorescence emission peaks (685 and 730 nm) were observed in each of the plant spectra. These peaks are attributed to the fluorescence of chlorophyll and may be an indication of the activity of different photosynthesis reaction centers in plant chloroplasts. Notice in the Fig. 2 spectra (at both laser excitation wavelengths) that the ratio of the 685-nm peak to the 730-nm peak is considerably smaller in the narrow-leaf plants (loblolly pine and dune grass) than in the broadleaf plants (black cherry and wax myrtle). This suggests the possibility that one may be able to discriminate between broadleaf and narrow-leaf plant

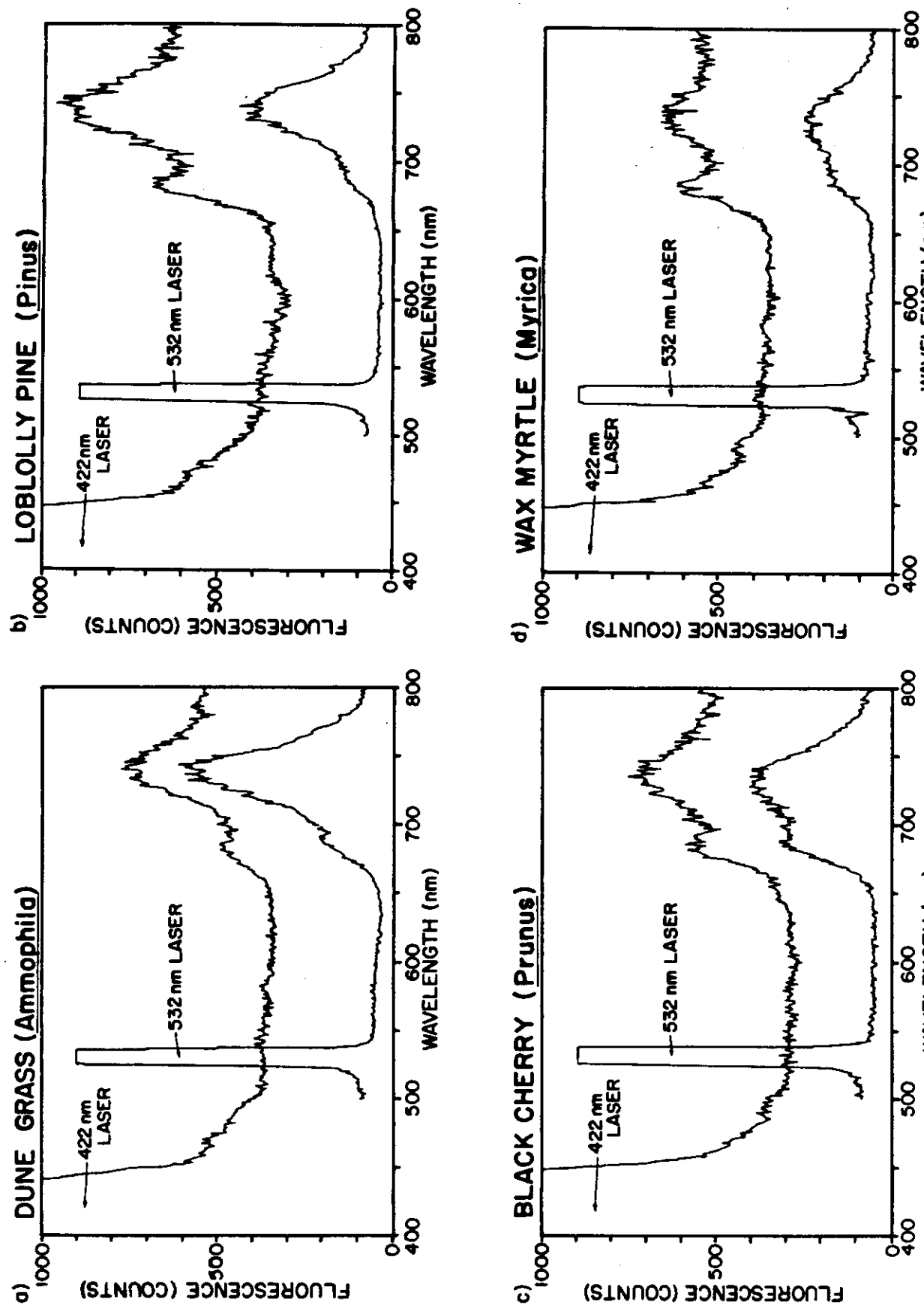

Fig. 2. Frequency-doubled Nd:YAG (532 nm) and 422-nm dye laser-induced fluorescence spectra of (a) dune grass, (b) loblolly pine needles, (c) black cherry, and (d) wax myrtle leaves. The blue excitation is a preferred wavelength since a borader and potentially more useful emission spectrum is produced.

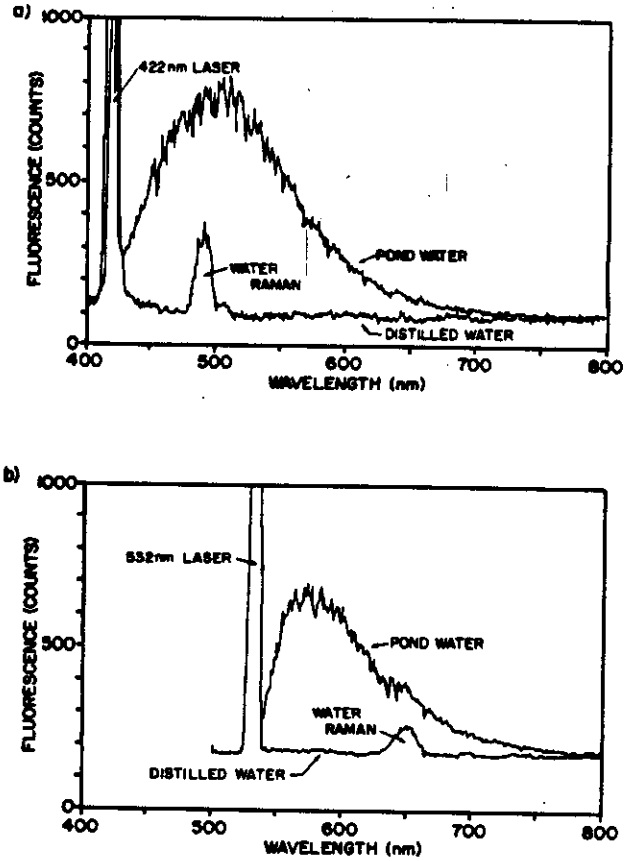

Fig. 3. (a) LIF spectrum of a Wallops Island fresh water pond sample using 422-nm excitation. The spectrum is dominated by the fluorescence from dissolved organic matter (DOM). A distilled water spectrum plotted for comparison reveals only the Raman scatter at 493 nm. (b) LIF spectrum of the same pond water using 532-nm excitation. The DOM fluorescence is so strong that the Raman scatter is virtually obscured.

types. It is recognized that there are considerable physiological differences in the structure of the leaf mesophyll in broadleaf and narrow-leaf plants.

Figures 3(a) and (b) show emission spectra of marsh water (collected from the north section of Wallops Island) resulting from laser excitation at 422 and 532 nm, respectively. The marsh water shows considerable fluorescence over a broadband (400–700 nm for the 422-nm laser excitation, and 500–775 nm for the 532-nm laser excitation). This broadband fluorescence, sometimes referred to as Gelbstoff, is associated with the presence of humic materials in the marsh water.[29] The spectra in Fig. 3 will be used to assist in the interpretation of the airborne LIF data to be discussed. A distilled water spectrum reveals only a water Raman line in each case.

The plant LIF spectral data indicate that the possibility exists of differentiating plant species. However, significant additional laboratory experiments are needed to confirm this thesis. We are continuing laboratory investigations on seasonal and stress variability to assess the full usefulness of the LIF technique for the discrimination of plant species. In addition, if the emission peaks exhibited in the laser-induced fluorescence spectra are an indication of photochemical activity, it may be possible to monitor productivity using this type of technique.

IV. Description of Field Experiment

The field experiment was conducted 3 May 1982 over the northern portion of Wallops Island, Va., which is part of the NASA Goddard Space Flight Center's Wallops Flight Facility (WFF). Wallops Island is one of a chain of barrier islands flanking the Atlantic shoreline of Maryland and Virginia. It is reasonably well protected from ocean storms by the protrusion of Assateague Island to the north and a series of shoals to the east. Vegetational coverage on the island is a quite varied assortment of plant types generally associated with barrier islands of the region.[30] The selection of Wallops Island for these tests was made for other considerations and, as will subsequently be seen, the large diversity of plant types found over relatively short spatial expanses on the island is somewhat of a disadvantage for interpreting results obtained from the airborne system at the present stage of instrument and technique development. More than fifty varieties of plants are found on both nearby Assateague and Paramore Islands. The flight lines over the test site were arranged to pass over ocean, beach, sand dunes, marsh, marsh grasses, bushes, and deciduous and evergreen trees. No conscious effort was made to include certain grasses, trees, or bushes within the flight line. Thus, a reasonably random cross section of indigenous vegetation is found along each flight track.

This field effort represents the initial attempt at obtaining fluorescence from terrestrial vegetation using an airborne laser system. As such, the laser pulse power required to obtain reasonable fluorescence from the plant pigments was essentially unknown, thus the experiment was designed to gauge laser power requirements for future missions as well as to check quality and characteristics of the airborne fluorescence spectra. The photomultiplier tube (PMT) voltage arrays utilized for the initial portion of the experiment were optimized to allow the acquisition of LIF from the strong 532-nm YAG laser. Due to the extreme disparity in power between the two lasers, usable LIF from the dye laser was not obtained on these initial passes. Two additional passes were made at the end of the experiment with only the dye laser operating and with higher PMT voltage array settings optimized for the weaker dye laser allowing sample spectra to be recovered from 422-nm excitation. The PMTs located in the 590- and 730-nm spectral region were of considerably lower sensitivity than those spanning the region around 680 nm. The increased voltage levels necessary to accommodate the fluorescence from excitation with the lower power dye laser resulted in saturation of the weaker PMTs in areas where strong LIF was encountered. The fluorescence from the 590- and 730-nm spectral regions is therefore not included in the data presented for the final two passes made with the dye laser. The PMTs located in these spectral regions have since been replaced. This modification will permit the acquisition of complete

spectra across the yellow and red spectral regions on future missions flown with either the dye laser or the YAG laser adjusted to eye-safe power levels with neutral density filters. The results from the initial pass (YAG laser) and the final two passes (dye laser) are presented separately in the next section of this paper.

The use of the higher powered 532-nm frequency-doubled Nd:YAG laser necessitated (for eye safety considerations) that the experiment be conducted over a land region which is secured from access by both public and private personnel. Accordingly, the flights were executed over controlled government property after normal work hours and just before dusk. The 422-nm dye laser output was well within eye-safe limits at the 150-m altitude flown and the transmitter beam divergence used during the experiment. As will be noted in the concluding portion of this paper, the results of these investigations indicate that ample fluorescence can be obtained from terrestrial vegetation with laser transmitters operating within eye-safe power and beam divergence levels. The major disadvantage of the low ambient light conditions at the time of this experiment was that the supporting photography and recorded video tapes were of too low a quality to allow detailed study, especially in the latter passes made over the island. We emphasize that the near-dusk experiment time was dictated by the eye-safe constraint and not a laser receiver system limitation. The AOL is equipped to operate in conditions of full sunlight in mid-latitude regions. Results acquired in normal daylight conditions have been reported for a number of marine fluorosensing investigations.

V. Airborne Lidar Results

Several passes were made over each of two separate flight lines at an altitude of 150 m using the dual laser configuration of the AOL. However, as previously discussed, only a single laser excitation wavelength was used on a particular pass. Figure 4 shows profiling data obtained with the 532-nm YAG laser on the initial pass over Wallops Island. These data were acquired at 6.25 pps and were processed with a 5-point moving average filter in order to reduce target-induced noise. Since the nominal flight speed was 100 m/sec, the spatial average resulting from this digital filter was ~80 m. Fluorescence responses obtained from channels corresponding to the chlorophyll spectral peaks at 685 and 730 nm are compared in Fig. 4(a). The 685-nm fluorescence profile is repeated in Fig. 4(b) for ease of comparison with the fluorescence signal obtained at 590 nm. Figure 4(c) shows the 532-nm on-wavelength laser backscatter signal and elevational (laser ranging) measurements, as well as target annotation developed from the photographic records obtained simultaneously. Field trips were also made to the site to verify the photographic and laser data findings. As can be seen from the elevation profile in Fig. 4(c) the heights of trees and bushes (as well as the terrain) can be metrically measured, thus providing a valuable degree of foliage identification and discrimination within itself. (High accuracy topographic mapping using the bathymetric mode of the AOL has been previously reported and the reader is referred to that publication[31] for details.) These elevation or slant range measurements may also be used to normalize the intensity of fluorescence signals to correct for differences in the distance of a respective targets from the aircraft. The elevation profile has a small amount of low frequency aircraft vertical motion contained within it. Future airborne experiments over vegetation will utilize recently developed aircraft motion removal techniques.[32] The pass is seen to begin over the ocean (Chincoteague Inlet), proceed across the island, and terminate in the salt marsh on the mainland side of the island. The on-wavelength laser backscatter profile is relatively monotonous except over the beach and the seaward side of the dune which both appear as unvegetated sand on the photographs. (More extensive investigations utilizing on-wavelength laser backscatter for target discrimination and mapping[33] with the AOL have been reported.) As would be expected, the fluorescence signals are all depressed over the beach and dune portion of the flight line. The level of signal at the 685-nm chloropyll spectral peak appears to be of approximately the same strength over the expanse of Chincoteague Inlet near the beginning of the pass as was observed over vegetation on the terrestrial portion of the transect. Also, the relative strengths of the 685- and

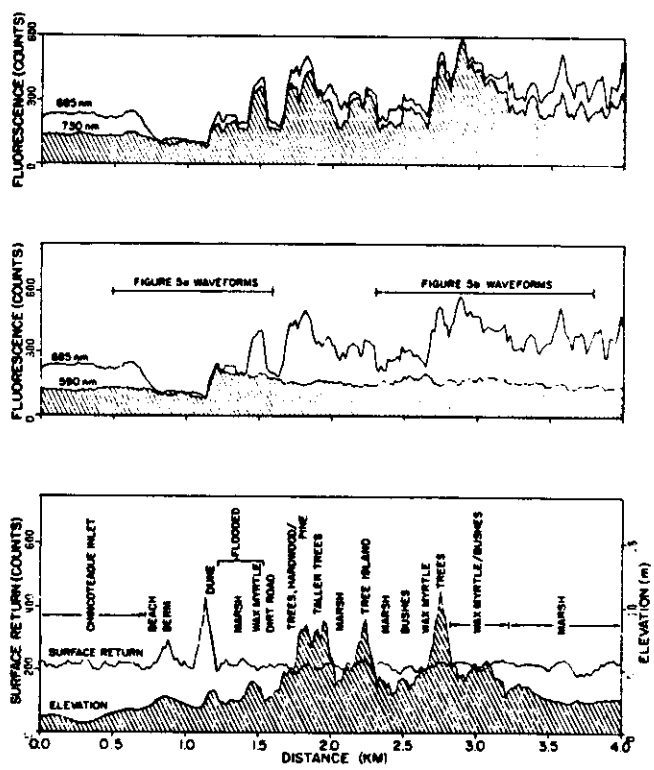

Fig. 4. Profiles of airborne 532-nm laser-induced fluorescence at (a) 730 and 685 nm and (b) 590 and 685 nm, (c) terrain elevation and on-wavelength laser backscatter (surface return). The 685-nm profile is repeated in (b) to facilitate comparison and to improve the overall clarity of the figure. Note that some of the low lying grasses and bushes yield fluorescence that is of the same approximate magnitude as sections of taller trees.

730-nm chloropyll fluorescence signal are approximately equal over the terrestrial portion of the flight line in Fig. 4(a), as was also observed in the laboratory spectra presented in Fig. 2. The 730-nm chlorophyll fluorescence response is appreciably lower than the 685-nm signal in the segment of the transect acquired over the Chincoteague Inlet. For waterborne phytoplankton, the longer wavelength tail of the chlorophyll *a* fluorescence is generally much smaller than the principal response band centered near 685 nm.[34,35] It is evident from an examination of the chlorophyll bands profiled in Fig. 4(a) and the elevational profile in Fig. 4(c) that considerable fluorescence is acquired from lower height vegetation such as grasses as well as from the higher shrubs and trees, the presence of which are indicated by inflections in the elevational profile.

There is general coherence between the 685- and 730-nm chlorophyll response profiles in Fig. 4(a). These results are consistent with the laboratory observations which showed only subtle shifts in the relative intensities of the two peaks. Likewise in the airborne data, some changes in the ratio between the 685- and 730-nm responses can be seen at various points along the transect. Owing to the high variability in plant types over relatively short spatial extents, the individual targets have not been identified, thus the significance of the observed changes in the relationship between the two chlorophyll peaks in the airborne data set cannot be verified or assessed. The 590-nm fluorescence signal in Fig. 4(b) is rather monotonous except in the area landward of the dune where higher signal is seen relative to the chlorophyll peaks. The relatively low and constant signal in the yellow spectral region over most of the vegetation covering the flight line is again consistent with results obtained with the laboratory laser system using 532-nm excitation. The LIF spectra acquired from selected plant leaves during the laboratory analysis did not indicate any notable increase in the 590-nm region (see Fig. 2). The section of the transect from which the elevated signal at 590 nm was observed contained a considerable expanse of standing fresh marsh water at the time of the experiment. Laboratory laser excitation of the coffee colored water sampled at several points yielded LIF spectra similar to the one presented in Fig. 3 which shows a significant Gelbstoff fluorescence contribution with both 532- and 422-nm excitation. It therefore appears reasonable to explain the LIF acquired with the airborne system over the flooded portion of the transect as resulting from the convolution of LIF from the living plants covering the region with LIF from the water ladened with a high organic material load that was found beneath the plants.

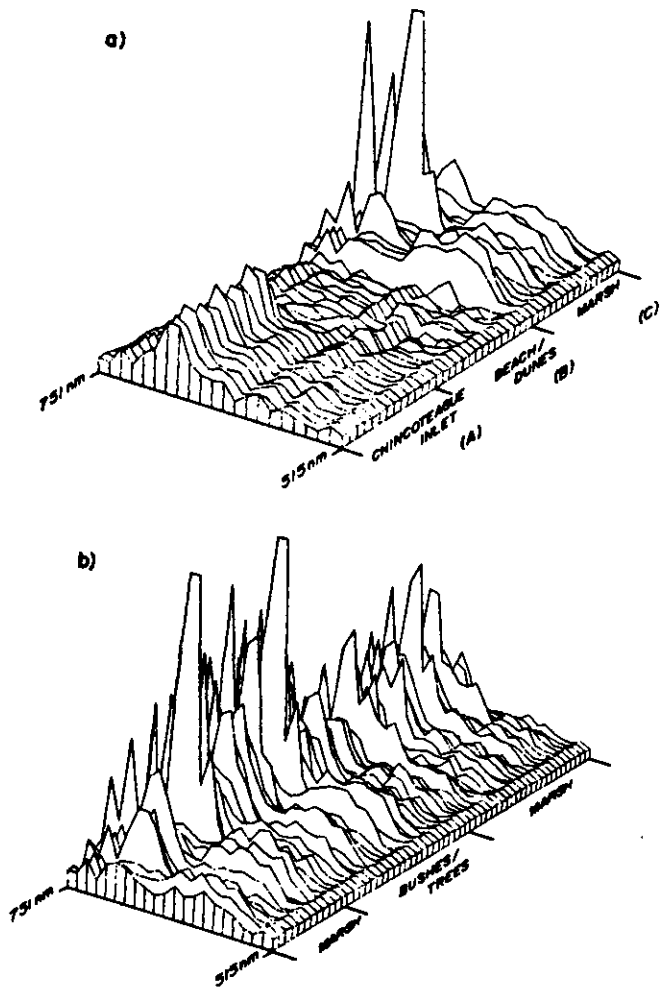

Fig. 5. (a) Individual, unaveraged LIF waveforms resulting from each single transmitted laser pulse during the water, beach, and marsh portions of the flight line shown in Fig. 4. (b) Waveforms from the marsh and bush/tree regions of the flight line are identified in Fig. 4.

Additional discrimination is potentially available by using the entire LIF waveform. Detection algorithms may be developed to allow more subtle variations to be revealed. Figure 5 shows two groups of raw or unaveraged waveforms from the respective regions labeled within Fig. 4(a). Every other waveform from each of these spans is provided in Fig. 5. Each of these LIF spectral waveforms is the result of a single laser pulse. Within Fig. 5(a) it is relatively easy to recognize the high levels of yellow fluorescence in region *A* and the elevated red fluorescence in region *C*. The pulse-to-pulse variability is primarily induced by spatial variability of the target and is not a result of system noise levels or solar background radiation. This was verified by observing with the AOL a static, fluorescent ground target during daylight hours at a distance of ~150 m. In these ground test conditions the waveform-to-waveform variability is significantly lower than was seen in the airborne data in Figs. 5(a) and (b). Our premission ground test on a 150-m distant fluorescent target yielded a rms of only ~6% of the mean at fluorescence levels comparable with those observed along the flight line. The waveform-to-waveform variability from terrestrial targets seen in Figs. 5(a) and (b) can be qualitatively compared with the variability observed in the spectra obtained from the ocean water near the beginning of Fig. 5(a) (segment *A*). However, the physical conditions accounting for the pulse-to-pulse fluctuations seen in the LIF from waterborne pigments are generally somewhat different

from those inducing the variability in the LIF from terrestrial vegetation. The higher frequency modulation observed in LIF from phytoplankton results more from the effects of water surface gravity and capillary waves than from gross differences in concentration and species over relatively short spatial extents.

Figure 6 shows elevation and 685-nm fluorescence profile data obtained with 422-nm excitation using the excimer pumped dye laser. These data have likewise been smoothed with a 5-point moving average filter to reduce noise from target variation. However since the laser was operated at 50 pps, the spatial averaging used in processing the measurements represents a distance of ~10 m. The higher laser repetition rate enabled the acquisition of increased spatial resolution in both elevation and fluorescence. This resulted in greater detail over the highly varied vegetation types along the flight line, thus a shorter 1-km segment over the central portion of the flight line has been selected for plotting in Fig. 6. Here, as noted in the previously discussed data acquired over the island with the YAG laser, there is considerable contribution to the 685-nm chlorophyll fluorescence from shorter vegetation as well as from the trees and shrubs. This can be seen by comparing the elevation and chlorophyll fluorescence profiles.

Figure 7 shows elevation and fluorescence profile data obtained with the 422-nm dye laser over a larger area adjacent to Wallops Island. The greater spatial extent and the reduced diversity of target types provides an improved test area for gauging the potential effectiveness of airborne fluorosensing for acquiring chlorophyll LIF over terrestrial vegetation. For convenience of discussion, the major areas within the flight line have been labeled and numbered in order of occurrence. These areas include brown fields (BF), plowed fields (PF), green crop covered fields (GF), stands of pine trees (PT), and stands of pine and mixed deciduous trees (MT). Abrupt breaks in the 685-nm chlorophyll signal can be observed at changes in target types, especially at boundaries between green and plowed fields and between brown fields and forests. Some variability in chlorophyll fluorescence signal level can be seen in comparing BF 1 and 2 with BF 3, 4, and 5, as well as in the intercomparisons of green fields 1–5 and the forested areas. In this initial and limited study no attempt was made to determine reasons for these differences (such as different grass heights, plant types, etc.) by examination of the targets from the ground.

One may immediately argue that the discrimination of a BF from a GF is not a particularly important result, especially since any airborne color camera could more easily perform a similar feat. However, we remind the reader that with sufficient development the laser discrimination can be performed during the darkness of night. The importance of these results is that the strength of the signal and similarity of the response patterns over targets of the same general type suggest a potential of the technique for providing data of sufficient precision for conducting biomass and other studies related to plant pigment distribution over broad areas.

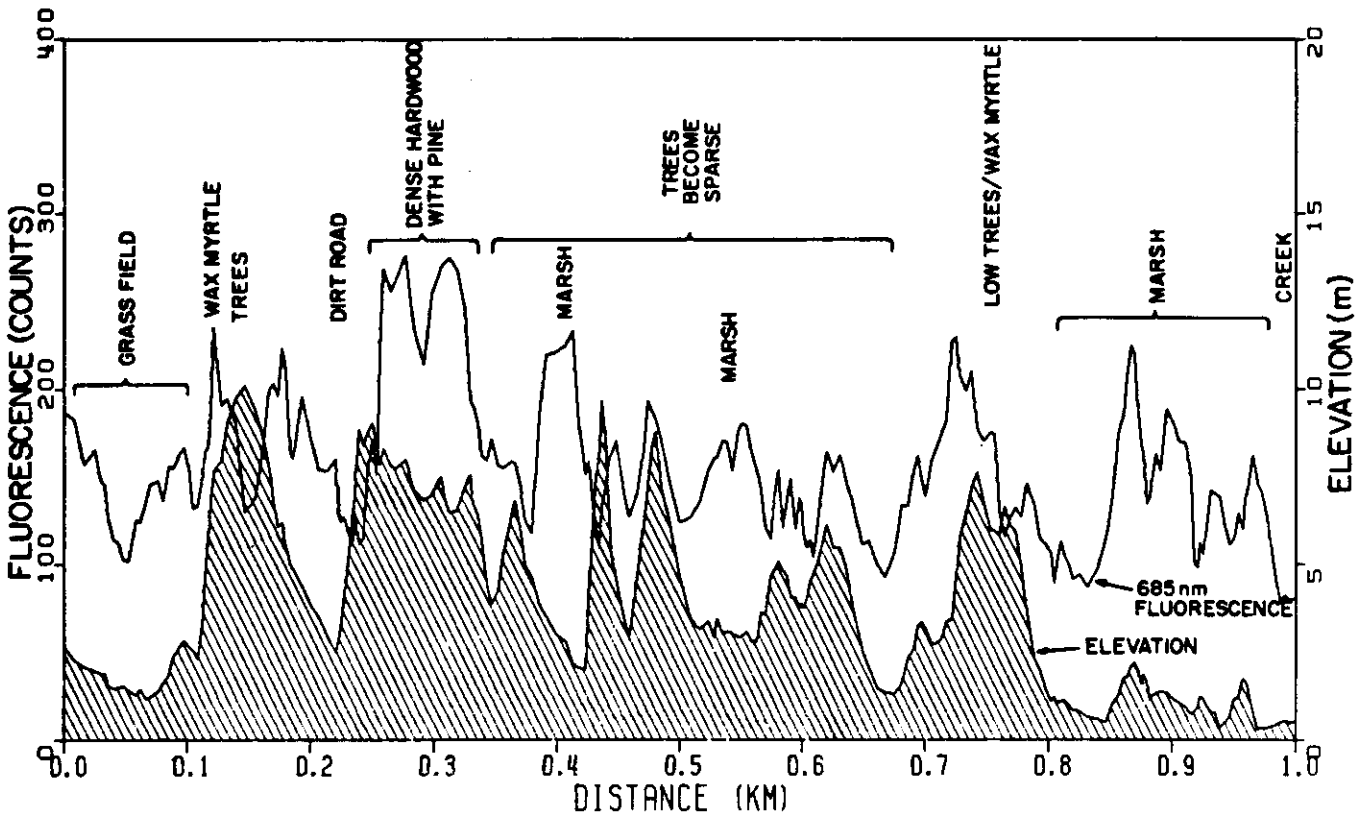

Fig. 6. Profiles of terrain elevation and 422-nm LIF emission at 685 nm.

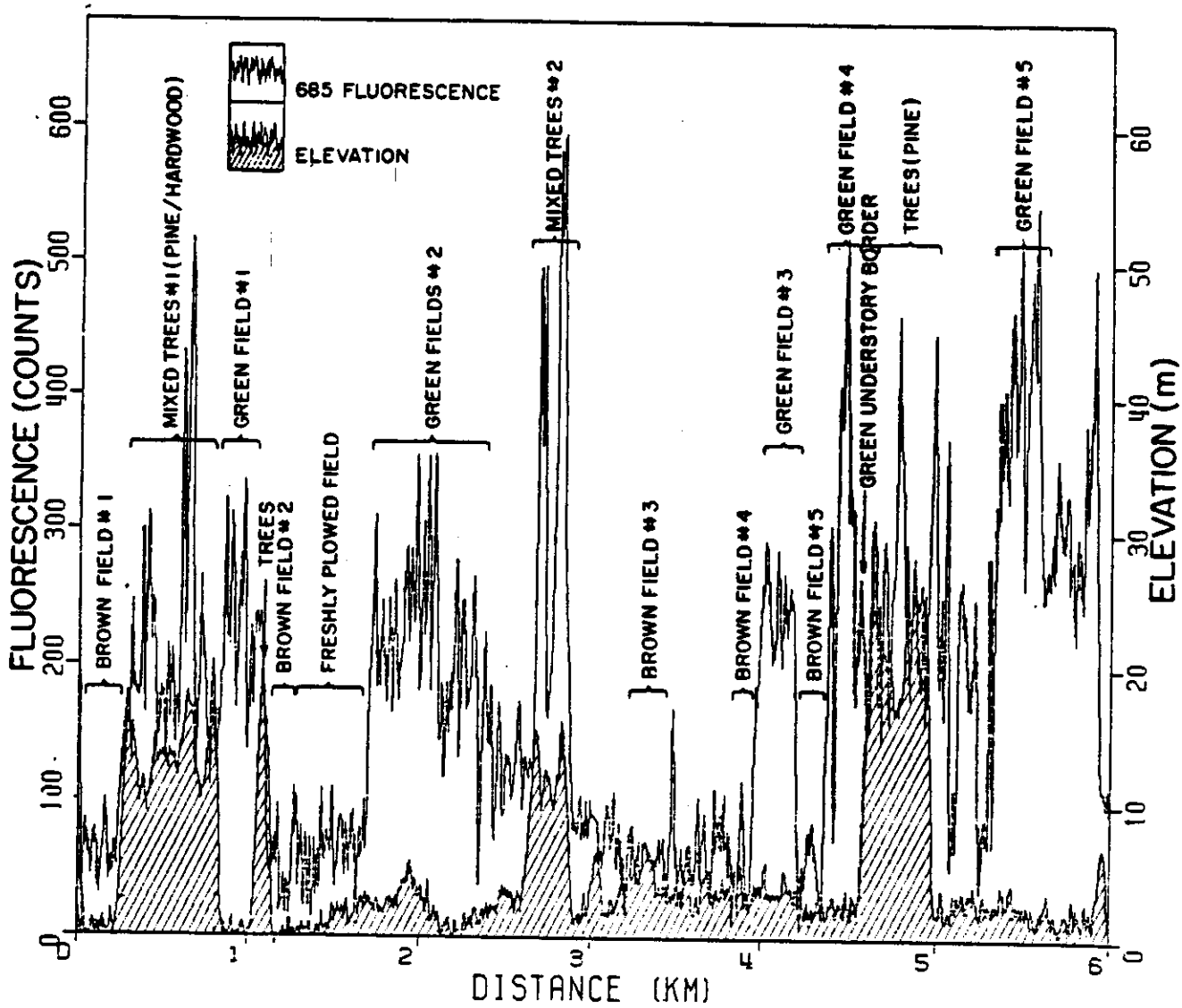

Fig. 7. Profile of 422-nm LIF emission at 685 nm obtained across various targets of fields and trees. The terrain elevation is shown by the crosshatched profile. Note that some grass covered fields yield fluorescence levels whose magnitude is approximately the same as that from the stands of trees.

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VI. Concluding Remarks and Recommendations

We have demonstrated the feasibility of the airborne detection of the laser-induced fluorescence spectral emissions from living terrestrial grasses, shrubs, and trees using existing levels of lidar technology. These initial airborne tests have further shown that the high spatial frequency of occurrence of flora in natural coastal zone habitats will dictate that the highest practical laser pulse repetition rates be used in these regions. For food and tree crops cultivated over contiguous wide areas, the pulse rates may be relaxed. However, the row crop spacing and angle-of-approach may have to be considered together with the aircraft horizontal velocity to ascertain the minimum useful laser pulse rate. It is recommended that further testing of the airborne technique be performed over larger, documented tree farms and/or agricultural sites to facilitate the unambiguous interpretation of (a) the airborne data relative to the ground targets together with (b) the comparison of the airborne spectra with laboratory LIF spectra of truth samples from the test site regions. Then the ongoing and historical knowledge of the site species, soil type, soil constituents and moisture, ambient light levels, etc. can be used to better understand some of the more important variables. It is also suggested that passive or solar reflectance data be purposely used in tandem with the laser fluorescence data. In this regard the AOL is presently being modified to essentially record passive reflectance data during the dead time between laser pulses. Thus we should be able to obtain reflectance data that encompasses the laser pulse footprint to within several millimeters.

Supporting laboratory work must be conducted to more thoroughly investigate the fluorescence spectral variations as a result of seasonal, moisture, ambient light, and nutrient changes on selected species of plants. A broader and potentially more useful spectrum can be obtained with a 422-nm laser when compared with the longer wavelength 532 nm. Since the lower power, shorter wavelength 422-nm airborne LIF efforts were successful, these wavelengths would be preferred and therefore recommended for field experiments. The lower peak power requirement is also consistent with the operation of lasers at the desired higher repetition rates. There seems to be little advantage to conducting terrestrial fluorosensing investigations with long-wavelength low repetition rate, high power lasers, the latter characteristics of which can present a noneye-safe condition.

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