Lecture 36. Target Lidar (1) Laser Induced Fluorescence Lidar

❑ Motivations for Target Lidar

❑ Fluorescence Spectroscopy

❑ Fluorescence Lidar Principles

❑ Applications of Fluorescence Lidars

      1) Marine Monitoring

      2) Vegetation Monitoring

      3) Historical Monuments

      4) Insects and Birds Monitoring

❑ Summary

Motivations to Study Targets

❑ Discussed in previous lectures concern about atmospheric lidars, with the main purposes to study the atmosphere composition, structure and dynamics. These lidars are based on the scattering processes (including elastic and inelastic scattering, absorption, and resonance fluorescence) from gas phase atoms and molecules as well as aerosols and clouds.

❑ Besides atmosphere, our environment includes many other things, like the solid earth, cryosphere, hydrosphere, and non–gas–phase objects on the earth, in the ocean, and in the air (e.g., plants, oil, buildings), etc. Study of our environment demands good measurement technologies and approaches for measurements in all sorts of occasions. Therefore, lidar technology for target (anything other than atmospheric compositions and objects) detection is essential and highly demanded.

❑ Two main categories for target lidars: (1) laser-induced-fluorescence lidars, and (2) lidars for ranging (laser range finder or laser altimeter).

❑ Laser altimeter – to monitor sea level, cryosphere and earth surfaces, vegetation distribution, military precise range determination, etc.

❑ Fluorescence lidar – environmental study of hydrosphere, solid earth, croysphere, plants, oil films on the surface, pollutant, etc.

An Ocean Lidar: LIF Measurement

❑ 3-D laser-induced fluorescence (LIF) spectra are effective for *in vivo phytoplankton classification. Laser source is* an optical parametric oscillator (OPO) with wavelength tunable from 410 to 670 nm. A PMT with 32 anodes was employed to detect 32 wavelengths. The 3D LIF spectra of 13 typical red-tide species of East China Sea were measured at OUC.
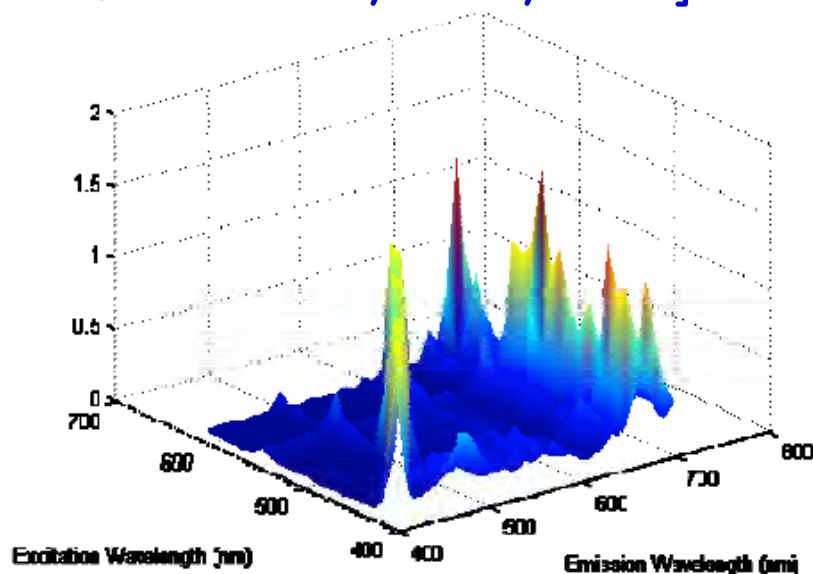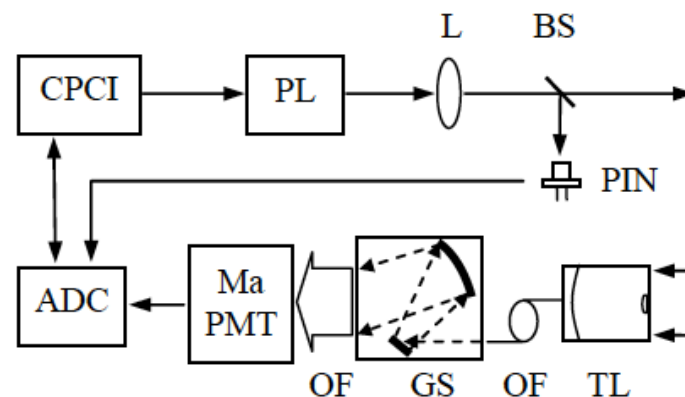
[Jintao Liu et al., ILRC, 2012]

(CPCI: CompactPCI computer, PL: Pulsed laser, L: Lens, BS: Beam splitter, PIN: PIN diode, Ma PMT: Multianode PMT, OF: Optical fiber, GS: Grating spectrometer, OF: Optical fiber, TL: Telescope)

Fig. 1. Schematic diagram of the ocean lidar system

Fig. 2   The 3D LIF spectra of *Skeletonema costatuma* (*Sk*)
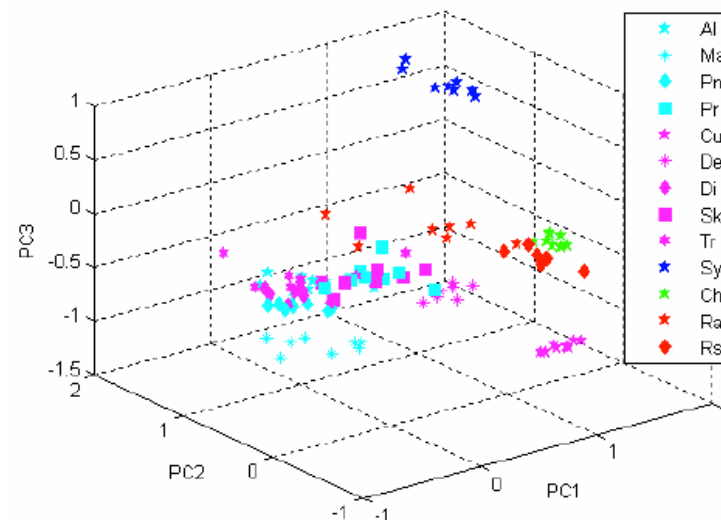
Fig. 3   The classification result

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More Target Lidar / Imaging Lidar

❑   Besides laser altimeter and fluorescence lidar, other target lidars include the lidars for detecting fish school (fish lidar, NOAA), for detecting vibrations (Coherent Technologies, Inc), for detecting or imaging buildings, military targets, airplanes, etc.

❑ They all utilize the time-of-flight between the reflected laser pulses or light from the targets and the transmitted laser pulse to determine the positions (range or 3-D spatial position) of targets.

❑   The scanning type of target lidars is sometimes called "ladar", meaning "laser radar" or "imaging lidar".

❑   By scanning fluorescence lidars, the mapping of ocean surface or plant distributions can be obtained.

❑   Airborne and spaceborne lidars, especially the laser altimeter and fluorescence lidar, have found wide application range and usefulness.

❑   Compact laser altimeter aboard Unmanned Aerospace Vehicle (UAV) has promising applications. Aerospace faculties and students are very active in the efforts to develop UAV-borne laser altimeters.

Fluorescence Spectroscopy

❑ A good reference book for fluorescence spectroscopy is the "Principles of Fluorescence Spectroscopy" by Joseph R. Lakowicz (2006).

❑ Our textbook Chapter 6 by Sune Svanberg serves as the fluorescence lidar reference. His group at Lund, Sweden is very active in LIF lidar.

❑ Fluorescence spectroscopy and time-resolved fluorescence are considered to be primarily research tools in biochemistry and biophysics.

❑ Fluorescence is now a dominant methodology used extensively in biotechnology, flow cytometry, medical diagnostics, DNA sequencing, forensics, and genetic analysis, to name a few.

❑ There has been dramatic growth in the use of fluorescence for cellular and molecular imaging. Fluorescence imaging can reveal the localization and measurements of intracellular molecules, sometimes at the level of single-molecule detection.

❑ Luminescence is the emission of light from any substance, and occurs from electronically excited states. Luminescence is formally divided into two categories – **fluorescence and phosphorescence** – depending on the nature of the excited state.

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Fluorescence Spectroscopy

❑ **Fluorescence** is emission of light from singlet excited states to the ground states (singlet). The electron in the excited orbital is paired by opposite spin to the electron in the ground-state orbital. Since $\Delta S = 0$, the transition is allowed (E1 – electric dipole transition) thus owing very high emission rate of fluorescence (typically 10^8 s^{-1}). A typical fluorescence lifetime is about 10 ns.

❑ **Phosphorescence** is emission of light from triplet excited states to the ground states (singlet). The electron in the excited orbital has the same spin orientation as the ground-state electron. Since $\Delta S = 1$, the E1 transitions to the ground state are forbidden. Higher-order transitions are still possible but with very slow emission rates (10^3 to 10^0 s^{-1}). Phosphorescence lifetimes are typically ms to seconds. Even longer lifetime are possible, as is seen from 'glow-in-the-dark' toys.
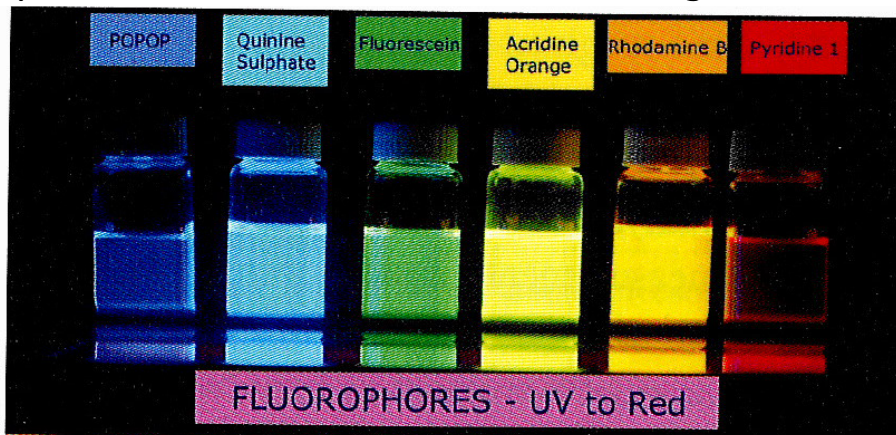
[Lakowicz, book, 2006]

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Fluorescence Spectroscopy Timescale

❑ Several terms in fluorescence spectroscopy, e.g., absorption, internal conversion, fluorescence, intersystem crossing, phosphorescence, are illustrated. Quenching, energy transfer, solvent interactions are excluded.

❑ Transitions (absorption and emission) occur in 10^{-15} s (instantaneous).

❑ Internal conversion occurs within 10^{-12} s or less.

❑ Fluorescence lifetimes are typically near 10^{-8} s.

❑ Phosphorescence lifetimes are about ms to seconds or even minutes.
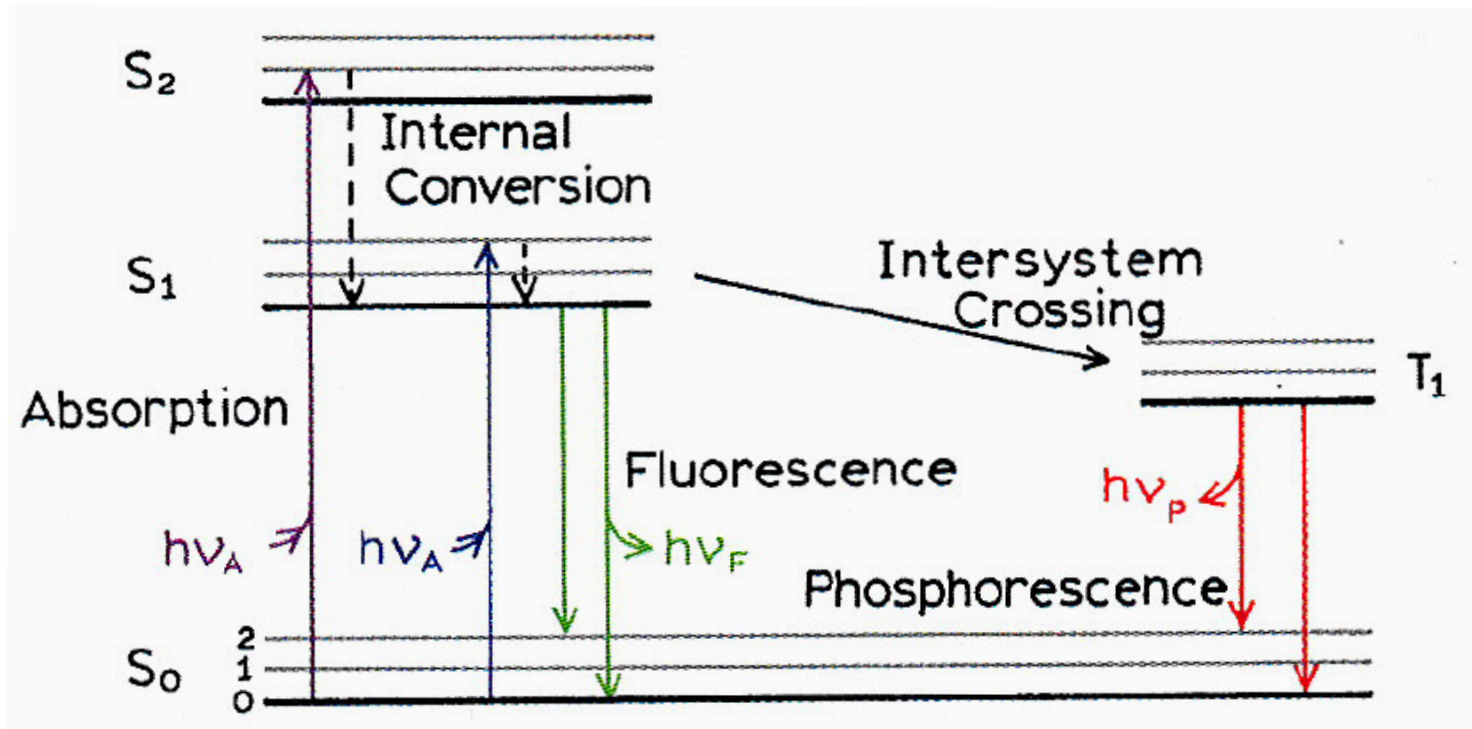
A Jablonski diagram from Lakowicz's book [2006]

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Instrumentation for Fluorescence Spectroscopy

❑ By detecting the fluorescence from the sample with PMT, both excitation and emission spectra can be recorded.

❑ An emission spectrum is the wavelength distribution of an emission measured at a single constant excitation wavelength.

❑ An excitation spectrum is the dependence of emission intensity, measured at a single emission wavelength, upon scanning the excitation wavelength.
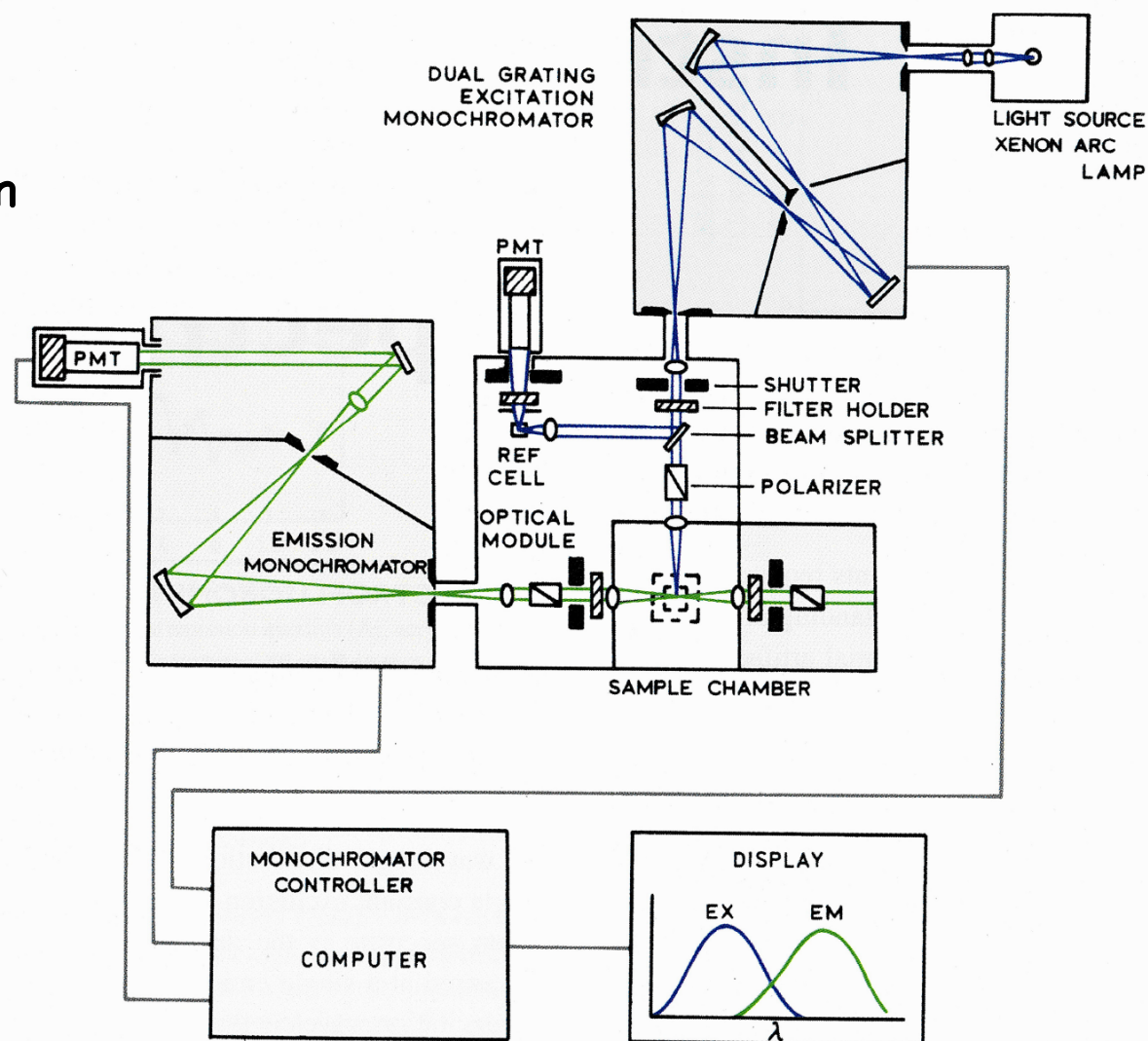
Schematic diagram of a spectrofluorometer [Lakowicz's book, 2006]

Fluorescence for Lidar Technique

❑ In contrast to free atoms and molecules (gas phase), solids and liquids exhibit broad absorption and emission spectra because of the strong intermolecular interactions.

❑ A fixed frequency laser can be used for the excitation due to the broad absorption.

❑ Following the excitation, there is a very fast (ps) radiationless relaxation down to the lowest sub-level of the excited state, where the molecules remain for a typical excited-state fluorescence lifetime (10 ns).

❑ The decay then occurs to different sub-levels of the ground state giving rise to a distribution of fluorescence light, which reflect the lower-state level distribution.

❑ Fixing the excitation wavelength, we can obtain fluorescence spectra. While fixing the detection channel and varying the excitation wavelength, an excitation spectrum can be recorded.

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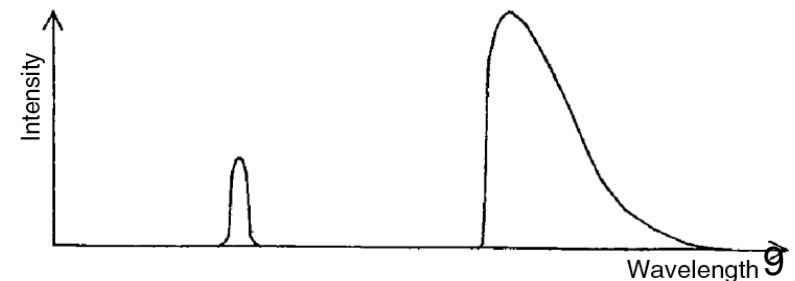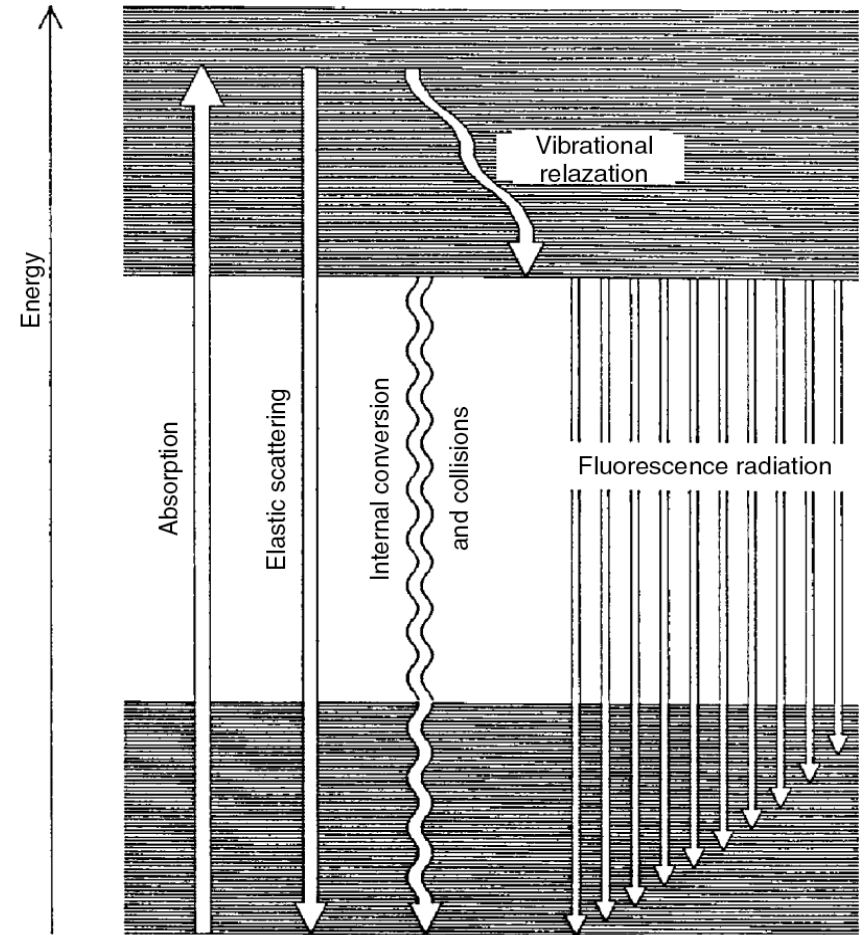
Laser-Induced-Fluorescence Lidar

❑ For laser-induced fluorescence lidar, the laser beam is directed toward a solid or liquid target, and the distance to that target is determined by measuring the time delay for the detection of the distinct echo.

❑ The elastic backscattering is blocked while the fluorescence induced by the laser pulse hitting the target is wavelength dispersed and detected by a photo detector, a fluorescence lidar system is established.

❑ To suppress background light, which now enters the wide wavelength region needed for capturing the fluorescence light distribution, the detection is restricted to a narrow temporal window corresponding to the time of the arrival of the pulse. In this way, fluorescence can be detected remotely, even in the presence of full daylight.

❑ Like in all remote sensing applications, a good basis is needed in 'ground-truth' measurements, where standard spectra are recorded under well-controlled conditions. The point-monitoring fluorosensor can be used to record the standard spectra in laboratory conditions.

Fluorosensor for Fiber-Optic Point Monitoring
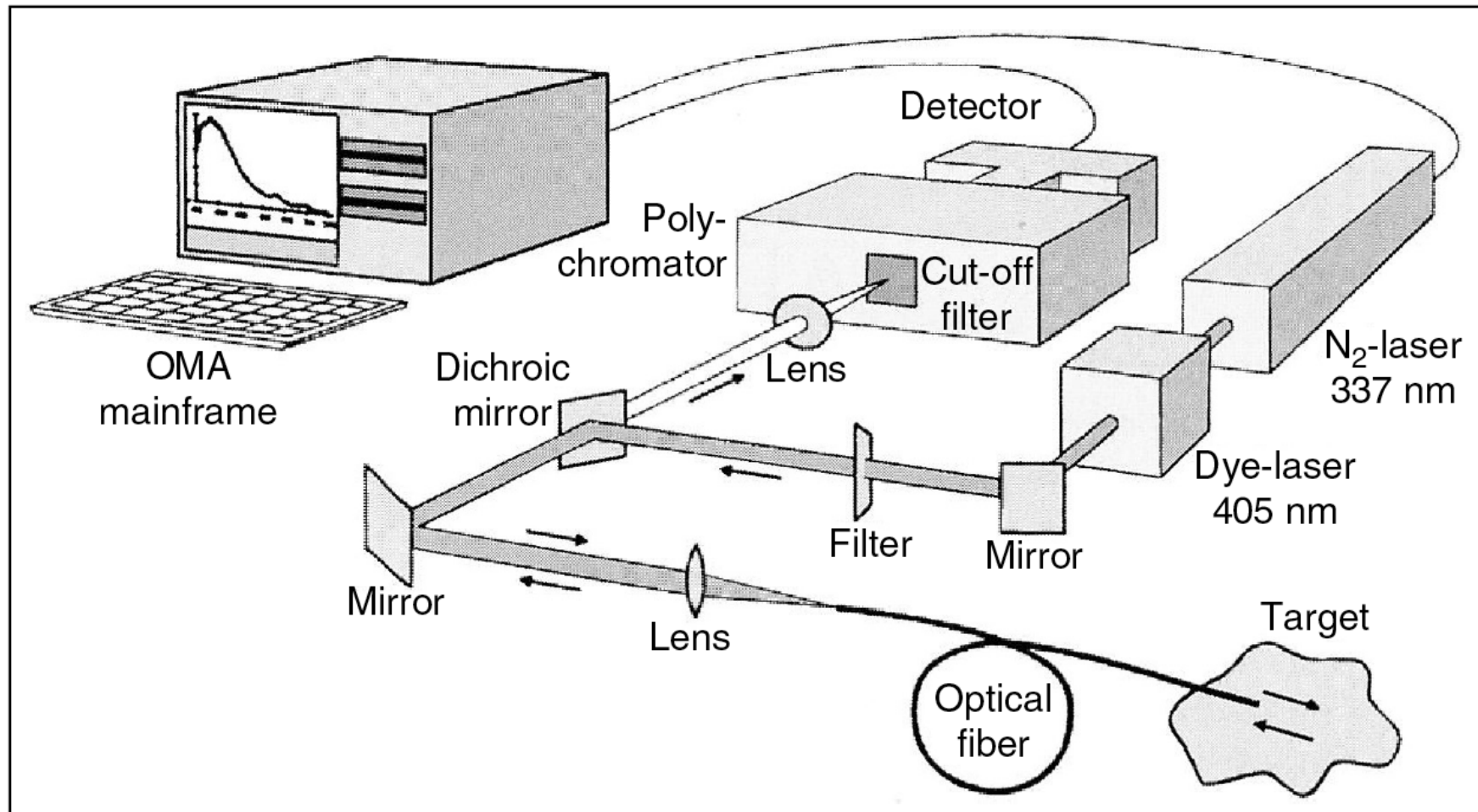
Figure 6.2 in Chapter 6 of our textbook

Ground-Truth: Fluorosensor

❑ Excitation: 337nm from N_2-laser, or 405 nm from dye-laser

❑ Fiber: transmit laser pulse to target and then collect the laser-induced-fluorescence

❑ Filters: Dichroic mirror reflects laser light but transmits red-shifted fluorescence; cut-off filter further reducing background

❑ Time-gating: only accept light during a narrow time window (100 ns) after certain delay time corresponding to the time of the arrival of the pulse - efficiently eliminate background light

❑ Detector: spectrometer + CCD to record full spectrum covering 350-800 nm following each laser shot

❑ Multiple shots can be averaged to increase the signal-to-noise ratio.

❑ Note: This is a setup for time-integrated fluorescence detection. Time-resolved detection of fluorescence can provide additional diagnostic information of the sample under study: different species have different fluorescence lifetimes.

❑ Remote fluorescence measurements must provide means to isolate temporal delays due to excited-state lifetime from temporal delays due to larger physical distance in a 3-D target. By first monitoring the elastic range-resolved backscatter from a canopy, into which the laser beam successively penetrates, and then recording the fluorescence lidar return for some wavelengths, it is possible to separate lifetime effects from propagation effects.

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Example Spectra from Fluorosensor

Chlorophyll Fluorescence

405 nm exc.

Spectra from Leaf Structure & Wax Layer

337 nm exc.
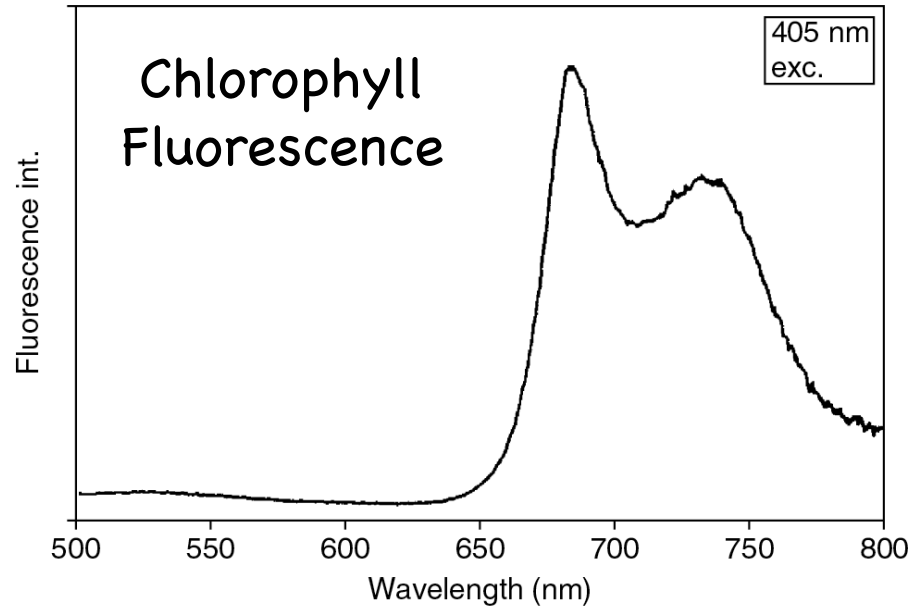
❑ When excited by 405 nm, the chlorophyll fluorescence is clearly visible with peaks at 690 and 735 nm. This also means that chlorophyll has strong absorption at the red spectra.
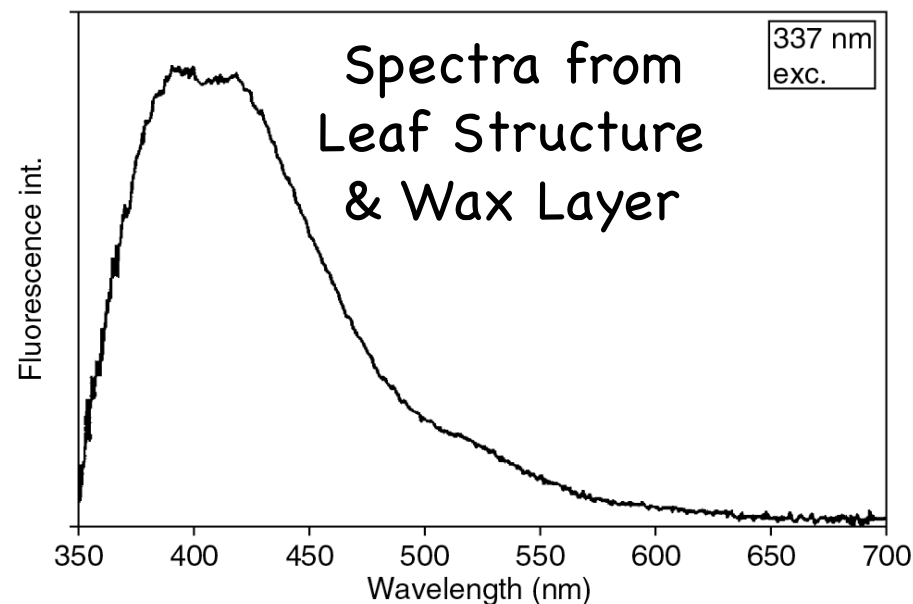
❑ When excited by 337 nm, the fluorescence from wax layer is strong in the blue spectra, while protection layer prevents the penetration of UV light reaching chlorophyll.

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Fluorosensor with Blue Diode Lasers
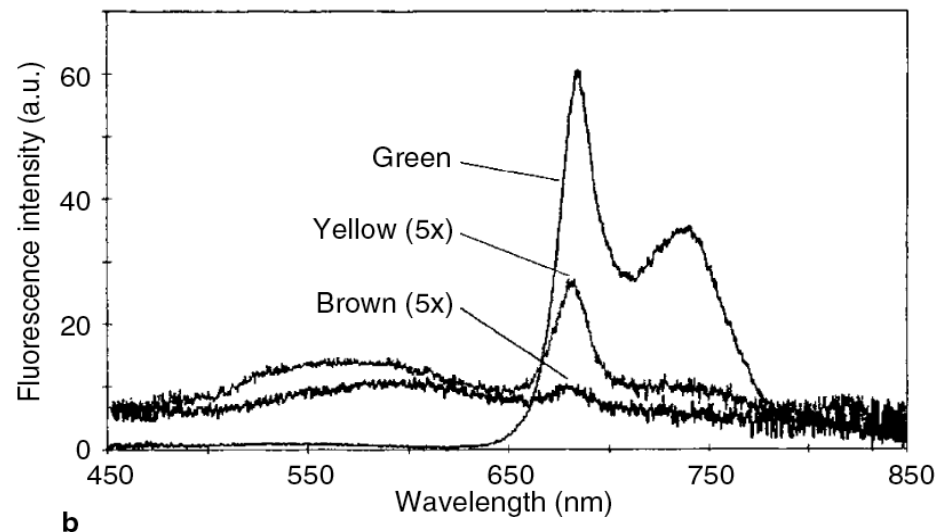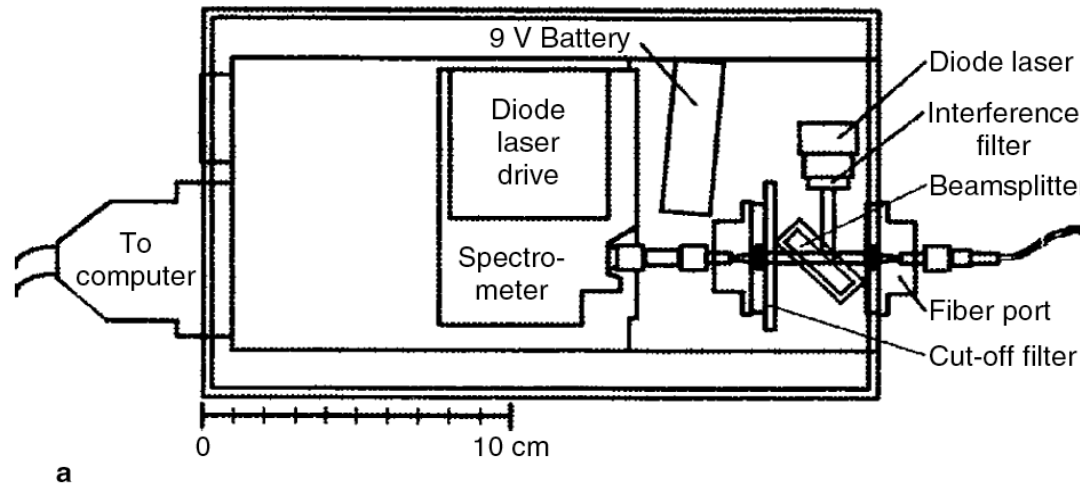
Figure 6.4   (a) Compact blue fluorosensor based on a violet diode laser. (b) Fluorescence spectra from different parts of a beech leaf, showing green, yellow, or brown color in reflectance. (From Gustafsson, U. et al., *Rev. Sci. Instrum.*, 71, 3004, 2000. With permission.)

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Scenarios for Fluorescence Lidar
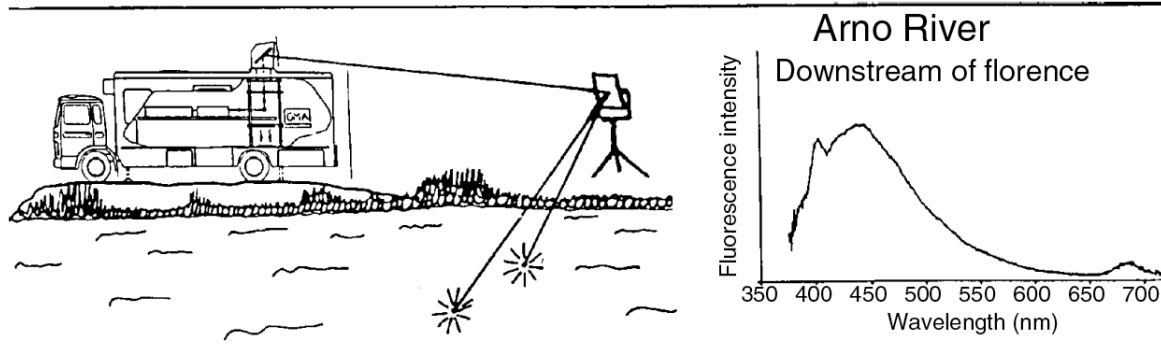
Aquatic monitoring
Via folding mirror
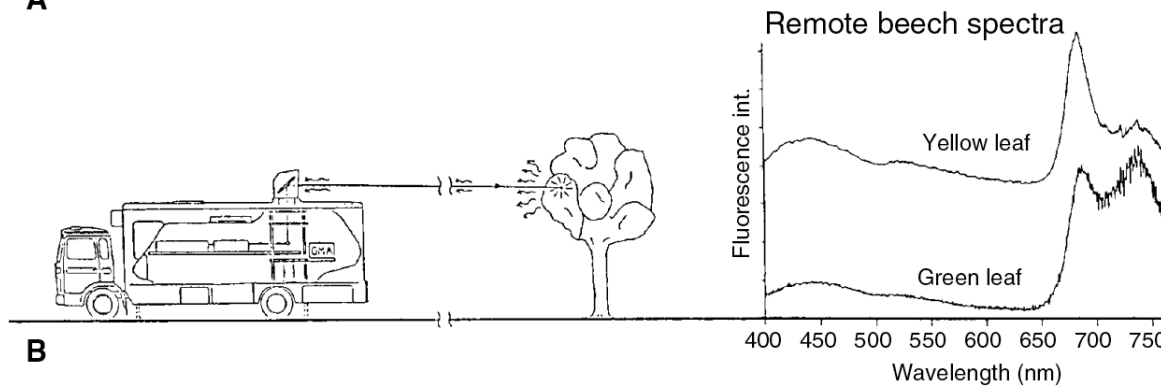
Vegetation
Monitoring
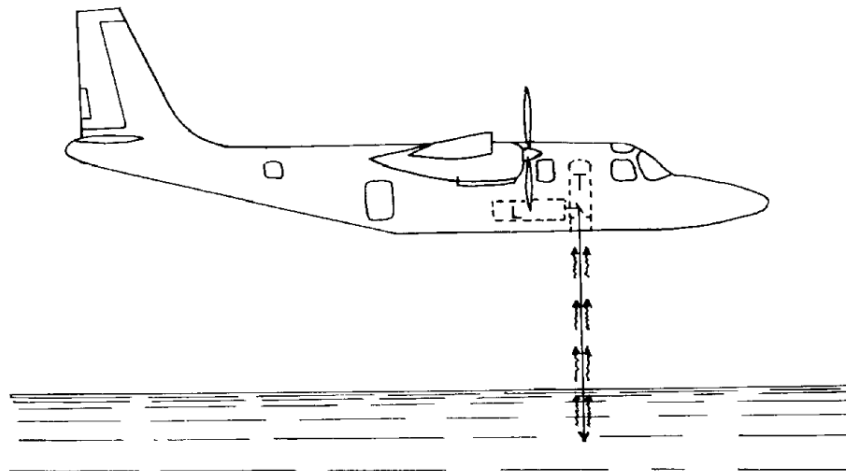
Airborne
Fluorescence

Fluorescence Lidar System
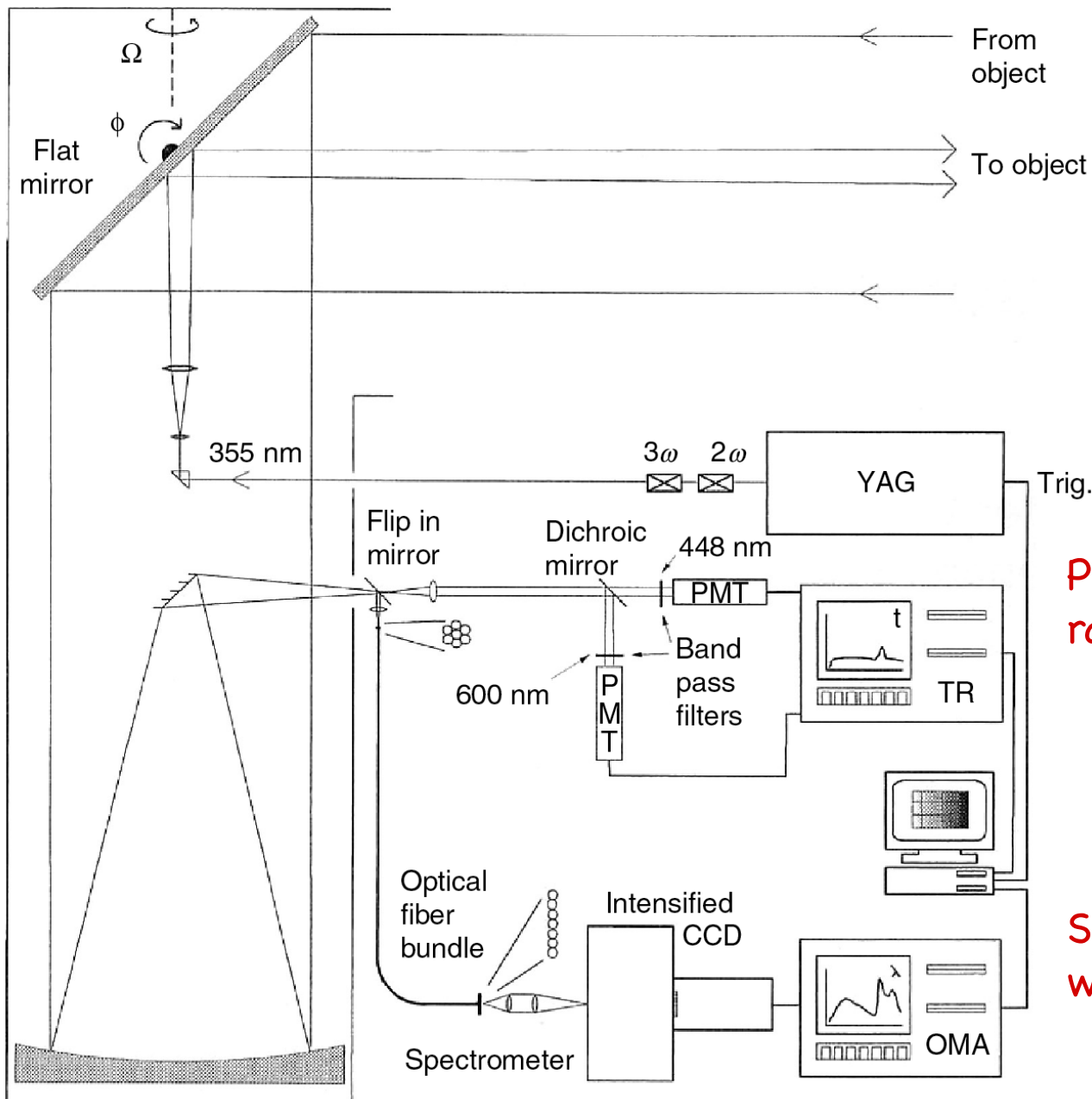
PMT for time-resolved, i.e., range-resolved signal

Spectrometer + CCD for wavelength-resolved signal

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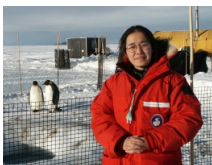
Scenarios for Fluorescence Imaging
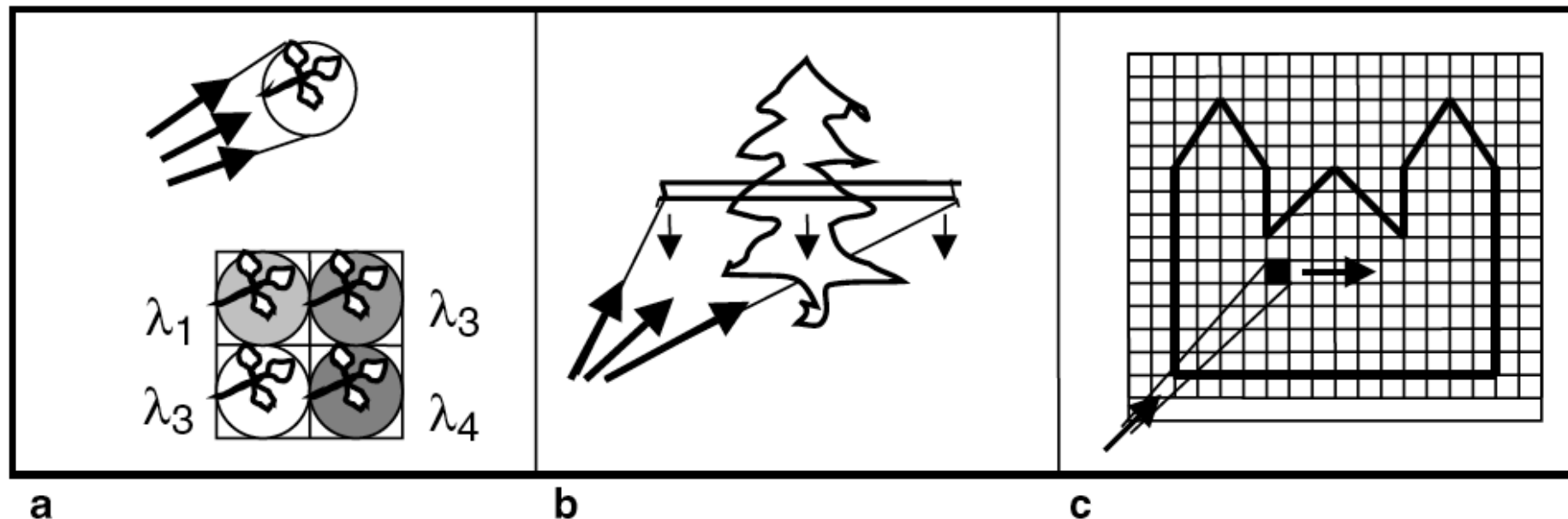
Figure 6.7 Scenarios for remote fluorescence spectroscopy and fluorescence imaging with special consideration of background: (a) simultaneous four-color imaging; (b) pushbroom imaging; and (c) scanning pointwise imaging.

Fluorescence imaging is governed by two considerations: stationary or moving targets, and signal-to-background conditions.

Application: Marine Monitoring
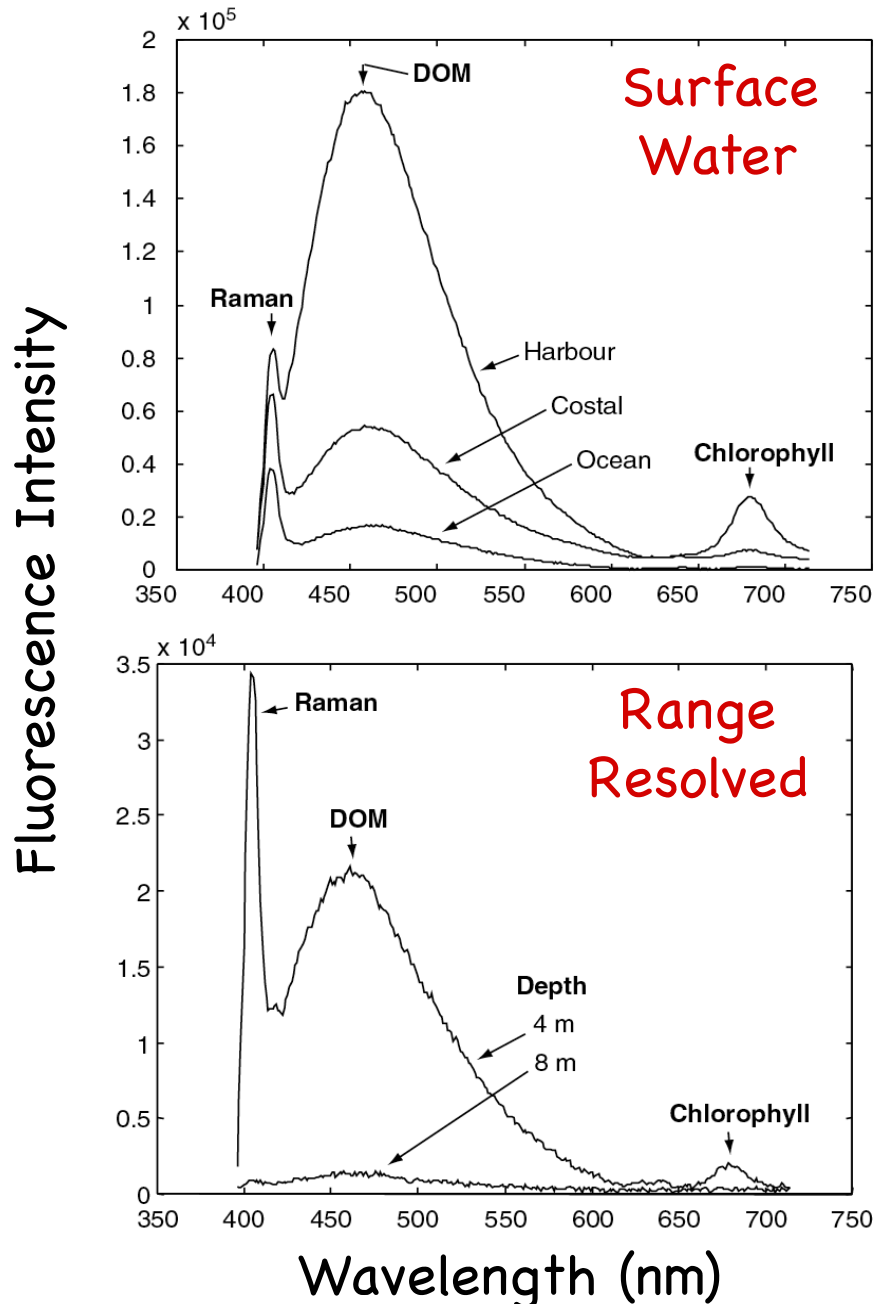
- ❏ Excitation at 355 nm

- ❏ Raman scattering from H_2O at 404 nm (Raman shift: 3400 cm^{-1}) – Because the aggregation of water molecules depends on the temperature, the analysis of the detailed shape of the Raman signal can be utilized to measure surface water temperature.

- ❏ DOM (Dissolved Organic Matter) fluorescence in the blue-green spectral region for assessment of the general level of DOM.

- ❏ By normalizing the DOM signal to the bkg-free water Raman signal, the percentage of DOM in water can be derived (a built-in reference).

- ❏ Range-resolved fluorescence data can be taken by gating the image intensifier at different delays.

Application: Vegetation Monitoring
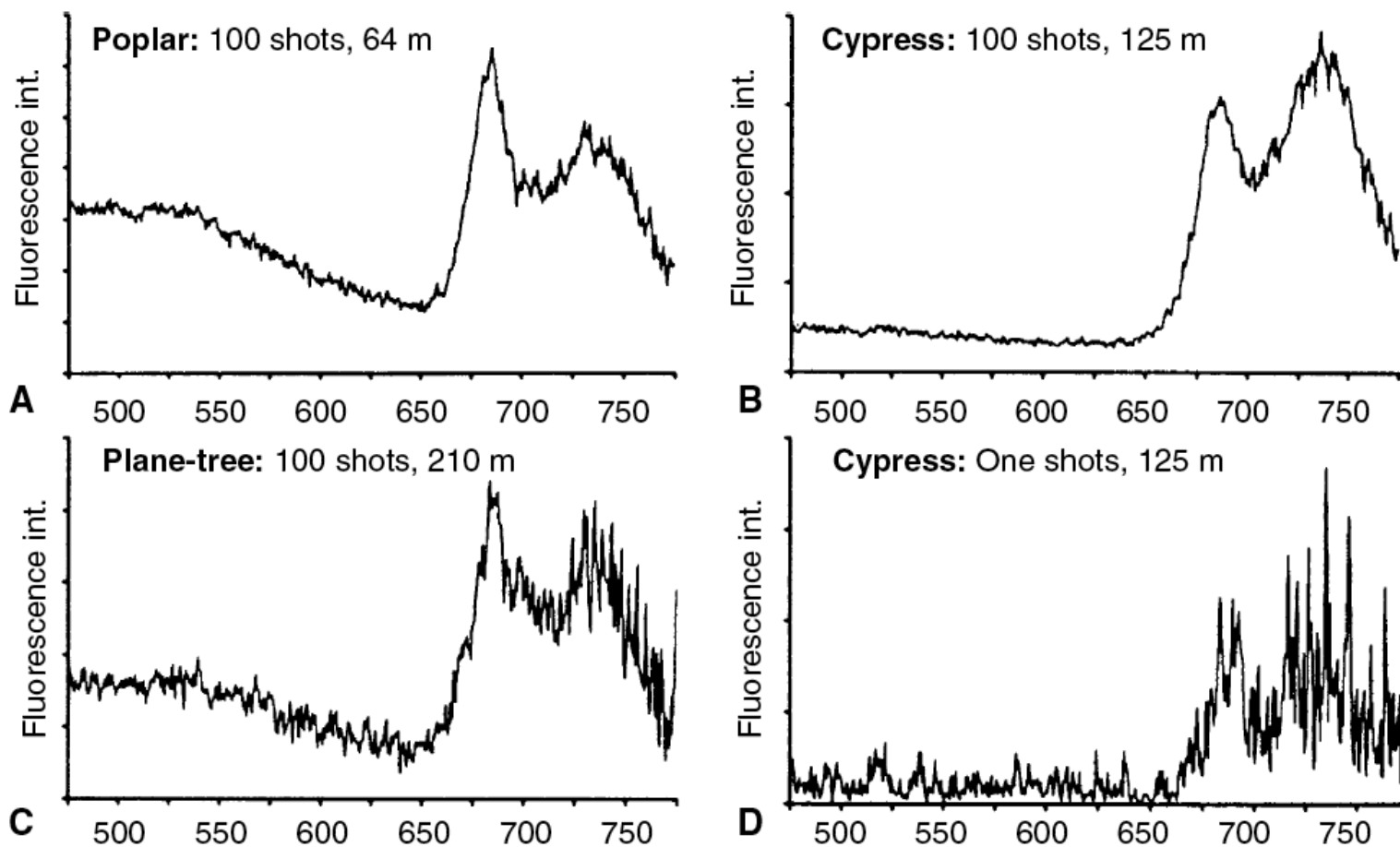
Figure 6.10 Fluorescence spectra of poplar, cypress, and plane-tree recorded at different ranges employing 100 laser shots. Spectra for cypress are shown using 100 as well as one laser shot. (From Andersson, M. et al., Proc. ISPRS Symposium on Physical Measurements and Signatures in Remote Sensing, Cal d'Isère, 1994; With permission.)

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Detection of Historic Monument
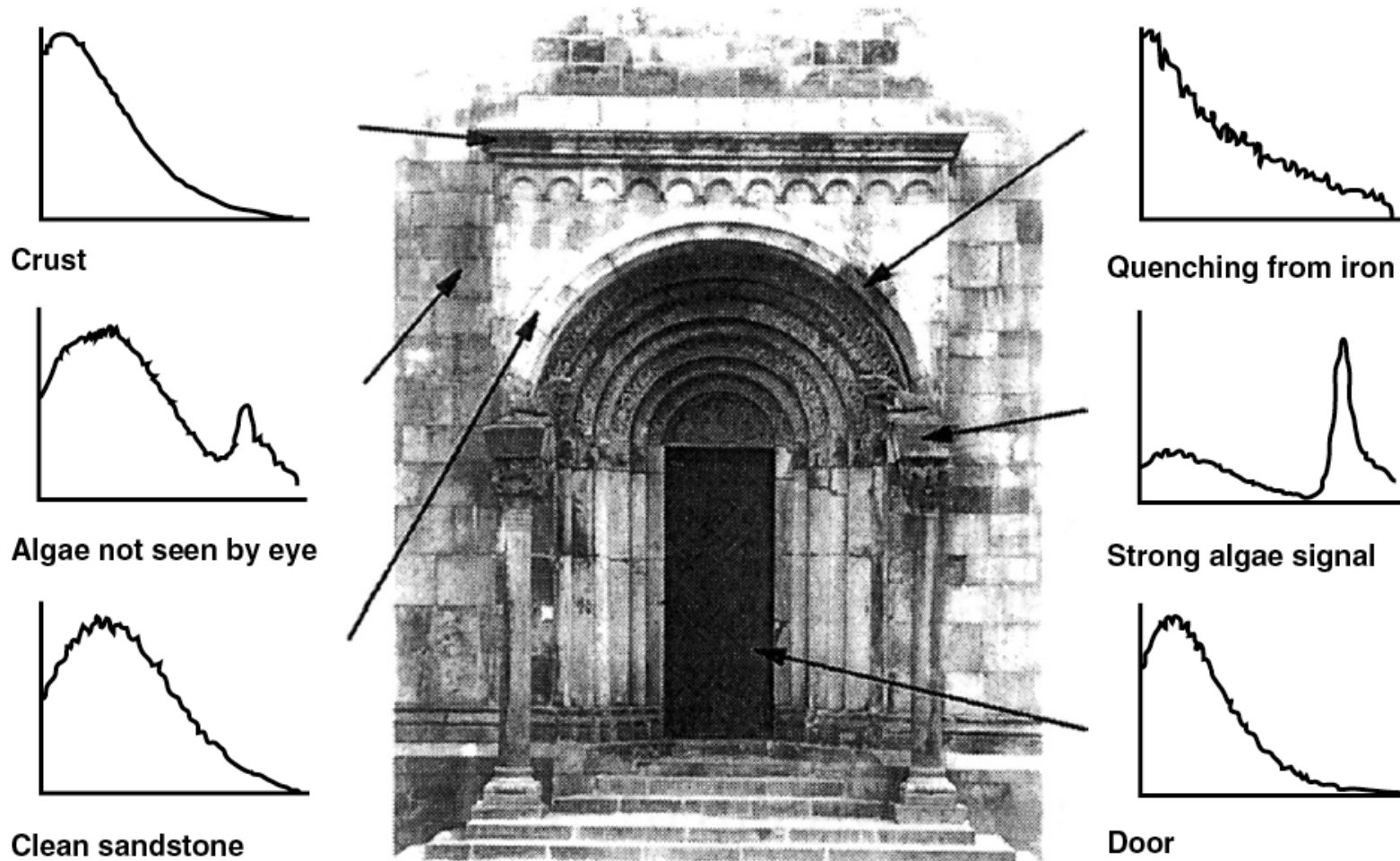
Figure 6.13 Photograph of the northern gate of the Lund Cathedral and six remotely recorded fluorescence spectra. (From Weibring, P. et al., *Appl. Opt.*, 40, 6111, 2001. With permission.)

Lidar in Cultural Heritage Monitoring
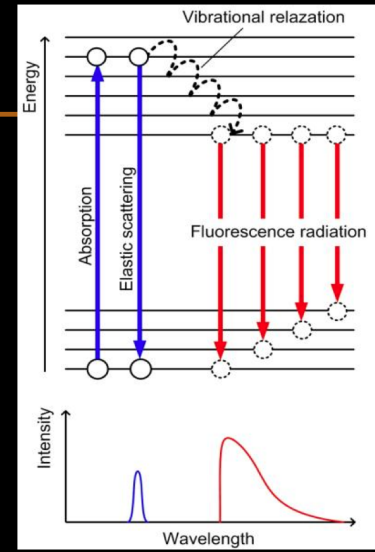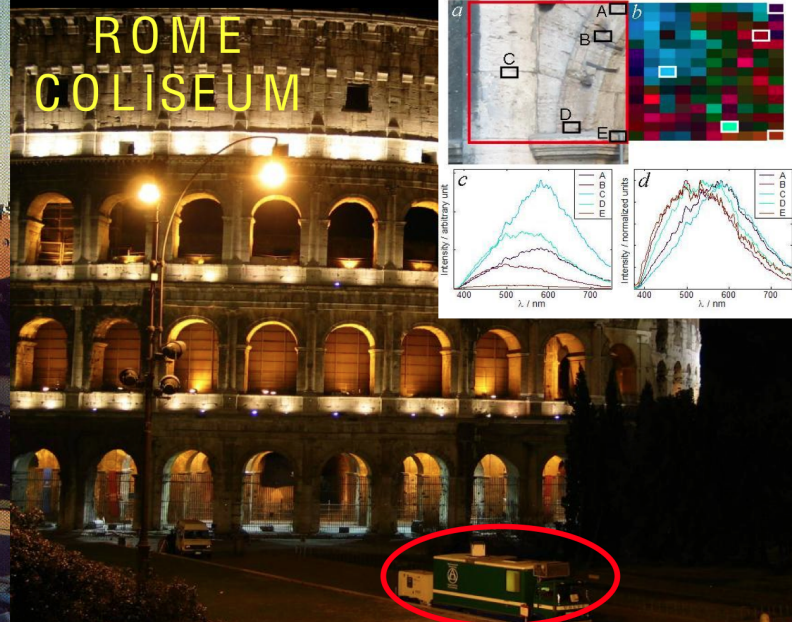
[Courtesy to Lund University and Dr. Zuguang Guan, ILRC, 2010]

[Courtesy to Dr. Zuguang Guan, ILRC, 2010]

Fluorescence lidar for insects and birds monitoring
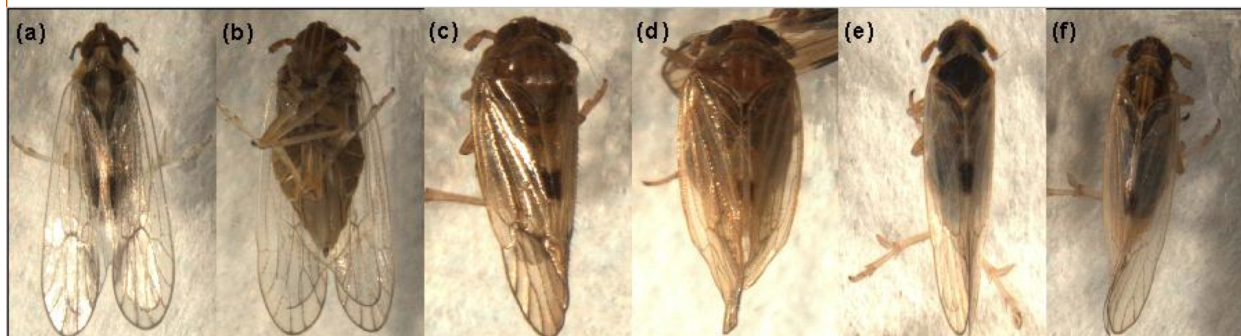
China's most destructive agricultural pests

- Huge economic damage to the rice crop and cotton.
- Northward migration during summer from Indo-China peninsula to Yangtze area
- Evaluation of pheromone traps for pest control

C. virgo male   *C. virgo* female

C. splendens male   *C. splendens* female
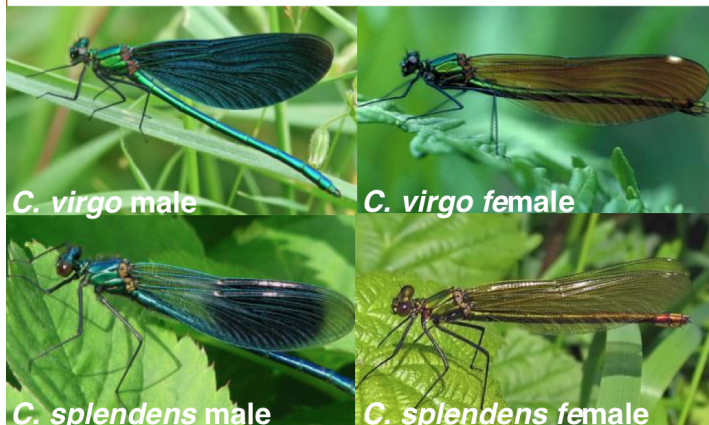
Damselflies

- Biomarkers
- Dispersal study

- Species, sexes, ages, migration time, flight direction, altitude
- Spread of bird-born diseases

Bird migration (internet picture)

- *Fish school: Fredriksson et al., GIPR-162, 1978*
- *Honeybee: Repasky et al., Appl. Opt., 2006*
    Hoffman, et al., Appl. Opt., 2007

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[Courtesy to Dr. Zuguang Guan, ILRC, 2010]

A vehicle-based mobile lidar system
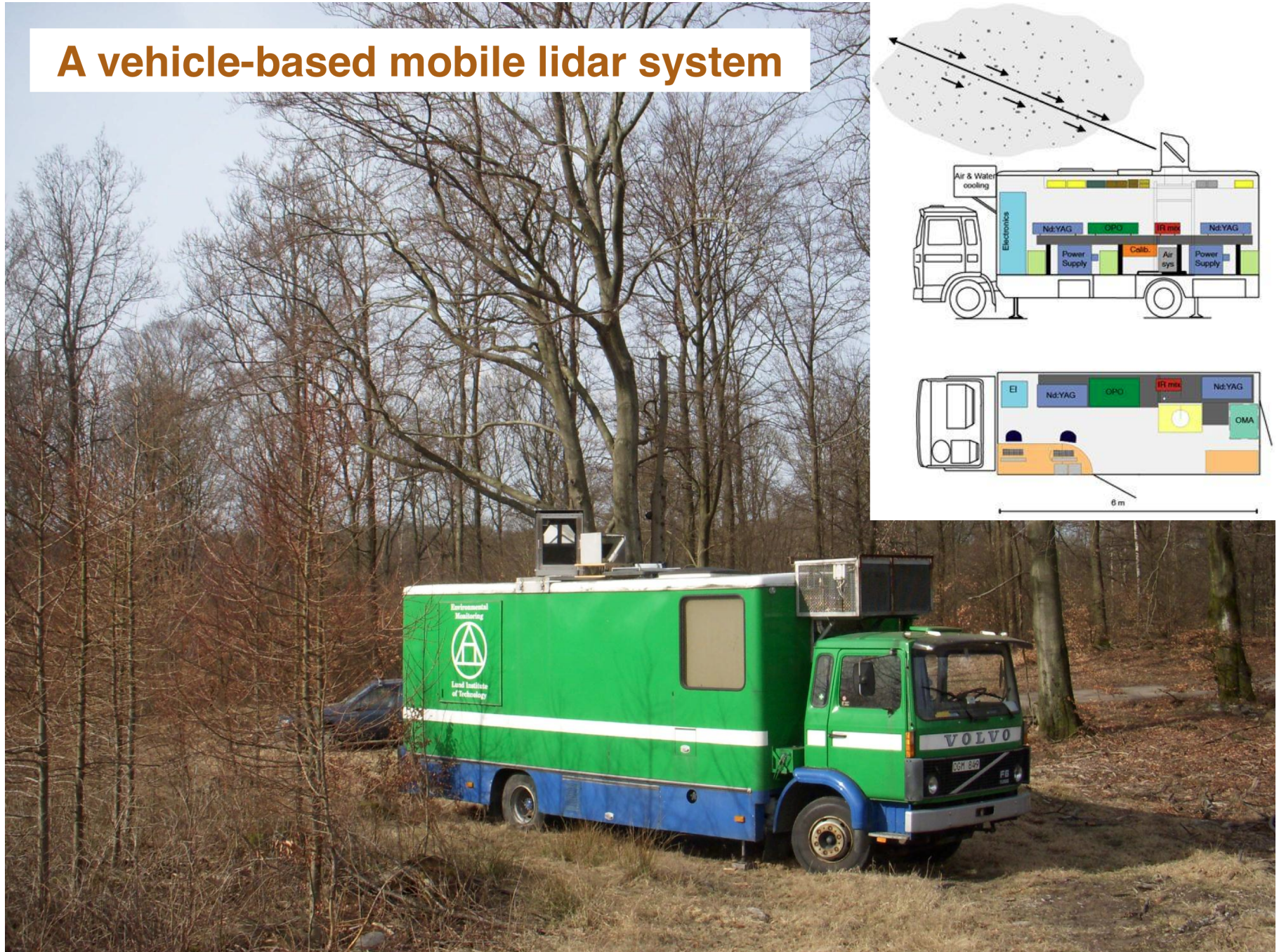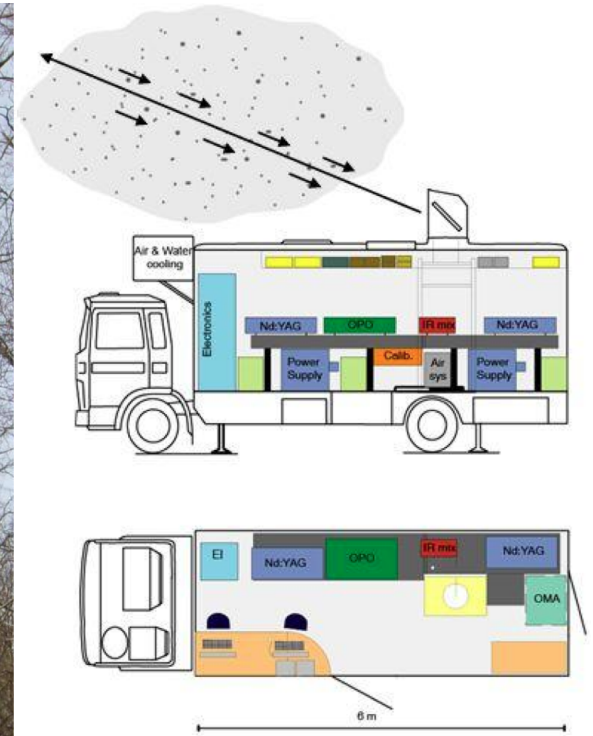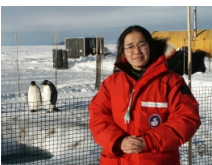
[Courtesy to Dr. Zuguang Guan, ILRC, 2010]

Key components

Nd: YAG (355/266 nm)
Expander
Delay
P
M
SF
LM
LF
LF
DF
PMT1
PMT2
PMT3
Oscilloscope
1:
2:
3:
GPIB
Spectro-scopy
I-CCD
Computer
OMA
Telescope

ILRC25 2010, St. Petersburg
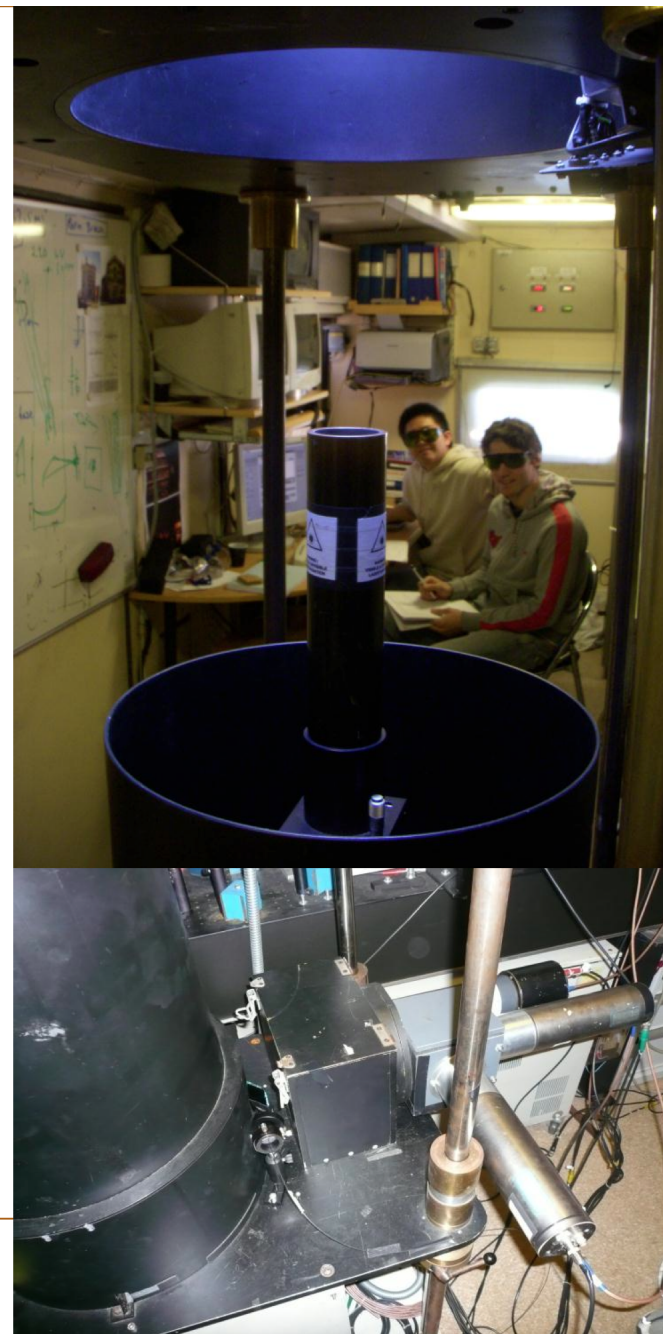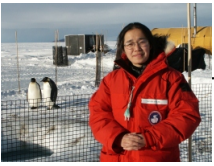
Feasibility test – agriculture pests

Mei et al., Agriculture Pest Monitoring with Fluorescence LIDAR Techniques, to appear
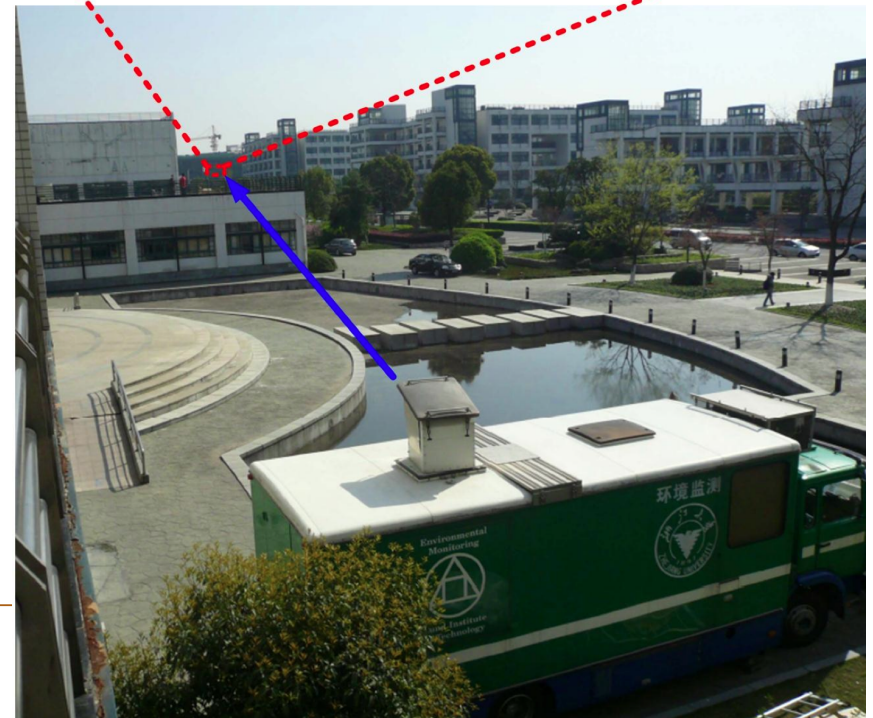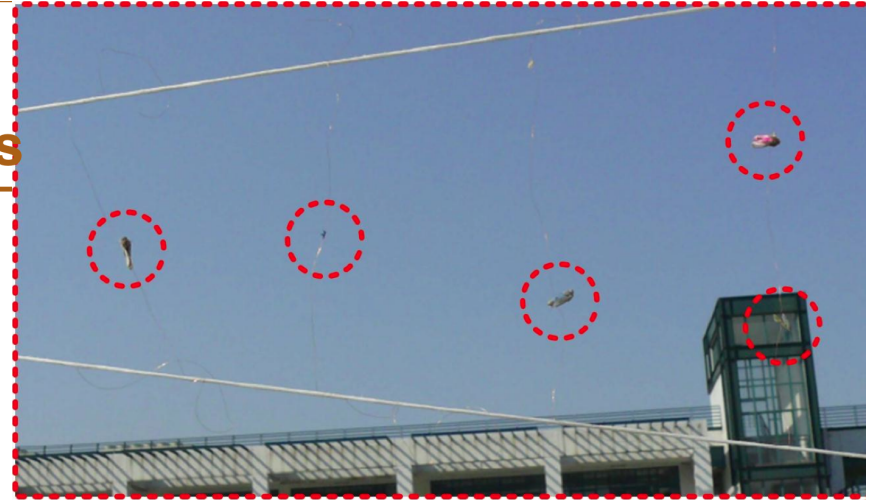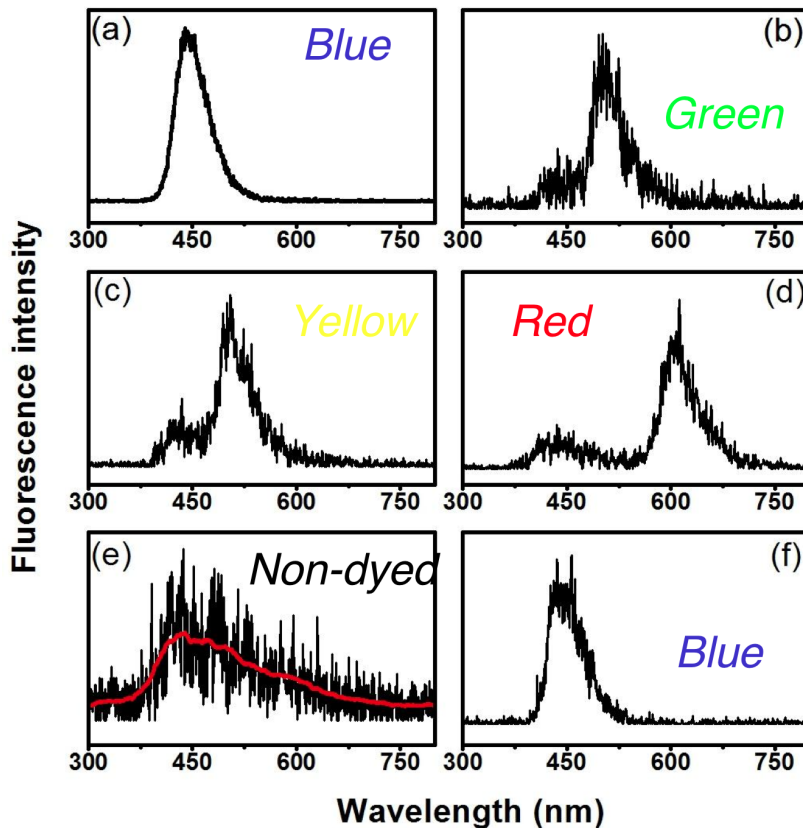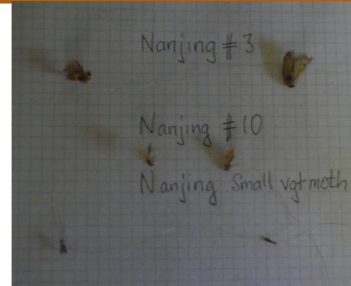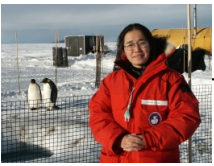
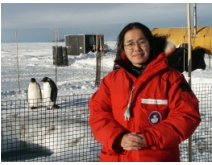[Courtesy to Dr. Zuguang Guan, ILRC, 2010]

Feasibility test – damselflies

C. virgo male

C. virgo female

C. splendens male

C. splendens female
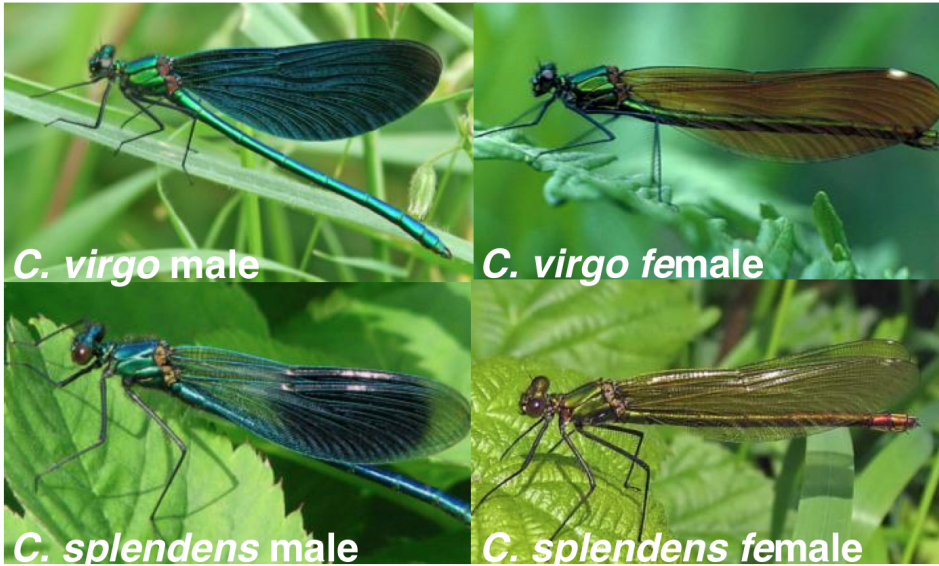
Brydegaard et al., Appl. Opt., 2009

ILRC25 2010, St. Petersburg
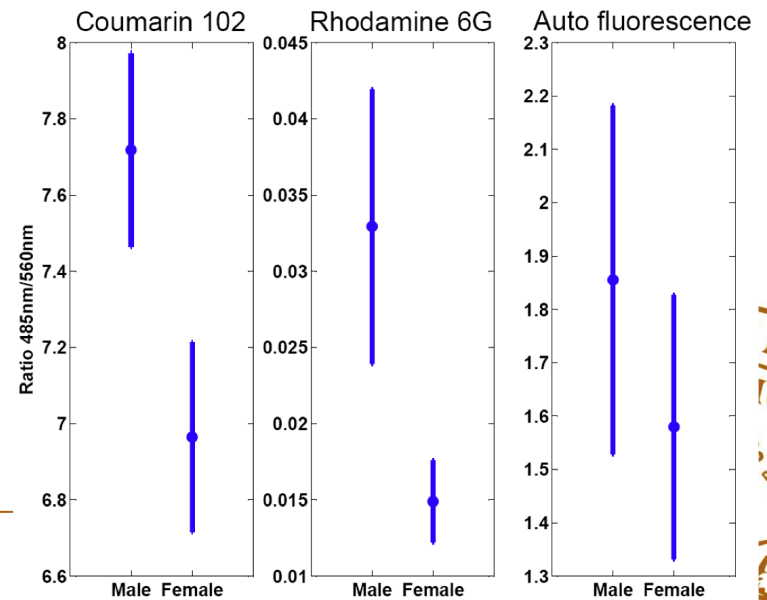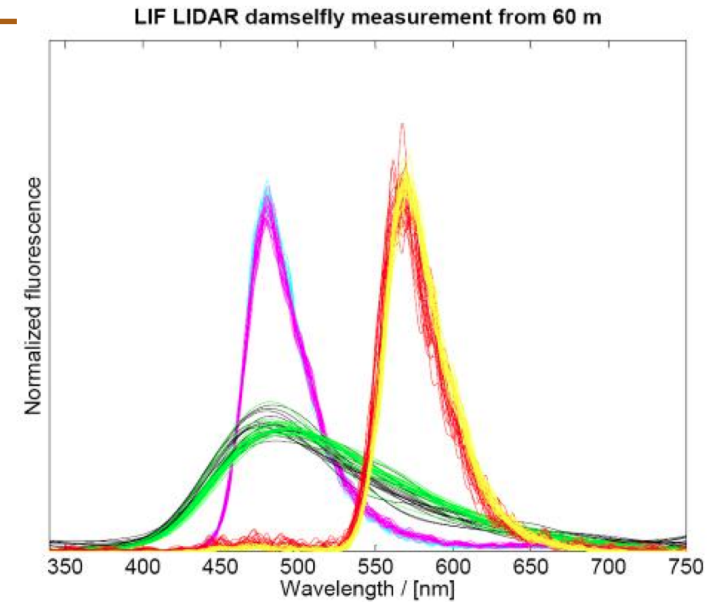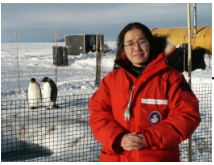
Feasibility test – damselflies

ILRC25 2010, St. Petersburg

[Courtesy to Dr. Zuguang Guan, ILRC, 2010]
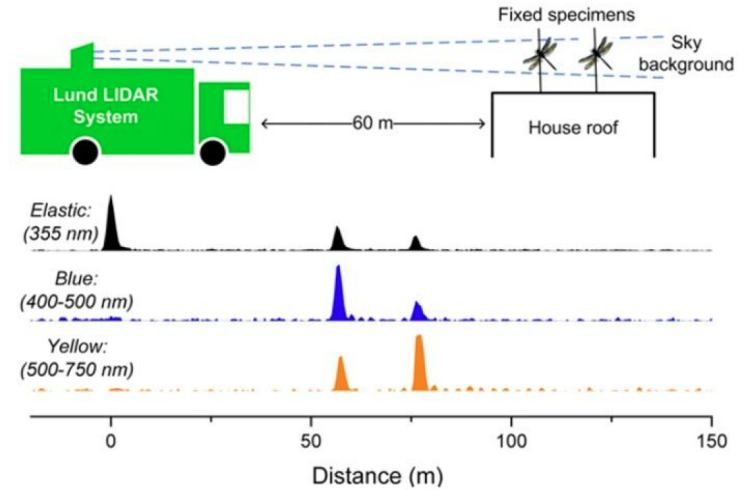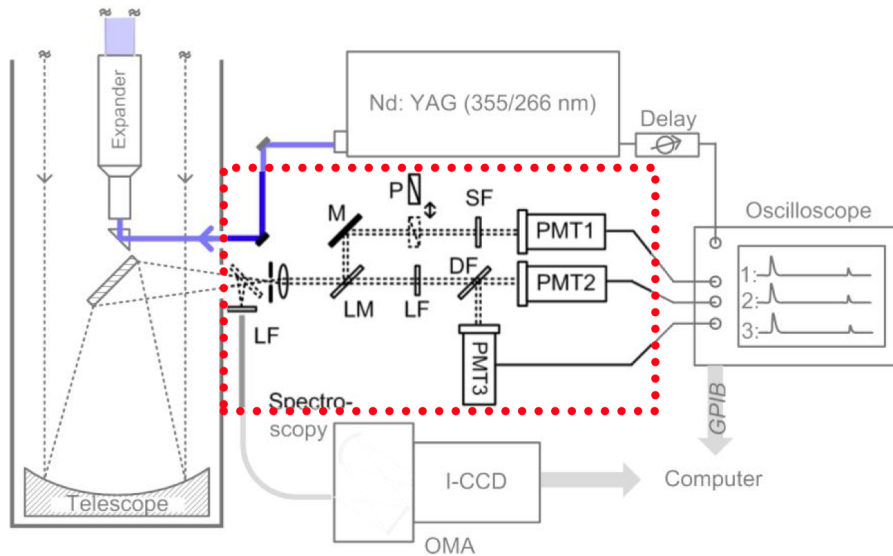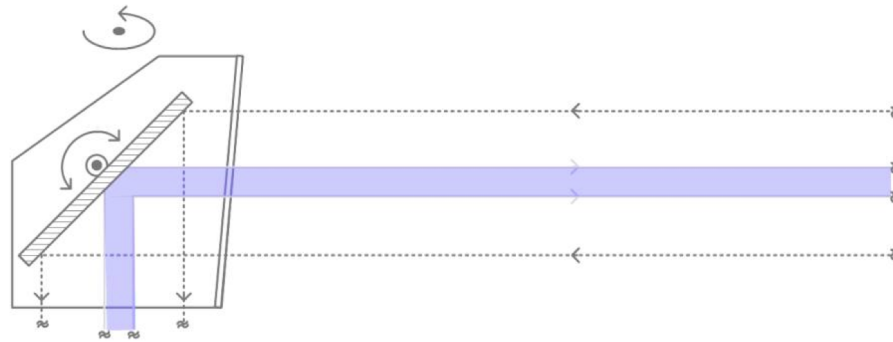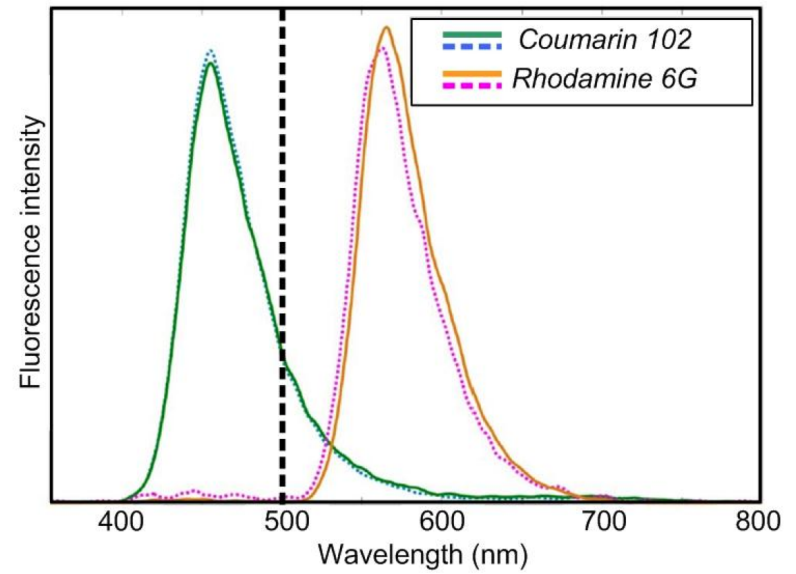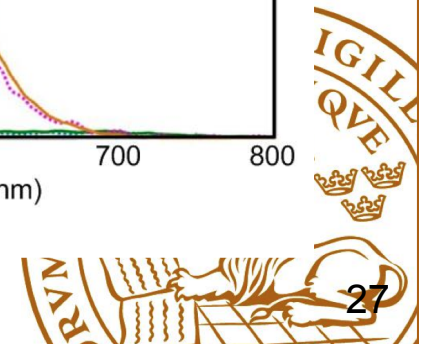
Feasibility test – Birds

Robin

Blue tit

Jackdaw

European reed warbler

Starling

Rook

Starling

Great reed warbler

Black cap

ILRC25 2010, St. Pe

Brydegaard et al., Appl. Opt., to appear

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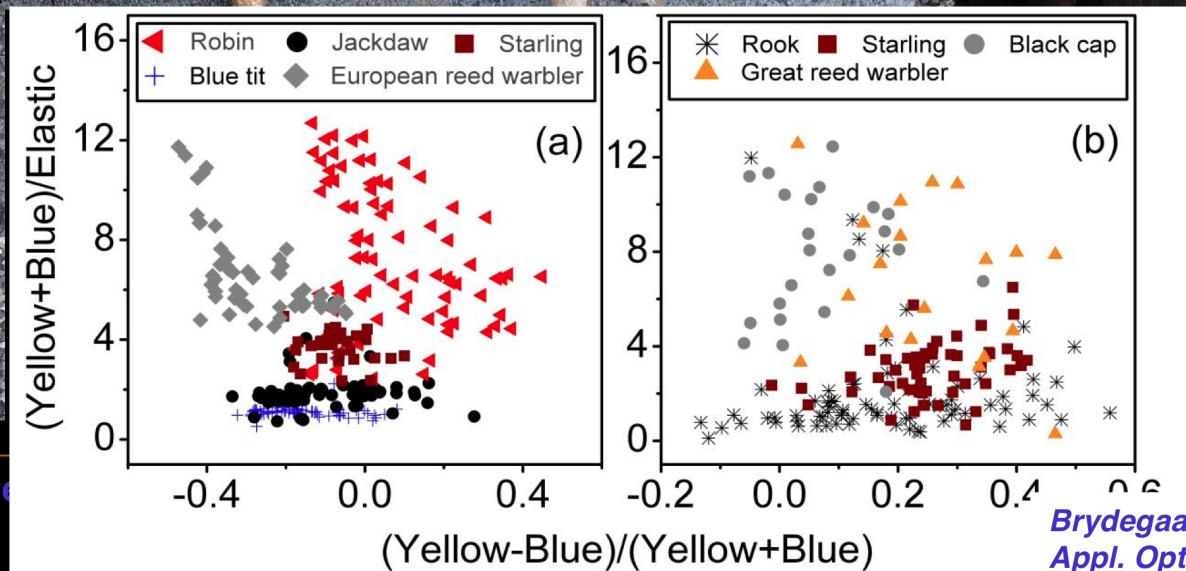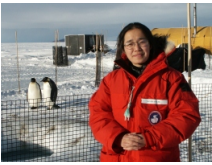
[Courtesy to Dr. Zuguang Guan, ILRC, 2010]

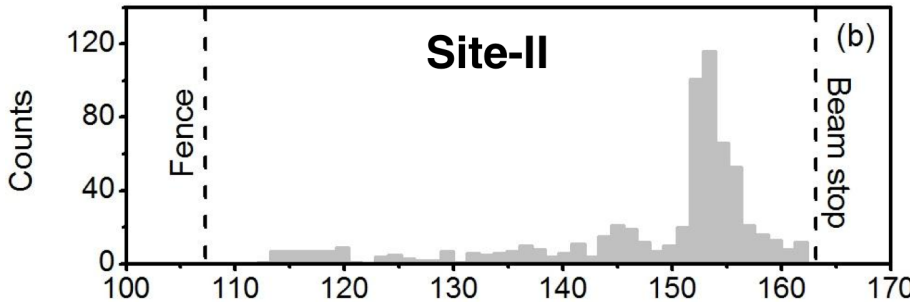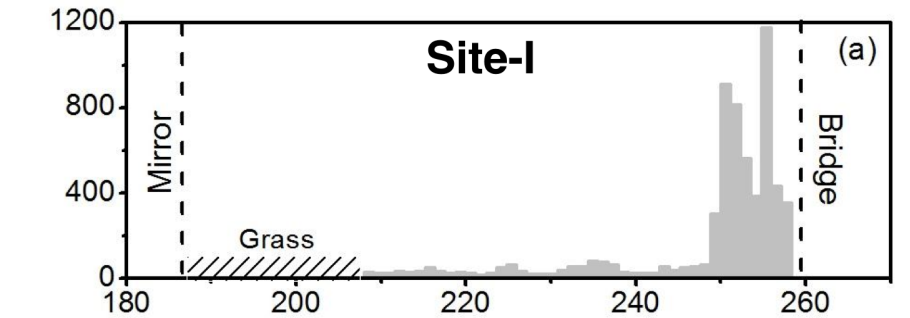## Field experiments – Damselflies
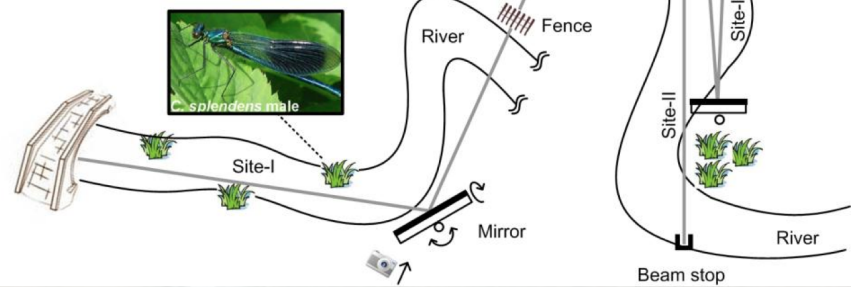
Klingavälsån river, Veberöd
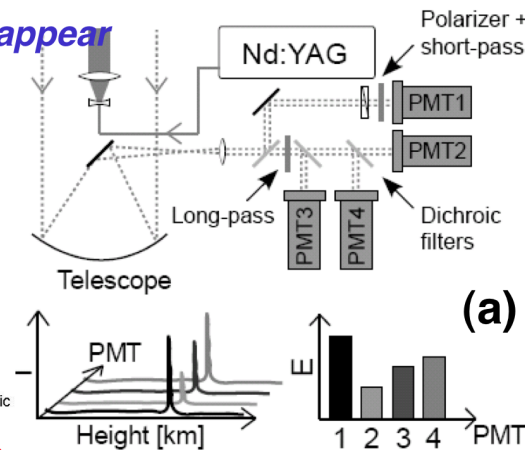(55 38' N, 13 29' E)

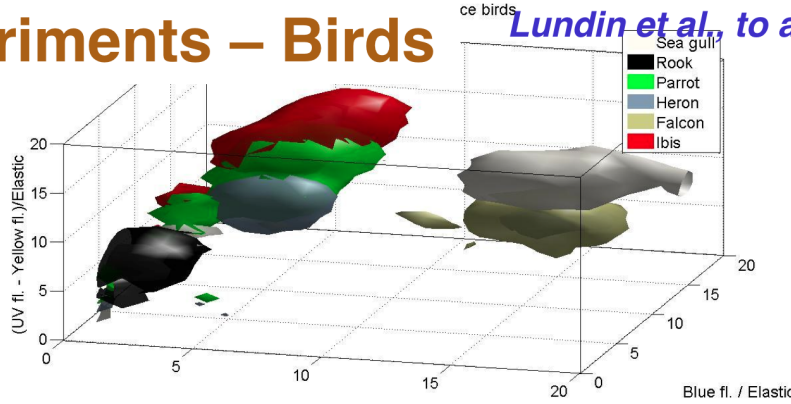[Courtesy to Dr. Zuguang Guan, ILRC, 2010]

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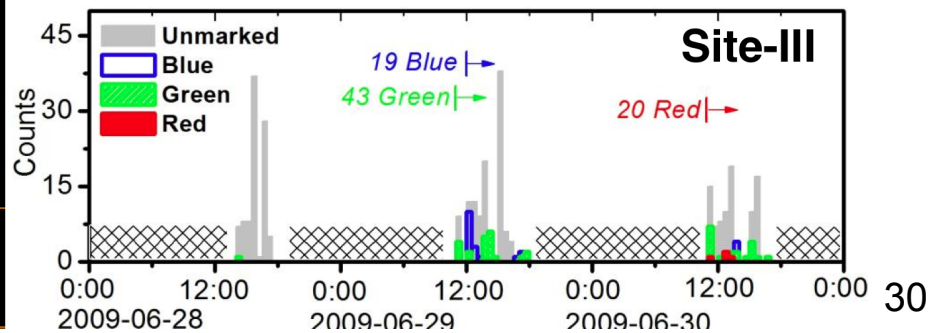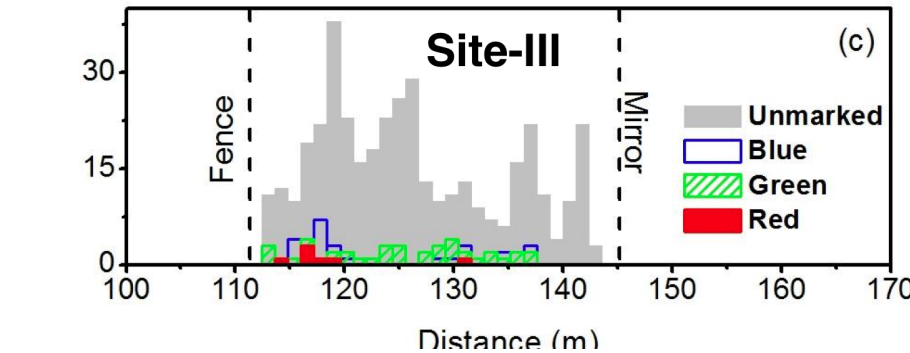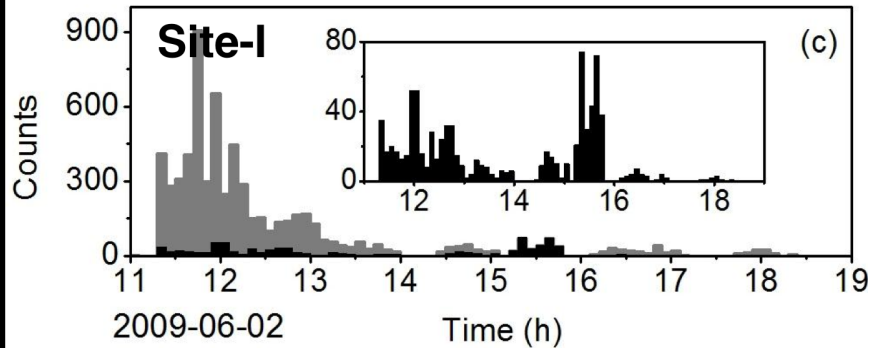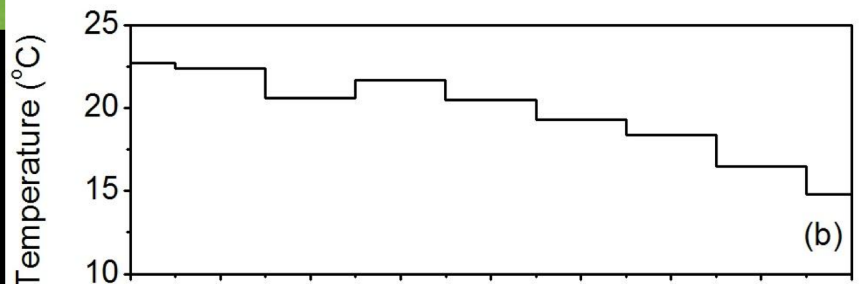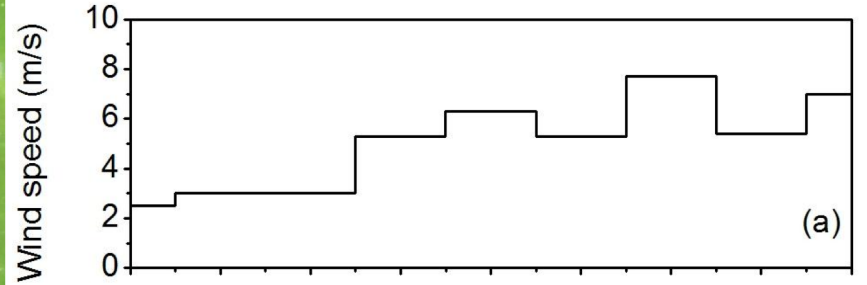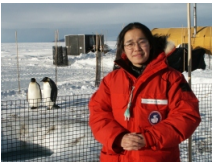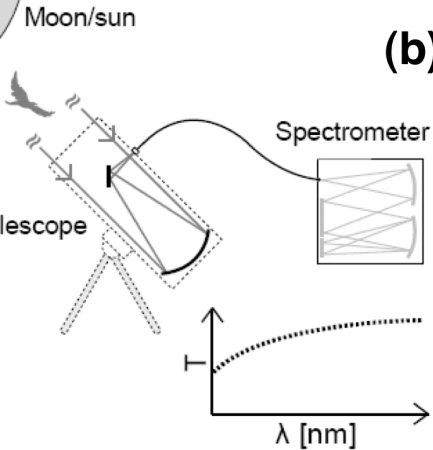
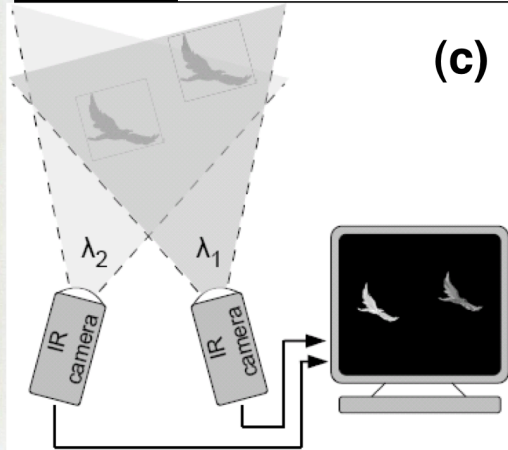[Courtesy to Dr. Zuguang Guan, ILRC, 2010]
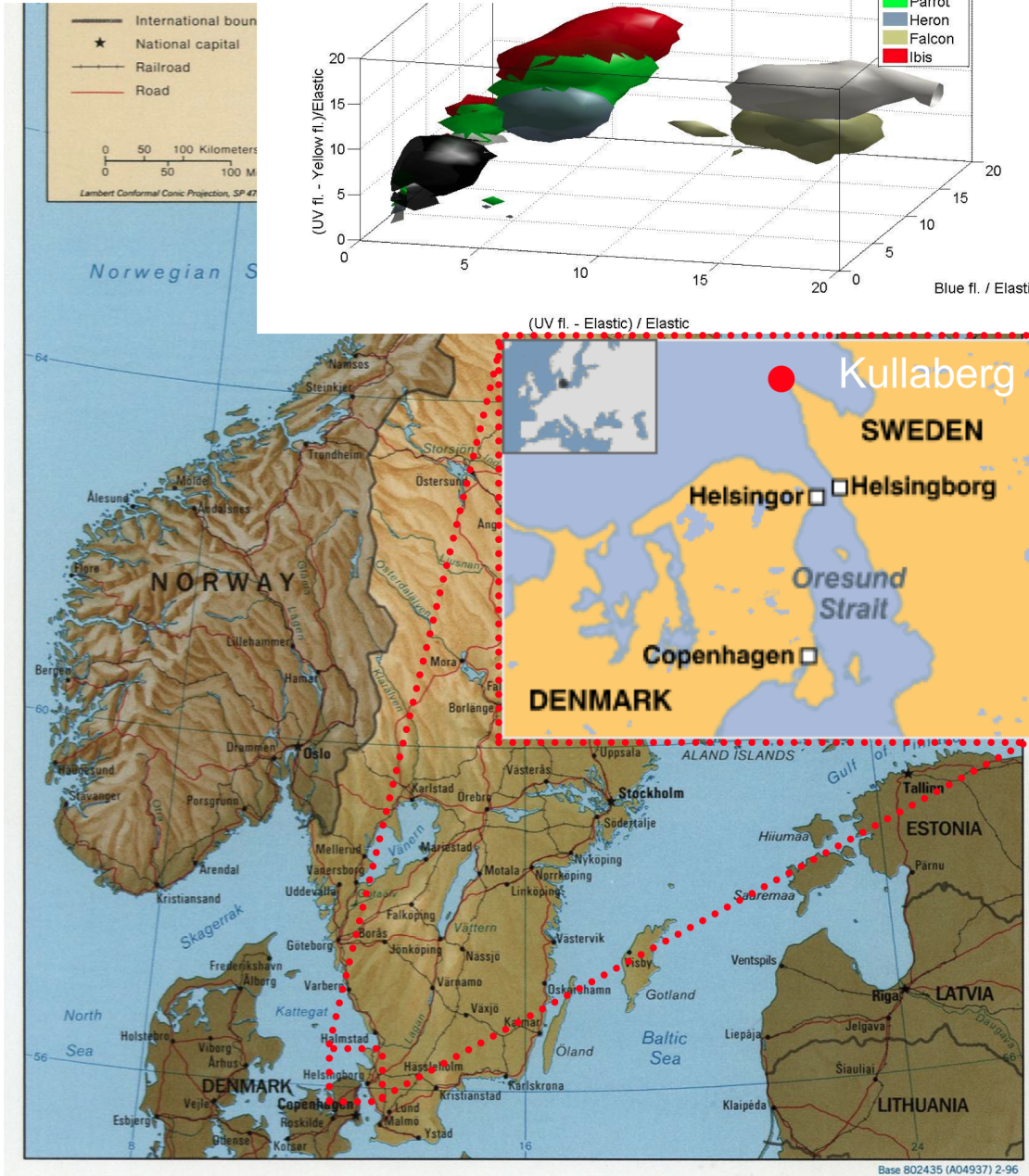
Field experiments – Birds

Lundin et al., to appear

Summary of Fluorescence Lidar

❑ Fluorescence spectroscopy has widely been used in many applications, such as the indoor experiments of forensic science, art inspection, and tissue diagnostics as well as biochemistry and biophysics.

❑ Fluorescence lidar techniques make it possible to extend the application of fluorescence spectroscopy to the outdoor environment (remote sensing), where large distance and uncontrollable background light have to be dealt with.

❑ Liquid or solid targets may have fluorescence effects with the fluorescence wavelengths red-shifted. By monitoring the fluorescence signals (in a wide wavelength range), faint species can be identified. This is especially useful in marine and vegetation monitoring.

❑ By proper gating the timing, range-resolved fluorescence can be collected from different ranges. Thus, the fluorescence lidar provides species information versus range.

❑ By scanning the lidar beam in combination with modern signal processing techniques, fluorescence lidar can also map the targets, revealing many features that are invisible to naked eyes.

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