Active remote sensing

Multispectral imaging (FAFF 020, FYST29)
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Overview

• Long-path absorption techniques
• Light detection and ranging (LIDAR)
• Differential absorption LIDAR (DIAL)
• Fluorescence LIDAR and imaging
Spectral irradiance of the sun

Sunlight at Top of the Atmosphere

5250°C Blackbody Spectrum

Radiation at Sea Level

O₃, O₂, H₂O, H₂O, H₂O, H₂O, CO₂, Absorption Bands
Basic principle of remote sensing

We know that optical spectroscopy can be used to analyze samples in the laboratory. Clearly, in order to extract information about the environment, e.g. the atmosphere, we need to be able to perform measurements at a distance. Such measurements are called *remote sensing*.

Interaction between radiation and object

Radiation through medium → Signal through medium

- Radiation source
- Receiver and detector
- System control and data acquisition
- Data analysis and interpretation
Passive remote sensing

Naturally occurring radiation is used for sensing

- Solar radiation through medium
- Interaction
- Signal through medium

Receiver and detector

System control and data acquisition

Data analysis and interpretation

- Photography
- Radiometer
- Spectrometer
- Interferometer
- ...

Photography
Radiometer
Spectrometer
Interferometer
...
Active remote sensing techniques

Long-path absorption measurements

Light intensity through an absorbing medium reduces according to:

\[ I(z, \nu) = I_0 e^{-\sigma(\nu)Nz} \]  

(Beer-Lambert law)

where \( \sigma(\nu) \) is absorption cross section (m\(^2\)) and \( N \) is number density (molecules/m\(^3\)).
Long-path absorption techniques – DOAS

• Based on long-path absorption of light from a broadband source, like the sun, the moon, or a lamp.
• **Merit:** Can deliver precise concentrations of multiple species simultaneously.
• **Limitations:** a) No range resolution. b) Constrained by their light sources. Methods that use the sun or moon as light sources are path- or intensity-limited

UV-DOAS system

from http://www.opsis.se

DOAS = Differential Optical Absorption Spectroscopy
Differential Optical Absorption Spectroscopy
DOAS
- Remote measurements of atmospheric trace gases in the atmosphere.
- Measurement is based on absorption spectroscopy in the UV and visible wavelength range
- To avoid problems with extinction by scattering or changes in the instrument throughput, only signals that vary rapidly with wavelength are analysed (thus the differential in DOAS)
- Use of simple, automated instruments for continuous operation

Satellite DOAS measurements

- NO$_2$ and NO (NOx) are key species in tropospheric ozone formation.
- They also contribute to acid rain.
- Sources are mainly anthropogenic (combustion of fossil fuels) but biomass burning, soil emissions and lightning also contribute.

- GOME and SCIAMACHY are satellite borne DOAS instruments observing the atmosphere in nadir.
- Data can be analysed for tropospheric NO$_2$ providing the first global maps of NO$_x$ pollution.
- After 10 years of measurements, trends can also be observed.

A. Richter et al., Increase in tropospheric nitrogen dioxide over China observed from space, *Nature*, 437 (2005).
Active remote sensing techniques

Long-path absorption measurements

Laser

Receiver

Retro-reflector

R

Light detection and ranging (LIDAR) a.k.a. laser radar

Laser

Receiver

The cloud serves as a “distributed mirror”
Concept of light detection and ranging (LIDAR)

Based on a pulsed laser and time-resolved detection of backscattering

The range is determined from the time-of-flight: \( R = \frac{c \cdot \Delta t}{2} \) (where \( \Delta t \) is the time-of-flight)

The highest range resolution is \( \Delta R = \frac{\tau_p c}{2} \) (\( \tau_p \) is the duration of the laser pulse)
The LIDAR equation

Assuming a single absorbing molecular species

\[ P(R,\Delta R) = C W N_b(R) \sigma_b \frac{\Delta R}{R^2} \exp \left\{ -2 \int_0^R [\sigma(\nu)N(r) + K_{ext}(r)]dr \right\} \]

The exponential factor describes the attenuation of the laser beam and the back-scattered radiation due to the presence of absorbing molecules and due to attenuating particles.

C: System constant
W: Transmitted pulse energy
N_b: Number density of scattering objects
\sigma_b: Backscattering cross section
N: Number density of absorbing molecules
\sigma(\nu): Absorption cross section
K_{ext}: Extinction coefficient
LIDAR applications

Atmospheric science

Ecology

Cultural heritage

Forestry
LIDAR for atmospheric probing

Resonant fluorescence from metal atoms

Rayleigh scattering from air molecules

Mie scattering from aerosols
Typical atmospheric LIDAR profile

Airborne Lidar Profile
25 March 1990
11.9°N 157.6°W

Photon Counts

Rayleigh Scattering
Detector Gain Switching
Aerosol Layers

Sodium Resonant Scattering
Meteor Trail

Δt = 12 s
Δz = 37.5 m
LIDAR using topographical target

- A topographical target, e.g. a brick wall or a mountain, results in a strong optical echo.
- The echo serves the role of a power meter.
- The intensity of the echo depends on several factors:
  - Laser pulse energy
  - Distance (which is easy to determine)
  - Telescope area
  - Reflectance (albedo) of the target
  - Absorption cross section of the atmosphere, $\sigma(\lambda)$
- If only $\sigma$ varies for a pollutant gas when $\lambda$ is changed from $\lambda_{on}$ to $\lambda_{off}$ and no other gaseous species interfere, the average concentration of the pollutant can be determined quantitatively from the Beer-Lambert law:

$$
\frac{P(\lambda_{on})}{P(\lambda_{off})} = e^{-2NR(\sigma(\lambda_{on})-\sigma(\lambda_{off}))}
$$

No range resolution!
LIDAR platforms

**Stationary**

Arctic Lidar Observatory for Middle Atmosphere Research (Alomar), Andøya, Norway

**Mobile**

**Airborne**

**Space**

www.fs.fed.us/pnw/olympia/silv/lidar/

www.nasa.gov
Lund mobile LIDAR system
Lund mobile LIDAR system
Differential absorption LIDAR (DIAL)

Same idea as LIDAR with topographical target, but now with range resolution

- DIAL allows species-specific concentration measurements of gaseous pollutants.

- Typically a tunable laser, alternately tuned on ($\lambda_{on}$) and off ($\lambda_{off}$) an absorption line of the species of interest, is used.

- The difference between $\lambda_{on}$ and $\lambda_{off}$ should be as small as possible (so that the backscattering cross section and extinction is the same for both wavelengths)

\[
P(\lambda_{on}, R) = e^{-2(\sigma(\lambda_{on}) - \sigma(\lambda_{off})) \int_0^R N(r) \, dr}
\]

\[
N(R) = -\frac{1}{2\Delta \sigma} \frac{d}{dR} \left[ \ln \frac{P(R, \lambda_{on})}{P(R, \lambda_{off})} \right]
\]
DIAL measurement of $O_2$ in ambient air

For uniform concentration, the DIAL equation is simplified:

$$\frac{P(\lambda_{on}, R)}{P(\lambda_{off}, R)} = e^{-2NR(\sigma(\lambda_{on})-\sigma(\lambda_{off}))}$$

$$N = -\frac{1}{2R(\sigma_{on}-\sigma_{off})} \ln \frac{P(\lambda_{off}, R)}{P(\lambda_{on}, R)}$$

The DIAL curve follows a single-exponential decay as expected.
DIAL measurement of sulphur dioxide (SO$_2$)

Absorption cross section

\[ \lambda_{\text{on}} \rightarrow \lambda_{\text{off}} \]

\[ N(R) = -\frac{1}{2\Delta\sigma} \frac{d}{dR} \left[ \ln \frac{P(R, \lambda_{\text{on}})}{P(R, \lambda_{\text{off}})} \right] \]
SO$_2$ plume DIAL scan at a Swedish paper mill

• DIAL measurements in 15 different vertical directions downwind from a paper mill

• The map can deliver the total SO$_2$ flux:
  - Integrate the concentrations over the area of the plume cross section
  - The flux is then obtained by multiplying this value with the wind velocity component perpendicular to the measurement plane
  - The flux is found to be 230 kg/h for the data shown to the right.
DIAL measurement of SO$_2$ emission from Etna

Laser beam

Flux: 50 000 kg/hour
Atomic Mercury
LIDAR Mapping and Flux Measurement
Rosignano Solvay, Italy
Fluorescence LIDAR
Fluorescence Spectroscopy - a well-established technique in many fields

Microscopy
Forensic science
Art inspection
Medical diagnostics

All these are indoor applications, but fluorescence methods can also be used in outdoor environments

Courtesy of Katarina Svanberg
Laser-induced fluorescence from liquids and solids

- In contrast to free molecules (gases) a fixed-frequency laser can often be used because of the broad absorption bands.

- Very fast (ps) radiationsless relaxation to the lowest level in the upper state. The shape of the fluorescence spectrum is therefore independent of the exact excitation wavelength.

- The overall fluorescence intensity is however dependent on the excitation wavelength. This dependence is revealed in an excitation spectrum, where the total fluorescence intensity is measured while the laser wavelength is scanned.

- Information can be obtained from:
  - Excitation spectrum
  - Fluorescence spectrum
  - Fluorescence lifetime
Fluorescence LIDAR basics

Background light is suppressed by restricting the detection to a very short temporal window. This is referred to as gated detection.
Fluorescence LIDAR system
Fluorescence LIDAR of vegetation

Point spectra

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a) Poplar: 100 shots, 64m
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b) Cypress: 100 shots, 125m
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c) Plane-tree: 100 shots, 210m
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d) Cypress: One shot, 125m
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Wavelength (nm)  Wavelength (nm)
Fluorescence LIDAR imaging

Two major considerations:
• Stationary or moving targets?
• Signal-to-background ratio

Three different imaging strategies:

Simultaneous 4-color imaging

Pushbroom imaging

Scanning pointwise imaging
Fluorescence LIDAR imaging of vegetation
Simultaneous 4-color imaging of benthic vegetation

Images recorded at four different center wavelengths

Spectrum of water
Spectrum of red alga
Spectrum of the two green algae
Fluorescence LIDAR imaging of vegetation

Pushbroom imaging

Norway spruce (*Picea abies*)
LIDAR IN CULTURAL HERITAGE MONITORING

LUND CATHEDRAL
Scheimpflug principle

Theodor Scheimpflug (British patent 1904)

Jules Carpentier (British patent 1901)

Scheimpflug Lidar

Subject plane

Focal plane

Lens plane

Image plane

CCD

No tilt

Scheimpflug intersection

Hinge intersection

Laser beam
Mobile Scheimpflug lidar

High power laser diodes from visible to near infrared region are widely available!!
• Telescope battery
  - \( \phi = 300 \text{ mm}, f = 1200 \text{ mm} \) (2)
  - \( \phi = 100 \text{ mm}, f = 500 \text{ mm} \) (2)
  - \( \phi = 100 \text{ mm}, f = 1300 \text{ mm} \)
• Lasers
  - 405, 445, 532, 660, 810, 980 nm (cw diode lasers)
  - 1550 nm (pulsed fiber laser)
• Photodiodes
  - Si quadrant (20 kHz)
  - InGaAs quadrant (20 kHz)
• Cameras
  • Line scan cam. (18 kHz)
  • High-speed cam. (170 Hz)
• Spectrograph
• Weather station
Entomological kHz CW lidar @ 808 nm

Telescope battery
Beam termination
Redeployment
All insects goes bright in the SWIR
Thanks for your attention!