AEROSOL TYPE IDENTIFICATION USING UV-NIR-IR LIDAR SYSTEM

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Abstract

During the last few years there is a growing interest in accurate monitoring of natural and anthropogenic aerosols due to their effect on climate forcing, public health and agriculture [1]. Aerosols type identification and their chemical composition determination may help to trace their origin using back trajectory calculations. Aerosols chemical composition, size distribution and particles shape, manifest themselves in their spectral scattering cross-section. In order to make a reliable discrimination, comprehensive spectral analysis of aerosol scattering should be carried out. Usually, spectral Lidar measurements of aerosols are most efficiently performed using an Nd:YAG laser transmitter in the fundamental frequency and its 2nd, 3rd and 4th harmonics. In this presentation we demonstrate detection and identification of several aerosol types, using a multi-spectral lidar system operating in the IR, NIR and UV spectral regions. The Lidar transmitter is based on a single Nd:YAG laser. In addition to the 3rd and 4th harmonics in the UV, two optical parametric oscillator units produce the eye-safe 1.5 μm wavelength in the near IR and up to 40 spectral lines in the 8-11 μm long wave IR. The combination of wide spectral range, the backscattering spectral features as well as fluorescence analysis, enable a reliable discrimination between several common aerosols. In order to utilize efficiently the system capabilities, discrimination and fast operational algorithms were developed. The system operation principals, description of the algorithms and some examples of aerosol discrimination including LIDAR real time operation will be demonstrated.

Lidar system description and the layout of testing field

The LIDAR transmitter is based on a Nd:YAG laser. The 3rd and 4th harmonies are generated in conventional BBO crystals. The eye-safe 1.5 μm of the near IR radiation is generated in an OPO system. Another OPO unit produces any selectable spectral line in the 8-11μm range (IR), having a spectral resolution of 5cm^{-1} [3]. The spectral lines are chosen using a programmed protocol (spectral position and appearance order). The spectral lines are transmitted sequentially, at the laser repetition rate of 10 Hz.

The detection unit, composed of three different sensors, covers the widely separated spectral channels. This versatile LIDAR system enables sensitive aerosol detection in the 1.5 μm channel followed by a detailed spectral analysis of aerosols backscattering. Both IR scattering, as well as fluorescence radiation resulted of UV exposure, form the basis for aerosol discrimination. Spectral analysis of the fluorescence signals is performed using an eight-channels spectrometer in the UV-VIS parts of the spectrum. In correspondence to the transmitter operation, the detection unit can be switched automatically between the spectral channels (based on a pre-designed detection protocol) or operate at specific wavelengths within one of the spectral channels.

Regarding the spectral capabilities of the IR laser, a detailed analysis can be performed using its quasi-continuous spectral operation. However, since the system repetition rate is 10 Hz and the wavelengths are transmitted sequentially, a detailed quantitative spectral analysis may take a few seconds. Investigation of transient phenomena and the need of a certain level of signals integration in order to ensure the appropriate signal to noise ratio, limit the number of practical transmitted wavelengths. A careful choice of the minimal wavelengths set that best discriminates the investigated aerosols should be made.

The detection unit of the UV channel utilizes a spectrometer with a linear array of photomultipliers. For the configuration of eight spectral channels the Regarding the wide spectral bands typical to the fluorescence phenomena, the number of the channels and their spectral width were chosen to give the best SNR and yet allow good discrimination of the investigated materials.

The entire system is controlled by three software packages: 1. Hardware control: This software package operates the laser (power, repetition rate), controls the movement of optical units directing one of the three spectral channels as the transmitted beam. It also directs the collected light into the appropriate detector. 2. Signal acquiring and preliminary processing. This package collects the received signals and the monitored transmitted laser power. The software package is composed of three units, suited to process each spectral channel. It generates a vector of the collected energy for every wavelength in the transmitted channel (IR) or fluorescence band (UV). 3. Discrimination algorithms. The package operates the

NIR detection channel, and according to its findings transmits the IR or UV channels. It receives the collected signals and performs a quantitative analysis using inversion techniques based on classical least squares method. The result is a combination of aerosols features that are represented in the system library.

The spectral data-base for the lidar performance evaluation consists of several dust types, oil aerosols and diesel fogs. Their spectral backscattering was measured in the laboratory for a specific realization of particles size distribution. For a more general class of size distribution functions the backscattering coefficient was calculated using Mie scattering formalism. The refractive index needed for the Mie calculations was evaluated from absorption measurements using the Kramers-Kronig relation. The spectral scattering cross-section was calculated for a number of size-distribution functions [2]. In order to demonstrate the system capabilities a few aerosol types were used. Oils were chosen to represent anthropogenic materials. Due to their low volatility, stable aerosol size distributions can be realized. Diesel fog was chosen since it has a distinctive backscattering IR spectrum and strong fluorescence.

Aerosols detection and discrimination test was performed using several aerosol dissemination points located at distances of 0.5-3 km from the lidar. The lidar scanned a wide angular section, performing detection and discrimination. The size distribution varied with cloud dispersion and fluctuated due to the natural atmospheric turbulence challenging the discrimination algorithm. Automatic detection and discrimination was achieved by employing a decision protocol that controlled the choice of the spectral channel, the scanning procedure and reported the finding.

Lidar operation and discrimination results

Discrimination of aerosols type using spectral scattering was demonstrated previously by a lidar operated in the IR region [2]. An early version of the lidar, employing a CO_2 laser as transmitter, was operated. The four spectral bands of the CO_2 laser, covered parts of the 9-11 μm spectral region. Two types of dust and the oil aerosols were analyzed using that IR lidar. Though spectral differences were evident, the difficulty to discriminate between two aerosol types that had a similar chemical content was noted.

In this presentation we demonstrate improved discrimination ability. The improvement is achieved due to the quasi-continuous spectral coverage of the 8-11 μm spectral range and the contribution of the two other spectral channels. Lidar operation is divided into two stages: detection and discrimination.

Detection

The detection procedure starts with the NIR channel activated. The relative high energy and large scattering cross-section provide sensitive aerosol detection capability that is used to define the cloud extent. Automatic aerosols detection starts when the spatial, temporal and signal to noise criteria for the backscattered signal are reached. The cloud extent is defined as the angular section including all LOSs containing aerosols that passed these criteria: the signal should be higher than certain times the noise root mean square. Aerosol type discrimination is performed using the spectral IR and UV spectral backscattering. Fig 1 shows an example of wide field detection. The cloud is shown at a distance of 600 meters, along several lines (circled) during one of the testing operations.

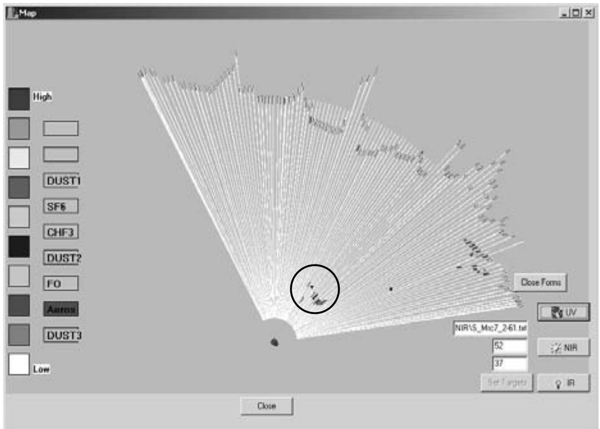

Figure 1: A field scan to locate aerosol clouds (enclosed by a circle).

Discrimination

The discrimination algorithms use a library that contains the spectral features of the aerosol expected to be present in the scene. Due to variations in the aerosol size distribution it is impractical to predict the exact backscattering spectrum. For each aerosol type a few variations of the spectral backscattering can be included in the library. However, inclusion of excessive variations of a similar spectrum can degrade the algorithm performance.

To demonstrate system performance we employed two dust types having differences in their spectral characterization, Diesel fog oil and silicone oil droplets. For this task the following spectral scheme was chosen for aerosol identification: a nine wavelengths set in the IR and the eight bands in the fluorescence detection package of the UV channel. The same spectral range was used to analyzed the fluorescence signal resulting from the 3rd and 4th Nd:YAG harmonics transmission. The elastic backscattering of the transmitted signals were optically filtered out therefore did not interfere with the fluorescence signals. Accurate discrimination of the diesel and dust was made through the combination of the IR and UV channels information.

The discrimination is based on a procedure that finds the best fit to a combination of aerosols from the spectral library. The algorithm output is the relative weights of the aerosols in library that forms the best spectral fit in terms of least squares. In order to improve the discrimination between similar aerosols that exhibits similar spectral characteristics within the chosen spectral bands, several constrains were imposed. They are primarily based on the spectral variations extant among the aerosols spectra. For example, spectral wavelengths that show low variance (aerosol size, refractive index) get a higher weight in the algorithm relative to those with larger variance. A detailed discussion of the lidar operation procedure will be given in the presentation. An example showing silicon oil discrimination, normalized to path-concentration that produces signal to noise of unity, is shown in Fig 2. The silicon oil aerosol is represented by two, somewhat different, backscattering spectra addressing small variations in spectral characteristics (marked silicone I and II). This spectral difference is associated with two different aerosol size distributions. The difference between the weighted concentration of the silicon oil and that of the other specimen in the library is evident. The concentration of silicone type I is considerably larger than that of silicone type II, during the entire measurement.

The UV channel is based on the transmission of the two wavelengths: 355 nm and 266 nm. The fluorescence resulting from the Nd:YAG 4th harmonics proved to be a reliable tool for aerosols discrimination, especially in the case of Diesel fog oil. However, due to the poor atmospheric transmittance of this wavelength, the 3rd harmonics was also used. In most applications the information of the two channels could be added to increase reliability. An example of Diesel fog oil detection in the two UV channels, and the ratio of the concentrations derived separately from each channel, is depicted in Fig. 3. Discrimination between dust and Diesel fog could rely at certain concentration levels on spectral IR backscattering. The crossing of the information between the IR and UV channels can help to discriminate between them during events of low signal to noise ratio.

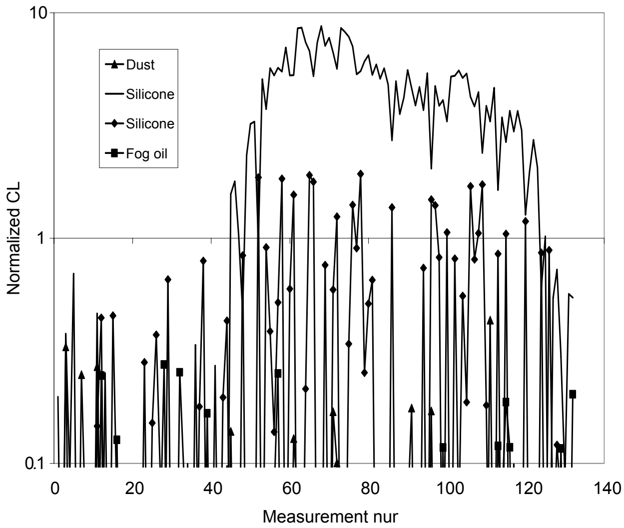

Figure 2.: Detection of silicone cloud in the field as a function of time.

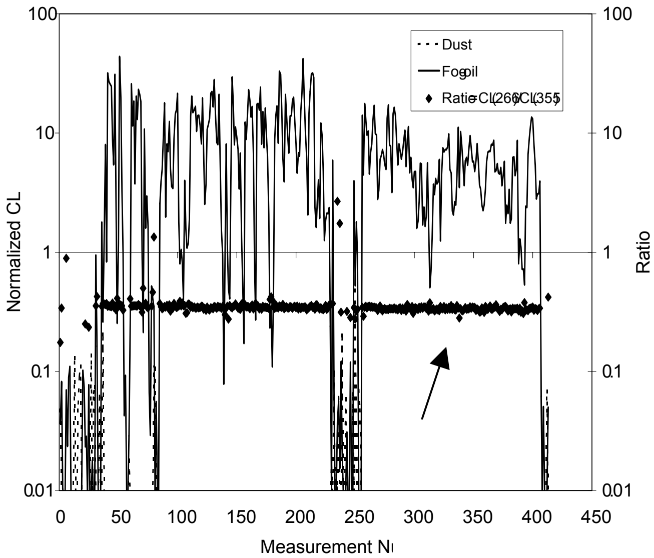

Figure 3.: Detection and identification of Diesel fog oil from fluorescence measurements. The arrow points on the ratio of the concentrations derived from the two wavelengths transmition.

Automatic operation

In order to achieve efficient use of the system wide spectral coverage, automatic operation should be employed. This operation algorithm should maintain fast switching among the spectral channels and the operation of the appropriate channel according to the lidar finding. Such an operation is similar to a feed closed loop controlled system. The major stages of the operational algorithm developed are listed below:

- NIR detection: Performed over the entire angular field of the system. Aerosol detection determines a sub angular field in which the cloud is included. Discrimination procedure is performed over this partial field section (as depicted in fig .1)
- IR operation: A few bursts of the wavelength sets are transmitted. The LIDAR can perform spatial scanning or measure along a single line of sight according to the application. Discrimination algorithm is performed on each spectral set. In the case of confident discrimination the LIDAR sends a report and repeats this operation n times to gain reliability. If reliability criterion is achieved (m out of n discriminations) the LIDAR is switched to the NIR channel for cloud tracking. If the aerosol was not discriminated or the discrimination needs a confirmation, the system is switched to the UV channel.
- UV operation is performed as described above. In case of accurate discrimination the LIDAR is switched to the NIR channel for cloud tracking. If the aerosol was not discriminated the LIDAR is switched to the NIR channel back to the beginning of the process in order to optimize the cloud angular allocation.

The parameters governing LIDAR operation depend on the application and can be changed easily. These parameters include: The number of transmitted wavelengths, the n and m parameters, the level of temporal integration needed to gain accurate discrimination.

The detailed lidar characteristics, their implication on the spectroscopic features used in these measurements and examples of the automatic operation, will be presented.

Summary

Spectral discrimination of several aerosol types was demonstrated using a unique multispectral UV-NIR-IR LIDAR. Efficient fast algorithms were developed for automatic system operation and accurate discrimination. System operation and its capability were demonstrated with the detection and discrimination of four aerosols types was demonstrated. The LIDAR detection and discrimination scheme is parametric and can be tailored to suit best the expected aerosols on the scene.

Most airborne and space lidar systems are based on Nd:YAG laser transmitter. Improvement of atmospheric monitoring capabilities can be achieved by adding the spectral information offered by the UV/IR channels of this system.

Literature

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