Appl. Phys. B 55, 13–17 (1992)

Applied Physics B Photophysics and Laser Chemistry

A Four-Wavelength Depolarization Backscattering LIDAR for Polar Stratospheric Cloud Monitoring

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Received 29 November 1991/Accepted 6 March 1992

Abstract. A four wavelength backscattering depolarization LIDAR designed for polar stratospheric cloud and stratospheric aerosol measurement is described. The system uses the following wavelengths: 355 nm, 532 nm, 750 nm, and 850 nm. These wavelengths, obtained by means of the third- and second-harmonic of a Nd:YAG laser and by means of a tunable Ti:Sapphire laser, are chosen in a way to better characterize the particel size of such stratospheric aerosols. They are not emitted simultaneously as the LIDAR system is designed with only two detection channels permitting to detect, in the analog and in the photon counting mode, both the direct and the depolarized backscattered signal. The system has been operational in northern Finland since the end of November 1991.

PACS: 42.68.Ay, 42.68.Ge, 42.68.Mj, 93.30.Sq

A four-wavelength depolarization backscattering LIDAR has been designed and developed in the frame of the European Arctic Stratospheric Ozone Experiment, within the subprogram "Experiment LIDAR Stratosphere Arctique" (ELSA). The present LIDAR system derives from a previous model which has already been operational in the Antarctic for three consecutive years [1] and has been implemented with the new wavelengths: the system now operates at 355 nm, 532 nm, 750 nm, and 850 nm. Additionally, on each wavelength the signal depolarization can be measured. The wavelengths have been chosen to be able to distinguish between background aerosols, volcanic aerosols, polar stratospheric clouds (PSC) of type Ia and b and polar stratospheric clouds of type II. PSCs play a major role in the physical chemistry of the *Ozone Hole*. On the surface of the cloud particles heterogeneous reactions occur causing denitrification and dehydration of the polar stratosphere and liberating active chlorine compounds.

1 Description of the LIDAR System

1.1 Why a Four-Wavelength LIDAR?

Polar stratospheric clouds can be devided into two main categories [2–4]: nitric acid trihydrate (NAT) clouds and ice water clouds. The first are generally referred as PSCs of type I, the latter of type II. Type I clouds, from experimental measurements, present two different habits, the so called PSC Ia and PSC Ib [4]. In Table 1 their main characteristics are indicated.

Table 1. Polar stratospheric clouds type I: NAT clouds

	Type Ia	Type Ib
Particle shape	aspherical	spherical
Particle size	$> 1\,\mu m$	$\approx 0.5\,\mu m$
Cloud particles/CN	$\ll 1$	1
Depolarization ratio	$>10\%$	$<10\%$
Backscatter ratio	< 2	> 2

PSCs of type II should present large depolarization ratios and a large backscatter ratio. This case should be easy identifiable by means of a simple depolarization LIDAR. More complex could be the identification of the two types of NAT clouds, because of the small size of their particles. The combined use of the depolarization technique and different wavelength will enhance the possibility of deriving information of the particle size distribution. The selected range of wavelengths, from 355 nm to 850 nm, should permit to invert the LIDAR signature in order to obtain realistic size distributions in the range from $0.05\,\mu m$ to $2\,\mu m$. From Mie calculations carried out for spherical particles with variable index of refraction ($1.33 \le n \le 1.5$) [5, 6] and with log-normal size distribution it results that using this range of wavelengths it is possible to distinguish aerosols with a mean radius of the order indicated above. This solution responds also to an easy to handle and technically feasible system.

This solution corresponds also to the fact that in the Arctic region mainly NAT clouds should be detectable, therefore to clouds formed by substantially small crystals in the micron and submicron range.

1.2 The Transmitting Section

The LIDAR system is housed in a standard 20 feet shelter, thermally insulated for operation in polar regions.

The transmitter is formed by two solid state lasers, namely a Nd:YAG laser operating in the second- and third-harmonic and Ti:Sapphire laser. The main characteristics of the Nd:YAG laser are given in Table 2.

The system is studied in a way that only one wavelength may be coupled out into the atmosphere at a time. A motorized slit introduces, at the requested time, the THG into the optical path. A half wavelength plate is inserted into the path in order to obtain both the 532 and the 355 nm radiation at the output with the same polarization. A dichroic beamsplitter is inserted into the optical path, when the THG is inserted, to eliminate the residual 532 nm radiation. The change in wavelength, the number of pulses, the pulse repetition frequency, and the sequence of laser firing intervals can directly be controlled via a computer.

On a mechanical bench on top of the Nd:YAG laser a flashlamp pumped Ti:Sapphire laser is mounted. This laser has been designed by the Freie Universität Berlin. The characteristics of the laser are given in Table 3.

Heart of the laser is a 8 mm diameter Sapphire rod, 180 mm long, doped with 0.1 wt.% titanium. It is pumped by four flashlamps in a diffuse cavity. As the lifetime of the upper level of Ti:Sapphire is only 3.2 µs the lamps have to be driven with a rather high voltage to give a very short light pulse. In order to reduce the discharge time, a prepulse is used which lowers lamp inductance just before the high-voltage pulse. The prepulse also stabilizes the spark and allows the use of a smaller simmer current. Although short light pulses are the most demanding operational mode for flashlamps, the use of four lamps with only 35 J pulse energy each and the reduced simmer current prolongs the lifetime of the lamps to about 10^6 shots.

Table 2. Nd:YAG laser characteristics (Quanta Systems, model SYL 202)

Resonator	Unstable Gaussian
Pulse energy (532 nm)	350 mJ
Pulse energy (355 nm)	150 mJ
Pulse repetition rate	10 Hz
Beam divergence (full angle)	0.5 mrad

Table 3. Ti: Sapphire laser characteristics

Tuning range	720–870 nm
Pulse repetition rate	1–10 Hz
Energy (750 nm)	100 mJ
Energy (850 nm)	100 mJ
Beam divergence (full angle)	2 mrad

In a plane convex resonator the laser threshold is reached at 30 J pump energy. With a maximum pump energy of 150 J the laser pulse energy reaches 400 mJ at 800 nm. In free running mode the pulse length varies between 200 ns with a single spike and 4 µs with several spikes in laser pulse depending on pulse energy. Pulse length can be reduced to about 500 ns using an acoustooptic modulator or less by a Pockel's cell for Q-switching inside the resonator.

For tuning the wavelength and reduction of bandwidth a four plate Lyot filter is used. It allows tuning from 720 nm to 870 nm with 0.2 nm bandwidth. This tuning range is limited by the reflectivity of the mirrors used in the cavity.

The beam diameter is 5 mm at the output coupling mirror and 15 mm after a beam expander with a resulting beam divergence of 0.5 mrad (full angle).

During automatized PSC measurements the laser is controlled by a small realtime computer. It allows high-voltage, trigger control and wavelength tuning as well as, moving a beamsplitter for pulse metering, peak detection of the pulse meter output, A/D conversion, and statistical analysis of pulse energies. It communicates with the host computer steering the experiment and performs operations in a multitasking mode.

The optical layout is such that the output beams of the two lasers, by means of totally reflecting mirrors and one dichroic beamsplitter, are coupled out into the atmosphere in a coaxial configuration with the receiving telescope. The dichroic beamsplitter is placed in the vertical path above the center of receiving telescope. This beamsplitter is transparent for UV and 532 nm radiation and is reflective in the infrared region. All the optical path has been carefully designed in order to preserve the polarization at the various wavelengths. The last optical element before the output window is a movable beamsplitter used to monitor the energy of the LIDAR pulses. That mirror is controlled by the computer and driven via the dedicated microprocessor. About 8% of the total energy pulse is fed to a power meter. After having averaged the output energy over N shots it can be automatically removed from the optical path.

The output laser pulses and the backscattered radiation are coupled out of and into the shelter via a 600 mm × 600 mm double fused silica window. At the center of this window, there is a circular aperture where a 200 mm diameter fused silica window is mounted. This double window is high-power antireflection coated for the output laser beam.

1.3 The Receiving Section

The receiver is formed by a double folded Newtonian telescope (500 mm in diameter), with lateral output. In the focal plane of the telescope different field stops can be inserted, in order to change the receiver's field of view. The output wavelengths are collimated and the parallel radiation encounters a filterwheel, with four possible positions, where the narrow bandwidth interference filters are mounted. The filterwheel is motorized and computer driven. In Table 4 the characteristics of the interference filters are given.

After the interference filters two cube polarizers are mounted in order to obtain the maximum separation of the two polarizations.

Table 4. Interference filter characteristics

Wavelength [nm]	Bandwidth [nm]	Transmittance
355	1	0.3
532	0.15	0.4
750	1	0.75
850	1	0.75

Both analogue and photon counting detection are simultaneously performed. This is obtained by using a 100 MHz amplifier at the output of the PMTs (two EMI 9658 photomultiplier tubes), which present two separate exits: one signal is sent to the transient digitizer, the second to the photon counting chain. Both PMTs present a gating circuitry to reduce the effect of overloading in the near altitude range.

1.4 The Acquisition Electronics

The acquisition electronics is formed by LeCroy modules which both provide analogue and photon counting acquisition mode. The acquisition unit is substantially equal to the one described in a contribution [7].

All acquisition electronics is housed in a LeCroy crate (model 14428A). Two 5 MHz, 12-bit 6810 transient digitizers are used for the analogue mode detection, each one serving one PMT. Two photon counting chains formed by the following units are used (one for each PMT):
- 8501 programmable clock generator;
- Model 3521 multichannel scaler (1 µs minimum dwell time, 100 MHz max. counting rate);
- MM8206A, 64 Kbyte/16-bit auxiliary memory module

A MAGIC-GPIB 6010 interface connects the LeCroy crate to a 386 based rack-mounted P.I.CO ASEM-industrial personal computer. This interface is an intelligent system driven by a Motorola microprocessor. To this unit also the lasers, filterwheel, and energy meter are connected via dedicated interfaces.

1.5 Processing Electronics

A second 386 ASEM personal computer is housed inside the shelter and dedicated to data processing. The two computers are connected via RS232 interfaces for data exchange procedure. A set of processing programs have been written both for quick look purposes and for final data analysis.

2 Ancillary Instrumentation

A PRT-5 narrow bandwidth, narrow field of view radiometer, operating in the 8–10 µm range has been mounted outside the shelter. This radiometer points vertically, with the aim to measure in the same volume as the LIDAR. The PRT-5 has been produced with costumer requested specifications with a radiative temperature range from 0 to −90° C. This should allow to measure radiative properties of PSCs. The output of the PRT-5 is directly interfaced with the acquisition computer via a slow A/D converting unit.

A vertically pointing wide angle TV camera with time lapse videorecorder is mounted vertically to monitor, when possible, cloud coverage.

3 Acquisition Software

This LIDAR system permits both tropospheric clouds LIDAR measurements and stratospheric measurements of aerosols, clouds, and upper stratospheric temperature.

Different acquisition modes can be chosen. One to four wavelengths can be chosen for each set of measurements. Measurements can be carried out either on one detection channel or on two. It is possible to make simultaneous analogue and photon counting mode acquisition or to choose one single type of mode.

Pulse repetition rate and number of shots to be performed by each laser can be chosen by the operator.

For each PMT the gated time interval during which the PMT has a low gain can be selected. The linearity of the PMTs in the gated time interval has been tested.

Once the operator has chosen all these independent parameters and the number of sequential measurements which have to be performed, the LIDAR measurement can be started.

All the acquisition programs are resident in the MAGIC-GPIB controller, which is activated by means of the master computer. The measurements start at a given wavelength. As reference wavelength the 532 nm line has been chosen. When the Nd:YAG laser is ready to fire at 532 nm, the appropriate interference filter is moved automatically into position and the pulse repetition rate is set. The first laser fires for the number of programmed shots, then it stops, the new wavelength is inserted (in the normal operation this is the 355 nm line), the filterwheel is placed in the new position, and a new set of LIDAR pulses is fired. When the complete cycle has been performed the next step consists in setting the Nd:YAG laser in stand by mode and preparing act the Ti:Sapphire laser for firing by choosing the proper wavelength by driving into position the Lyot filter and moving the filterwheel into the right place. The first IR operation will be at 750 nm. At the end of this cycle the next wavelength is chosen both for the laser and the filterwheel. At this point a first set of measurements has been performed. An iteration procedure permits the acquisition of the desired number of measurements. At the beginning of each measurement at each wavelength an energy measurement is carried out over a number of shots. The energy at each wavelength is recorded. Typically, a stratospheric aerosol measurement is carried out under the following conditions:
- Acquisition on the parallel and depolarization channel in analogue and photon counting mode;
- The Nd:YAG laser operates at 10 Hz and averaging in the UV and visible is performed over 1000 to 2000 shots;
- The Ti:Sapphire laser operates at 3 to 10 Hz, acquisition is performed averaging over 1000–2000 shots.

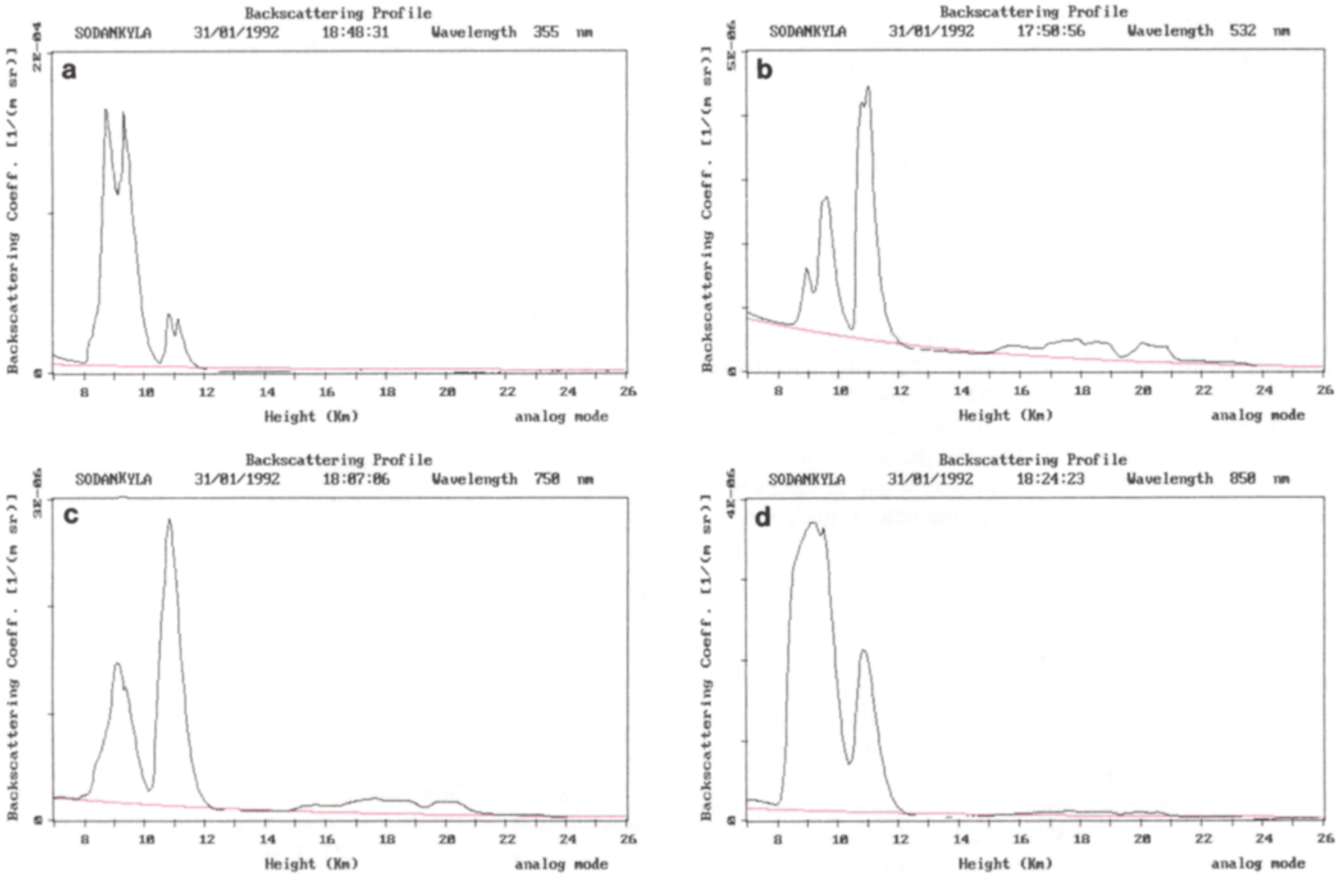

Fig. 1. Backscattering profiles vs height measured in Sodankyla, January 31, 1992. The measurements are performed at 355 nmm 532 nm, 750 nm, and 850 nm. Between 14 and 22 km a diffuse stratospheric aerosol layer due to Pinatubo appears to be present.

One set of measurements is carried out in a maximum time interval of 15 minutes. This time seems reasonable taking into account the experience derived from PSCs measurements in the Antarctic [4].

4 Processing Software

A quick look data analysis program has been developed in order to have a first, almost in real time, analysis of the event. This program computes, using a subarctic molecular atmospheric model, the backscattering coefficient, the backscattering ratio, and the depolarization ratio at each wavelength. Figure 1 shows the backscattering profile between 7 and 26 km altitude at 355 nm, 532 nm, 750 nm, and 850 nm. These measurements were performed in Sodankyla, in northern Finland on January 31, 1992 during the EASOE campaign. From all the figures it appears clearly that the LIDAR can penetrate cirrus clouds and detect aerosol layers located above. The Pinatubo cloud between 14 and 24 km is evident. Cirrus clouds appear at the bottom of the Pinatubo layer between 8 and 12 km altitude. Figure 2 shows the relative scattering and depolarization ratios. It is to be noted that in the measurements carried out at 750 nm and 850 nm there is an approximately 5% level of constant depolarization present due to the nonperfect polarization of the output Ti:Sapphire laser pulse. In a further data processing step this fact can be taken into account. From the behavior of the scattering ratio at the various wavelengths in the Pinatubo layer, from Mie calculations for spherical particles, and the index of refraction corresponding to a solution of sulfuric acid, it derives that the Pinatubo particle sizes have to be smaller than 0.6 μm. This is also confirmed by the negligible depolarization ratio computed inside the Pinatubo layer. The sensitivity of the instrument to depolarization is shown from the values obtained inside the cirrus layer. From these figures it appears that a good signal is still obtainable at heights of the order of 26 km for all wavelengths also in the presence of a relatively optically thick cirrus layer.

The quick look processing program permits also to produce an output file containing all important information about the measurement in its header: location, time, wavelength etc., then from the aerosol bottom to the top at 150 m intervals the scattering ratio and the depolarization ratio are listed.

A similar program is also being assembled which uses the data obtained by the daily radiosonde as molecular atmosphere measurements. The LIDAR signature is then inverted using a simple Klett method which permits a realistic correction of the extinction. Such a program will be used for the final analysis of the data.

Inversion algorithms for deriving particle size distributions have been prepared at the University of Berlin, at the Observatoire Cantonale de Neuchatel and at IROE-CNR.

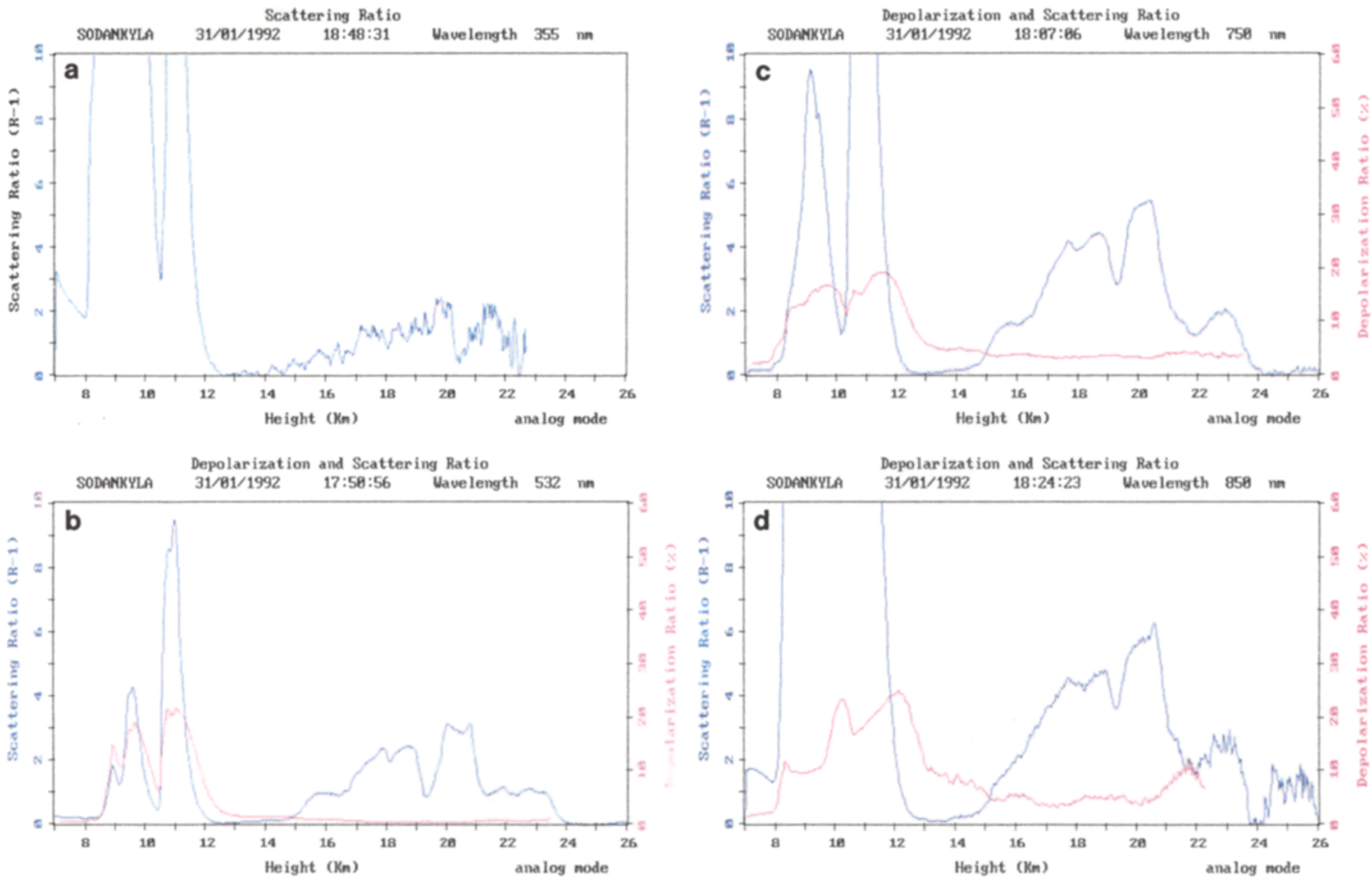

Fig. 2. For the same event of January 31, 1992, the depolarization ratio and scattering ratio vs height are plotted for the four wavelengths. The lower curve (red) indicates the depolarization ratio, the upper the scattering ratio (blue). For the 355 nm only the scattering ratio has been plotted. A substantially negligible depolarization appears especially in volcanic aerosol, while a strong depolarization is obtained in the presence of cirrus clouds

Acknowledgements. This research was carried out in the frame of the Italian Special Program on Electro-optical Technologies (TEO). The EASOE campaign was founded both by national agencies and the Commission of the European Communities.

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