NEW TROPOSPHERIC LIDAR SYSTEM IN OPERATION AT ALOMAR (69°N, 16°E)

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ABSTRACT

The ALOMAR Observatory at 69°N 16°E (Arctic Lidar Observatory for Middle Atmosphere Research) offers an international research infrastructure particularly designed for the operation of advanced lidars [1]. Three lidar systems, namely an advanced RMR lidar for mesopause investigations [2], a metal resonance Na lidar [3] and an elastic DIAL O_3 lidar [4] are exploring the Arctic middle atmosphere. ALOMAR is owned and operated by the Andøya Rocket Range, the world's northernmost permanent launch site for atmospheric-sounding rockets.
Recently the University of Oslo and ALOMAR built a new, fourth lidar system, the tropospheric lidar. As the other lidars are not sensitive to returns from the troposphere, this system fills the gap from almost ground level to the stratosphere. The present paper presents the system's scientific aims, its capabilities and the first obtained results.

1. INTRODUCTION

Despite their potential importance for climate, aerosols in the Arctic have not been studied in detail. Due to the rough climate, the lack of a close network of stations together with logistical challenges, aerosol properties, transportation mechanisms and impacts on the global climate are rather poorly known. Nevertheless, a thorough understanding of aerosol properties is needed for the protection of the vulnerable ecosystem at high latitudes, which is presently affected by climatic changes and the impact of long-range transport of pollutants. Correspondingly the optical properties of arctic cirrus clouds and their radiative impact are important for the understanding of the global climate.
In the Arctic, long term observations, especially in-situ and a few aerosol lidar measurements, have been started at Ny-Ålesund/Svalbard (79°N) [5].
The location of ALOMAR, north of the Arctic circle and on an island, a few hundred meters from seashore and about 30 km off the continent makes it ideal for investigations related to Arctic phenomena such as noctilucent clouds, polar stratospheric clouds and Arctic haze. For air masses from the north and north-west ALOMAR can represent a reference station for almost unpolluted, clear air. Air masses advected above ALOMAR with back-trajectories from the north-east transport continental air from the urban centers in northern Russia, whereas western and south-western back-trajectories have a strong maritime influence. ALOMAR's year-around capability is essential for long term studies to include intra-annual variations. The new troposphere lidar significantly extends the dataset compiled by the combination of active optical instruments and allows also to link middle atmosphere observations to the processes of the troposphere. Co-located systems such as a sun photometer, a meteorological station, a balloon release facility and a MST radar (VHF 53 MHz) allow an interpretation of the lidar-acquired data in a broader context of the physical and dynamical processes involved.

2. INSTRUMENT

The most relevant technical characteristics are presented in Table 1. Since daytime capabilities are particularly relevant in the summer Arctic, the interference filters for the elastic channels and Raman channels are chosen rather narrow. Crucial for the daylight capability is also the powerful laser (1020 mJ at 30 Hz repetition rate), which has been used before for a mesosphere system. Part of the original 1064 nm light is transformed into its second (532 nm) and third harmonics (355 nm). The light at the latter two wavelengths is linearly polarized. A refractive beam-widening telescope expands the outgoing beam to about 5 cm and reduces the beam divergence to less than 140 µrad. The configuration of the lidar can be changed from co-axial to bi-axial through tilting the second beam guiding mirror and adding/removing a third guiding mirror on top of the telescope. The telescope is a Newtonian type with a parabolic primary mirror (focal length 125 cm). The effective focal length of the lidar is reduced in the focal box to about 60 cm. Also in the focal box the spectral selection (<450 nm , 450-600 nm, >600 nm) and the selection of the parallel- (p) and cross-polarized components (s) at 532 nm are performed. The two wavelength bands <400 and >600 nm are guided via optical fibers to a spectral analyzer separating elastic and different inelastic channels. These spectrally (and by polarization) separated channels are then additionally filtered using narrow band interference filters, what minimizes crosstalk and background noise. Behind the filters the beam is focussed on photomultiplier tubes or an APD, and finally the electronic output is analyzed by a combination of one transient recorder and one photon counting device for each channel. At the moment only 5 detection channels are used, but we will extend the data acquisition electronics to detect simultaneously the three remaining channels.

Transmission			
Laser type	seeded Nd:YAG Quanta Ray GCR 6-30		
Wavelengths	355, 532, 1064 nm		
Pulse energies (typical)	120, 290, 610 mJ		
Repetition rate	30 Hz		
Beam full divergence	400-700 microrad		
Detection			
	Interf. filter characteristics		
Channel * : future update	CW [nm]	BW [nm]	Transm. [%]
1064 nm o (no pol.)	1064.6	0.2	>50
532 nm p (parallel pol.)	532.3	0.35	>50
532 nm s (perp. pol.)	532.3	0.35	>50
355 nm o (no pol.)	354.8	0.2	>30
387 nm o (N_2 Raman)	386.8	0.2	>50
408 nm o (H_2O Raman) *	407.6	0.2	>50
608 nm o (N_2 Raman) *	607.7	0.2	>50
660 nm o (H_2O Raman) *	660.7	10	>50
Acquisition			
Transient recorder:	LICEL TR 20-160		
Analog mode			
A/D resolution	12 bits		
Raw resolution	7,5 m		
Photon counting			
Max count rate	250 MHz		
Discriminator	64 levels		

Table 1. Main device specifications (see also text)

3. MEASUREMENTS AND FIRST RESULTS

3.1 Measurements

Since the beginning of its operation in July 2005, the lidar has been operated for about 350 hours, including several time-series of more than a full daily cycle. The chosen temporal resolution is of 70 s while the range resolution 7.5 m is determined by the acquisition rate.
The far-field capability is exemplified in Fig 1, in which the signal-to-noise ratio is reported. It demonstrates that the lidar provides returns at 355 nm

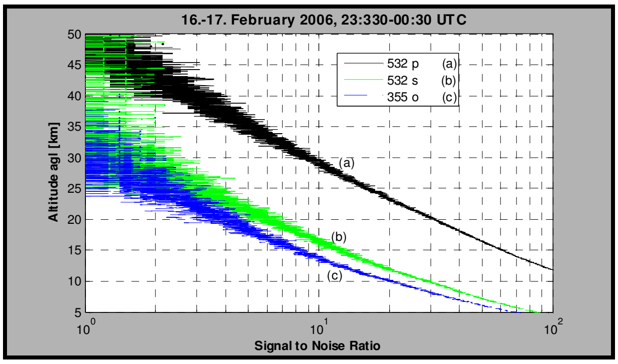

Fig.1 Signal-to noise ratio evaluated from the photon-counting data for three elastic channels. The integration time is 1 h (16.-17. February 2006, 23:30-00:30). The range resolution is 7.5 m.

and 532 nm up to the lower stratosphere. The much weaker return at 1064 nm (not shown) is connected to a rather high dark noise for the APD and to higher performance in analog than in photon counting mode, as confirmed by the manufacturer.

3.2 Processing methods

The profiles of aerosol backscattering coefficient (β_a) can be obtained by the signal inversion following the method proposed by Fernald [6]. This procedure requires a reference value as boundary condition and a relation between the aerosol extinction and the aerosol backscattering. The reference value is usually obtained by fitting the signal to a model signal from a purely molecular atmosphere in the upper troposphere. The relation between aerosol extinction and backscattering is given by assuming a value for their ratio, known as the lidar ratio (*lr*). Previous studies [e.g., 7-8] report typical *lr* values for different typical expected aerosol mixtures. In [7], lidar ratios evaluated from Mie-theory are within 20–25 sr for maritime aerosol and 55-60 sr for continental type. On the other hand, [8] reports measured values of 33 sr and respectively 68 sr for summer respectively winter time above the PBL at Kühlungsborn, i.e. close to the sea.
Several methods are used to characterize the vertical and temporal variation of the distribution of the tropospheric aerosol from lidar measurements at a single elastic wavelength (see e.g. [9-11]). These methods, particularly well adapted to the determination of the mixed layer height or PBL top, are based on the vertical gradient of the Range Corrected Signal (*RCS*). In order to compare different time-series and to eliminate the influence of the variation of the laser power at any chosen wavelength during long time-series, we use here the gradient of the logarithm of *RCS*

$$\frac{d\left(\log\left(RCS\right)\right)}{dz} = \frac{1}{\beta}\frac{d\beta}{dz} - 2\cdot\alpha \qquad (1)$$

where z is the altitude, β is the total backscattering coefficient, α the total extinction coefficient. The derivative term on the right side of (1) yields a visualization of the boundaries between aerosol layers.

3.3 Example of aerosol backscattering profiles

On 26 October 2005, the synoptic situation over Northern Norway was characterized by a transient high pressure ridge and clear skies between two frontal systems. On that day, the average wind speed measured at ALOMAR was about 6.1 ms^{-1} with a persistent orientation E – SE, while the average temperature was -3 °C. Since we expect both maritime and continental influences under such conditions, we chose a lidar ratio value of 40 sr for the inversion procedure.

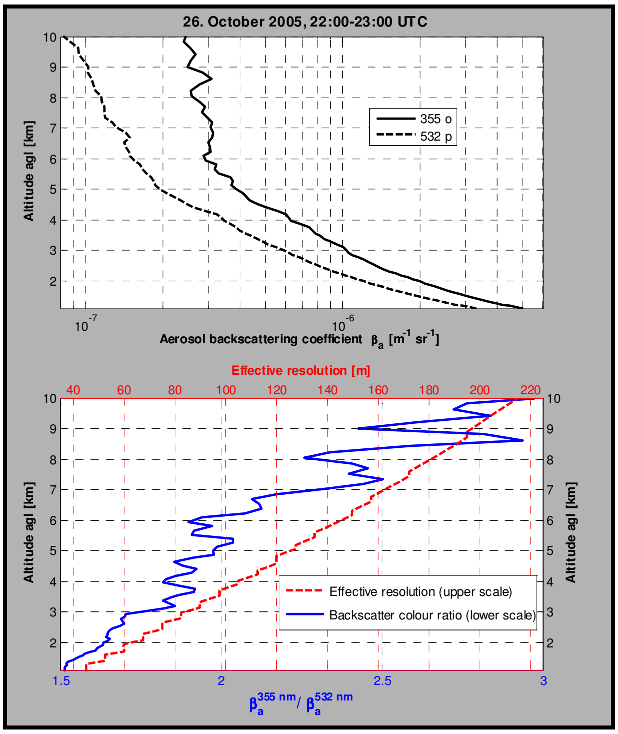

Fig. 2. Inversions' products from the elastic signals for the indicated channels. The assumed lidar ratio is 40 sr. The upper panel shows the derived profiles of aerosol backscattering coefficients. The lower panel shows the colour ratio of aerosol backscattering coefficients. In the same panel, the effective height resolution is indicated by the dashed line. In the upper troposphere and lower stratosphere (15 – 30 km), the measured signals have been fitted to model signals for a molecular atmosphere based on temperature and pressure profiles provided by the ECMWF database.

Fig. 2 reports derived profiles of aerosol backscattering coefficient (β_a) for the channels 355 nm and 532 nm (p) as deduced from a 1 h accumulation (22:00-23:00).
The obtained β_a values are quite typical ones. The ratio of aerosol optical coefficients at different wavelengths (colour ratio) gives information on the particle size. For that particular case, we notice a particularly strong increase of the colour ratio with altitude, what is the likely signature of a strong decrease of the average particle size, since this ratio is expected to vary typically from 1 for very large particles (white scattering) to about 5 for very small ones (Rayleigh limit). The height dependency of the colour ratio needs to be investigated on a statistical basis in connection with the synoptic conditions and air mass origin.
A quantitative evaluation of the average particle size would require at least lidar backscatter measurements at 3 elastic wavelengths and 2 Raman signals for an independent determination of the extinction at two wavelengths. Presently, the N_2 Raman at 608 nm is not available while the elastic signal at 1064 nm as well as the N_2 Raman signal at 387 nm present too poor signal-to-noise ratios for that purpose.

3.4 Example of aerosol stratification

Fig. 3 presents a time-series for measurements done in the middle of a period of about 10 days with stable anti-cyclonic conditions.

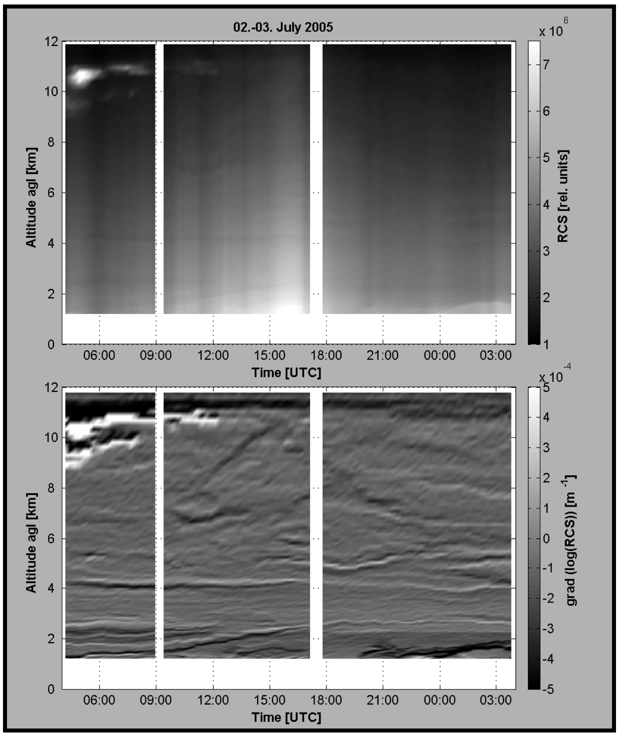

Fig. 3. Diurnal cycle of lidar observation on 2-3 July 2005. The temporal resolution is 15 minutes. The top panel shows the time-series of range-corrected signals (*RCS*) for the 532 nm (p) channel. The bottom panel show the corresponding altitude log-derivative, revealing the development of the aerosol stratification. In both panels, saturated colours are used.

During that diurnal cycle, the solar radiation was almost maximum (clear sky, midnight sun). The ground temperature measured at ALOMAR was 14 – 18 ºC, the pressure was within the range 975.77 – 977.95 hPa and the mean wind speed was 2.6 ms^{-1}. For technical reasons reliable data were only available above 1300 m above ground.

The *RCS* values inform about the aerosol content, but their temporal variation also depends on the transmission below 1300 m, that may vary considerably within an hour. The enhanced values from about 10:00 to 16:00 are likely associated with an enhanced convective activity under higher solar radiation. The inspection of the gradient of the log of *RCS* informs about the vertical aerosol distribution and its temporal development. For example the top of the aerosol layer around 1400 m before 10:00 is seen to grow up to about 2500 m at 19:00. Between 3000 m and 10000 m, we still notice a complex long lasting stratification over a predominantly well-mixed and aerosol poor background. The gradient also reveals clearly the presence of two cirrus layers for the first three hours of measurements and helps to identify their spatio-temporal extent Signatures of cirrus clouds are seen in the backscatter data about two hours longer as they were visible by naked eye.

4. SUMMARY AND OUTLOOK

A new fourth lidar system has been built at ALOMAR. This new system has shown its capability to provide returns up to the low stratosphere. In the long term, it will enable to investigate on a statistical basis the transportation of pollutants to the Arctic, the characterisation of Arctic cirrus clouds and of polar stratospheric clouds. In conjunction with the existing high atmosphere lidars and other in-situ and remote-sensing instruments it will link their data to the aerosol dynamics in the troposphere.

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REFERENCES

1. Thrane, E. V., and U. von Zahn, ALOMAR - A new facility for middle atmosphere research at Arctic latitudes, *J. Geomag. Geoelectricity* 47, 921-928, 1995.

2. von Zahn, U., G. von Cossart, J. Fiedler, K. H. Fricke, G. Nelke, G. Baumgarten, D. Rees, A. Hauchcorne, and K. Adolfsen, The ALOMAR Rayleigh/Mie/Raman lidar: Objectives, configuration and performance, *Ann. Geophys.* 18, 815-833, 2000.

3. Fritts, D. C., B. Williams, C.-Y. She, J. Vance, M. Rapp, F.-J. Lübken, and R. A. Goldberg, Observations and dynamics of extreme temperature and wind gradients near the summer mesopause during the MACWAVE/MIDAS rocket program, *Geophys. Res. Lett.*31, L24S06, doi:10.1029/2003GL019389, 2004.

4. Hansen, G., K. Bramstedt, V. Rozanov, M. Weber, and J. P. Burrows, Validation of GOME ozone profiles by means of the ALOMAR ozone lidar, *Ann. Geophys.* 21, 8, 1879-1886, 2003.

5. Ritter, C., Kische, A., Neuber, R.. Tropospheric Aerosol characterized by a Raman Lidar over Spitsbergen, Reviewed and revised papers presented at the 22nd ILRC, 12 - 16 July 2004, Matera, Italy, *ESA Publications Div.,* 459-462. ,2004.

6. Fernald F.G., Analysis of atmospheric Lidar observations: some comments, *Applied Optics* 23 (5), 652-653 ,1984.

7. Ackermann J., The Extinction-to-Backscatter Ratio of Tropospheric Aerosol : A Numerical Study, *Journal of. Atmospheric and Oceanic Technology* 15, 1043-1050, 1998.

8. Schneider and Eixmann, Three years of routine Raman lidar measurements of tropospheric aerosols: Planetary boundary layer heights, extinction and backscatter coefficients, *Atmos. Phys. Chem. Discuss.* 2, 75-107, 2002.

9. Melfi S.H., J.D. Spinhire, S.H. Chou, and S.P. Palm, Lidar observation of vertically organized convection in the planetary boundary layer over the ocean, *Journal of Climate and Applied Meteorology* 24, 806-821, 1985.

10. Flamant C., J. Pelon, P.H. Flamant and P. Durand, Lidar determination of the entrainment zone thickness at the top of the unstable marine atmospheric boundary layer, *Boundary-Layer Meteorology* 83, 247-284, 1997.

11. Menut L., C. Flamant, J. Pelon and P.H. Flamant, Urban boundary-layer height determination from Lidar measurements over the Paris area, *Applied Optics* 38, 945-954, 1999