EVALUATION OF CLOUD-TOP DETECTION BY SATELLITE-BORNE PSEUDO-RANDOM NOISE CONTINUOUS WAVE BACKSCATTER LIDAR

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ABSTRACT

We present an evaluation of the performance of the PRNcw backscatter lidar for cloud top detection from a polar orbit. The specifications of such perspective lidar are based on the use of a current state-of-the-art laser, detector and optical filter technology. The results show that such lidar have the necessary potential for both daytime and night time cloud top detection with high altitude and horizontal resolution.

1. INTRODUCTION

The principle of the amplitude modulated Pseudo-random noise continuous wave (PRN cw) backscatter lidar is presented in [1-3]. This type of lidar is suggested for various applications [3-6]. The advantage of the PRN cw lidar is in the use of cw lasers in range-resolved remote sensing. This possibility allows the system to be robust, compact and power efficient, what makes this lidar a convenient candidate for space missions.

It is also known that the detection performance in this lidar technique suffers more from the optical background and from stronger scattering features in the probed path, than the pulse based technique [7, 8]. These require a careful trade-off of this technique with an evaluation of the performance in the specific application.

Recently there is a substantial advance in fiber lasers and amplifiers, detector and filter hardware in the near infrared spectral range, with potential application in PRN cw lidars [9-12]. The availability of the novelty technologies requires a re-evaluation of PRN cw lidar performance with respect to various space-borne applications, already started in [13] for altimetry. With respect to such re-evaluation, this study presents performance simulations of cloud-top detection by a perspective PRN cw backscatter lidar on polar orbit.

2. PRN-CW LIDAR

In the power modulated PRN cw lidar the power of a transmitted cw laser is modulated by a PRN code with "full power" and "no power" corresponding to "1"-s and "0"-s in the code. The detected backscattered signal is cross-correlated with the initial PRN code, from where the response function of the probed media is assessed. In terms of received number of photons, the SNR of the PRN cw backscatter lidar is expressed as [1-3, 7]

$$SNR(j) = \sqrt{L}\,\frac{\bar{n}_{s,cc}(j)}{\sqrt{N\left(\bar{n}_s + \bar{n}_b + \bar{n}_d\right)}}, \qquad (1)$$

The value $\bar{n}_{s,cc}(j)$ is the cross-correlated backscattered photon-counts number from (altitude) sample j, averaged over the sequences, determined as

$$\bar{n}_{s,cc}(j) = \frac{N+1}{2}\xi_d \tau_c P_0 \bar{g}(j) \qquad (2)$$

Here ξ_d is the detection efficiency, P_0 is the averaged transmitted power, τ_c is the single bin duration in the PRN sequence and $\bar{g}(j)$ is the response function of the probed media for altitude sample "j" [1,2].

In (1) $\bar{n}_s$, $\bar{n}_b$ and $\bar{n}_d$ are respectively: the mean value of the detected backscattered photon-counts per bin and sequence, the same for the photon-counts numbers of the optical background and the detector dark noise. L and N are respectively the numbers of the PRN sequences in the measurement and the number of the bins in the PRN sequence.

The determination of the cloud top altitude may follow the "threshold procedure" as it is with the pulse lidar. [14]. The threshold procedure will use the cross-correlated signal of the cloud top instead of the direct lidar signal. Our objective is to evaluate the cross-correlated backscatter signal from the cloud top, necessary to determine its altitude. For such procedure we relay of the peak of the cross-correlated backscatter signal at the cloud-top, i.e., we do not intend to analyse the cloud backscatter signal with respect to the cloud bulk properties [15, 16]. In this way we may use single scattering as a first approximation for the backscatter response evaluation only from the cloud top.

The consistency of this approach was tested using a PRN cw backscatter lidar presented in [17]. The lidar operated in photon counting mode with a cw power of 11mW, from a diode laser at 780nm and a photon-counting detector. Fig. 1 presents the cross-correlated signal from a cloud base. The signal is accumulated for 2.55sec (night-time) with altitude resolution of 15m.

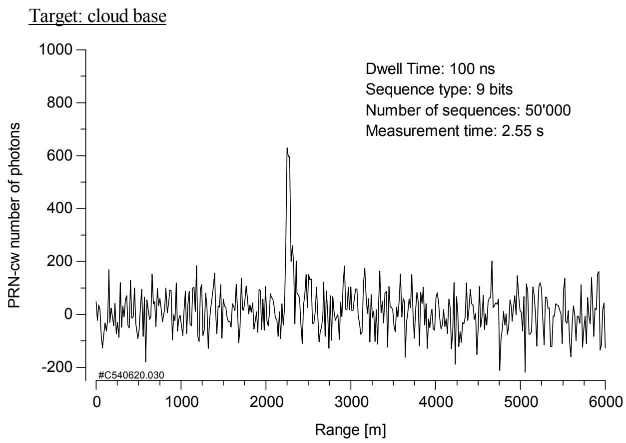

Fig.1. Cross-correlated backscatter signal from a cloud base: measured with a PRNcw lidar demonstrator.

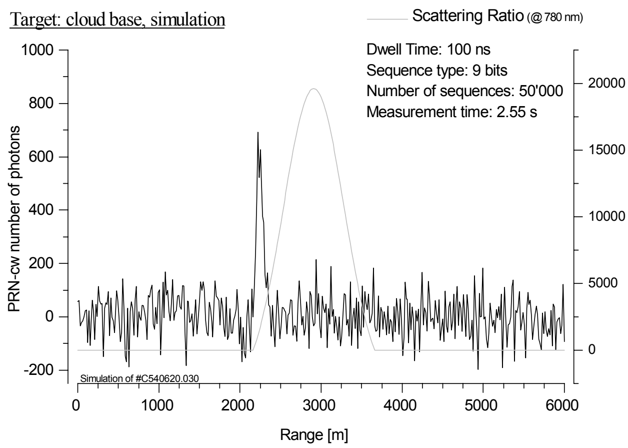

Fig.2. Cross-correlated signal from a cloud base: numerical simulation, cloud SR is shown in the right vertical axis.

We determined the transmitted power and the overall efficiency of the lidar with a series of calibration measurements. The specifications were used as inputs in the numerical simulations of the signal detected from a cloud. The cloud signal in the numerical simulations was assumed from a layer with a parabolic altitude distribution of the scattering ratio (SR), which is a variable parameter in the simulations. Other parameters of the cloud particles were assumed as: "lidar ratio"=20; "Angstrom exponent"= -1. The cross-correlated cloud signal, the altitudes of the cloud base and SR, for which the simulated signal appears identical to the actually detected one, are presented in Fig. 2.

3. INPUS FOR THE NUMERICAL SIMULATIONS

In our simulations we assume the following concept: A low-power cw diode laser (master) generates radiation with narrow spectral bandwidth in the range of 1.55μm (not coinciding with the absorption lines of any of the atmospheric components), what determines the possibility to use in the receiver an ultra-narrow-band filter [12]. The laser beam is modulated by a PRN code via convenient optical modulator. The PRN modulated beam is sent to the input of a fiber amplifier. In this way the transmitted beam has the spectral characteristics of the cw laser and the power is determined by the fiber amplifier gain [9, 10]. The basic subsystems specifications of the assumed PRN cw lidar are presented in Table 1.

Table 1. Specifications for the subsystems of the PRN lidar, assumed in the numerical simulations. The transmitted power and detector specifications are consistent with respectively [9, 10] and [11].

Satellite orbit, altitude	800km
Probing wavelength	1550nm
PRN code bin duration/altitude resolution	400ns/60m
PRN code bin number	2^{10}-1
Transmitted mean power	7.5W - 20W
Receiver aperture	180cm
Receiver field of view	0.1mrad
Optical Filter, FWHM	25pm
Optical Filter transmission	60%
Optical efficiency without the filter	50%
Detector quantum efficiency/dark noise	15% /500sec^{-1}
Integration time	0.1sec

We assume the cloud as an aerosol layer with parabolic altitude distribution of SR, with a maximum at 4700m asl. The cloud base and the cloud top are respectively at 3200m and 5600m, where SR=1. The cloud particles are with a "lidar ratio" =20 and "Angstrom exponent"= -1. The value of the SR at the maximum varies from 180 till 2600, at wavelength 532nm, determining optical depth (OD) at 532nm from 1.074 till 16.850.

4. RESULTS FROM THE SIMULATIONS

Figure 3 presents the altitude distribution of the SR in the cloud and the obtained SNR. The assumed transmitted power is 12.5 W. The cloud OD=5.18 at 532nm, with SR distribution as described above.

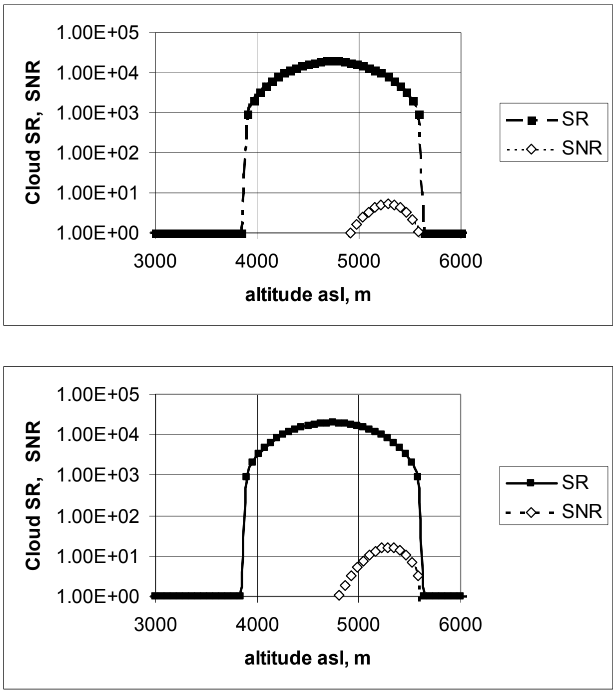

Fig.3. Cloud SR at 1550nm and SNR for cloud-top signal detection. Upper panel: daytime detection; lower panel: night-time detection. transmitter power 12.5W. The cloud OD=5.18 at 532nm.

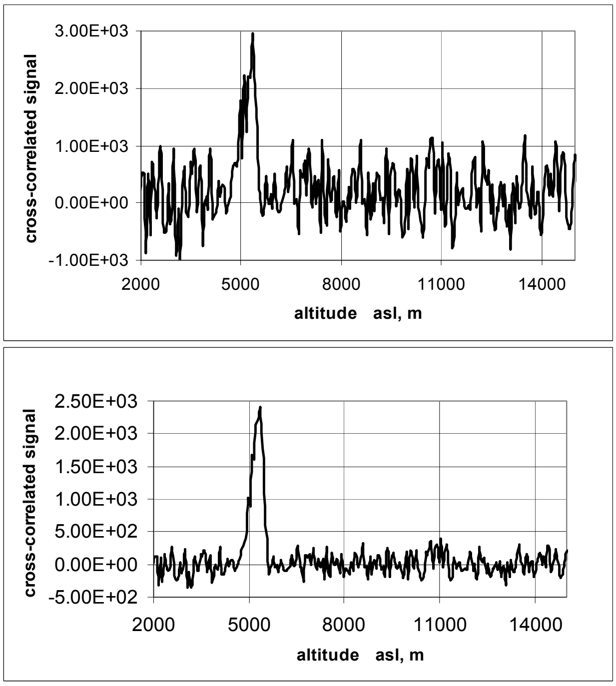

Fig.4. Cross-correlated backscatter signals from the cloud top. The cloud SR and the instrument specifications are as for the results in Fig. 3. Upper panel: daytime detection; lower panel: night-time detection.

As we see, both for day and night, the SNR allows a confident determination of the cross-correlated signal from the cloud top. The cross-correlated signals from the cloud top are also presented in Fig. 4 in linear scale, for a better evaluation of the possibility to apply the threshold method for evaluation of the cloud top altitude.

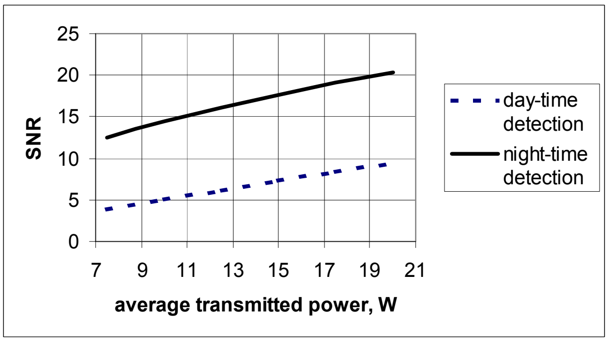

Fig.5. Dependence of the SNR on the transmitted power. Cloud SR is 180 at 532nm (OD=1.074 at 532nm).

The dependence of the SNR on the transmitted power is presented in Fig. 5. The numerical simulations are performed for cloud with OD=1.074 at 532nm, i.e., SR=180. This value of OD is considered as relatively low in reported statistical studies. The results presented in this figure show that the transmitted power necessary to achieve a confident cloud top detection is in the reach of the present fiber amplifiers, even for a cloud with relatively low OD.

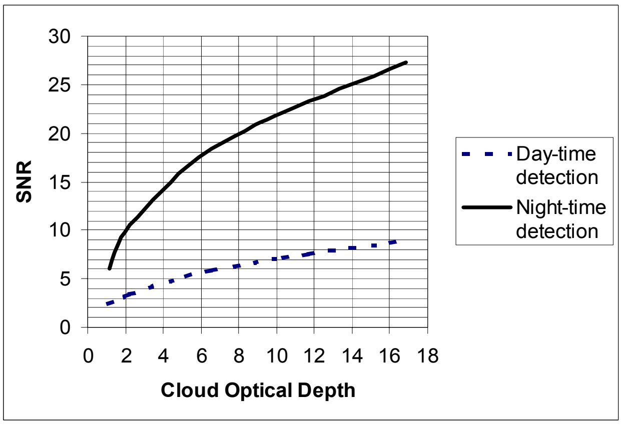

Fig.6. Dependence of the SNR for cloud-top signal detection on the cloud optical depth. The OD values are given 532nm. The transmitter power is 12.5W.

Figure 6 presents the SNR for averaged transmitted power 12.5W for cloud OD variation from 1.1 to 16.8. The results are presented for daytime and for night-time detection with integration time of 0.1sec. As we may assess, the SNR is sufficient for a confident detection event at the lower range of power variation.

The results in Figs. 5 and 6 also imply to the possibility for confident cloud top detection with shorter integration time but with higher power, i.e., for a cloud top detection with increased time resolution.

The $SNR(j) \sim \sqrt{t_{int}}$, where $t_{int} = LN\tau_c$ is the integration time. The results in Figs. 5 are obtained with integration time of 0.1 sec. We may evaluate that an increase of the transmitted power to ~20W during night time and to ~35W during daytime, may reduce the integration time to 0.01sec for detection of the top of a layer with OD~1 in the visible range, with still a confident SNR ~6. This determines a horizontal resolution for cloud top detection of ~80m.

5. CONCLUSUION

We present results from numerical simulations of the cloud response in PRN cw backscatter lidar. The results show that cloud-top detection with such lidar on polar orbit is feasible both day and night.

The specifications of the assumed PRN cw lidar are realistic with respect to the state-of-the-art in the laser, detector and filter technology. The fiber amplifier technology, combined with a master laser with stabilised line of emission, allows the use of a narrow-band optical filter. In this way, it is possible to achieve a SNR sufficient for a stable cloud top detection.

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