Simulation Study of Cloud and Aerosol Measurements With ELISE

Zhaoyan Liu,* Peter Voelger, and Nobuo Sugimoto
National Institute for Environmental Studies, Tsukuba, Japan

1. Introduction

During the last years the National Space Development Agency of Japan has been developing a space lidar system, the so-called Experiment Lidar In Space Equipment (ELISE) (Imai et al., 1997; Sasano et al., 1998). It was designed for a lifetime of one year or more, therefore giving the possibility to globally collect measurement data covering all seasons.

We conducted prelaunch studies including the development of data analysis algorithms and the simulation study for ELISE observations to preestimate the ELISE observation performance and to explore as many applications of ELISE data as possible. In the simulation study, the lidar return signals for ELISE were first simulated for an artificial two-dimensional atmospheric model. The signal detection processes were simulated realistically by including various sources of noise. The generated lidar signals were then used as the input for simulations of data analysis to investigate the quantitative measurements of clouds and aerosols with ELISE. The results showed that ELISE can well provide cloud and aerosol measurements in a global scale.

2. Specification of ELISE

ELISE was designed as a two-wavelength three-channel backscatter lidar. Its major specifications are listed in Table 1. One receiver channel is operated in an analog mode (AN) at 1053 nm for day and night observations; another two are operated in a photon counting mode (PC) at 527 nm and 1053 nm for night observations, respectively.

3. Simulation Results

Lidar Signal Generation

We have developed procedures for PC and AN signal generation and simulated lidar signals for all ELISE detection channels using the system parameters listed in Tab.1 for an artificial two-dimension model atmosphere. The model includes stratospheric and tropospheric aerosols and clouds with different structures. The procedures take into account both the digitized data sampling processes and the nonlinear response features of data acquisition system and other possible noise sources. Therefore, the generated lidar signals are quite realistic. The generated ELISE return signals are shown in Fig.1. Each profile is integrated over 20 laser shots. Multiple scattering is not considered. An investigation of multiple scattering effects on ELISE measurements is being conducted (Voelger et al., 2000). The maximum and minimum of the gray scale for each panel are taken according to the maximum and minimum detectable photo-electron numbers for both PC and AN channels. For analog detection, an 8-bit digitizer is assumed and its full scale is at a signal level for the target with a backscatter coefficient of 0.1 (km^{-1} sr^{-1}).

It can be seen from Fig.1 that most structures of clouds can be observed with all channels except for the optically thin part of cirrus and the lower part of optically dense clouds which the laser beam cannot penetrate completely. Aerosol layers in the troposphere can be observed even if there are cirrus clouds above. Also, the stratospheric aerosol can be detected with the 527-nm PC channel which has highest detection sensitivity.

However, strong saturation is seen in clouds and at the earth's surface in the 527-nm PC channel. Saturation is also seen in the 1053-nm PC and AN signals for dense clouds and the surface. This may limit quantitative retrievals of cloud and aerosol optical properties.

Table 1 Designed ELISE major specifications

Satellite	
Orbit:	sun-synchronous near-polar
Height:	550 ± 5 km
Ground speed:	6.983 km/s
Measurement	
Direction:	nadir
Vertical resolution:	100 m
Horizontal resolution:	AN: 1.4 km/4.2 km; PC: 1.4 km/21 km
Transmitter	
Laser:	LD-pumped Nd:YLF
Output energy:	84 mJ@1053nm 10 mJ@527nm
Repetition rate:	100 pps
Beam divergence:	0.17 mrad (full angle)
Receiver	
Eff. diameter:	1 m
FOV:	0.21 mrad
Detector:	Si-APD

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* Corresponding author address:
Zhaoyan Liu, National Institute for Environmental Studies
Onogawa 16-2, Tsukuba, Ibaraki 305-0053, Japan
Tel: +81-298-50-2477; Email: liu@nies.go.jp

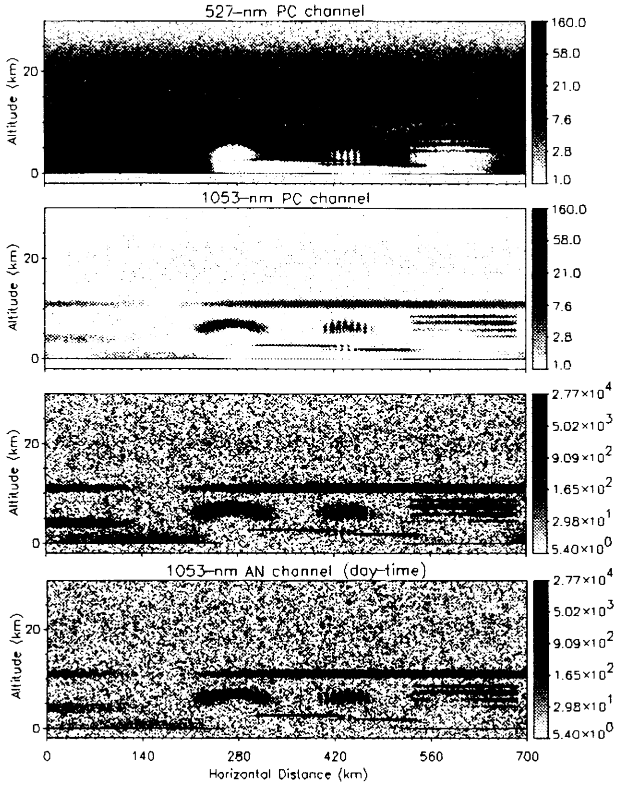

Fig.1 Simulated return signals of ELISE for an artificial two-dimensional model atmosphere.

Calibration

The received lidar return signals can be described by the lidar equation:

$$P(r) = \frac{1}{r^2} C \cdot \beta(r) \cdot T^2(r).$$

Here $P(r)$ is the received lidar signal from range r, $\beta(r)$ is the atmospheric backscatter coefficient at r and $T(r)$ is the transmittance from lidar to r. For the calibration of ELISE, the lidar constant C which contains system parameters and other range-independent quantities has to be determined for each channel.

527-nm PC channel can be directly calibrated with the return signals from 30-35 km altitudes where signals can be regarded as only due to molecular scattering. Simulations showed that the lidar constant for the 527-nm channel can be accurately determined with a standard deviation of 2.4 % when 2000 laser shots are integrated. This corresponds to an observation time of 20 s or a horizontal distance of ~140 km.

The lidar constant of 1053-nm PC channel can be determined relatively with 1053-nm and 527-nm PC channel signals from 30 -35 km altitudes. According to our simulations, the lidar constant of 1053-nm PC channel can be determined with a standard deviation of 5.6 % when 2×10^5 laser shots (~14000 km horizontal distance) are integrated.

For the 1053-nm AN channel, the lidar constant can be determined relatively from the ratio of integrated 1053-nm AN and PC channel signals from cirrus clouds or some dense aerosol layers. Since the signals from cirrus clouds or dense aerosol layers are much stronger than molecular scattering signals from 30 - 35 km altitudes as used in 527-nm and 1053-nm PC channel calibrations, a better accuracy for the 1053-nm AN channel calibration can be obtained with much fewer laser shots. Figure 2 shows examples of determination of the lidar constant ratio of two 1053-nm channels using the generated lidar signals from Fig.1. Signals from the dust (Kosa) layer at 3-5 km altitudes, the Planetary Boundary Layer (PBL), and the cirrus layer at 10-12 km altitudes are used. The lidar profiles are averaged over only 200 laser shots corresponding to 14 km in horizontal distance. The lidar constant ratio can be determined with a standard deviation of less than 7% for Kosa and PBL and 3% for cirrus.

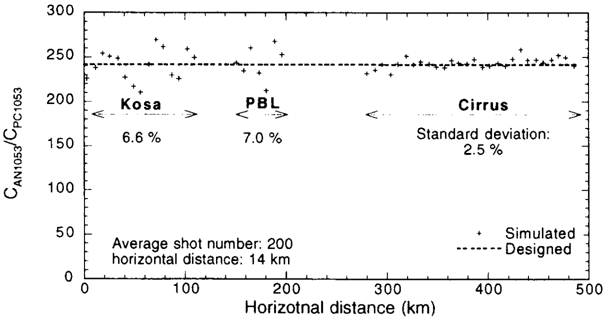

Fig.2 Simulation of calibration of 1064-nm AN channel.

Cloud Detection

The threshold method is suitable for the cloud detection with ELISE. It compares the measured lidar profiles with a reference lidar profile. If the measured lidar signal at any altitude exceeds a reference by a certain value (threshold), it is interpreted as cloud. The reference lidar profile can be estimated for each channel theoretically with a standard atmosphere or from the observed data in clear atmospheric conditions. The threshold is determined according to the noise level. For ELISE cloud data analysis, we select a value of 2 for the threshold-to-noise ratio (*TNR*) which may result in a noise false alarm probability of 2.3%, thus, the non-detection probability is less than 2.3% when signal-to-noise ratio (*SNR*) is larger than 4.

We estimated the detectable backscatter coefficients at the cloud top and base for a rectangularly distributed homogeneous cloud. Table 2 lists the results. We assumed that the typical altitudes of PSC, cirrus and water clouds are 20 km, 10 km and 4 km, respectively. It can be seen that a larger cloud backscatter is required

Table 2 Minimum backscatter coefficients of a homogeneous cloud required to detect its top and base [a]

	PC 527-nm, night			PC 1053-nm, night			AN 1053-nm, night			AN 1053-nm, day		
Laser shots	1	20	300	1	20	300	1	20	300	1	20	300
Top [b] $\beta(m^{-1}sr^{-1})$	1.1e-5 1.2e-5 1.2e-5	6.4e-7 9.0e-7 1.1e-6	8.9e-8 1.6e-7 2.3e-7	1.6e-4 1.7e-4 1.7e-4	8.0e-6 8.3e-6 8.5e-6	5.4e-7 5.9e-7 6.3e-7	3.2e-5 3.3e-5 3.4e-5	6.2e-6 6.5e-6 6.6e-6	1.6e-6 1.7e-6 1.7e-6	4.1e-5 4.3e-5 4.4e-5	8.4e-6 8.7e-6 8.9e-6	2.1e-6 2.2e-6 2.2e-6
Base [b] $\beta(m^{-1}sr^{-1})$	-	6.6e-7 9.4e-7 1.2e-6	8.9e-8 1.7e-7 2.3e-7	-	1.4e-5 1.5e-5 1.6e-5	5.5e-7 6.0e-7 6.4e-7	-	8.9e-6 9.4e-6 9.8e-6	1.7e-6 1.7e-6 1.8e-6	-	1.6e-5 1.7e-5 1.9e-5	2.3e-6 2.4e-6 2.5e-6
Detectable type [c] (top)	W Cl, Ci	W Cl, Ci, PSC I_b, II	W Cl, Ci, PSC I_b, II	W Cl	W Cl, Ci	W Cl, Ci, PSC II	W Cl	W Cl, Ci	W Cl, Ci	W Cl, Cl	W Cl, Ci	W Cl, Ci

[a] Cloud physical thickness: 1 km; lidar ratio S_l=20 sr; vertical resolution: 100 m; TNR=2; SNR=4.

[b] Three value are given for the altitude of 20 km, 10 km and 4 km where PSC, cirrus and water clouds are assumed to typically exist, respectively.

[c] Ci: cirrus; W Cl: water cloud; PSC: polar stratospheric cloud.

to detect the cloud base than the cloud top with the same average number of laser shots because of attenuation in the cloud. However, although a cloud with large backscatter coefficient can produce strong scattering signal, it also causes large attenuation of the laser pulse, resulting in the return signal smaller than the threshold.

For water clouds their tops can always be detected by all three detection channels even with a single laser shot. However, cloud base detection is not possible with a single shot. Some optically thin clouds such as cirrus can be detected by averaging a number of laser shots. Type Ia PSCs cannot be detected even by the 527-nm PC channel with 300 laser shots. An even larger number of shots is needed for detecting this type of PSCs. However, the number of shots will be limited by the horizontal scale of the cloud.

Retrievals of Optical Properties

Retrieval simulations of the cloud and aerosol optical properties were conducted using the lidar data analysis algorithms summarized and discussed previously (Liu and Sugimoto,1998; Liu et al., 2000). Two-component inversion algorithm (Fernald,1984) is essentially used to invert lidar signal to deduce backscatter coefficient of clouds and aerosols. The inversion can be initiated at altitudes above 30 km where the boundary condition which is required in the lidar signal inversion can be easily determined. The lidar ratio (extinction to backscatter ratio) of the cloud and aerosol is another input parameter for the inversion. Here we use modeled values of the lidar ratio for different kinds of scatterers. However, it should be noted that large errors can be expected for optically thick scattering media such as clouds or dense aerosol layers if the model value of the lidar ratio is different from the real value. Fortunately, some modified inversion algorithms (e.g., Young, 1995; Sasano and Browell, 1989; Liu et al., 2000) can be used for high altitude optically thin cloud layers or tropospheric aerosol layers. Thus, both the lidar ratio and the backscatter (extinction) coefficient can be determined simultaneously.

As shown in Fig.1 the 527-nm PC channel is suitable for observations of the stratosphere. By using integrated 527-nm signals several optical parameters of the stratospheric aerosol, e.g., the backscatter coefficient, the integrated-backscatter-coefficient (IBC) and the extinction coefficient, can be retrieved with a known lidar ratio determined from other measurements. The aerosol lidar ratio in the stratosphere does not change much with time. Hence, it can be derived from in-situ data or other remote sensing instruments such as Raman lidar. Yet, the retrieval of backscatter coefficient is not sensitive to the lidar ratio because the optical depth in the stratosphere is generally small. This channel can also provide observations of tropospheric aerosols and molecules as long as they are not hidden by dense clouds. The molecular signals can be used as a reference in the data analysis for some thin clouds such as cirrus. Although cloud signals may cause saturation in this channel, the scattering signals from above and below the clouds can be used to determine its transmittances. Thus, its (effective) optical depths can

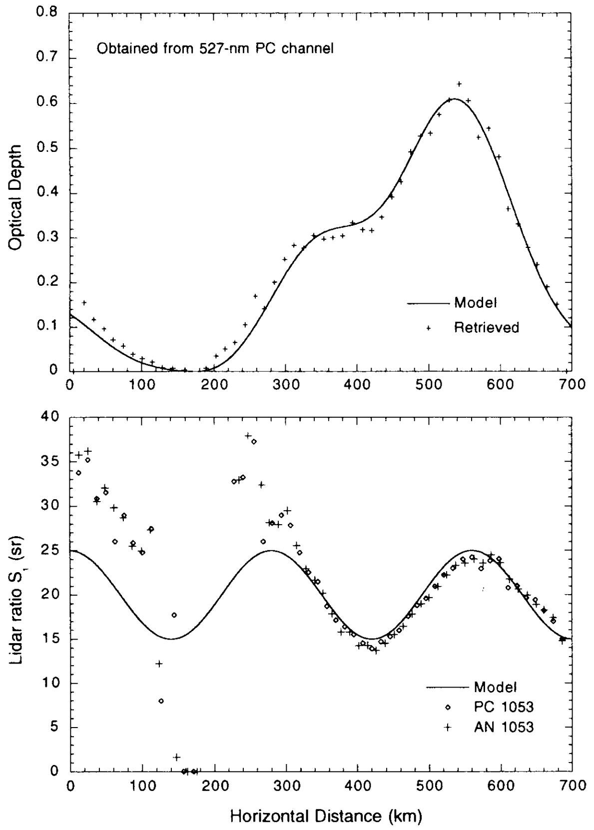

Fig. 3 Retrieved cirrus optical depth and lidar ratio.

be retrieved. Moreover, determined cloud optical depths can be used as an extra constrain to simultaneously determine the cloud lidar ratio using an iterative method as discussed by Young (1995).

The 1053-nm PC and AN channels are mainly aimed to observe clouds and dense aerosols. From the 1053-nm PC or AN signals the backscatter coefficient and effective extinction coefficient of thin clouds can be retrieved with Young's method when using the effective optical depth determined from the 527-nm PC signal as a constrain. Figure 3 presents cirrus optical properties retrieved in the above mentioned way. The cirrus optical depths for different profiles were derived by comparing signal from below the cirrus with that of a cirrus-free profile at 175-km horizontal distance. The retrieval works better when the cirrus optical depth is larger than 0.2.

Our simulation showed that the 1053-nm PC signal can also be used to retrieve aerosol optical properties in the stratosphere at this wavelength when the backscatter signal is averaged over 2000 shots. In that way, the wavelength dependence of the stratospheric aerosol optical property can be studied along with the PC 527-nm channel signal.

Aerosol optical properties in the troposphere can be retrieved from 527-nm PC channel signal and 1053-nm PC or AN channel signal using two-wavelength data analysis algorithm (Sasano and Browell, 1989) and a modified two-wavelength algorithm (Liu et al., 1999). The analysis of the modeled Kosa data showed that the lidar ratio, backscatter and extinction coefficients at 527 nm and backscatter coefficient at 1053 nm can be retrieved.

4. Conclusion

Our simulations show that with three channels operated at two wavelengths ELISE can yield not only the global observation of cloud and aerosol structures but also the quantitative measurements of cloud and aerosol optical properties. The following information can be expected from ELISE measurements:

(1) Cloud: cloud structures including PSCs; cirrus optical properties; cloud cover rate.
(2) Stratosphere: aerosol backscatter and its wavelength dependence; large-scale aerosol distributions.
(3) Troposphere: aerosol optical properties; long-range aerosol transportation; PBL height and structure.

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