What will we see from space using a Mie lidar ?

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1. Introduction

The present paper describes the results of surveys concerning the scientific significance and technical feasibility of space-borne lidars (hereafter called "space lidars"), which were conducted from FY 1991 to 1994 as one of the researches by the Global Environment Research Fund from Environment Agency of Japan. Lidars, which are also called laser radar, are one of the remote sensing technologies utilizing lasers. Lidars can detect distributions of particulates such as clouds and aerosols, and gaseous concentrations of ozone and water vapor, using various principles of interaction between light and materials.

Ground-based lidars have shown their usefulness through numerous field measurements. In 1994, NASA successfully utilized a lidar on a space shuttle to provide significant data on clouds and aerosols. The shuttle lidar was able to maintain almost the same "resource conditions", e.g., power consumption, load mass, etc., as those used in ground-based experiments. Since a shuttle, however, cannot be occupied for long-term observation, it is necessary to develop a space lidar system, which can tolerate tight conditions of power and mass allocation.

At the early stage of our investigation, a large satellite, like an ADEOS class, and a small satellite that could be launched by a J-1 rocket were considered as candidates for a space lidar platform. As the result of a detailed trade-off analysis, we found that there was a considerable interdependency between the specifications of each subsystem, mass, power consumption, and measurement performance (precision, spatial resolution) and found it very difficult to define clearly system specifications because of the large flexibility in this interdependency. We finally decided to propose a space lidar system for a small satellite, though this may impose relatively severe restrictions on mass and power consumption.

The space lidar system proposed here meets, as much as possible, the mission requirements for reduced mass and power consumption. This does not necessarily mean that its performance is inadequate from the practical point of view; it merely gives a baseline for design which can be upgraded in measurement performance by relaxation of mass and power consumption restrictions.

2. Background and summary of the survey

2.1 Background

It is well recognized that remote sensing from space is quite important and essential to understanding the global environment and various efforts have been made world-wide to achieve it. Techniques utilized in those efforts in atmospheric measurements are basically passive remote sensing, in which emission, absorption, and/or scattering of electromagnetic waves are measured. The source of electromagnetic waves could be the sun or the atmosphere itself.

Cloud distributions are detected by image sensors aboard satellites. However, they have a disadvantage in that they can neither give height information on clouds nor detect multiple layer structures of clouds. Lidars have been widely used to detect aerosols and clouds from ground level and from aircraft.

Lidars are one of the active remote sensors, which is considered very promising. To demonstrate the feasibility of space lidars, NASA made a Shuttle experiment and took a lidar to space last year. The experiment was called Lidar In-space Technology Experiment (LITE) and obtained a lot of data.

Under these circumstances, we believed that the time had come in Japan to start basic studies on space lidars as effective tools that could contribute to global environment monitoring. The objectives of these basic studies were:

(1) definition of scientific goals and instrumental performance,
(2) numerical simulation for defining instrument specifications,
(3) data retrieval algorithms,
(4) scientific analysis method,
(5) laboratory experiments for verifying technical feasibility, and
(6) evaluation of available techniques and feasibility study.

The present study aims at investigating items (1) and (2) to show the significance of space lidars in global environment monitoring, and proposes a possible space lidar system in connection with global monitoring of clouds and aerosols, on the basis of technical feasibility studies.

The study was conducted mainly by the Investigating Panel (Chair: Prof. T. Kobayashi, Fukui University) convened by the Optoelectronic Industry and Technology Development Association, under contract with the National Institute for Environmental Studies (NIES). The panel included several scientists involved in meteorology, climatology and global circulation modeling, lidar studies and space technology.

2.2 Significance of space lidar observations of clouds

The Investigating Panel pointed out the following important issues:

(1) To solve global warming problems, it is essential that the effects of clouds and oceans on climate be investigated and incorporated into climate models.
(2) Information should be gathered on cloud distribution, especially height distribution, because clouds act differently on the atmospheric radiation fields depending on their height, water content, optical thickness, and so on.
(3) Overlapping of cloud layers should be clarified from observations since it is quite important in both long wave and short wave transfer in the atmosphere.
(4) Different models of climate do not necessarily predict identical climate changes because of defects in parameterizing cloud production and its effects on radiative transfer.
(5) Mechanisms of ozone destruction have been studied in detail, especially in relation to heterogeneous reaction on aerosol/PSC surfaces. Observation of aerosols/PSCs over high latitudes and polar regions are required. However, passive remote sensing from satellite does not provide good spatial coverage.
(6) To learn the effects of clouds on climate, it is essential to understand worldwide cloud distribution and overlapping, to discriminate water droplets from ice particles, and to observe size distribution, vertical profiles, optical thickness, and so on.
(7) Cirrus clouds could be a good target for space lidar measurements, especially their spatial distribution, size distribution of particles, and temporal changes.
(8) Extremely accurate information on cloud tops, cloud thickness, and overlapping could be provided with space lidars, information that would contribute to the verification and improvement not only of climate models but also of cloud analysis which uses geostationary satellite data.
(9) A combination of passive sensors and a space lidar could simultaneously observe clouds parameters (height distribution, optical thickness, and so on) that can characterize the effects of clouds on the global environment.

(10) Since requirements for scales and resolution, both temporal and spatial, depend on observation purposes, sampling problems must be resolved to meet requirements for global mapping.

To summarize, while it is quite important to understand the roles that clouds play when discussing global warming mechanisms, it is clear that there has been a lack of information on the global distribution and frequency of appearance as functions of height, and optical and radiation properties of clouds. Conventional passive sensors do not provide such information very well and ground-based lidar networks give those information but with limited spatial coverage, thus leading to poor data accumulation. Space lidars are active sensors which give information on height, thickness, and overlapping of clouds in two-dimensions, especially of cirrus clouds, that is a great advantage of space lidar observations. Further details can be found in Sasano and Kobayashi (1992, 1993).

3. Results of technical feasibility survey

The present study assesses the status of lidar technology presently available and the possible future development of some key technologies for space lidars. It concludes that there are no serious problems in developing space lidars.

An issue to be studied in detail is whether it is possible to build a lidar system within the allotted limits of mass and electric power. The main components of the total mass are the transmitting/receiving optical subsystem, laser transmitter subsystem, thermal control subsystem and body structures. To reduce the mass, we must reduce the diameter of a receiving telescope by developing higher sensitivity detectors, and provide a compact electric power supply to laser oscillators by lowering the average laser output energy. The most power-consuming component is the laser oscillator. Therefore solid state lasers using diode lasers as pumping light source are desirable. Further details can be found in Sasano and Kobayashi (1994, 1995).

The proposals submitted by three major space instrument manufacturing companies indicated that a space lidar with a mass of less than 150 kg and electric power consumption of less than 150 W could be realized from technologies available now or in the very near future. This meets our requirement for a space lidar that can be launched aboard a small satellite.

4. Proposal of a space lidar for cloud/aerosol measurements

Based on the survey previously described, a space lidar was proposed with the specifications shown in Table 1. Mass and power assignments are shown in Table 2. There are still options for laser crystals (selection of laser wavelengths) and laser energy per pulse (laser repetition rate and beam divergence), which must be studied further in the designing stage. Fig. 1 shows some conceptual drawings of space lidars.

The space lidar proposed here can measure cloud and aerosol distribution with the S/N ratios shown in Fig. 2. The S/N curves were calculated for a typical atmospheric condition with cirrus clouds. Calculations were made for vertical resolution of 100 m and horizontal resolution of 1.5 km with background conditions of earth surface at night and a low-level cloud deck illuminated by the sun.

The graph shows that the lidar can detect cirrus clouds at a height of 10 km with an S/N ratio of about 10, thus giving the cloud top height and thickness. Since low-level clouds and the earth's surface have obviously much larger scattering cross-sections than the cirrus clouds, the topography of the earth's surface and the low-level cloud tops is easily detected, even with the presence of cirrus clouds above.

Aerosols in the lower troposphere are difficult to measure under the conditions given here. The horizontal resolution, however, does not need to be 1.5 km unless local distribution of aerosols, such as those related to air pollution problems, is targeted. The horizontal resolution can be relaxed to several tens or even hundreds of km when atmospheric boundary layer heights over the ocean are measured, thus providing a much better S/N ratio for the signal.

Stratospheric aerosols with background conditions (in the non-perturbed stratosphere) are difficult, but it is possible to detect enhanced aerosol layers, for example after a large volcanic eruption with reduced spatial resolutions.

5. Conclusion

It was shown that current technology can develop a space lidar which can be launched by a small satellite and used for 3-dimensional global mapping of clouds and enhanced aerosol layers. Data obtained by such measurements could provide essential information for improving global climate models through better understanding of cloud-radiation interactions.

References (in Japanese: available from NIES).
Sasano, Y. and T. Kobayashi (ed.) : Feasibility study on space lidars for measuring global atmospheric environment No.1, F-43-'92/NIES, 1992
Sasano, Y. and T. Kobayashi (ed.) : Feasibility study on space lidars for measuring global atmospheric environment No.2, F-50-'93/NIES, 1993
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Table 1 Specifications of a space lidar

laser wavelength (nm)	around 1060
laser energy (mJ/pulse)*	50 / 500
pulse repetition (pulse/sec)	100 / 10
transmittance of transmitting optics	0.85
beam divergence (mrad)	0.1 / 0.3
diameter of receiving telescope (m)	1.0
effective area of telescope (m2)	0.7
field of view (mrad)	0.1 / 0.3
transmittance of receiving optics	0.1
filter band width (nm)	0.1
photon counting	
detector	Si-APD
quantum efficiency	0.02
dark count	100
analog detection	
detector	Si-APD
quantum efficiency	0.3
multiplication factor	100
noise factor	0.003
accumulation number	20 / 2
vertical resolution (m)	100
horizontal resolution (km)	1.5

*Two possibilities of pulse repetition

Table 2 Mass and power assignment

Mass (kg)	
receiving telescope	48
receiving optics/detectors	5
transmitting optics	2
laser oscillation	10
laser power supply	30
signal processing	10
power supply	7
thermal control	6
structures	25
harness and others	7
total	150
Power (W)	
laser oscillator	80
detectors	10
signal processing	22
power supply	10
thermal control	10
others	18
total	150

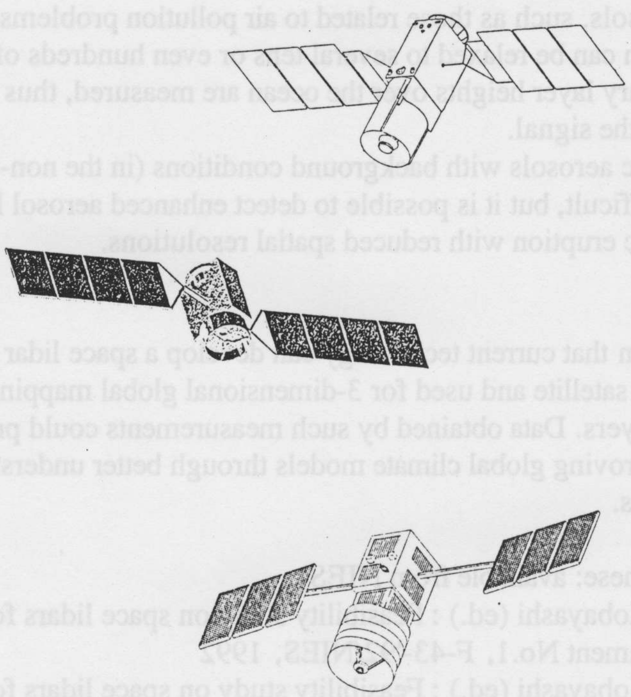

Fig. 1 Schematics of space lidars

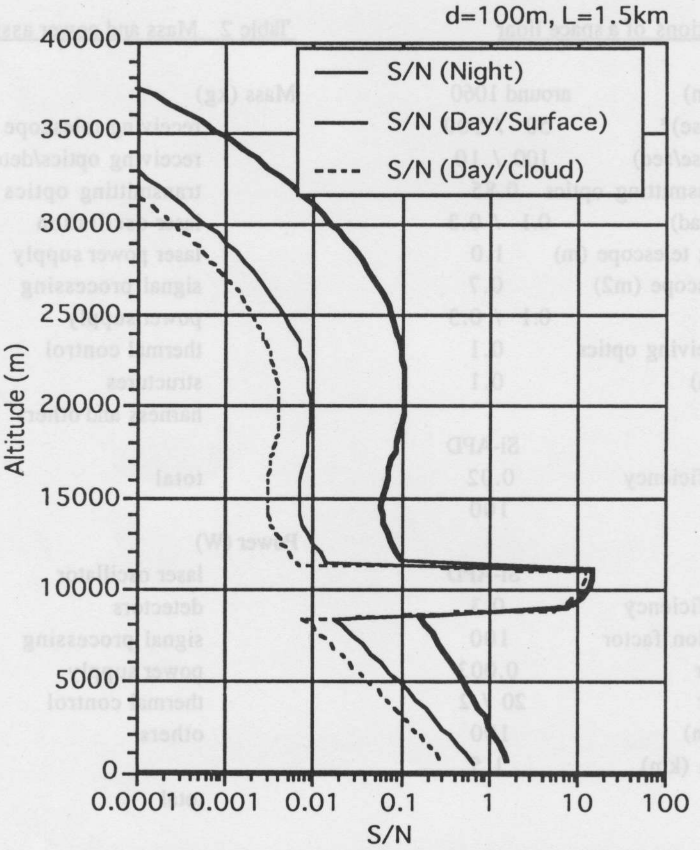

Fig.2 Example of signal to noise (S/N) ratio profile of space lidar measurement of cirrus clouds and aerosols.

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Overview

- Introduction
- Clouds and climate
- Feasibility studies on satellite-borne lidars
  - Possible targets of lidar observations
  - Technical feasibility
  - Simulations
  - Proposal
- Research topics

Introduction

Background

- Global environment issues,
  - especially global warming problem and ozone depletion
- Uncertainties in climate change predictions
  - Problems in cloud modeling
- Matured and advancing lidar technologies
  - Ground-based, air-borne, Shuttle-borne

Feasibility studies on satellite-borne lidars

- Definition of a baseline for future development

Clouds and climate

Radiative balance

- Low clouds cause a surface cooling
- Cirrus, depending on optical depth, may produce warming or cooling at the surface.

Atmospheric dynamics

- Convective clouds; heat and water vapor transport

Feasibility studies on satellite-borne lidars

Possible targets of lidar observations from space

Technical feasibility

Simulation study

Proposal

Possible targets of lidar observations from space

- Cirrus clouds
  - Climatology, optical thickness, size distribution (?)
- Low-level clouds
  - Climatology
- Overlapping clouds
  - Climatology
- Tropospheric background aerosols
  - Aerosol-cloud interaction

- Stratospheric aerosol and PSCs
  - Heterogeneous chemistry (ozone depletion problem)
- Boundary layer heights
  - Parameterizations for boundary conditions for GCMs

Technical feasibility survey

Diode-laser pumped Nd:YAG (or Nd:YLF) laser
    Life time, heat control

Large-aperture and light-weight telescope

Narrow band filter for daytime measurements

Eye-safe operation
    Laser energy, pulse repetition and beam divergence

Avalanche photo diode

Concept of a satellite-borne lidar (proposal)

Basic ideas

- Use of techniques available currently or in the very near future
- Design applicable to a small satellite
    payload < 150 kg in mass, <150 W in electricity
- No scanning mechanism
- Eye-safe system
- Clouds distribution as a main target (day and night)

Specifications of a space lidar (proposed)

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beam divergence (mrad)	0.1 / 0.3
receiving telescope dia.(m)	1.0
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transmittance of rec. optics	0.1
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photon counting detector	Si-APD
quantum efficiency	0.02
dark count (/sec)	100
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quantum efficiency	0.3
multiplication factor	100
noise factor	0.003

accumulation number	20 /2
vertical resolution (m)	100
horizontal resolution (km)	1.5

*Two possibilities of pulse repetition

Mass and power assignment (proposed)

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transmitting optics	2
laser oscillation	10
laser power supply	30
signal processing	10
power supply	7
thermal control	6
structures	25
harness and others	7
total	150

Power (W)	
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detectors	10
signal processing	22
power supply	10
thermal control	10
others	18
total	150

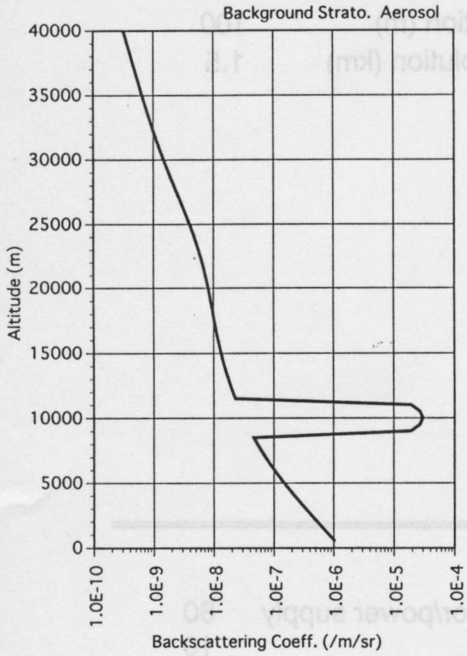
Simulations

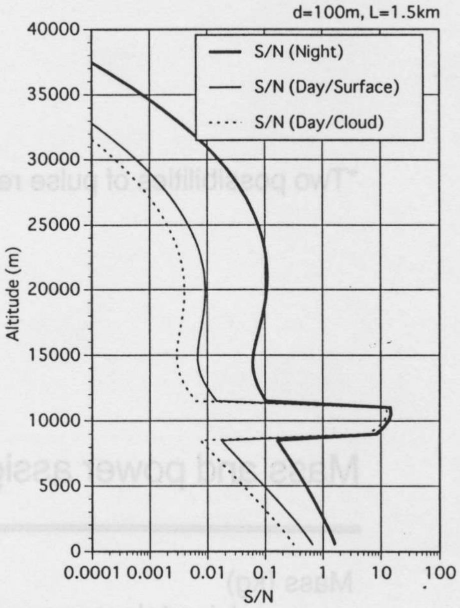
Models

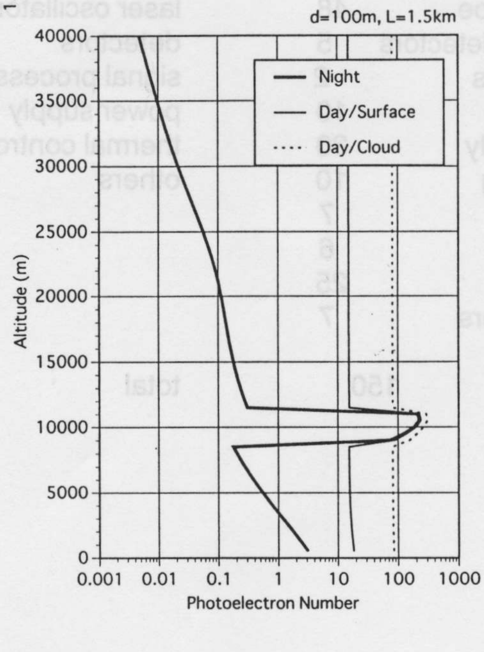
Cirrus layer from 9 km to 11 km in altitude
Background aerosols (troposphere and stratosphere)
Ground surface or low-level cloud in daylight condition

S/N calculation

Shot-noise limited
Horizontal resolution of 1.5 km
Vertical resolution of 100 m





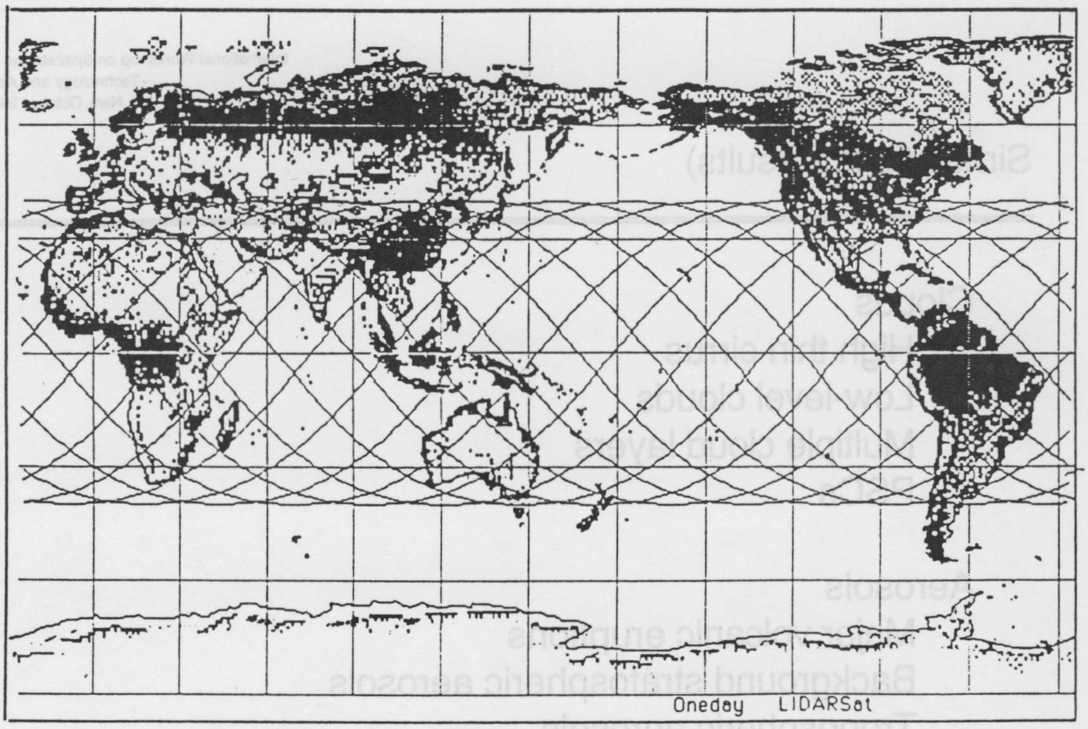


Simulations (results)

- Clouds
  - High thin cirrus
  - Low-level clouds
  - Multiple cloud layers
  - PSCs
- Aerosols
  - Major volcanic eruptions
  - Background stratospheric aerosols
  - Tropospheric aerosols
- Boundary layer heights

Research topics

- Calibration techniques and quantitative analysis
- Multiple scattering evaluation and correction
- Sampling strategy for cloud climatology
- Synergistic analysis of lidar and passive sensors data
- Improvement of climate models



One-day ground track of a satellite with an altitude of 500km and an inclination angle of 40 deg.

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