Hardware design and development plan of Experimental Lidar In Space Equipment (ELISE)

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Abstract

ELISE, one of NASDA's lidar programs, means the two-wavelength backscatter lidar. It is planned to be loaded onto the Mission Demonstration Satellite(MDS)-2 planned to be launched early in 2001. One of the special features of ELISE is to be developed in short period using two models called the Basic Test Model(BTM) and the Demonstration Model(DM). Through this program, we try to demonstrate some key devices, such as a lightweight Laser Diode-pumped high power laser, a large diameter telescope and a photon counting detector using Si-APD, which are required for future spaceborne lidars. The experimental data of key devices in the space environment will be obtained. Furthermore, ELISE will observe clouds in the high altitude (mainly cirrus), multi-layered clouds, aerosols and the atmospheric density through one year. This observation will reveal the scientific value and the availability of spaceborne lidars. The collection of the information on clouds, aerosols and the atmospheric density will be a great help to the design of future spaceborne lidars.

1. Introduction

Clouds and aerosols are very important factors affecting global climate through radiation balance between atmosphere and earth surface. In addition, aerosols have great influence on the destruction of ozone layer in the polar region. However, it is not well understood whether feedback between 'global warming' and 'clouds and aerosols' are positive or negative. This is because distributions of thin clouds(mainly cirrus), multi-layered clouds and aerosols are not clear. Furthermore this is because it is difficult to measure global distributions of those objectives. Therefore observing distributions of clouds and aerosols and understanding characteristics of these objectives are very important to predict the change of terrestrial environment. LIDAR has enough capability to observe these objectives and lidar technologies for measuring clouds and aerosols are well matured for ground-based and airborne measurements. Now, many ground-based lidars has been operated to measure distributions of clouds, aerosols, water vapor, ozone density and multi-layered clouds. Airborne lidar has been also operated to observe clouds and aerosols in the comparatively wide area. However, ground-based and airborne lidars can observe limited area, while spaceborne lidar can observe these objectives in the global area.

In 1994, NASA conducted an experiment of lidar onboard space shuttle(LITE : Lidar In-space Technology Experiment) and showed its capabilities to detect clouds and aerosols from space although the experiment period was only 53 hours. The next step would be a satellite-borne lidar for long term monitoring the atmosphere. From 1991 to 1994, National Institute of Environmental Studies in Japan conducted a feasibility study on the evaluation of global atmospheric environments by satellite-borne lidars. This study concluded that the most feasible and effective candidate for satellite-borne lidars to be developed would be a type of backscatter lidar for measuring three dimensional distributions of clouds and aerosols. Based on the result of this study, NASDA started the study on satellite-borne lidars, and now is about to embark on the MDS-LIDAR project, which is now called ELISE project. ELISE is going to be loaded onto the MDS-2 planned to be flown to circular orbit (altitude : 550km, inclination : 30 degree) by H-IIA rocket in early 2001. It will observe clouds and aerosols in tropical and subtropical zone through one year.

The current status of ELISE is described in the following sections.

2. The objectives of the ELISE program

Since one of the objectives of ELISE program is to establish key devices required for future satellite-borne lidars, ELISE is planned to demonstrate the key devices as follows,

1. laser diode pumped high power solid-state laser ,
2. high efficiency detectors (especially Single Photon Counting detector using a Si-APD).

The observation of clouds, aerosols and the atmospheric density for one year is also the purpose of ELISE, since the information on these objectives is needed for the design of future spaceborne lidars. Main objectives of ELISE are follows,

1. clouds (mainly cirrus, multi-layered clouds),
2. aerosols,
3. the atmospheric density.

NASDA cooperates with Earth Science Technology Organization to determine these scientific missions of ELISE. ELISE is expected to observe and get the data of these objectives through one year. This data will reveal the scientific value and availability of spaceborne lidar. The scientific mission of ELISE is briefly indicated here. More detail of the scientific mission was discussed by Sasano(1).

3. The instrument

ELISE is a typical backscatter lidar system. A schematic diagram of ELISE is shown in Fig. 1. It consists of a laser transmitter, transmitter optics(including alignment optics), a telescope, a receiver, signal processor, and supporting electronics for data handling. The laser transmitter is a laser diode pumped Q-switched Nd:YLF(Yttrium Lithium Fluoride) laser with second harmonic generation crystal $KTiOPO_4$(KTP). It produces simultaneous 84mJ and 10mJ output energy at the wavelength of 1053 and 527nm, respectively. The pulse repetition frequency is 100Hz and the beam divergence is 0.17mrad. The telescope consists of the 1m primary mirror and the 20cm secondary mirror, each of which is made of Beryllium. An aperture stop is located at the focus of the telescope and acts as the field stop. The field of view(FOV) is 0.22mrad. Received back scattered light from targets is led to the receiver through an aft optics and detected by three Si-APD detectors. One of three detectors detects 527nm light in the photon counting mode. The others detect 1053nm light in analogue and photon counting mode.

The ELISE instrument is designed with capability to make measurements of clouds(mainly cirrus), aerosols and the atmospheric density with the signal to noise ratio(SNR) over 10. Main system parameters of ELISE are shown in Table 1. The configuration of ELISE is shown in Fig. 2. Some components are detailed in the following section.

4. The performance of main components

4.1 Transmitter assembly

The design and space qualification of the laser transmitter is the most challenging task in the development of the ELISE instrument. Figure 3 shows the schematic of the laser transmitter. The laser diode pumped Q-switched Nd:YLF laser is chosen. This laser operates on a fundamental wavelength of 1053nm and includes harmonic generator to produce he second harmonics of the wavelength 527nm.The laser architecture is an oscillator only configuration. To obtain the reliability for vibration and shocks, the resonator must be insensitive to misalignment. Thus we adopt the crossed roof prism-roof-prism resonator. In this crossed prism-prism resonator, each prism compensates the misalignment of the opposite one.

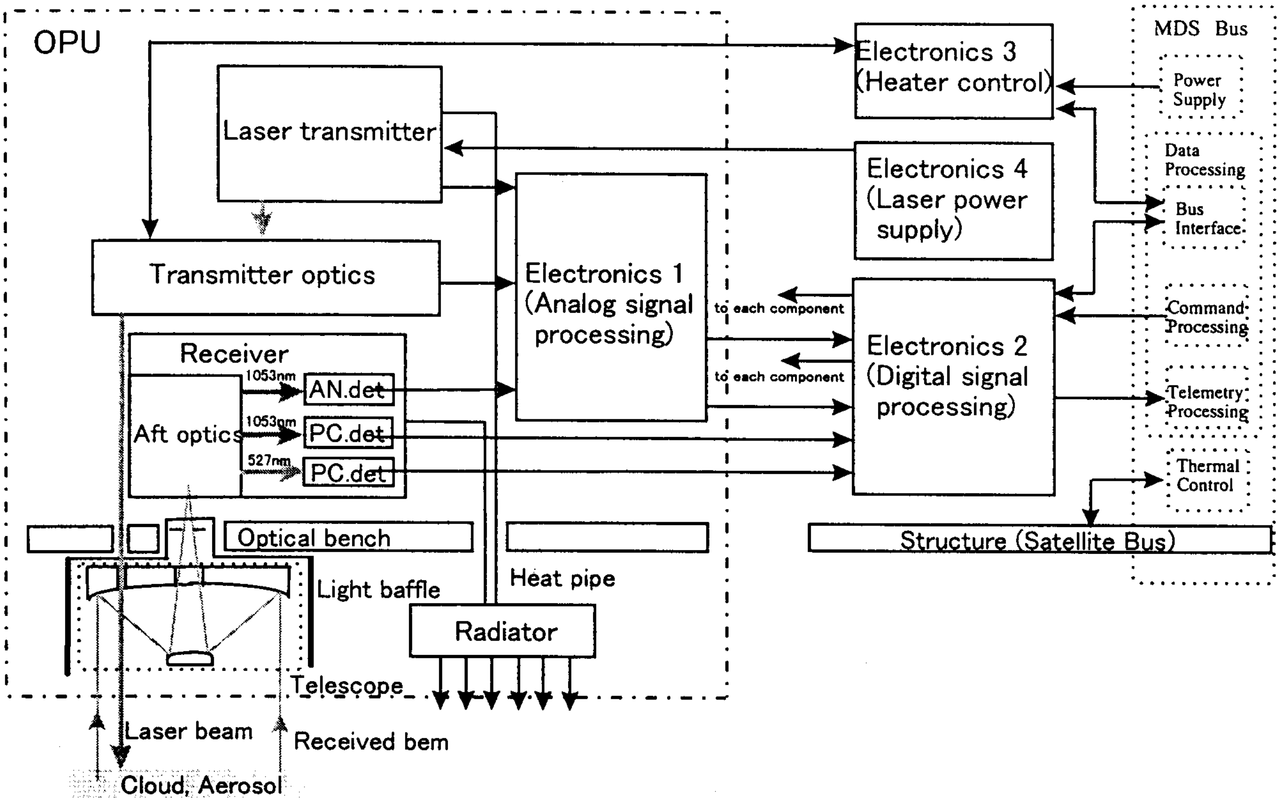

Fig.1 ELISE system functional diagram.

Table 1. System parameters of ELISE(preliminary)

Items		Analog detection	Photon Counting detection		Notes
		Fundamental	Fundamental	SHG	
Performance	The vertical res.	100 m (667 nsec)			Data sampling rate
	The horizontal res.	0.4 km (Int. 5) 1.45 km (Int. 20)	1.45 km (Int. 20) 14.1 km (Int. 200)		
	SNR	>10			
Transmitter	Laser	LD pumped Q-switch Nd:YLF laser + KTP			
	Wavelength	1053.2 nm		526.6 nm	
	Output energy	84 mJ		10 mJ	
	P R F	100 pps			
	Beam divergence	0.17 mrad			
Receiver	Telescope diam.	1000 mm			
	Field of view	0.22 mrad			
	Filter band width	0.3 nm	4 nm		
	Opt.transmission	40 %	6.5 %	60 %	
	Quantum efficiency	31.5 %	----	----	
	Det.probability	----	1.25 %	34 %	
	Dymamic range	50.6 dB	68.2 dB		Integration 20
	Data bit lengh	12 bits / data			
Mass		250 kg			
Power		250W			

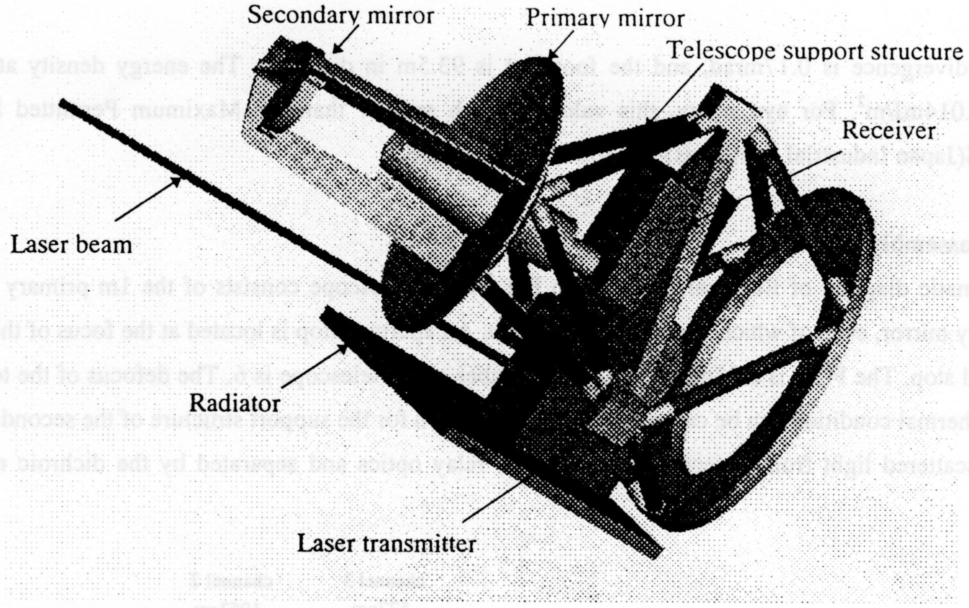

Fig. 2 The preliminary configuration of ELISE

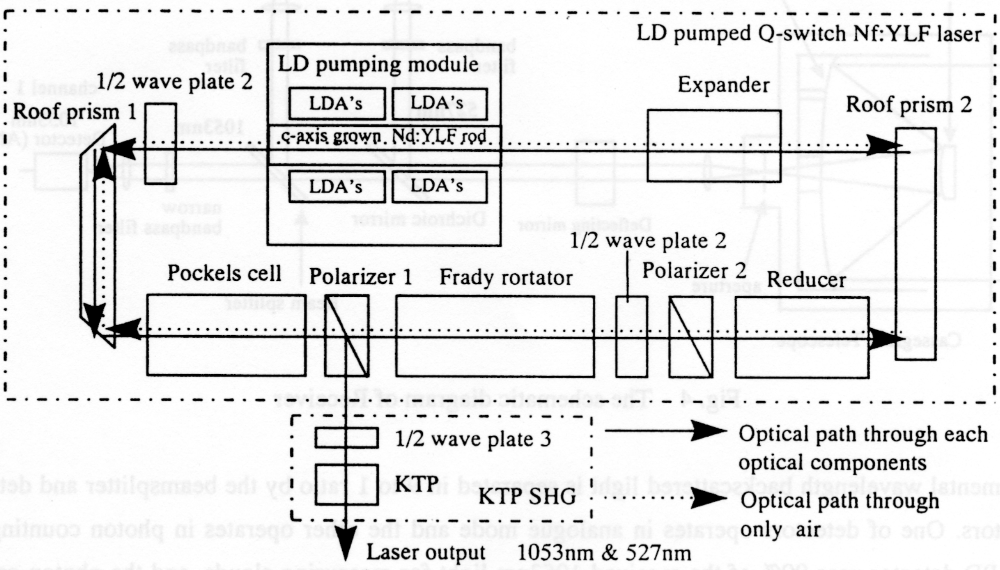

Fig. 3 The schematic of the LD pumped Nd:YLF laser.

The laser consists of pump module, two crossed roof prism, Pockels cell, Farady rortator, the polarizer and waveplates. The laser rod is pumped by twelve 5-bar arrays with a total optical output of 0.72J at a pulse width 200 μ sec. This laser produces simultaneous 84mJ and 10mJ output energy at the wavelength of 1053 and 527nm, respectively. The pulse repetition frequency is 100Hz. The output power of each wavelength is monitored by the detectors in the transmitter optics using 0.5% of the output power of laser.

As a misalignment between LASER transmitter and Receiver is the most critical problem, the boresight misalignment can be corrected in the Alignment Adjuster by a couple of rotatable deflecting prisms. An alignment correcting range is $\pm$2mrad and resolution is 0.01mrad.

When lasing, the laser oscillator consumes 124W of power and most of which is converted to the waste heat from the LD and the laser rod. This heat is removed by heat pipes to the radiator panel. The area of the radiator panel needs approximate 2m^2 to remove the waste heat.

The beam divergence is 0.17mrad, and the footprint is 93.5m in diameter. The energy density at the ground is approximate 0.014mJ/m^2. For eye safety, this value is much smaller than the Maximum Permitted Exposure level specified in JIS(Japan Industrial Standards)-C-6802 or ANSI-Z-136.1.

4.2 Receiver assembly

The schematic diagram of Receiver is shown in Fig. 4. The telescope consists of the 1m primary mirror and the 20cm secondary mirror, each of which is made of Beryllium. An aperture stop is located at the focus of the telescope and acts as the field stop. The FOV is 0.21mrad, and the F-number of the telescope is 6. The defocus of the telescope by the change of the thermal condition can be canceled by using Titanium for the support structure of the secondary mirror. The received backscattered light from objectives is led to the relay optics and separated by the dichroic mirror into two colors.

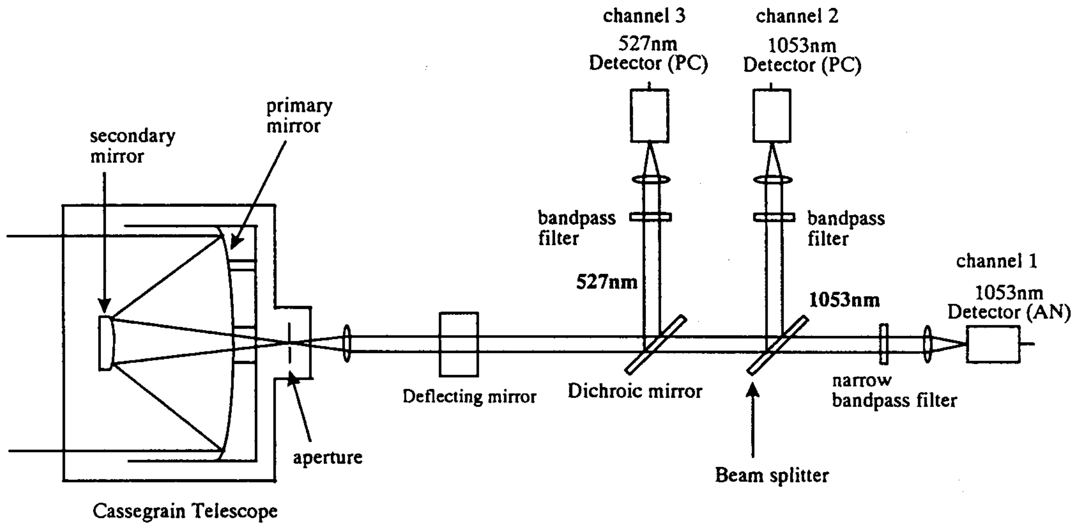

Fig. 4 The schematic diagram of Receiver

The fundamental wavelength backscattered light is separated in 9 to 1 ratio by the beamsplitter and detected by two Si-APD detectors. One of detectors operates in analogue mode and the other operates in photon counting mode. The analogue Si-APD detector uses 90% of the received 1053nm light for measuring clouds, and the photon counting mode Si-APD detector uses the rest of received 1053nm light for measuring aerosols. The second harmonics is detected by the photon counting mode Si-APD detector only to observe aerosols and the atmospheric density.

Since ELISE observes clouds in day and night time, the narrow bandwidth(0.3nm, FWHM) interference filter is used for analogue detection to exclude background noise, while the 10nm band width interference filter is used for photon counting detection, because the observation of aerosols and the atmospheric density is operated in night time only. The quantum efficiency of the analogue mode Si-APD is 31.5%. The detection probability of the photon counting mode Si-APD is 34% at 527nm and 1.25% at 1053nm.

5. The Instrument Operation

ELISE has 5 operating modes on orbit, which are the observation mode 1, 2, 3, the alignment mode and the stand-by mode. The detail of each mode is shown in Table 2. During the launch time, ELISE is in the all-off mode, then move to the stand-by mode in the first visible time in orbit. In orbit, the operating mode is changed by the commands from the ground station(Tracking and Control Center). The alignment mode will be used in case of misalignment between the laser transmitter and the receiver happening.

Table 2 The operating mode of ELISE

channel / mode	ch1 1053nm (AN)	ch2 1053nm (PC)	ch3 527nm (PC)	heater
observation mode 1	ON	OFF	OFF	ON
observation mode 2	OFF	ON	ON	ON
observation mode 3	ON	ON	ON	ON
alignment mode	OFF	OFF	ON	ON
stand-by mode	OFF	OFF	OFF	ON

6. The Signal to Noise Ratio Simulation

6.1 The LIDAR equation

The single scattering lidar equation is written in the following formula.

$$N_s(z) = n \cdot \eta \cdot \frac{K \cdot A \cdot c \cdot T^2(z) \cdot \beta(z) \cdot E_0}{2(z_L - z)^2} \cdot \frac{2 \cdot \Delta z \cdot \lambda}{h \cdot c^2} \quad \text{----------} (1)$$

Where,

$N_s(z)$: the number of the received signal of the back-scattered photons from targets at range z

n : the number of laser shots

η : the quantum efficiency of Si-APD

K : transmission of lidar optics

A : the receiving telescope area

c : the velocity of light

T(z) : the atmospheric transmission between lidar and targets

z : altitude

β(z) : the volume backscatter coefficient of targets at altitude z

E_0 : the laser pulse energy

h : Plank's constant

λ : the wavelength of fundamental

Δz : the vertical resolution of atmospheric layer

z_L : the altitude of ELISE ; 5.5×10^5[m]

β(z) includes the effect of atmospheric molecules, clouds and aerosols. T(z) is calculated by the following equation,

$$T^2(z) = e^{-2\int_z^{z_L} \sigma(z')dz'} \quad \text{----------} (2)$$

where σ is the volume extinction coefficient, which also includes the effect of atmospheric molecules and aerosols.

6.2 The SNR simulation of the analogue detection

The S/N of the data obtained by the analogue detection is also calculated by the lidar equation and the following formula using the system parameters shown in Table 1.

$$S/N = \frac{P_s R M n^{1/2}}{\left[2q(P_s + 2P_b)RM^2 F_m B + 2\left(I_n^2 + I_{APD}^2\right)B\right]^{1/2}} \quad , \quad R = \frac{\eta q \lambda}{hc} \quad \text{----------} (3)$$

Where,

P_s : the received signal power

P_b : the background power

M : the multiplication factor of Si-APD

B : the band width of amplifier

F_m : the excess noise factor

I_n : the amplifier noise current

I_{APD} : the Si-APD noise current

In this calculation, M, F, B, ΔZ and n are 100, 2.5, 1.5MHz, 100m and 20, respectively. The vertical distribution of atmospheric molecules and aerosols are based on the U.S. Standard Atmosphere model(2) and the EOS Report(3), respectively. The cirrus model is based on Sasano and Kobayashi(4). The result of the SNR simulation is shown in Table 3. The maximum value of the SNR is over 10 at about 10km.

6.3 The SNR simulation of Photon Counting detection

The SNR of the data obtained by the photon counting detection(527nm) is also calculated by the lidar equation and the following formula using the system parameters shown in Table 1.

$$S/N = \frac{N_s(z)}{\sqrt{N_s(z) + 2N_d}} \cdot \sqrt{n} \quad \text{----------} (4)$$

where N_s and n are the same as in 6.2. N_d is the number of the dark count of the detector. Because the photon counting detection is operated only in nighttime, the background noise is not in this formula. In this calculation, N_d and n are 250[counts per second] and 2000, respectively. The vertical distribution models of cirrus, aerosols and atmosphere are also same as in 6.2. The result of the SNR simulation is shown in Table4. The peak value of the SNR is over 10 at 35km.

Table 3. The result of the SNR simulation(1053nmAN)

Condition			Min.	Nominal	Max.
Object	Back ground radiance (W/m² sr nm)	Integration for the horizontal			
Cirrus $\beta=3\times10^{-5}$ h=9-11km	0.17 Day Low altitude cloud Albedo:0.2 Optical depth 128	20	10.4	14.4	18.2
Cirrus $\beta=3\times10^{-5}$ h=9-11km	43×10^{-3} Day Earth surface Albedo:0.2	20	16.2	22.5	28.8
Cirrus $\beta=3\times10^{-5}$ h=9-11km	0.17×10^{-6} Night,Full moon Low altitude cloud Albedo:0.2 Optical depth 128	20	22.6	32.0	41.3

Table 4. The result of the SNR simulation(527nmPC)

Condition			Min.	Nominal	Max.
Object	Back ground radiance (W/m² sr nm)	Integration for the horizontal			
Air h=35km	0.49×10^{-6} Night,Full moon Low altitude cloud Albedo:0.2 Optical depth 128	2000	11.1	14.1	17.2
Air h=35km	0.13×10^{-3} Night, Full moon Earth surface Albedo:0.2	2000	15.4	19.0	22.7

7. Summary

ELISE is the two-wavelength backscatter lidar which will be loaded on the MDS-2. The MDS-2 is planned to be launched by H-IIA rocket and flown to the circular orbit(altitude 550km, inclination 30 degree) early in 2001. The purpose of ELISE mission is as following,

1. Demonstration of the key technologies like LD-pumped high power LASER and high efficiency detectors
2. The collection of the information on clouds and aerosols for the design of future satellite-borne lidars

Now, the preliminary design is finished. The S/N simulation studies are conducted to confirm the performance of ELISE using the preliminary system parameters. The result shows that ELISE can observe cirrus and the atmospheric density with S/N over 10.

References

(1) Sasano, Y. "MDS-lidar scientific mission", Proceeding of International Workshop on Spaceborne Lidar 1996, pp. 211-224.

(2) NOAA, NASA, U.S. Air Force, "U.S. STANDARD ATMOSPHERE, 1976", NOAA-S/T 76-1562

(3) NASA, "LASA Lidar Atmospheric Sounder and Altimeter Instrument Panel Report", Earth Observing System Reports Volume IId, P17

(4) Sasano, Y. and T. Kobayashi(ed.) : Feasibility study on space lidars for measuring global atmospheric environment, No.4 Final Report, F-82-1995/NIES(1995)

Table 1 Instrument requirements

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ELISE Instrument requirements

1.Operational requirements

- **ELISE shall perform measurements continuously in orbit for one year**

2. Spectral Requierments

- **ELISE shall operate at two wavelength of 1053nm and 527nm**
- **1053nm for Cloud, 527nm for Air molecule and Aerosol**

3. Geometrical Requirements

- **The lidar beam shall be pointed towards nadir.**
- **Measurement altitude range :from the surface of the ellipsoid of WGS-84 up to 35km altitude.**

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Table 2 Cloud and aerosol measurement requirements

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ELISE Cloud & Aerosol Measurement Requirements

1. Resolution

For cirrus top detection at day and night

vertical	100 m
horizontal	1.5 km

For aerosols detection at night

vertical	1 km
horizontal	150 km

2. Signal to Noise ratio

SNR **>10**

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ELISE | **ELISE system functional diagram**

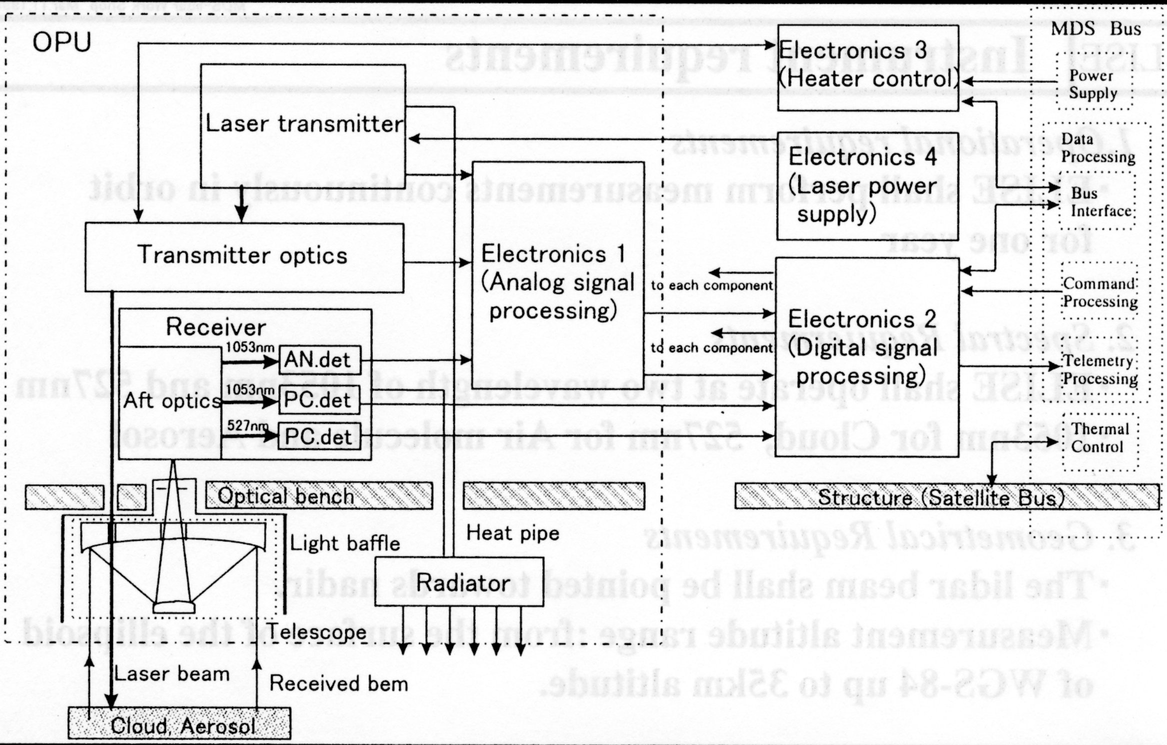

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Fig.1 ELISE system functional diagram

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ELISE | **ELISE instrument layout (without light baffle)**

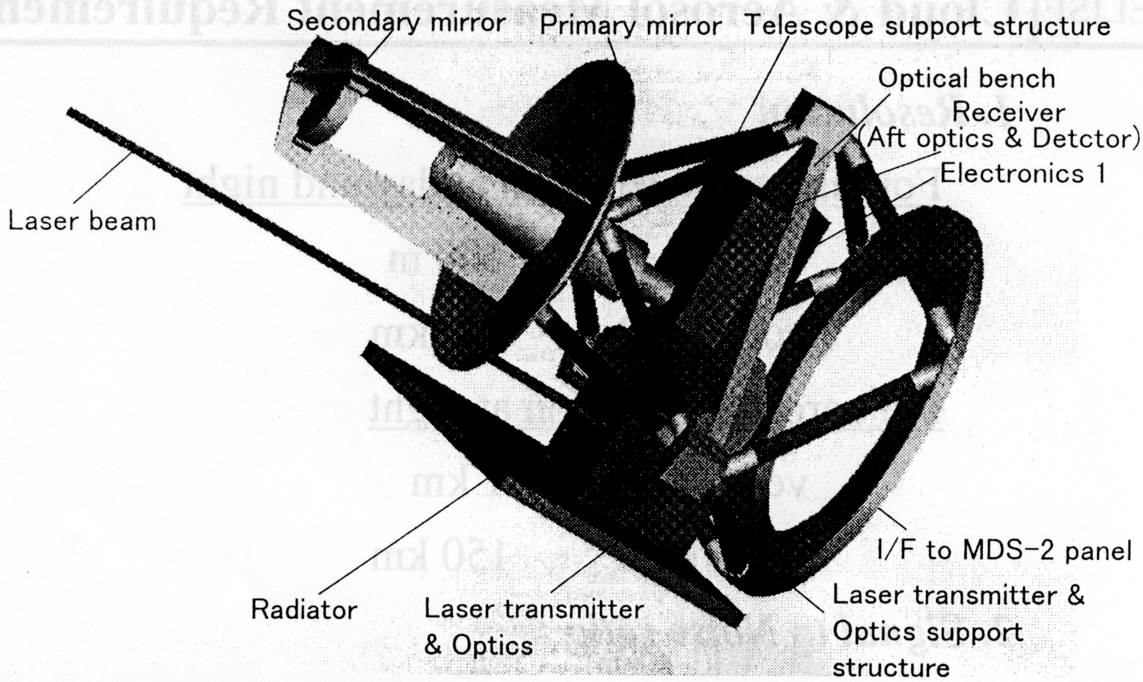

Fig.2 ELISE instrument layout without light baffle

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ELISE | ELISE instrument layout

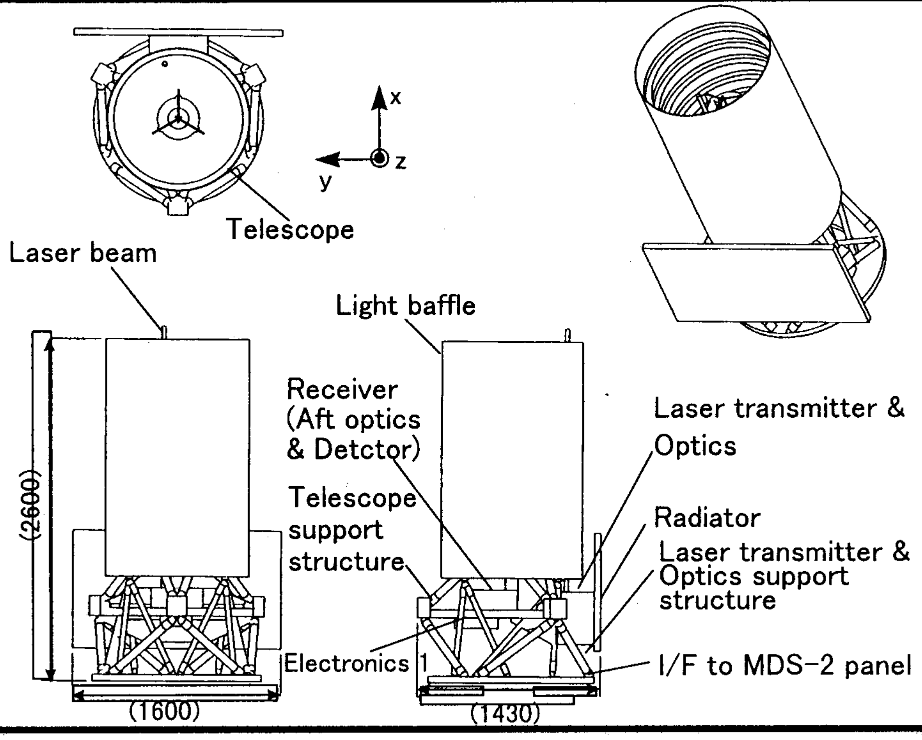

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Fig.3 ELISE instrument layout

ELISE | The Schematic of the LD pumped Nd:YLF laser

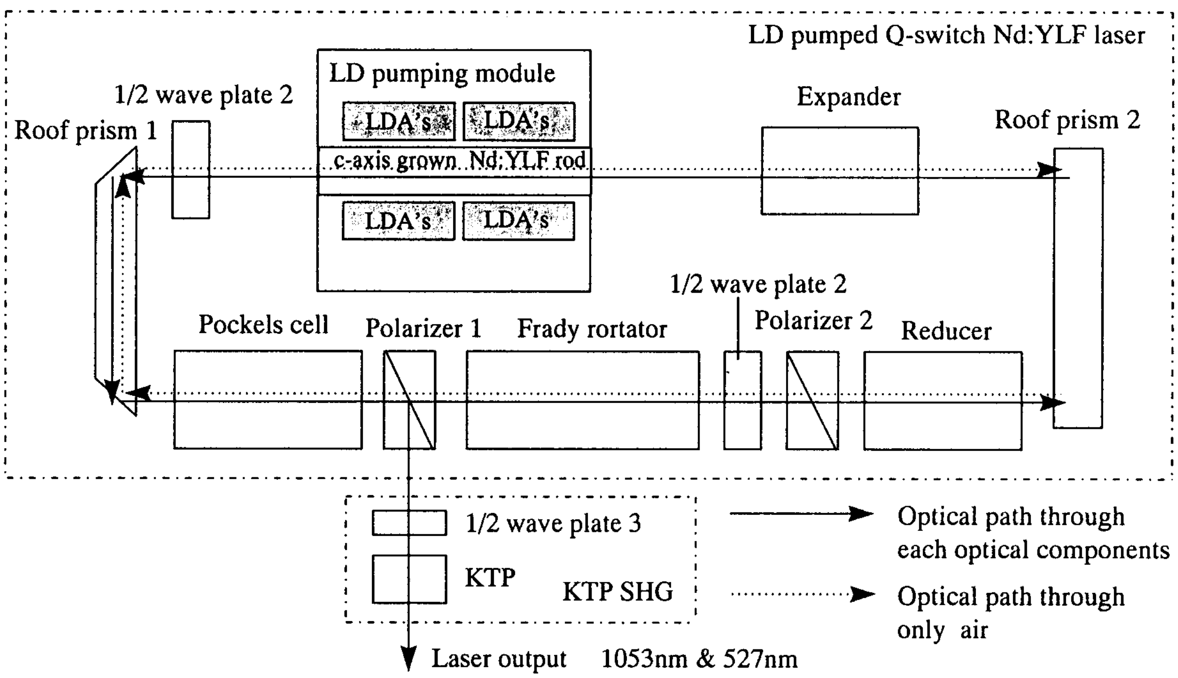

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Fig.4 The schematic of the LD pumped Nd:YLF laser

ELISE The Schematic diagram of Receiver

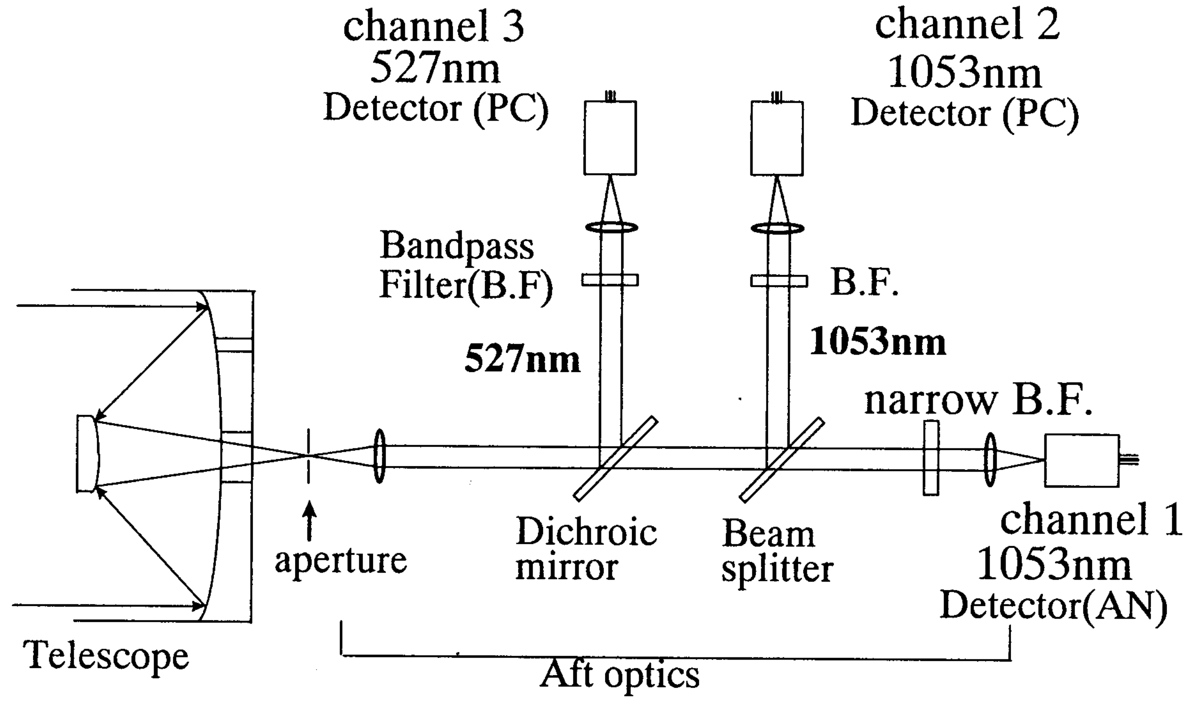

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Fig.5 The schematic diagram of Receiver

Table 3 Atmospheric model

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ELISE Atmospheric model

Atmospheric feature	Volume Backscatter coefficient(msr)$^{-1}$	Scattering Parameter	Altitude Range(km)	Notes
Rayleigh Scattering Characteristics				
Air Molecules	$1.54 \times 10^{-6} \times (532/\lambda)^4 \times \exp(-h/7)$	$8\pi/3$	0 to 35	
Aerosol Characteristics				
PBL Aerosols	———	———	———	
Troposheric Aerosols	$\{2.47 \times 10^{-6} \exp(-h/2) + 5.13 \times 10^{-9} \exp(-(h-20)^2/6^2)\}(532/\lambda)$	50	0 to 35	Including Volcanic Stratospheric,back-ground Stratospheric Aerosols
Cloud Characteristics				
Low altitude cloud	———	———	———	Cumulus,Stratus etc
Cirrus	$3.0 \times 10^{-5} \times \exp[-(h-10)^2/1.5^2]$	10	9 to 11	
Polar Stratosheric cloud	———	———	———	

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Table 4 SNR calculating conditions(1053nm AN)

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ELISE SNR calculating condition(1053nm AN)

Parameters		Min.	Nominal	Max.
Satellite altitude (km)		545	550	555
The vertical resolution (m)			100	
Transmitter	Laser output energy (mJ)	81.1	84	89.5
	Optical throughput		0.9	
	Beam divergence (mrad)	0.165	0.17	0.175
Telescope	Effective diameter(m)		1	
	Field of view (mrad)	0.21	0.22	0.23
	Optical throughput	0.78	0.80	0.81
Aft opt.	Optical throughput	0.47	0.50	0.53
	Filter band width (nm)		0.3	
Receiver	Quantum efficiency	0.27	0.315	0.36
	Multiplication factor		100	
	Excess noise factor		2.5	
	Noise current (A/Hz $^{1/2}$)	3.3×10^{-13}	3.5×10^{-13}	4.0×10^{-13}
Receiveing optics axis shift		0.8	0.9	1.0
Wavelength shift		0.8	0.9	1.0

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Table 5 Example of SNR(1053nm AN)

ELISE Example of SNR (1053nm AN detection)

Condition			Min.	Nominal	Max.
Object	Back ground radiance (W/m² sr nm)	Integration for the horizontal			
Cirrus β =3x10^{-5} h=9-11km	0.17 Day Low altitude cloud Optical depth 128	20	10.4	14.4	18.2
Cirrus β =3x10^{-5} h=9-11km	43x10^{-3} Day Earth surface Albedo:0.2	20	16.2	22.5	28.8
Cirrus β =3x10^{-5} h=9-11km	0.17x10^{-6} Night,Full moon Low altitude cloud Albedo:0.2 Optical depth 128	20	22.6	32.0	41.3

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Table 6 ELISE system parameters

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ELISE ELISE system parameters

Items		Analog detection	Photon Counting detection		Notes
		Fundamental	Fundamental	SHG	
Performance	The vertical res.	100 m (667 nsec)			Data sampling rate
	The horizontal res.	0.4 km (Int. 5) 1.45 km (Int. 20)	1.45 km (Int. 20) 14.1 km (Int. 200)		
	SNR	>10			
Transmitter	Laser	LD pumped Q-switch Nd:YLF laser + KTP			
	Wavelength	1053.2 nm		526.6 nm	
	Output energy	84 mJ		10 mJ	
	P R F	100 pps			
	Beam divergence	0.17 mrad			
Receiver	Telescope diam.	1000 mm			
	Field of view	0.22 mrad			
	Filter band width	0.3 nm	4 nm		
	Opt.transmission	40 %	6.5 %	60 %	
	Quantum efficiency	31.5 %	----	----	
	Det.probability	----	1.25 %	34 %	
	Dymamic range	50.6 dB	68.2 dB		Integration 20
	Data bit lengh	12 bits / data			
Mass		250 kg			
Power		250W			

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