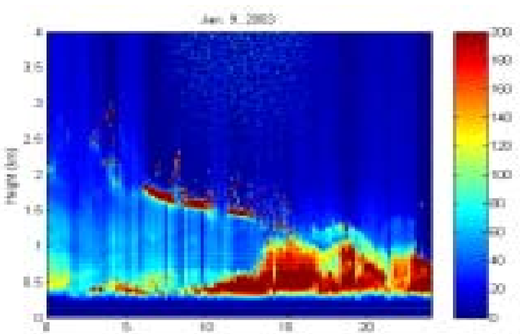
Lidar activities at CEReS

Center for Environmental Remote Sensing (CEReS), Chiba University

Hiroaki Kuze

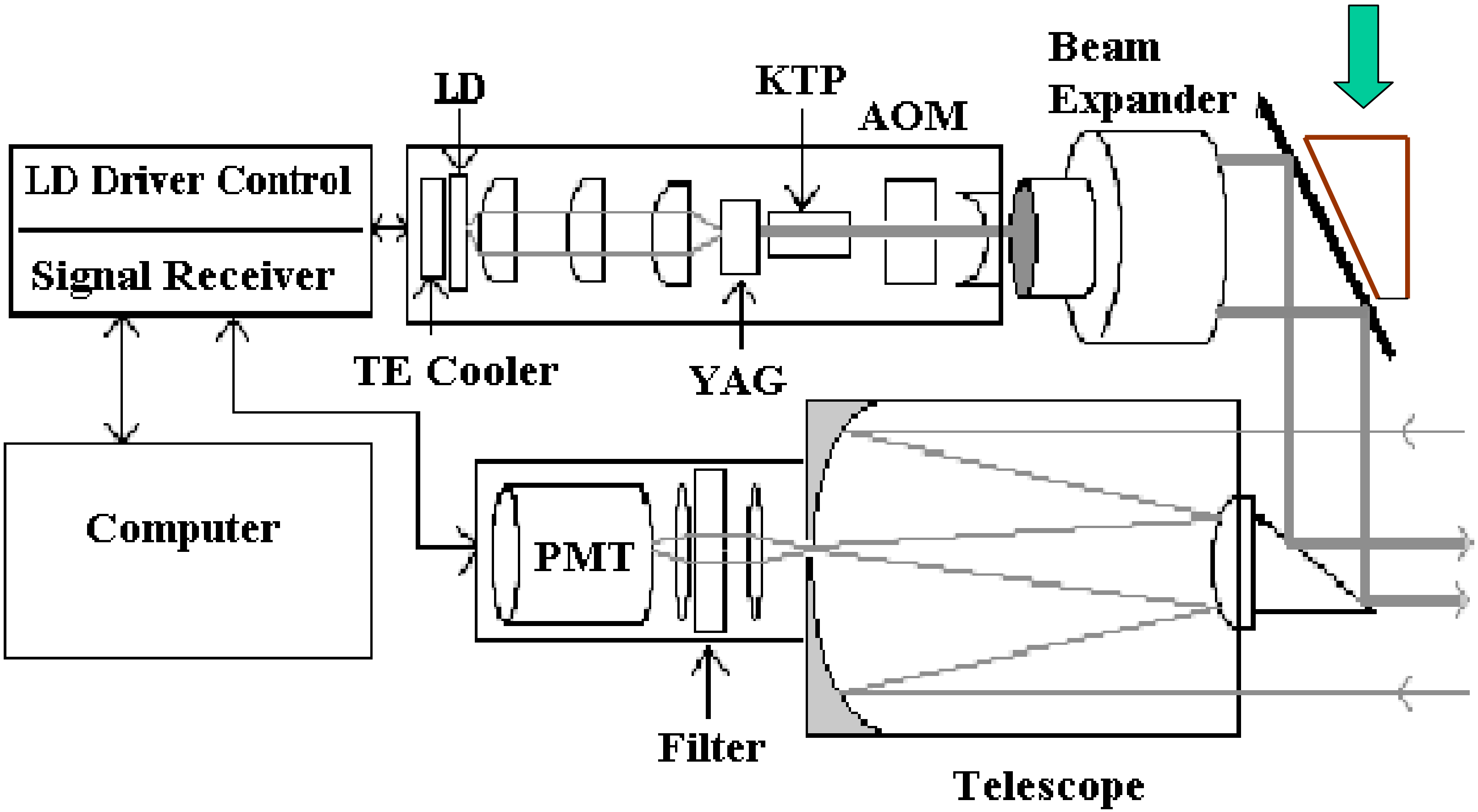


hkuze@faculty.chiba-u.jp

Lidar activities at CEReS

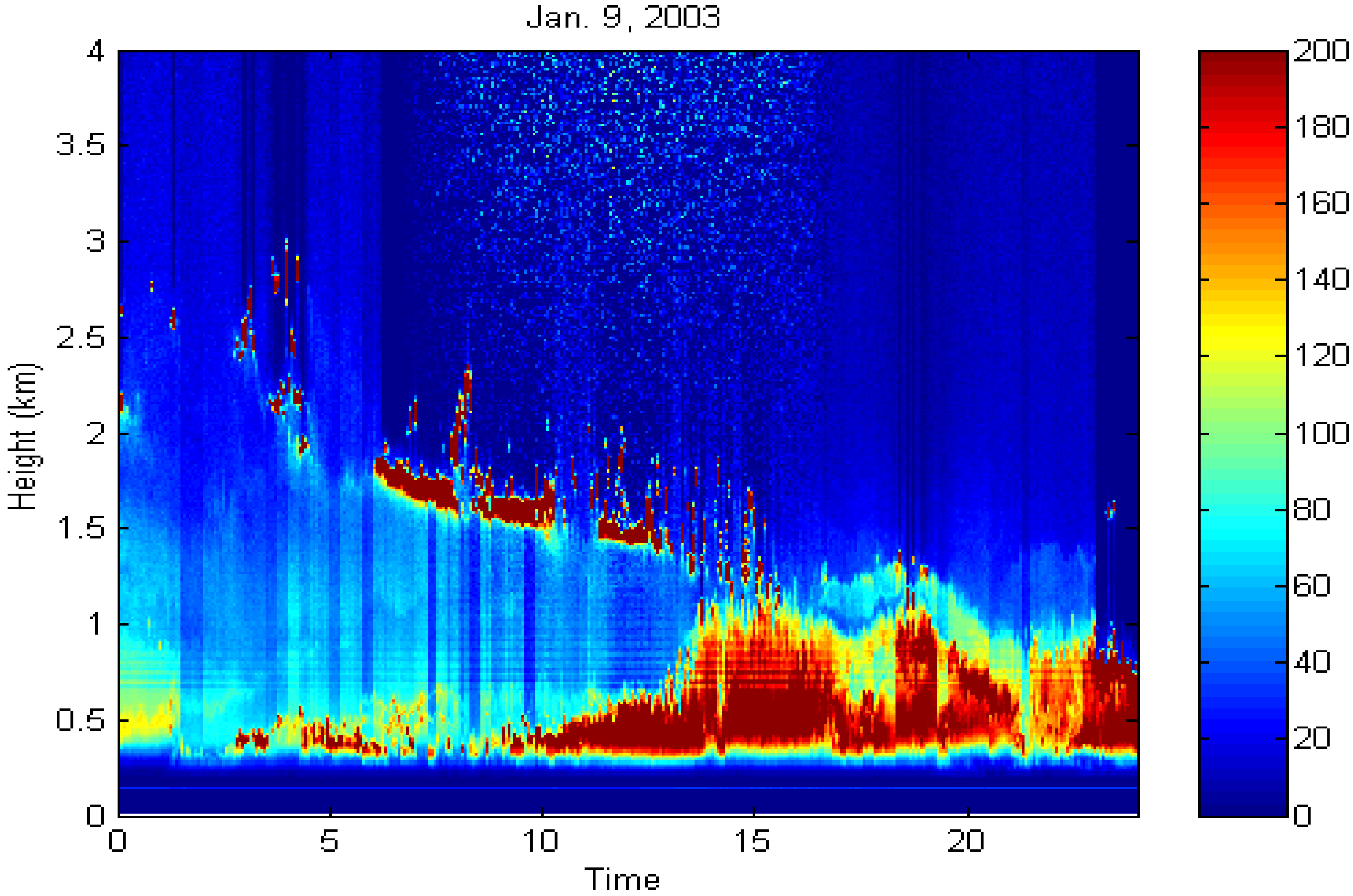
- **Portable Automated Lidar (PAL)**
- **Micro Pulse Lidar (MPL)**
- **Four-wavelength Lidar – Look-up Table approach for the determination of aerosol profiles**
- **Imaging Lidar – Application of the wide FOV telescope of the *Ashra-I* project**

Portable Automated Lidar (PAL)
Automatic alignment

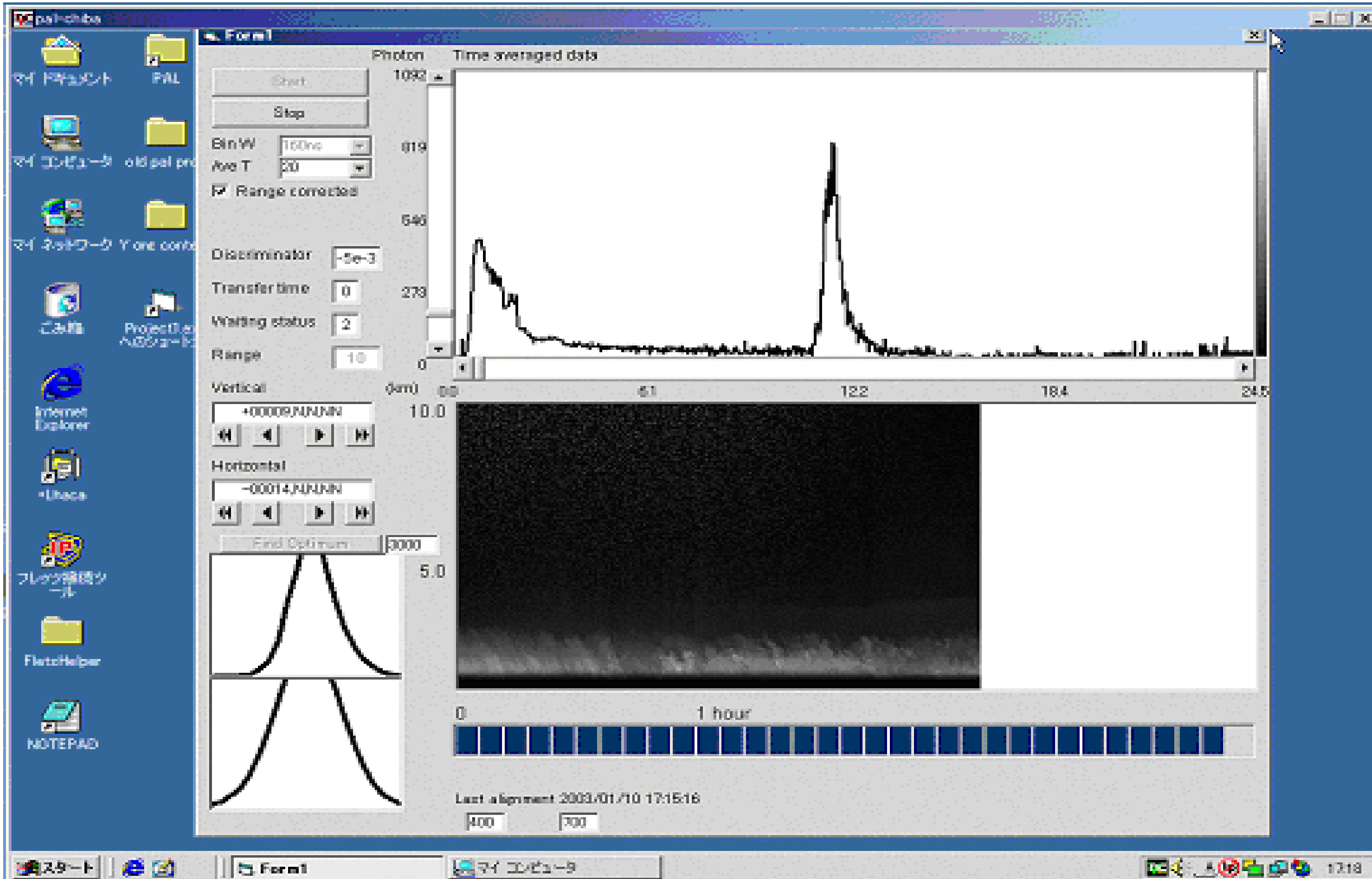


PAL (Portable Automated Lidar)

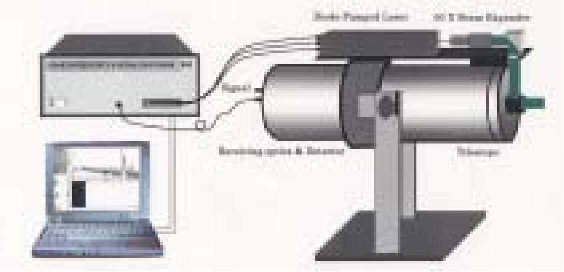
Observation of tropospheric aerosols and clouds

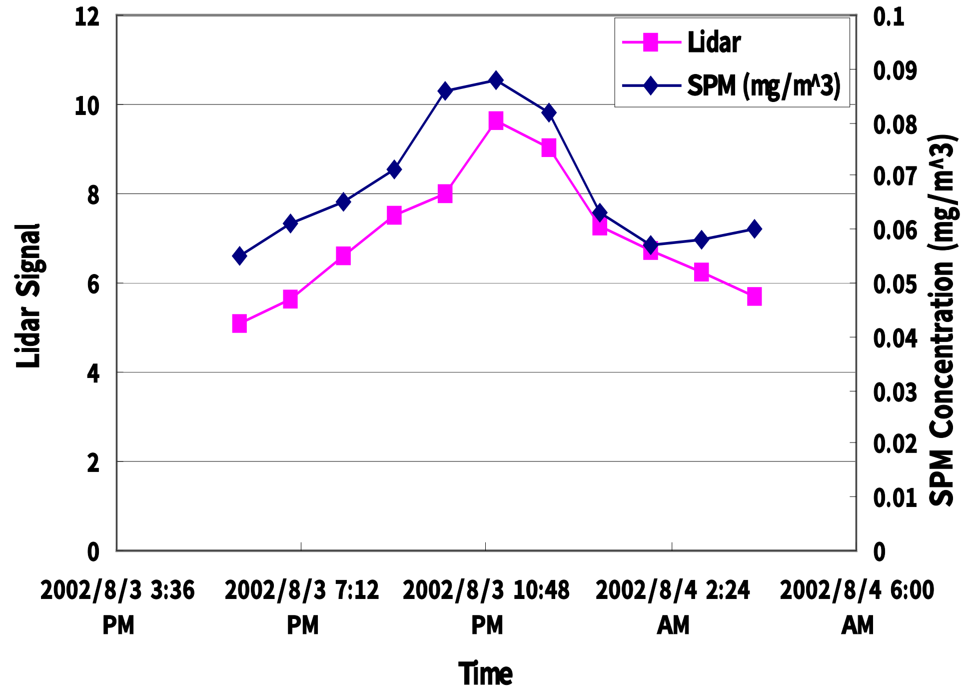


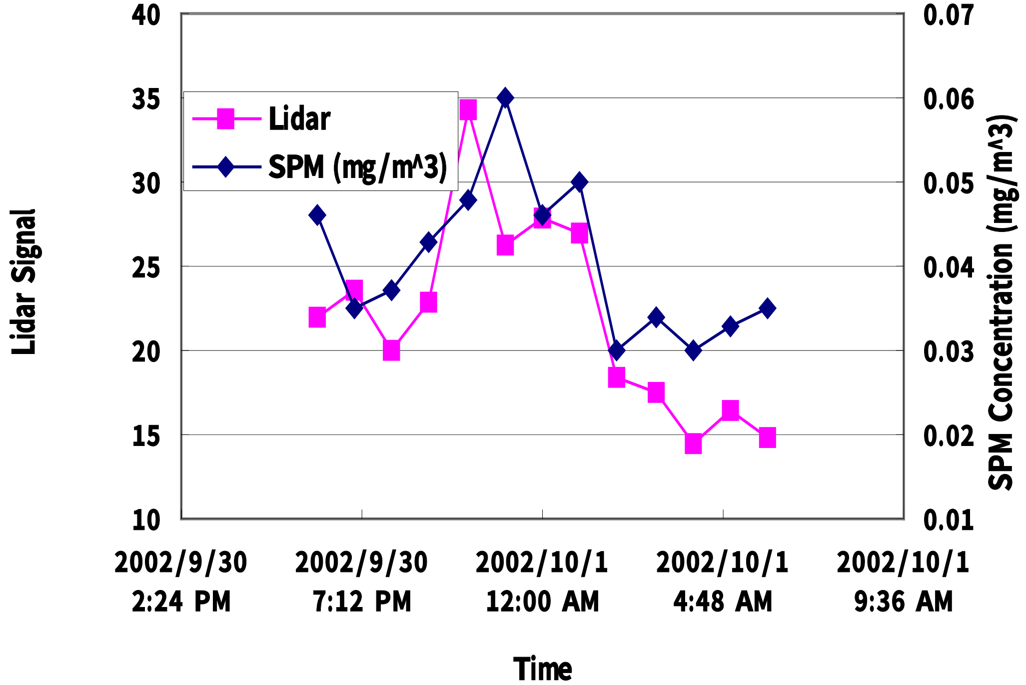
A-scope of PAL



Aerosol concentration in the boundary layer: comparison between PAL data and ground data







Micro-Pulse Lidar and Portable Automated Lidar

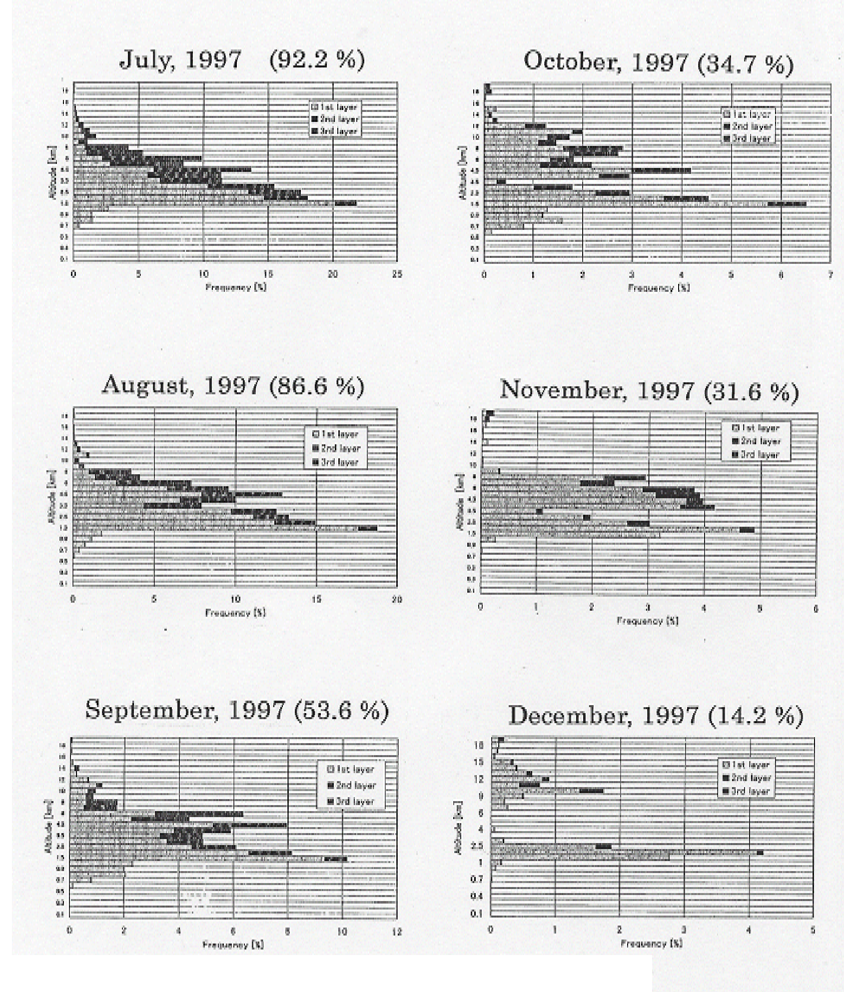
MPL

Display

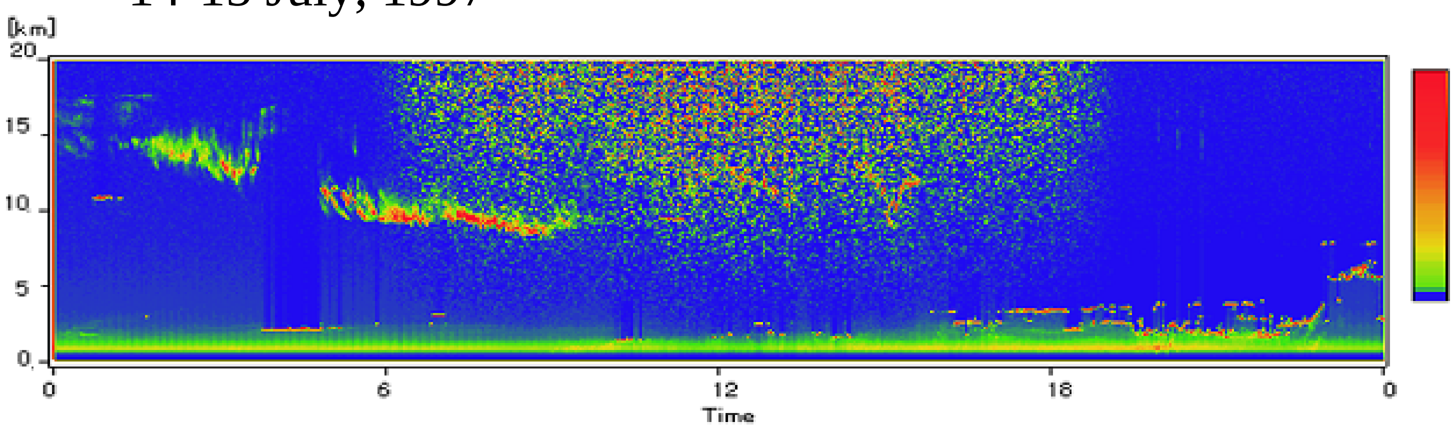
W. Chen *et al.*, Atmospheric Environment, 35 4273-4280 (2001).

	MPL	PAL
Laser	SHG of LD-pumped Nd:YLF	SHG of LD-pumped Nd:YAG
Wavelength	523 nm	532 nm
Laser pulse repetition	2.5 kHz	2.5 kHz／1.4 kHz
Pulse energy	4 μJ/pulse	6 μJ/pulse
Telescope	Cassegrainian 20cmφ	
Transmitter	In-line type	collinear
Target	Aerosol, boundary layer, cloud height	
Detection mode	Photon counting	
Detector	Si-APD	PMT

Autonomous monitoring of cloud base height with MPL



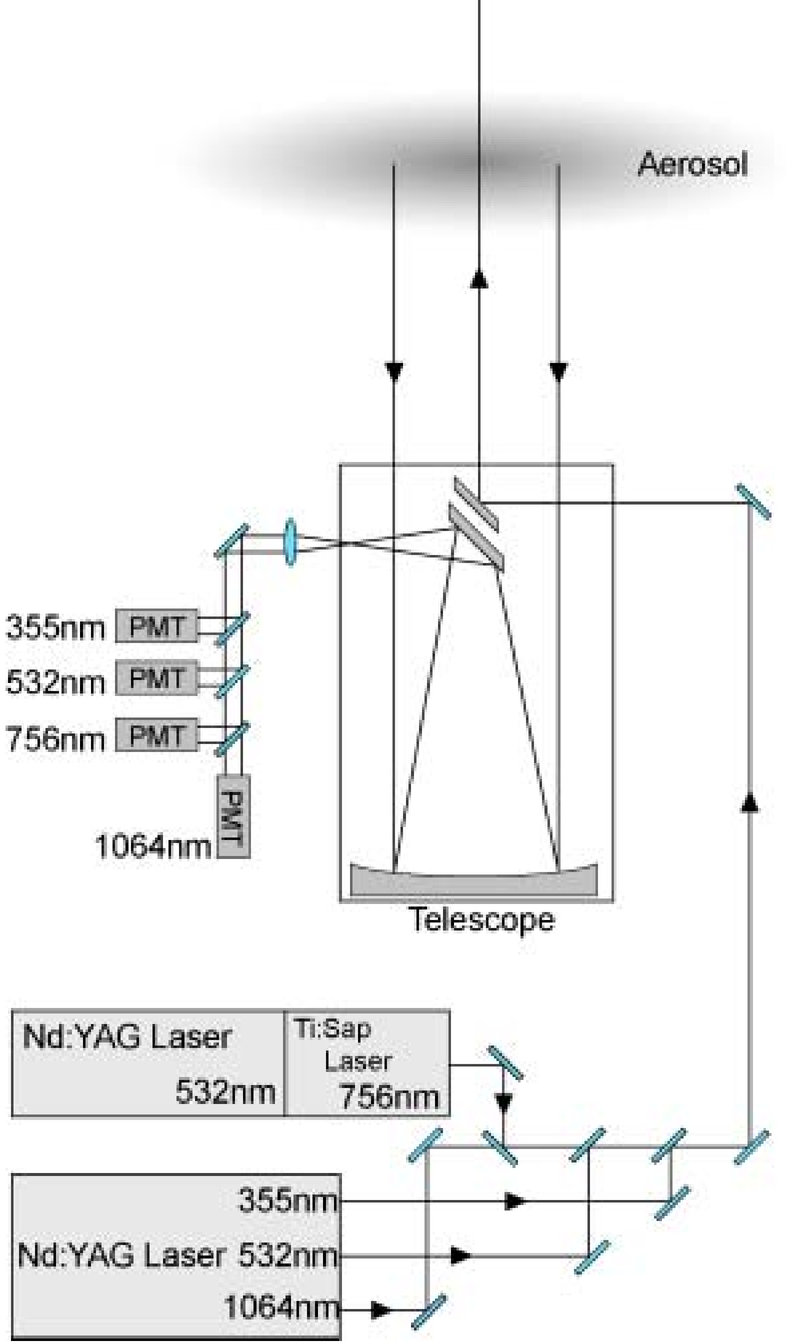
Sukhothai, Thailand,
14-15 July, 1997



Aerosol profile measurement with the CEReS 4-wavelength lidar

- 355, 532, 756, and 1064 nm
- 80 cm telescope with 4 photomultipliers

Kinjo *et al.* , Jpn.J. Appl.Phys., 40, 434-440 (2001); Yabuki *et al.* Jpn.J.Appl.Phys., 42, 686-694 (2003).



Lidar Equation

$$P(R) = P_0 \frac{c\tau}{2} AK \frac{G(R)}{R^2} \beta(R) \exp\left[-2\int_0^R \alpha(R')\,dR'\right]$$

R target range [m]

$P(R)$ detected power [W]

P_0 emitted power [W]

$\beta(R)$ backscattering coefficient [$m^{-1}sr^{-1}$]

$\alpha(R)$ extinction coefficient [m^{-1}]

c light speed [m/s]

τ laser pulse duration [s]

A telescope area [m^2]

K optical efficiency

$G(R)$ overlapping function

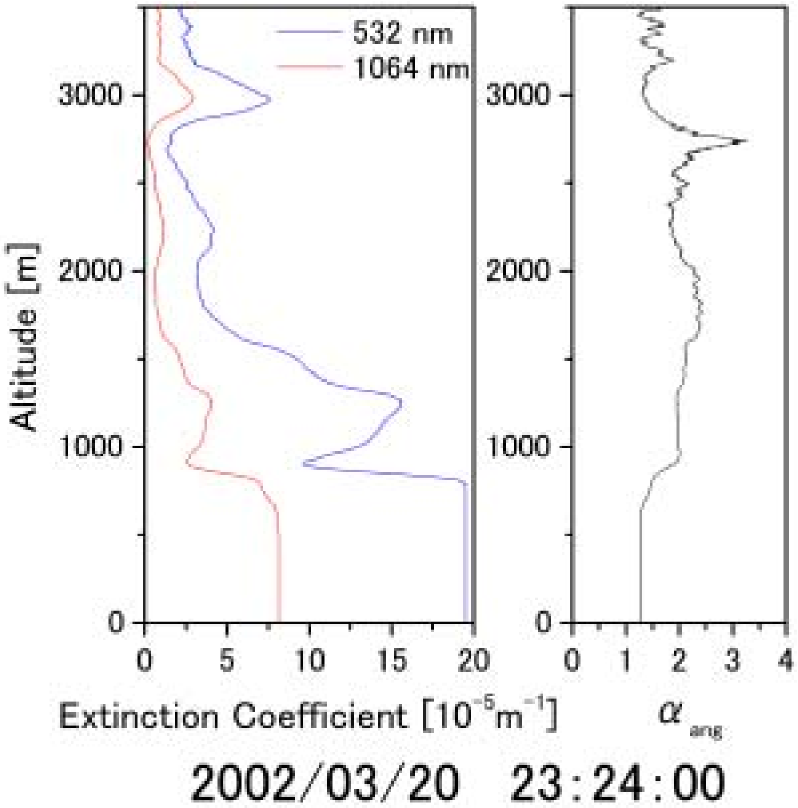
Solution of the lidar equation (Fernald method)

$$S_1(R) = \alpha_1(R)/\beta_1(R) = \sigma_1(R)/\left(\frac{d\sigma_1}{d\Omega}\right)_{\theta=\pi}, \quad S_2(R) = \alpha_2(R)/\beta_2(R) = 8.52 \text{ sr}$$

$$\alpha_1(R) = -\frac{S_1(R)}{S_2}\alpha_2(R) + \frac{S_1(R)\,X(R)\exp I(R)}{\dfrac{X(R_c)}{\dfrac{\alpha_1(R_c)}{S_1(R_c)} + \dfrac{\alpha_2(R_c)}{S_2}} + J(R)}$$

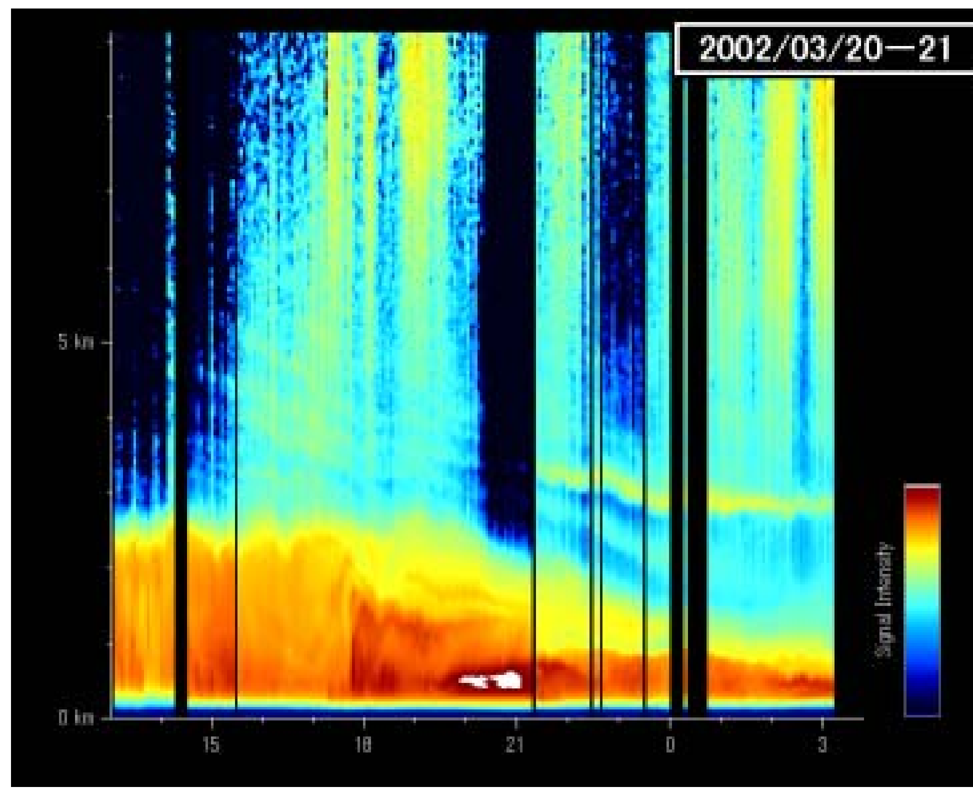
$$X(R) = R^2 P(R), \qquad I(R) = 2\int_R^{R_c}\left[\frac{S_1(R')}{S_2} - 1\right]\alpha_2(R')\,\mathrm{d}R'$$

$$J(R) = 2\int_R^{R_c} S_1(R')\,X(R')\exp I(R')\,\mathrm{d}R'$$



Aerosol extinction coefficient and the Angstrom parameter

Time evolution of the aerosol vertical profile (2002.3.20, 13:00 – 3.21, 3:00)



Look-up table (LUT) method

•**Size distribution** [*R. Jaenicke*, 1993]

$s(u)$: u = 0 to 10

Logarithmic division of the Urban and Maritime aerosol models

•**Complex refractive index**

real part $m(j_1)$: j_1 = 0 to 21

1.40 − 1.60 (0.01)

imaginary part $k(j_2)$: j_2 = 0 to 300

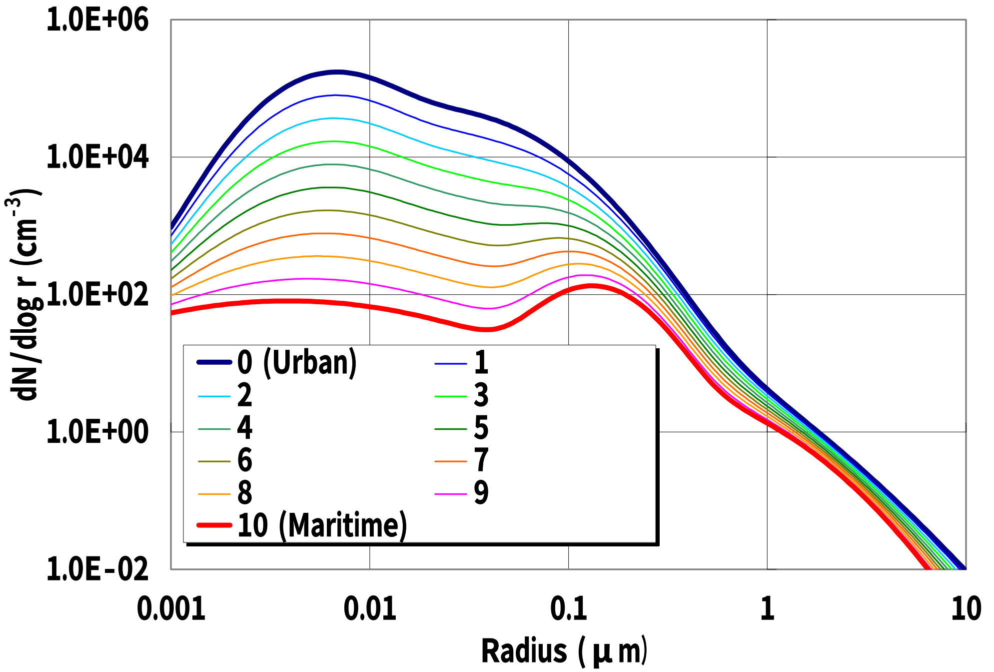
0.0000 − 0.0300 (0.0001)

•**Wavelength $\lambda(\ell)$: ℓ=1 to 4**

355, **532**, **756**, **1064 nm**

$S_1^{(LUT)}(\ell, j_1, j_2, u)$: **S_1 parameter**

$\alpha_1^{(LUT)}(\ell, j_1, j_2, u)$: **Extinction coefficient**



Aerosol size distribution for LUT. s =0 corresponds to the urban model, and s =10 to the maritime model.

Theory of Mie scattering

Scattered radiance

$$I(\theta) = \frac{I_0}{R^2}\frac{d\sigma_{scat}}{d\Omega} = \frac{I_0}{R^2}\frac{|F_1(\theta)|^2 + |F_2(\theta)|^2}{2k^2}$$

Differential cross section

Scattering amplitude

$$F_1(\theta) = \sum_{l=1}^{\infty}\frac{2l+1}{l(l+1)}\{a_l\pi_l(\cos\theta) + b_l\tau_l(\cos\theta)\}$$

$$F_2(\theta) = \sum_{l=1}^{\infty}\frac{2l+1}{l(l+1)}\{b_l\pi_l(\cos\theta) + a_l\tau_l(\cos\theta)\}$$

$$\pi_l(\cos\theta) = \frac{1}{\sin\theta}P_l^{(1)}(\cos\theta)\ , \qquad \tau_l(\cos\theta) = \frac{d}{d\theta}P_l^{(1)}(\cos\theta)$$

Associated Legendre functions

Constants determined by the boundary conditions: $(a_l,\, b_l)$

$$a_l = \frac{\psi_l'(\tilde{n}ka)\psi_l(ka) - \tilde{n}\,\psi_l(\tilde{n}ka)\psi_l'(ka)}{\psi_l'(\tilde{n}ka)\varsigma_l(ka) - \tilde{n}\,\psi_l(\tilde{n}ka)\varsigma_l{}'(ka)}$$

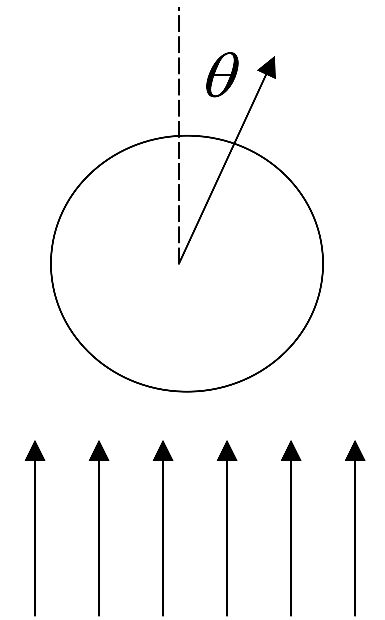
$$b_l = \frac{\tilde{n}\,\psi_l'(\tilde{n}ka)\psi_l(ka) - \psi_l(\tilde{n}ka)\psi_l'(ka)}{\tilde{n}\,\psi_l'(\tilde{n}ka)\varsigma_l(ka) - \psi_l(\tilde{n}ka)\varsigma_l{}'(ka)}$$

$\tilde{n}$: complex refractive index

$k = 2\pi/\lambda$

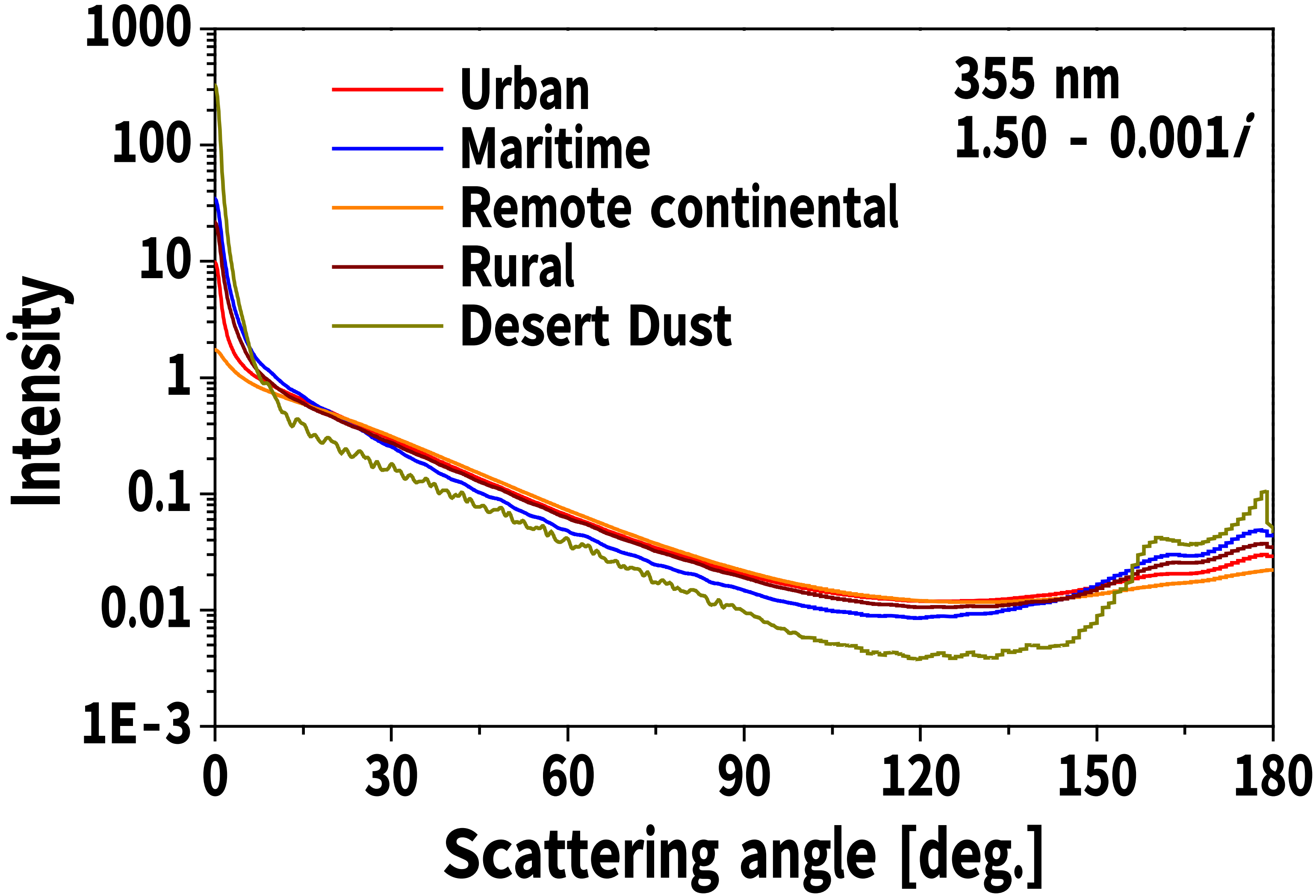
a : radius of the dielectric sphere

$$\begin{cases} \psi_l(\xi) = (-1)^l \xi^{\,l+1} \left(\dfrac{1}{\xi} \dfrac{d}{d\xi} \right)^l \left(\dfrac{\sin\xi}{\xi} \right) \\ \chi_l(\xi) = (-1)^l \xi^{\,l+1} \left(\dfrac{1}{\xi} \dfrac{d}{d\xi} \right)^l \left(\dfrac{\cos\xi}{\xi} \right) \\ \varsigma_n(\xi) = \psi_l(\xi) + i\chi_l(\xi) \end{cases}$$

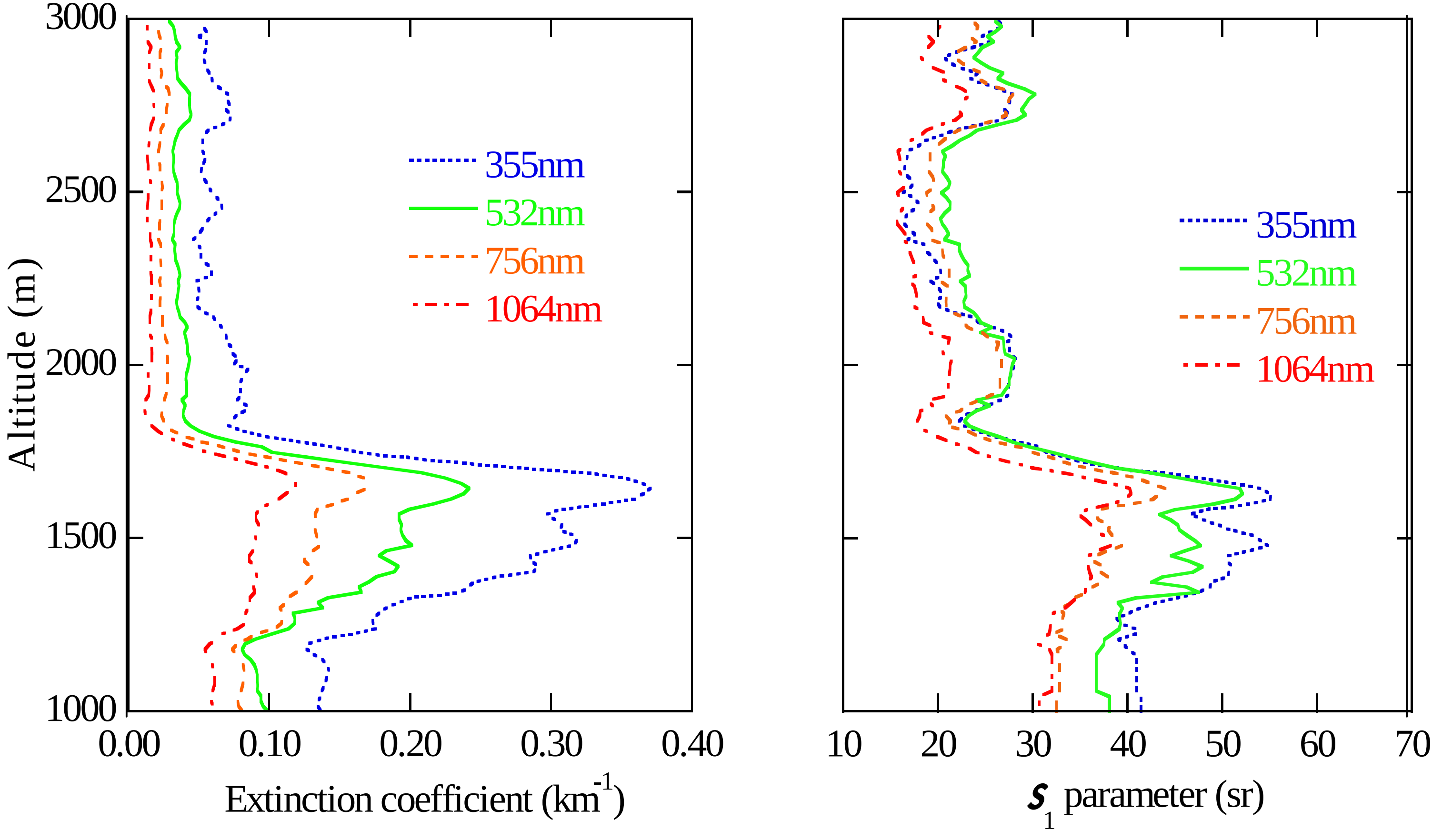


Phase functions

(Angular dependence of the differential cross section)



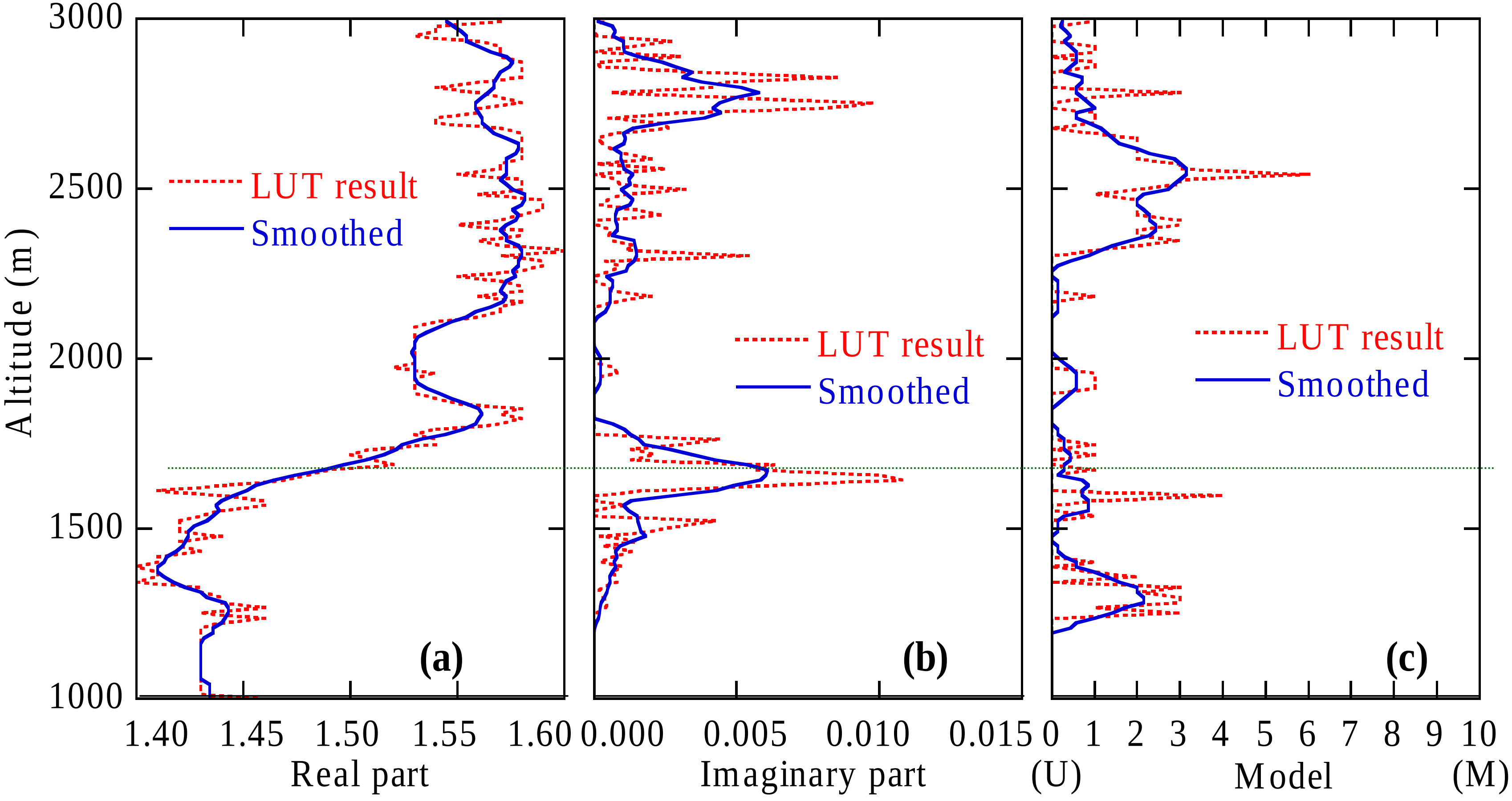
Extinction and S_1 profiles derived from the smoothed parameters (LUT method)



Extinction coefficient

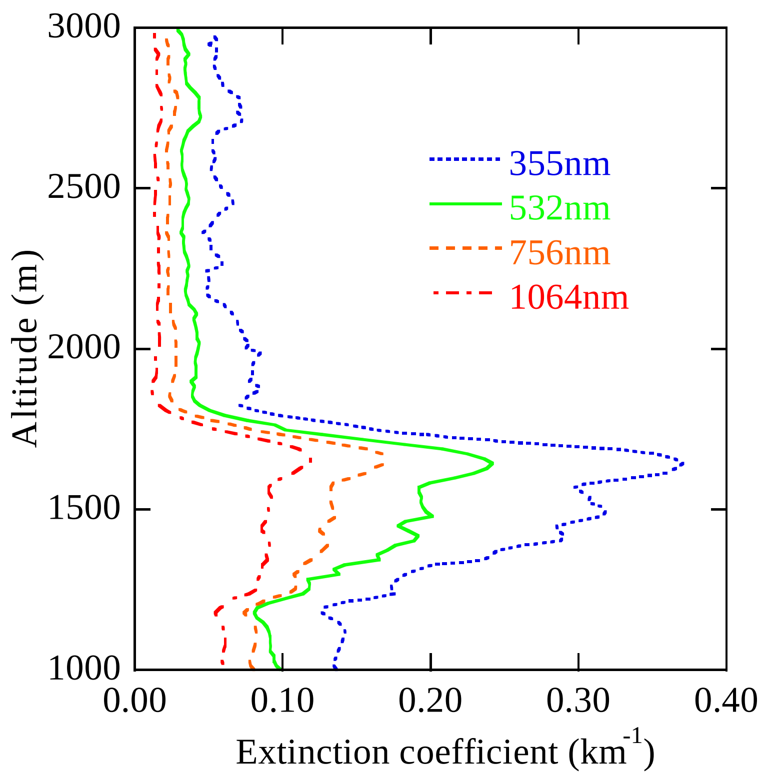
S_1 parameter (extinction/backscattering)

Vertical profiles of the complex refractive index and size distribution as derived from actual lidar data

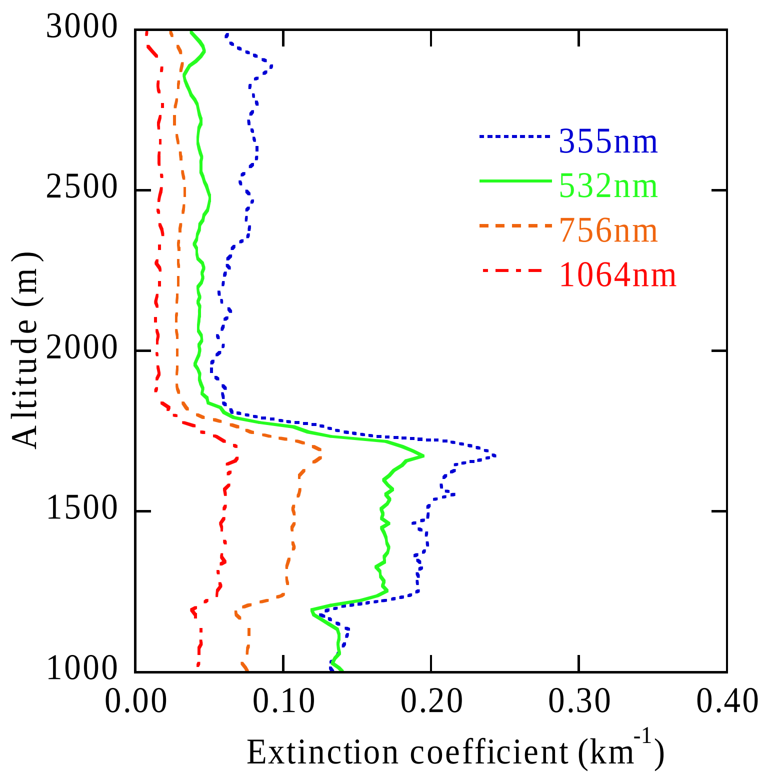


Real part **Imaginary part** **Size distribution model**

Comparison of aerosol extinction profiles between the LUT and conventional methods



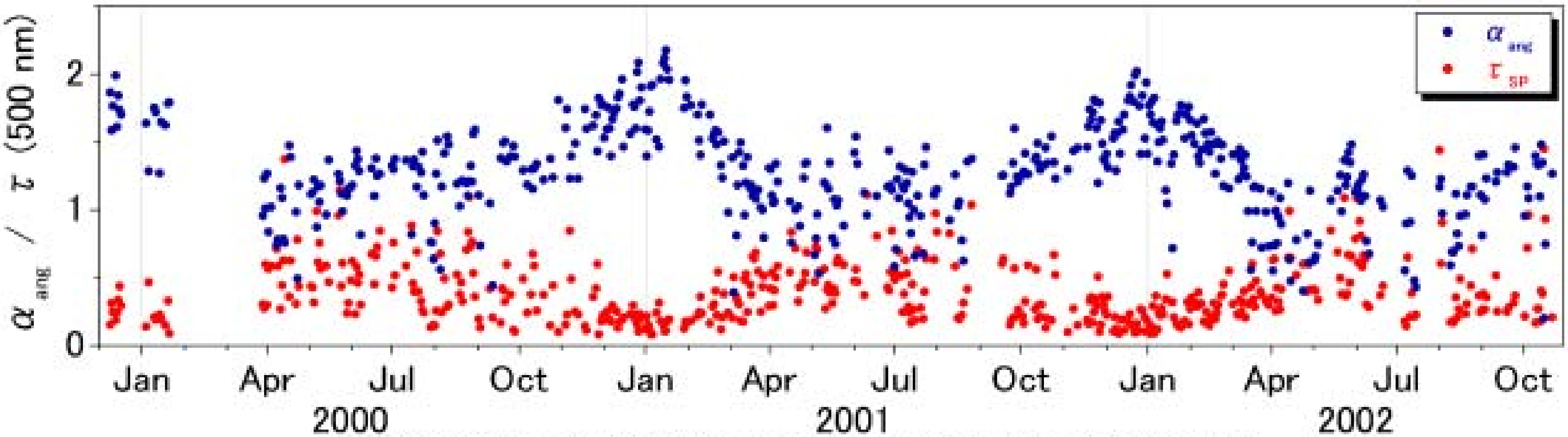
LUT method



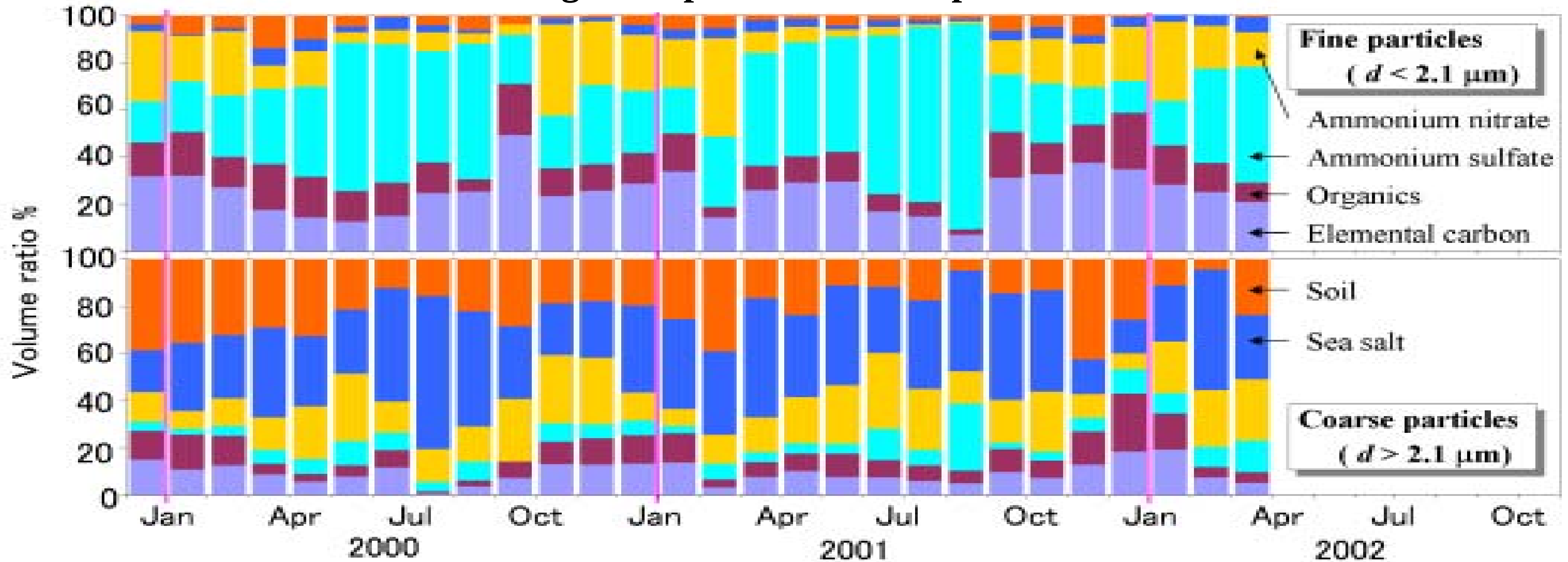
Fernald method

Wavelength (nm)	355	532	756	1064
S_1(sr)	49.8	47.9	43.3	37.9

Aerosol characteristics over the urban Chiba area



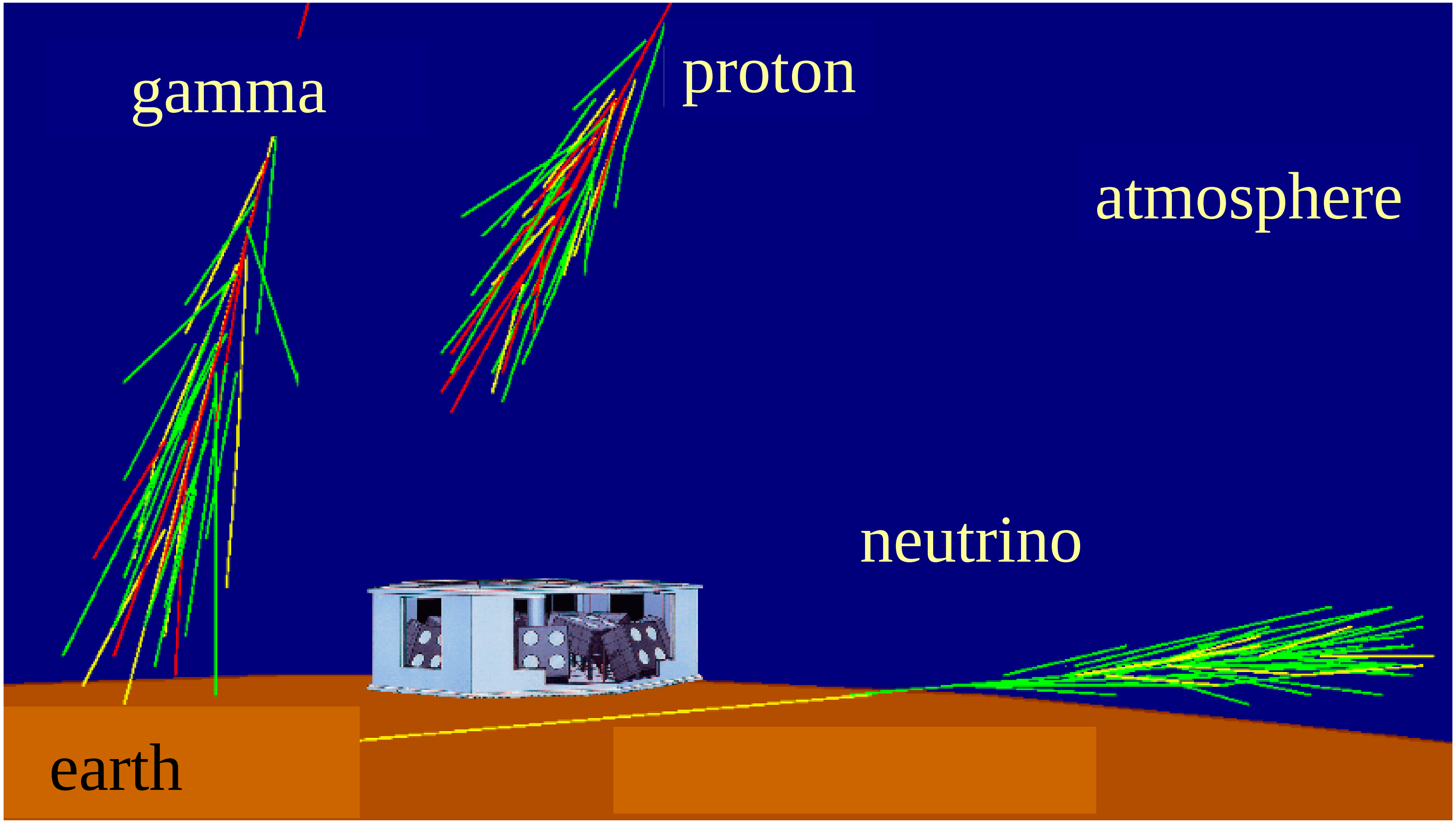
Variation of Angstrom parameter and optical thickness



Monthly change of the aerosol types from the chemical measurements.

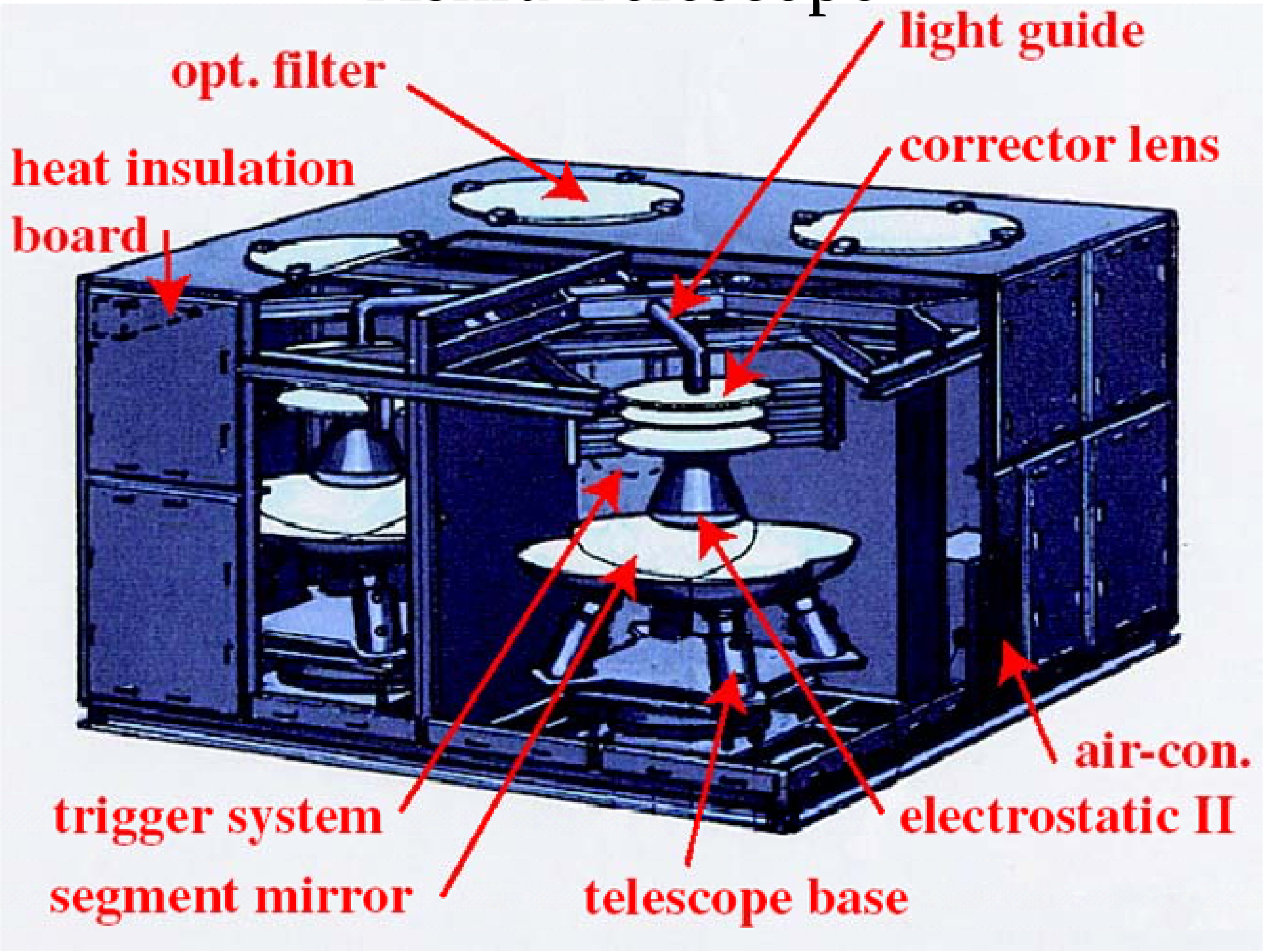
Detection of VHE cosmic-ray particles

Air-shower emission of Fluorescence/ Cherenkov lights (300-400 nm)



Ashra (all-sky survey high resolution air-shower) telescope

Ashra Telescope



Regional atmospheric monitoring with an imaging lidar

System configuration

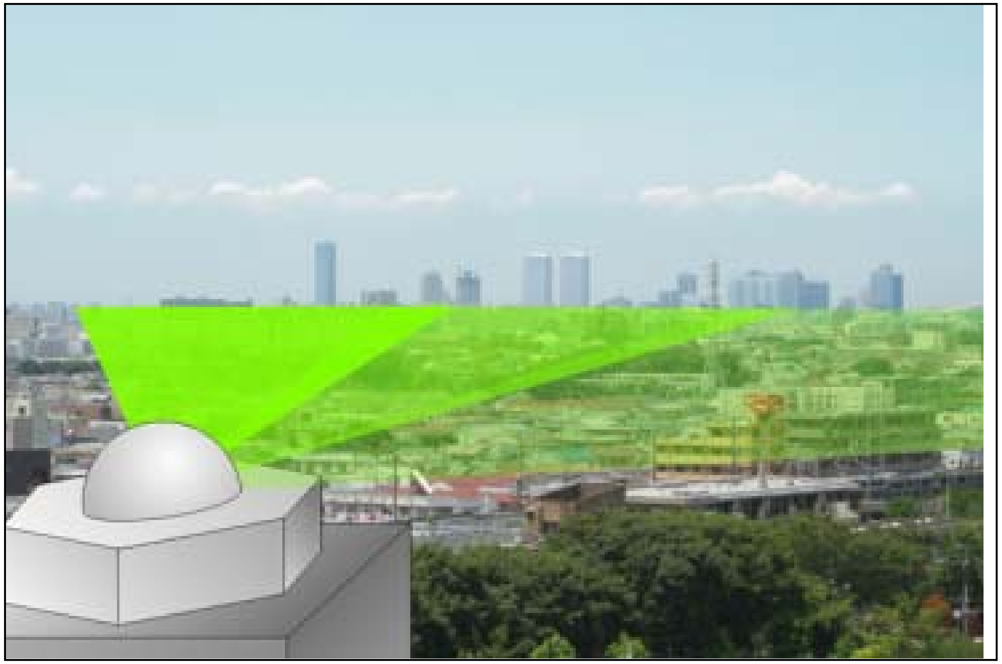
- **Wide FOV, high-resolution telescope**
- **Scanning laser**

Real time, 3-dim. measurement in a range of 100m～10km

Monitoring of urban atmosphere

- **Distribution of SPM**
  - Mie scattering lidar
- **Trace gases (pollutants)**
  - Raman lidar
  - Differential Absorption lidar (DIAL)
  - DOAS

Observation with an imaging lidar



Imaging lidar vs. conventional lidar

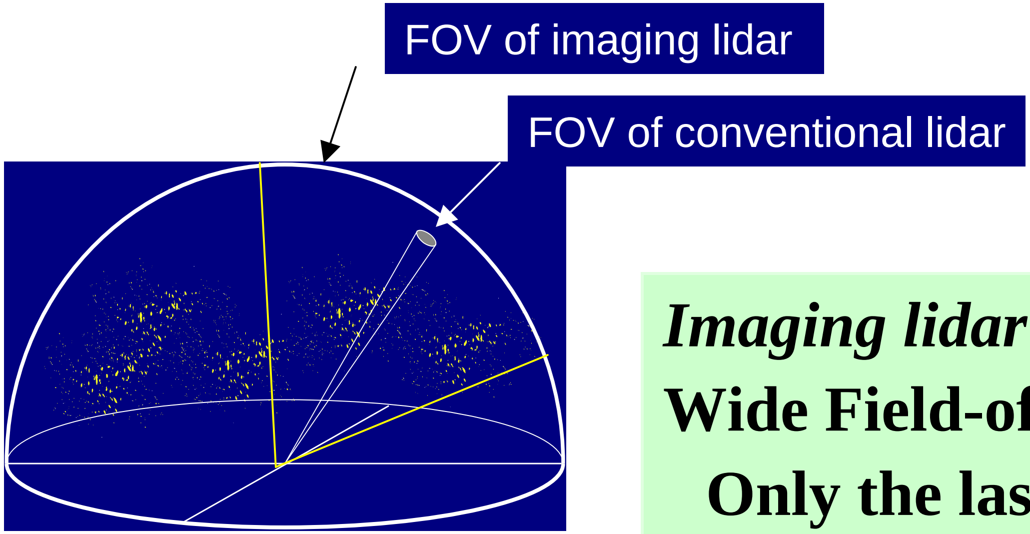
Conventional lidar (narrow FOV)

Angular scan is time consuming

Target may change during the measurement

➡ Time-Height indication (vertical profile)

Angular scan of a portable lidar



Imaging lidar

Wide Field-of-view (50 deg×50 deg)

Only the laser beam is scanned

→ Capability of quick measurement

Eye-safety

Laser power must be under the Maximum Permissible Exposure (MPE)

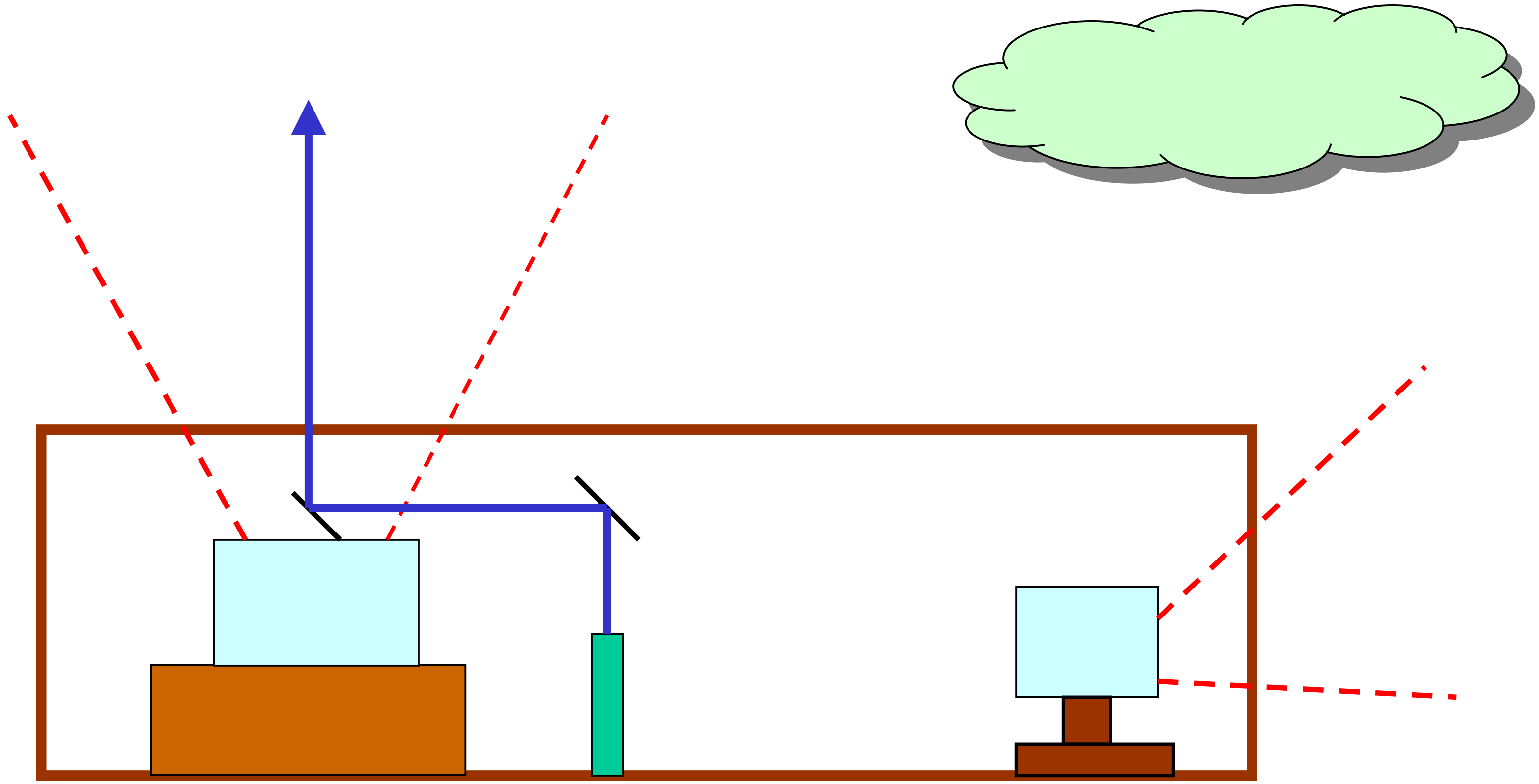
(JIS C6802 safety standard)

- **Operation wavelength of the Ashra telescope is between 300-420 nm.**

  (Wavelength range of the air-shower fluorescence)
- **For a pulse width of 20 ns with 2 kHz repetition frequency,**
  - **MPE = 4 J/m^2 @ 355 nm**

(about 300 μJ/pulse for a beam diameter of 10 mm)

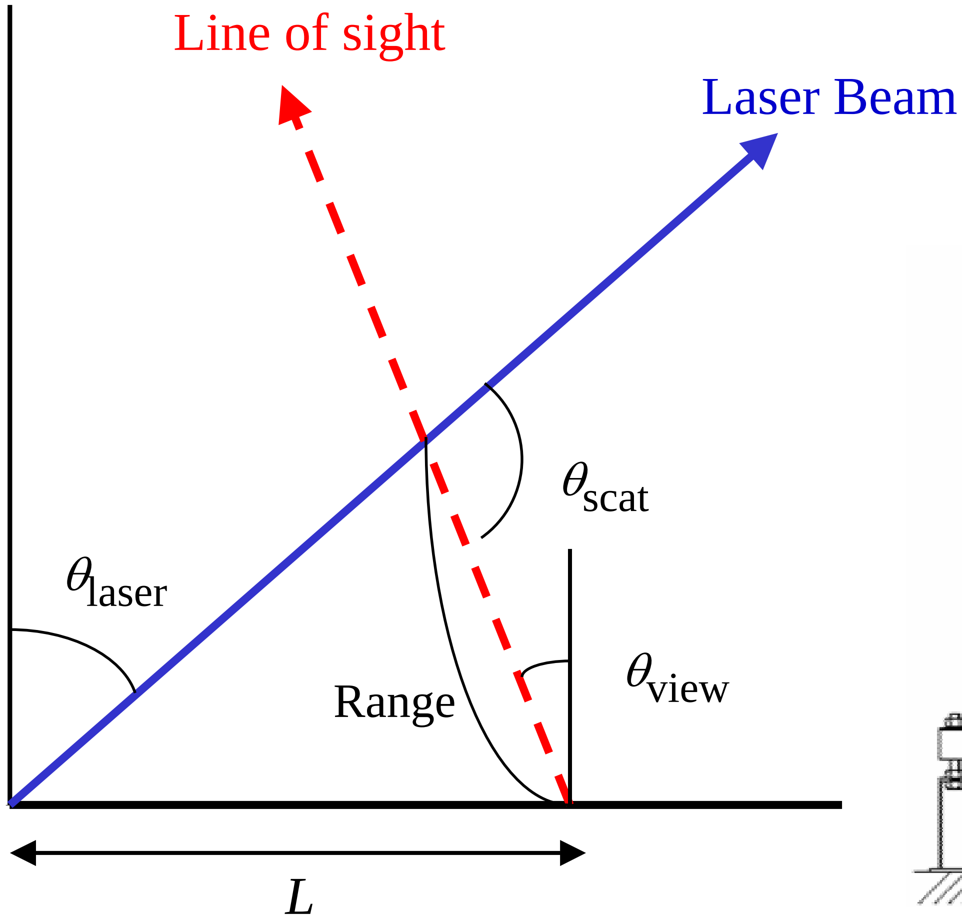
cf. MPE = 5 mJ/m^2 @ 532 nm



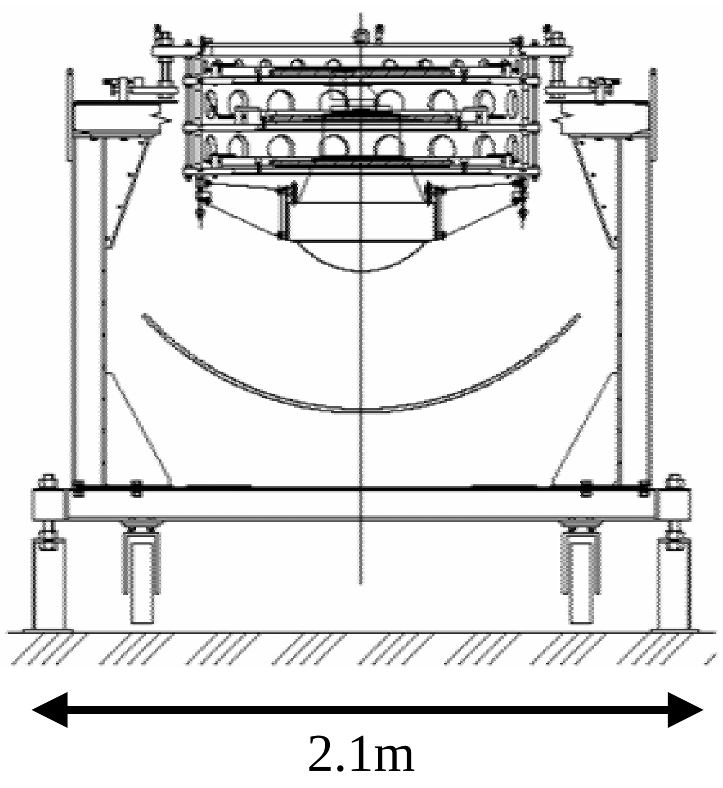
2/3 scale prototype 1/3 scale portable model

Two models

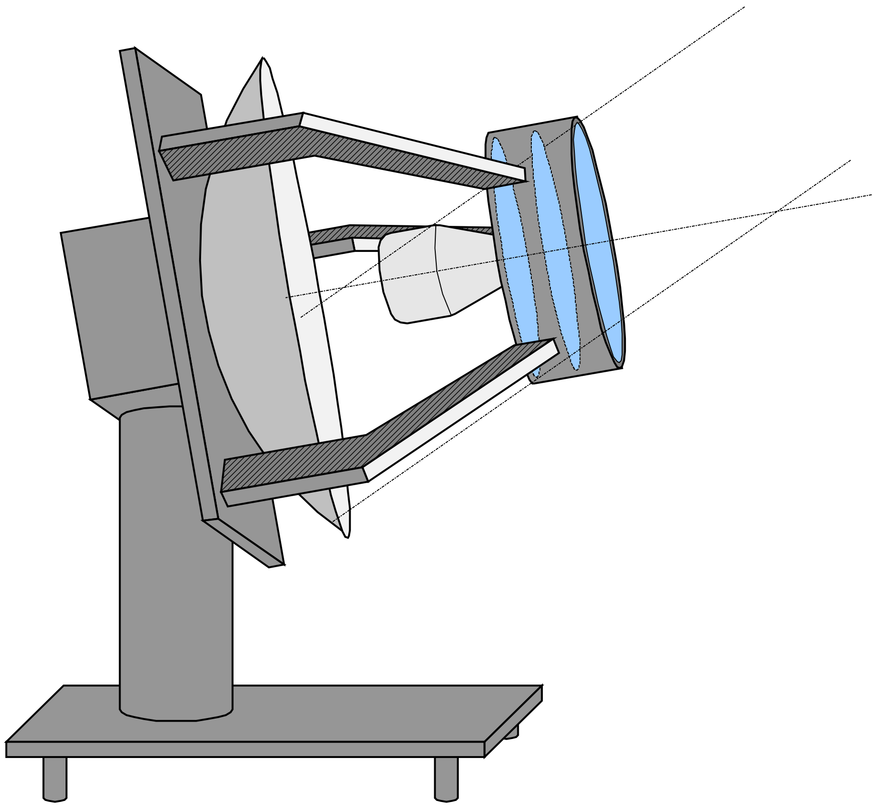
Geometry of bistatic measurement

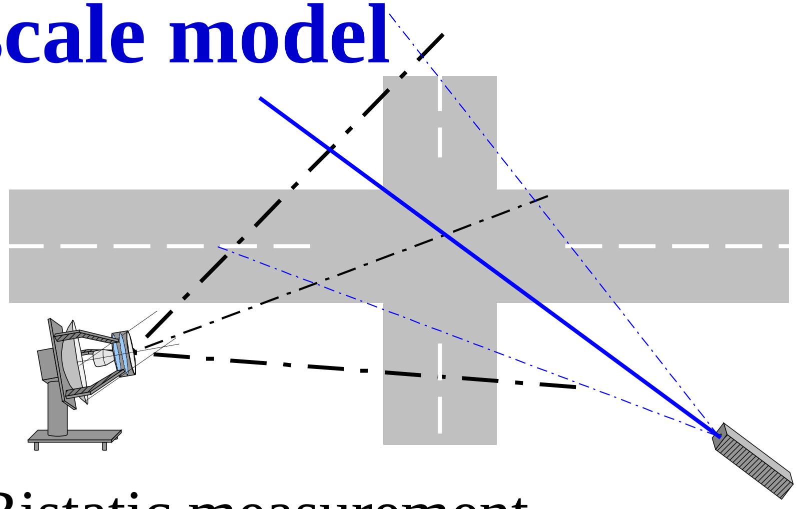


Ashra sub-telescope

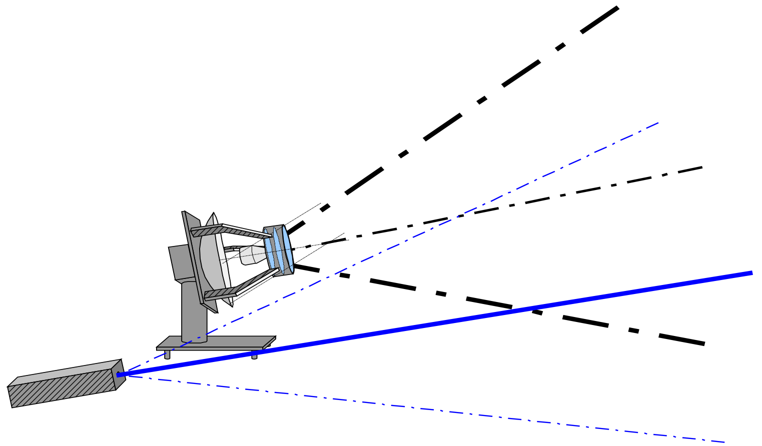


Ashra telescope ― 1/3 scale model





Bistatic measurement

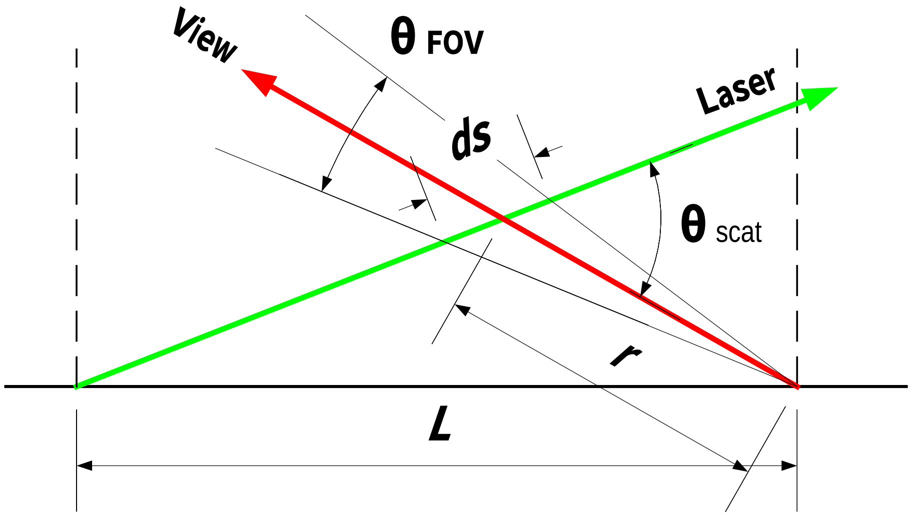


Backscattering measurement

Lidar equation for bistatic measurement

$$P = P_0 \; K \; \frac{A}{r^2} \; ds \; \beta(\theta_{\mathrm{scat}}) \; T_{\mathrm{t}} \; T_{\mathrm{r}}$$

where $$ds = \frac{r \; \theta_{\mathrm{FOV}}}{\sin(\theta_{\mathrm{scat}})}$$



P	Received power [W]
P_0	Transmitted power [W]
K	Optical efficiency of the telescope
A	Effective area of main mirror [m^2]
r	Range to the target [m]
ds	Laser path length in one pixel [m]
β	Scattering coefficient [m^{-1}sr^{-1}]
T_{t}	Transmittance from laser to target
T_{r}	Transmittance from target to telescope

Comparison of Lidar Parameters

Comparison of lidar parameters

	CEReS Multiwavelength Lidar	MPL	Ashra (2/3 scale) (near)	Ashra (2/3 scale) (far)	Ashra (1/3 scale)
Sensor	PMT	PMT	CMOS (128×128)	CMOS (3000×3000)	128×128
Target range	10 km	10 km	100 m	5 km	100 m
Wavel	355, 532, 756, 1064 nm	523 nm	351 nm	355 nm	351 nm
Telescope diam.	80 cm	20 cm	70 cm	70 cm	25〜35 cm
FOV	2 mrad (0.5〜10 mrad)	100 mrad	50°×50°	50°×50°	50°×50°
FOV/pixel	-	-	7 mrad	0.29 mrad	7 mrad
Laser power	100, 50, 70, 150 mJ	5 μJ	50 μJ	0.29 mrad	50 μJ
Pulse width	5〜9 ns[*6]	〜 10 ns	20 ns	5 ns	20 nsec.
Gate time	20 ns[*1]	-	1 μs[*2]	33 μs[*2]	1 μs[*2]
Repetition freq.	10 Hz	2.5 kHz	1kHz[*3]	10 Hz	1kHz[*3]
Gain	9.5×10^{6}, 5×10^{5} (1064 nm)	1×10^{6} [*7]	1×10^{6}	1×10^{6}	1×10^{6}
η tele	0.3	0.2[*7]	0.3[*5]	0.3[*5]	0.3[*5]
η PMT	0.3, 0.2, 0.084, 0.0006	0.2[*7]	0.2[*4]	0.2[*4]	0.2[*4]

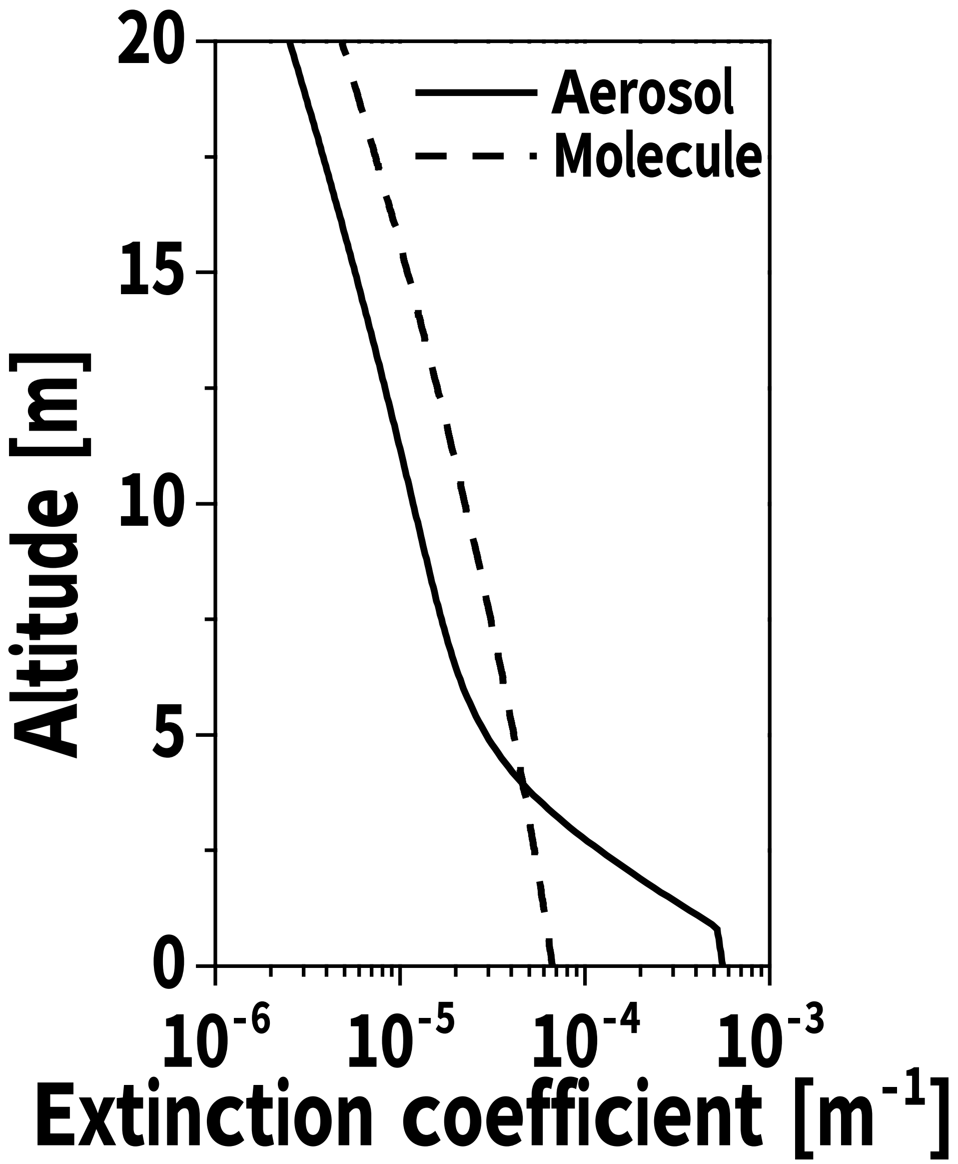
*1 Sampling frequency of digital CRO.
*2 With intelligent trigger, 〜 10 ns.
*3 Limited by the data processing speed.
*4 QE at the electrostatic I.I.
*5 Transmission of 3 lenses 0.9 each, mirror reflectance 0.8, detector eclipse ratio 50%
*6 355, 532 nm：5〜7 ns、756 nm：5〜9 ns、1064 nm：6〜8 ns
*7 Assumption

Parameters for 100 m range measurement

■ **Laser : Photonics Industries (DC30-351YLF)**

- **Wavelength 351 nm, Power 50 – 150 μJ**
- **Frequency 1-2 kHz, Pulse Width 20 ns**
- **Background 1.68×10^{-8} [$Wm^{-2}sr^{-1}nm^{-1}$] @ 355nm (Nighttime) (Ten times as bright as the new moon case)**
- **FOV/pixel 7 mrad (128×128 pixels),**
  0.29 mrad (3000×3000 pixels)
- **Filter Bandwidth 3 nm**
- **Shot counts 10000 (10 s)**

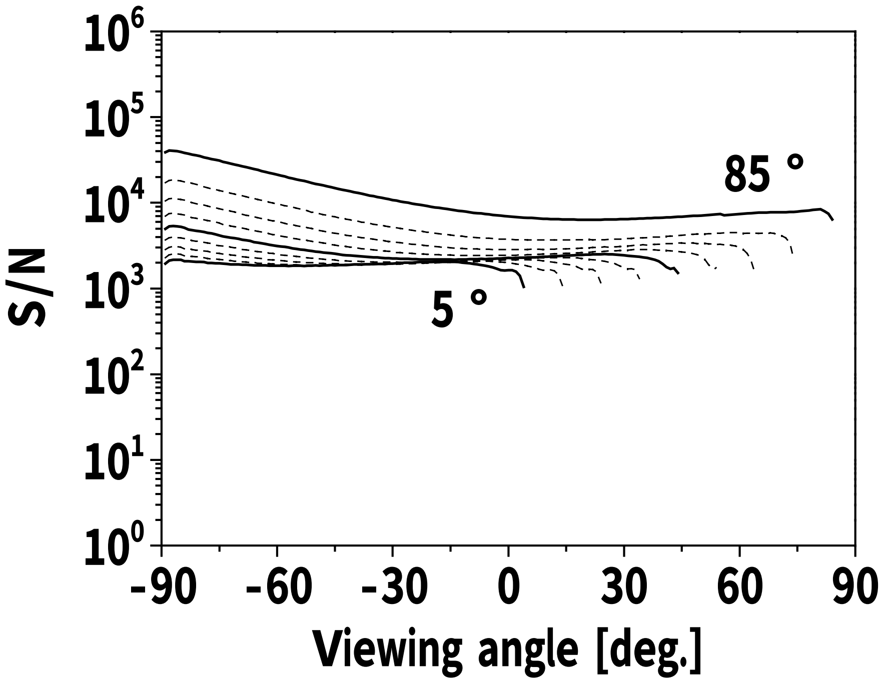
Model profile of the atmosphere



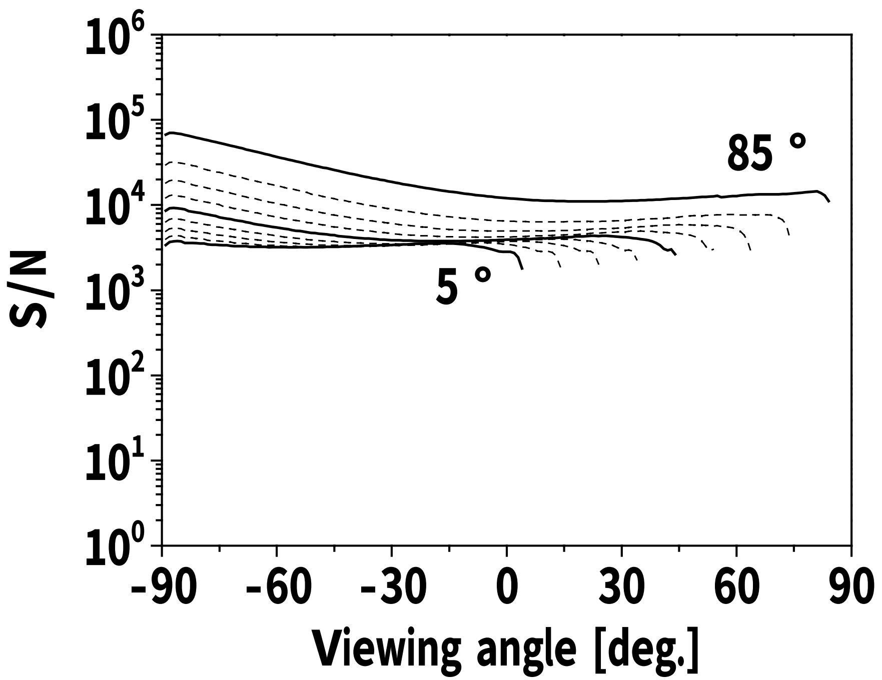
Laser power dependence

L = 100 m, Gate time = 1μs, night time background

50μJ/pulse



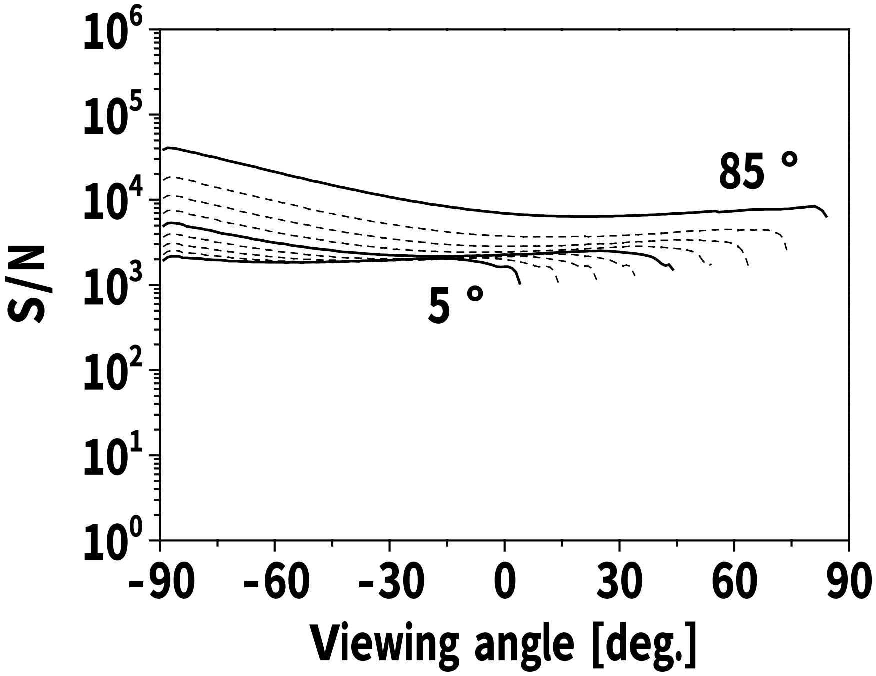
150μJ/pulse



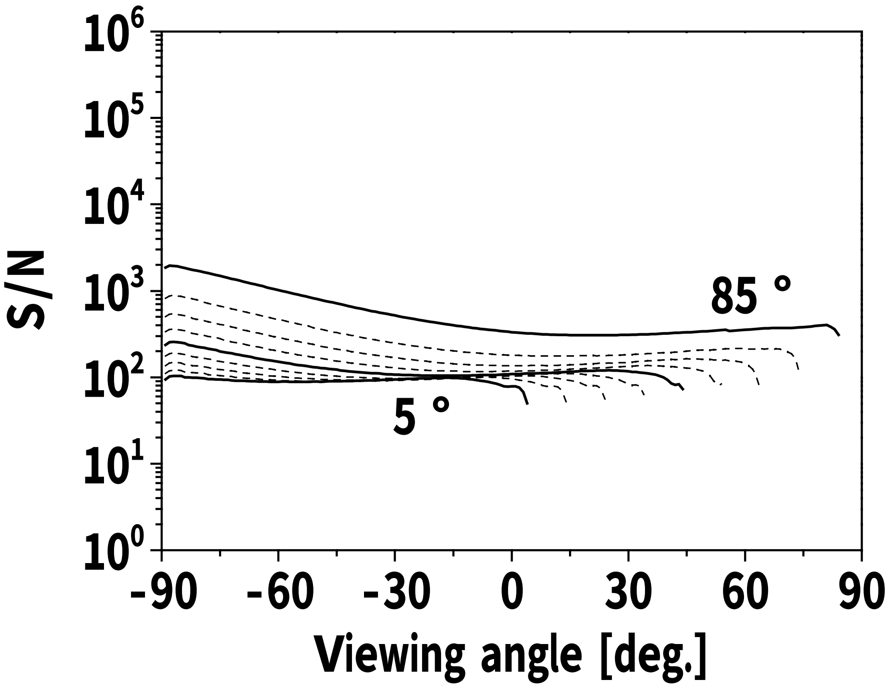
θ_{laser} is varied between 5 deg and 85 deg.

Angular resolution dependence

L = 100 m, Laser power = 50 μJ/pulse, Gate time = 1μs

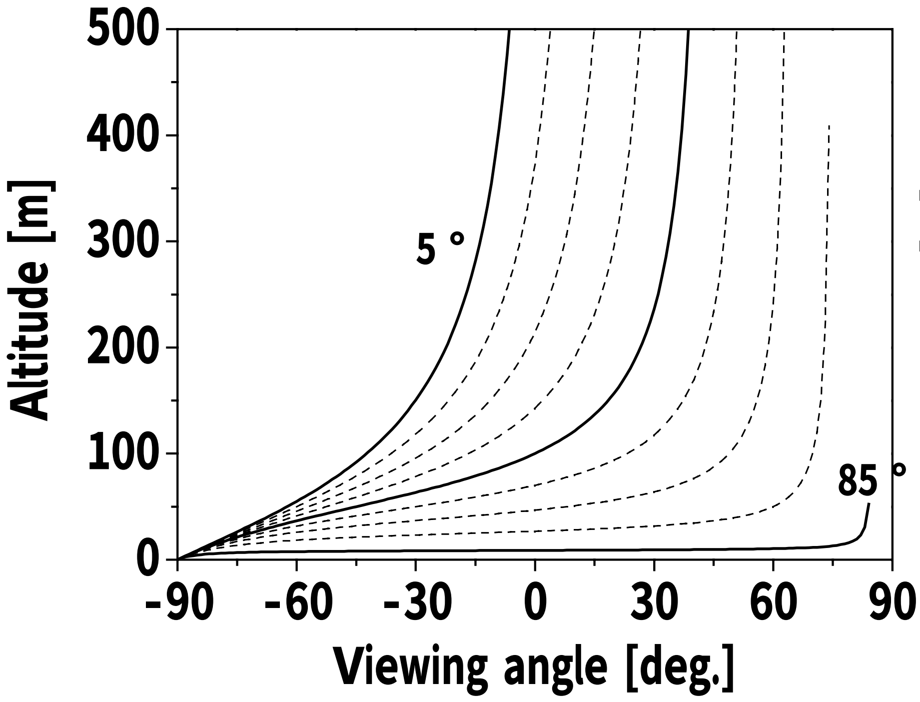


7 mrad (128✕128 pixels)

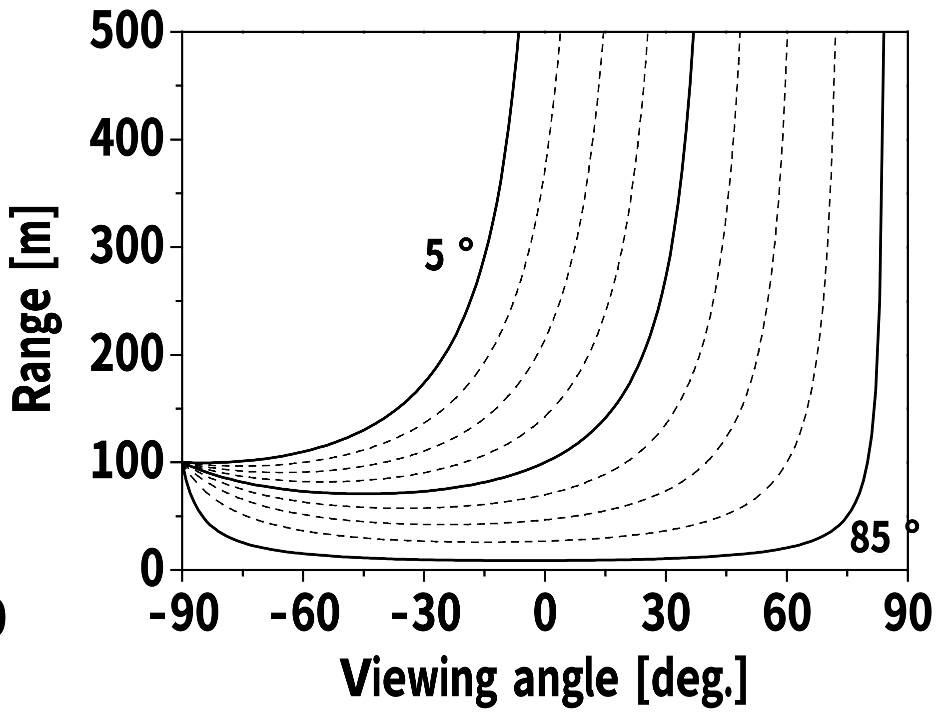


0.29 mrad (3000✕3000 pixels)

Altitude & Range (L = 100 m)



Altitude



Range

Parameters for 5 km range measurement

■ **Laser : Spectra Physics (GCR-130)**

・**Wavelength 355 nm, Power 80 mJ/pulse**

・**Frequency 10 Hz, Pulse Width 5 ns**

・**Background 1.68 × 10^{-8} [$Wm^{-2}sr^{-1}nm^{-1}$] for 355nm (Nighttime) (Ten times as bright as the new moon case)**

・**FOV/pixel 0.29 mrad (3000 × 3000 pixels)**

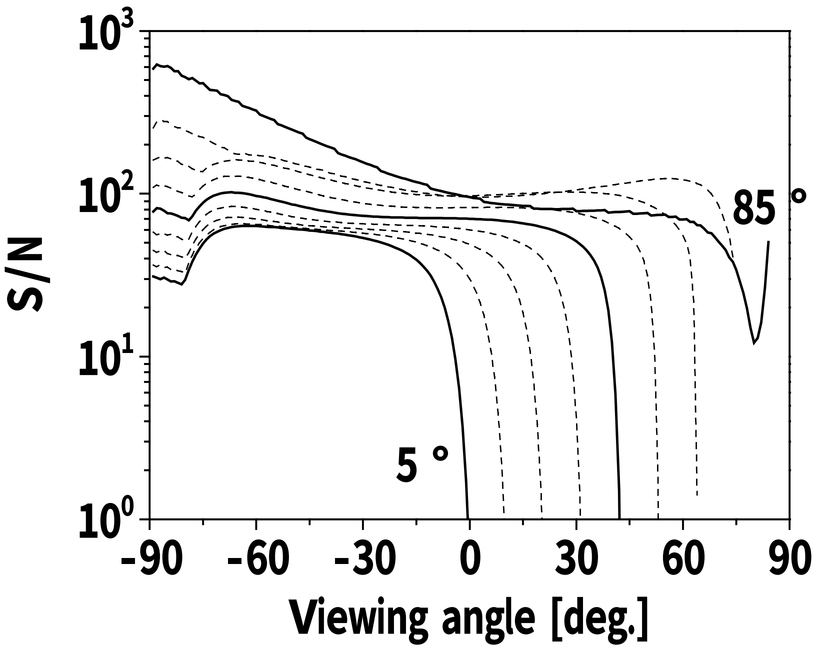
・**Filter Bandwidth 3 nm**

・**Shot Counts 100 (10 s)**

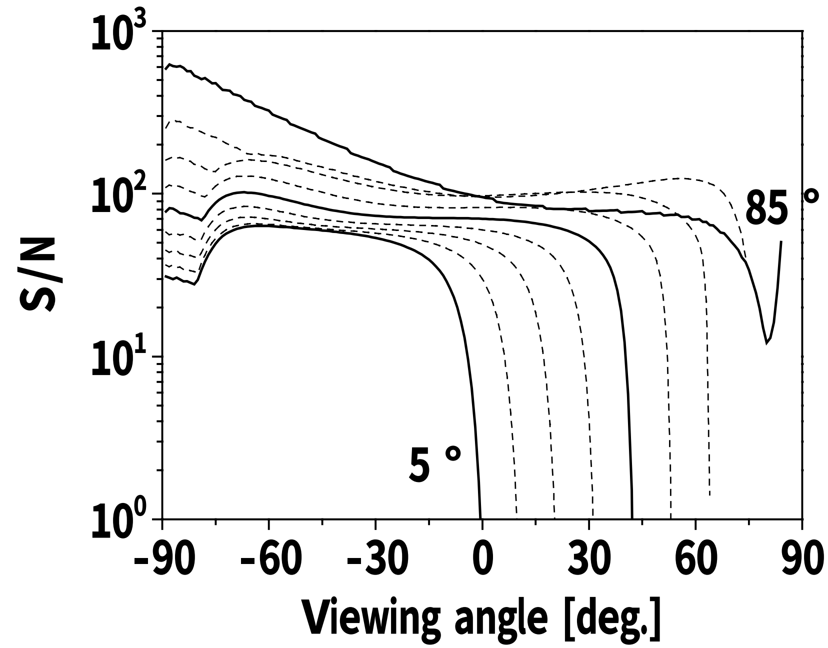
L=5 km (nighttime)

Intelligent trigger

33μs



100 ns

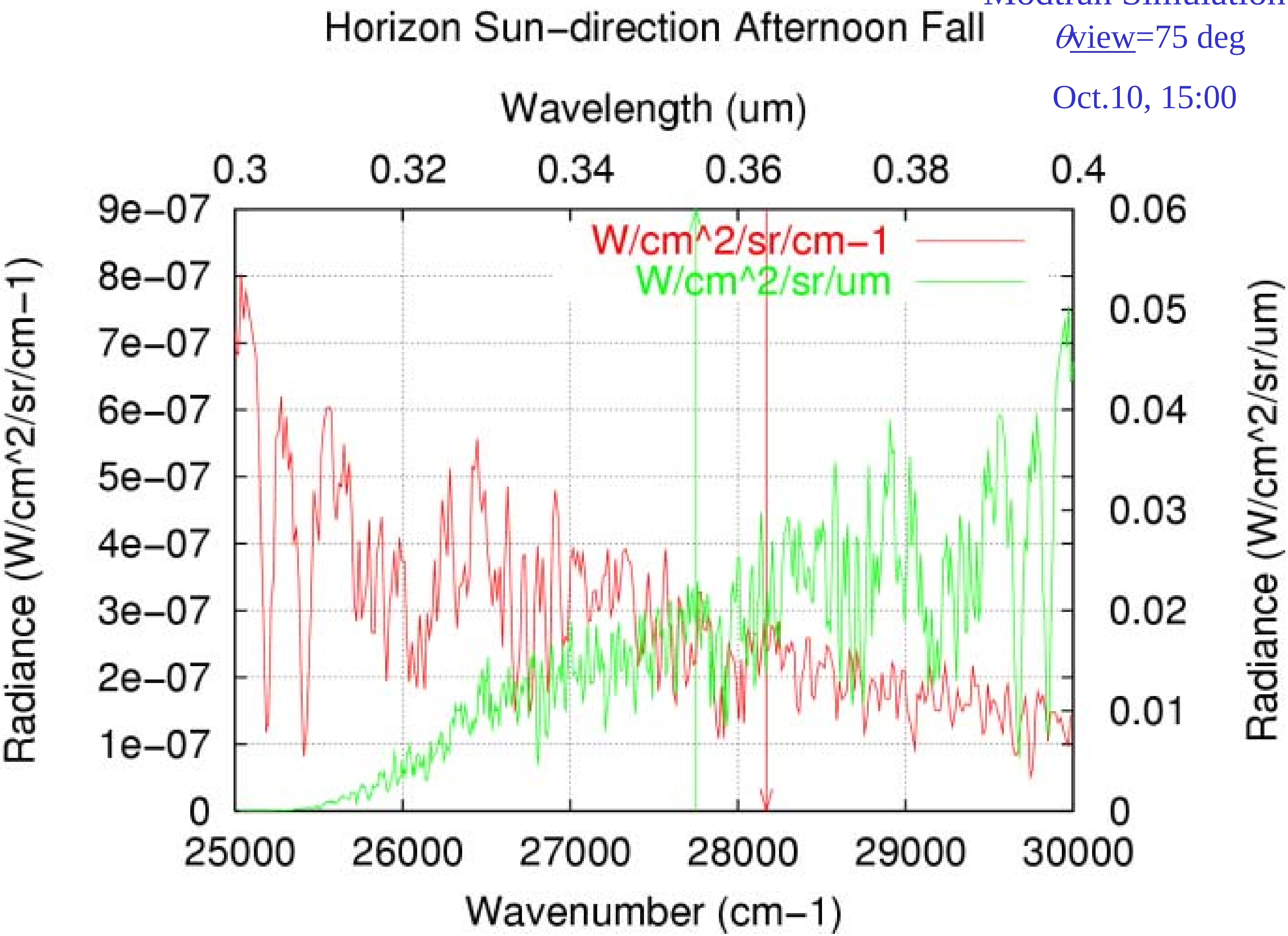


- **Because of the small background, longer gate time does not result in the S/N degradation.**
- **Gate time of 100 ns is roughly equal to the elapsed time in which the laser beam passes through a macro cell（24✕24 pixels）with the viewing angle of 0 ° at the range of 5 km.**

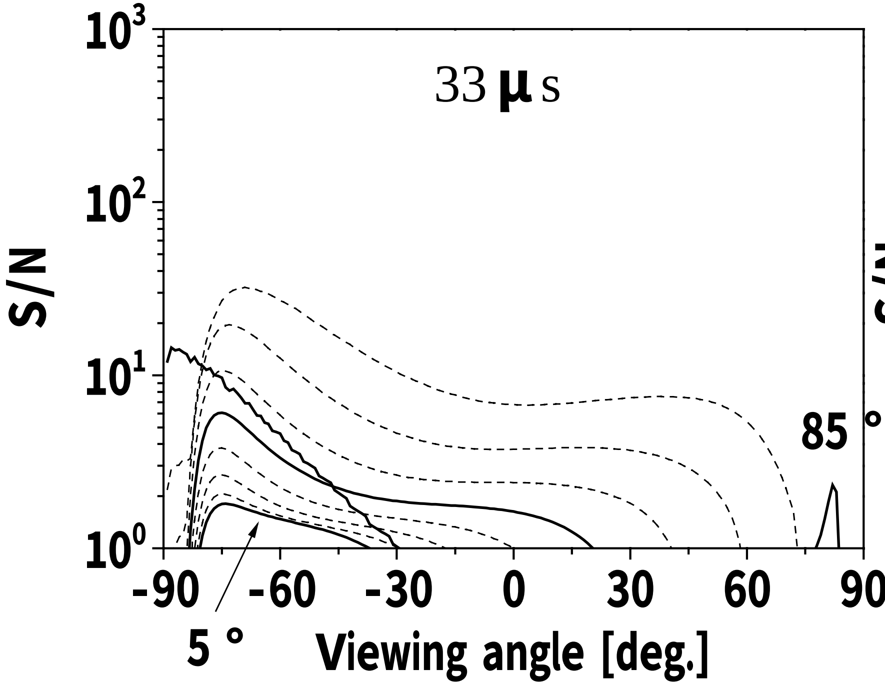
Modtran Simulation

θview=75 deg

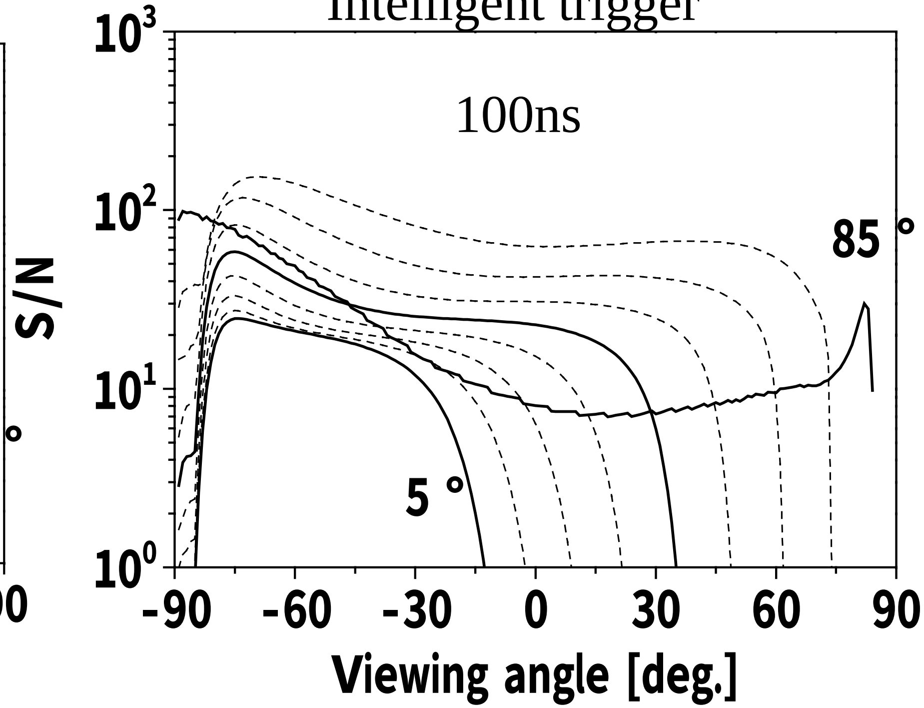
Oct.10, 15:00



L=5 km (daytime)

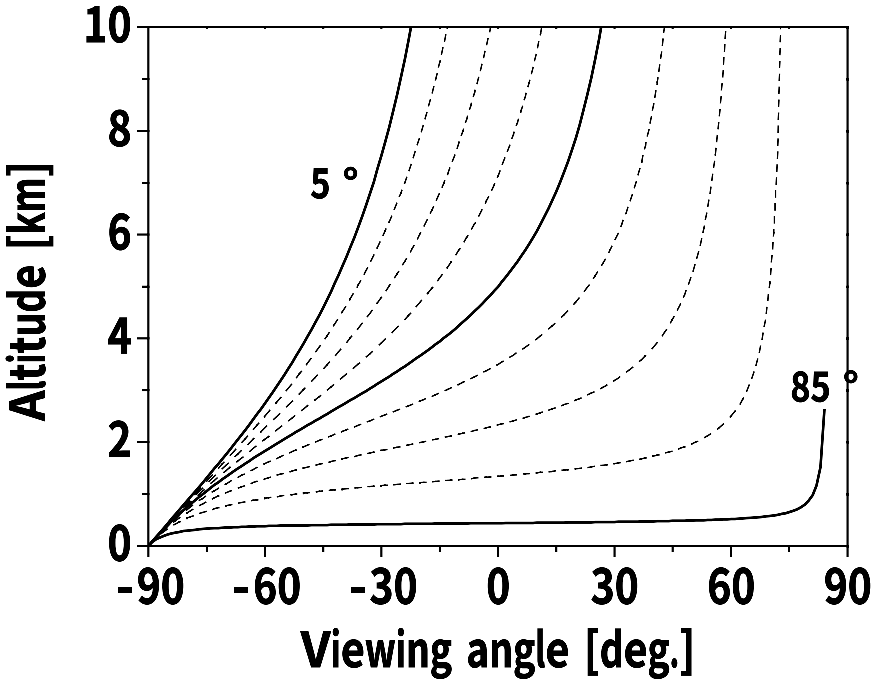


Intelligent trigger

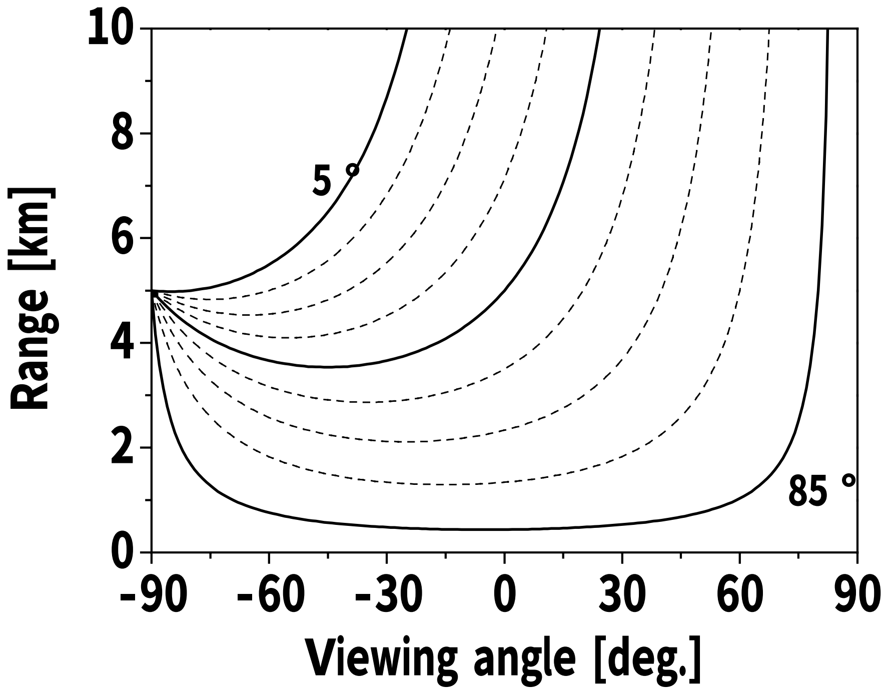


- Sky radiance at 355 nm is assumed to be 0.1 $Wm^{-2}sr^{-1}nm^{-1}$ on the basis of the MODTRAN simulation.
- Intelligent trigger is quite useful for the daytime measurement with a large background.

Altitude & Range (*L* = 5 km)



Altitude



Range

Summary for the imaging lidar project

- In the Ashra-I project, EHE cosmic-ray particles will be measured using wide-FOV, high-resolution telescopes. The FOV of 50 deg, resolution of 1 arcmin (0.29 mrad), intelligent high-speed shutter, and 1 kHz repetition rate indicate that the system has superior quality also for the telescope of an imaging lidar. The overall amplification factor of the detection system is 10^6, equivalent to that of a conventional PMT.
- The greatest advantage of this telescope for an imaging lidar is that it provides a wide receiving angle, as opposed to very narrow acceptance angle of the conventional lidar telescopes. In the receiving angle of 50 deg, lidar observation can be carried out by scanning the laser beam. At CEReS, we are going to develop a Mie-scattering imaging lidar for the two-dimensiona detection of aerosol particles.

Lidar activities at CEReS

- ***Lidar : Light detection and ranging***

Development of lidar observation of aerosols
— Multi-wavelength measurement of tropospheric aerosols
— Automated measurement with PAL and MPL
— Imaging lidar system using a wide FOV telescope

Multiple scattering calculations (Monte Carlo method)

Parameter	Value
Wavelength	532 nm
Receiver field-of-view FOV	3 mrad
Photon histories	5 million
Scattering order	10
Personal computer	350 MHz
Calculation time	about 4 hour

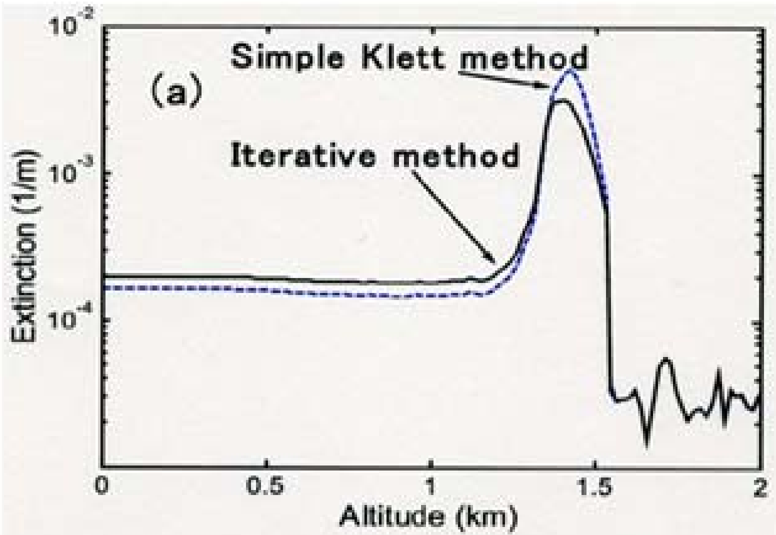
The probability of *n*th order photon scattering $P_n(R)$:

$$P_n(R) = \frac{A_r G(R)}{4\pi R^2} \exp\left[-\sigma_e\left(\sum_{i=1}^{n} L_n + R_n\right)\right]\sigma_s p(\theta)\cos(\alpha_n)$$

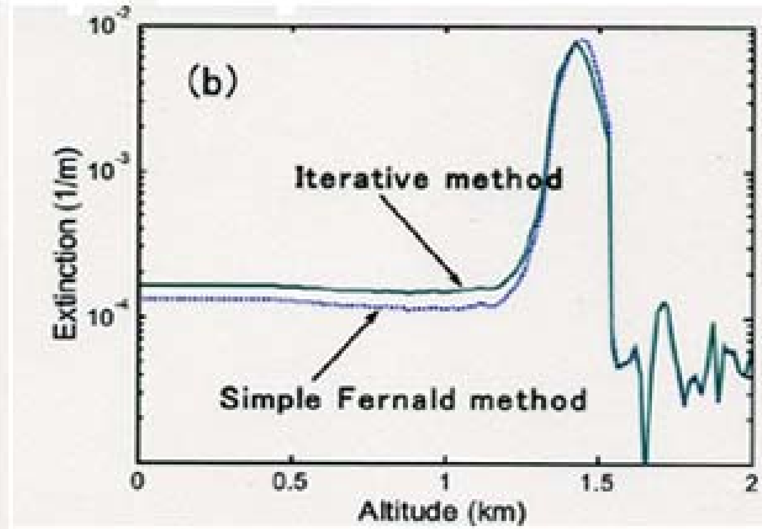
where

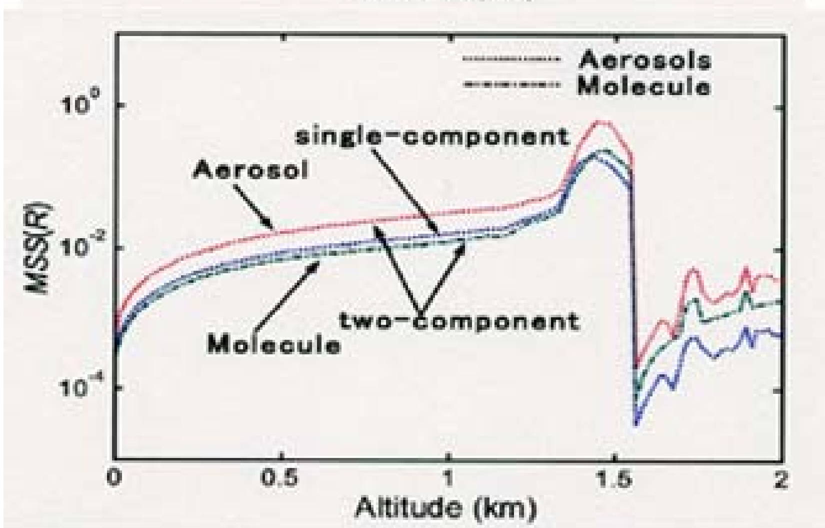
α_n = the arrival angle relative to the telescope axis (with an area A_r)
σ_e = the extinction coefficient which is equal to the scattering coefficient σ_s
$p(\theta)$ = the scattering phase function (Mie or Rayleigh)
L_n = the free-path length of the *n*th scattering photon
R_n = the distance between *n*th scattering photon and the receiver
$G(R)$ = the geometrical form factor of the lidar optics
R = the half distance in the total-path length of the photon.

Single Component Atmosphere



Two Component Atmosphere





Multiple-to-Single Scattering Ratio (MSS)