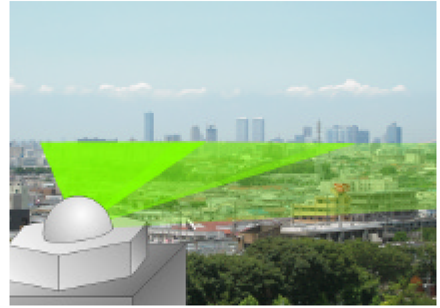
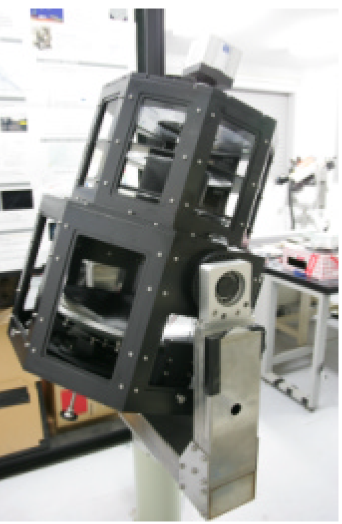


Environmental Application of Ashra Telescope - Imaging Lidar

Center for Environmental Remote Sensing (CEReS), Chiba University

Hiroaki Kuze

hkuze@faculty.chiba-u.jp



Application to environmental monitoring

Lidar technology

Wide FOV, high-resolution telescope

Real-time monitoring of air pollution

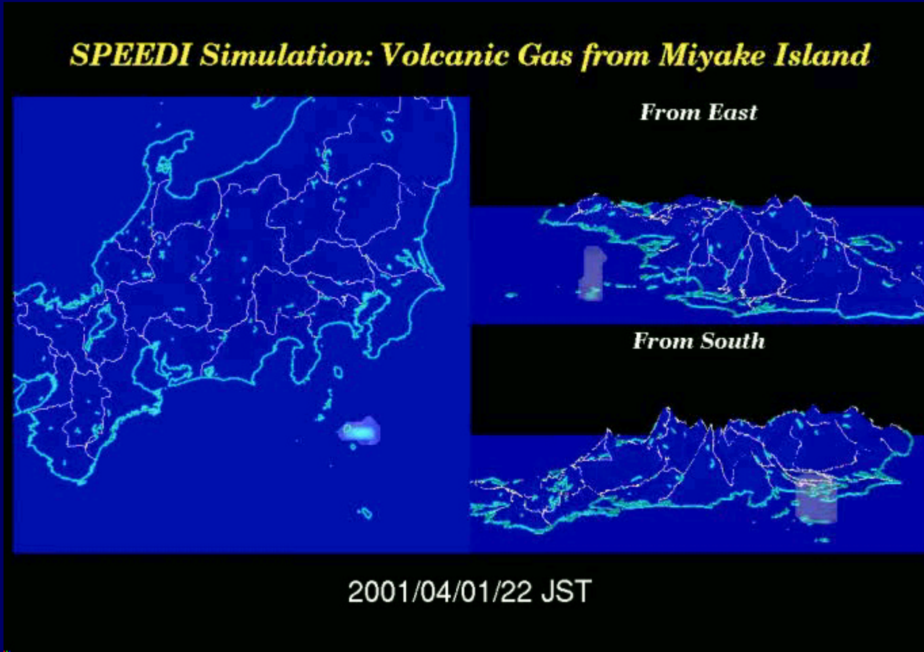
Imaging Lidar

Targets:

- **Suspended particulate matter (SPM); car emission**
- **Wind speed and direction**
- **Volcanic SO_2**

e.g. Eruption of Miyake-jima island
Advection of highly concentrated SO_2

SO_2 from Miyake-jima (simulation)



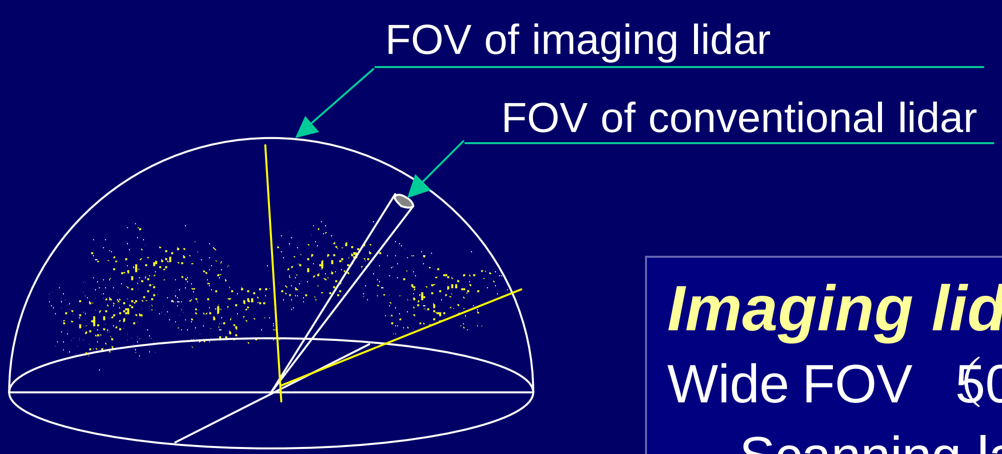
Imaging vs. conventional lidar measurement

Conventional system (narrow FOV)

?Time and labor consuming for scanning operations

? Normally time-height indication is employed for vertical measurement

Scanning



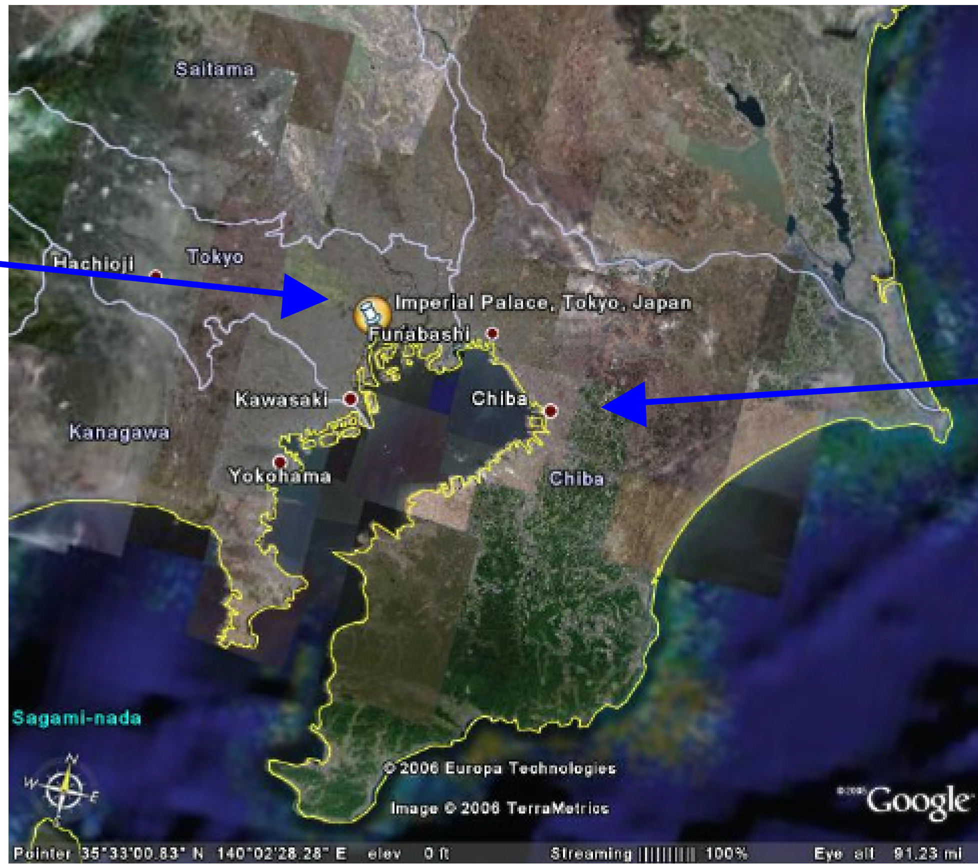
Imaging lidar

Wide FOV （50°×50°）: fixed direction

Scanning laser beam

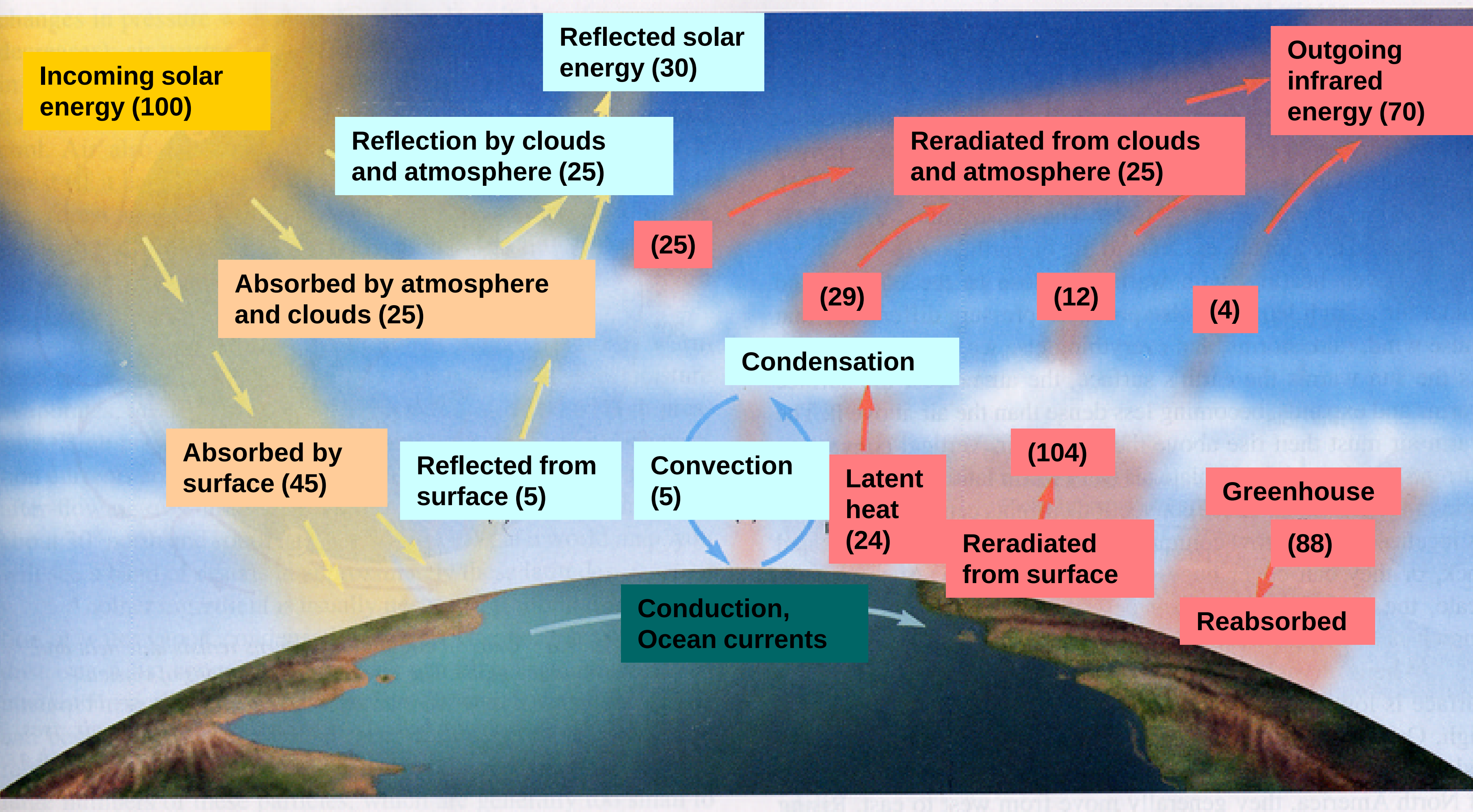
→ Real-time measurement of aerosol distribution

Aerosols

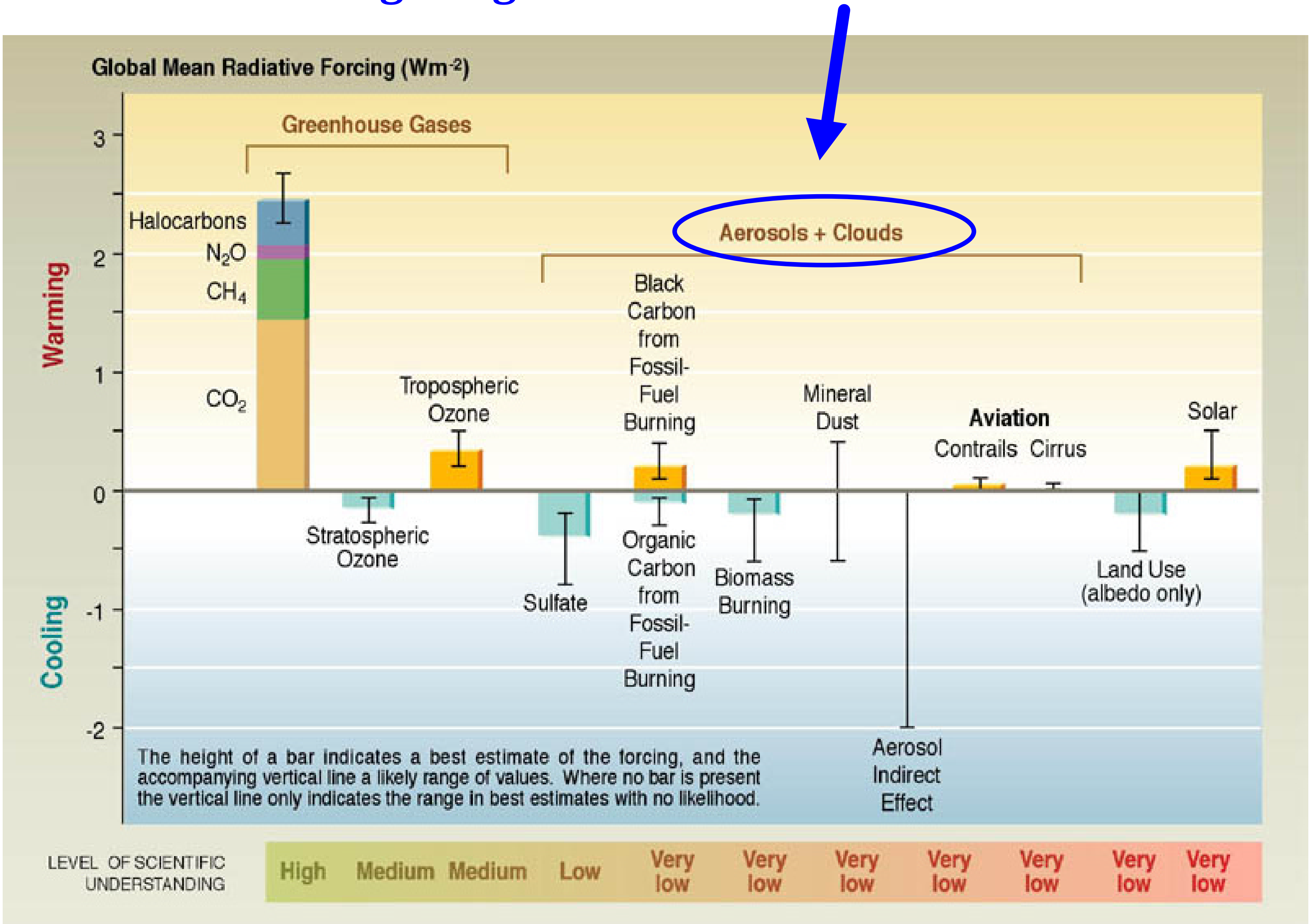

Tokyo
Chiba
Saitama
Hachioji
Tokyo
Imperial Palace, Tokyo, Japan
Funabashi
Kawasaki
Chiba
Kanagawa
Yokohama
Chiba
Sagami-nada
© 2006 Europa Technologies
Image © 2006 TerraMetrics
Google
Pointer 35°33'00.83" N 140°02'28.28" E elev 0 ft
Streaming 100%
Eye alt 91.23 mi

CEReS Project 3

Evaluation of radiation budget and long-term changes of atmospheric parameters using satellite and ground observation network data



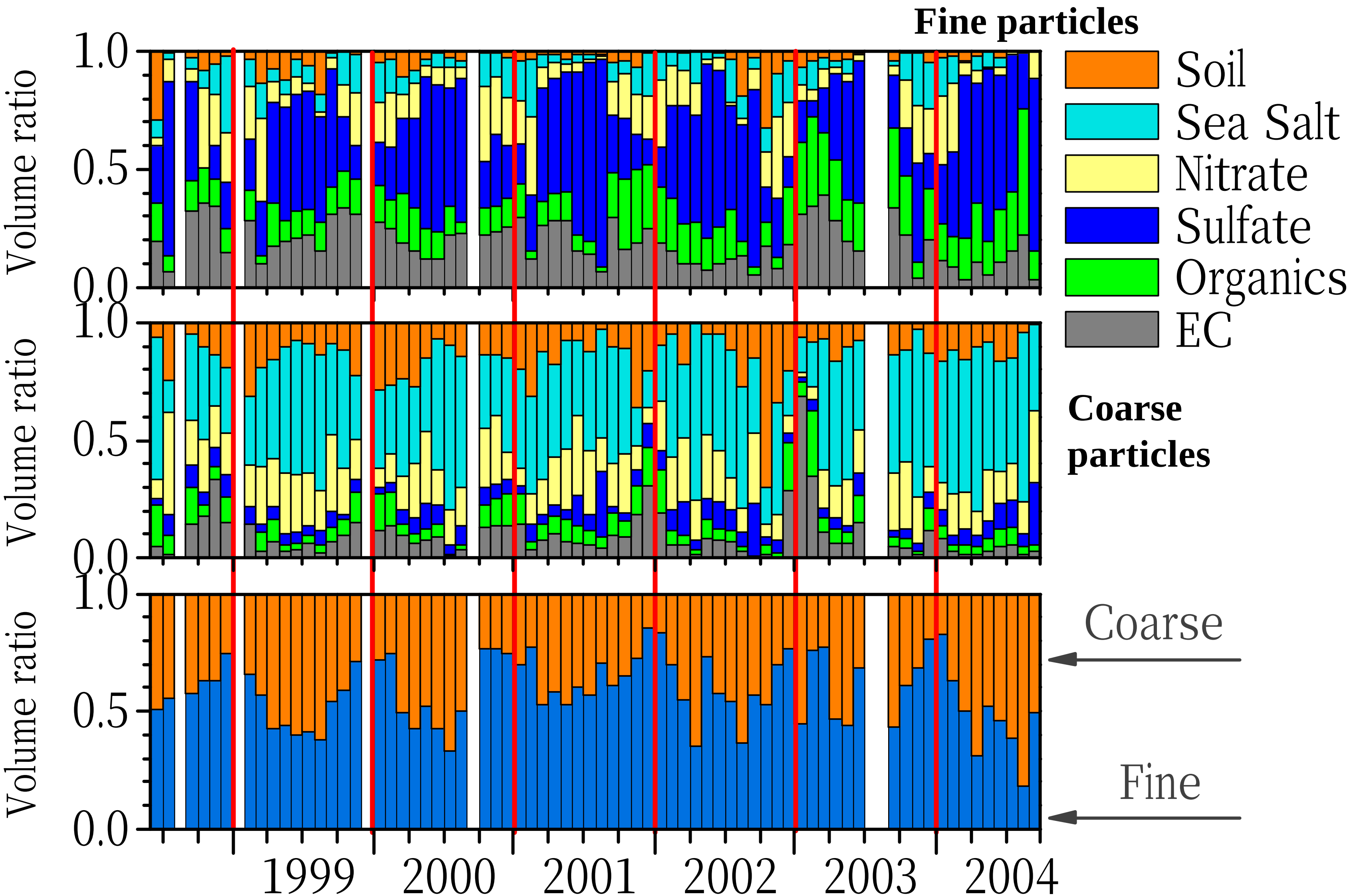
Radiative forcing: large error bars for aerosols and clouds



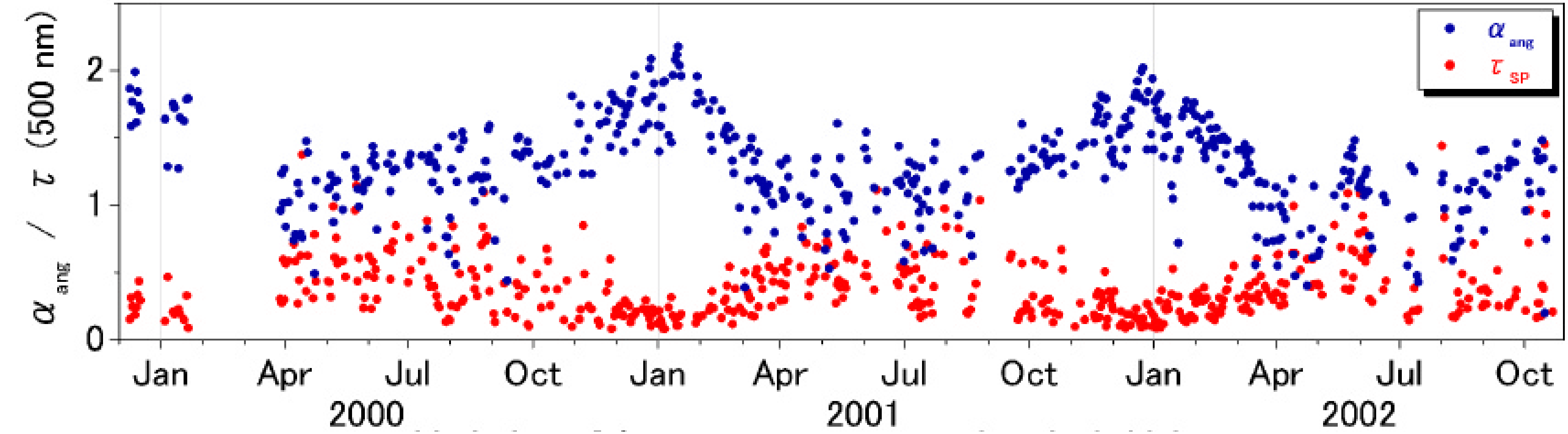
Source: IPCC (2001)

Long-term aerosol sampling in Chiba (1998-2004)

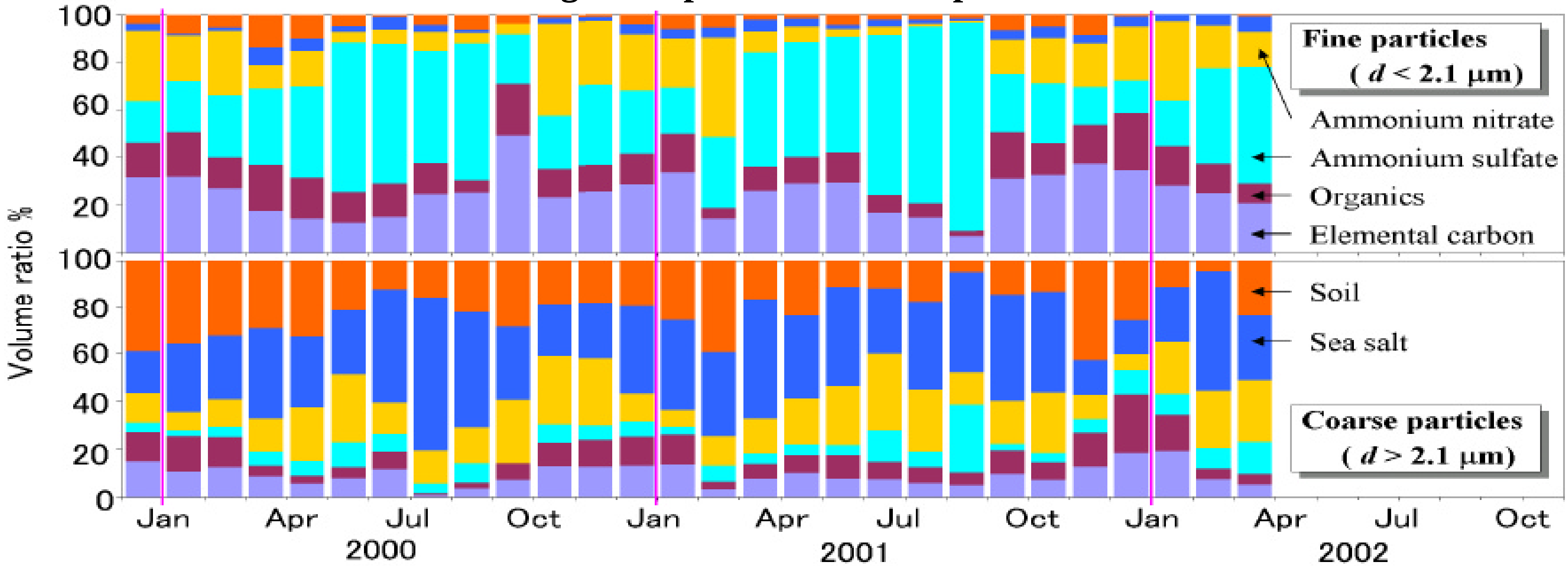
Fukagawa et al., Atmospheric Environment, ***40***, *2160 (2006)*



Aerosol characteristics over the urban Chiba area

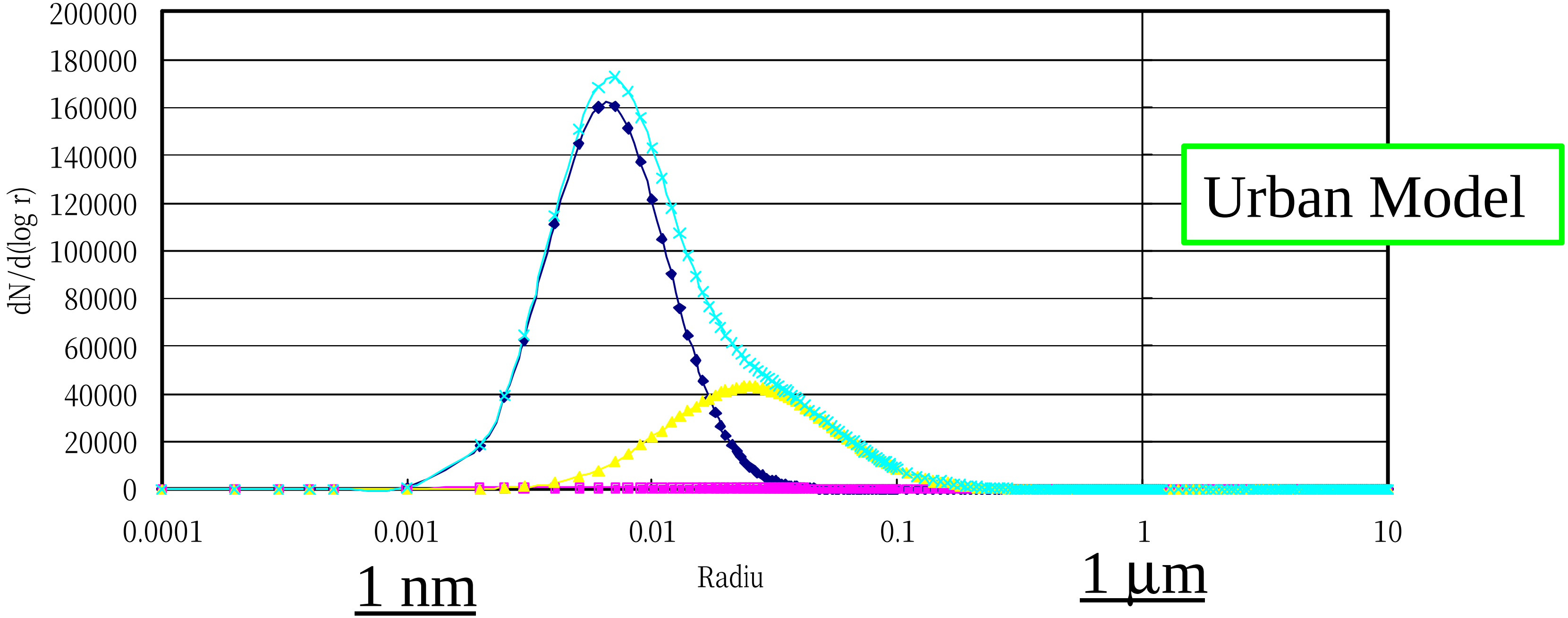


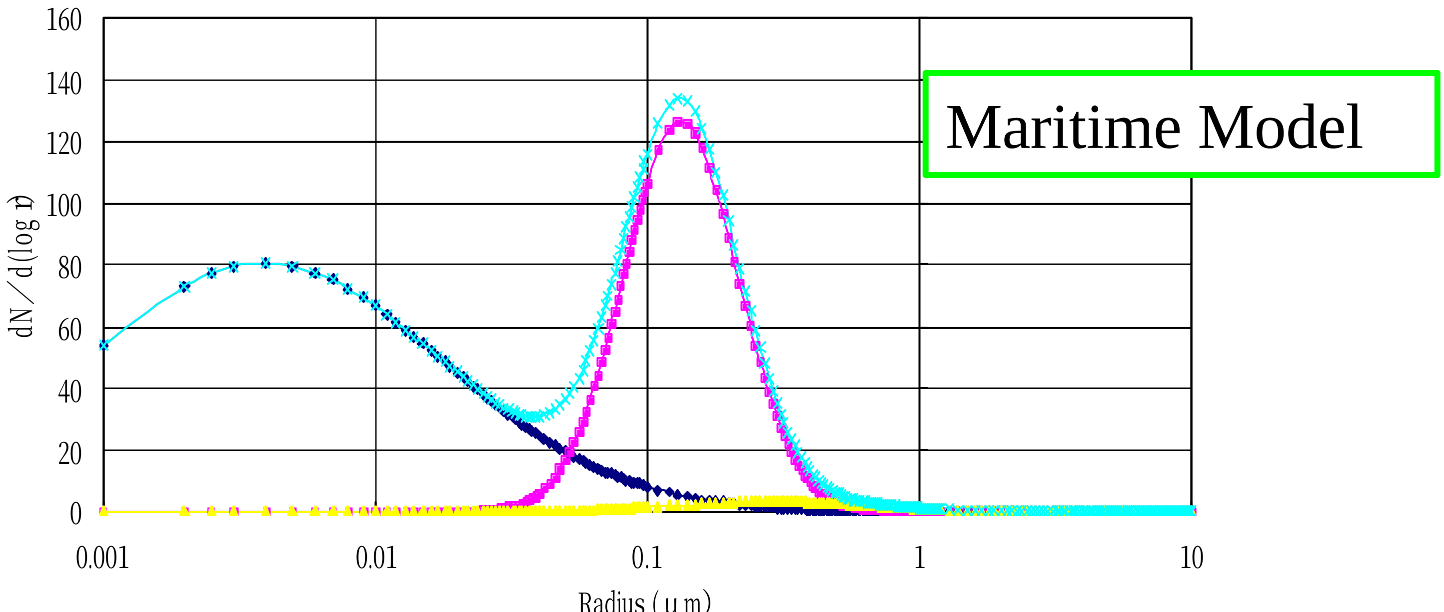
Variation of Angstrom parameter and optical thickness



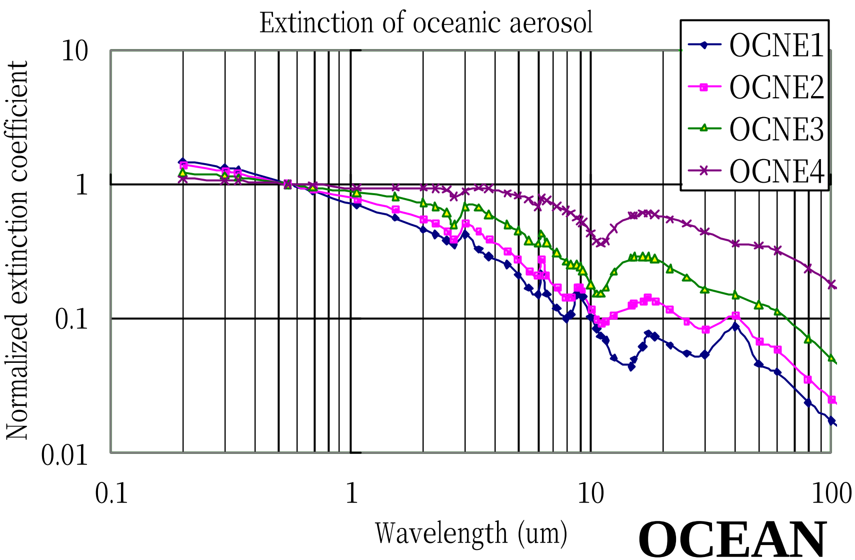
Monthly change of the aerosol types from the chemical measurements.

Aerosol size distribution

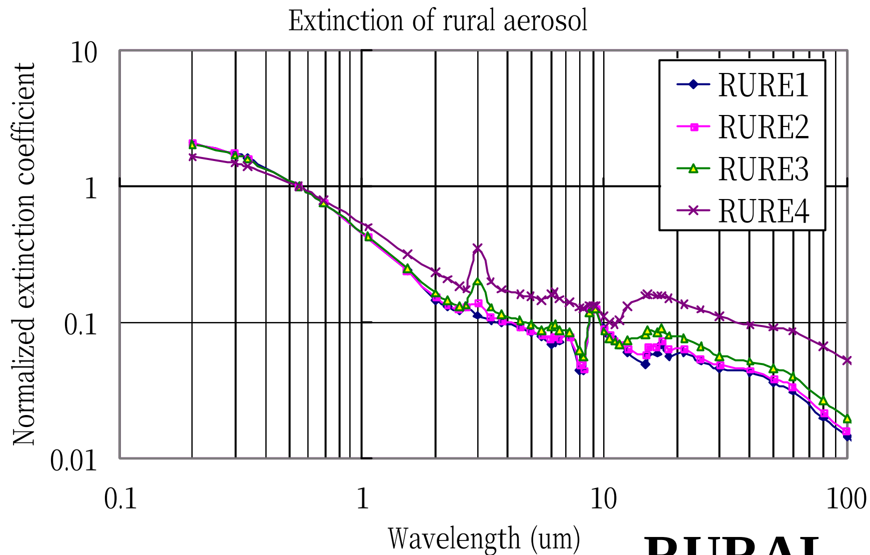




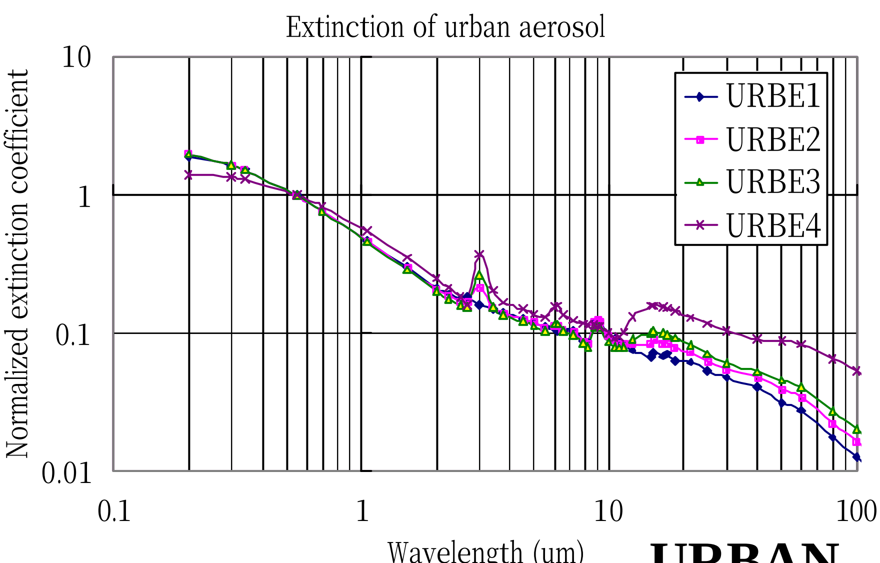
Wavelength dependence of aerosol extinction coefficients



OCEAN



RURAL

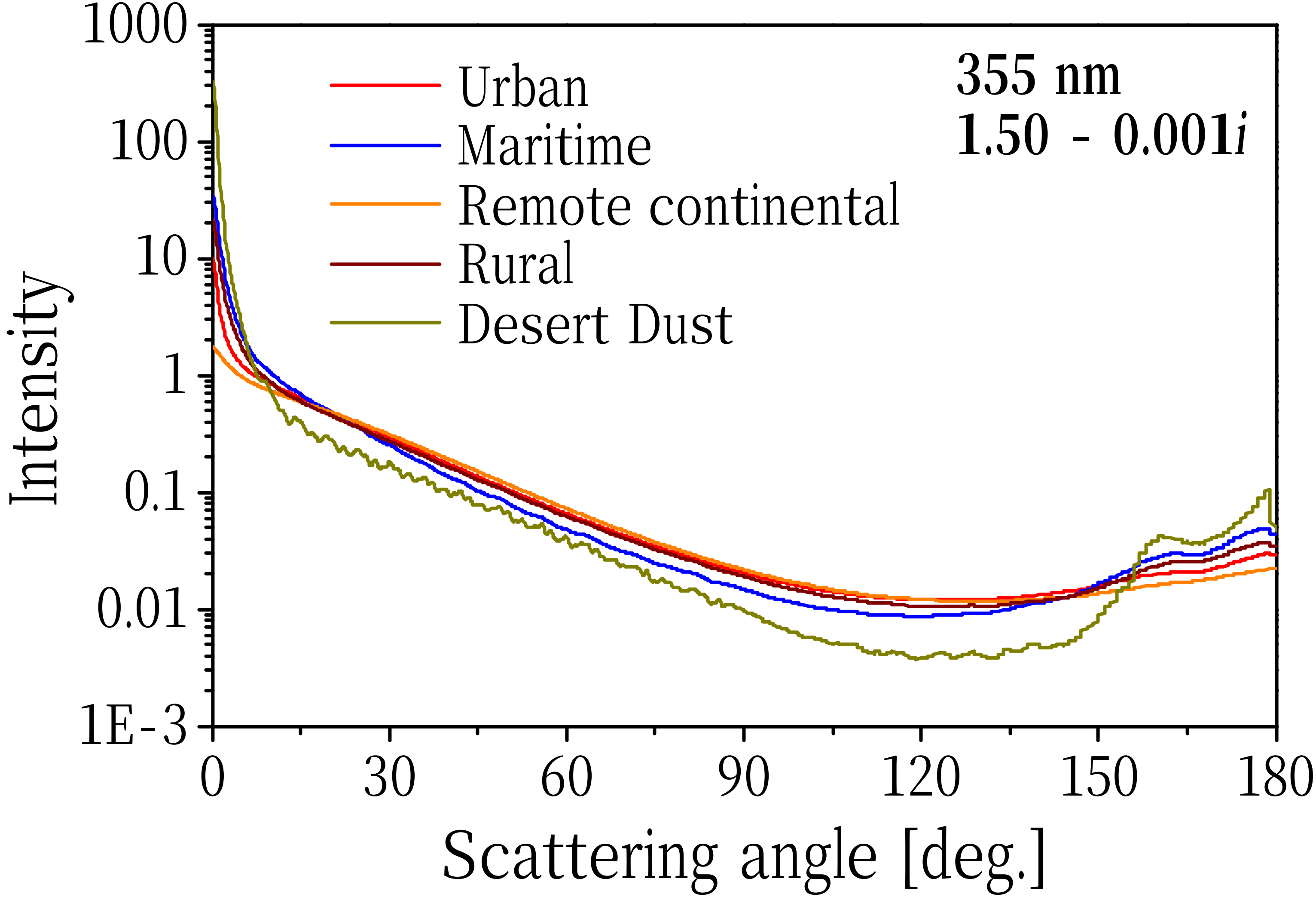


URBAN

OCNE1: RH = 0%
OCNE2: RH = 70%
OCNE3: RH = 80%
OCNE4: RH = 99%

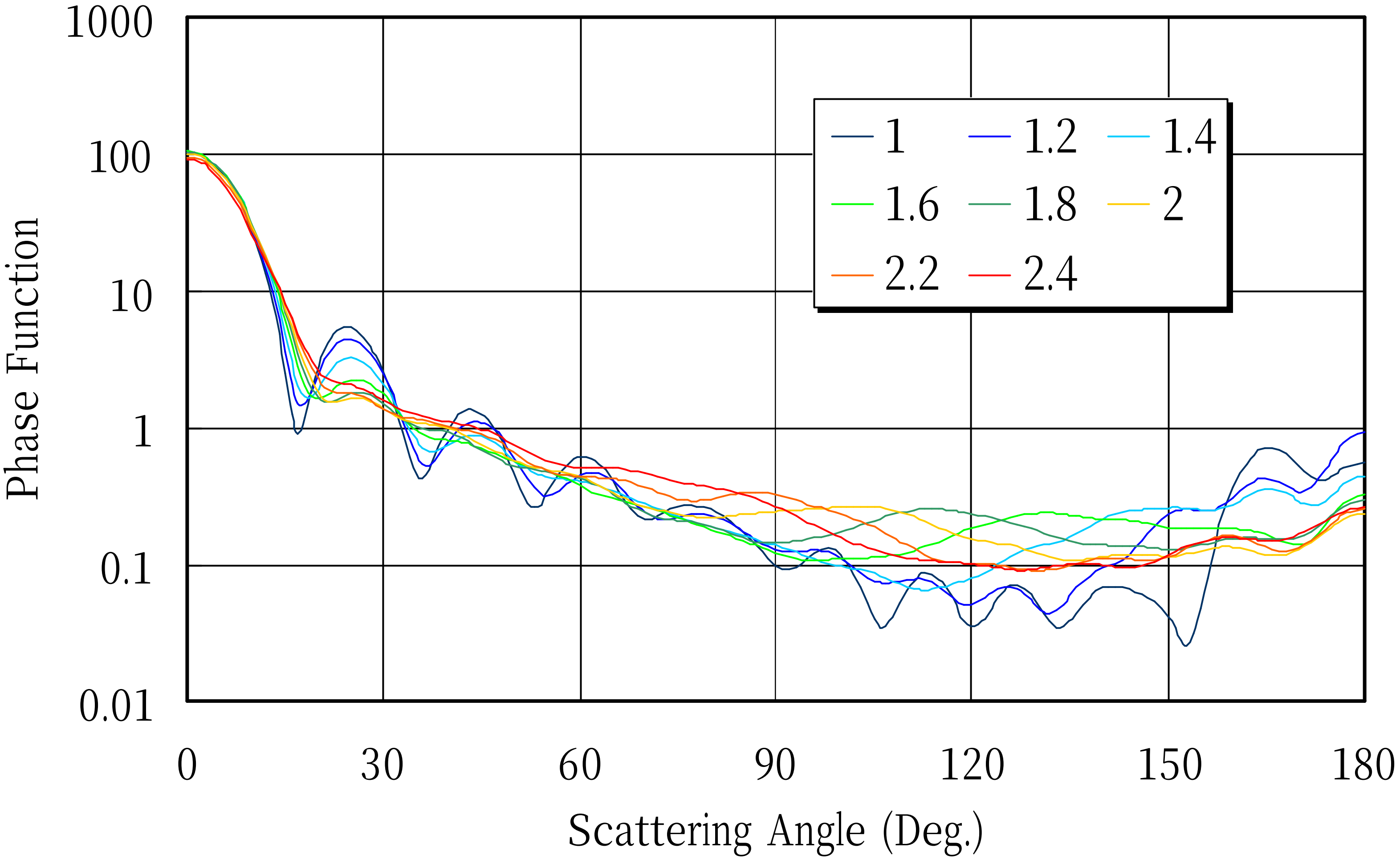
Phase functions

(Angular dependence of the differential cross-section)



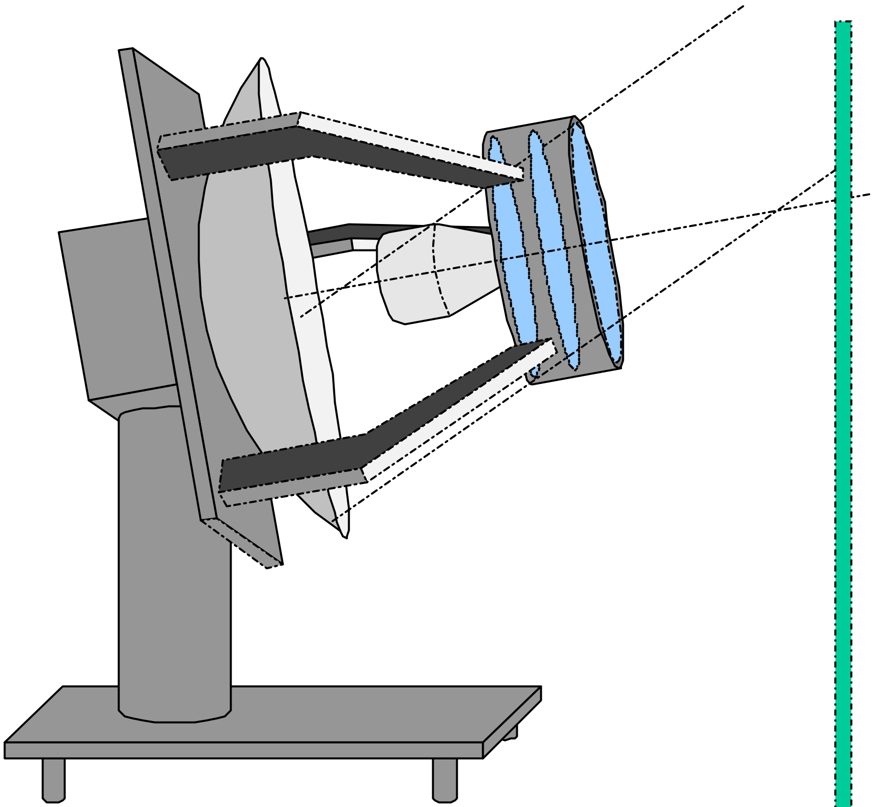
Non-spherical particles

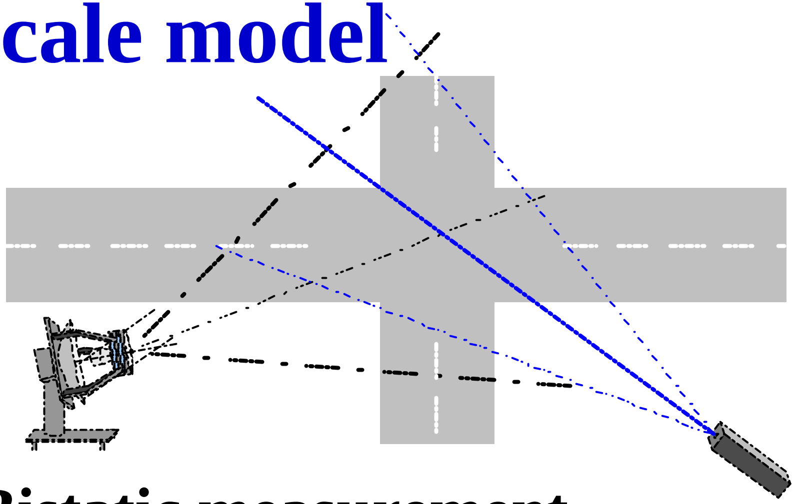
Prolate Spheroid, λ = 0.55 μm, r = 1.0 μm, n' = 1.53-0.008i



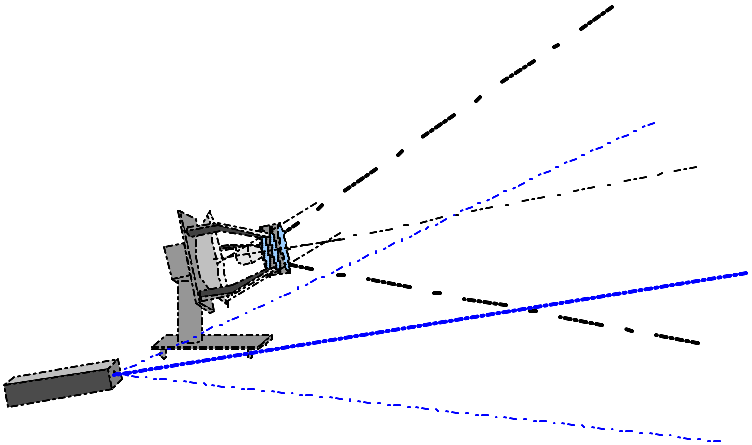
Lidar detection of aerosol particles

Ashra telescope — 1/3 scale model





Bistatic measurement



Monostatic (backscattering) measurement

- Both nighttime and daytime
- Range: 100 m - 3 km

Application: road-side measurement of SPM

Eye-safety

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

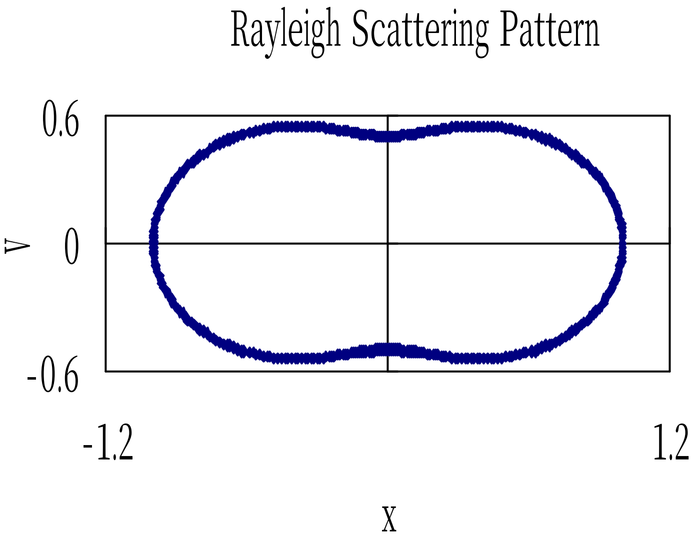
(JIS C6802 safety standard)

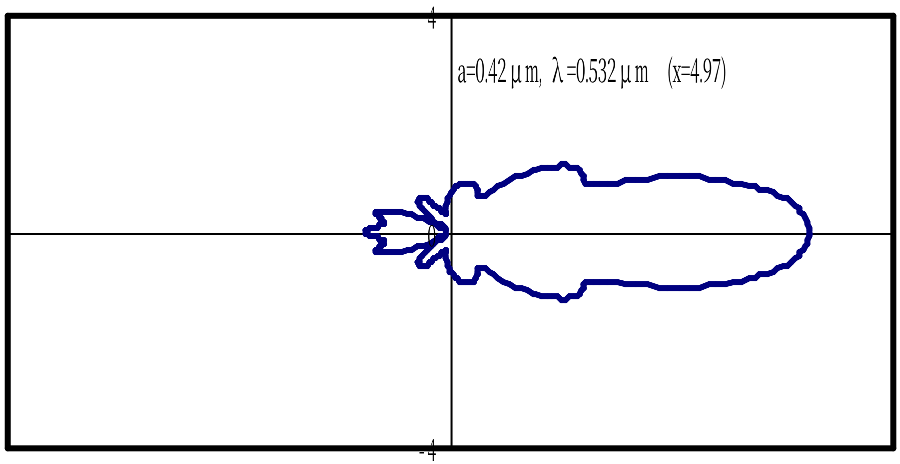
- **Operation wavelength of the Ashra telescope is between 300-420 nm.**
  (Wavelength range of the air-shower fluorescence)
- **For a pulse width of 20 ns with 2 kHz repetition frequency,**
  - **MPE = 4 J/m^2 @ 355 nm**

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

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

Rayleigh and Mie scattering patterns





$$f(\cos\theta) = \frac{3}{16\pi}(1+\cos^2\theta)$$

$$f(\cos\theta) = \frac{1}{\sigma}\left(\frac{d\sigma}{d\Omega}\right)_\theta$$

Theory of Mie scattering

Scattered radiance

$$I(q) = \frac{I_0}{R^2}\frac{ds_{scat}}{d\Omega} = \frac{I_0}{R^2}\frac{\left|F_1(q)\right|^2 + \left|F_2(q)\right|^2}{2k^2}$$

Differential cross section

Scattering amplitude

$$F_1(q) = \sum_{l=1}^{\infty}\frac{2l+1}{l(l+1)}\left\{a_l p_l(\cos q) + b_l t_l(\cos q)\right\}$$

$$F_2(q) = \sum_{l=1}^{\infty}\frac{2l+1}{l(l+1)}\left\{b_l p_l(\cos q) + a_l t_l(\cos q)\right\}$$

$$p_l(\cos q) = \frac{1}{\sin q}P_l^{(1)}(\cos q)\ , \qquad t_l(\cos q) = \frac{d}{dq}P_l^{(1)}(\cos q)$$

Associated Legendre functions

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

$$a_l = \frac{y_l'(\tilde{n}ka)\,y_l(ka) - \tilde{n}\,y_l(\tilde{n}ka)\,y_l'(ka)}{y_l'(\tilde{n}ka)\,V_l(ka) - \tilde{n}\,y_l(\tilde{n}ka)\,V_l'(ka)}$$

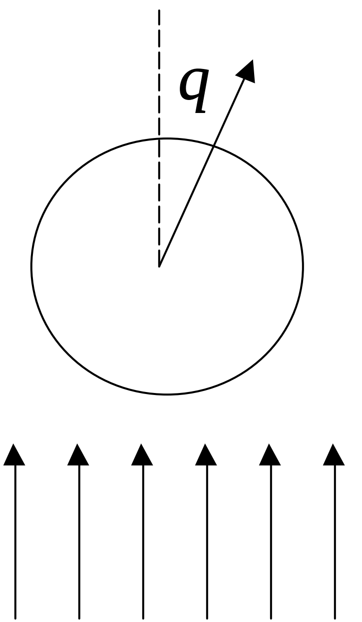
$$b_l = \frac{\tilde{n}\,y_l'(\tilde{n}ka)\,y_l(ka) - y_l(\tilde{n}ka)\,y_l'(ka)}{\tilde{n}\,y_l'(\tilde{n}ka)\,V_l(ka) - y_l(\tilde{n}ka)\,V_l'(ka)}$$

$\tilde{n}$: complex refractive index

$k = 2p / l$

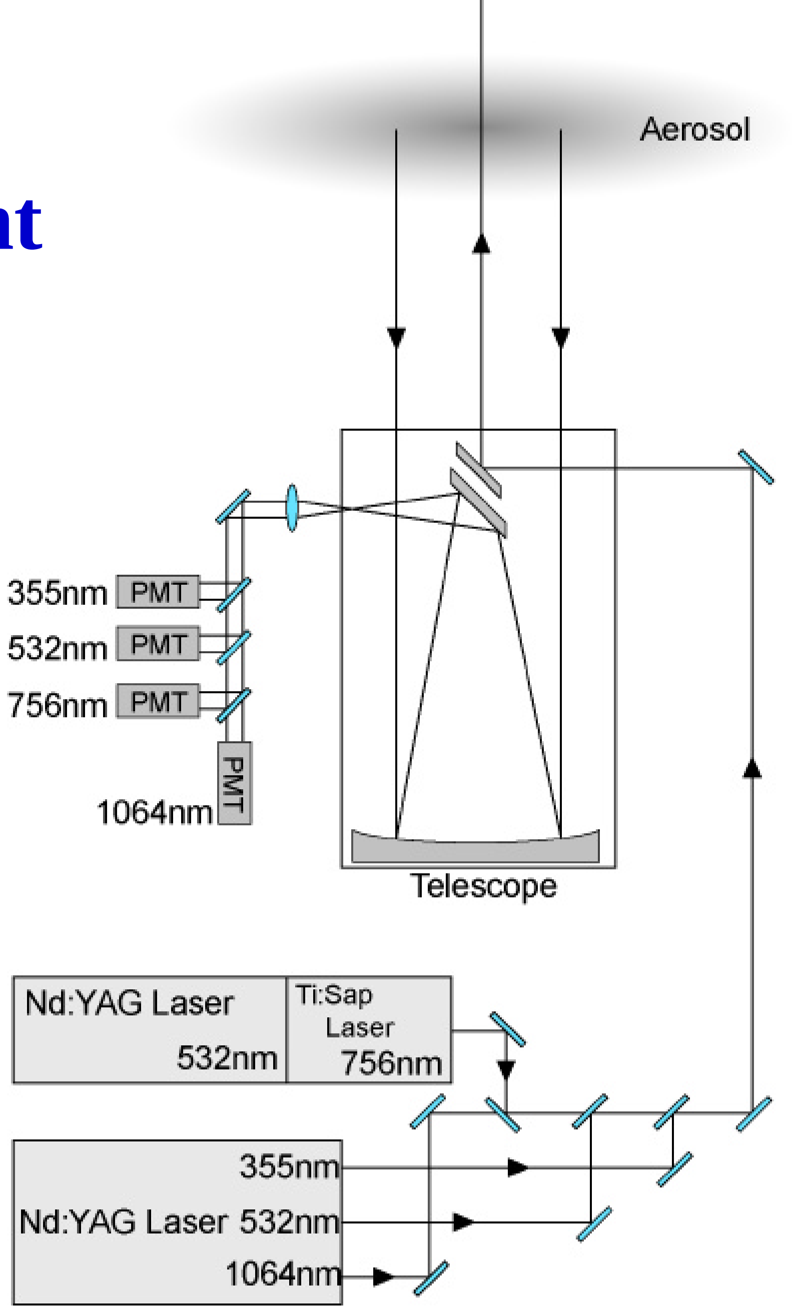
a : radius of the dielectric sphere

$$\begin{cases} y_l(x) = (-1)^l x^{l+1} \left(\frac{1}{x}\frac{d}{dx}\right)^l \left(\frac{\sin x}{x}\right) \\ c_l(x) = (-1)^l x^{l+1} \left(\frac{1}{x}\frac{d}{dx}\right)^l \left(\frac{\cos x}{x}\right) \\ V_n(x) = y_l(x) + i c_l(x) \end{cases}$$



Aerosol measurement using 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 (elastic backscattering)

$$P(R) = P_0 \frac{ct}{2} AK \frac{G(R)}{R^2} b(R) \exp\left[-2\int_0^R a(R')\, dR'\right]$$

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 lidar equation (Fernald method)

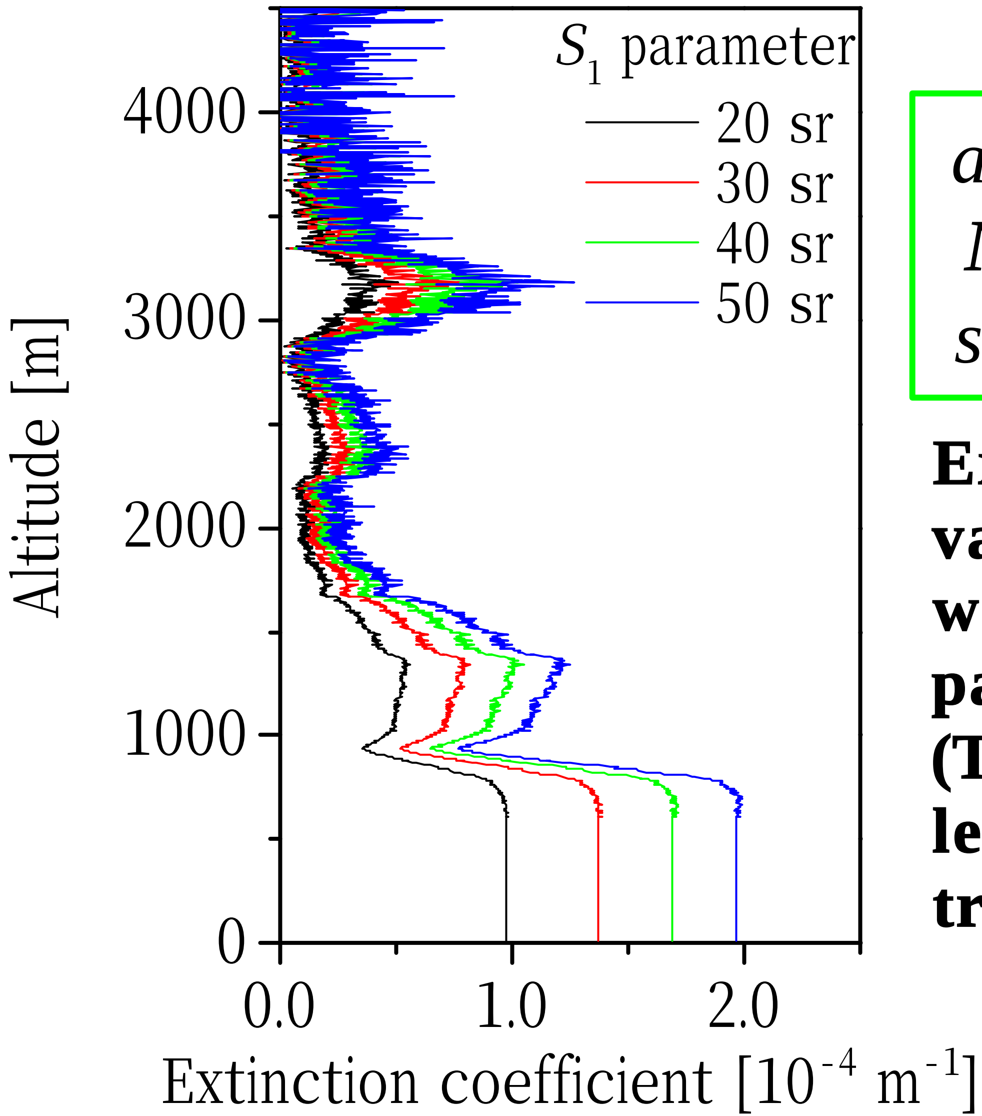
$$S_1(R) = a_1(R)/b_1(R) = s_1(R) \Big/ \left(\frac{ds_1}{d\Omega} \right)_{q=p} , \quad S_2(R) = a_2(R)/b_2(R) = 8.52 \text{ sr}$$

$$a_1(R) = -\frac{S_1(R)}{S_2} a_2(R) + \frac{S_1(R) X(R) \exp I(R)}{\dfrac{X(R_c)}{\dfrac{a_1(R_c)}{S_1(R_c)} + \dfrac{a_2(R_c)}{S_2}} + J(R)}$$

$$X(R) = R^2 P(R), \quad I(R) = 2\int_R^{R_c} \left[\frac{S_1(R')}{S_2} - 1 \right] a_2(R') \, \mathrm{d}R'$$

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

Aerosol extinction profile $a_1(z, l, S_1)$



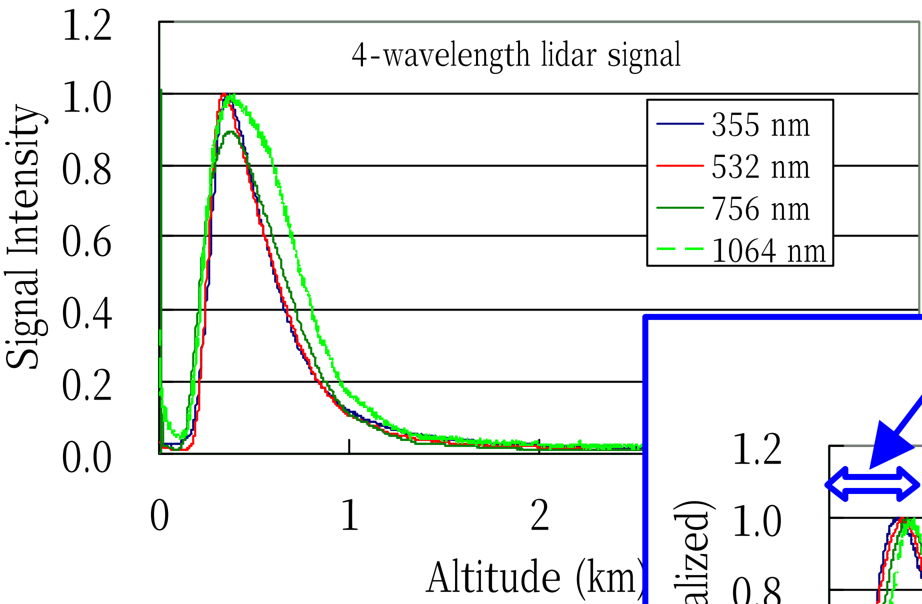
$a_1(z, l) = N(z)\, s_1(l)$

***N*:number density**

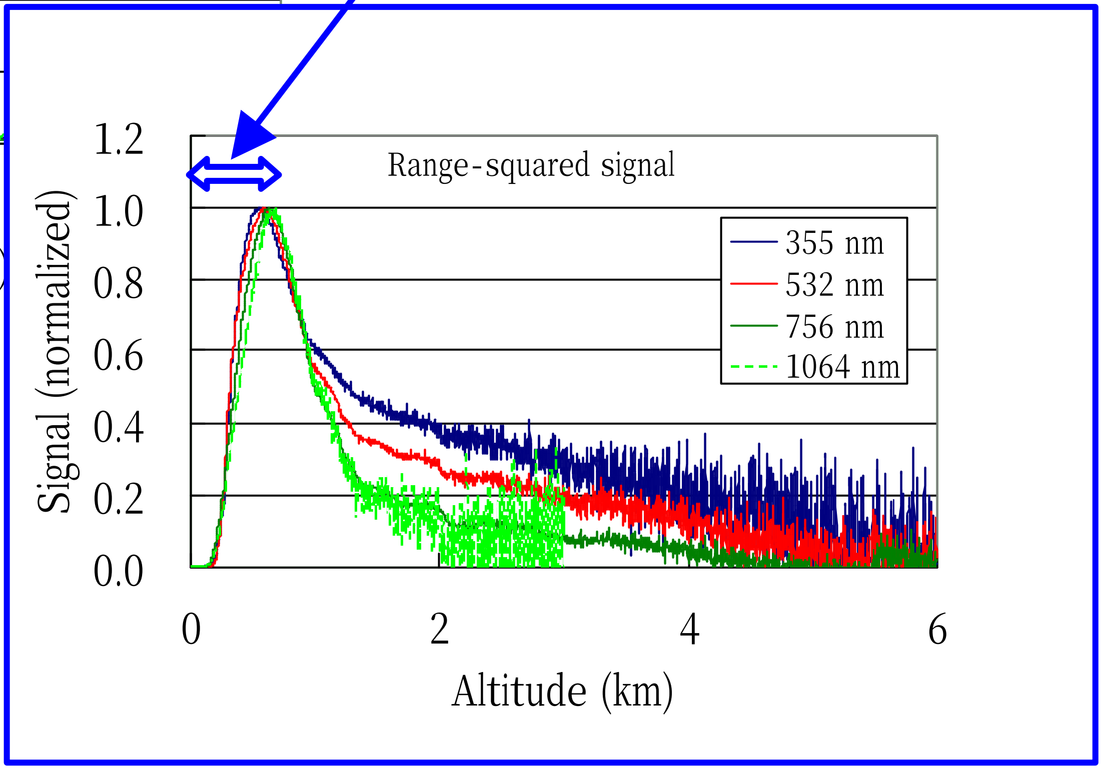
s_1:total cross section

Extinction profile varies when calculated with different S_1 parameter.
(The same lidar data leads to different transmittance.)

Raw and range-squared signals



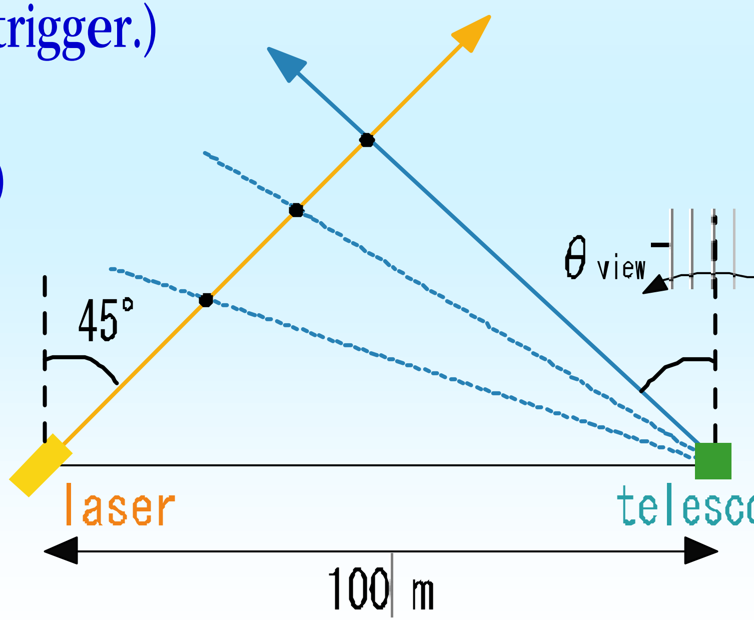
Near-range signals cannot be observed due to the overlap effect

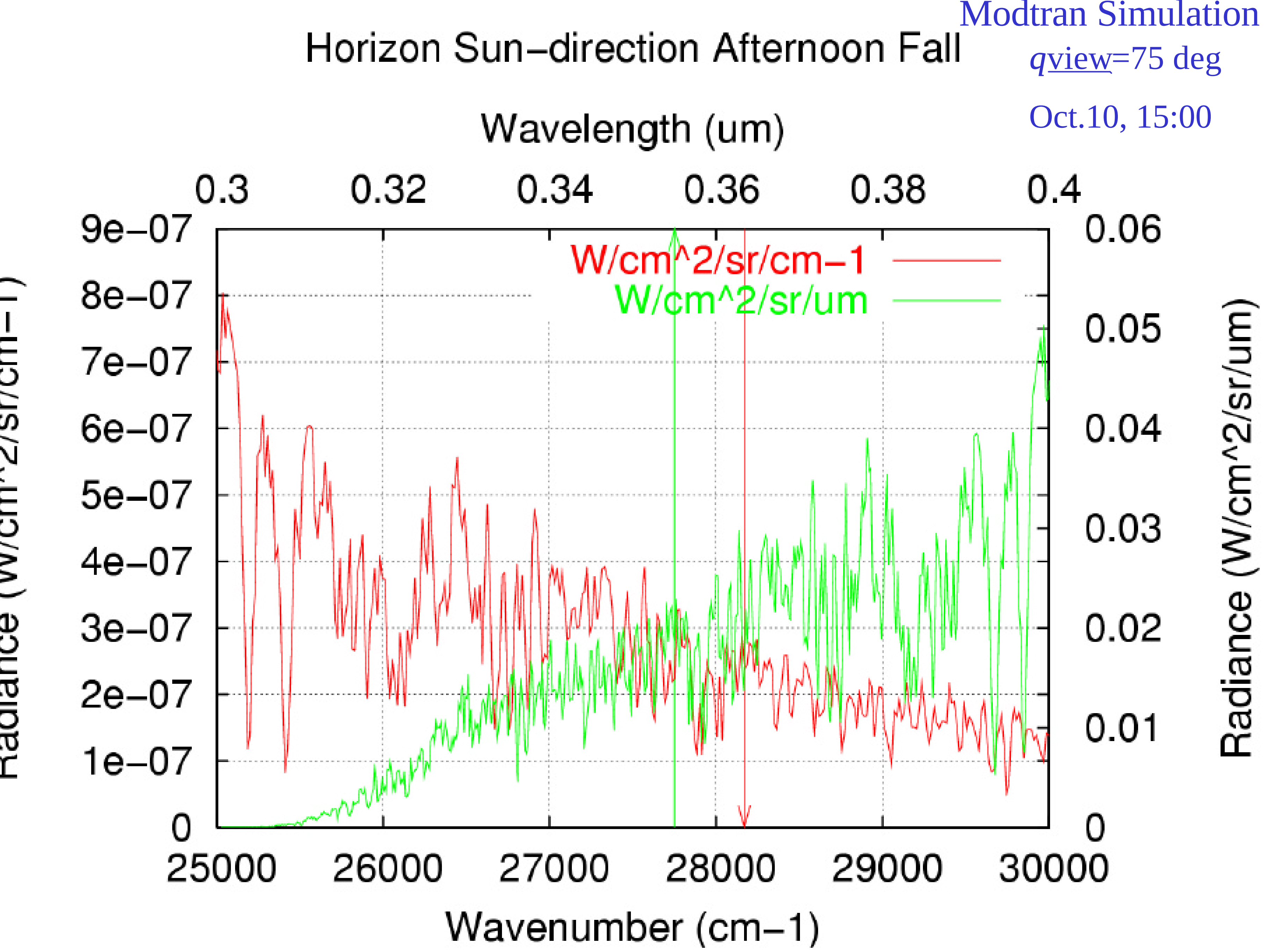


Wide dynamic range is required for long-range observations

Simulation of the signal-to-noise ratio

- Wavelength 351 nm (Photonics Industries, DC30-351YLF)
- Power 100 μJ/pulse
- Repetition rate 3 kHz
- Pulse Width 20 ns
- Background 0.01 [$Wm^{-2}sr^{-1}nm^{-1}$] @ 351 nm (Daytime)
- FOV/pixel 7 mrad (128×128 pixel)
- Shot counts 30000 shots (10 s)
- Gate time 100 ns (with intelligent trigger = decay time of P47)
  3.3 μs (without intelligent trigger.)
- Filter Bandwidth 50 nm (UV-II setup)
  10 nm (Tapered fiber setup)



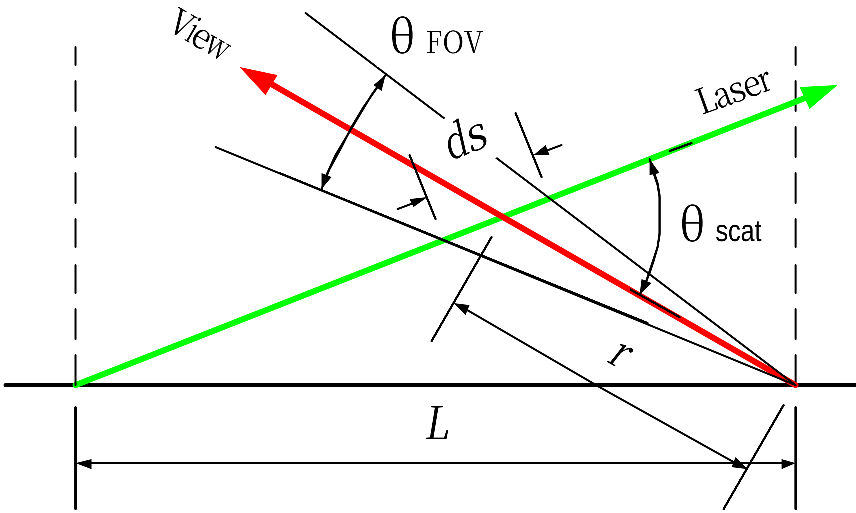


Modtran Simulation
qview=75 deg
Oct.10, 15:00
Horizon Sun−direction Afternoon Fall
Wavelength (um)
0.3
0.32
0.34
0.36
0.38
0.4
W/cm^2/sr/cm−1
W/cm^2/sr/um
9e−07
8e−07
7e−07
6e−07
5e−07
4e−07
3e−07
2e−07
1e−07
0
Radiance (W/cm^2/sr/cm−1)
0.06
0.05
0.04
0.03
0.02
0.01
0
Radiance (W/cm^2/sr/um)
25000
26000
27000
28000
29000
30000
Wavenumber (cm−1)

Lidar equation for bistatic measurement

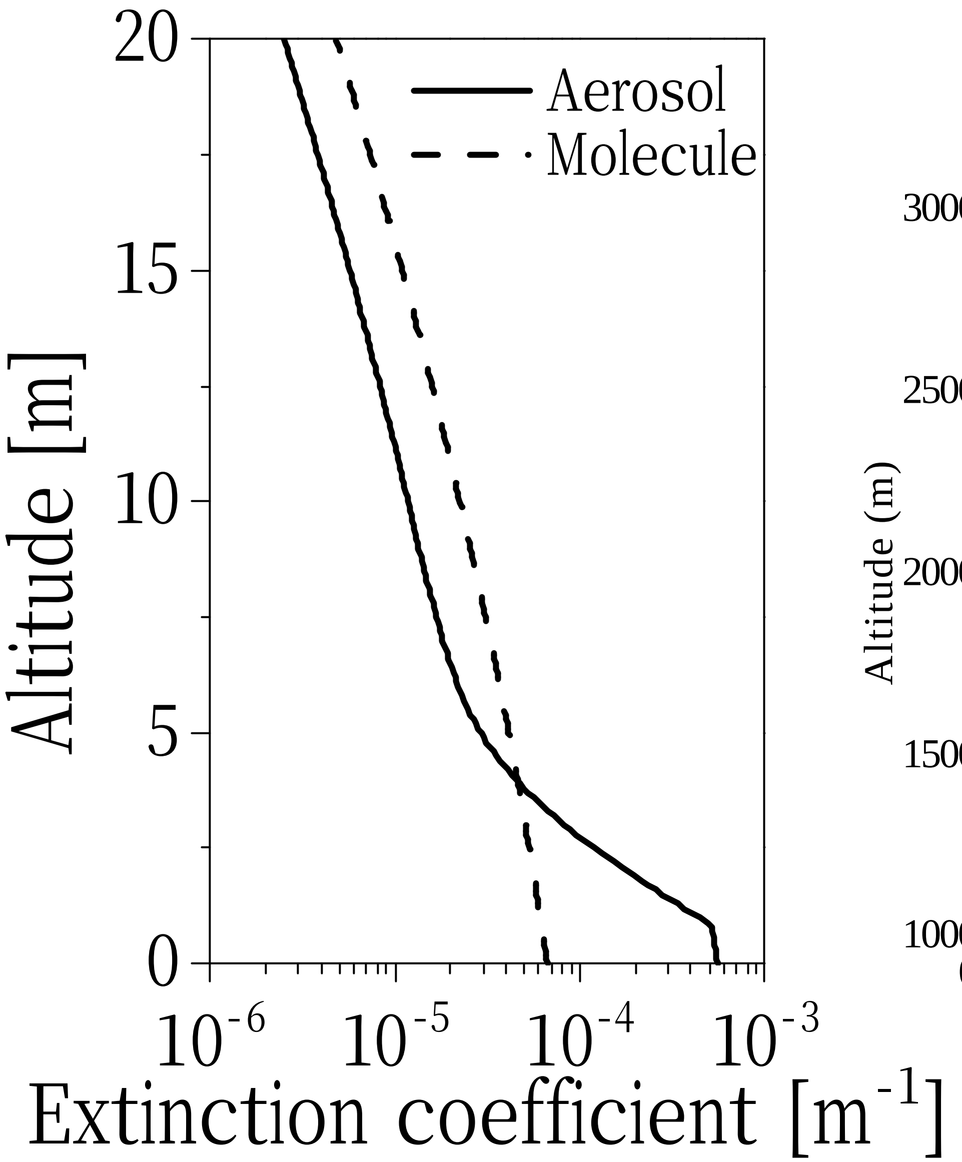
$$P = P_0 \; K \; \frac{A}{r^2} \; ds \; b(q_{\mathrm{scat}}) \; T_t \; T_r$$

where $$ds = \frac{r \, q_{\mathrm{FOV}}}{\sin(q_{\mathrm{scat}})}$$

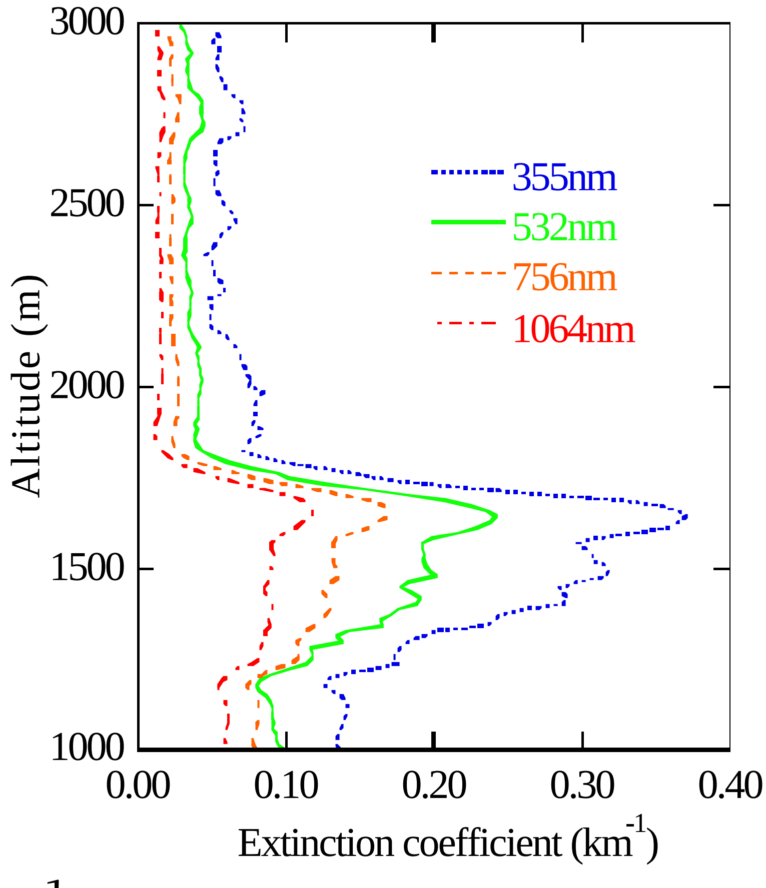


P	Received power [W]
P_0	Transmitted power [W]
K	Optical efficiency of the telescope
A	Effective area of main mirror [m^2]
r	Range to the target [m]
ds	Laser path length in one pixel [m]
β	Scattering coefficient [$m^{-1}sr^{-1}$]
T_t	Transmittance from laser to target
T_r	Transmittance from target to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

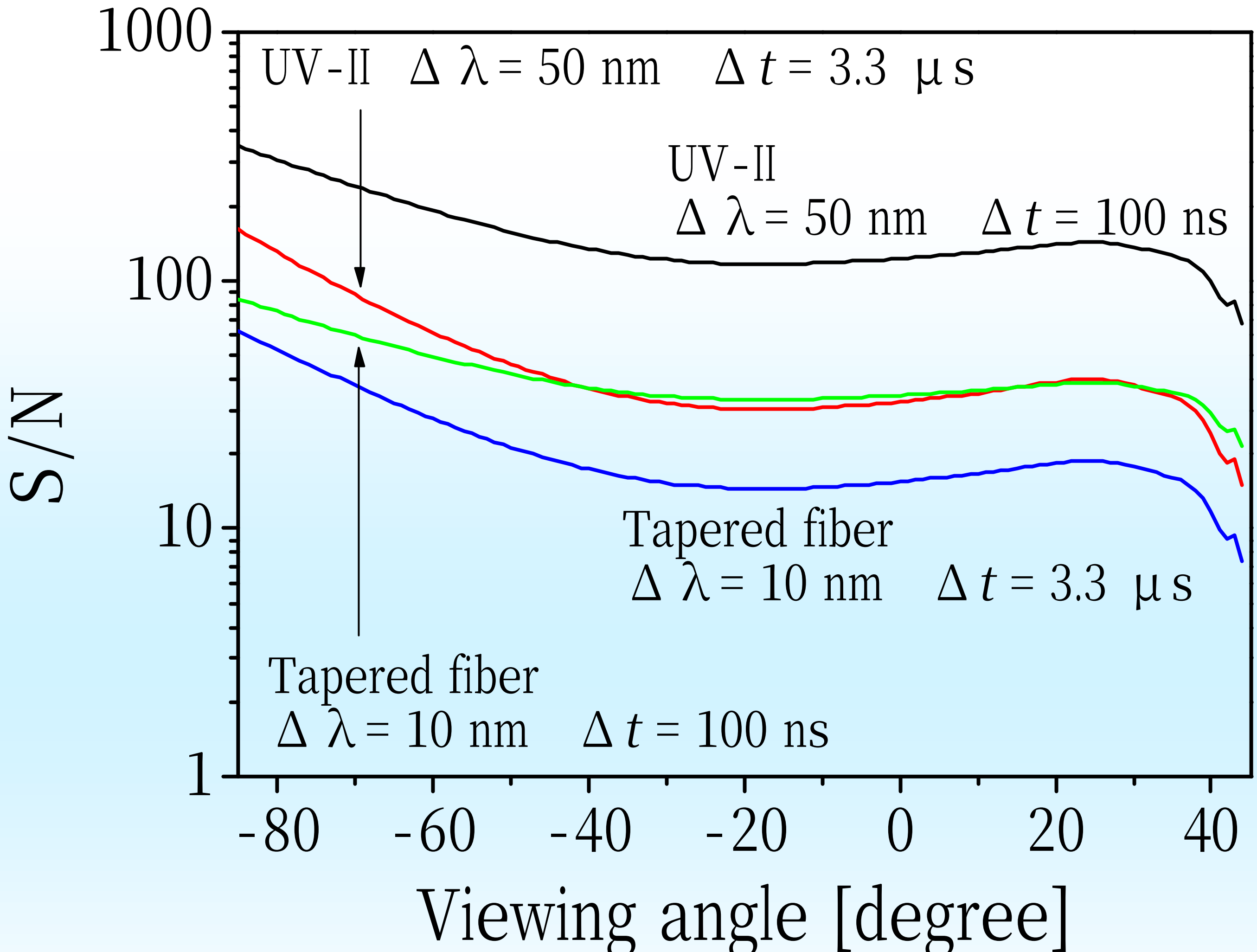
Model profile of the atmosphere



Real distribution



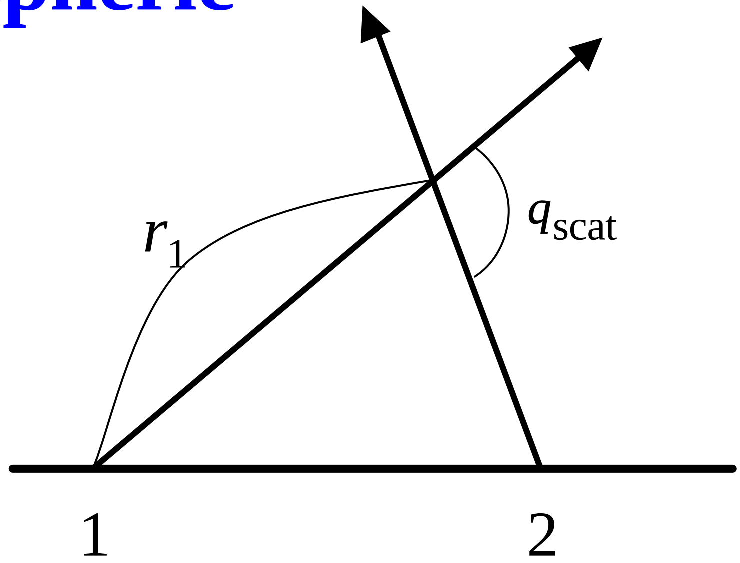
Signal-to-Noise Ratio



Δ λ : FWHM

Δ *t* : Gate time

Measurement of atmospheric transmittance



Signal & laser @ site 1

$$P_{11} = P_0^{(1)} K^{(1)} \frac{A_1}{r_1^{\,2}} dr_1 b(p) T_1^{\,2}$$

Signal & laser @ site 2

$$P_{22} = P_0^{(2)} K^{(2)} \frac{A_2}{r_2^{\,2}} dr_2 b(p) T_2^{\,2}$$

Signal @ site 1 (laser @ site 2)

$$P_{12} = P_0^{(2)} K^{(1)} \frac{A_1}{r_1^{\,2}} ds_1 b(q_{\text{scat}}) T_1 T_2 , \qquad ds_1 = \frac{r_1 q_{\text{FOV}}^{(1)}}{\sin q_{\text{scat}}}$$

Signal @ site 2 (laser @ site 1)

$$P_{21} = P_0^{(1)} K^{(2)} \frac{A_2}{r_2^{\,2}} ds_2 b(q_{\text{scat}}) T_1 T_2 , \qquad ds_2 = \frac{r_2 q_{\text{FOV}}^{(2)}}{\sin q_{\text{scat}}}$$

Solution of the coupled equations

$$\begin{cases} Q_{11} = b(p)T_1^{\ 2} \\ Q_{22} = b(p)T_2^{\ 2} \\ Q_{12} = Q_{21} = \beta(\theta_{scat})T_1T_2 \end{cases}$$

$b(p)$: **backscattering coefficient**

T_1**,**T_2**: transmittance**

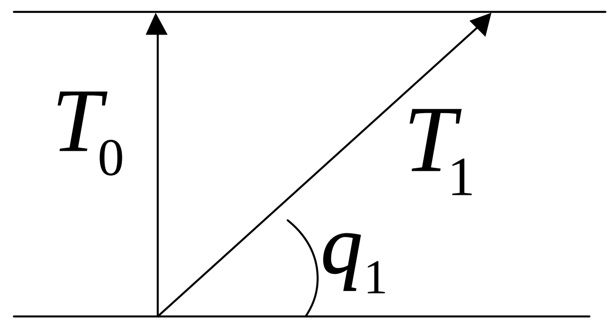
$$\Rightarrow \quad \frac{\beta(\pi)}{\beta(\theta_{scat})} = \frac{(Q_{11}Q_{22})^{1/2}}{Q_{12}} \quad , \quad T_2^{\ 2} = \frac{Q_{22}}{Q_{11}}T_1^{\ 2}$$

… General solution for non-homogeneous atmosphere

Solutions for the layered atmosphere

$$T_0(z) = \exp[-t_0(z)]$$

$$= \exp\left[-\int_0^z a(z')dz'\right]$$



$$T_1 = \exp\left[-\frac{t_0(z)}{\sin q_1}\right], \qquad T_2 = \exp\left[-\frac{t_0(z)}{\sin q_2}\right]$$

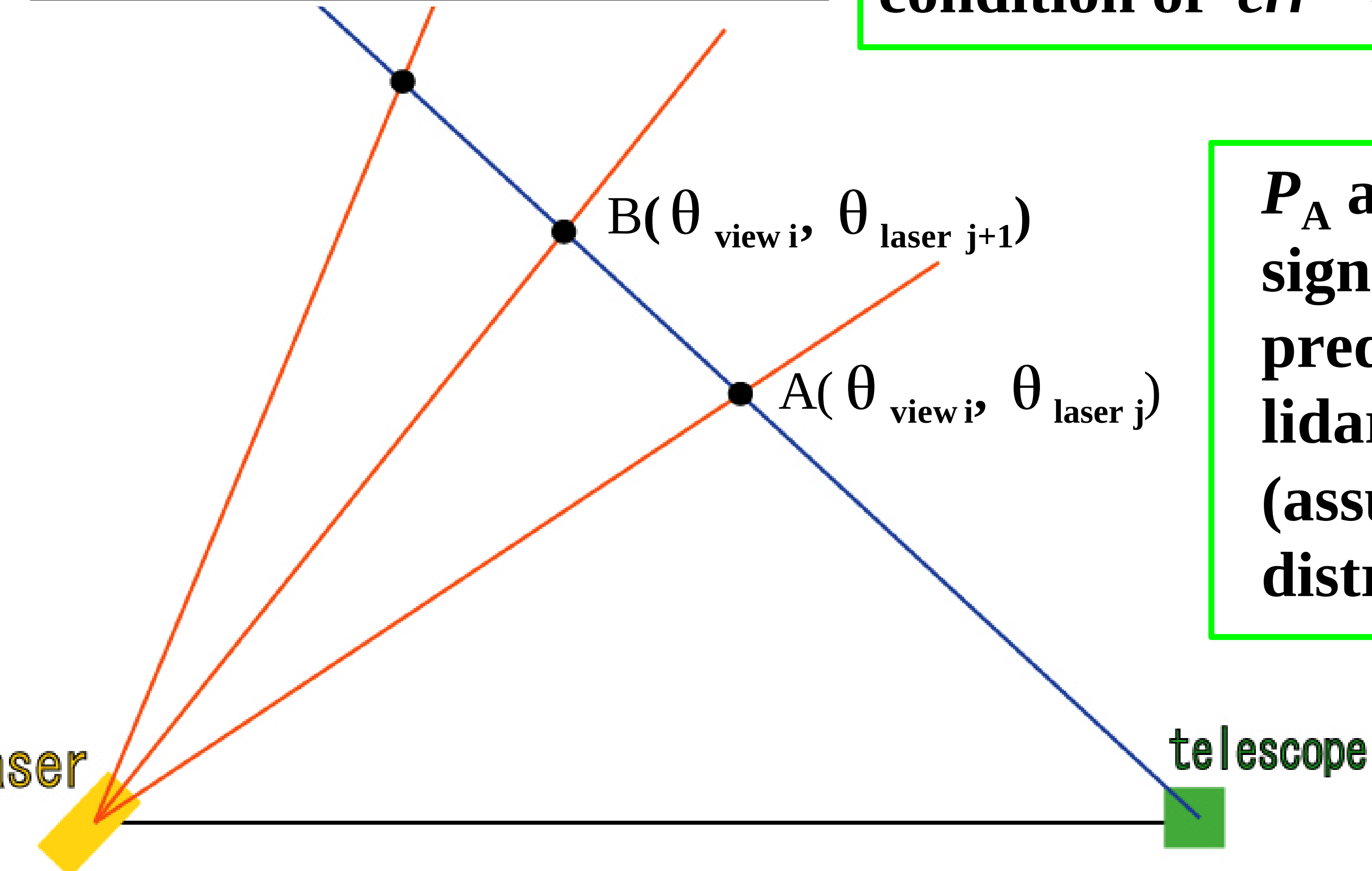
$$\sin q_1 \ln T_1 = \sin q_2 \ln T_2 \;, \quad T_1 = \exp\left[\frac{\ln(\frac{Q_{22}}{Q_{11}})}{2\left(\frac{\sin q_1}{\sin q_2} - 1\right)}\right]$$

Iterative analysis of bistatic lidar data

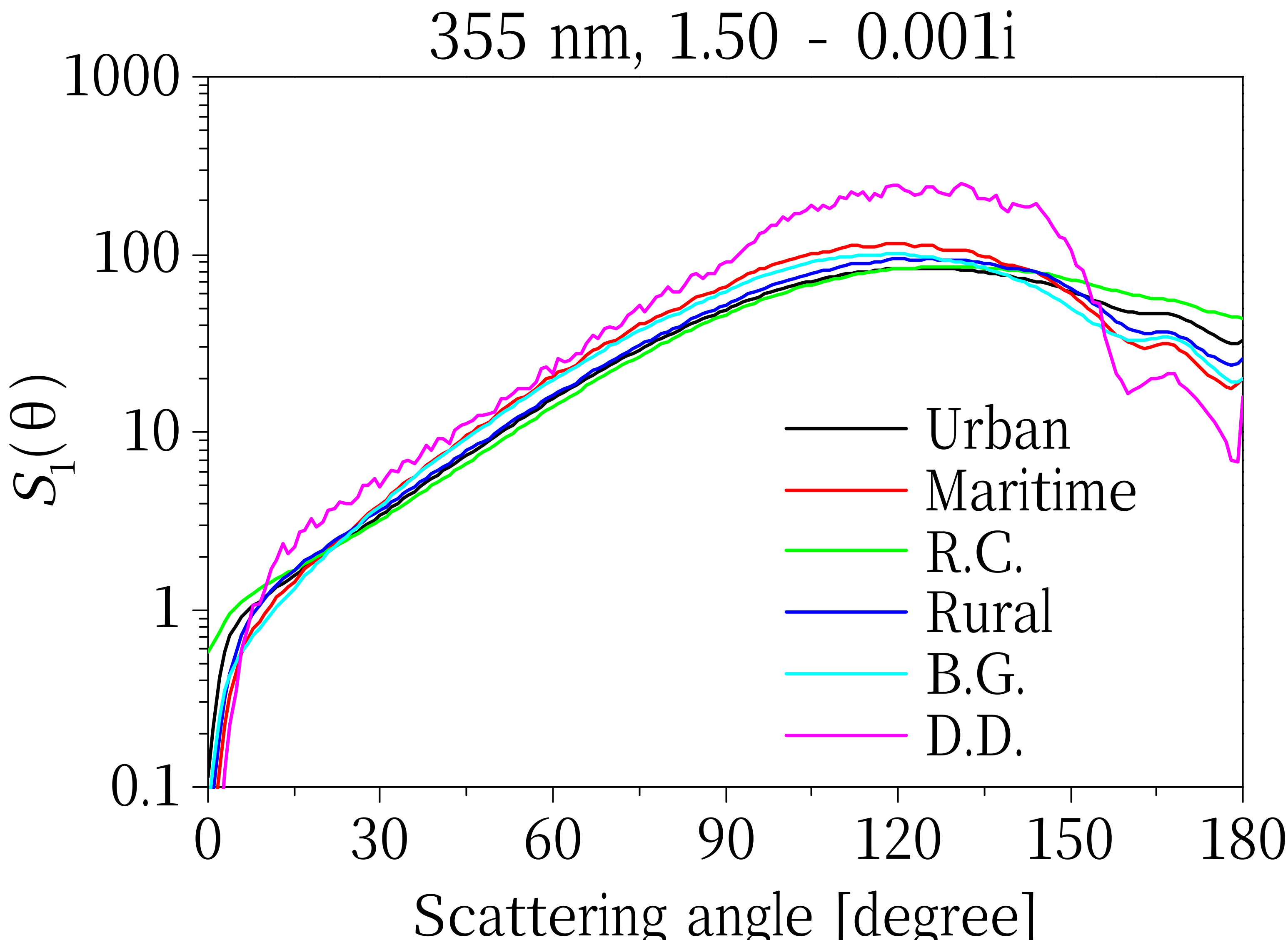
$$err = \frac{P_B^{(\mathrm{obs})}}{P_A^{(\mathrm{obs})}} - \frac{P_B}{P_A}$$

Once the aerosol extinction (a_1) at *A* is known, the extinction at *B* can be determined from the condition of *err* $\rightarrow$ 0

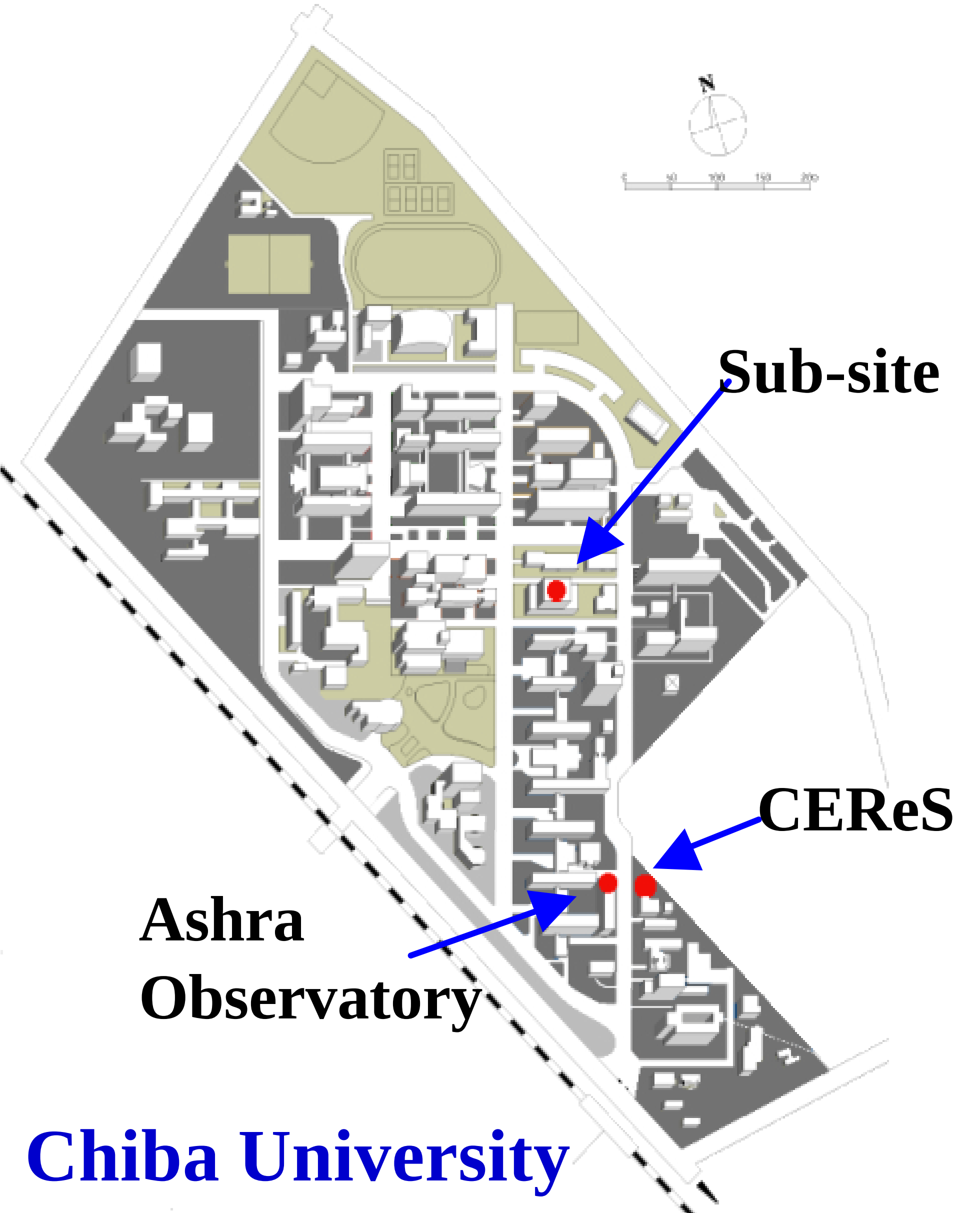
P_A and P_B are the signal intensities predicted by the lidar equation (assuming the distribution of α_1)



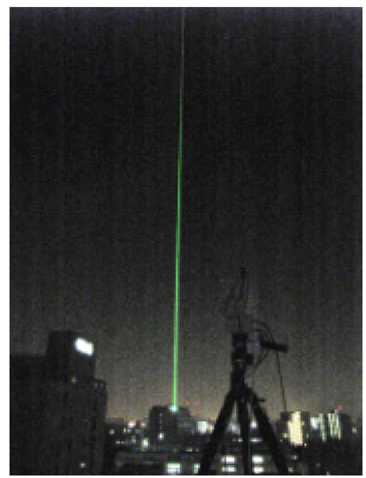
Angular dependent S_1 parameter



Imaging lidar



Chiba University Main campus

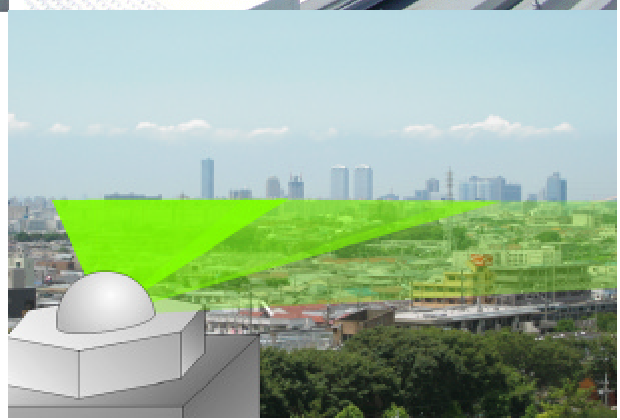


CEReS Observatory for Ashra Imaging Lidar









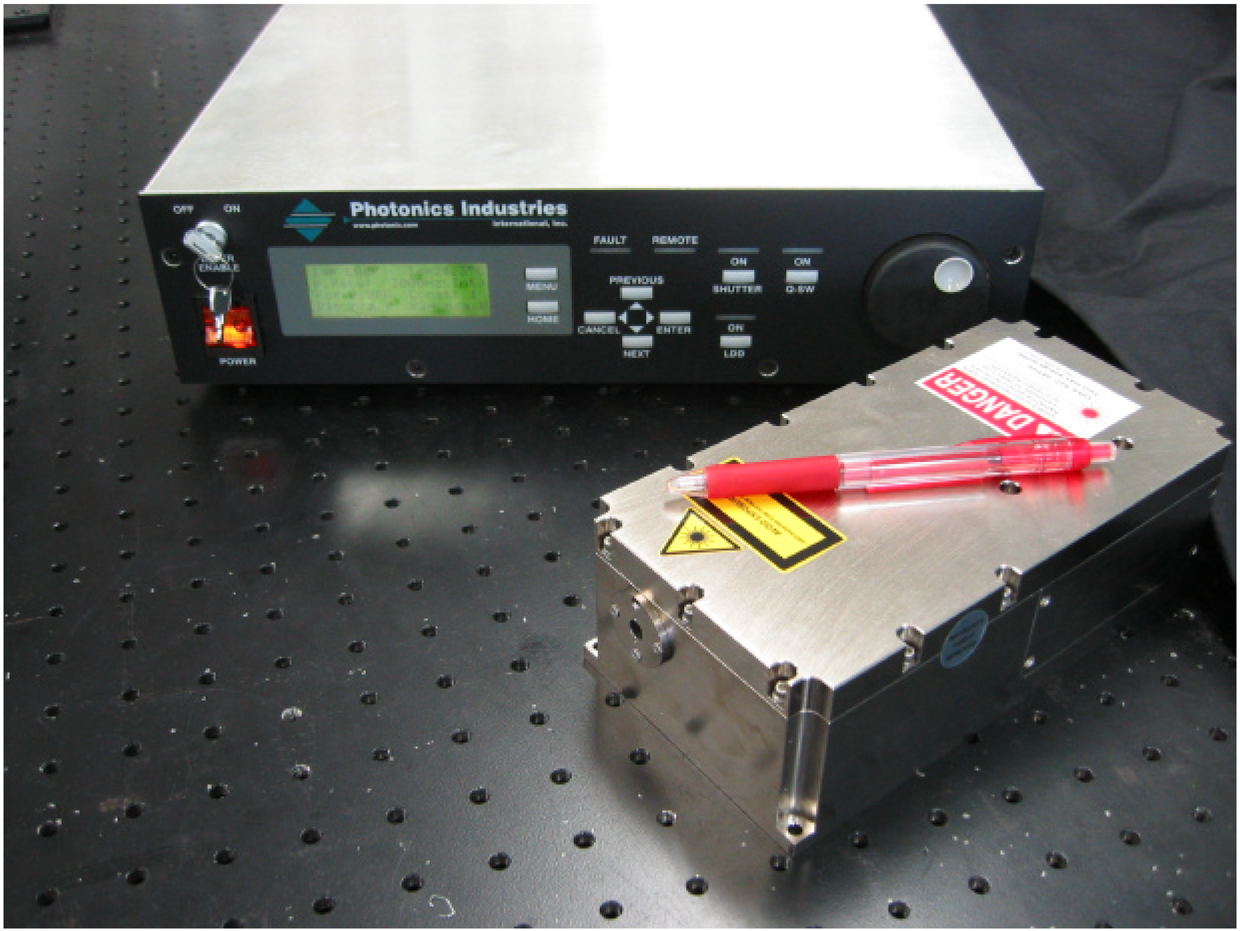
Photonics Industries DC-30-351SP

351 nm, Nd:YLF laser

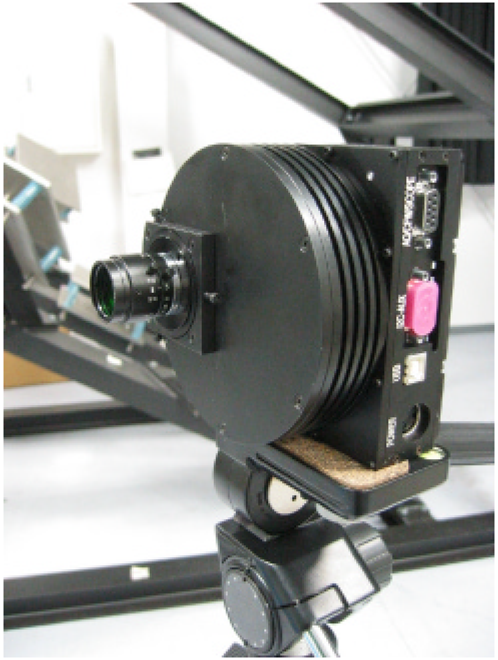
UV laser

300 mW @ 3 kHz (100 uJ/pulse)

10-25 ns, 0-10 kHz



CCD cameras

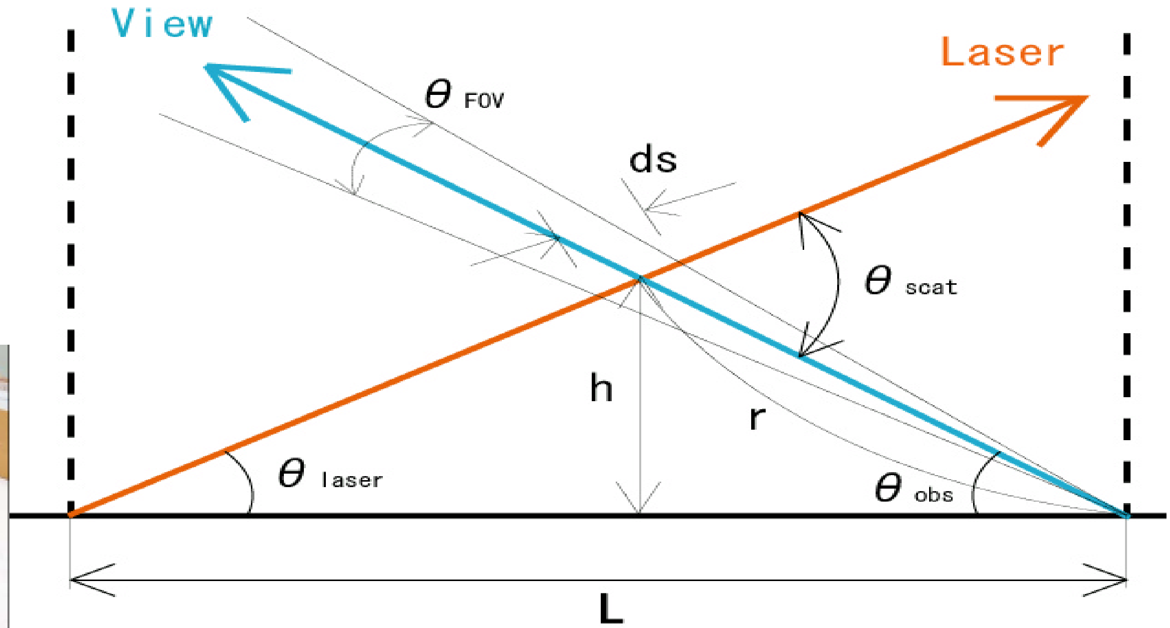


Cooled CCD SBIG ST7
765×510 pixels
QE 0.65 @ 532 nm
16 bit ADC
Lens FOV 46 deg
Aperture 25 mm
Filter T=0.54 @ 530nm

Cooled CCD BITRAN
4008×2672 pixels
QE 0.47 @ 532 nm, 16 bit ADC
Lens (SIGMA) 50mm, f/1, 39 deg
Filter T=0.54 @ 530 nm
Half bandwidth =100 nm

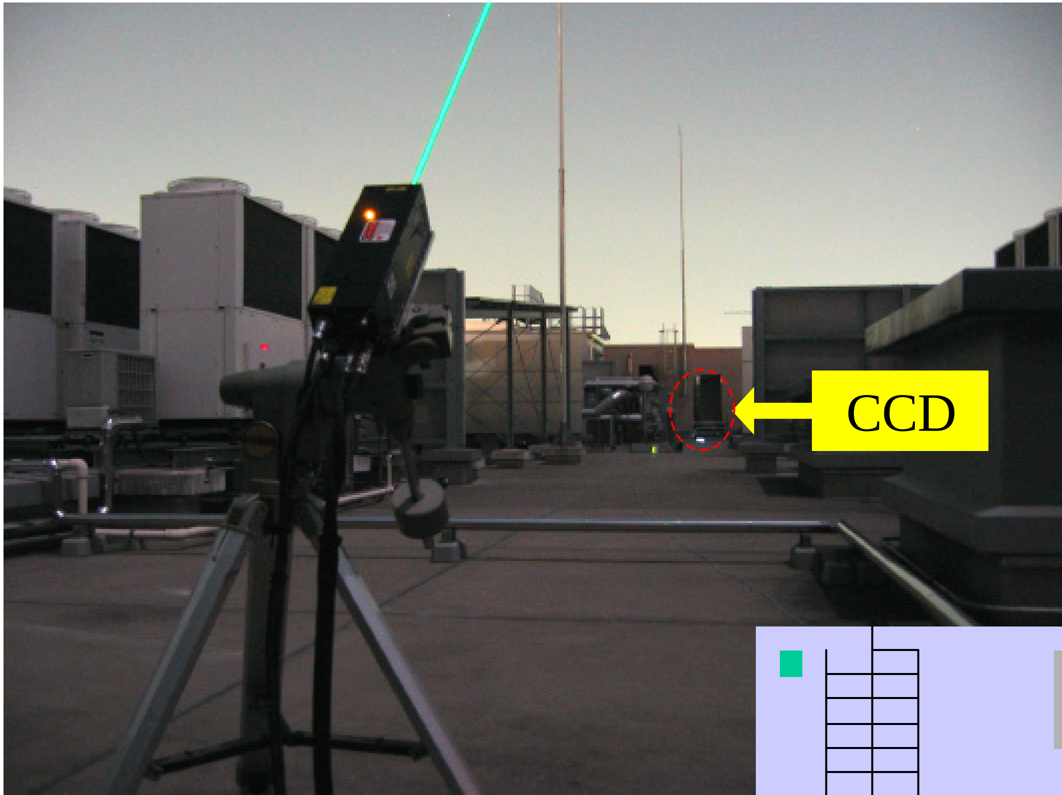
Gate I.I. (C9547-03MOD)
Gate time 10 ns –DC, max.rep. 10Hz
185-900 nm, 1 stage MCP
Luminous gain 1×10^4 (lm/m^2)·lx

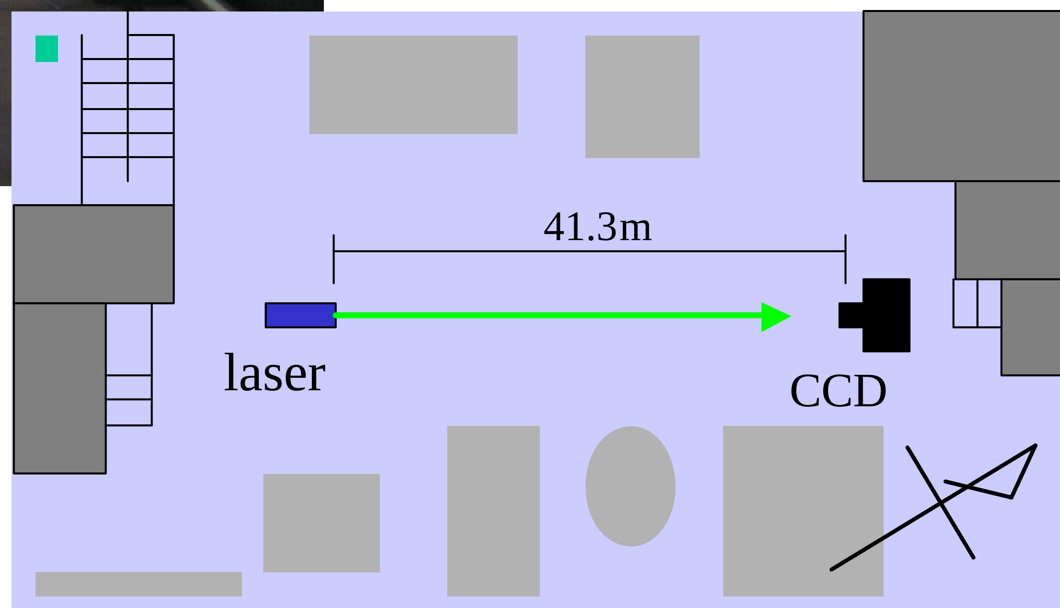
Imaging Lidar (IL)



- ? **Observation of very intense forward scattering**
- ? **Observation capability near the ground level**
- ? **Limited dynamic range for the detector**
- ? **Consideration for polarization, multiple-scattering, and phase function of aerosol particles**

Imaging Lidar Observation (CCD camera)





Roof on a building (9F)
@ Chiba Univ.

Extraction of Laser path intensity

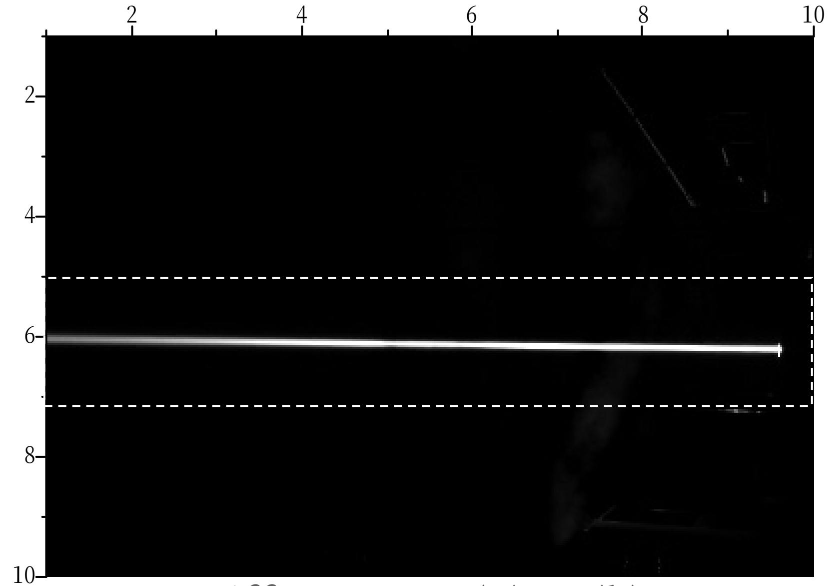
(a) Laser ON

04/11/02

Θ_{laser} = 10 deg.

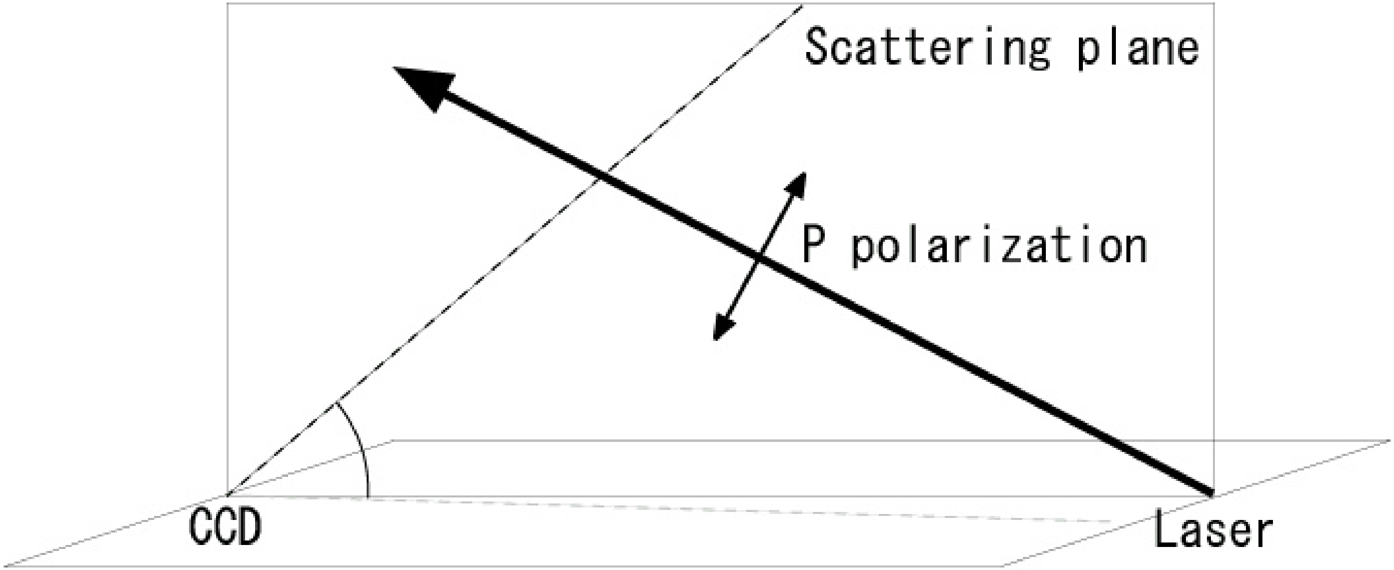
Exposure time = 0.5 s

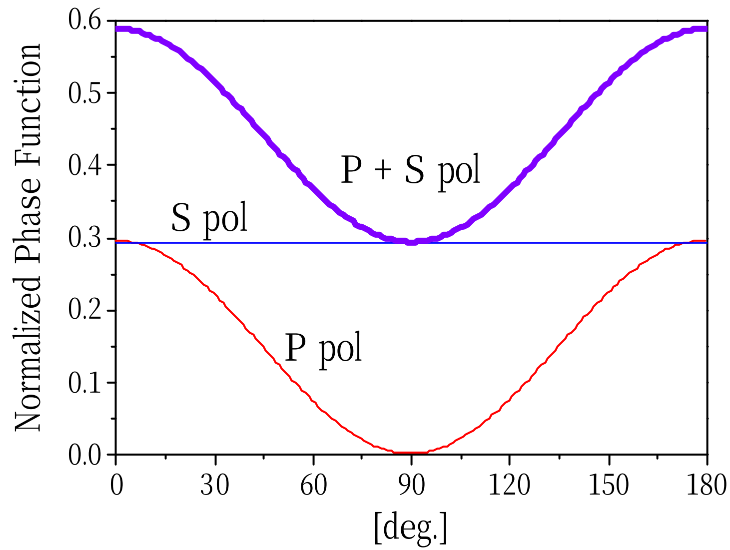
(b) Laser OFF



Difference : (a) – (b)

Geometry of the in-plane observation

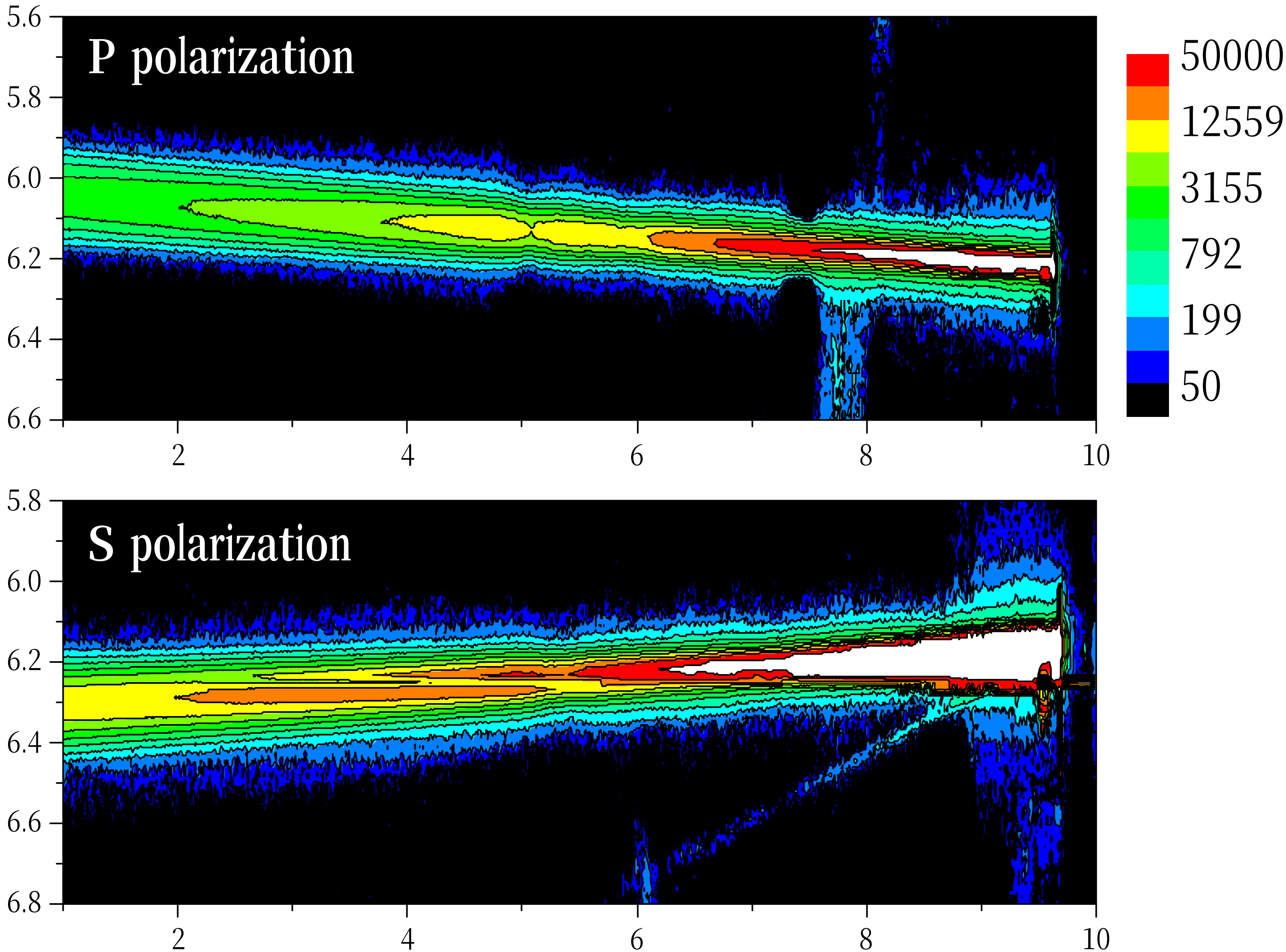




S **P**

$$\frac{ds}{d\Omega} = \left(\frac{\tilde{a}\ k^2}{4pe_0}\right)^2 \frac{1 + \cos^2 ?}{2}$$

Laser path intensity



Bistatic lidar equation

$$P(\theta_{\text{view } i}, \theta_{\text{laser } j}) = C \frac{\beta(\theta_{\text{scat } i,j}) \;\; T}{r \sin(\theta_{\text{scat } i,j})}$$

$$T = \exp[-(\tau_t + \tau_r)]$$

$$\tau_t = \frac{\int (\alpha_1 + \alpha_2)\, dz}{\cos q_{\text{laser}}}$$

$$\tau_r = \frac{\int (\alpha_1 + \alpha_2)\, dz}{\cos q_{\text{obs}}}$$

$$\theta_{\text{scat } i,j} = \pi - \theta_{\text{obs } i,j} - \theta_{\text{laser } i,j}$$

$$\beta(\theta_{\text{scat } i,j}) = \frac{\alpha_{1\,i,j}}{S_1(\theta_{\text{scat } i,j})} + \frac{\alpha_{2\,i,j}}{S_2(\theta_{\text{scat } i,j})}$$

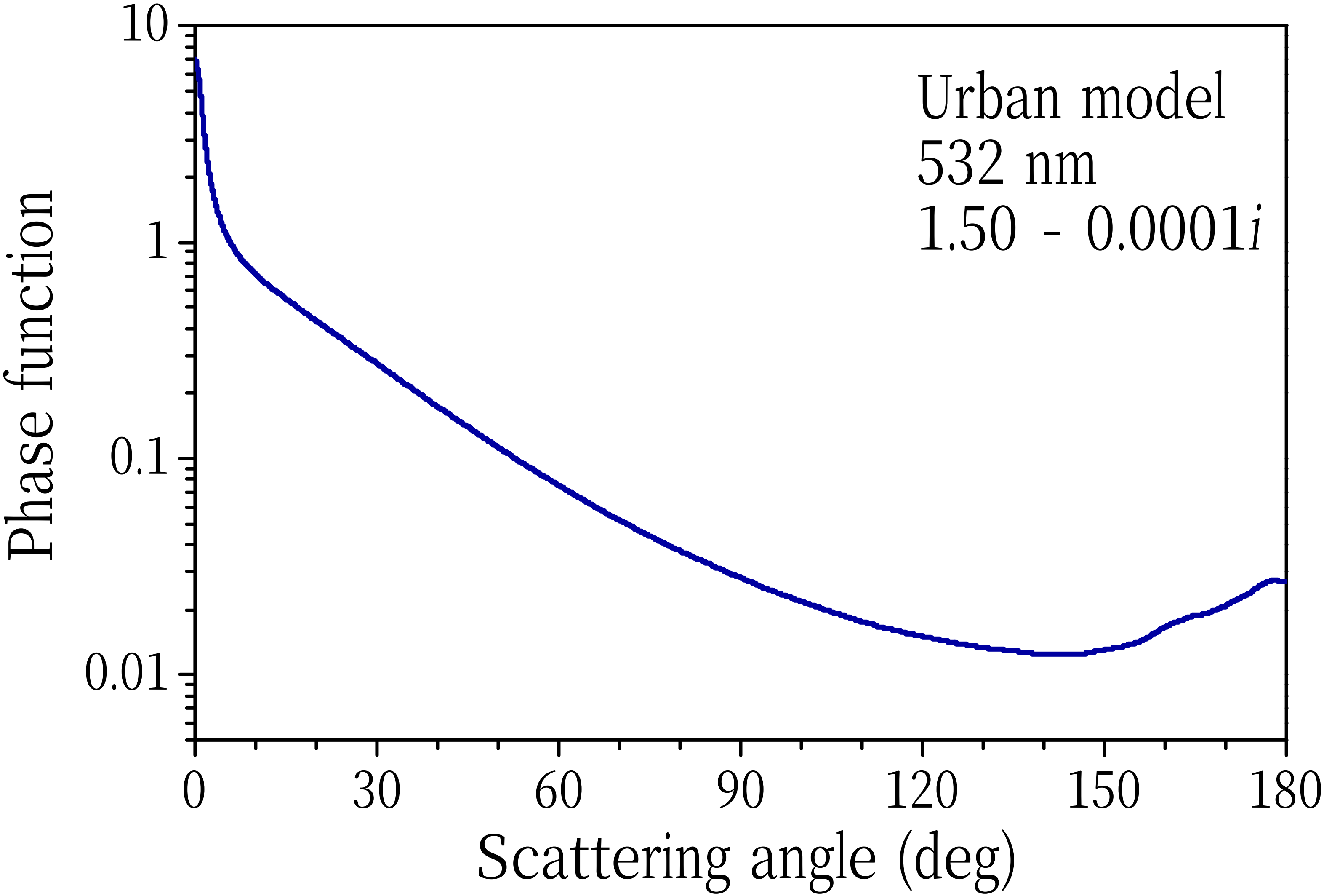
$$= \alpha_{1\,i,j}\; p_1(\theta_{\text{scat } i,j}) + \alpha_{2\,i,j}\; p_2(\theta_{\text{scat } i,j})$$

C : **Constant (independent of $\theta_{\text{scat } i,j}$)**

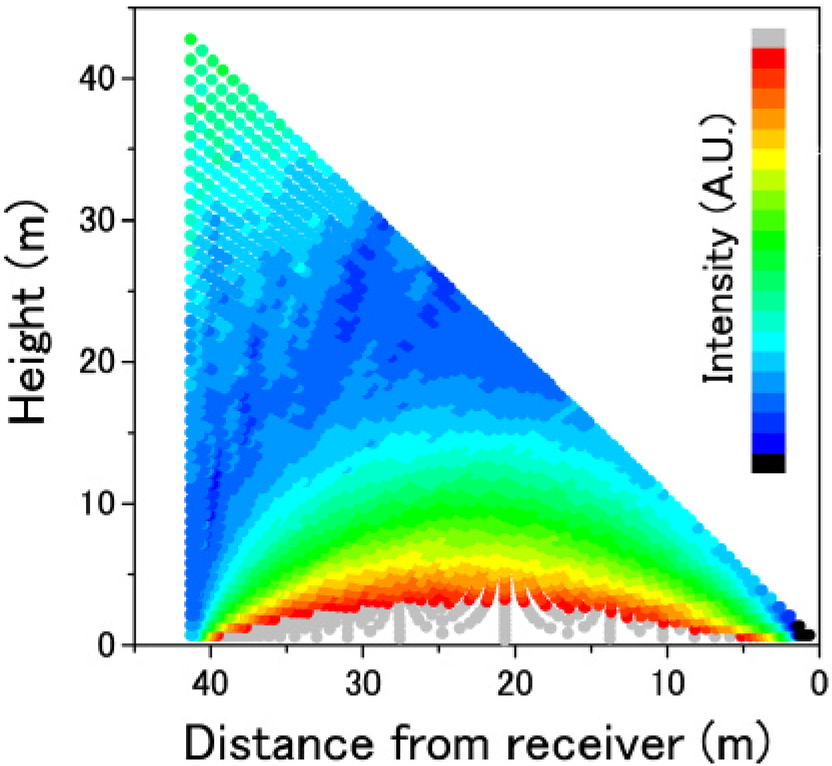
$p(\theta_{\text{scat } i,j})$: **Phase function (1:aerosol 2.air molecule)**

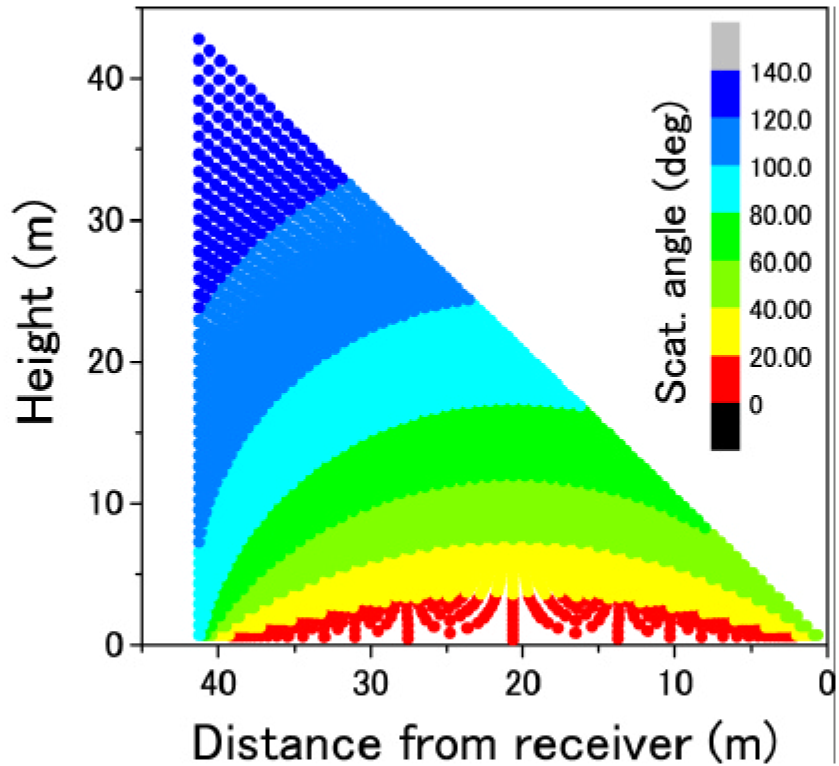
τ : **Optical thickness**

Phase function



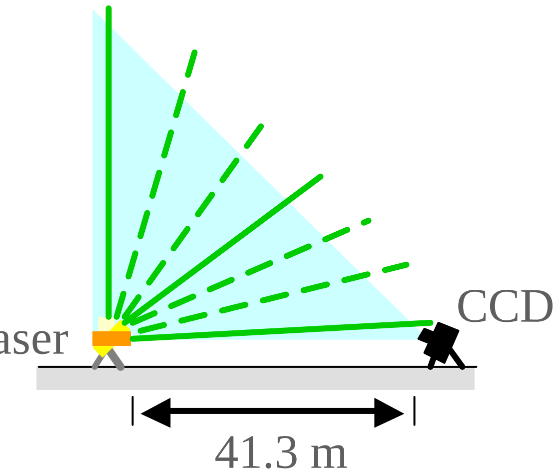
Observed signal intensity



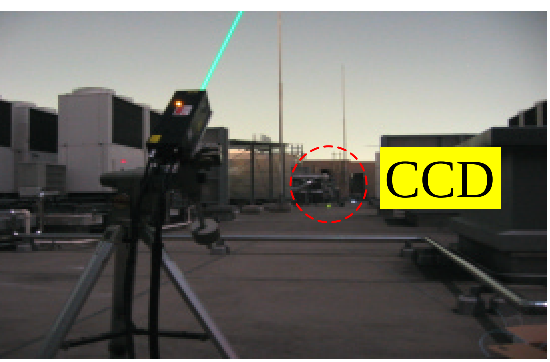


Imaging Lidar Observation – 532nm, In-plane

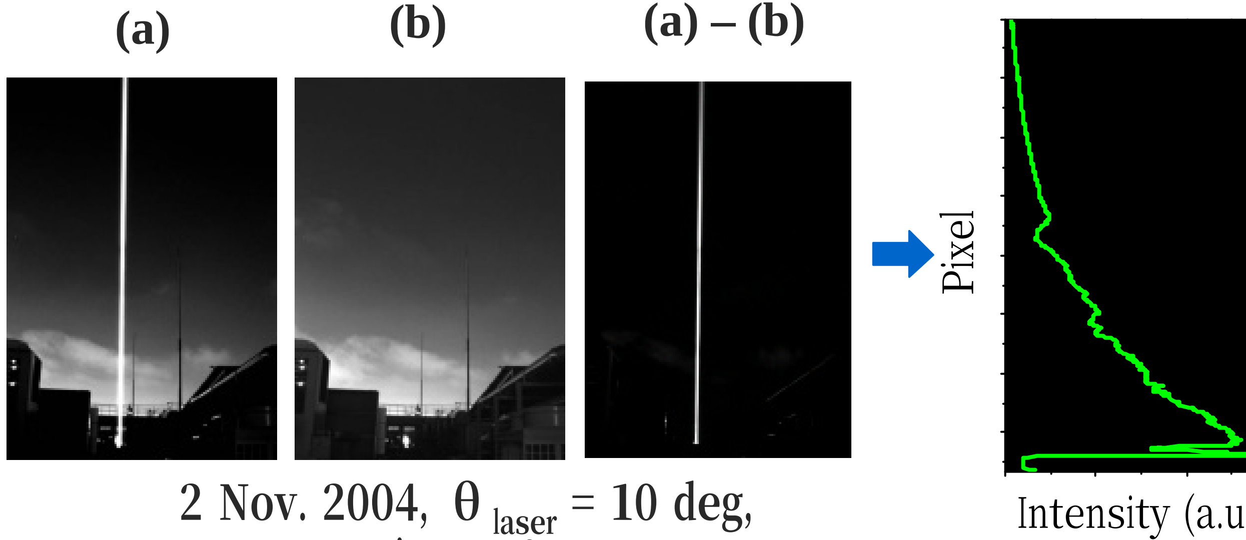
In-plane observation



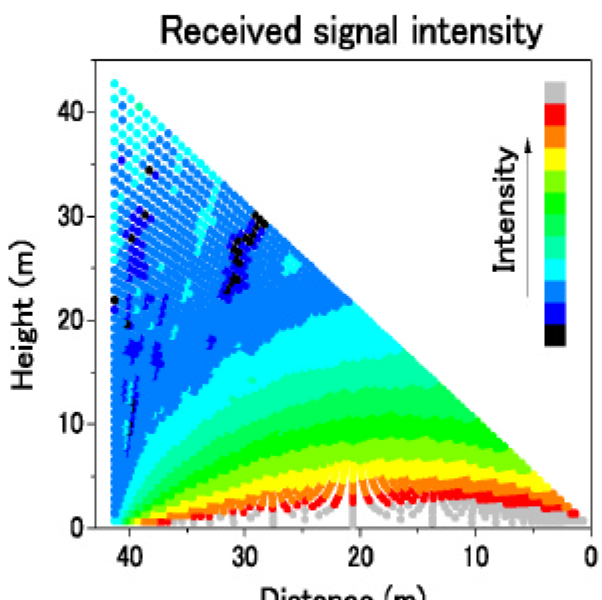
Nd:YAG Laser, 532nm
10Hz, 30mJ/pulse

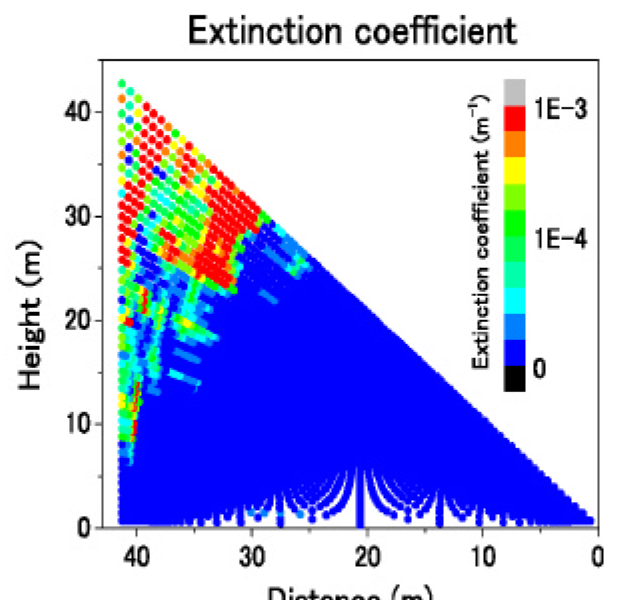


Laser ON (a) | **Laser OFF (b)** | **Difference: (a) – (b)**



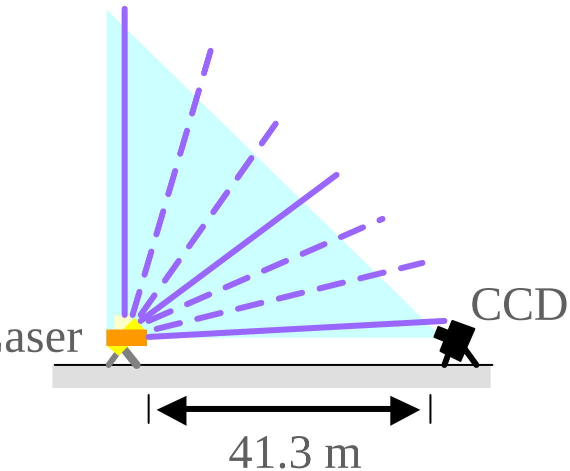
2 Nov. 2004, θ_{laser} = 10 deg,
exposure time = 0.5 s



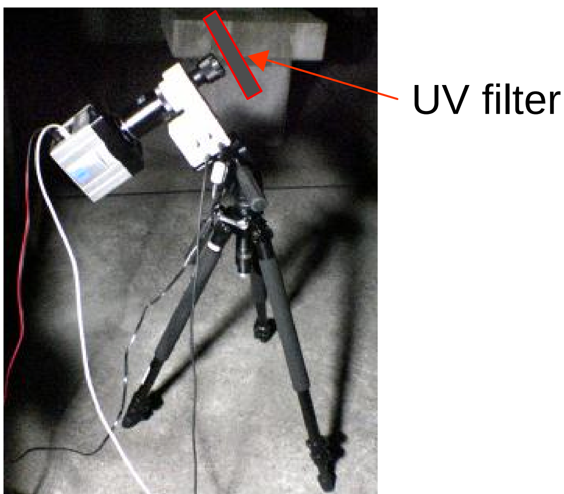


Imaging Lidar Observation – 351nm, In-plane

In-plane observation (UV)



Nd:YLF DPSS Laser, 351 nm
3kHz, 100 uJ/pulse
Laser elevation :10 deg

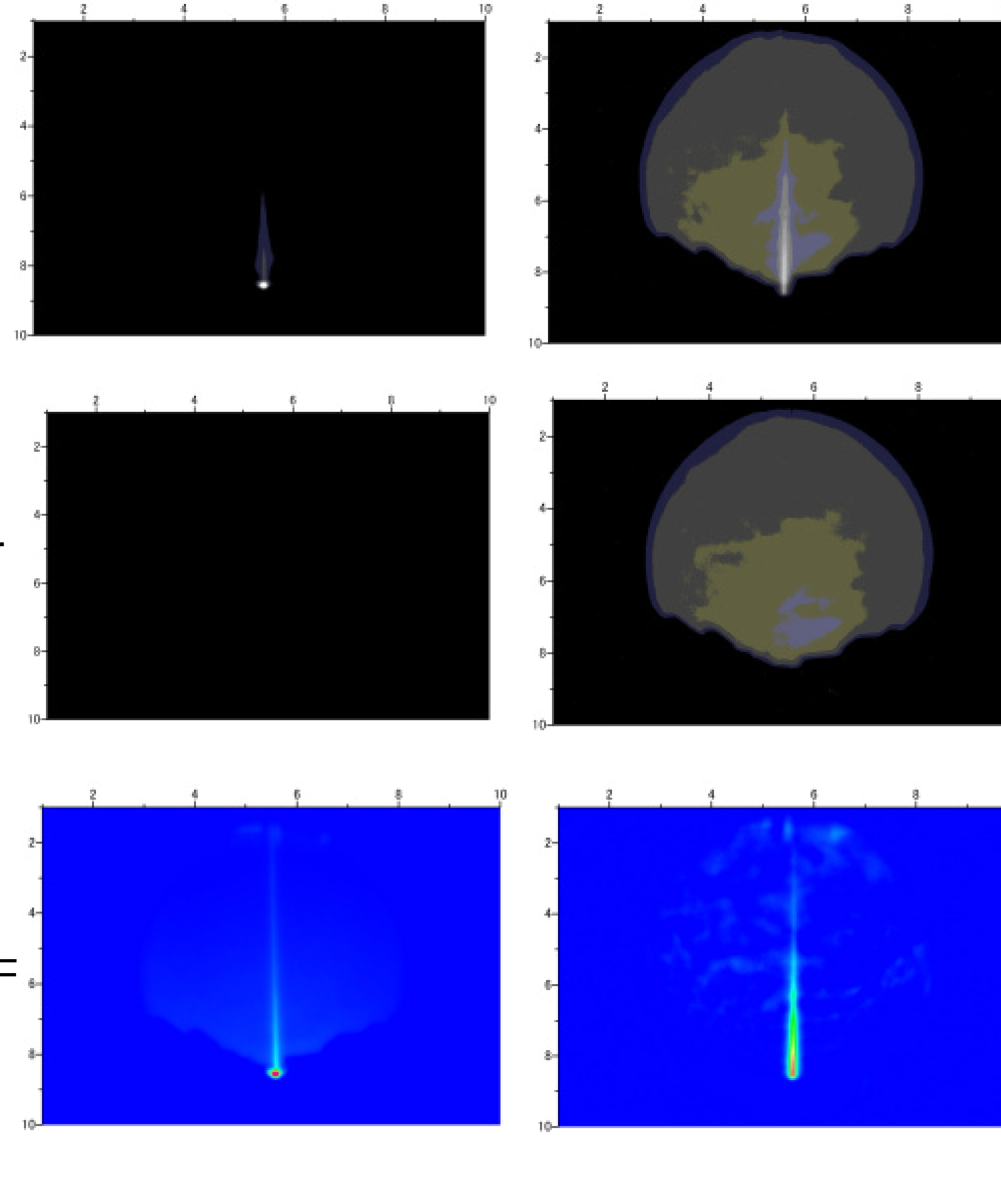


S-pol. :2 s   P-pol. :5 s

Laser ON

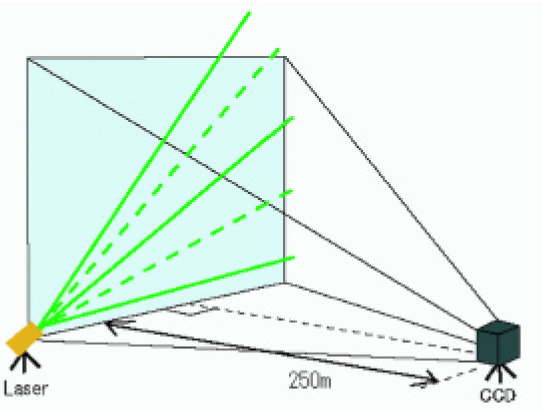
Laser OFF

ON－OFF



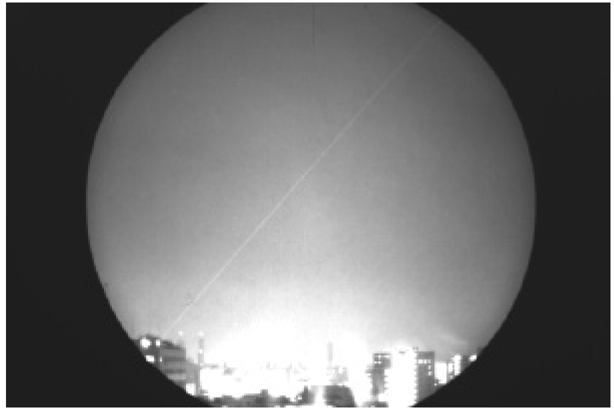
Imaging Lidar Observation – 532nm, Cross-plane

Cross-plane observation

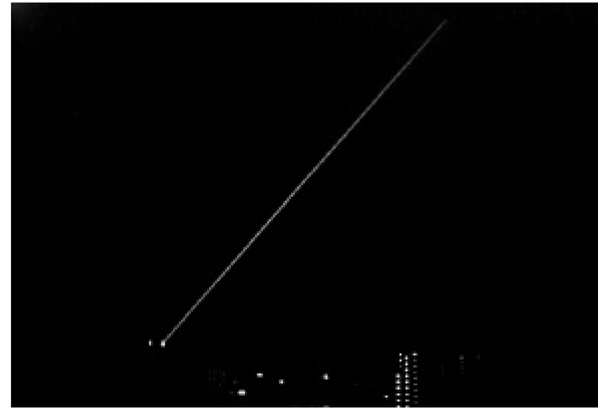


Nd:YAG Laser, 532nm
10Hz, 100mJ/pulse

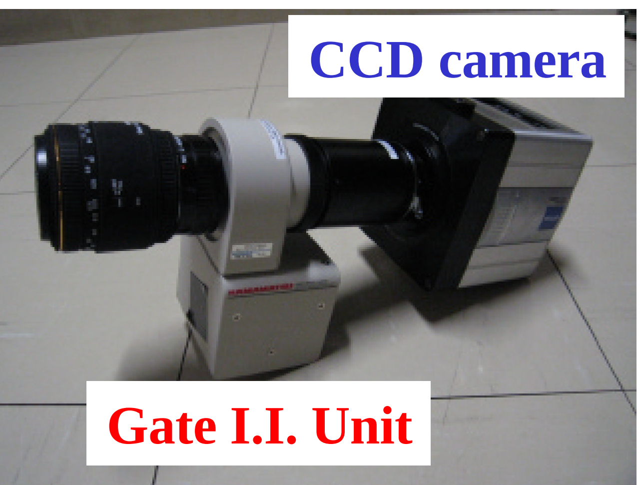
S/N Improvement with GPS 1PPS



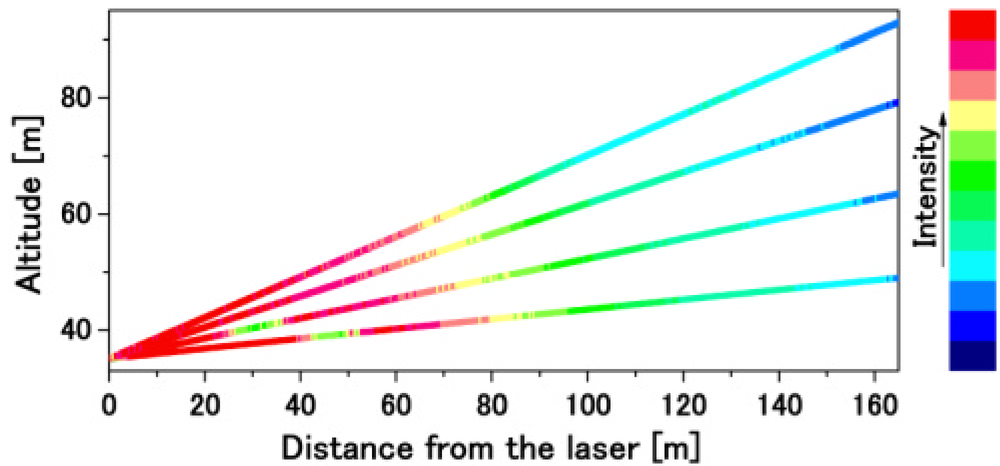
Continuous mode
(without gating)



Gated mode
Exposure time 2 s
Gate width 250 ms

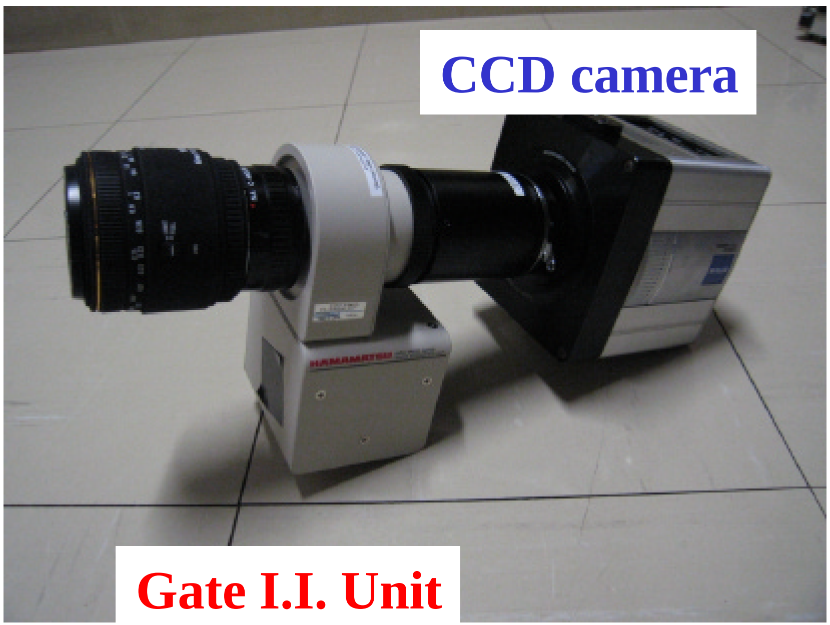


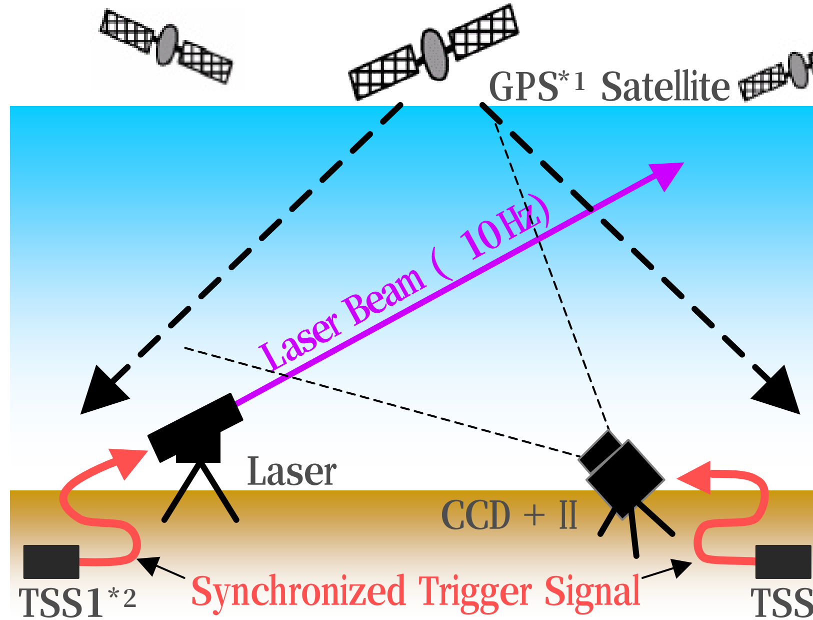
※ I.I. : Image Intensifier



GPS trigger synchronization system

Trigger synchronization system (TSS) has been developed to improve S/N by applying the GPS 1 PPS (pulse-per-second) system. Gating operation of I.I. is synchronized to the laser pulse emission with **the accuracy of approx. ±1 ms** (gate time > a few tens of ms).



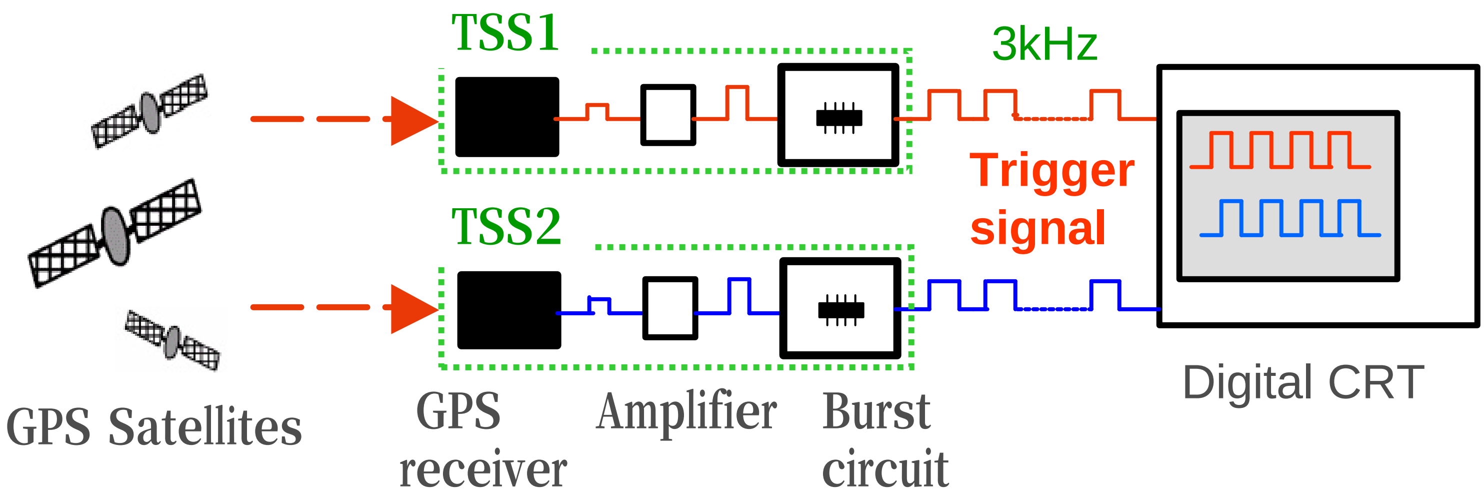


Fast-Gate Image Intensifier Unit

HAMAMATSU C9547-03MOD

Gate time	10ns～DC
Max. Gate Repetition rate	10kHz
Size of Input/Output surface	φ25mm
Wavelength range	185～900nm
MCP	1 stage
Luminous gain	1.0×10^4 (lm/m^2)・lx

Accuracy of trigger synchronization



Statistics of relative delay time between two TSS systems (10^4 pulses)

$s = \pm 0.41$ ms

This is much shorter than the gate opening duration (10 ms) for bistatic lidar measurements

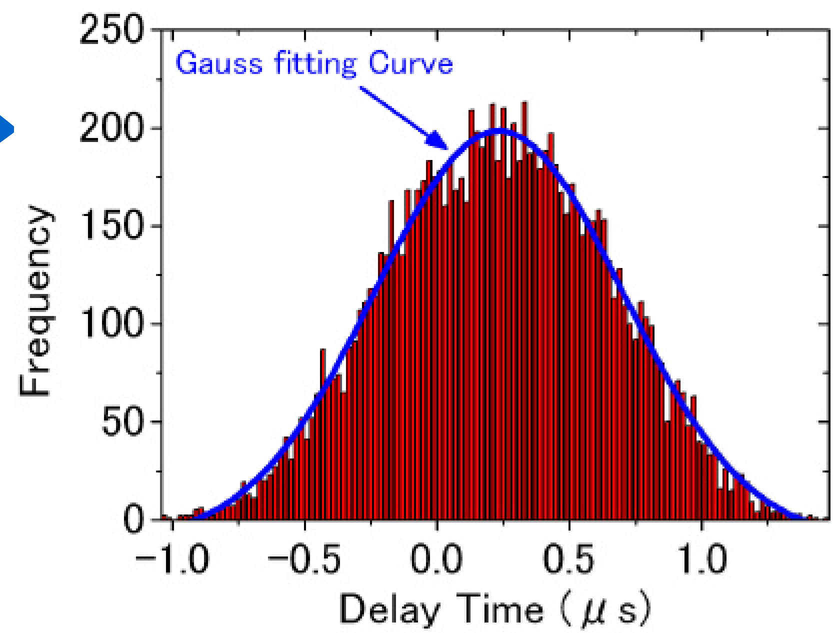
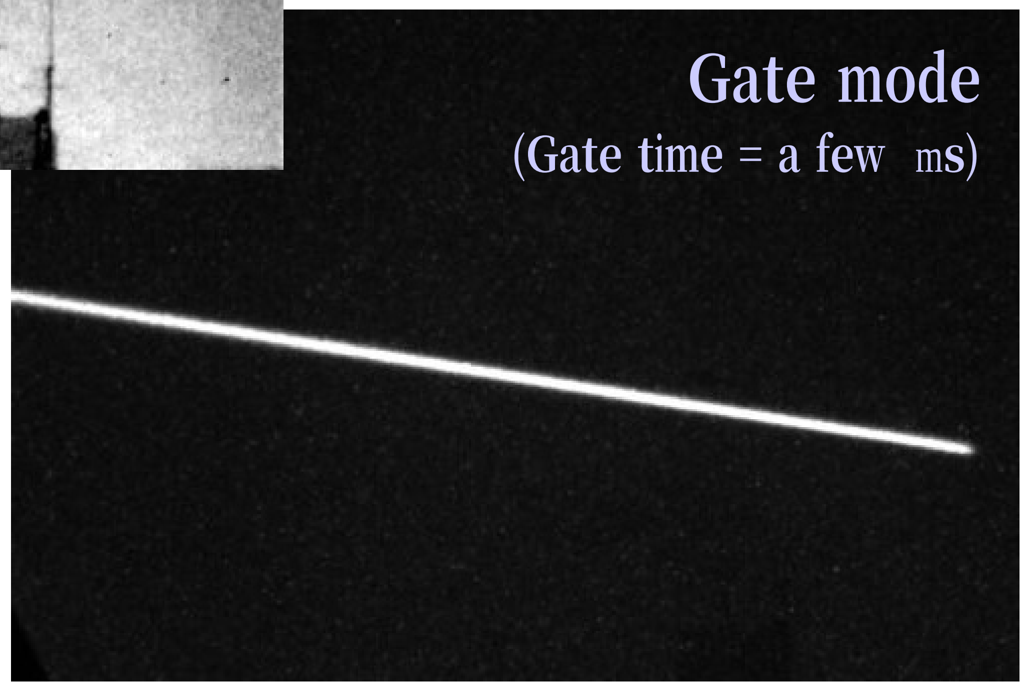


Image obtained with the gated I.I. + CCD

04/12/08
351 nm, 3 kHz
100 mJ/pulse
Exposure time = 1.0 s

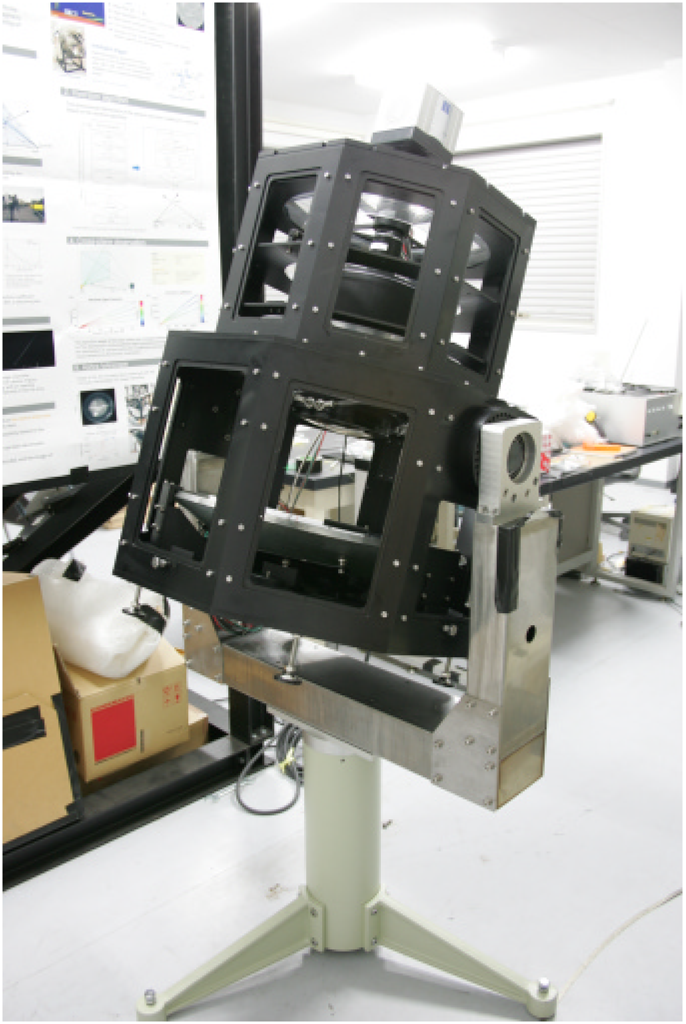
S/N = 4.2 (↑)

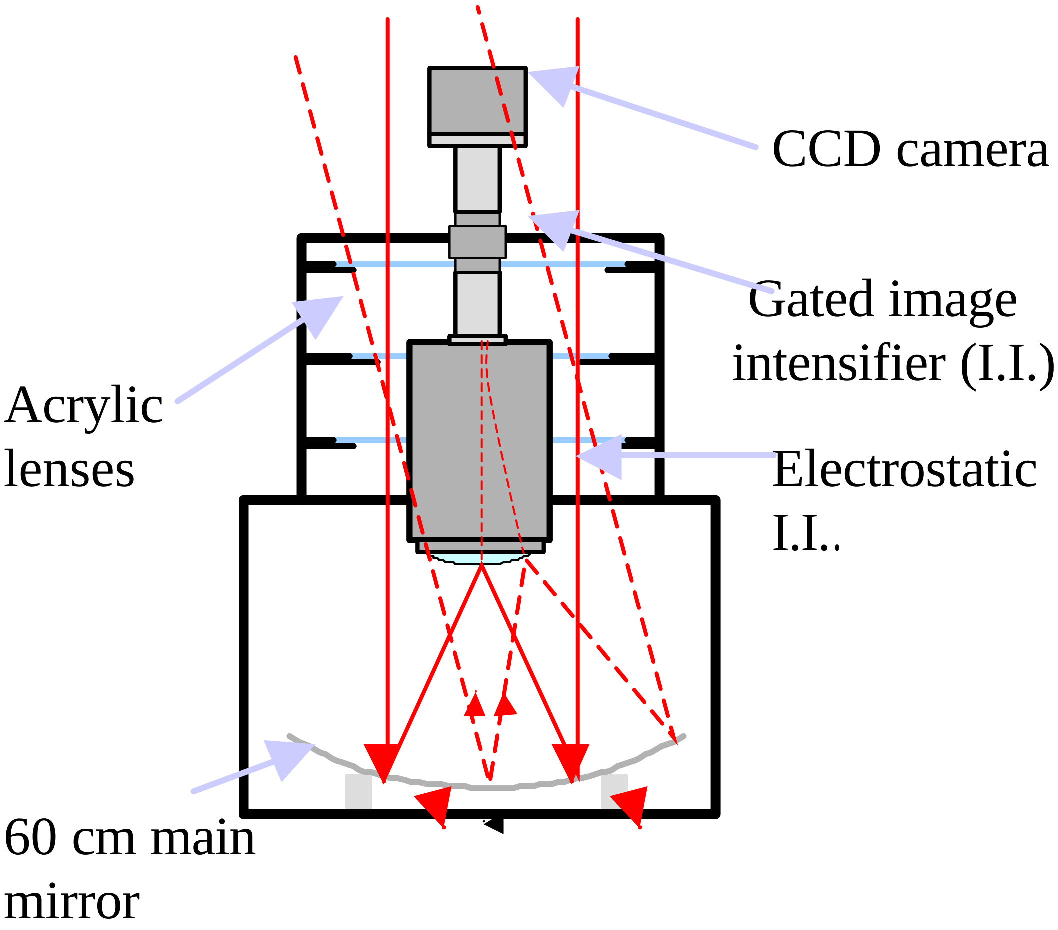


S/N = 24.8 (→)

Environmental Ashra telescope

1/3-scale Ashra telescope

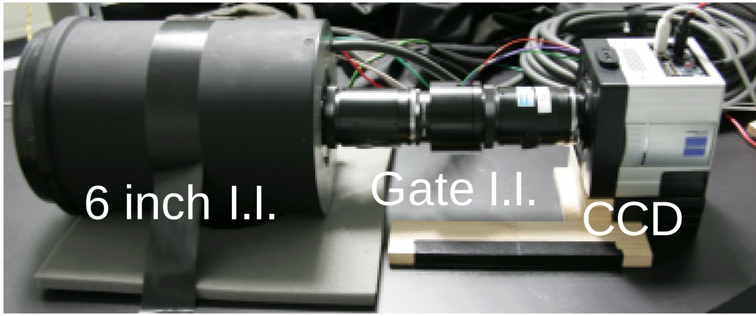


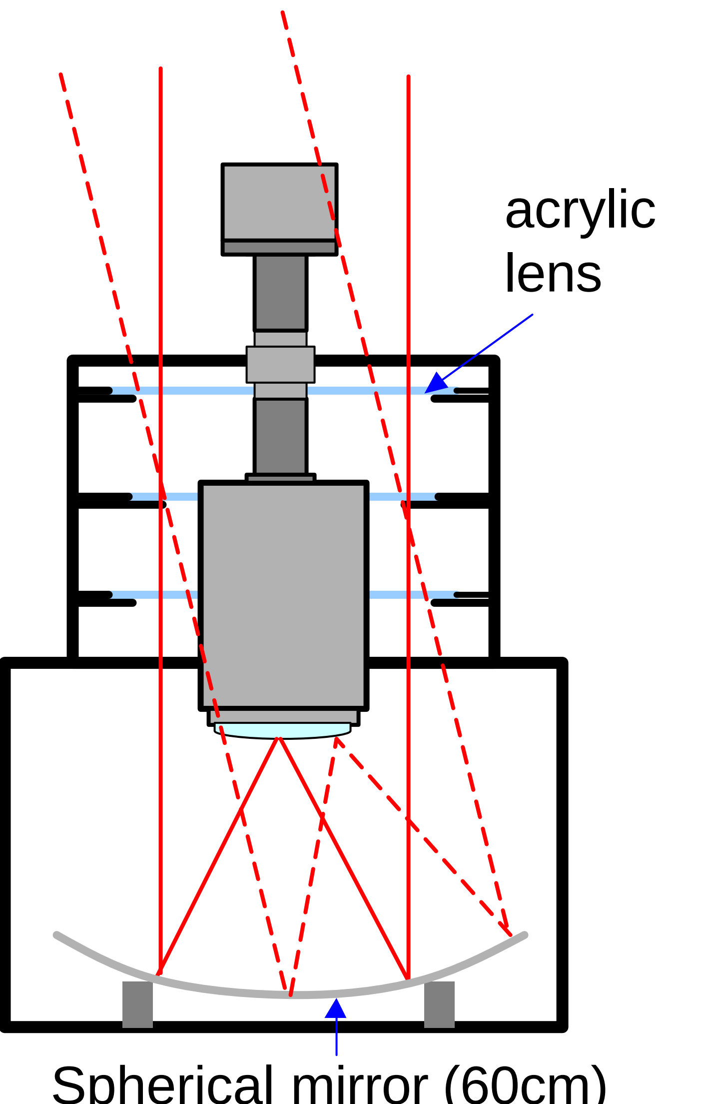


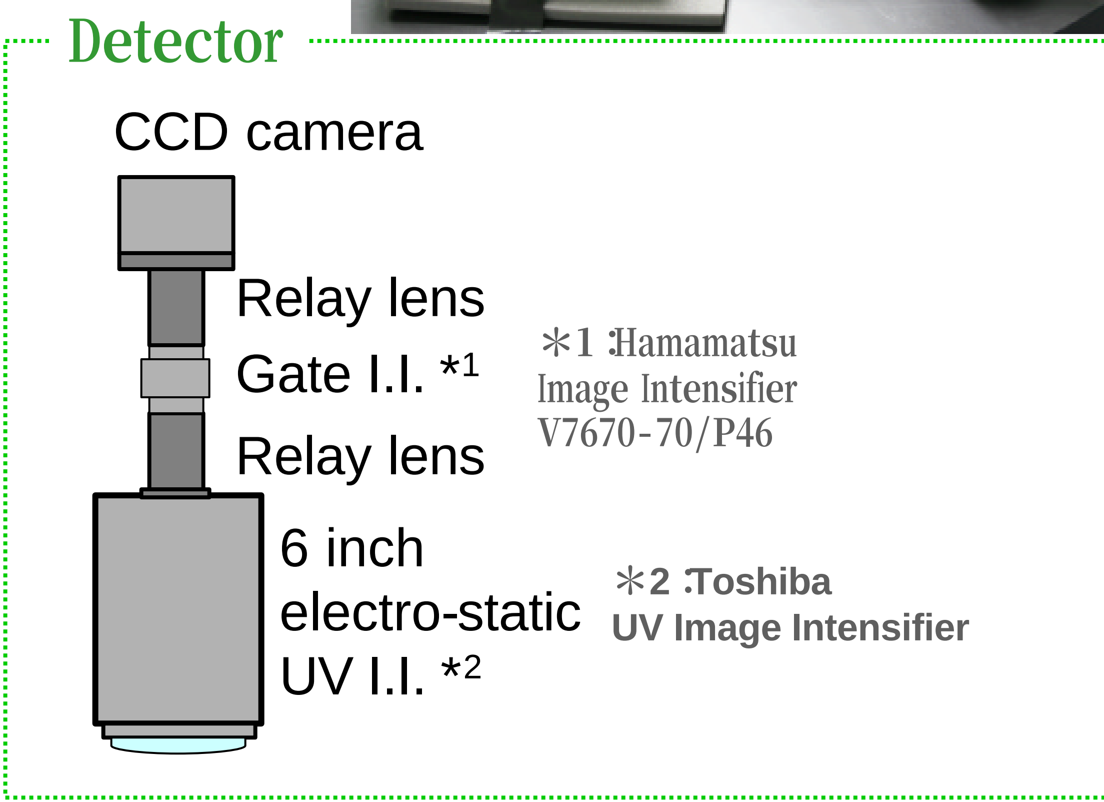
1/3 scale Ashra Telescope: configuration

Baker-Nunn optical system:

consisting of a spherical mirror with three correction lenses

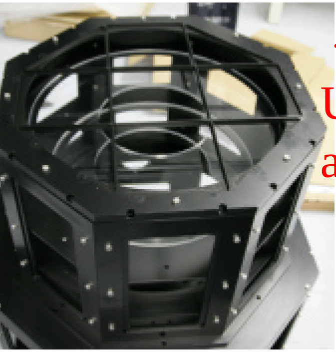




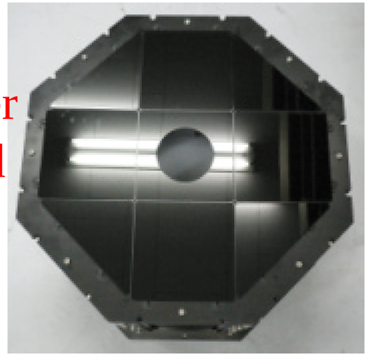


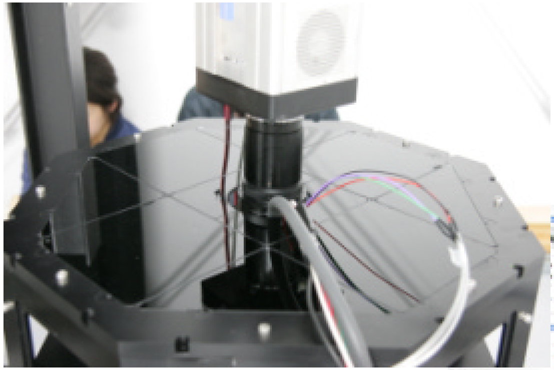
I.I. : Image Intensifier

1/3 scale Ashra Telescope: construction



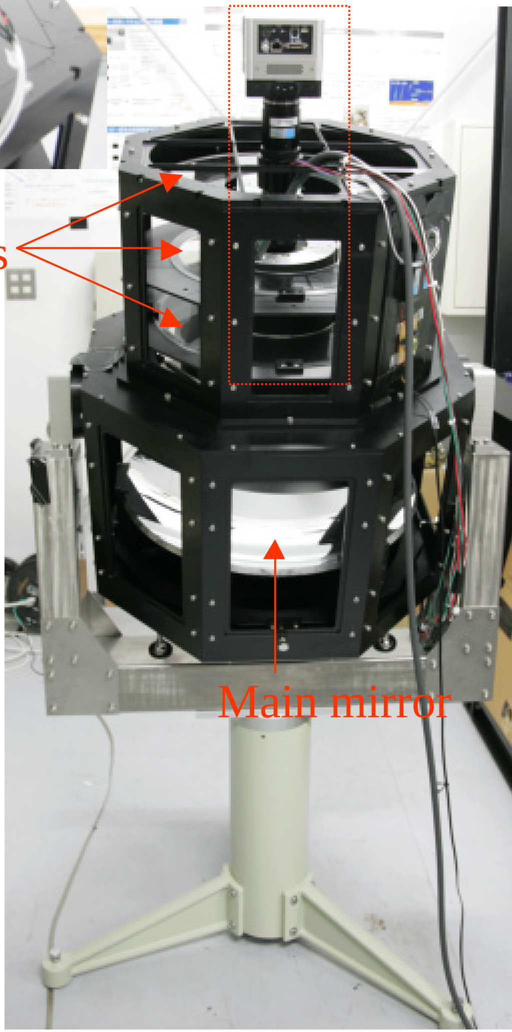
UV filter attached



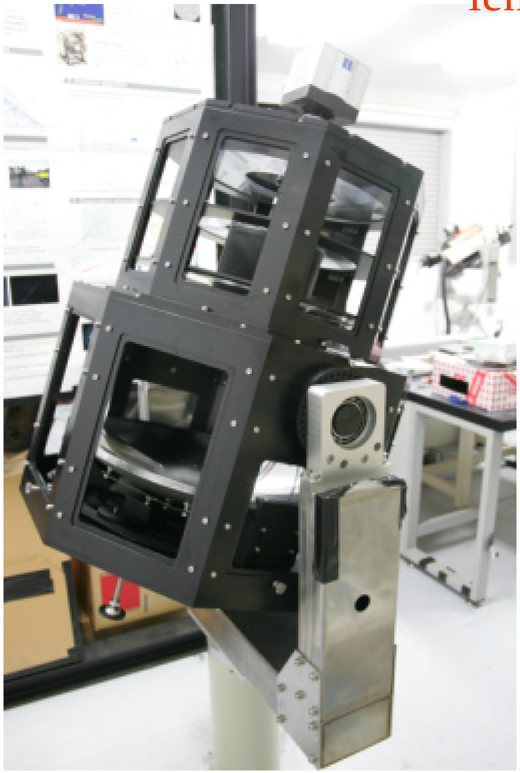


Detector

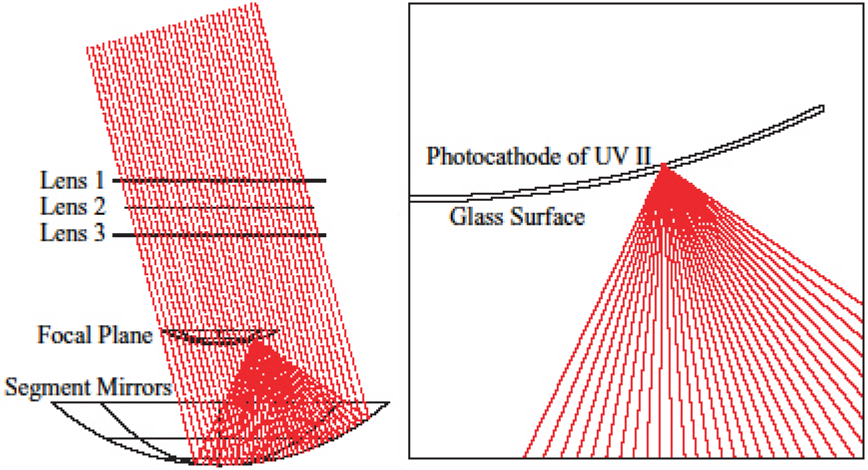
lenses



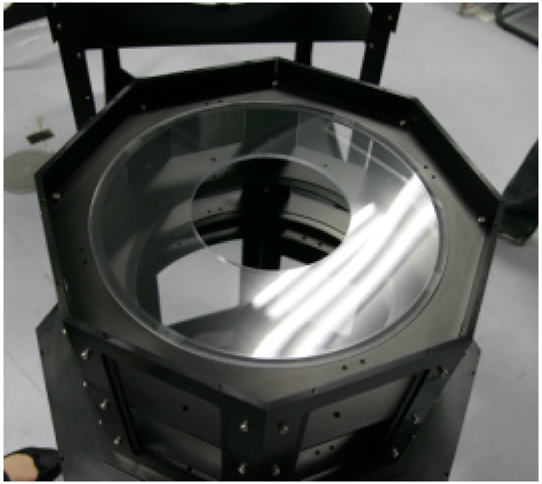
Adjustment of elevation angle

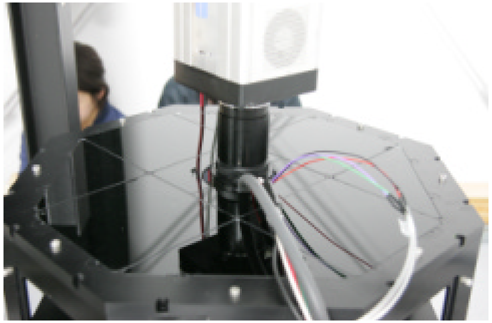


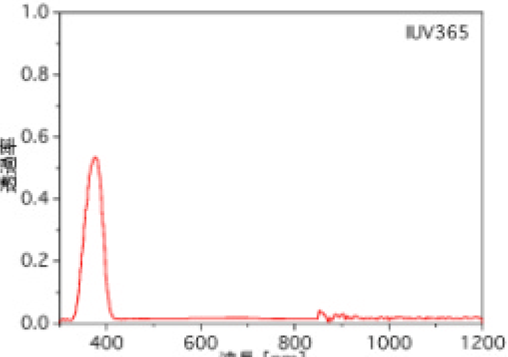
UV filter, lens, and main mirror



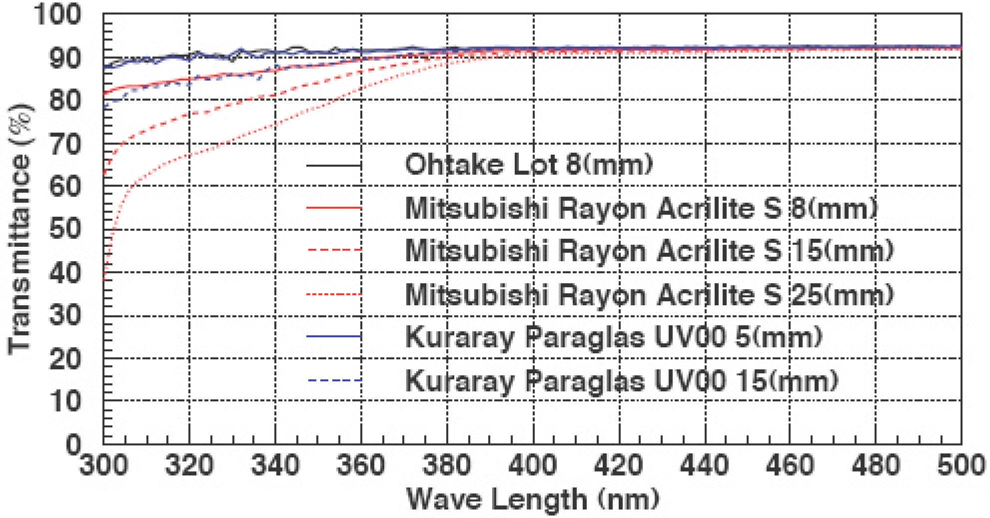
Modified Baker-Nunn optics





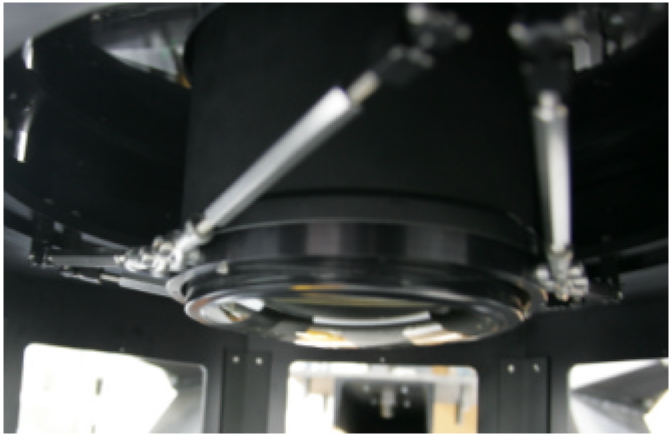


UV filter

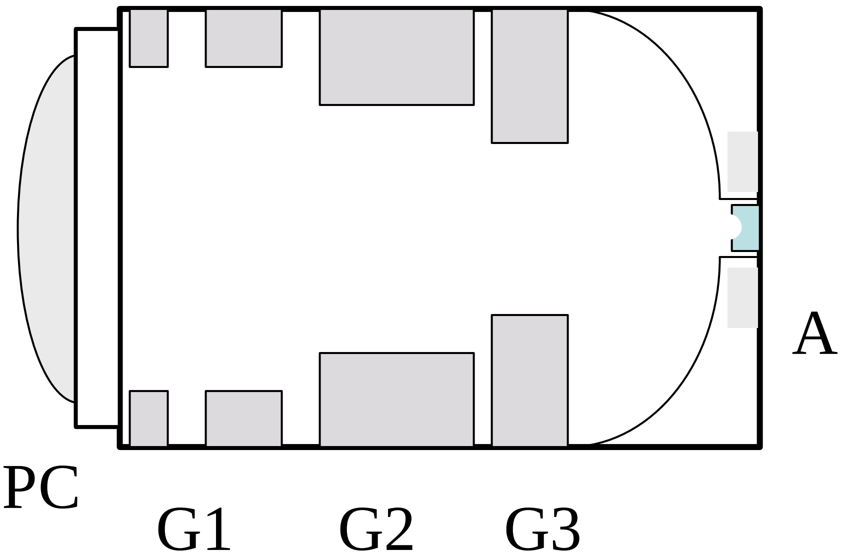


Acrylic lens

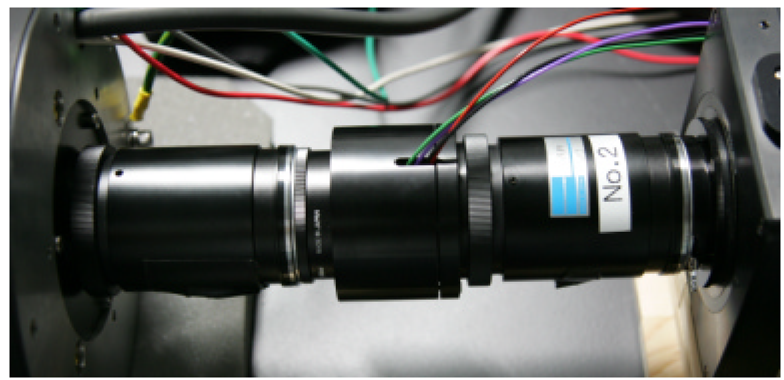
Electrostatic image intensifier



	Voltage (kV)
PC	**0**
G1	**0.342**
G2	**1.527**
G3	**11.07**
A	**30.3**

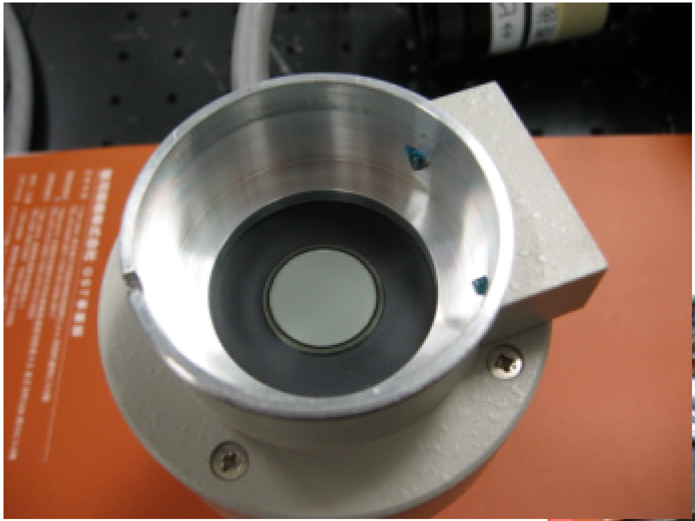


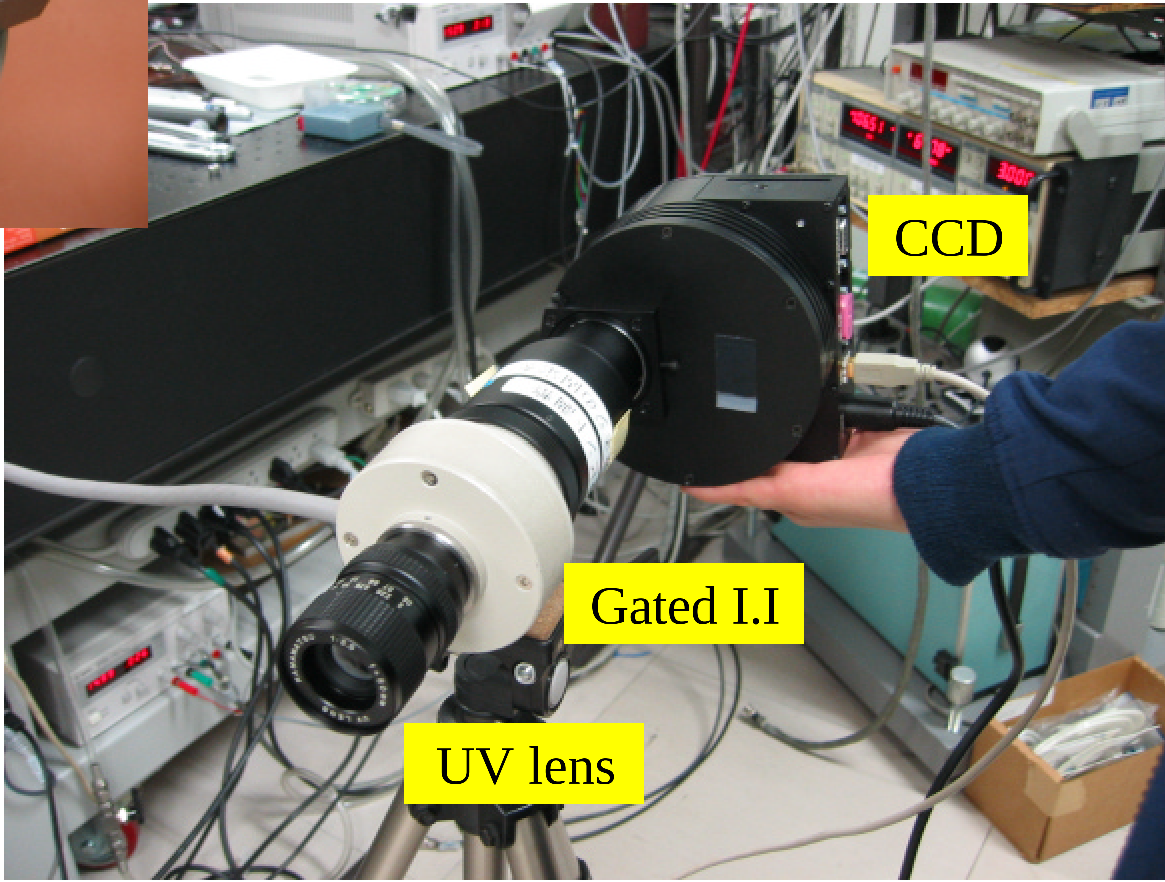
6-inch image intensifier



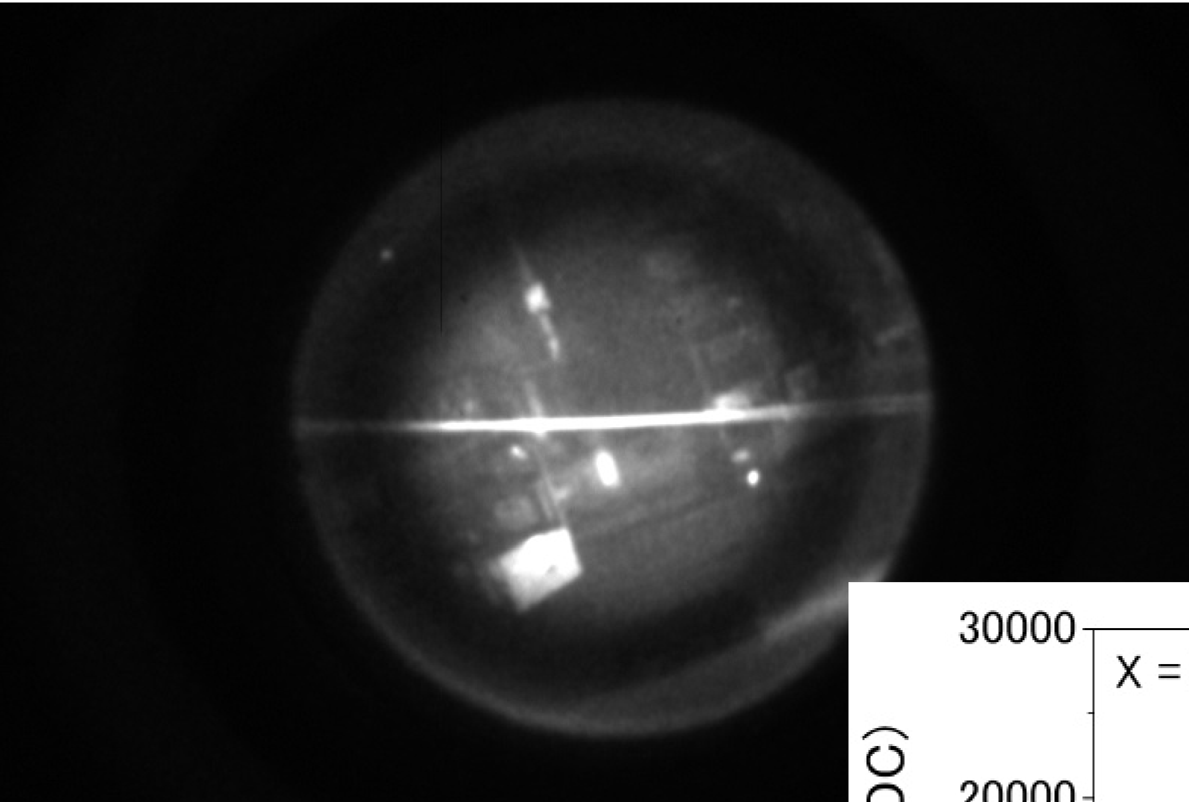
ES I.I. Gate I.I. CCD camera

Test system for UV laser light detection



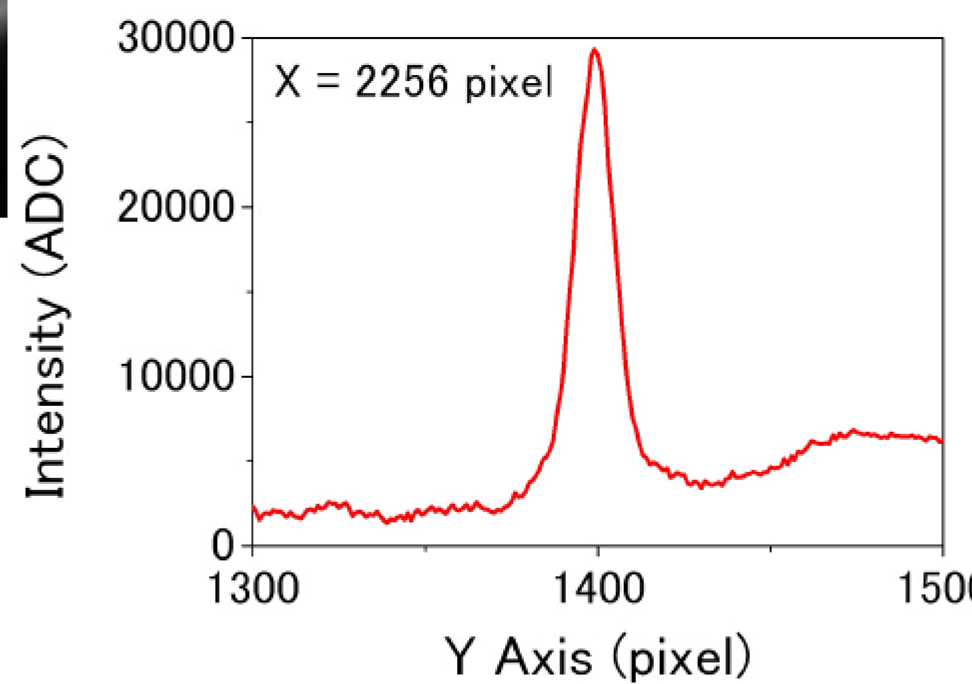


First observation of the UV laser beam



S/N = 136

(@ X = 2256 px)



Detector: UV II + gate II + CCD

Exposure: 1.0 s

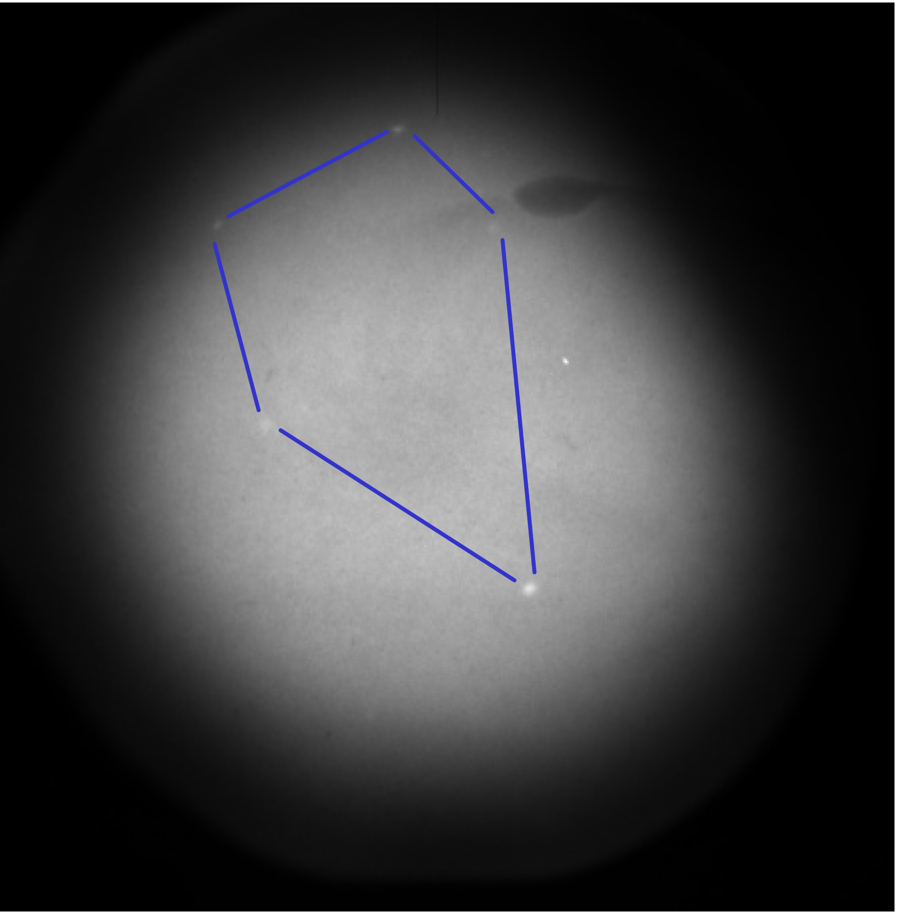
Laser output: 60 mJ/pulse, 3 kHz

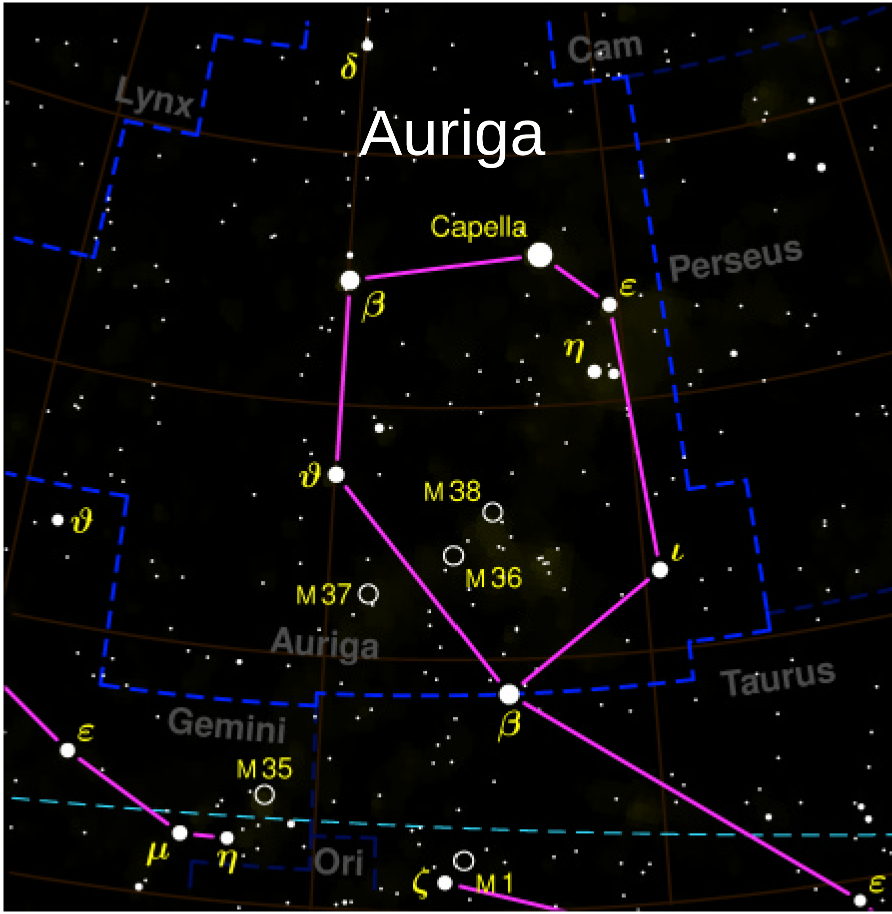
Gate time = 5 ms

Observation of stars at CEReS site

2007/2/21 19:10

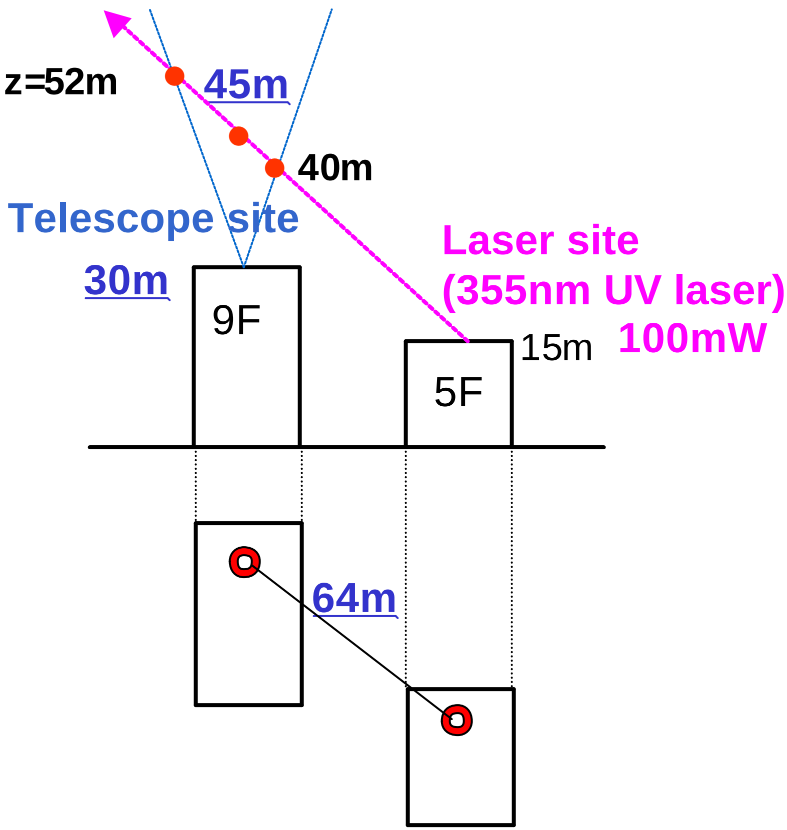
FOV= 42 deg, res=4.3 arcmin=1.3 mrad



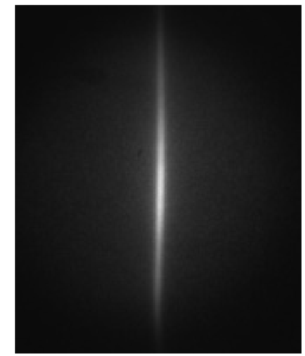


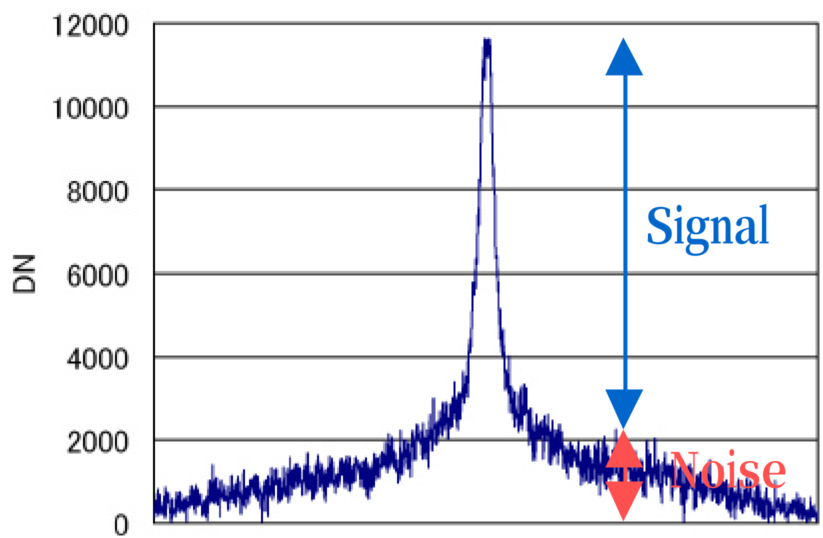
Performance of the 1/3-scale models

Configuration of the measurement



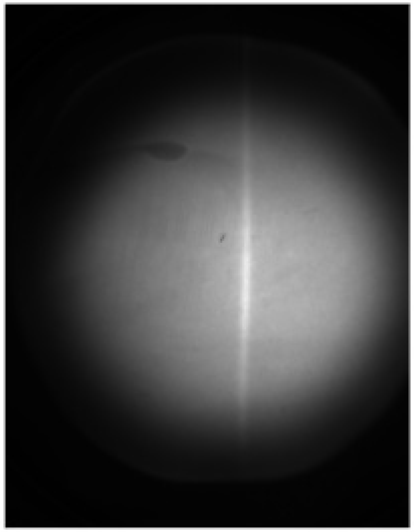
Observed image of the UV laser beam



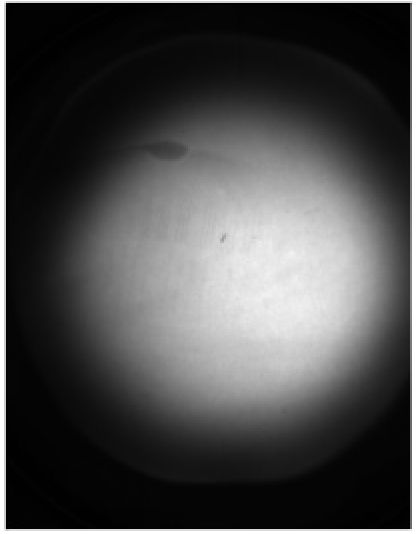


SN of UV laser beam observation

(a) Laser ON



(b) Laser OFF



Observation angle ：31 ° , Angular resolution ：3.
arcmin (1.1mrad)

Laser output energy ：10 mJ/pulse, 10 Hz

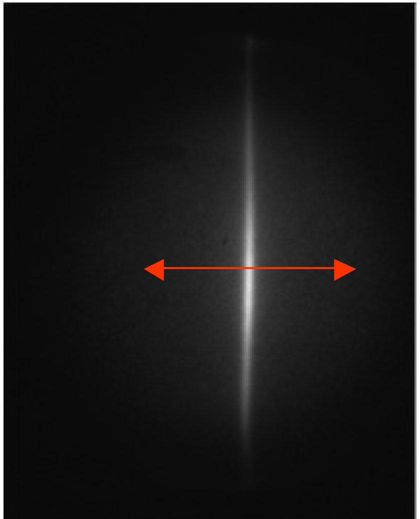
Elevation angle ：35 deg

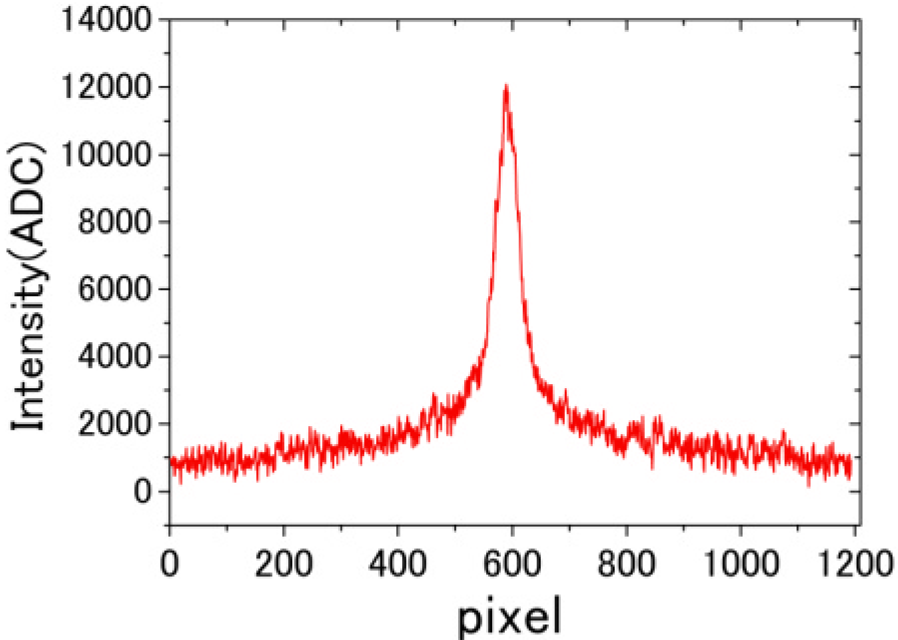
Exposure ：1 s

Gate I.I. Gain ：210 (lm/m^2)/lx
(Control voltage 7.0 V)

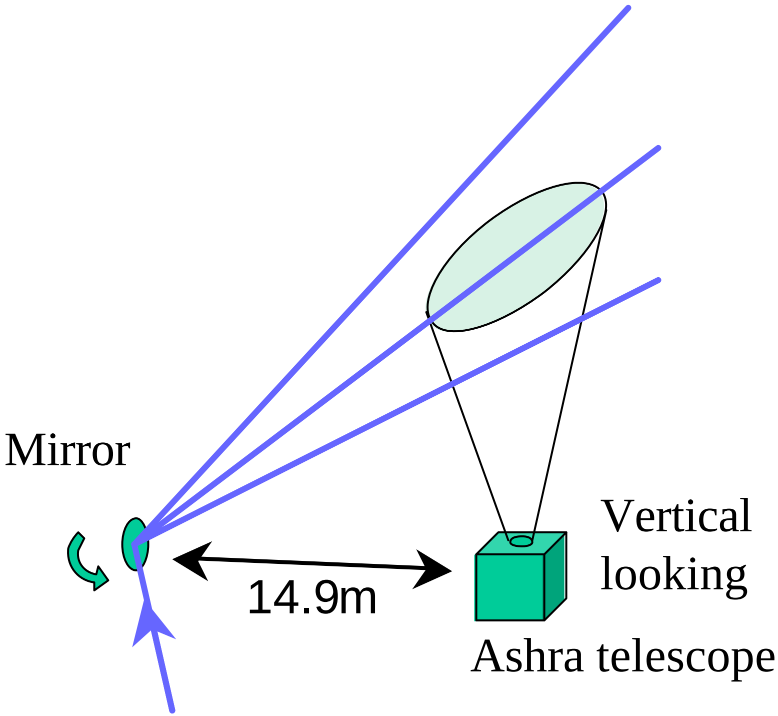
S/N = 24.1

Difference: (a) – (b)





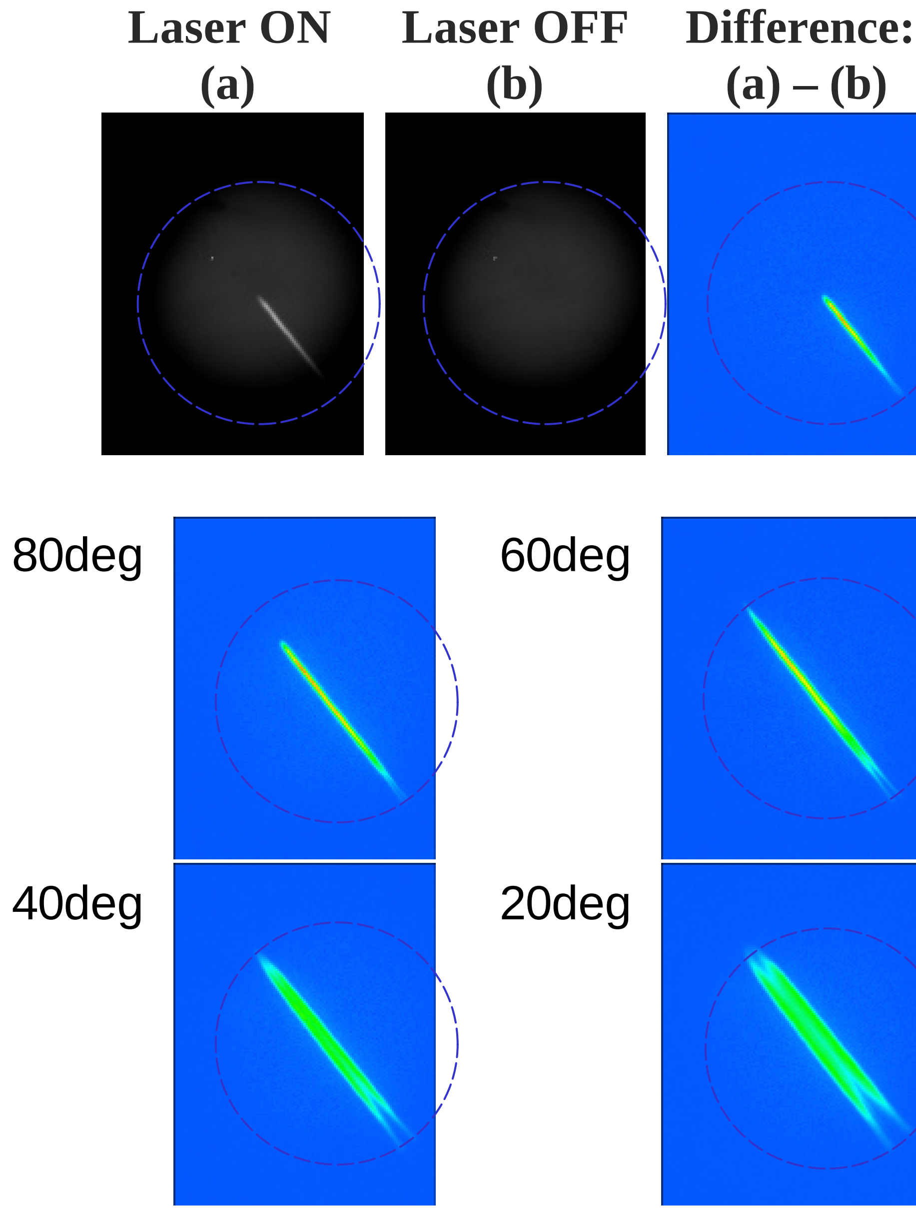
Scanning measurement (1)



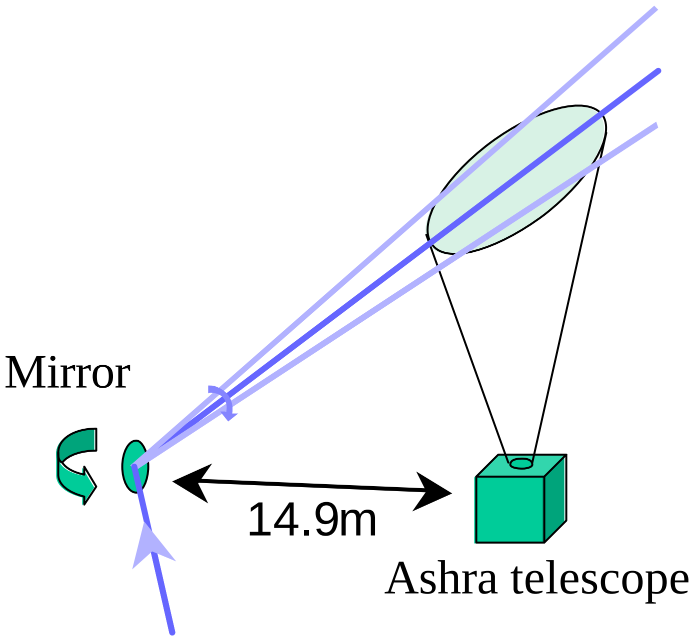
Laser : Nd:YLF DPSS Laser
351nm, 3kHz, 174mW

Gate I.I. gain 7.0V

Exposure: 1 s

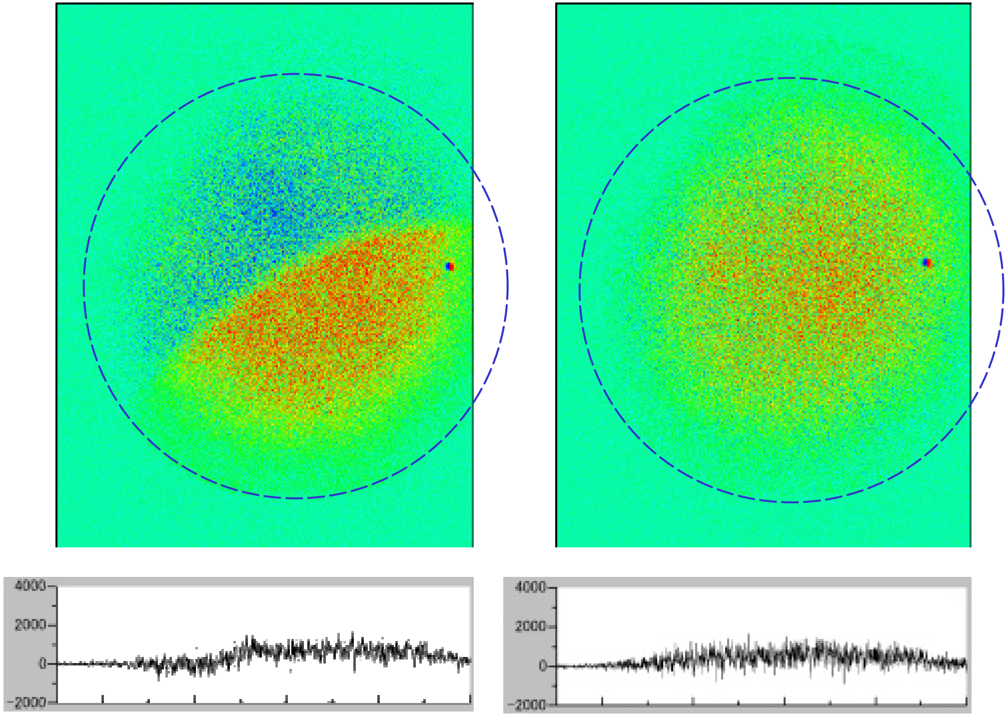


Scanning measurement (2)



Laser beam elevation: 85 deg

60deg



Laser : Nd:YLF DPSS Laser
351nm, 3kHz, 174mW

Gate I.I. gain 7.0V

Exposure: 10 s

2-dimensional distribution of scattered intensity

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.

- At CEReS, we are developing a Mie-scattering imaging lidar for **the two-dimensional detection of aerosol particles.** After completing the assembly of the 1/3-scale Ashra telescope, we are checking the overall performance of the system.