Aerosol Profiling by Raman Lidar in Nanjing

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LOGO

Something about aerosols
Our Lidar work
Question: why we use Raman Lidar?
Limitation of Raman Lidar
Analysis
Experiments
Conclusions

Nature disaster & pollutions



Volcano eruption



Industrial emissions



Haze and Dust



Vehicle exhaust

Aerosol: Global warming

Climate Change

Pollutions

PM10

PM2.5

Disease

People life

How to control and Suppress

Aerosol emission?

Volcano: no control



Pollutions:

1) Government

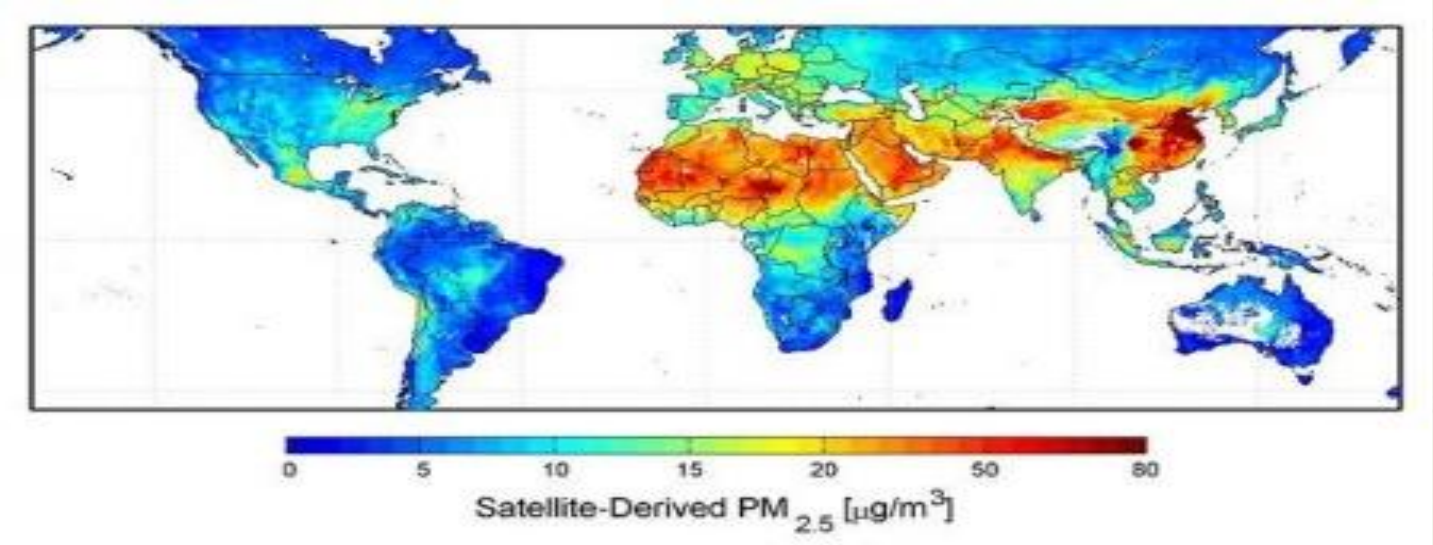
2) Atmospheric Physics & Chemistry Scientists

First step:

Measurements

◆Aerosol measurements

1.Satellite



2. Airborne survey

3. Ground-based observation

(1)Sunphotonmeter

(2)**Lidar(Profile, Resolution, accuracy,convenient)**



What is the Situation in Nanjing

?

What can the lidar measure ?













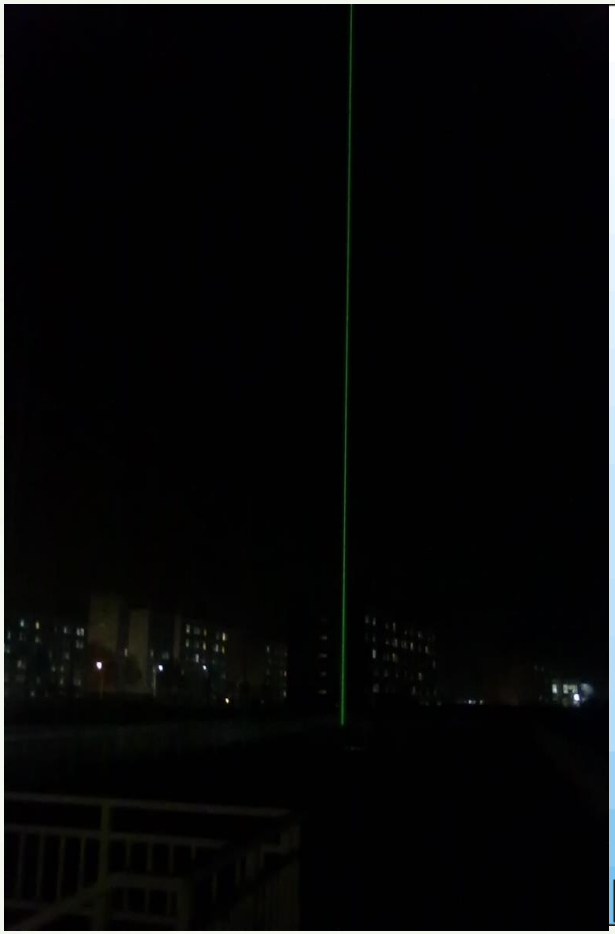


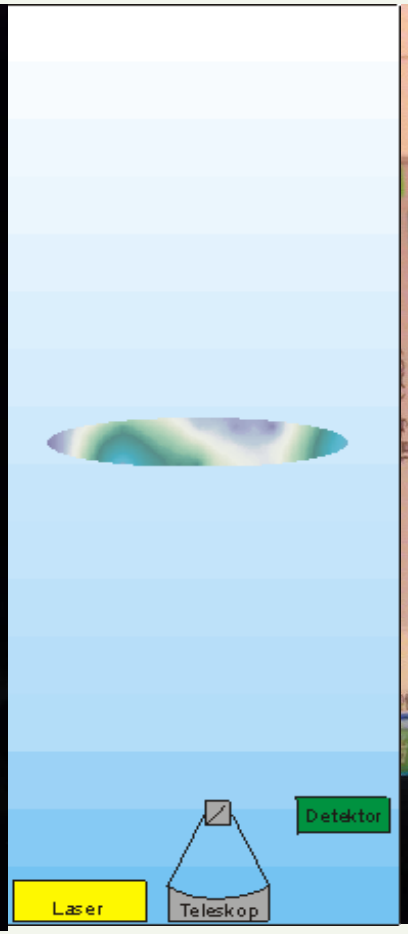


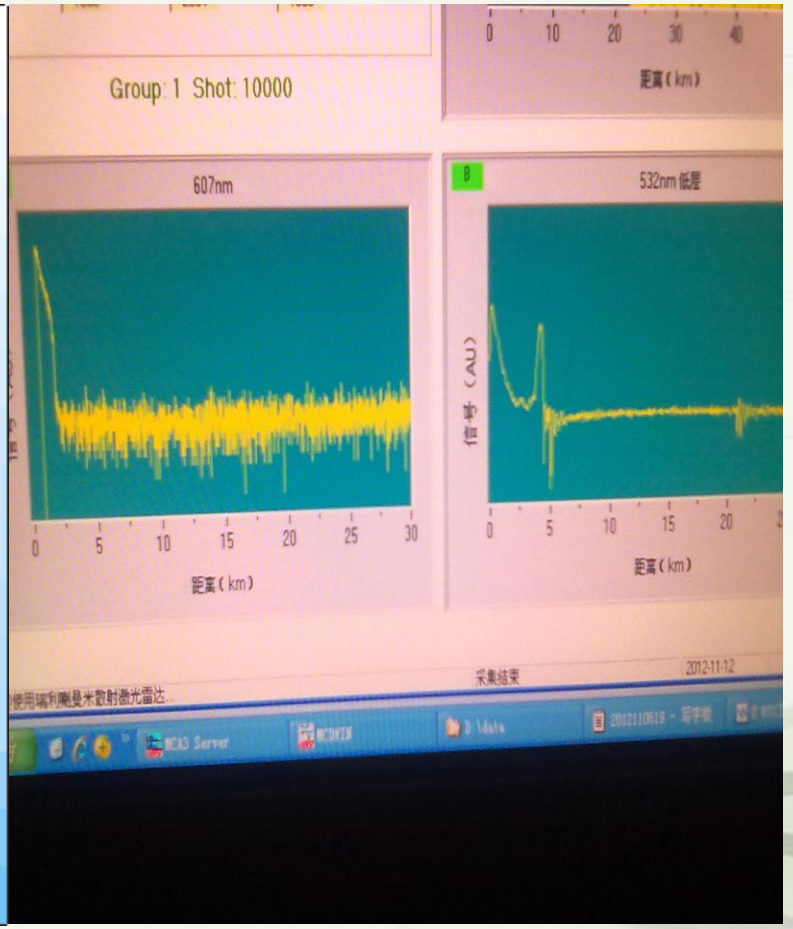


Lidar system

Ground based Raman-Rayleigh-Mie Lidar in Nanjing







Lidar system

- Mie-Rayleigh-Raman Lidar system

- Two wavelengths multi-functions
  1) Aerosol(Mie,Raman)
  2) Cloud (Mie)
  3)Temperature (Rayleigh)
  4) pollution (in the future)

Lidar system

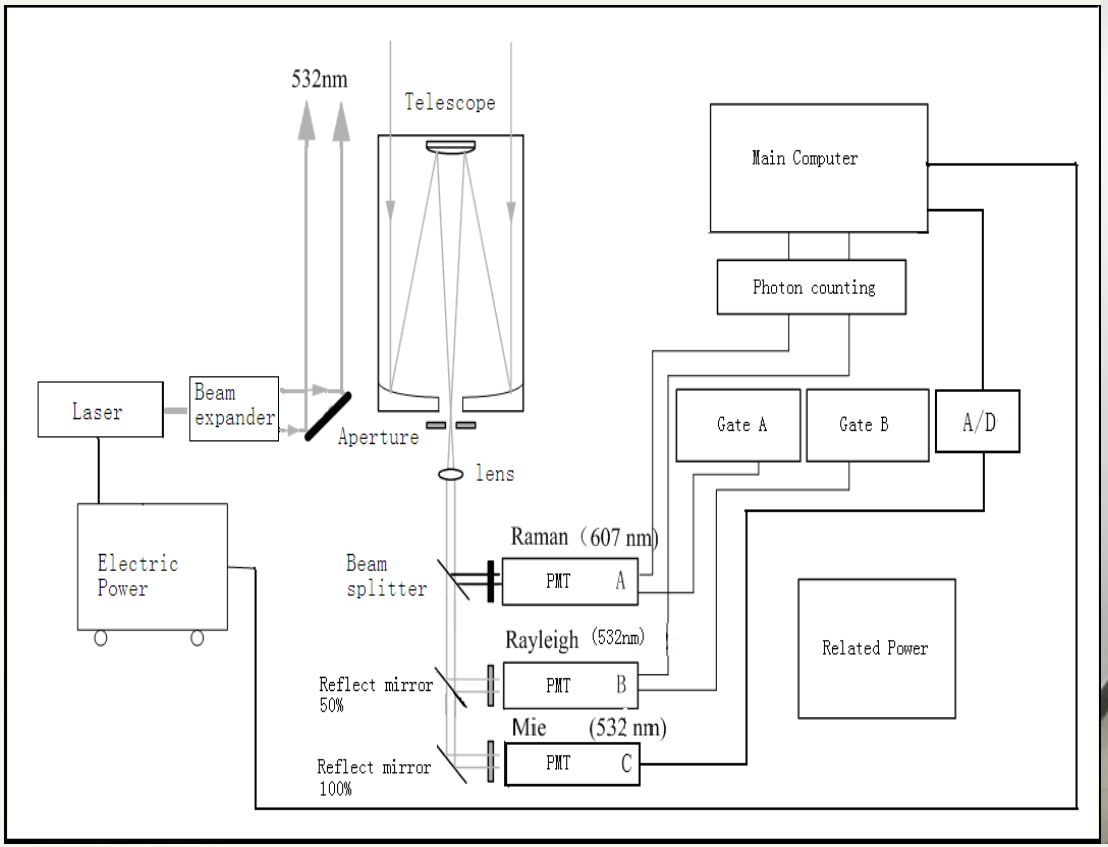
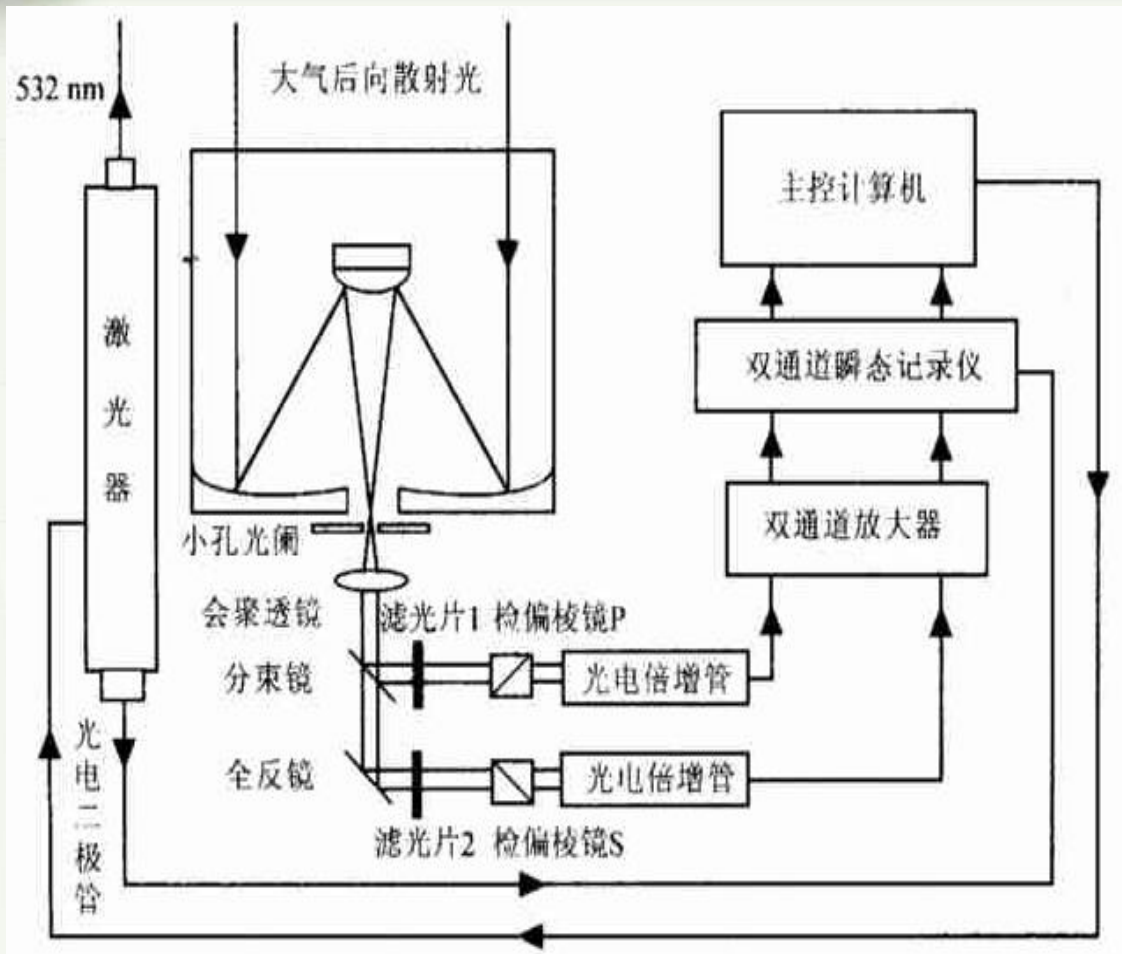


Diagram of the Lidar system



Lidar system

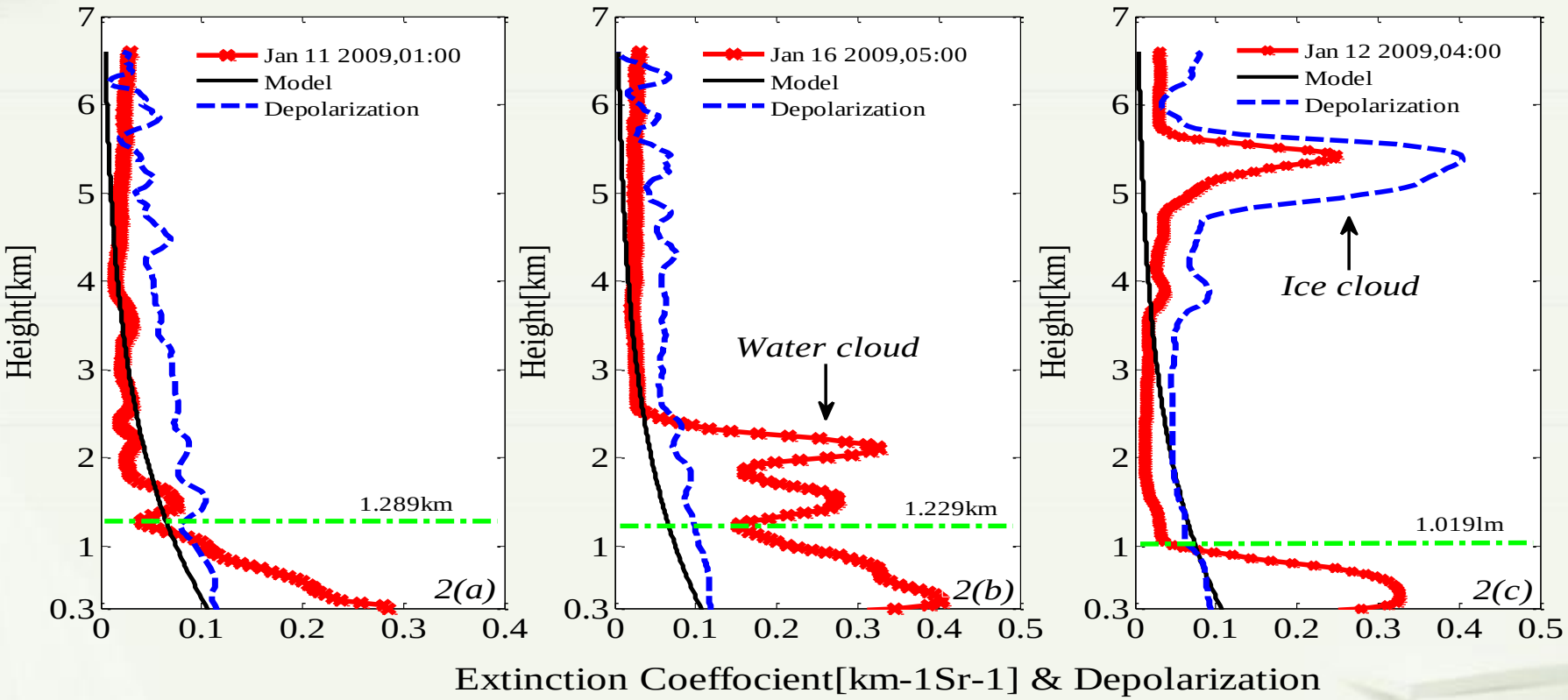
Company Logo



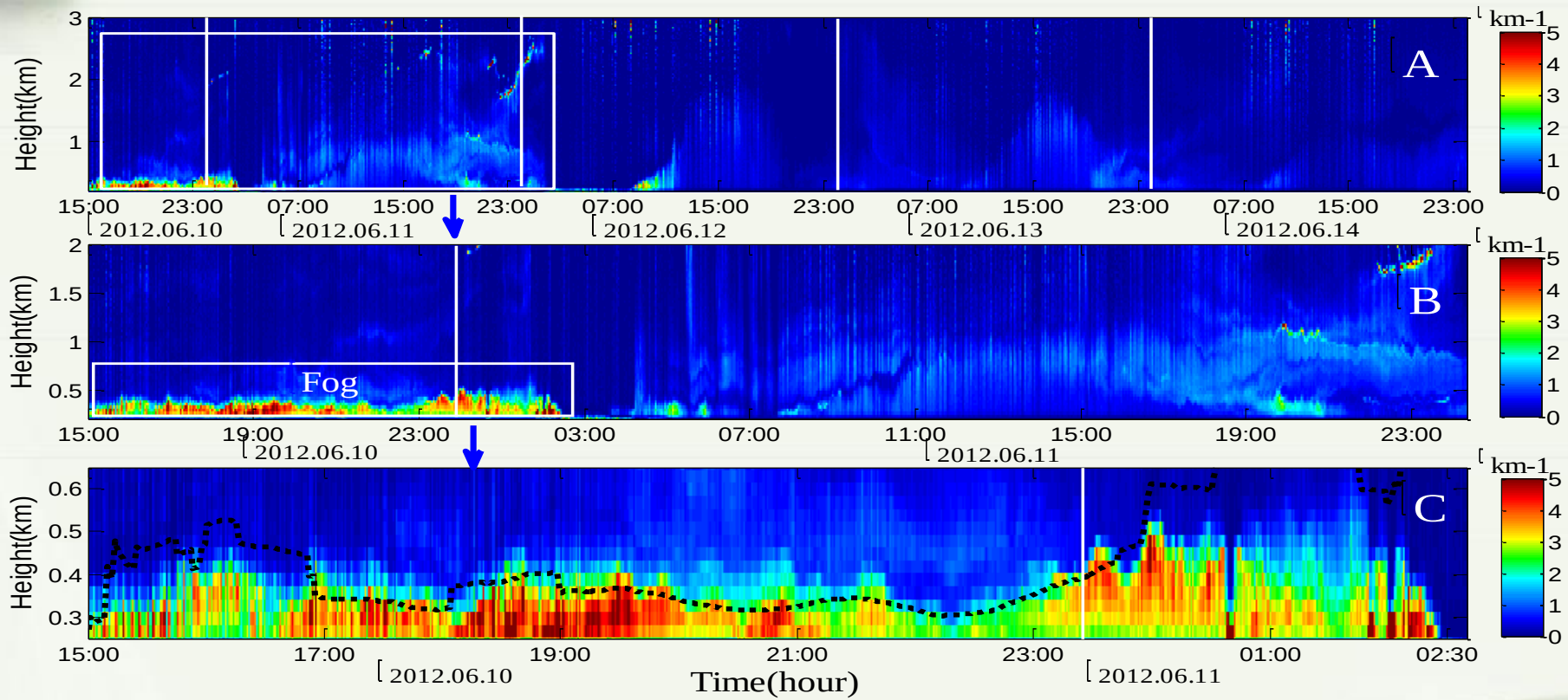
Diagram



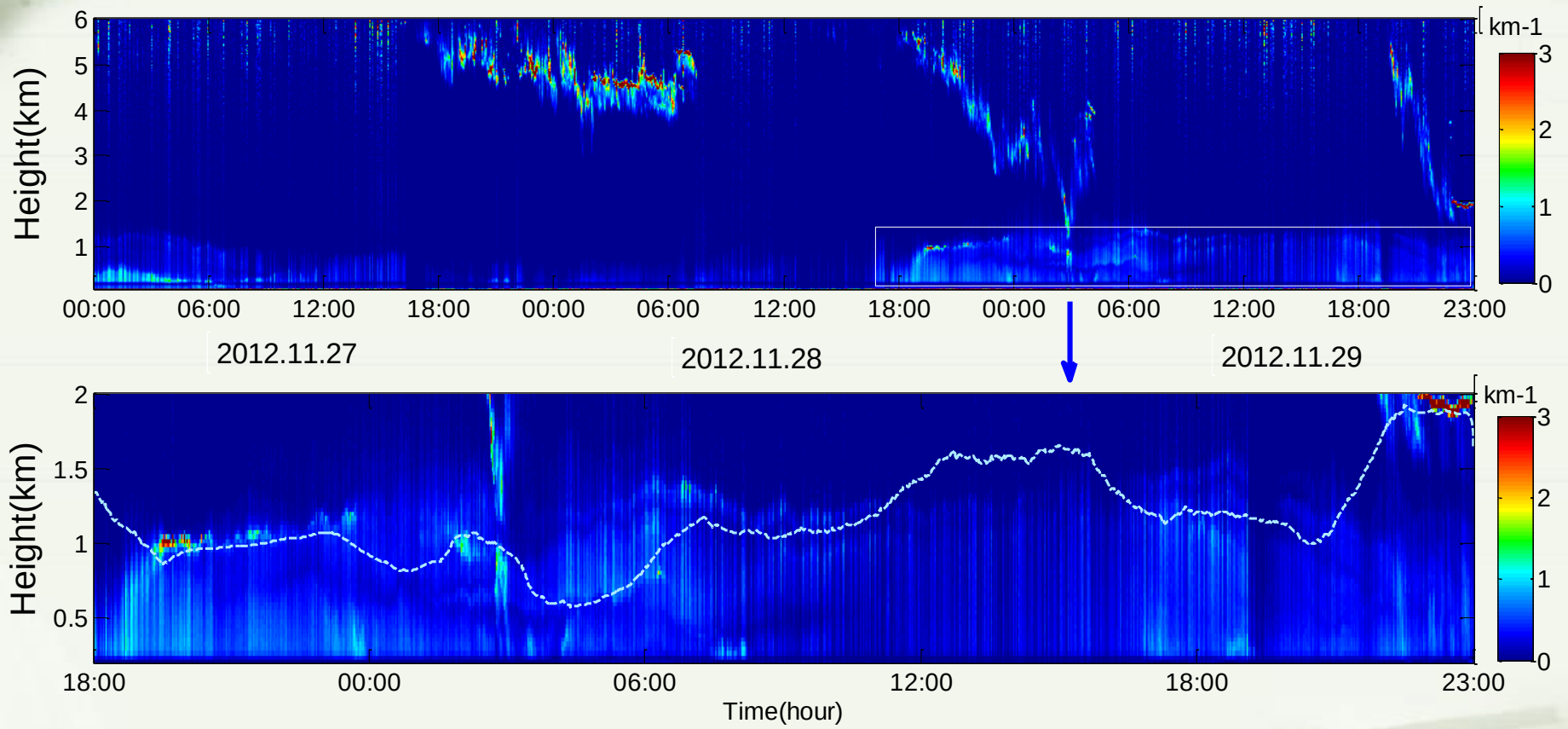
Polarization Lidar



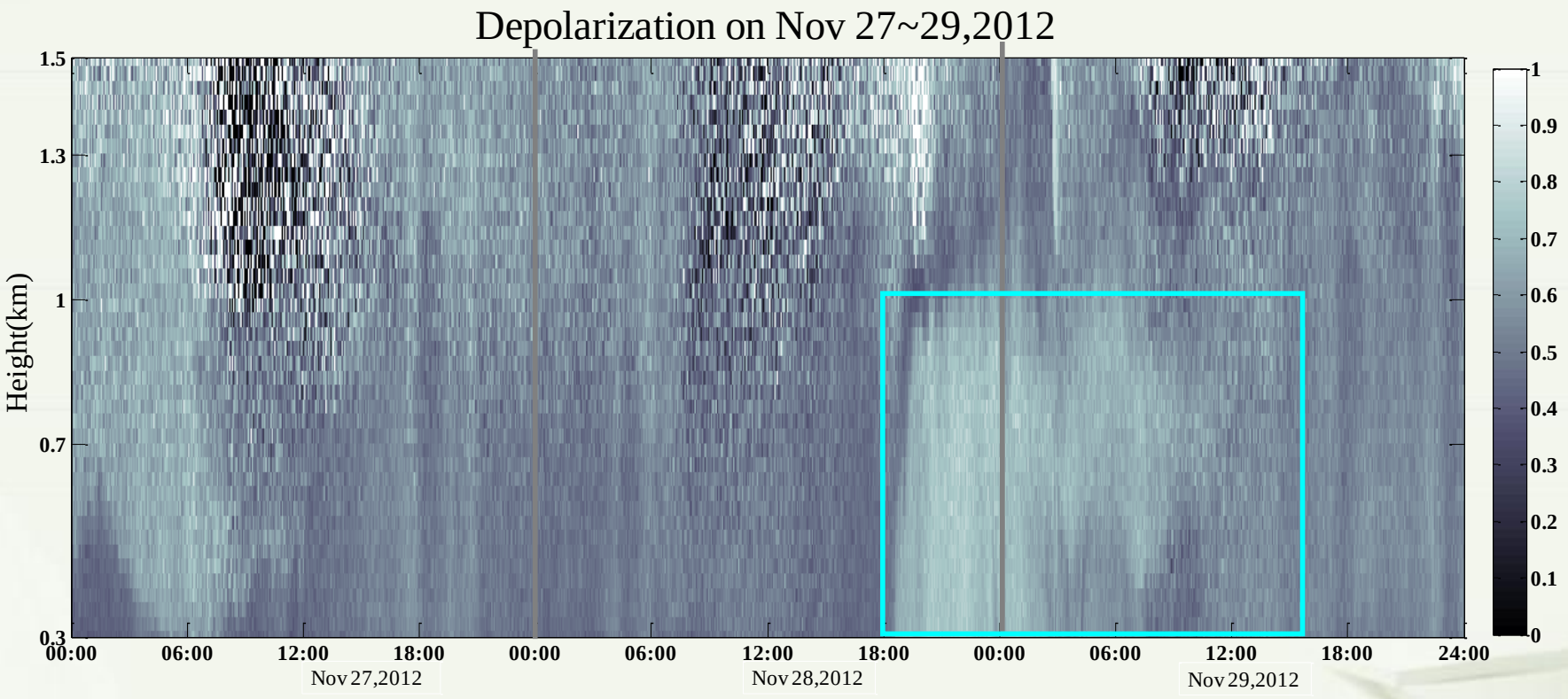
Extinction & Depolarization profile by MPL



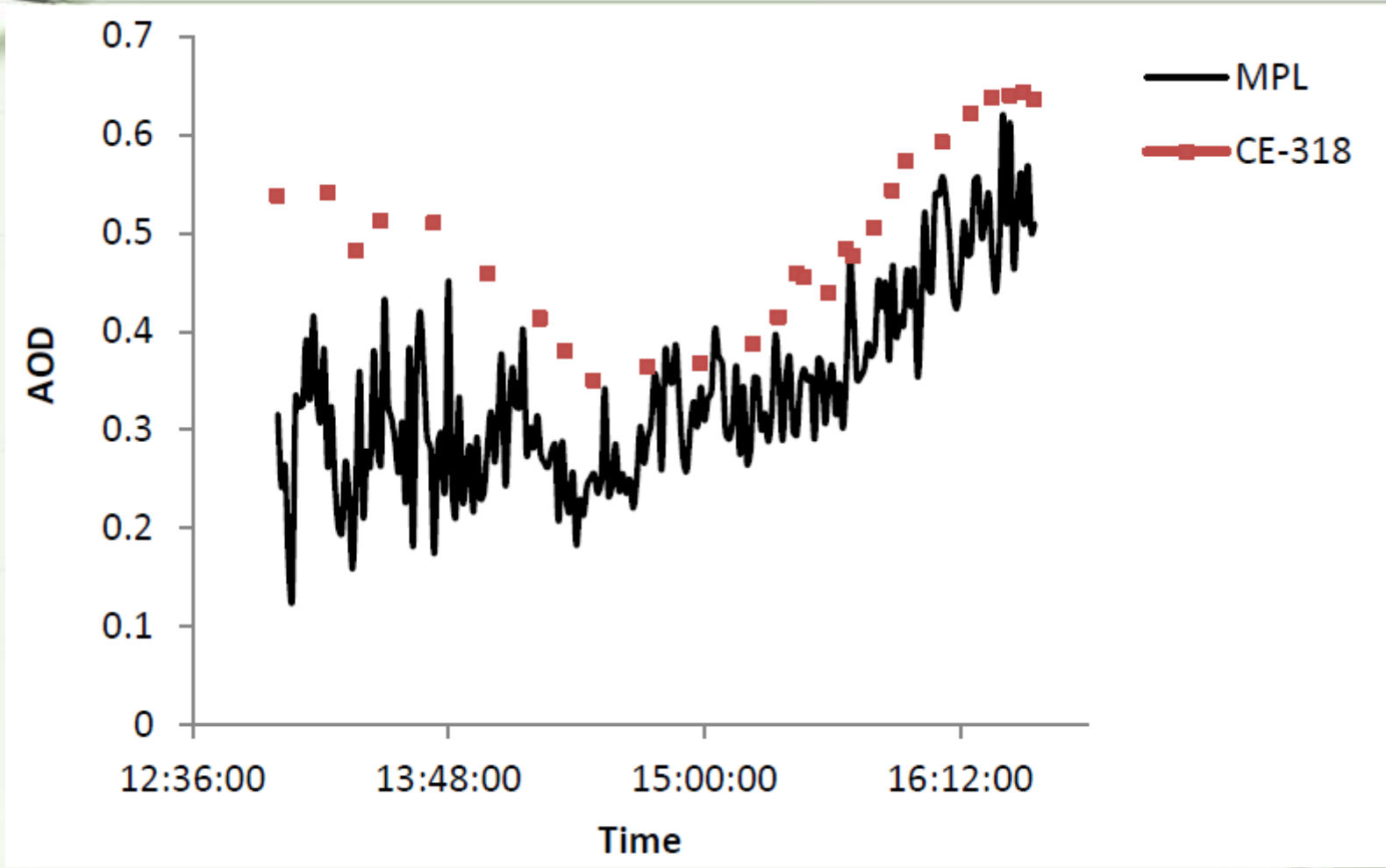
Haze & Fog measurements



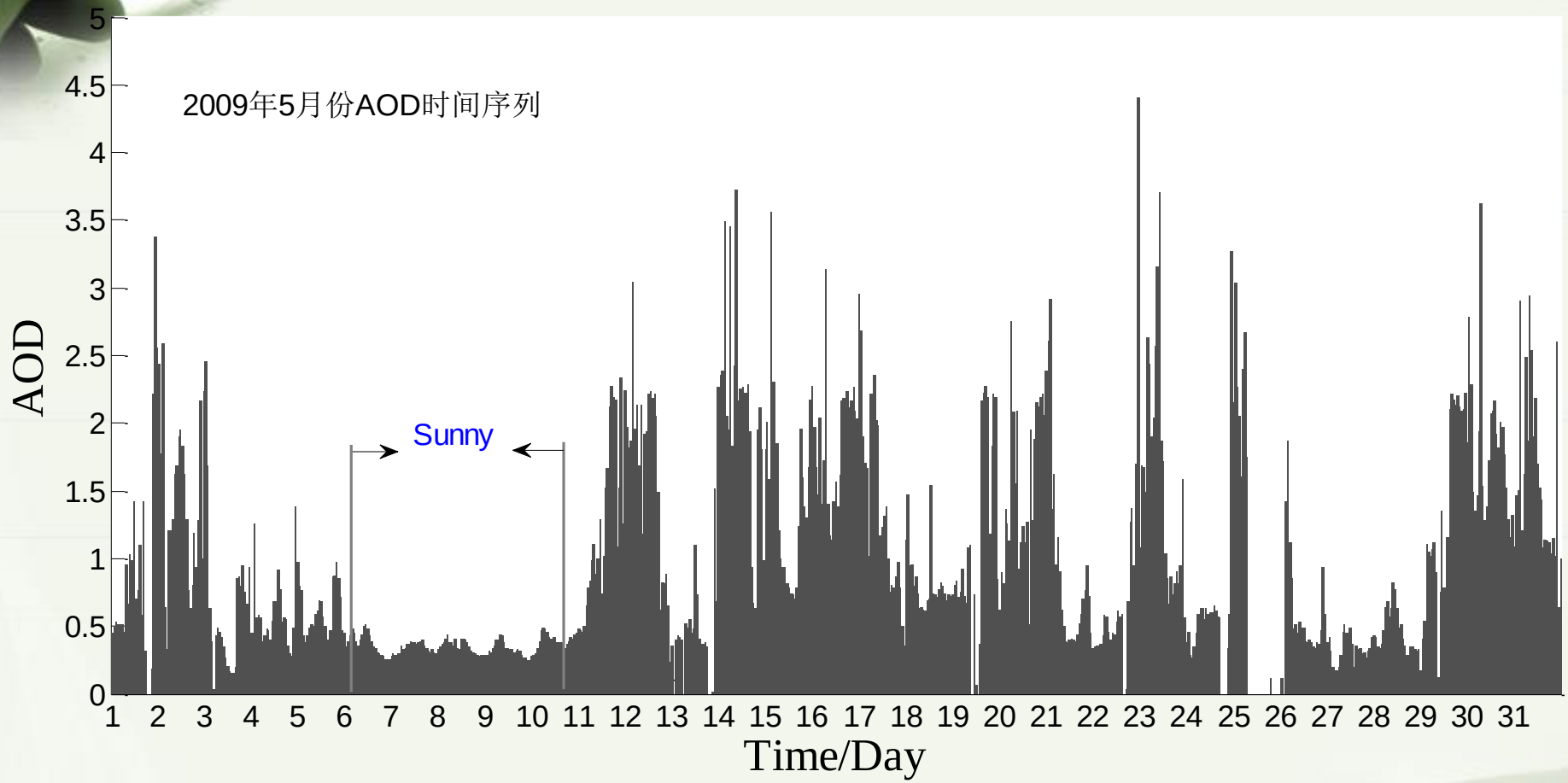
Dust measurements



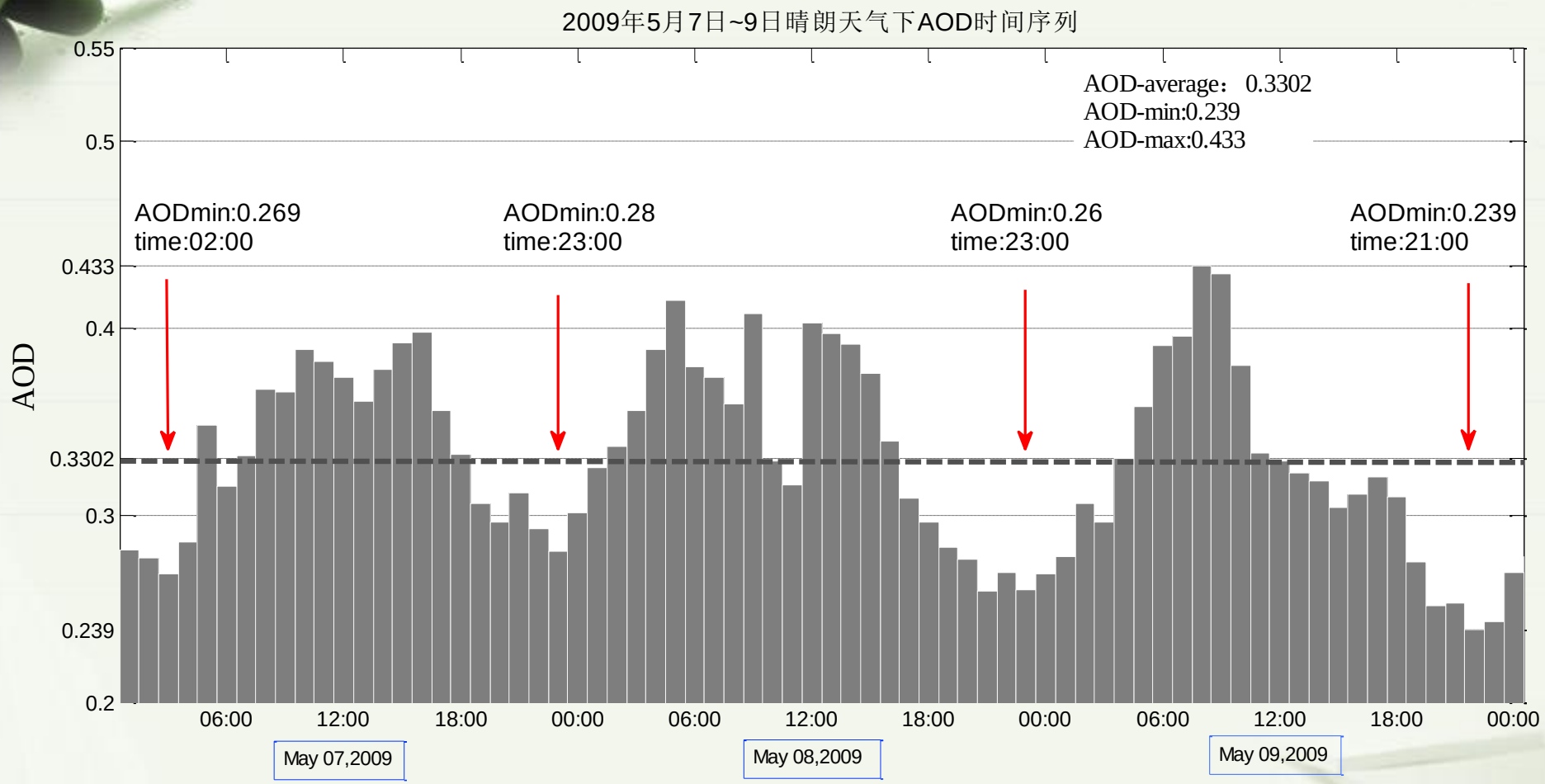
Depolarization for dust measurements



AOD comparison by MPL and sun photon meter


2009年5月份AOD时间序列
Sunny
AOD
Time/Day
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31

AOD by MPL


2009年5月7日~9日晴朗天气下AOD时间序列
AOD-average： 0.3302
AOD-min:0.239
AOD-max:0.433
AODmin:0.269
time:02:00
AODmin:0.28
time:23:00
AODmin:0.26
time:23:00
AODmin:0.239
time:21:00
AOD
0.55
0.5
0.433
0.4
0.3302
0.3
0.239
0.2
06:00
12:00
18:00
00:00
06:00
12:00
18:00
00:00
06:00
12:00
18:00
00:00
May 07,2009
May 08,2009
May 09,2009

AOD by MPL



Moon image taken at 20:00 on 2011/12/10
(fine)
scattering is small

Moon image taken at 17:00 on 2012/2/4
(fog)
forward and around scattering is big
backscattering is small

The first 6 graph are much smaller than others on last page because the former represents of fog which has small backscatter

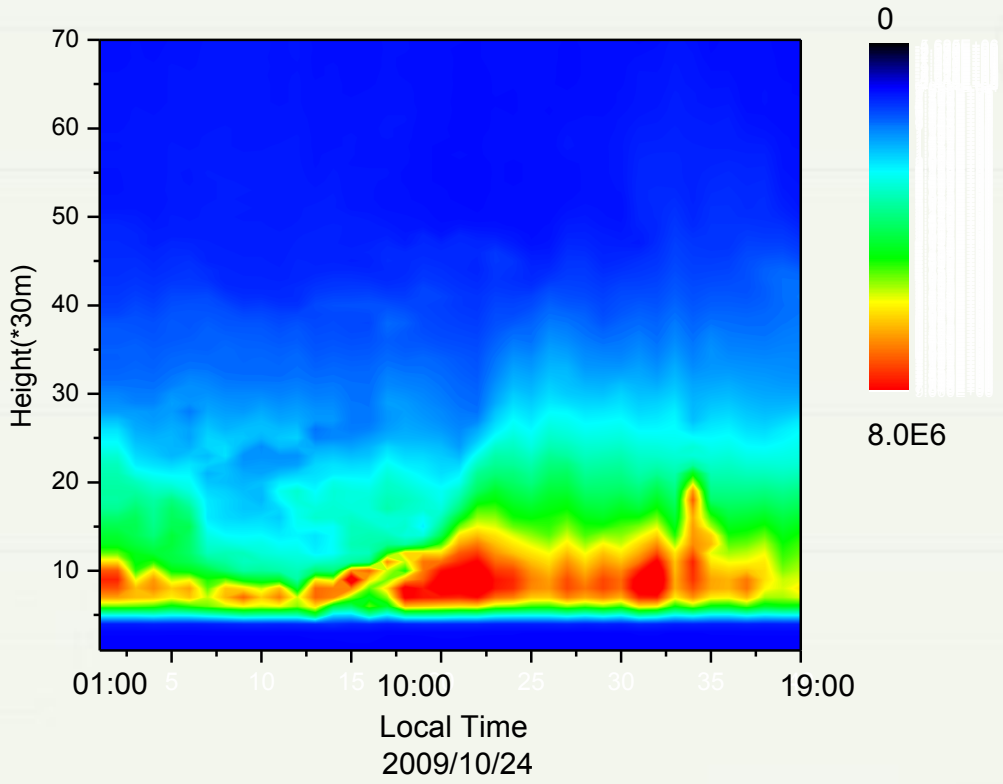
Weather

-fine at 8:00

-fog from 9:00 to10:00

-haze from 10:00 to 19:00

The fog-haze is at the low altitude about 300 meters



Continuous Fog-Haze measurements on 2009/10/24

What is the issue?

Traditional Mie lidar, uncertainties

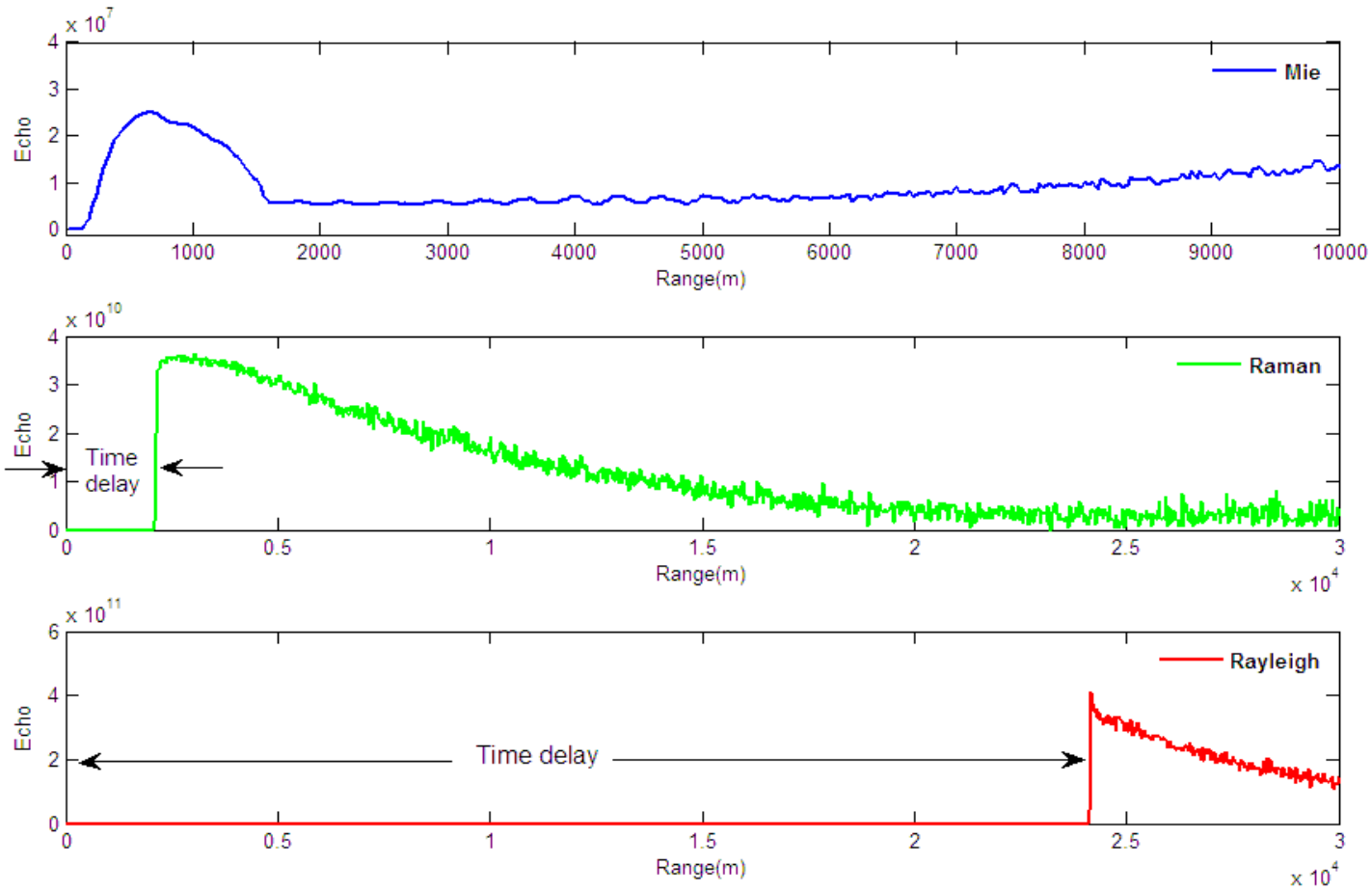
1 Boundary value,
2 Wavelength dependence,
3 Lidar ratio

Why we use Raman Lidar to measure aerosol ?

how to do ?

Raman Lidar

Lidar Signal



Why we use Raman lidar ?

- **Advantage**
  - reduce the assumptions
  - higher accuracy
- **Disadvantage**
  - Small signal
  - hard to control the signal to noise ratio
- **How to treat small Raman lidar signal**
  - statistical method
  - middle-average-value method

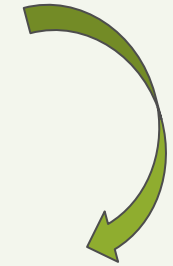
Limitation of Raman Lidar

Measurements error & Noise !!

Hardware: Photon counting

Cooling

Software



Aerosol ext.co error & noise

$$\alpha_{aer}(\lambda_L, z) = \left\{ \frac{d}{dz} \ln[\frac{N(z)}{z^2 P(\lambda_R, z)}] - \alpha_{mol}(\lambda_L, z) - \alpha_{mol}(\lambda_R, z) \right\} / \{1 + (\frac{\lambda_L}{\lambda_R})^k\} \quad (1)$$

Raman lidar noise signal is $\sigma(z)$, Raman lidar signal without noise is $P(\lambda_R, z)$. Raman lidar signal with noise $P(\sigma(z))$

$$\Delta\alpha_{aer} = \alpha_{aer}(\lambda_L, \sigma(z)) - \alpha_{aer}(\lambda_L, z) = \Delta\{\frac{d}{dz} \ln[\frac{N(z)}{P(\lambda_R, z) z^2}]\} \times (1 + \frac{\lambda_L}{\lambda_R})^{-k}$$

$$= \{\frac{d}{dz} \ln[\frac{N(z)}{P(\sigma(z) z^2)}] - \frac{d}{dz} \ln[\frac{N(z)}{P(z) z^2}]\} \times (1 + \frac{\lambda_L}{\lambda_R})^{-k} \quad (2)$$

Calculation of aerosol extinction coefficient

Take consideration of the following

$$\frac{d}{dz}\ln[\frac{N(z)}{z^2P(\sigma(z))}]-\frac{d}{dz}\ln[\frac{N(z)}{z^2P(z)}]=\frac{1}{P(z)z^2}\frac{d}{dz}[P(z)z^2]-\frac{1}{P(\sigma(z))z^2}\frac{d}{dz}[P(\sigma(z)z^2)]$$

And introduce variable $\Delta\Omega$,

$$\Delta\Omega=\frac{1}{P(z)z^2}\frac{d}{dz}[P(z)z^2]-\frac{1}{P(\sigma(z))z^2}\frac{d}{dz}[P(\sigma(z)z^2] \qquad (3)$$

We have equation （4）

$$\Delta\alpha_{aer}=\{\frac{1}{P(z)z^2}\frac{d}{dz}[P(z)z^2]-\frac{1}{P(\sigma(z))z^2}\frac{d}{dz}[P(\sigma(z)z^2)\}\times(1+\frac{\lambda_L}{\lambda_R})^{-k}$$

$$=\Delta\Omega\times(1+\frac{\lambda_L}{\lambda_R})^{-k} \qquad (4)$$

We can write the Raman signal with noise $P(\sigma(z))$ as following:

$$P(\sigma(z))=P(z)+\sigma(z) \qquad (5)$$

Calculation of aerosol extinction coefficient

Combine equation (4) and (5), we have

$$\Delta\Omega = \frac{1}{P(z)z^2}\frac{d}{dz}[P(z)z^2] - \frac{1}{(P(z)+\sigma(z))z^2}\frac{d}{dz}[(P(z)+\sigma(z))z^2]$$

$$= \frac{1}{P(z)z^2}\frac{d}{dz}[P(z)z^2] - \frac{1}{(P(z)+\sigma(z))z^2}\left(\frac{d}{dz}[P(z)z^2] + \frac{d}{dz}[\sigma(z)z^2)]\right)$$

$$= \frac{1}{P(z)z^2}\frac{d}{dz}[P(z)z^2] - \frac{1}{(P(z)+\sigma(z))z^2}\left(\frac{d}{dz}[P(z)z^2] + 2\sigma(z)z + z^2\frac{d}{dz}\sigma(z)\right)$$

$$= \frac{1}{P(z)z^2}\frac{d}{dz}[P(z)z^2] - \frac{1}{(P(z)+\sigma(z))z^2}\left(\frac{d}{dz}[P(z)z^2] + 2\sigma(z)z\right)$$

$$- \frac{1}{(P(z)+\sigma(z))}\frac{d}{dz}\sigma(z) \qquad (6)$$

Calculation of aerosol extinction coefficient

Take consideration of $P(z) >> \sigma(z)$,the expansion of the equation (6) is as following;

$$\Delta\Omega = \frac{1}{P(z)z^2}\frac{d}{dz}[P(z)z^2] - \frac{1}{(P(z)+\sigma(z))z^2}(\frac{d}{dz}[P(z)z^2] + 2\sigma(z)z) - \frac{1}{(P(z)+\sigma(z))}\frac{d}{dz}\sigma(z)$$

$$= \frac{1}{P(z)z^2}\frac{d}{dz}[P(z)z^2] - (\frac{1}{P(z)} - \frac{\sigma(z)}{P(z)^2} + \frac{\sigma(z)^2}{P(z)^3} + ...)\frac{1}{z^2}\frac{d}{dz}[P(z)z^2]$$

$$-(\frac{1}{P(z)} - \frac{\sigma(z)}{P(z)^2} + \frac{\sigma(z)^2}{P(z)^3} + ...)\frac{1}{z^2}2\sigma(z)z - \frac{1}{(P(z)+\sigma(z))}\frac{d}{dz}\sigma(z) \qquad (7)$$

Calculation of aerosol extinction coefficient

If neglect infinitesimal of higher order $\sigma(z)^3$, such as , we have

$$\Delta\Omega \approx (\frac{1}{P(z)^2 z^2}\frac{d}{dz}[P(z)z^2] - \frac{2}{P(z)z})\sigma(z) + (\frac{2}{P(z)^2 z} - \frac{1}{P(z)^3 z^2}\frac{d}{dz}[P(z)z^2])\sigma(z)^2 - \frac{1}{P(z)+\sigma(z)}\frac{d}{dz}\sigma(z) \quad (8)$$

When $\sigma(z) \approx cons\tan t$, it correspond to the low frequency noise signal, equation (8) can be rewritten as

$$\Delta\Omega \approx (\frac{1}{P(z)^2 z^2}\frac{d}{dz}[P(z)z^2] - \frac{2}{P(z)z})\sigma(z) + (\frac{2}{P(z)^2 z} - \frac{1}{P(z)^3 z^2}\frac{d}{dz}[P(z)z^2])\sigma(z)^2 \quad (9)$$

At condition of $\sigma(z) >> \sigma(z)^2$, $\sigma(z)^2$ is neglected, equation (10) comes out,

$$\Delta\Omega \approx (\frac{1}{P(z)^2 z^2}\frac{d}{dz}[P(z)z^2] - \frac{2}{P(z)z})\sigma(z) \quad (10)$$

According to equation (7), we can see the aerosol ext.co measurement error relates to Raman lidar noise $\sigma(z)$, $\sigma(z)^2$ and differential of noise: $\frac{d}{dz}\sigma(z)$.

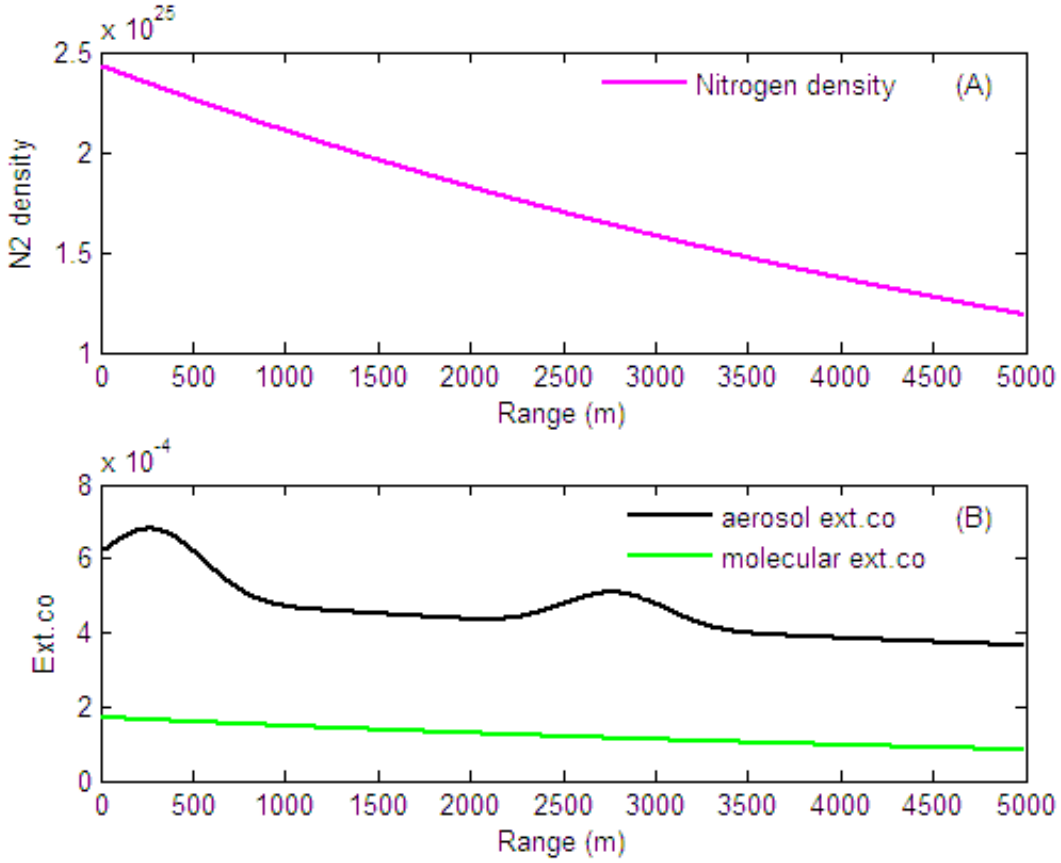
Noise: Low frequency, background noise

$$\sigma(z) \approx constant$$

High frequency, Random noise
Dark currents
Heating

Simulations

Fig.1:standard atmospheric conditions and aerosol ext.co

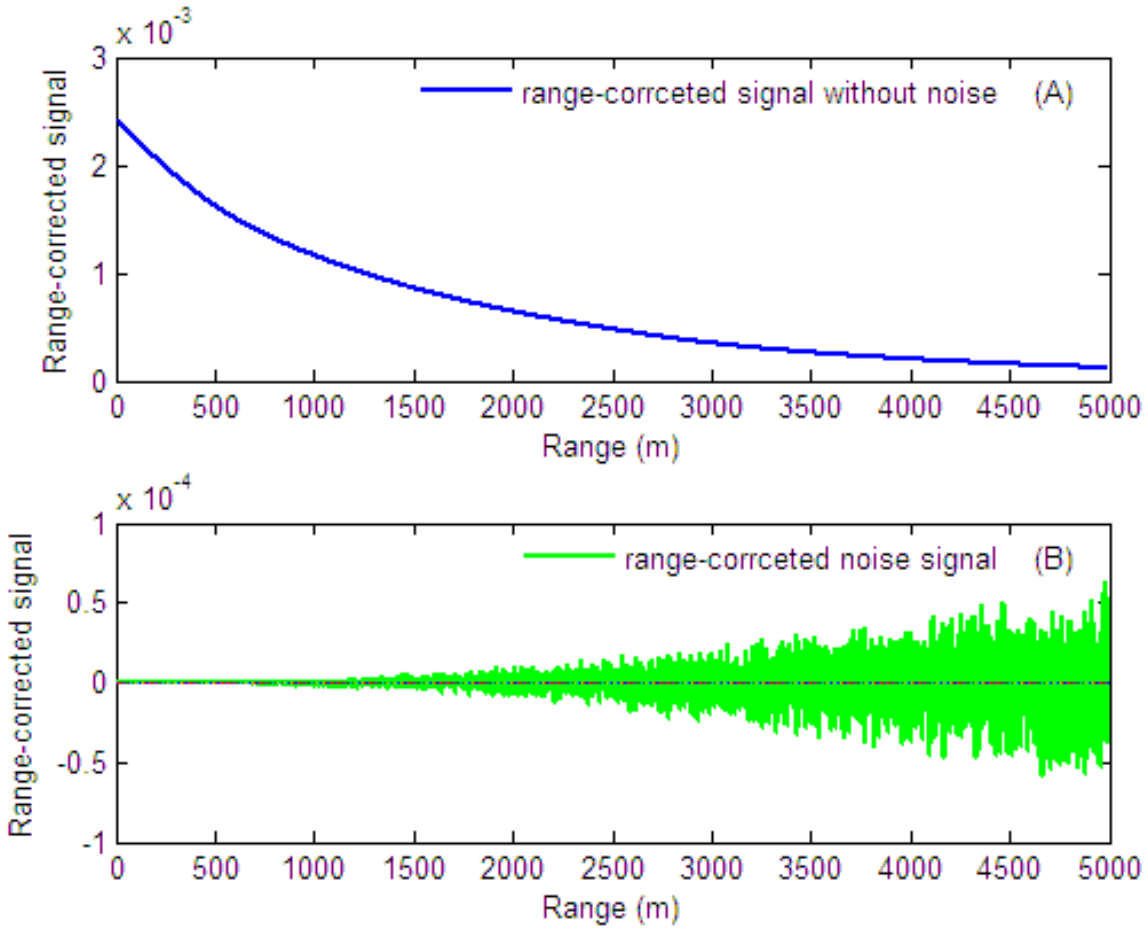


A: Nitrogen density

B: Black curve is aerosol ext.co and green one is molecular ext.co

Simulations

Fig.2:The simulated Raman lidar signals

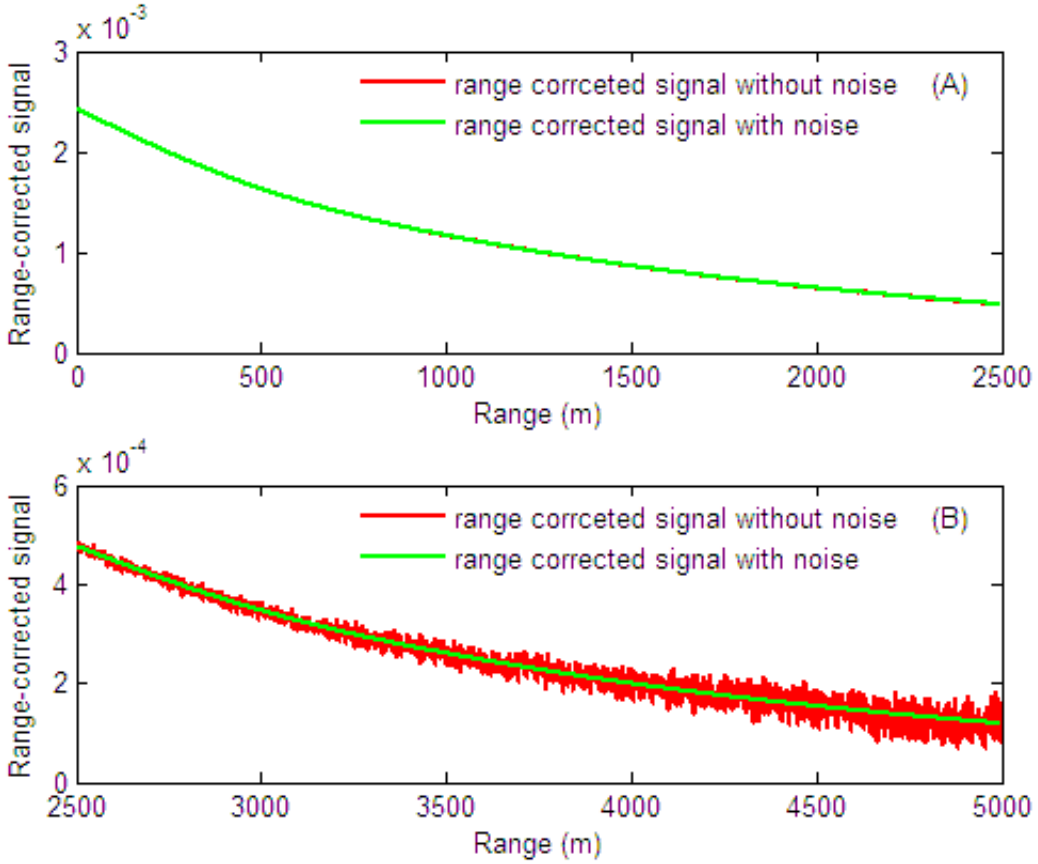


A : simulated range-corrected signal without noise

B : simulated range-corrected random noise signal

Simulations

Fig.3:Simulated Raman lidar signal with random noise addition

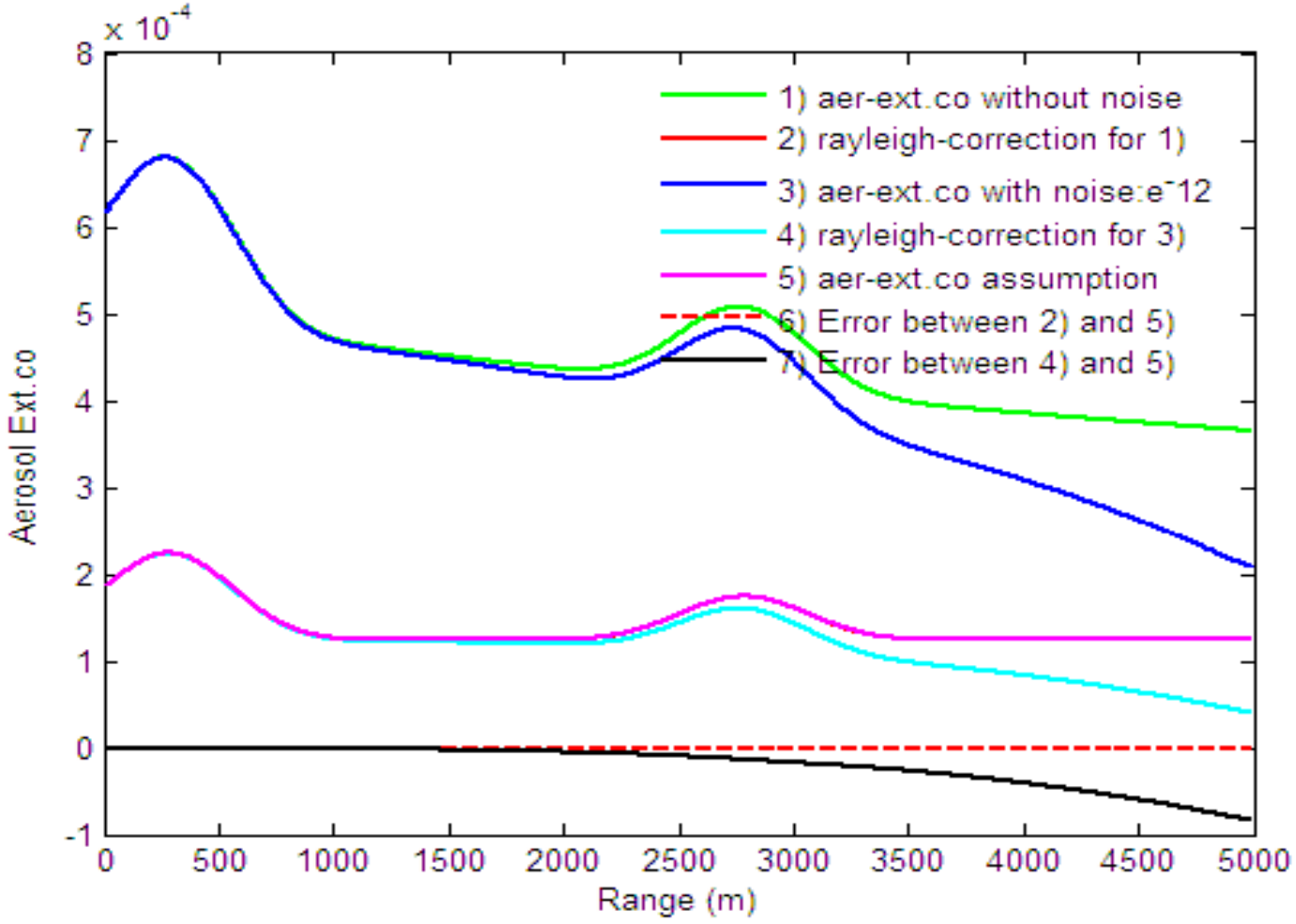


A: Range: 0 ~ 2500m

B: Range: 2500 ~ 5000m

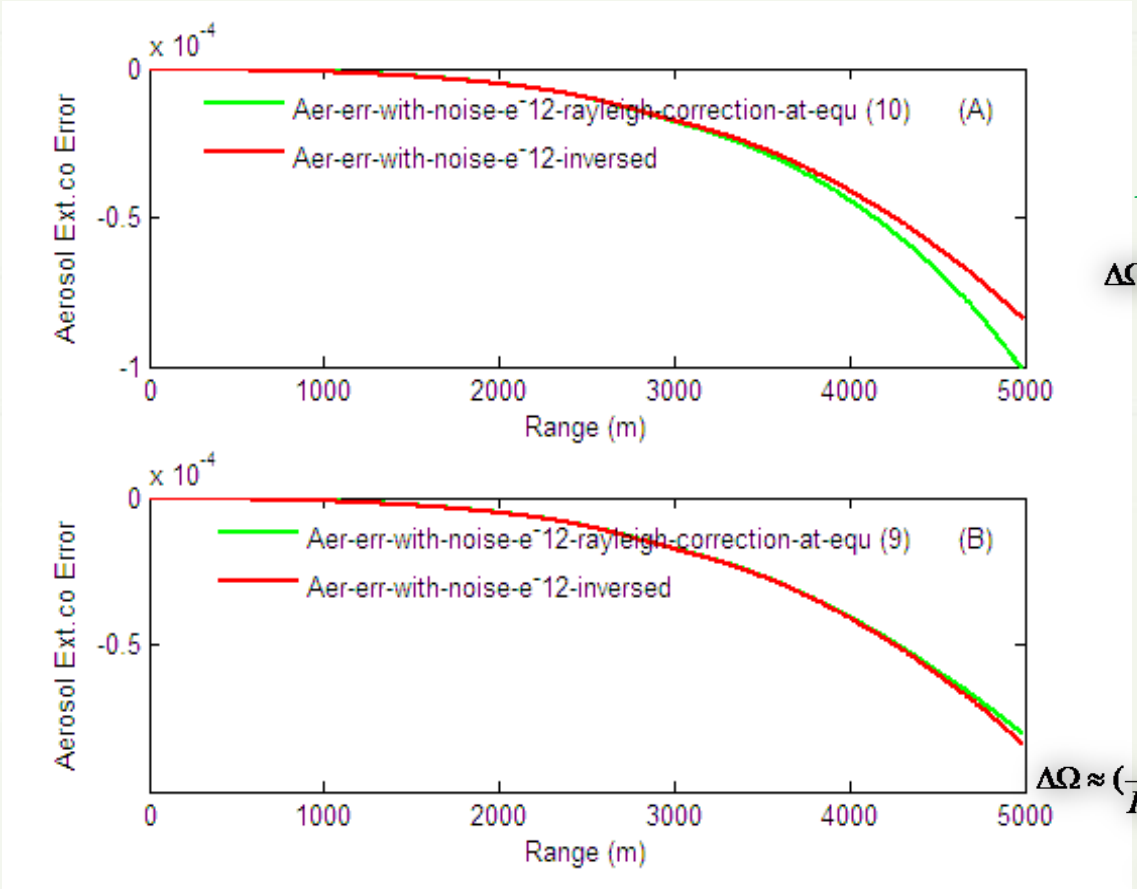
Ext.co inversion by simulation signals

Fig.4 :Aerosol Ext.co inversion by Raman lidar



simulation of aerosol extinction coefficient

Fig.5:Relation between Aerosol Ext.co error and noise



A: calculated using equation (10)

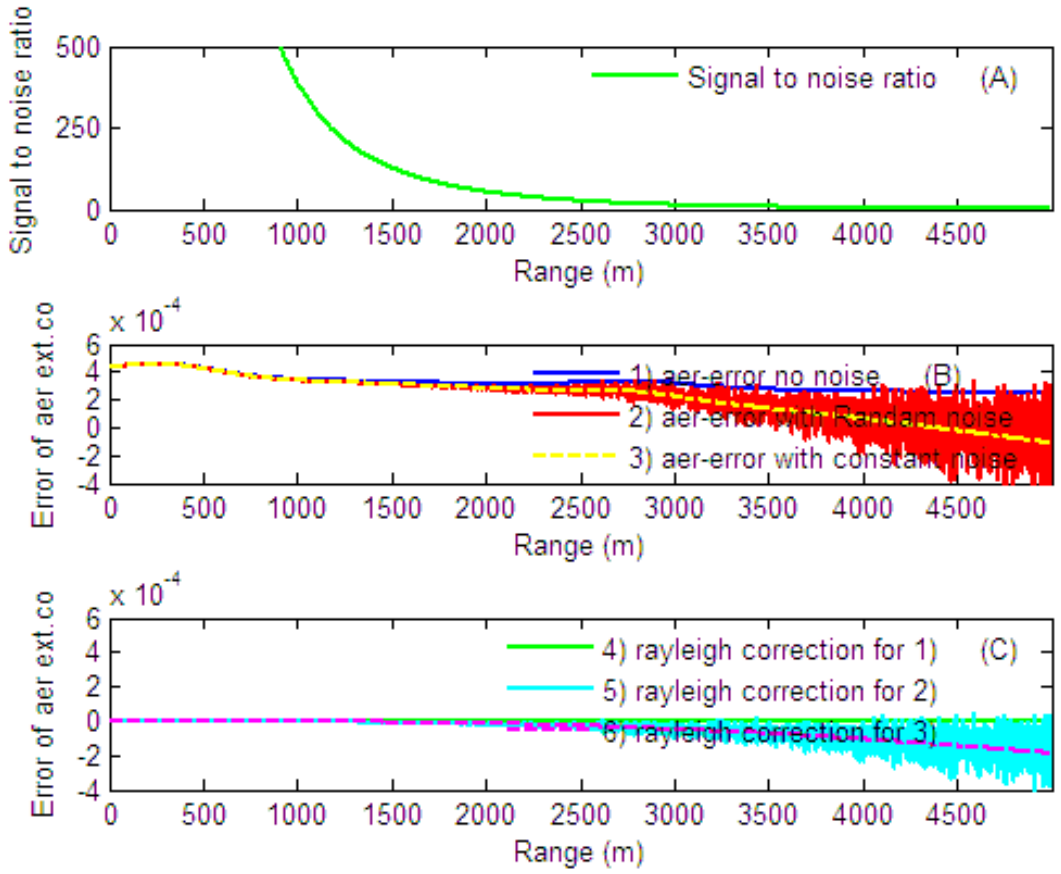
$$\Delta\Omega \approx \left(\frac{1}{P(z)^2 z^2}\frac{d}{dz}[P(z)z^2] - \frac{2}{P(z)z}\right)\sigma(z) \qquad (10)$$

B: calculated using equation (9)

$$\Delta\Omega \approx \left(\frac{1}{P(z)^2 z^2}\frac{d}{dz}[P(z)z^2] - \frac{2}{P(z)z}\right)\sigma(z) + \left(\frac{2}{P(z)^2 z} - \frac{1}{P(z)^3 z^2}\frac{d}{dz}[P(z)z^2]\right)\sigma(z)^2 \qquad (9)$$

simulation of aerosol extinction coefficient

Fig.6 Aerosol ext.co error relate to Signal to Noise Ratio



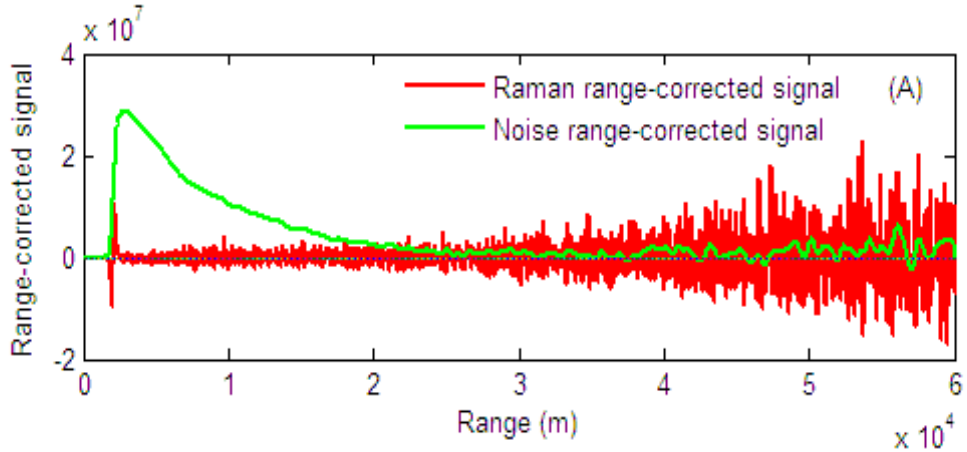
A: Signal to Noise Ratio

B: aerosol error calculation without Rayleigh correction

C: aerosol error calculation with Rayleigh correction

Experiments

Fig.7 Raman lidar experiment signals

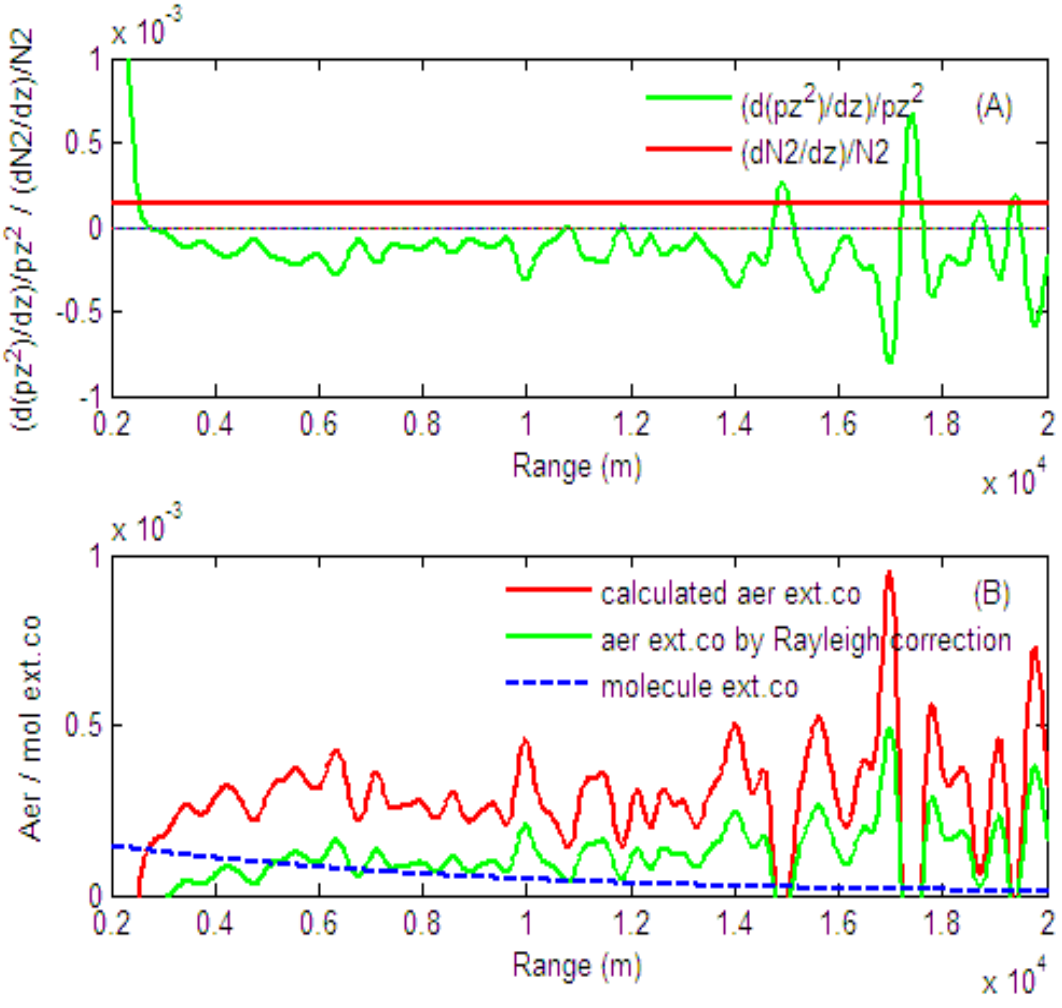


A:Range corrected signal and Range corrected noise signal

B:Range corrected signal with noise

Experiments

Fig.8 Experimental data analysis



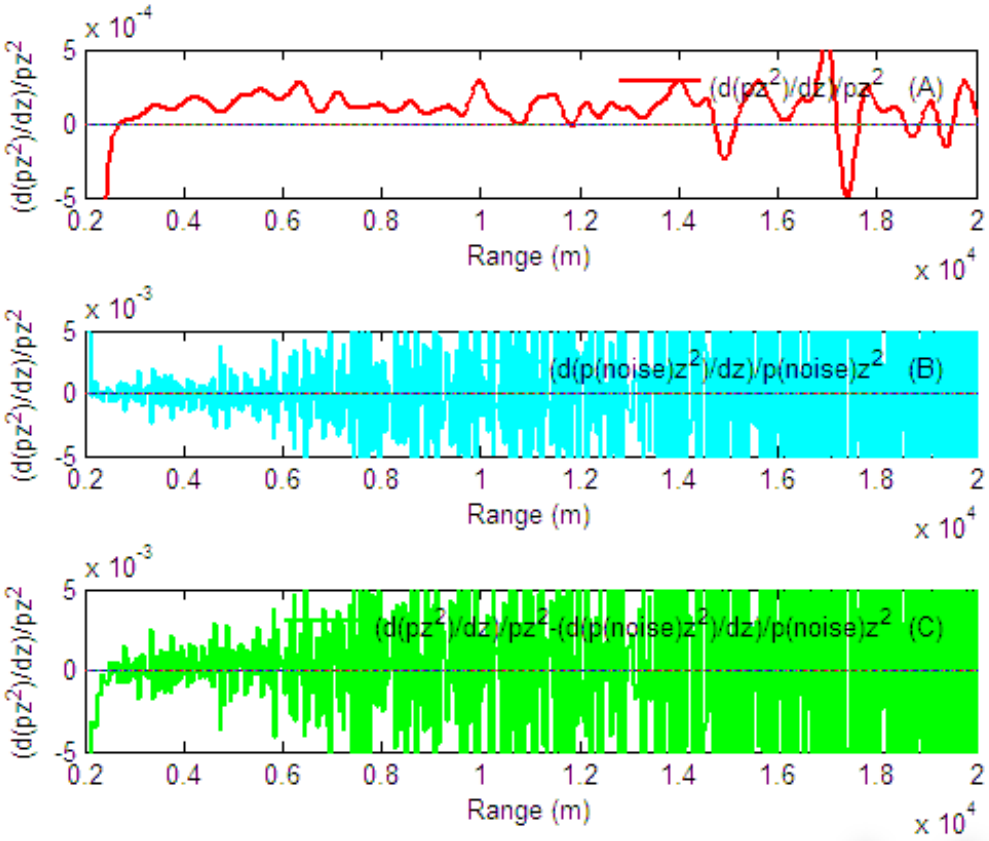
A: differential calculation for range corrected signal and Nitrogen density

B: calculated aerosol ext.co without and with Rayleigh corrections, and molecular ext.co profile

Company Logo

Experiments

Fig.9 Differential calculation



A: calculated by signal without noise (low frequency)

$$\frac{1}{P(z)z^2}\frac{d}{dz}[P(z)z^2]$$

B: calculated by signal with noise (high frequency)

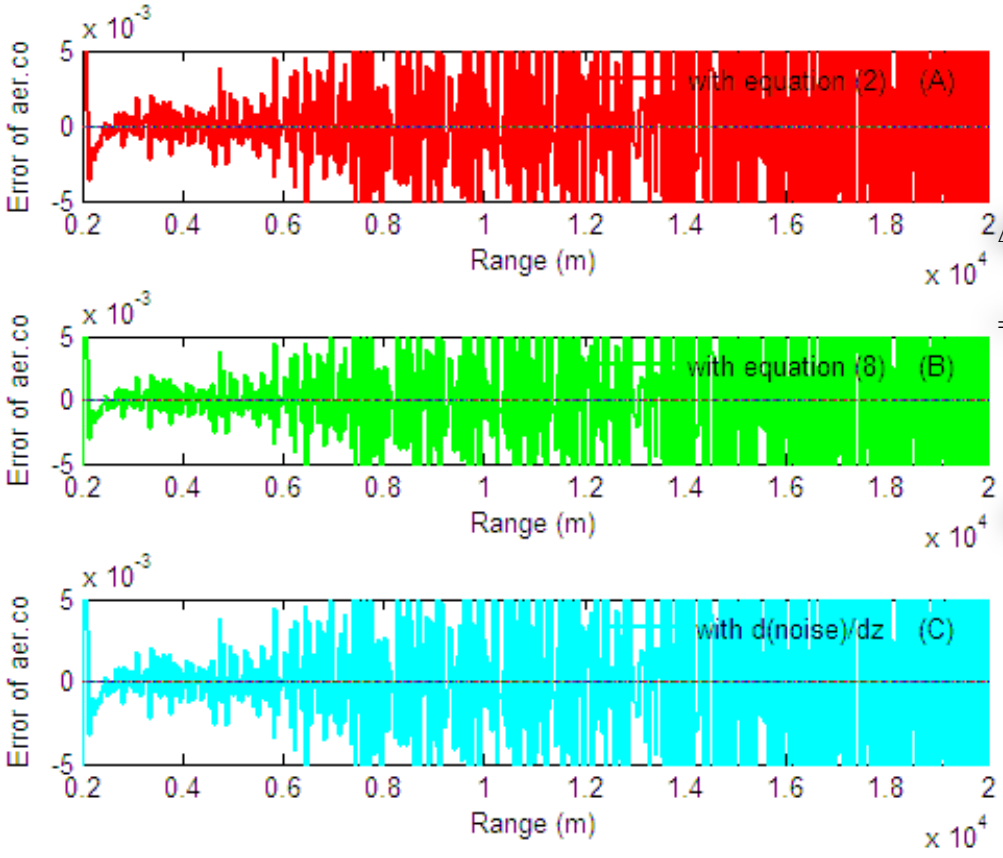
$$\frac{1}{P(\sigma(z))z^2}\frac{d}{dz}[P(\sigma(z)z^2]$$

C: A munis B

$$\Delta\Omega = \frac{1}{P(z)z^2}\frac{d}{dz}[P(z)z^2] - \frac{1}{P(\sigma(z))z^2}\frac{d}{dz}[P(\sigma(z)z^2] \qquad (3)$$

Experiments

Fig.10 Aerosol ext.co Error calculation



A: calculated by equation (2)

$$\Delta\alpha_{aer} = \alpha_{aer}(\lambda_L, \sigma(z)) - \alpha_{aer}(\lambda_L, z) = \Delta\{\frac{d}{dz}\ln[\frac{N(z)}{P(\lambda_R, z)z^2}]\} \times (1 + \frac{\lambda_L}{\lambda_R})^{-k}$$

$$= \{\frac{d}{dz}\ln[\frac{N(z)}{P(\sigma(z)z^2)}] - \frac{d}{dz}\ln[\frac{N(z)}{P(z)z^2}]\} \times (1 + \frac{\lambda_L}{\lambda_R})^{-k} \quad (2)$$

B: calculated by equation (8)

$$\Delta\Omega \approx (\frac{1}{P(z)^2 z^2}\frac{d}{dz}[P(z)z^2] - \frac{2}{P(z)z})\sigma(z) + (\frac{2}{P(z)^2 z} - \frac{1}{P(z)^3 z^2}\frac{d}{dz}[P(z)z^2])\sigma(z)^2$$

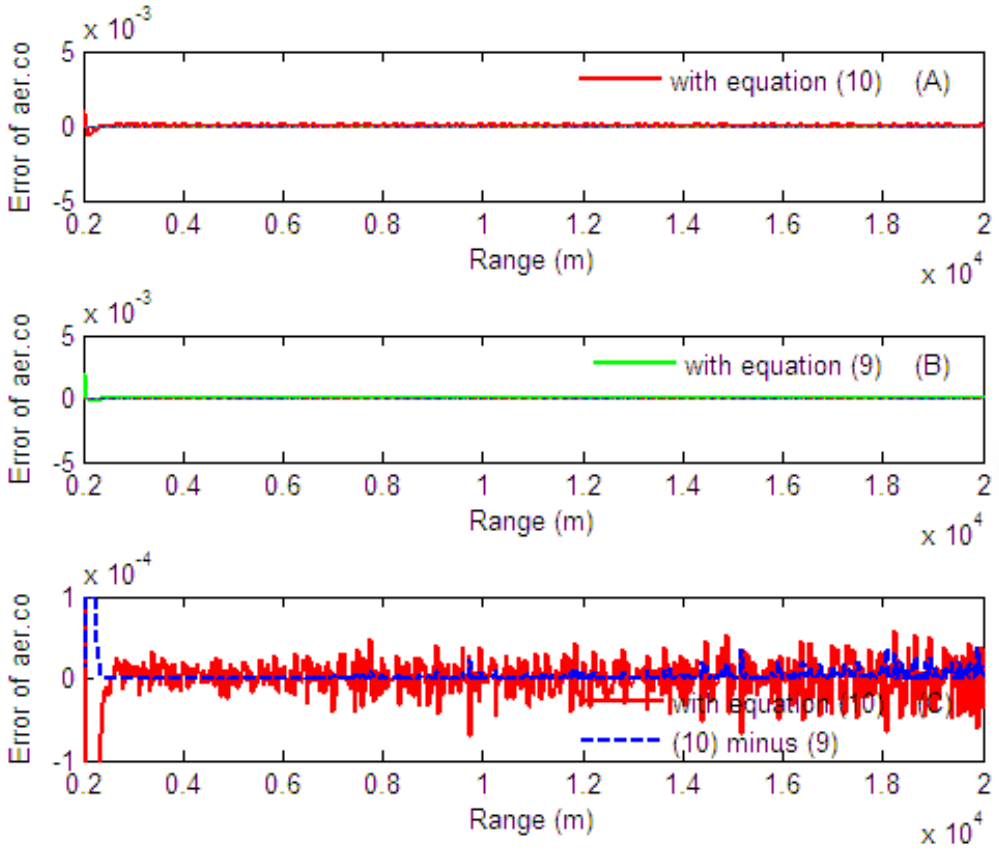
$$-\frac{1}{P(z)+\sigma(z)}\frac{d}{dz}\sigma(z) \quad (8)$$

C: differencial noise

$$\frac{d}{dz}\sigma(z)$$

Experiments

Fig.11 Aerosol ext.co Error calculation



A:calculated by equation (10)

$$\Delta\Omega \approx \left(\frac{1}{P(z)^2 z^2}\frac{d}{dz}[P(z)z^2] - \frac{2}{P(z)z}\right)\sigma(z) \qquad (10)$$

B: calculated by equation (9)

$$\Delta\Omega \approx \left(\frac{1}{P(z)^2 z^2}\frac{d}{dz}[P(z)z^2] - \frac{2}{P(z)z}\right)\sigma(z) + \left(\frac{2}{P(z)^2 z} - \frac{1}{P(z)^3 z^2}\frac{d}{dz}[P(z)z^2]\right)\sigma(z)^2 \qquad (9)$$

C: A and A minus B, displayed in larger scale

Conclusions

1) Raman better than Mie

2) $Error \propto f(\sigma(z), \sigma^2(z), \ldots, \frac{d\sigma(z)}{dz})$

3) Rayleigh correction, noise

4) High frequency, low frequency noise

5) Average calculation to remove the high frequency noise

Thank you!