Spectral direct solar UV measurements in Trondheim, retrieval of aerosol optical depth and aerosol size distribution in subarctic coastal region

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Keywords:

Direct solar UV measurements, instrumentation, AOD, aerosol effects and size distribution

Background

FARIN [Factor Affecting UV Radiation In Norway]

- **Participating Organisations in FARIN**
  - **Norwegian Institute for Air Research (NILU)**
    - Dr. Ola Engelsen (project coordinator)
    - M.Sc Kåre Edvardsen
  - **Norwegian University of Science and Technology (NTNU)**
    - Prof. Berit Kjeldstad
    - Ph.D Asadollah Bagheri
  - **University of Oslo (UiO)**
    - Prof. Arne Dahlback
  - **Norwegian Radiation Protection Authority (NRPA)**
    - M.Sc Bjørn Johnsen

Background

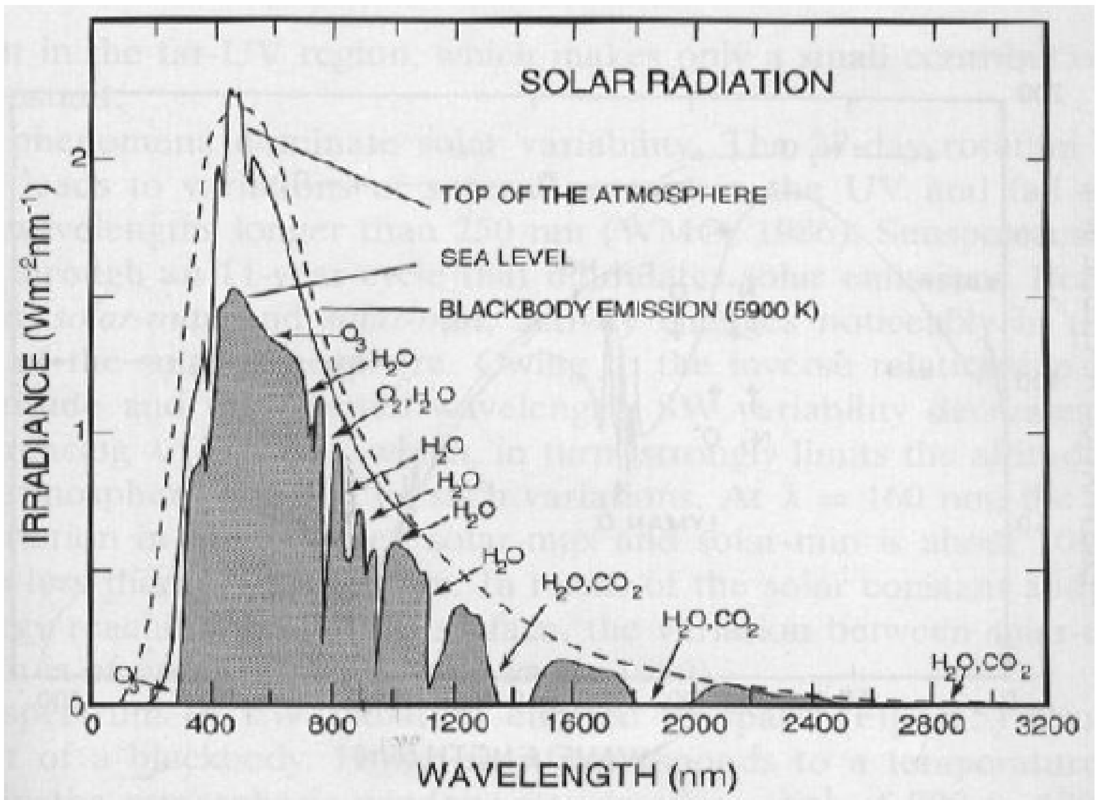
- NTNU task specification;
  - Measurements, Aerosol effects on UV
    - Measuring aerosols optical properties
    - Estimating aerosol effects, comparing to ozone effects (Hubber 95)
    - Aerosol size distribution from direct measurements
    - Diffuse measurments, spatial variation of UVB og UVA (Blumthaler 96), almucantar og zenithal measurements, calculation of phase function and size distribution from diffuse measurements (Kaufman 94)
  - Instrumentation
    - Improvments of solar tracking system

Theoretical background

EM radiation

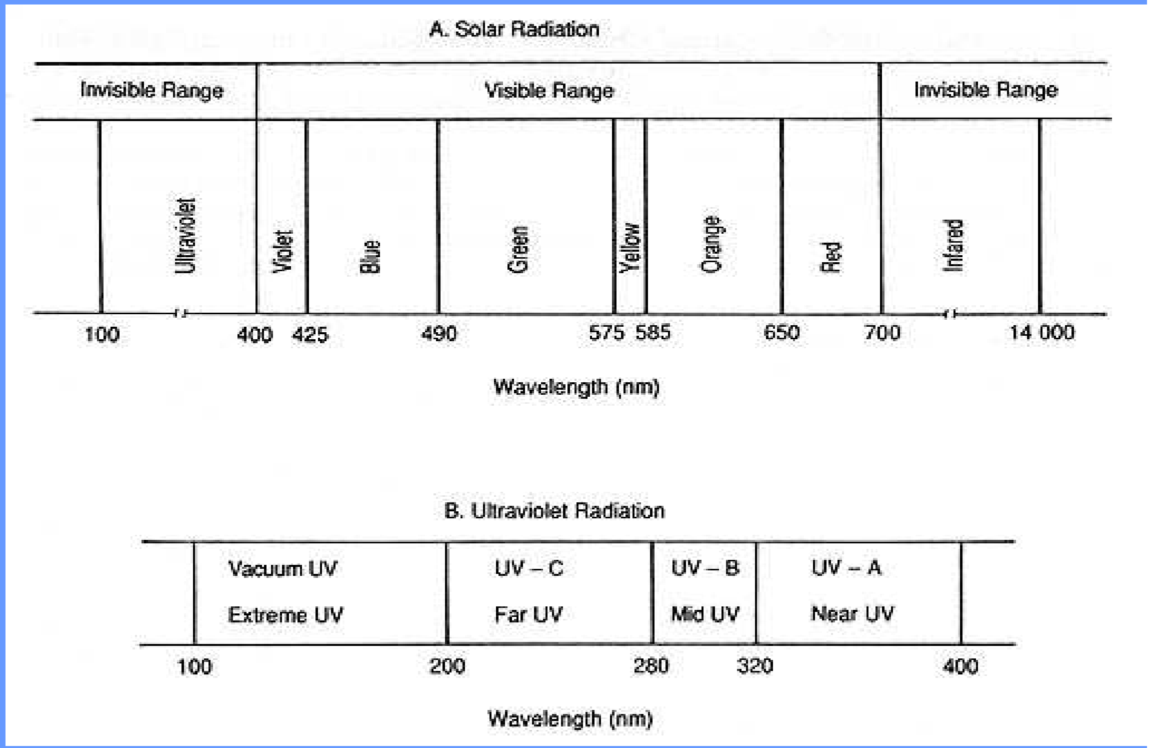
According to Planck's law **continuous spectra** originate from hot, dense objects like stars, planets, or sun. The continuous spectrum from these kinds of objects is also called a **thermal spectrum**, because hot, dense objects will emit electromagnetic radiation at all wavelengths.

Solar spectrum at the top of the atmosphere is shown by the solid line. For comparison the dashed line represents the Planck curve for a black body object with a surface temperature of $T = 5900K$. Shaded areas show the solar spectrum at sea level under a clear atmosphere. Selective absorption bands of water vapor and some gases are indicated.



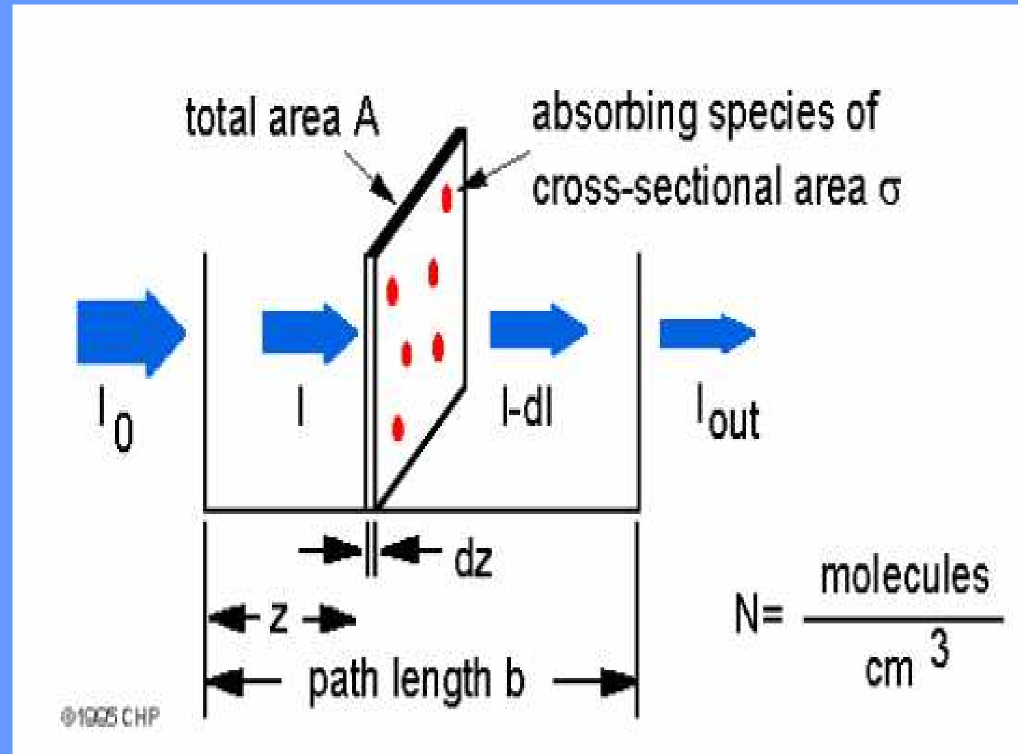
Theoretical background

- UV part of solar spectrum
- Aerosol in the atmospheric
  - Aerosol are mainly in troposphere and stratosphere layer, stratospheric aerosol are called Jung layer as well.
- UV transfer through the atmosphere, main processes;
  - Scattering, Mie and Rayleigh scattering (blue sky), aerosol and molecules
  - Absorption, N2, O2, Ozone, aerosol?
  - Direct approximation and Beer-lambert law



Theoretical background
Beer-Lambert Law

- Radiation intensity travesing a medium will be reduced caused by it's interaction with the matters in the medium.
- If the intensity I(z) become I(z)-dI(z) after traversing a thickness dz, then:



$$\frac{dI}{I_z} = -\sigma N dz$$

Instruments

- Bentham DM150
  - Spectral measurements
    - Global irradiance
    - Direct irradiance, field of view 1.5°
    - Radiance, diffuse
  - Range 250 to 600 nm, step 0.1nm, (1 nm step used)
  - *FWHM of about 0.8 nm*
  - Calibration, 1000 W NIST traceable standard lamp
- *Sun photometer, CIMEL CE318*
  - 9 spectral band measuring channels
    - Direct irradiance, field of view 1.2º
    - Radiance
    - *FWHM of about 2 – 10 nm*
  - Channels, 340, 380, 440, 500, 670, 870, 936, 1020 and 1640nm.
  - Calibration, manufacture

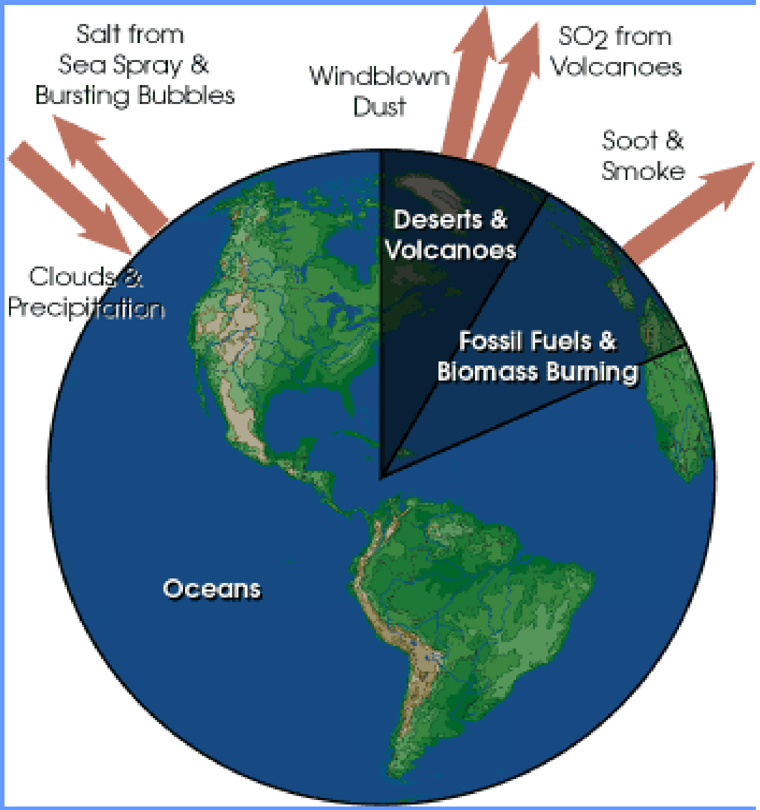
What are aerosols?

Aerosols

- Suspended solid or liquid matter
- Small settling velocity

Types

- Continental, dust, SO_2, SI
  - Volcanic SO_2, 0.25 H_2O+0.75 H_2SO_4
- Marine, salt 0.30NaCl+0.70H_2O
- Urban, soot & smoke



Size Spectra

- Aitken nuclei, Less than .2 µm
- Large aerosols, .2 to 2 µm
- Giant aerosols, Greater than 2 µm

Sources

- Aitken Nuclei (< .2 μm diameter)
  - *Nucleation Mode* (.01 μm)
    - Combustion
      - High Urban Concentrations
  - Forest Fires
  - Volcanoes
  - Gas-to-Particle Conversion
    - Trace Gases to Aerosols
      - Supersaturated Gases
      - Photochemical Reaction
- Large Aerosols (.2 to 2 μm)
  - *Accumulation Mode*
    - Coagulation of Aitken Nuclei
      - Brownian Motion
    - Cloud Droplet Evaporation
- Giant Aerosols(> 2 μm)
  - *Course Particle Mode* (10 to 20 mm)
    - Mechanical Processes
      - Wind Erosion
      - Industrial Processes
      - Sea Salt from Waves
      - Pollen

Sinks

- Aitken Nuclei
  - Coagulation
    - Brownian Motion
  - Capture by Cloud Particles
    - Diffusiophoretic Force
- Large & Giant Aerosols
  - Precipitation Scavenging (cleaned by rain/snow)
  - Gravitational Settling

Aerosol Importance

- Global warming, rising levels of greenhouse gases are wellknown.
- Aerosol impact as a more complex factor affecting radiation balance generally, UV specificly.
- Optical (optical depth, phase function, refractive index) and physical properties (shape, size distribution) are significant information for determination of aerosol effect on UV radiation.

Beer-Lambert Law

calculation of Aerosol Optical Depth (AOD)

Franco Marenco (1997), Hubber, LIOU

$$I(\lambda) = I_0(\lambda)e^{-\tau(\lambda)m}$$

$$\tau(\lambda) = \tau_A(\lambda) + \tau_R(\lambda) + \tau_{O_3}(\lambda) + \tau_W(\lambda)$$

$$\tau_R(\lambda) = 0,09364(\frac{\lambda}{\lambda_0})^{-4}[1 + 0,0374(\frac{\lambda}{\lambda_0})^{-2} + 0,00142(\frac{\lambda}{\lambda_0})^{-4}]$$

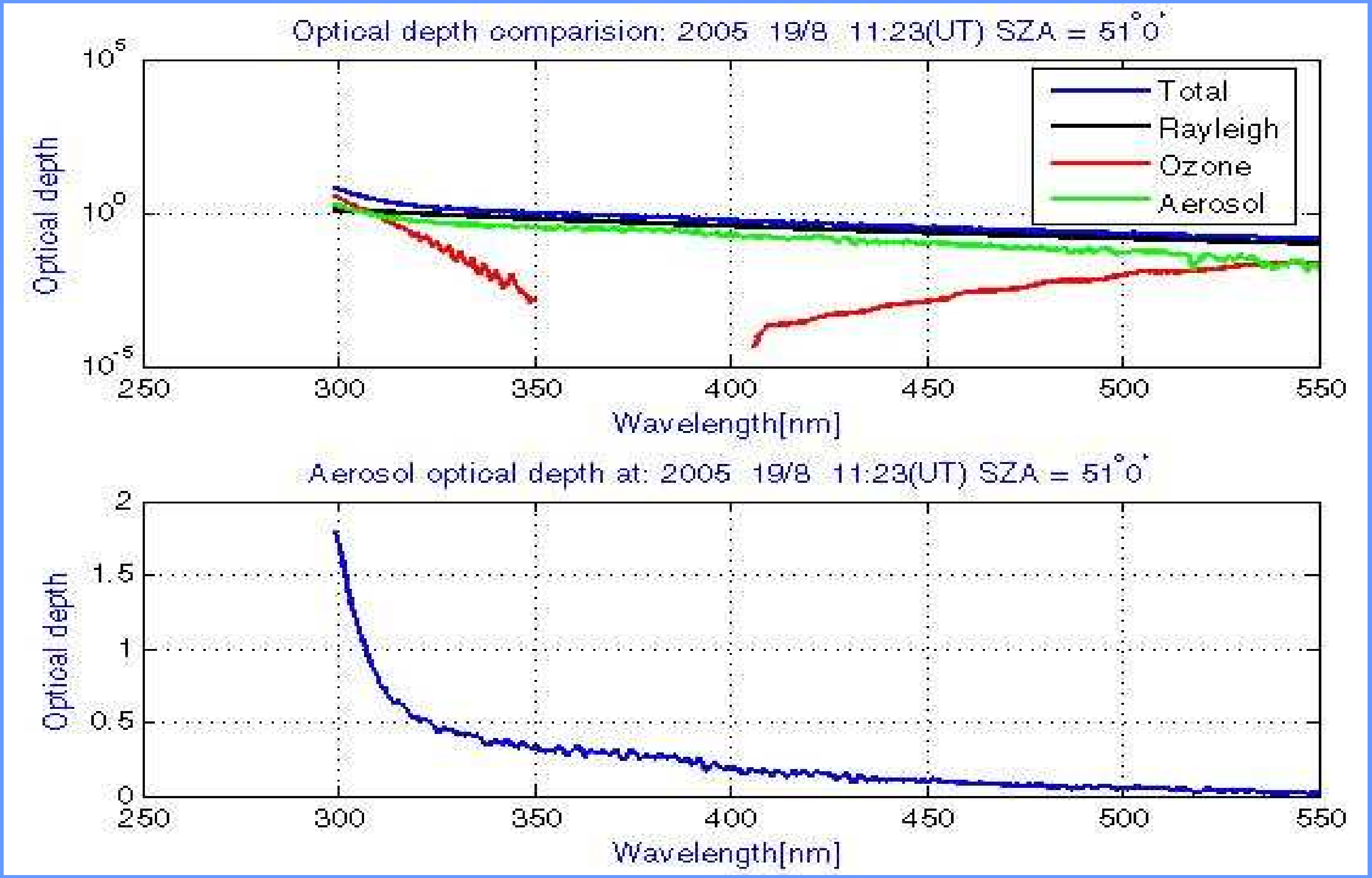
$$\tau_A(\lambda, Z, P, T) = (cos(\theta))ln\frac{I_0(\lambda)}{I(\lambda)} - \frac{P}{P_0}\tau_R(\lambda) - D_{O_3}k_{O_3}(\lambda)$$

Experimental error in AOD

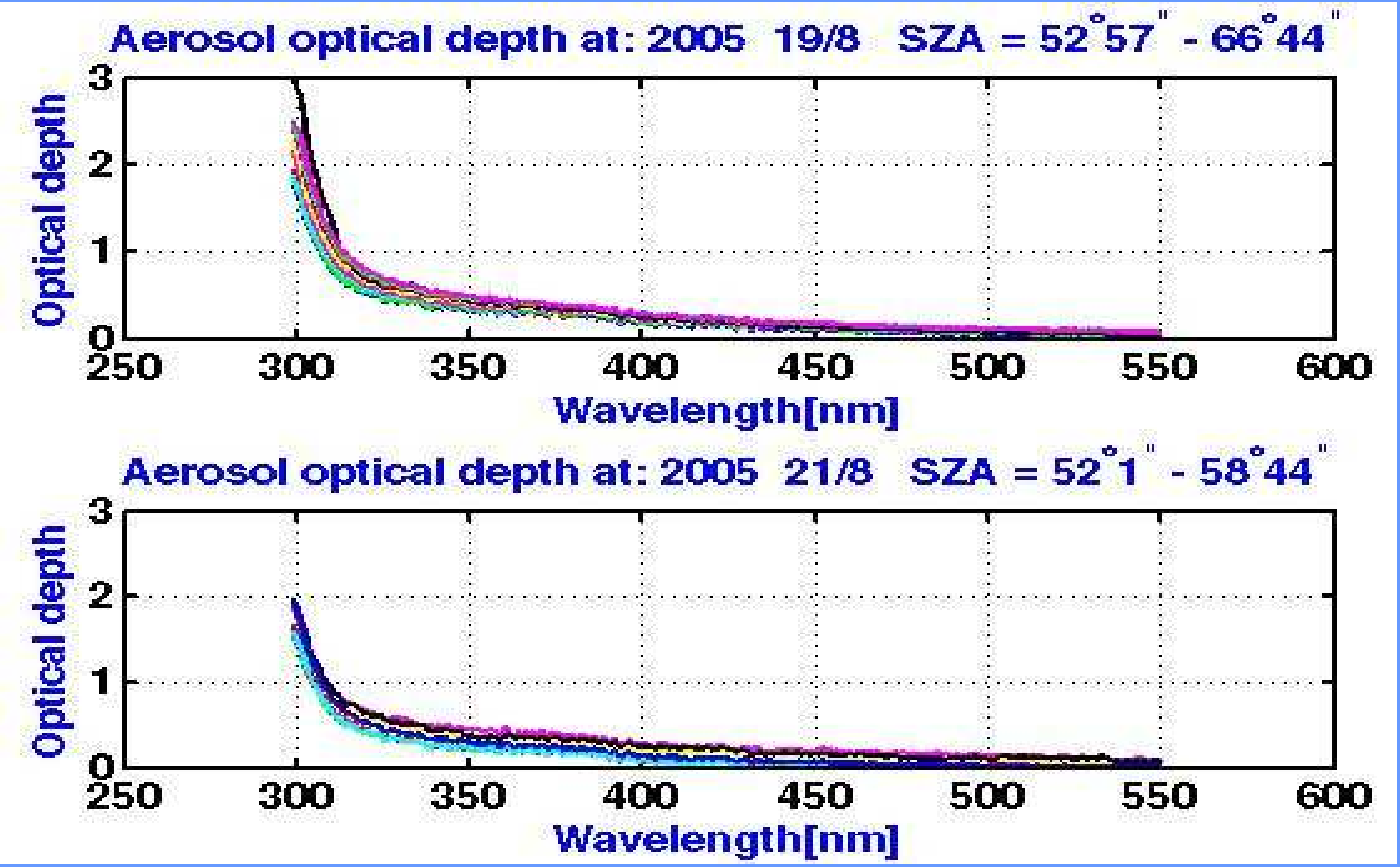
$$(\Delta\tau_A)^2 = cos^2(\theta)\left[(\frac{\Delta I_0}{I_0})^2 + (\frac{\Delta I}{I})^2\right] + (\frac{\Delta D_{O_3}}{D}\tau_{O3})^2;$$

- Comments:
  - Uncertainty in ET Atlas 2 and 3, Atlas3 for wl<407.8 nm; Atlas2 for 407.8nm < wl < 419.9 nm; KittPeak for wl > 419.9 nm, [Woods],
  - Uncertainty in ozone amount and cross section, [Molina]
  - Uncertainty in the instrument

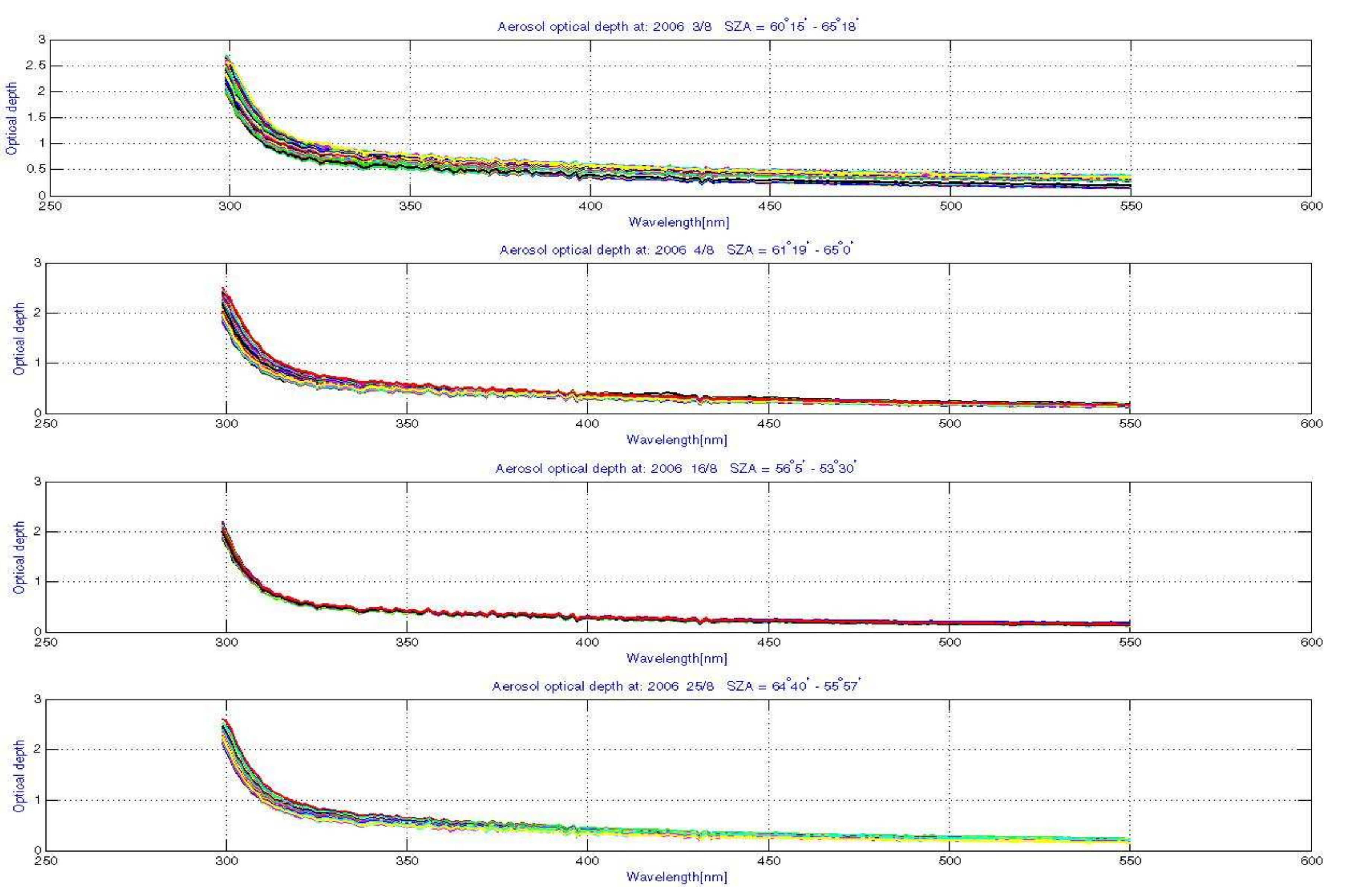
Measured AOD, 19 Aug. 2005, Trondheim



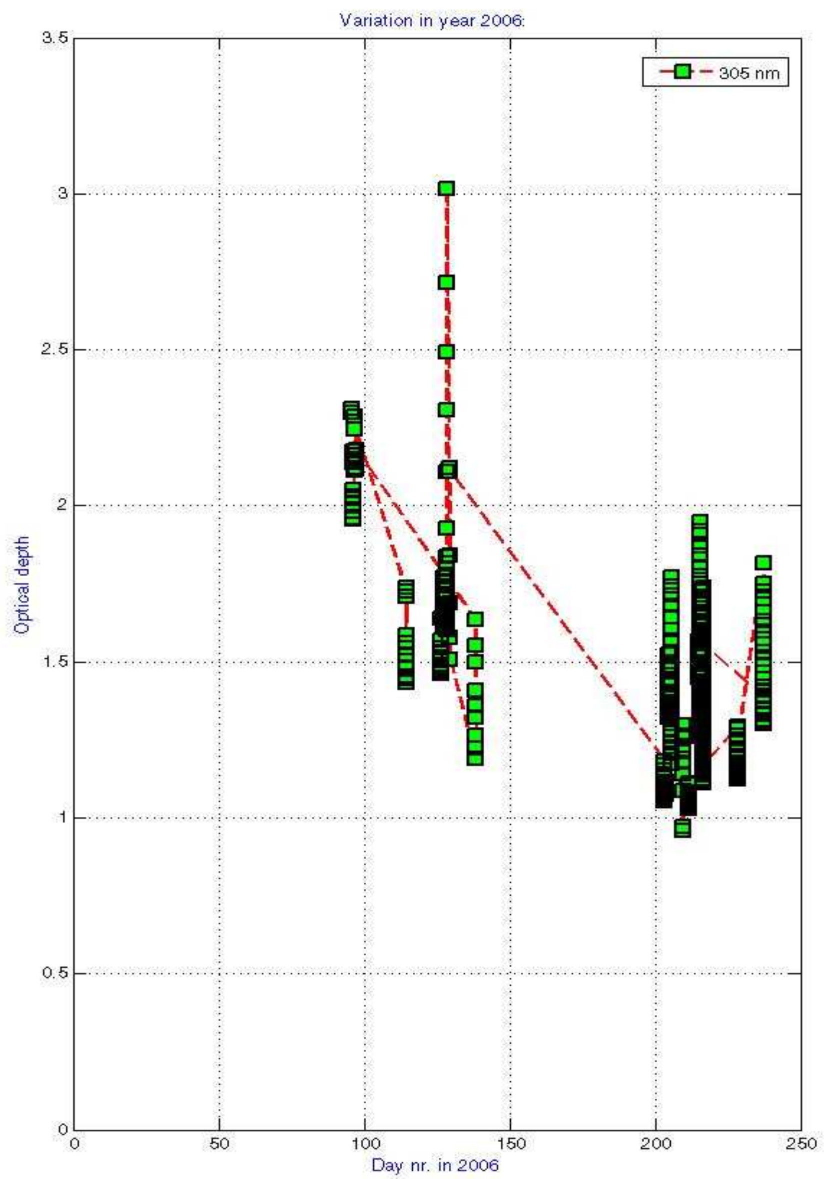
AOD August 2005, Trondheim

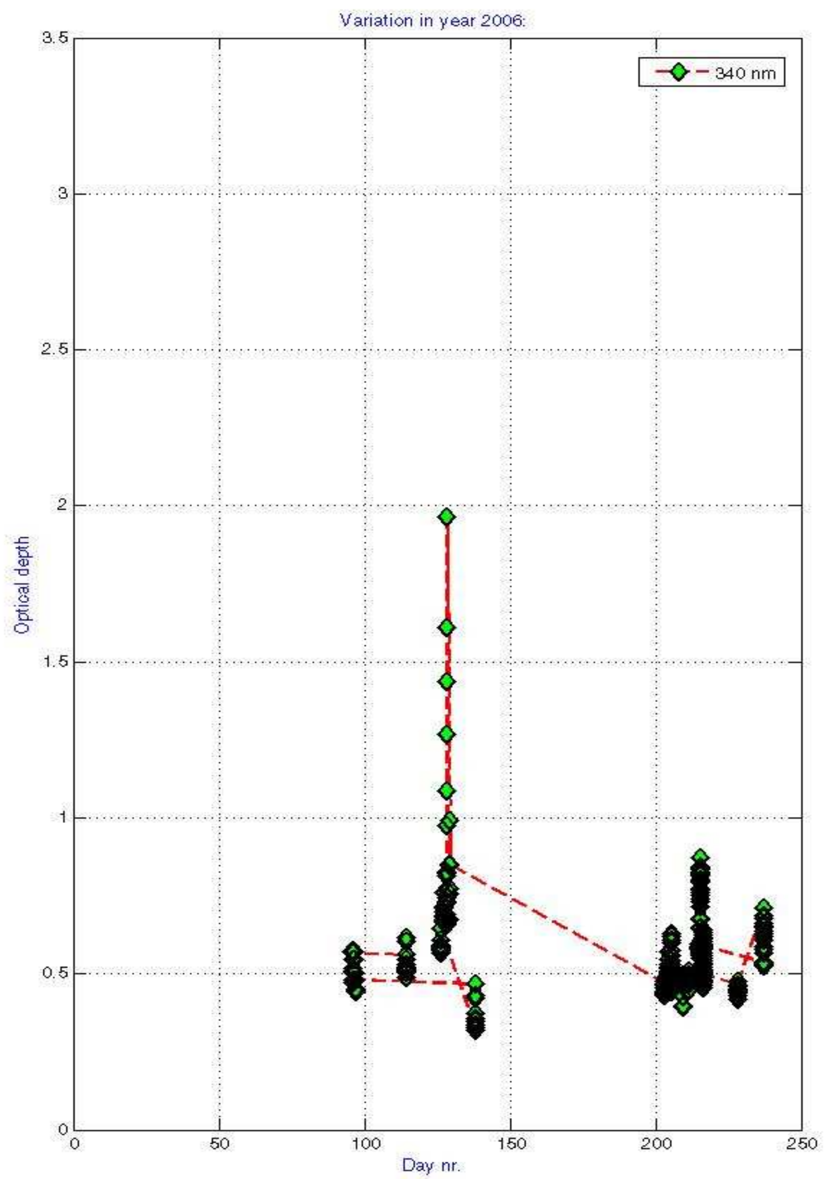


AOD August 2006, Trondheim

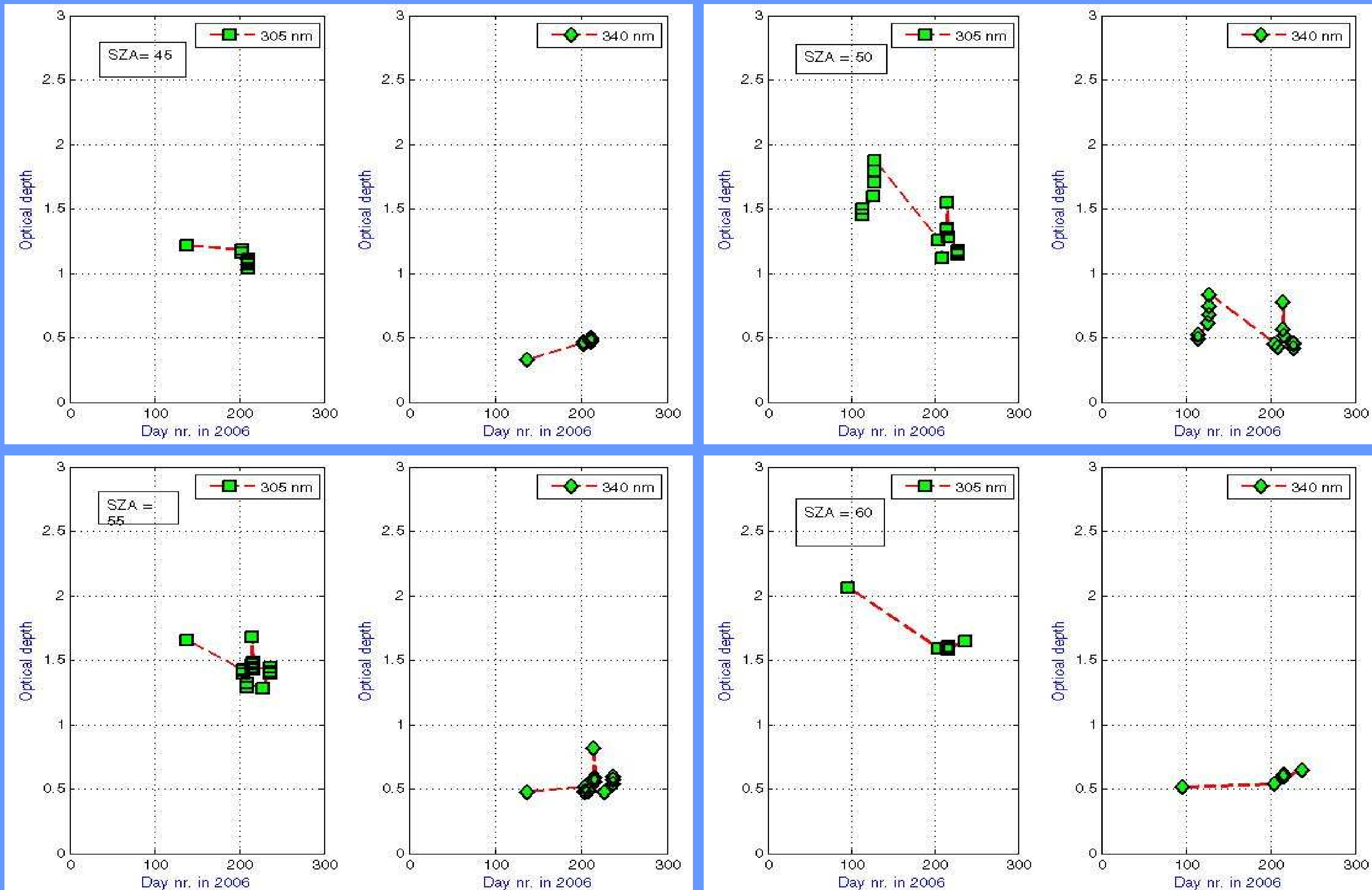


Variation of AOD, Trondheim, 2006





Variation of AOD, Trondheim, 2006



Aerosol size distribution

- Def. Of AOD in term of extinction coefficient [1/cm]:

$$\tau_A(\lambda) = \int_0^{Z_\infty} \beta_e(\lambda, z)dz$$

- And extinction coef. In term of extinction cross section [cm2] is given by:

$$\beta_e(\lambda, z) = \int_{r_j}^{r_{j+1}} \sigma_e(r, \lambda)n(r, z)dr$$

- Based on Lorenz-Mie theory (scattering of a plane wave by isotropic and homogeneouse sphere particles), we can express the extinction cross section in term of mie extinction efficiency Qe, which is function of aerosol radius, wavelength, and complex refractive index.

$$Q_e = \frac{\sigma_e}{\pi r^2} = \frac{2}{x^2} \sum_{n=1}^{\infty} (2n+1) Re(a_n + b_n)$$

- The integral equation which relates optical depth to the size distribution can be written as:

$$\tau_A(\lambda) = \int_0^{\infty} \int_0^{\infty} \pi r^2 Q_{ext}(r, \lambda, m^*) n(r, z) dz dr$$

- Assuming homogeneous atmosphere, the height integeration is constant, eq. of aerosol optical depth becomes:

$$\tau_A(\lambda) = \int_0^{\infty} \pi r^2 Q_{ext}(r, \lambda, m^*) n_c(r) dr$$

- n_c (r) is the unknown columnar aerosol size distribution, that is the number of particle per unit area per unit radius interval in a vertical column through the atmosphere.

- Assuming Junge distribution of aerosol, n(r) can be written as:

$$n_c(r) = \int_0^{Z_\infty} n(r,z)dz = f(r)h(r) = f(r)r^{(-\nu^*+1)}$$

- Note:
  - Log-normal and gamma distribution function can also be used (eq. 5.3.44 & 5.3.45 in LIOU), Junge distribution describes best aerosol in the range from about 0.01-10 µm
  - n(r) is separated into slowly and rapidly varing function represented by f(r) and h(r).
  - Nustar represent a shaping constant (Junge parameter) and is related to aerosol optical depth:

$$\tau_A(\lambda) = \beta\lambda^{-\alpha} = \beta\lambda^{(-\nu^*+2)}$$

- Limiting the integeration over each coarse intervals in r (coarse intervals have the same size on a log-scale), we get Fredholm integral equation:

$$\tau_A(\lambda) = \int_{r_j}^{r_{j+1}} \overbrace{\pi r^2 Q_{ext}(r, \lambda, m^*) r^{(-\nu^*+1)}} f(r) dr$$

- Assuming f(r) is constant within each coarse interval, a system of linear equations can be written as:

$$g = Af + \varepsilon$$

- Where:

$$g_i = \tau_A(\lambda_i) \qquad i=1,2,\ldots p$$

$$A_{ij} = \int_{r_j}^{r_{j+1}} \pi r^2 Q_{ext}(r,\lambda,m^*) r^{(-\nu^*+1)} dr \qquad j=1,2,\ldots q$$

$$f_j = f(\overline{r_j})$$

- And ε is the deviation between measurement (g) and theory (Af) which arise from measurements errors and uncertainties to the exact form of kernel function.

Constrained Linear Inversion [King and LIOU]

- Following the method suggested by Twomey and Phillips, the solution vector f is obtained by minimizing

$$\frac{\partial}{\partial f}\left[\sum_{i=1}^{p}\left(\sum_{j=1}^{q}A_{ij}f_j - g_j\right)^2 C_{ij}^{-1} + \gamma\sum_{j=2}^{q-1}(f_{j-1}-2f_j+f_{j+1})^2\right] = 0$$

- Which leads to:

$$\sum_{i=1}^{p}\left(\sum_{j=1}^{q}A_{ij}f_j - g_j\right) C_{ij}^{-1}A_{ij} + \gamma\sum_{j=2}^{q}H_{jj}f_j = 0$$

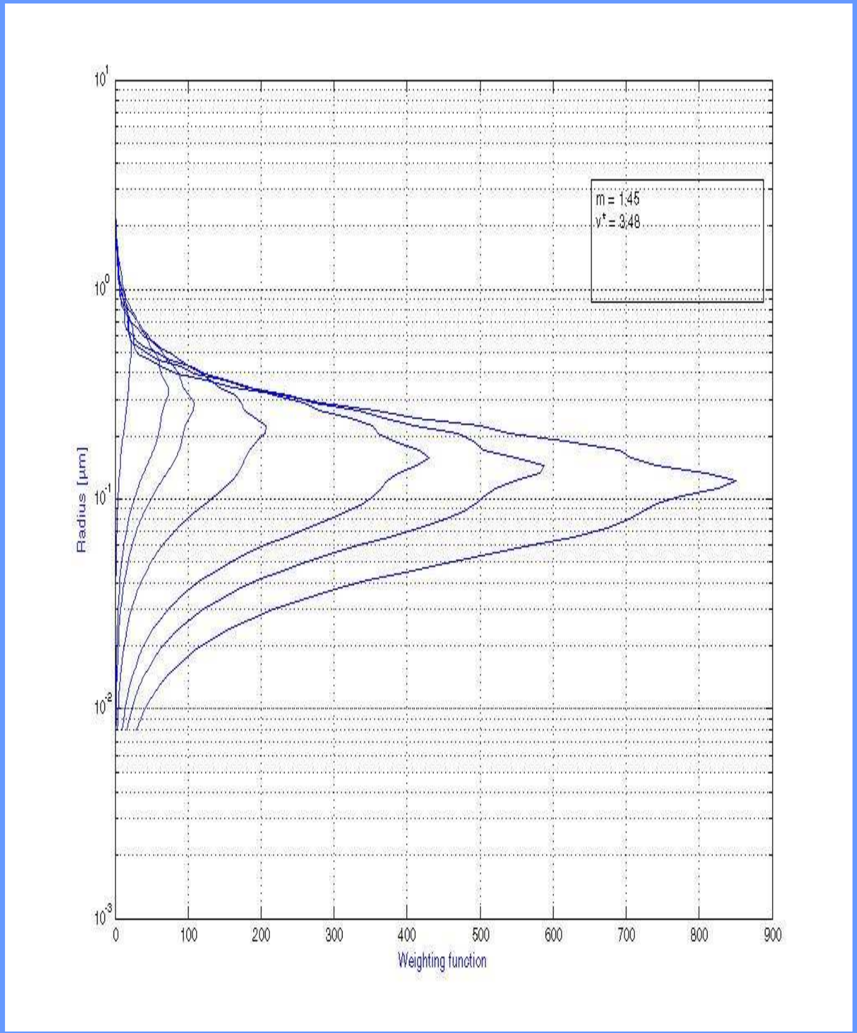
- In matrix form:

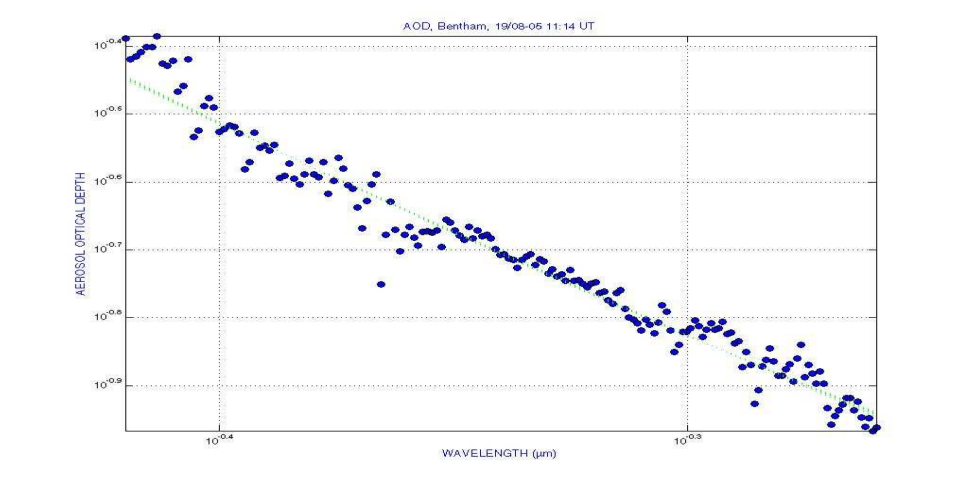
$$A^T A f - A^T g + \gamma H f = 0$$

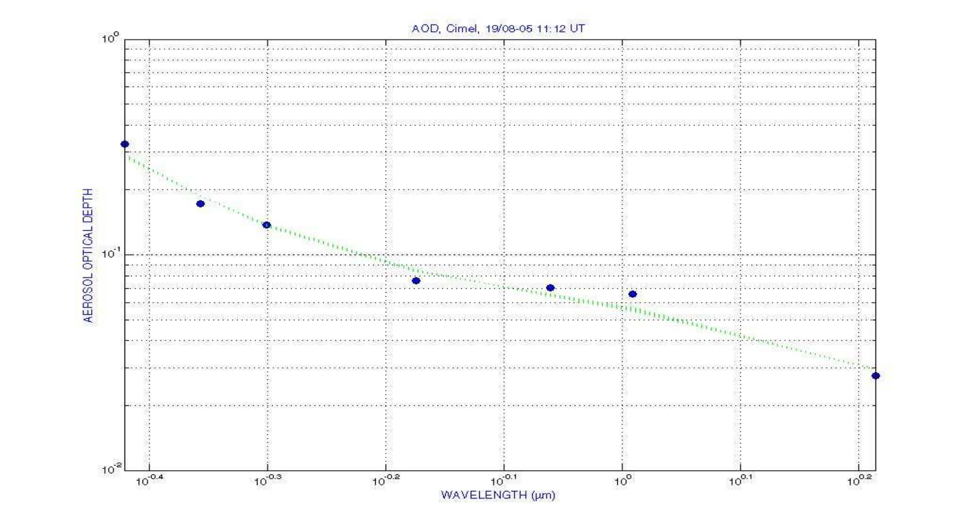
- The solution is given by:

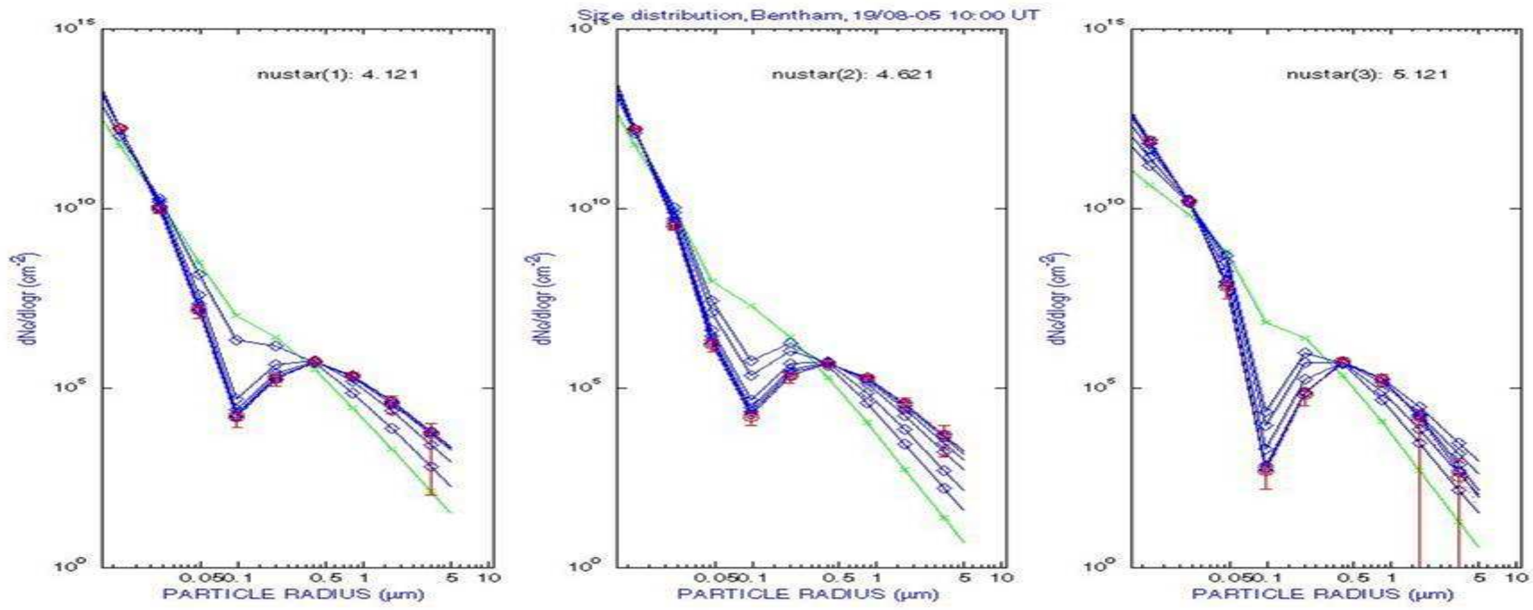
$$f = (A^T A + \gamma H)^{-1} A^T g$$

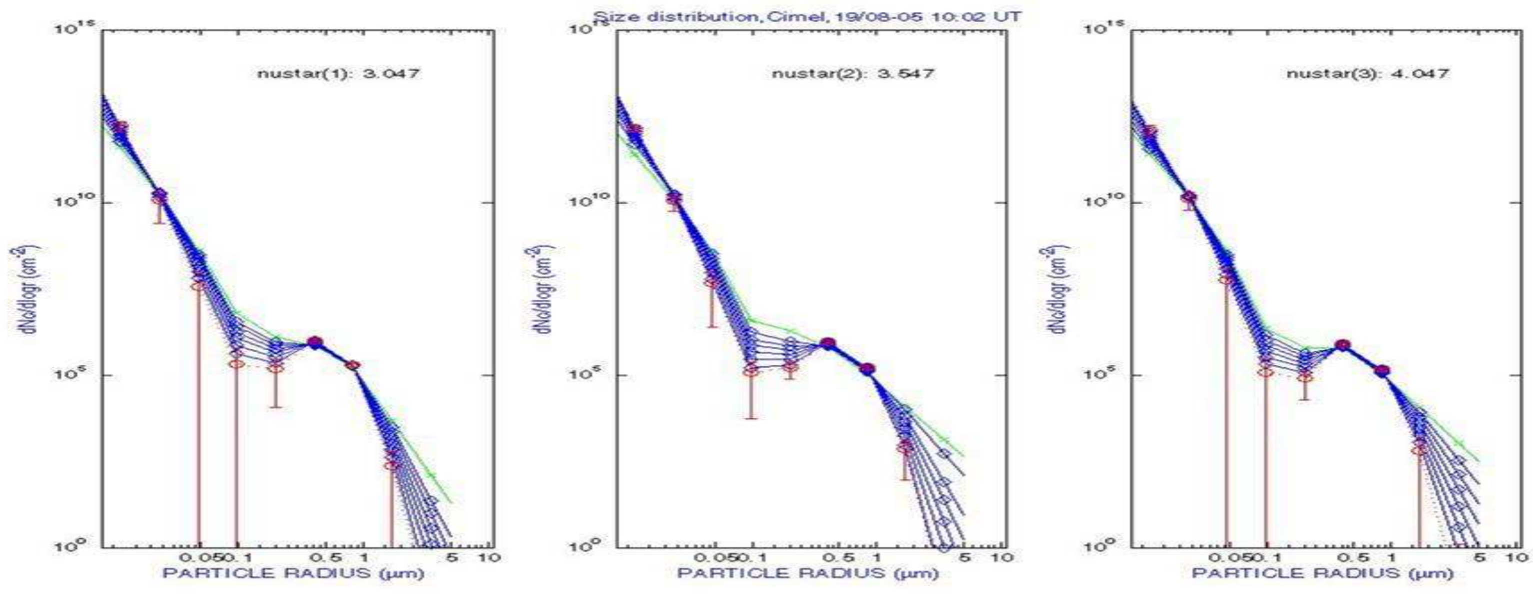
Results from CLI, 19/08-05, Cimel and Bentham data, Trondheim

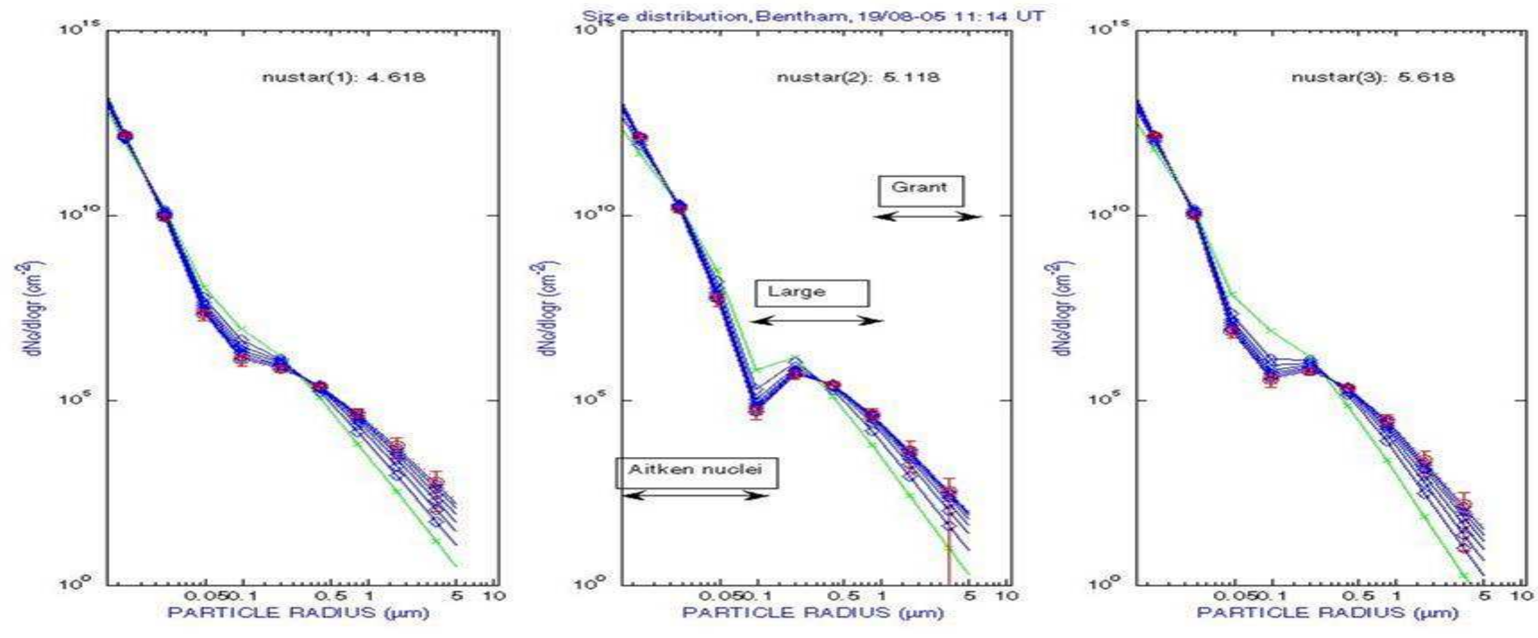


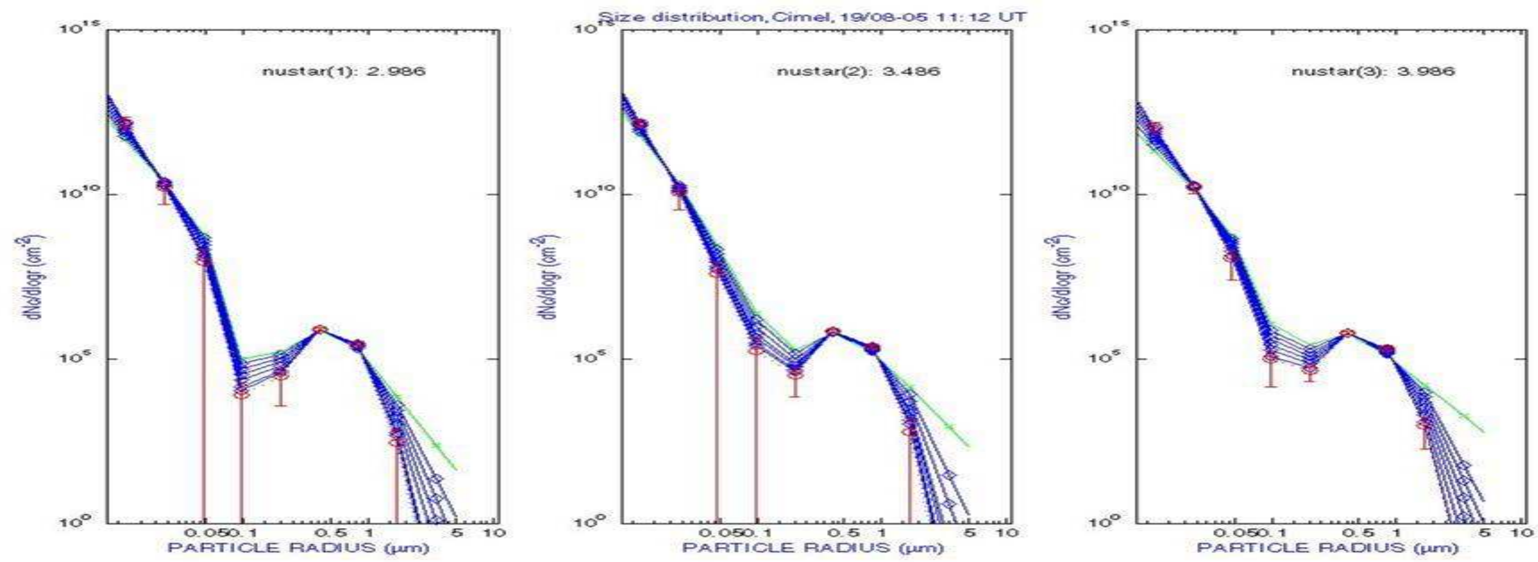




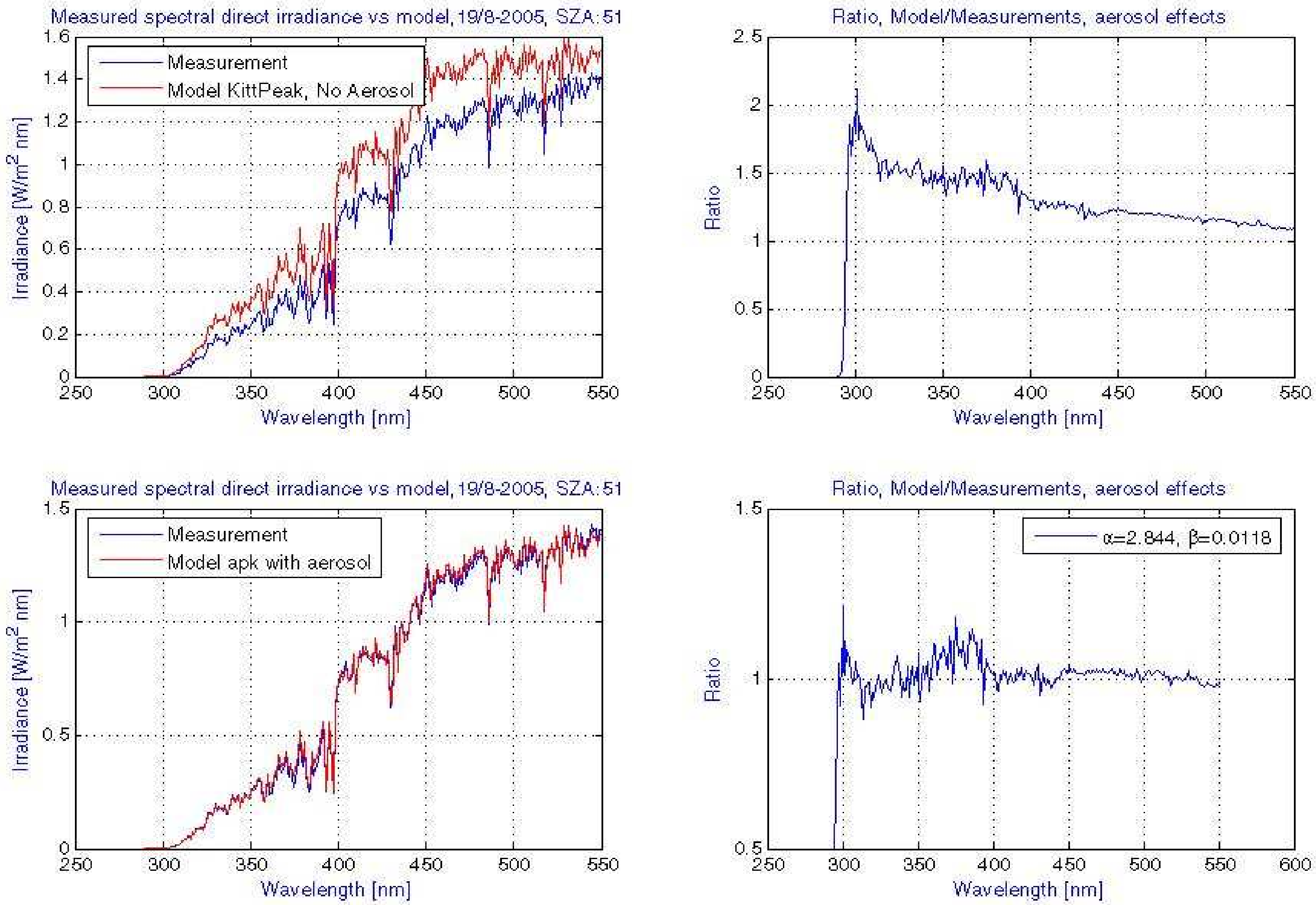

Size distribution, Bentham, 19/08-05 10:00 UT
nustar(1): 4.121
nustar(2): 4.621
nustar(3): 5.121
dN/dlogr (cm⁻²)
PARTICLE RADIUS (µm)

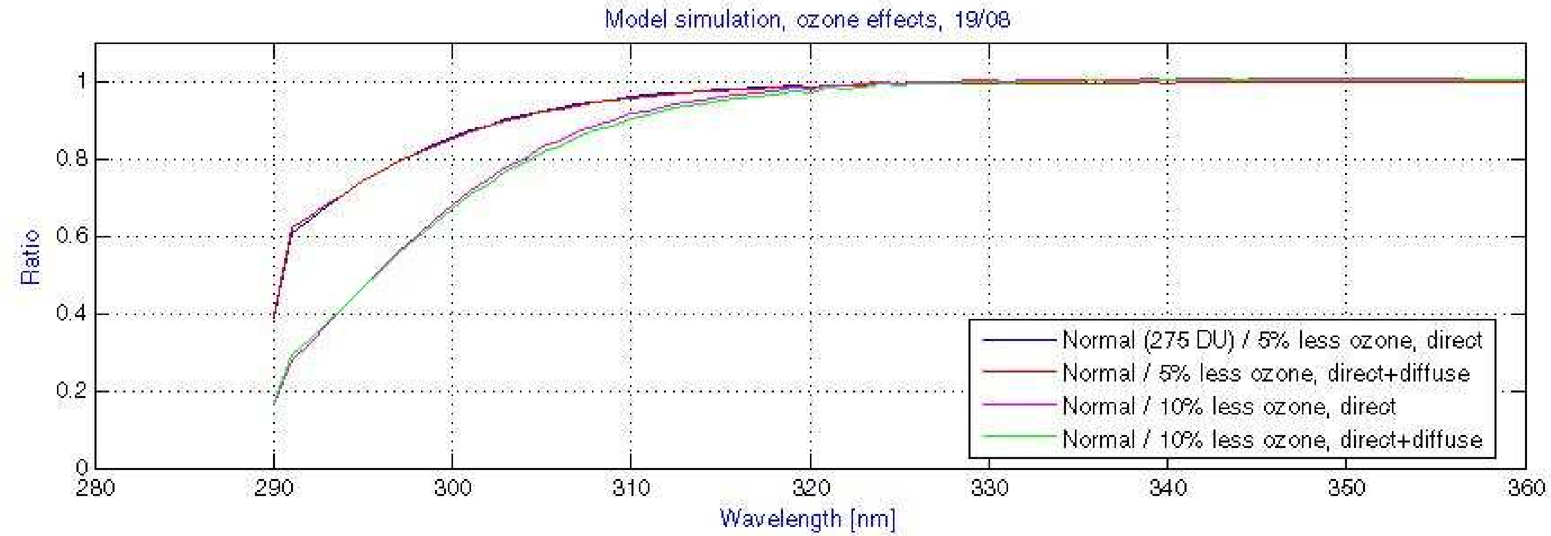

Size distribution, Cimel, 19/08-05 10:02 UT
nustar(1): 3.047
nustar(2): 3.547
nustar(3): 4.047
dN/dlogr (cm⁻²)
PARTICLE RADIUS (µm)

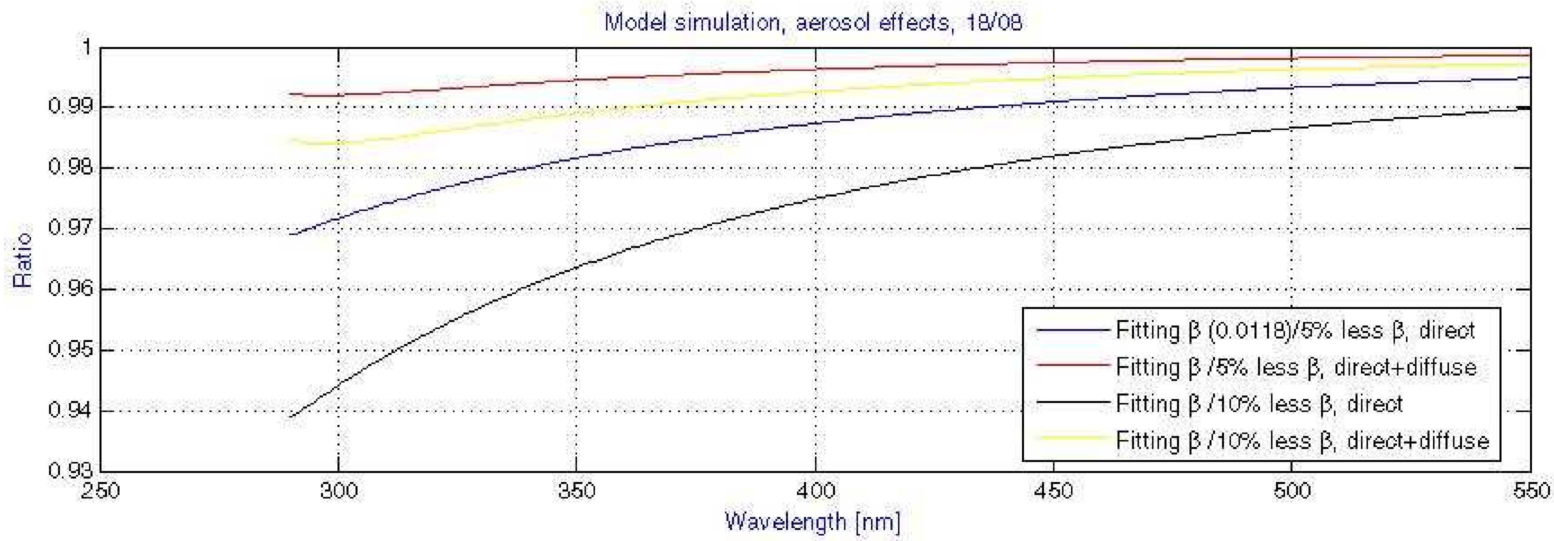

Size distribution, Bentham, 19/08-05 11:14 UT
nustar(1): 4.618
nustar(2): 5.118
nustar(3): 5.618
Grant
Large
Aitken nuclei
dN/dlogr (cm⁻²)
PARTICLE RADIUS (µm)


Size distribution, Cimel, 19/08-05 11:12 UT
nustar(1): 2.986
nustar(2): 3.486
nustar(3): 3.986
dN/dlogr (cm⁻²)
PARTICLE RADIUS (µm)

Aerosol effects, model simulation




Model simulation, ozone effects, 19/08
Ratio
Wavelength [nm]
Normal (275 DU) / 5% less ozone, direct
Normal / 5% less ozone, direct+diffuse
Normal / 10% less ozone, direct
Normal / 10% less ozone, direct+diffuse


Model simulation, aerosol effects, 18/08
Ratio
Wavelength [nm]
Fitting β (0.0118)/5% less β, direct
Fitting β /5% less β, direct+diffuse
Fitting β /10% less β, direct
Fitting β /10% less β, direct+diffuse

Comments &Conclusions

- **AOD retrieval;**
  - **Uncertainty; Bentham 5-10%, ET 5-10% [Woods, dependence on solar cycle], Ozone 1-2% [Molina]**
  - **We have spectral AOD in UV-VIS in Trondheim**
- **Size distribution;**
  - **Result shows that we have all three aerosol type in Trondheim, and they indicate bimodal mode on 19/08-05**
- **Aerosol effects;**
  - **model is very underestimated for wvl < 297,**
  - **clear effect of aerosol amount can be seen.**
  - **5-10% reduction in ozone will lead to ca. 17-35% more direct radiation at 300 nm, while 5-10% reduction in turbidity lead to about ca. 3-6% more direct radiation at 300 nm in Trondheim atmosphere.**
  - **Model simulation shows that aerosols have less effects on direct and global irradiance than ozone.**