Lidar/Sun-radiometer Remote Sensing Technique for Studying Long Range Volcano Ash Transport

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Motivation - because of impressive consequences of Eyjafjallajökull eruptions in 2010

- Scientific team from IPNASB and LOA:

  - carried out series of experimental observations of volcano ash transport in Minsk and Lille in April-May 2010;

  - developed technique of combined lidar and Sun-photometer aerosol sounding for retrieving large non-spherical aerosol particles

EARLINET network stations in studying volcano ash trunsport

Station for combine lidar and Sun-photometer sounding in Minsk, Belarus

Multiwavelength lidar and radiometer station in Lille campaign, May 2010, France

Background

Base principle: **calculation of aerosol layer model corresponding with AERONET and mutiwavlenth lidar data measured.**

Measuring Sun-Photometer data: **direct and scattered sun radiation**

Measuring lidar data:

-multiwavelength backscatter signals (355, 532, 1064 nm)

-parallel and cross-polarized backscatter signal (532 nm)

-Raman signal (*perspective*)

Methodology: **statistical regularization method for solving of incorrectly posed problems**

Results of retrieving: **optical model of aerosol layer characterizing altitude transformation of concentrations of aerosol modes**

Principle of economy (minimal sufficiency, Occam's razor) – Aerosol model should be the most simple if it sufficiently explains the observed data.

Main idea: **A.P. Chaikovsky, O. Dubovik, B.N. Holben, A.I. Bril, "Methodology to retrieve atmospheric aerosol parameters by combining ground-based measurements of multi-wavelength lidar and sun sky-scanning radiometer", Eight International Symposium on Atmospheric and Ocean Optics: Atmospheric Physics, Proceeding of SPIE, vol. 4678, pp. 257-268, 2002.**

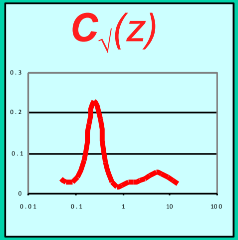
2. Algorithm of data processing

Constructing base equation set

LIDAR

Radiometer

Formatting the model for aerosol layer *$C_{\sqrt{}}(z)$*



Defining the likelihood function of *C√(z)* involving knowledge of data uncertainties

(defining Residual)

Computation of the desired aerosol parameter profiles $C_{\sqrt{}}(z)$ providing maximum of the likelihood function

(minimizing Residual)

LF -it is a conditional probability of parameters C√(z) if we fix values of the set of optical parameters that were measured in a specific experiment.

3. Base equation set

The equation set includes the three following subsystems :

- **Multi-wavelength lidar equations containing information on vertical aerosol parameter profiles.**
- **Integral aerosol layer characteristics provided by AERONET radiometer measurements (aerosol optical thickness values or integral content of aerosol modes over aerosol layer) as functions of $C_\nu(z)$.**
- **Smoothness constraints on vertical aerosol parameters distributions. It is a vector analogue of smoothness constraints to vertical profiles of $\mathbf{C}_\nu$ parameters;**

$\mathbf{0}_\nu^*$ is a null-vector corresponding to a preliminary estimation of the 2-nd order finite differences;

$$\mathbf{L}^*(\lambda_j, z_n) = \mathbf{L}(\lambda_j, \mathbf{C}_\nu(z_n), m_j, z_n) + \mathbf{\Delta}_L^j$$

$$\mathbf{W}^* = \mathbf{W}(\mathbf{C}_\nu(z_n)) + \mathbf{\Delta}_F$$

$$\mathbf{0}_\nu^* = \mathbf{S}_2\mathbf{C}_\nu + \mathbf{\Delta}_{0\nu} \quad (1)$$

Parameters in the left part of equations are measured by lidar and Radiometer or define a priory in the case of smoothness restrictions.

The analytical l expression of these parameters via concentrations of aerosol mode are in the right hand of Eqs.(1).

Base functional

$$\Psi\left(\mathbf{L}^*,\mathbf{W}^*_\nu,\mathbf{C}_\nu\right)=\Psi_1(\mathbf{L}^*,\mathbf{C}_\nu,R_N^j)+\Psi_2\left(V_\nu^*,\mathbf{C}_\nu\left(z_n\right)\right)+\Psi_3\left(\mathbf{C}_\nu\left(z_n\right)\right)=$$

$$\sum_{n=1}^{N-1}\sum_{j=1}^{J}\left(L_n^{*j}-L_n\left(\mathbf{C}_\nu\right)\right)^T\mathbf{\Omega}_L^{-1}\left(L_n^{*j}-L_n\left(\mathbf{C}_\nu\right)\right)+$$

$$\sum_\psi\left(W_\psi^*-\mathbf{W}_\psi\left(\mathbf{C}_\nu\left(z_n\right)\right)\right)^T\mathbf{\Omega}_W^{-1}\left(W_\psi^*-\mathbf{W}_\psi\left(\mathbf{C}_\nu\left(z_n\right)\right)\right)+\frac{E_m}{\chi_\nu^2}$$

- Ψ_1 **- contain lidar data**
- Ψ_2 **- contain radiometer data**
- Ψ_3 **- depend on smoothness of $C_\nu^k(z_n)$ profiles**

5. Involving of depolarization data measured

- Cross-polarized lidar signal corrected:

$$\mathbf{L}_{\perp}^{*}\left(\lambda_j, z_n, S^{*}\left(\lambda_j, z_n\right)\right) = \frac{S_{\perp}^{*}\left(\lambda_j, z_n\right)}{S_{\perp}^{*}\left(\lambda_j, z_N\right)} \beta_m^j(z_N) \exp(-2\tau_m(z_n, z_N))$$

$$\mathbf{L}_{\perp}\left(C_{\nu}, \lambda_j, z_n\right) = \frac{(1+\chi)\left(\beta_{\perp a}(\lambda_j, z_n) + \mu\beta_{\Uparrow a}(\lambda_j, z_n) + \frac{\chi+\mu}{\chi+1}\beta_m(\lambda_j, z_n)\right)}{\chi R_{\perp}(\lambda_j, z_N) + \mu R_{\Uparrow}(\lambda_j, z_N)} \exp\left(-2\int_{z_N}^{z_n} e_a(\lambda_j, z_n) dz\right)$$

where: $\chi(\lambda_j) = \frac{\beta_{\perp m}(\lambda_j, z_n)}{\beta_{\Uparrow m}(\lambda_j, z_n)}$, μ-penetration capability between channels $\Uparrow \Rightarrow \perp$

$$\beta_{\perp a}(\lambda_j, z_n) + \mu\beta_{\Uparrow a}(\lambda_j, z_n) = \sum_{\nu} C_{\nu}(z_n) \frac{B_{\Uparrow\nu,j}}{W_{\nu}} + \mu \sum_{\nu} C_{\nu}(z_n) \frac{B_{\Uparrow\nu,j}}{W_{\nu}}$$

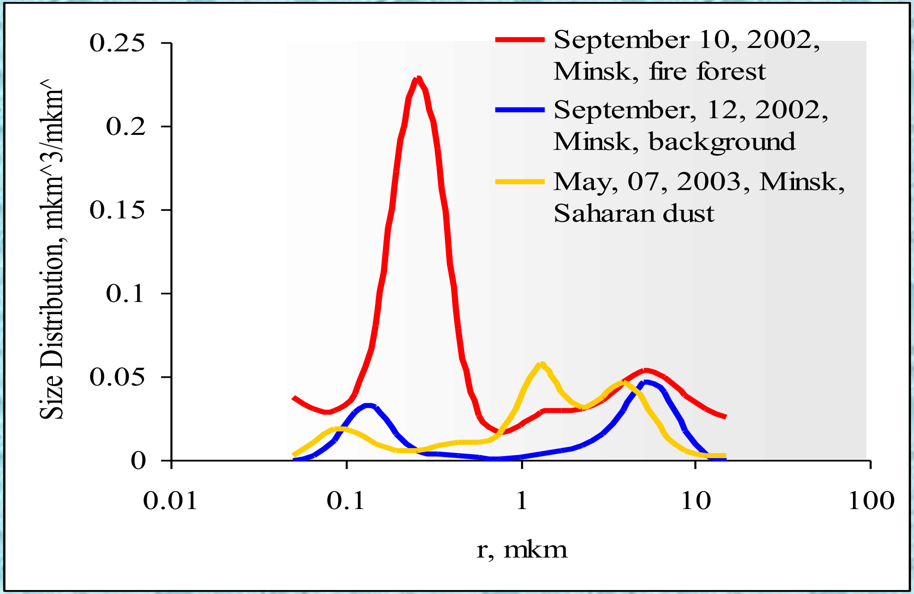
$$B_{\perp\nu,j} = \frac{1}{4\pi} \varpi_{0,\nu}(\lambda_j) \frac{P_{1,1}^{\nu}(\lambda_j, z_n, \theta = 180^0) - P_{2,2}^{\nu}(\lambda_j, z_n, \theta = 180^0)}{2} E_{\nu,j}$$

$$B_{\Uparrow\nu,j} = \frac{1}{4\pi} \varpi_{0,\nu}(\lambda_j) \frac{P_{1,1}^{\nu}(\lambda_j, z_n, \theta = 180^0) + P_{2,2}^{\nu}(\lambda_j, z_n, \theta = 180^0)}{2} E_{\nu,j}$$

Aerosol model and approaches in combined lidar/Sun-photometer technique

- **Aerosol layer is defined by two sets of parameters:**
- a) - for characterization aerosol layer as a whole – size distribution of fine and coarse modes, total content of aerosol fractions (column concentrations), their refractive index and sphericity (percentage of spherical particles in aerosol mixture);
- b)-concentrations of aerosol modes that changes over altitude.
- **Two variants of retrieving algorithms are developed:**
- ***sequential inversion*** of lidar and radiometer data that is realized by means of preliminary calculation of a-type parameters from radiometric measurements in accordance with AERONET inversion algorithm and subsequent inversion of b-type parameters using column characteristics of aerosol layer as a priori information;
- ***parallel inversion approach*** for calculation optimal aerosol model in joint procedure of inversion of united data of lidar and radiometer systems; ***specifics:*** improvement of a-type parameters (backscatter phase function, sphericity) and complication of calculation procedure.

4. Aerosol layer model



- Aerosol is a mixture of spheres and spheroids and their refractive index is constant over the all particles

- Aerosol consist of two modes. Parameters of each mode are retrieved from *synchronous* AERONET measurement. Concentrations of modes change over altitude

Aerosol model is determined by integral parameters of aerosol layer and two parameters: $C_1(z)$ and $C_2(z)$ - concentration of fine and coarse modes.

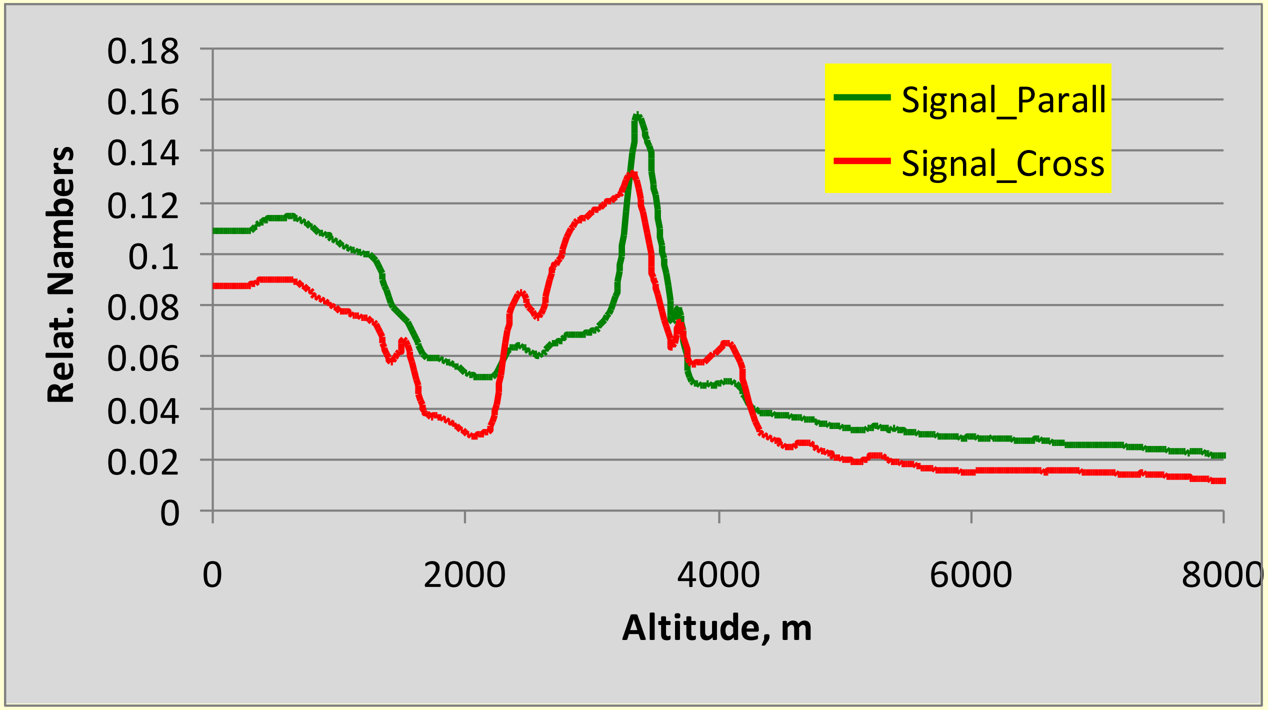
Interpretations of combined polarization lidar and photometer data- aerosol consists of three modes:

-fine mode as homogeneous mixture of spherical and spheroid particles, -

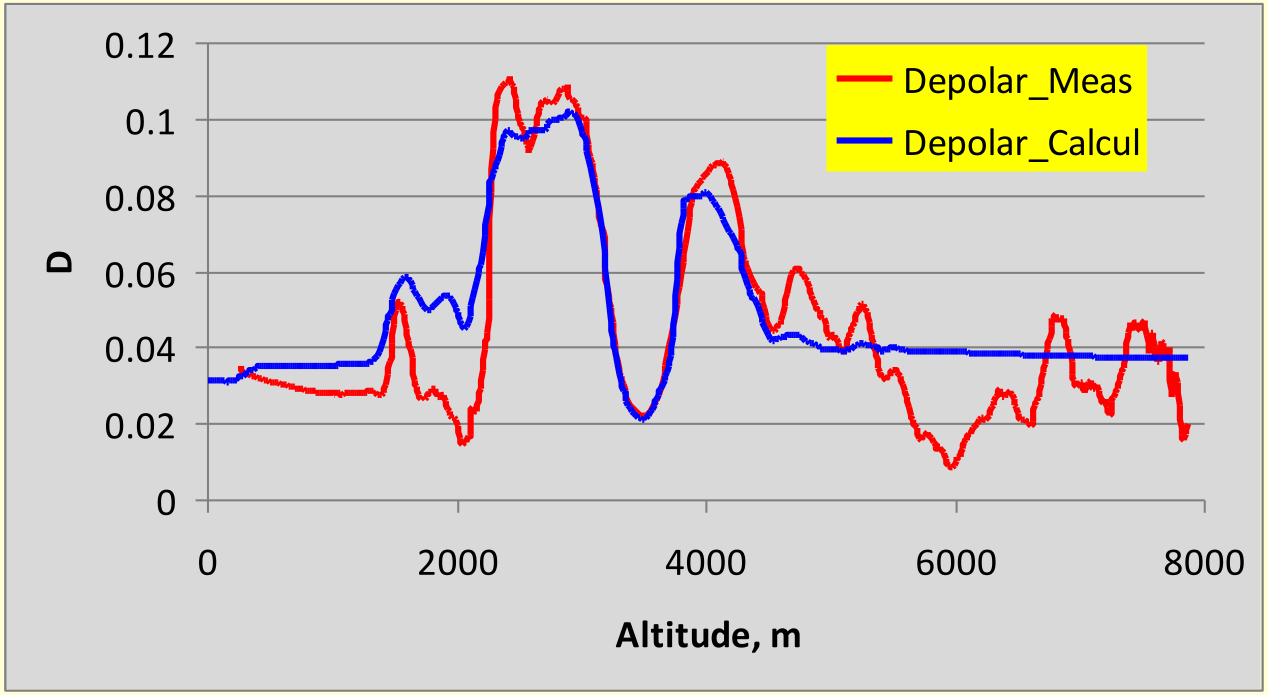
- coarse spherical mode

-coarse non-spherical mode

Parallel and cross-polarized components of lidar signal, 532 nm, dust events, 25-03-2007, Minsk



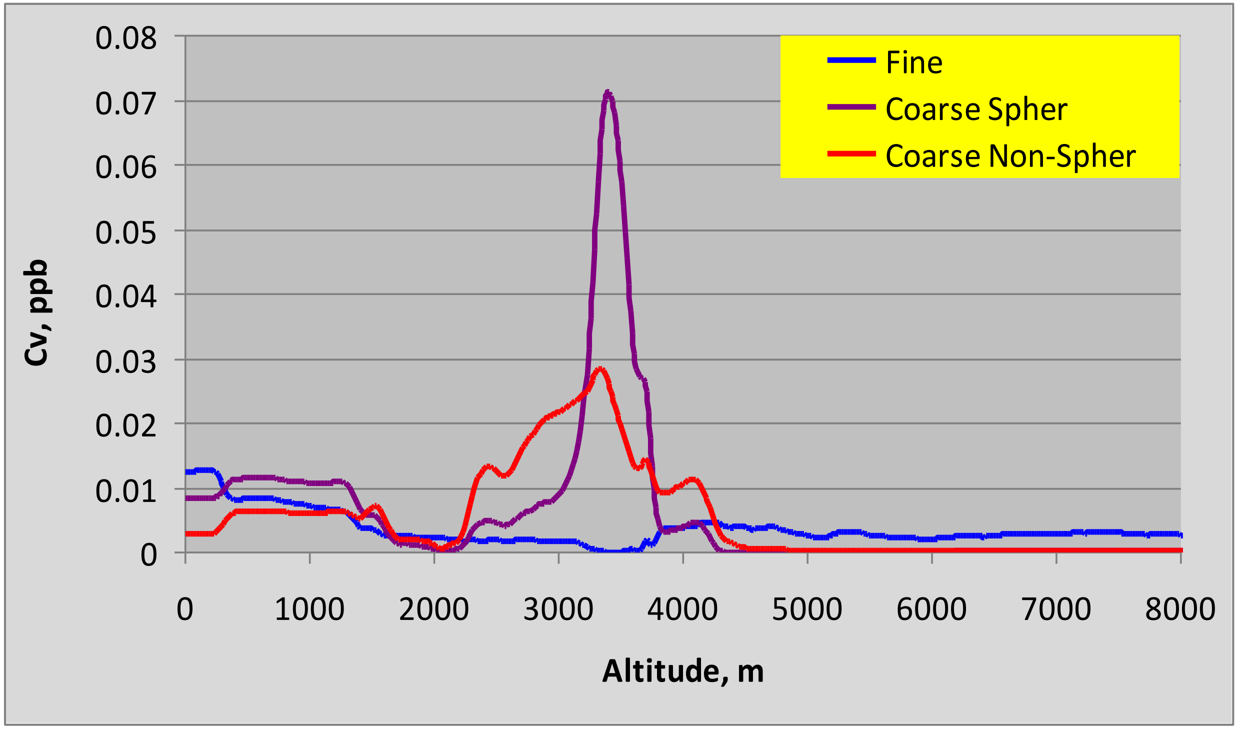
Measured and calculated aerosol depolarization ratio, dust events, 25-03-2007, Minsk



Retrieved altitude distributions of concentrations of aerosol modes, dust events, 25-03-2007, Minsk.

Mass concentration [ug/m^3] = Cv x 1000 ***d*** [g/cm^3];

d is a density of aerosol particles



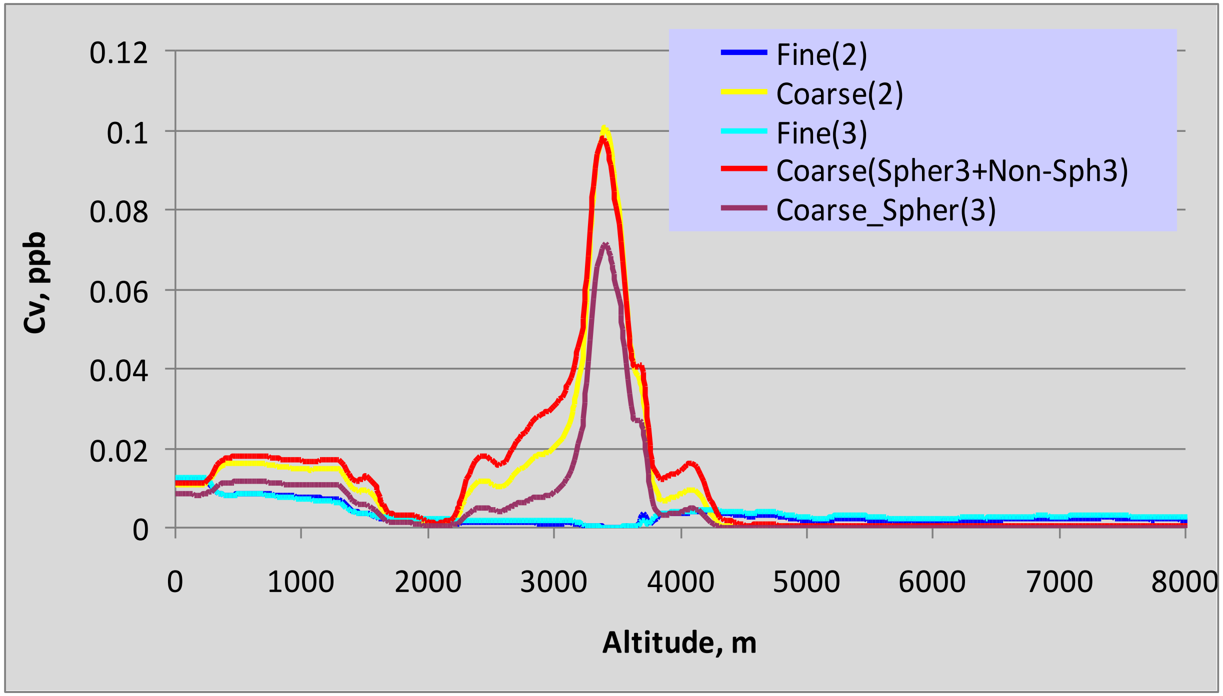
-Retrieved altitude distributions of concentrations of aerosol modes for two aerosol model:

fine and coarse modes;

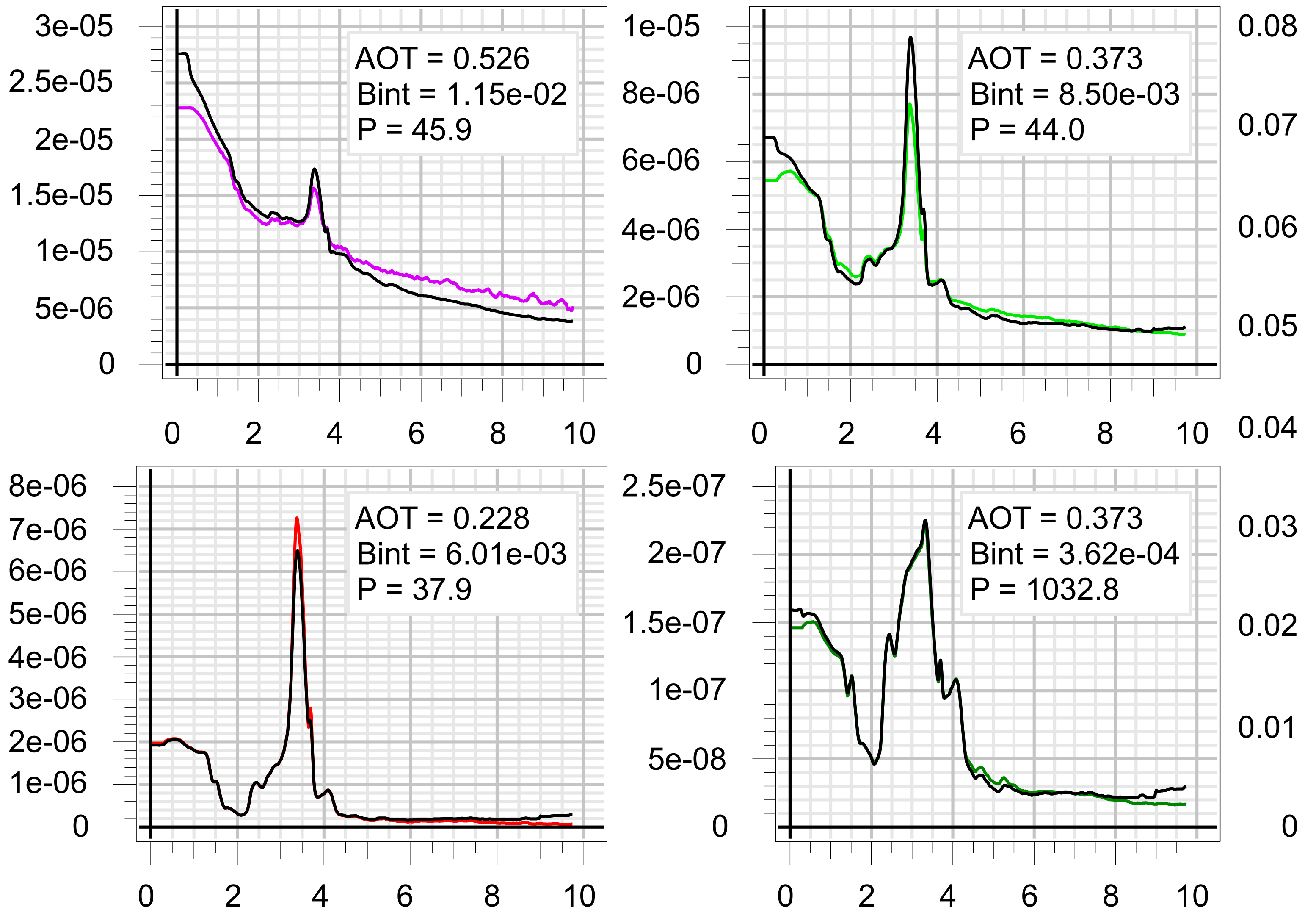
fine, coarse spherical and coarse non-spherical modes,

dust events,

25-03-2007, Minsk

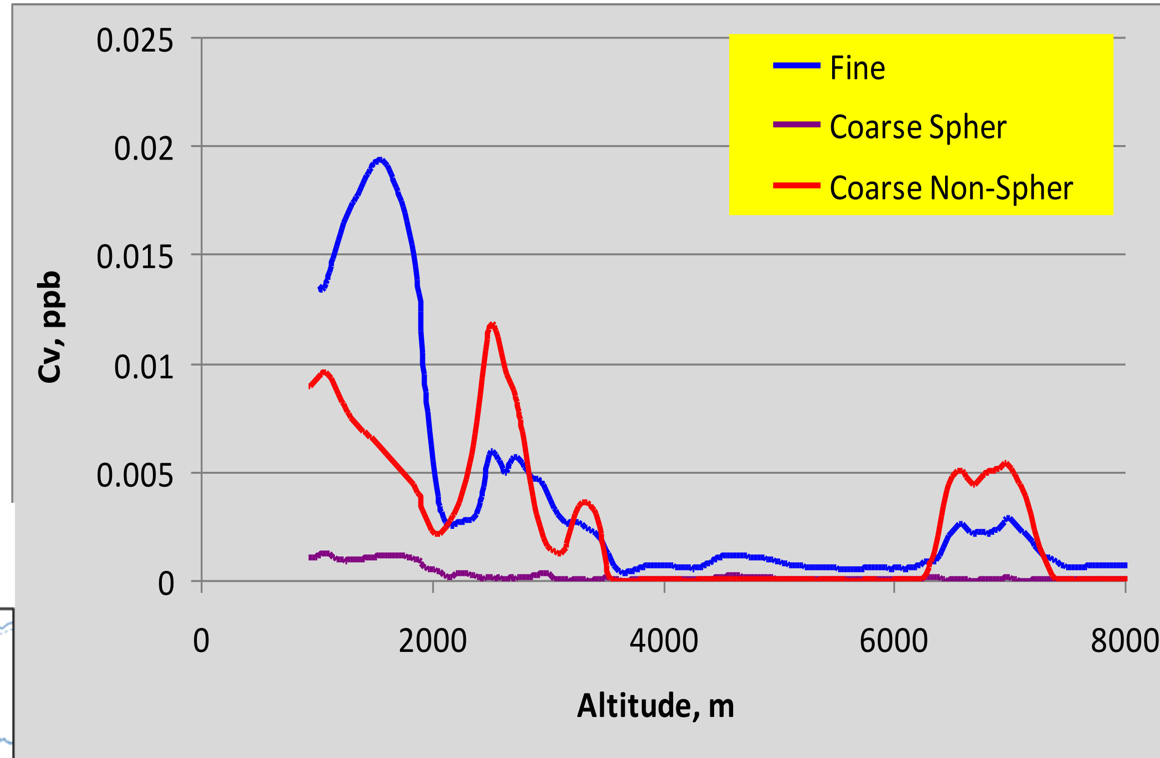


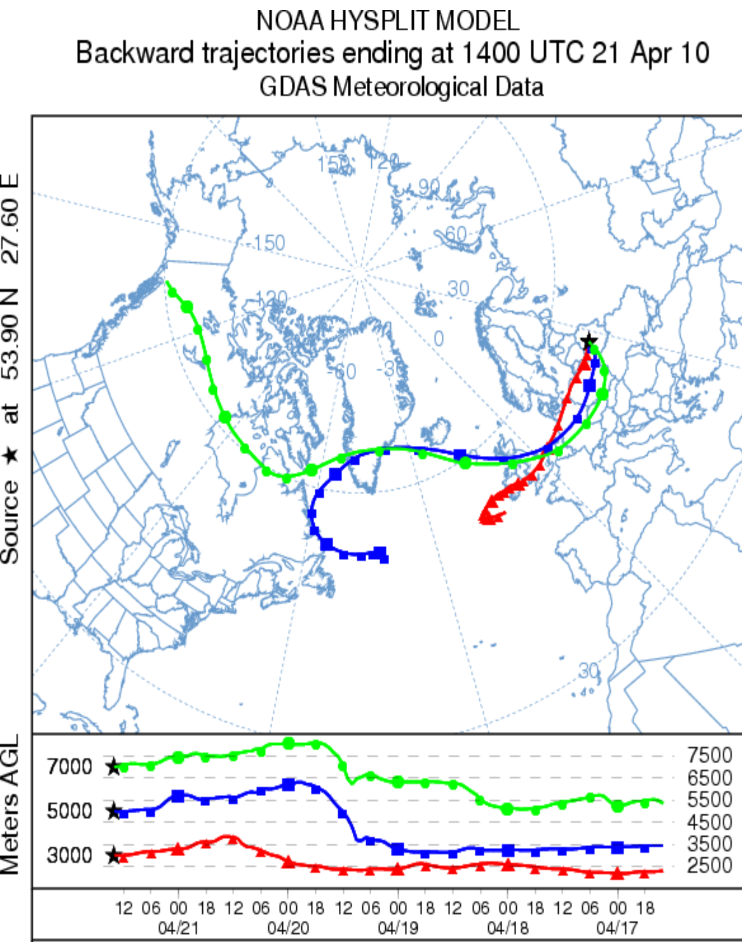
Software for processing data of combined lidar and sun-photometer sounding

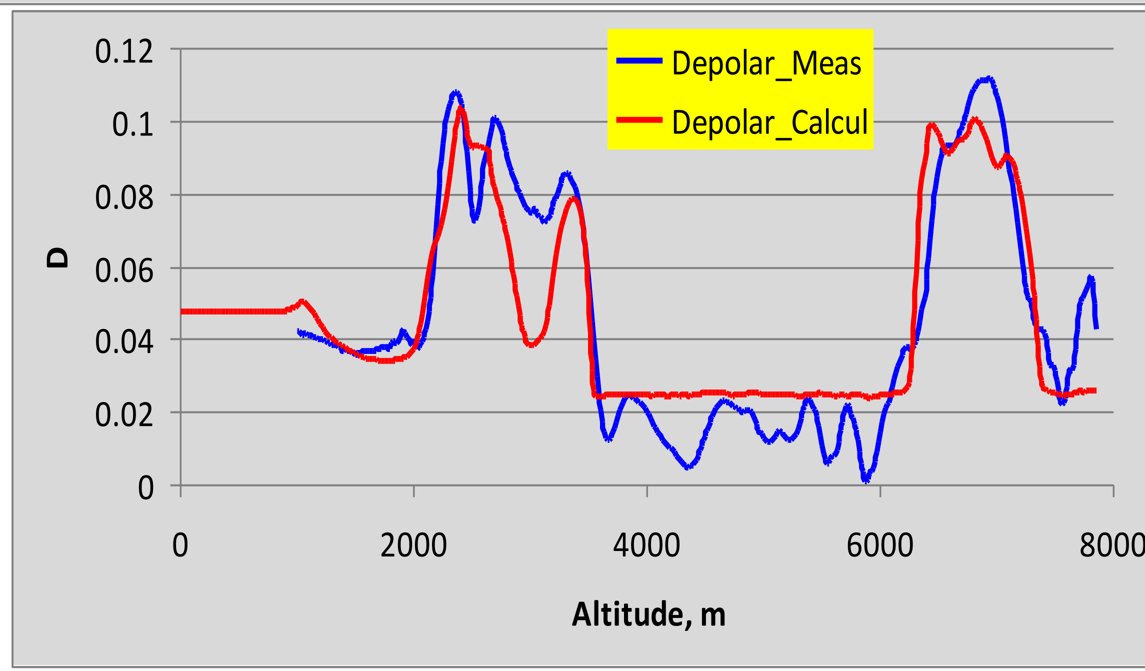


Measured and calculated lidar signal for three component aerosol model, dust event, 25-03-2007, Minsk

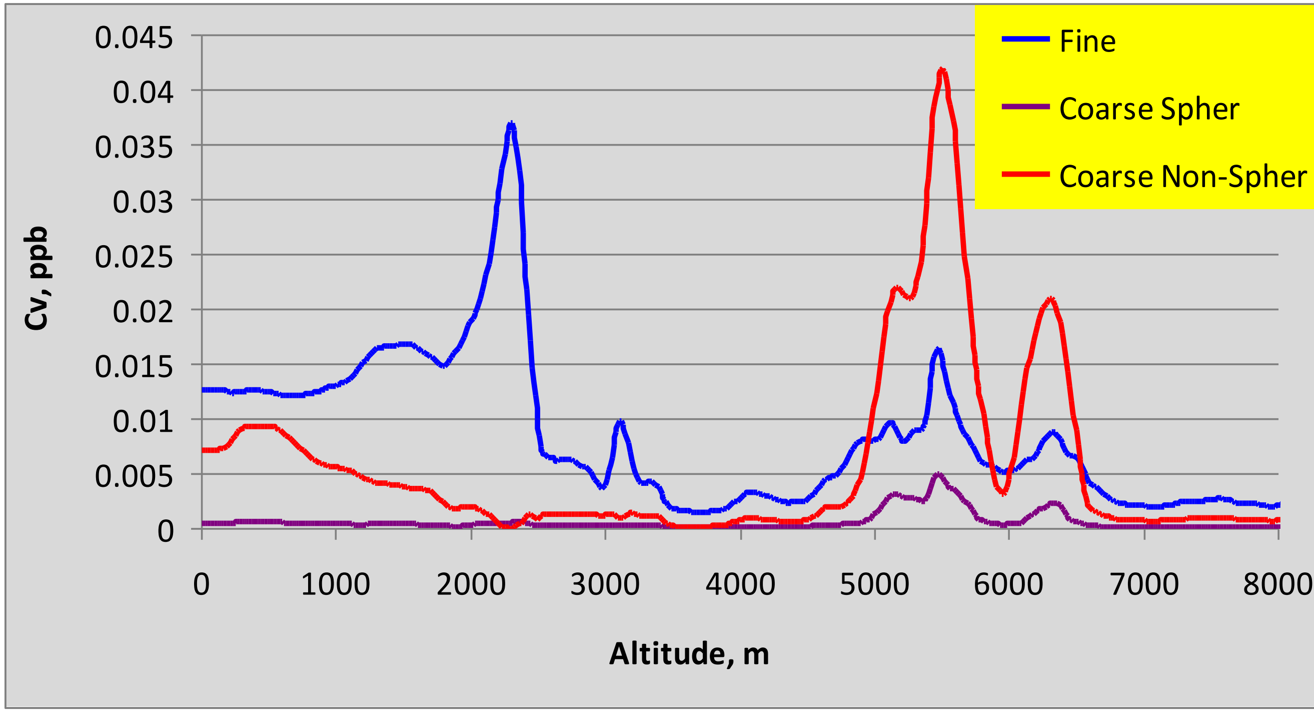
Transformation of aerosol parameters, volcano event, 21-04-2010, 14:07, Minsk



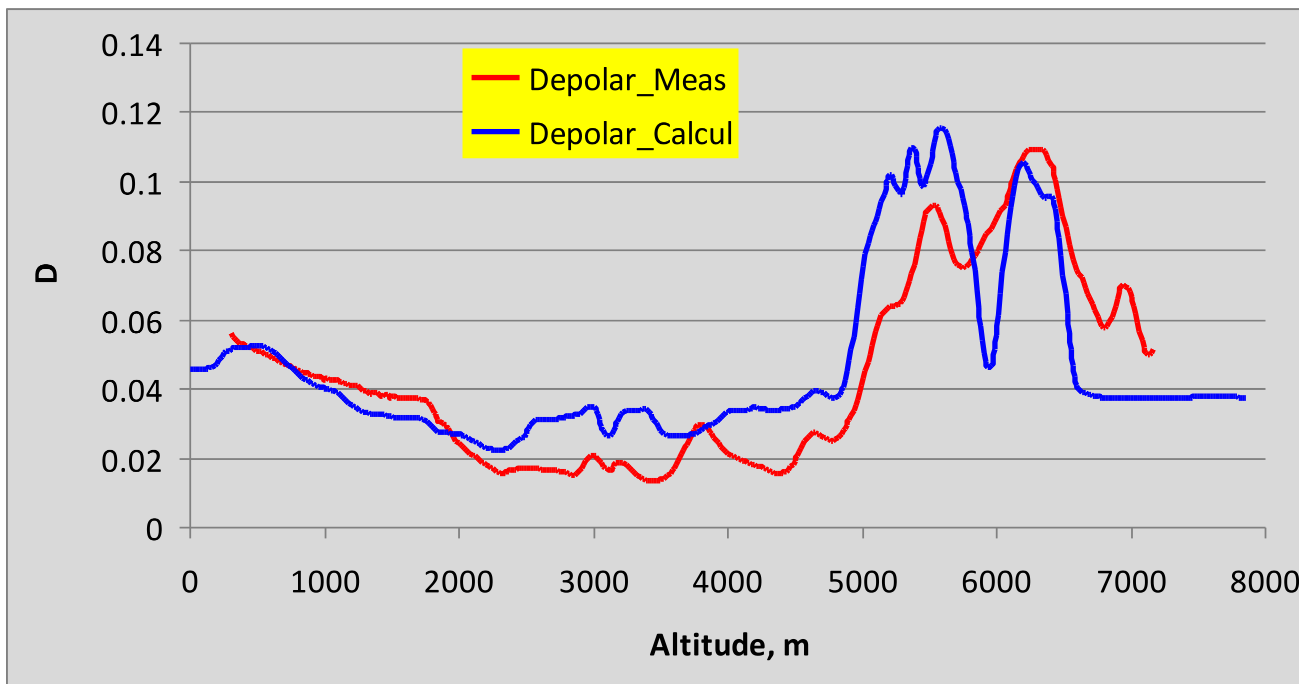




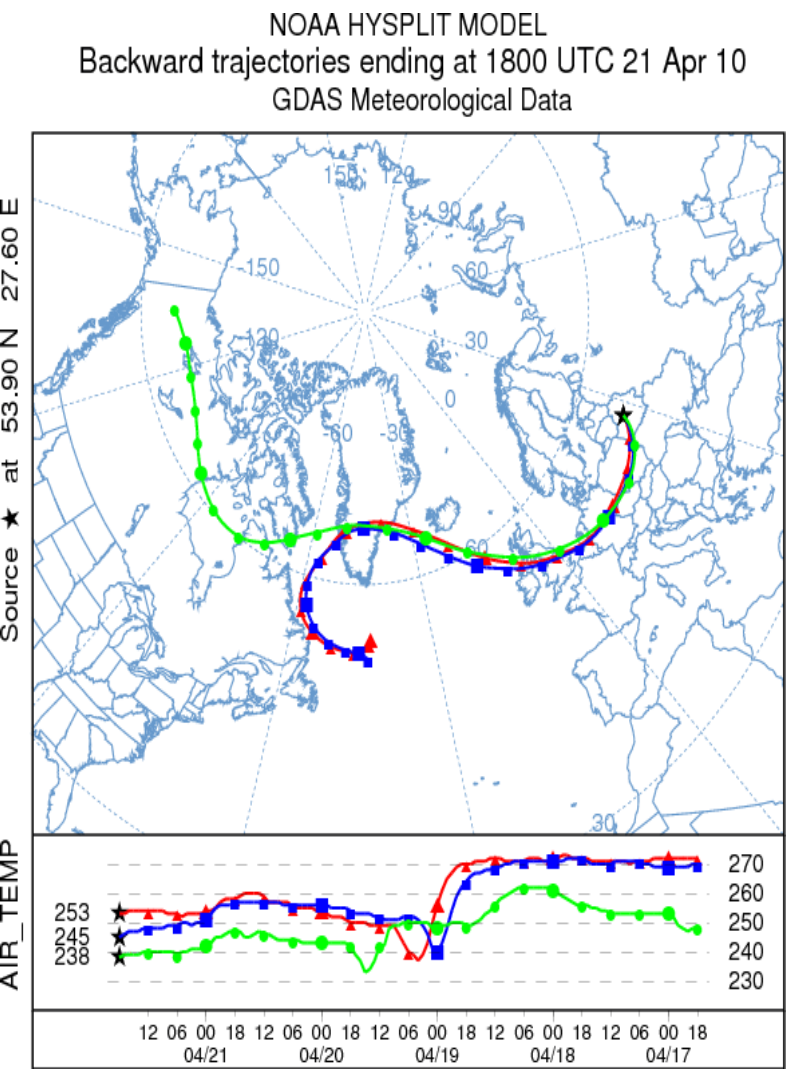
Retrieved altitude distributions of concentrations of aerosol modes, volcano event, 21-04-2010, 15:50, Minsk

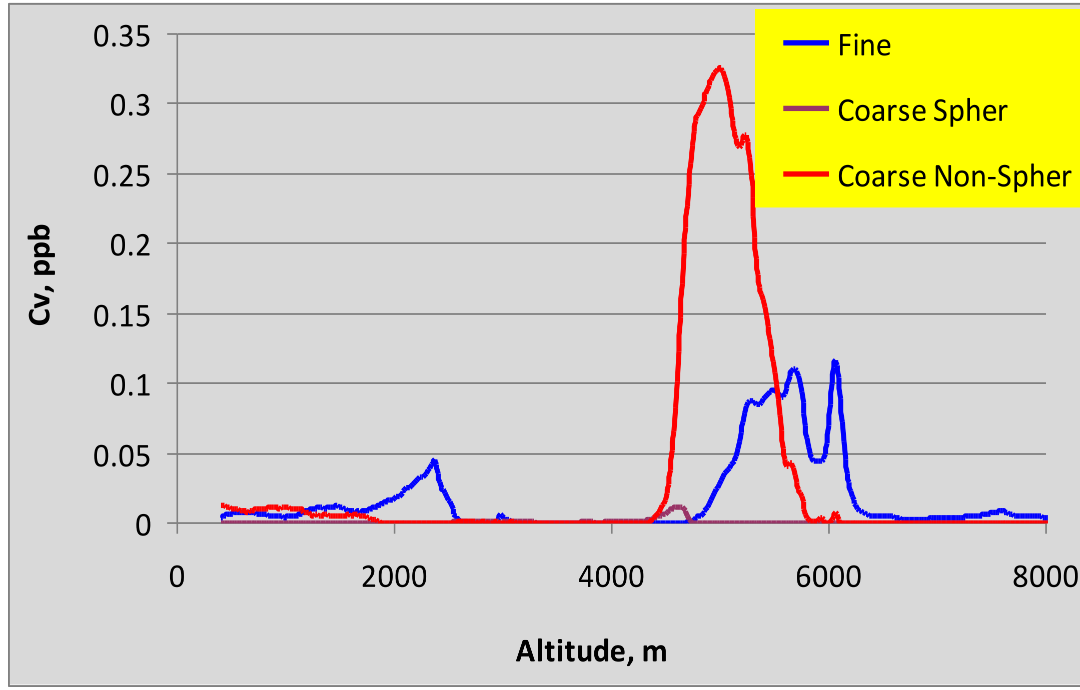


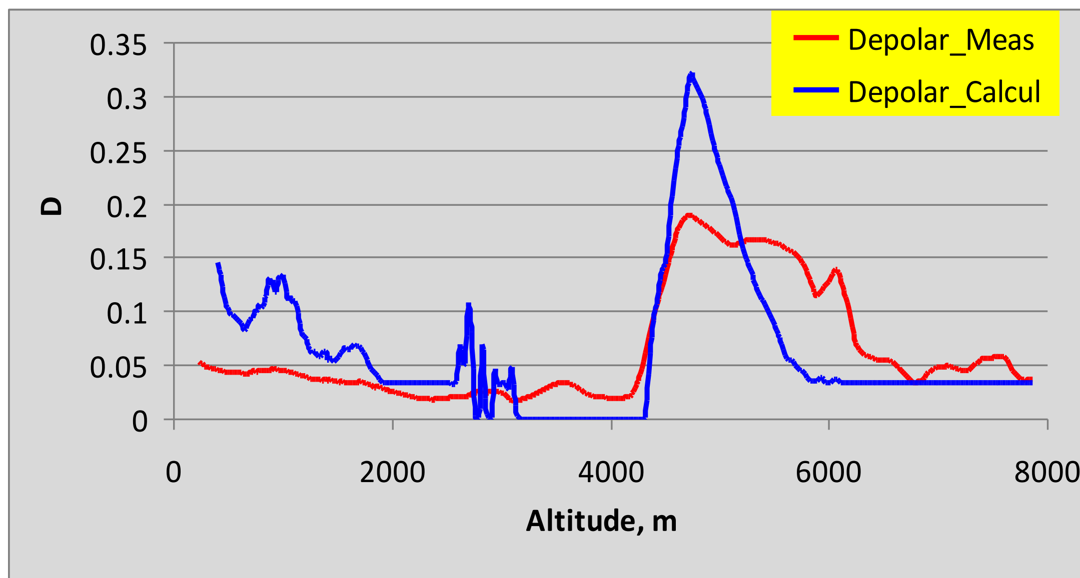
Measured and calculated aerosol depolarization ratio, volcano event, 21-04-2010, 15:50, Minsk



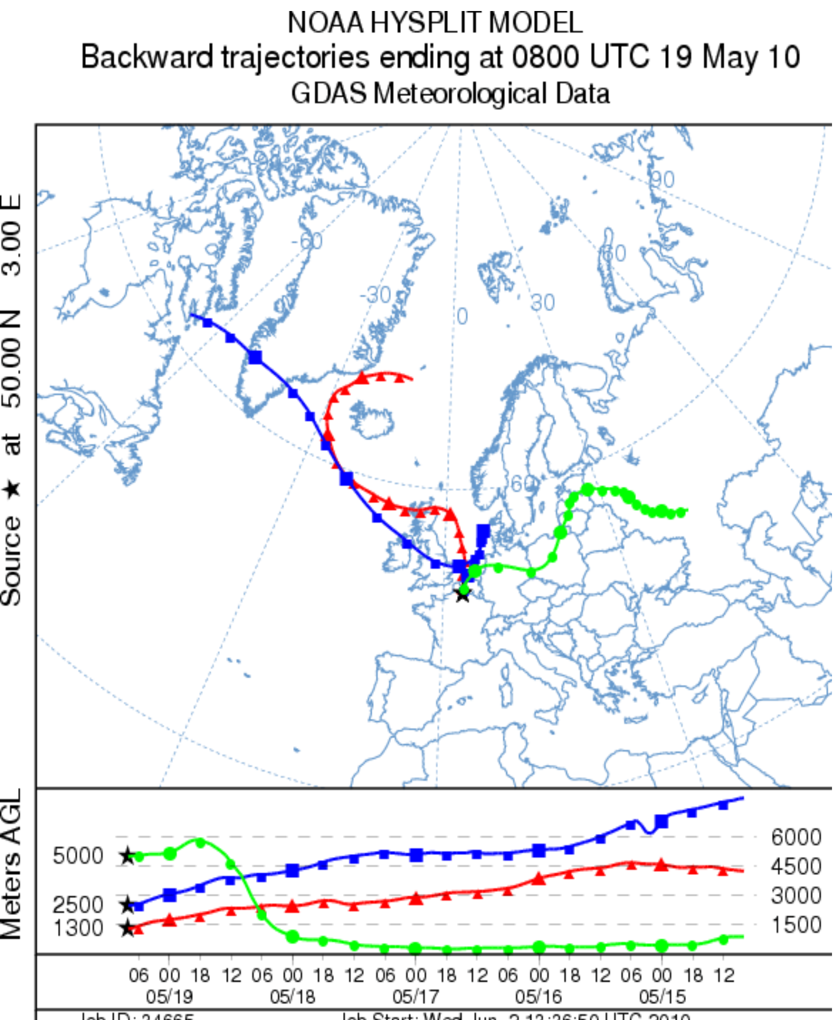
Transformation of aerosol parameters, volcano event, 21-04-2010, 18:10, Minsk

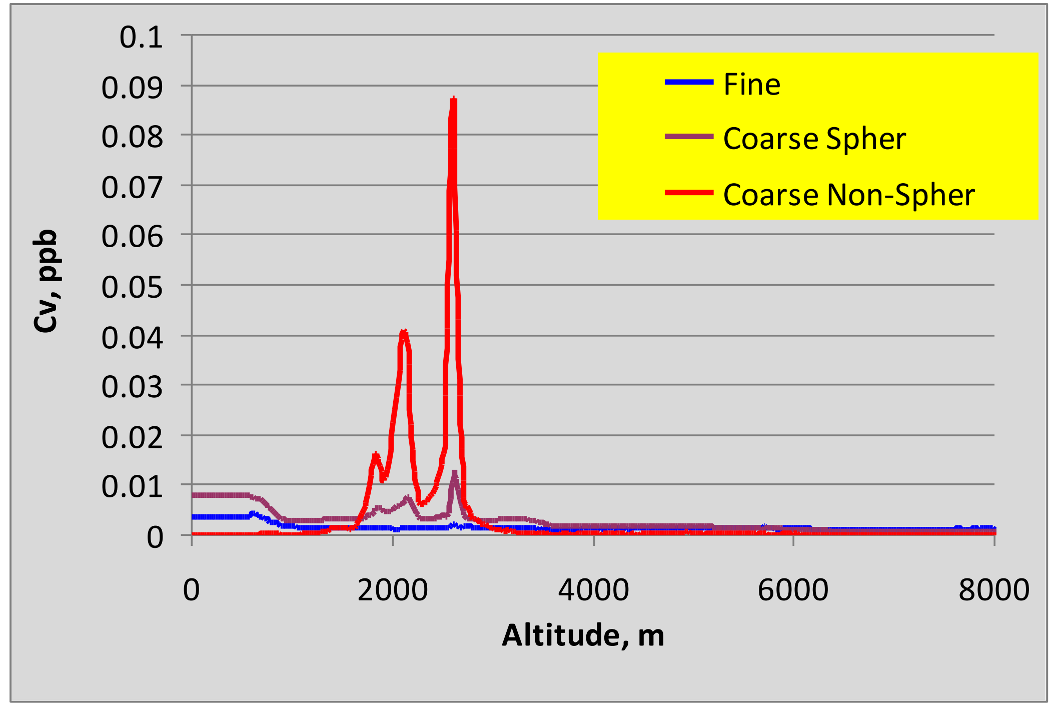


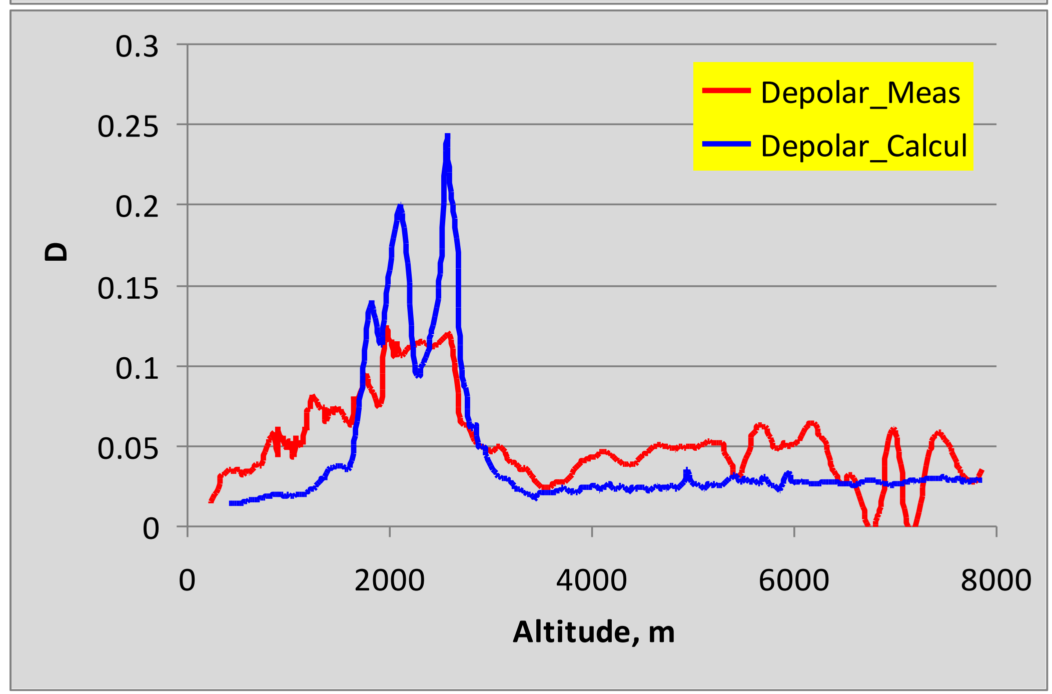




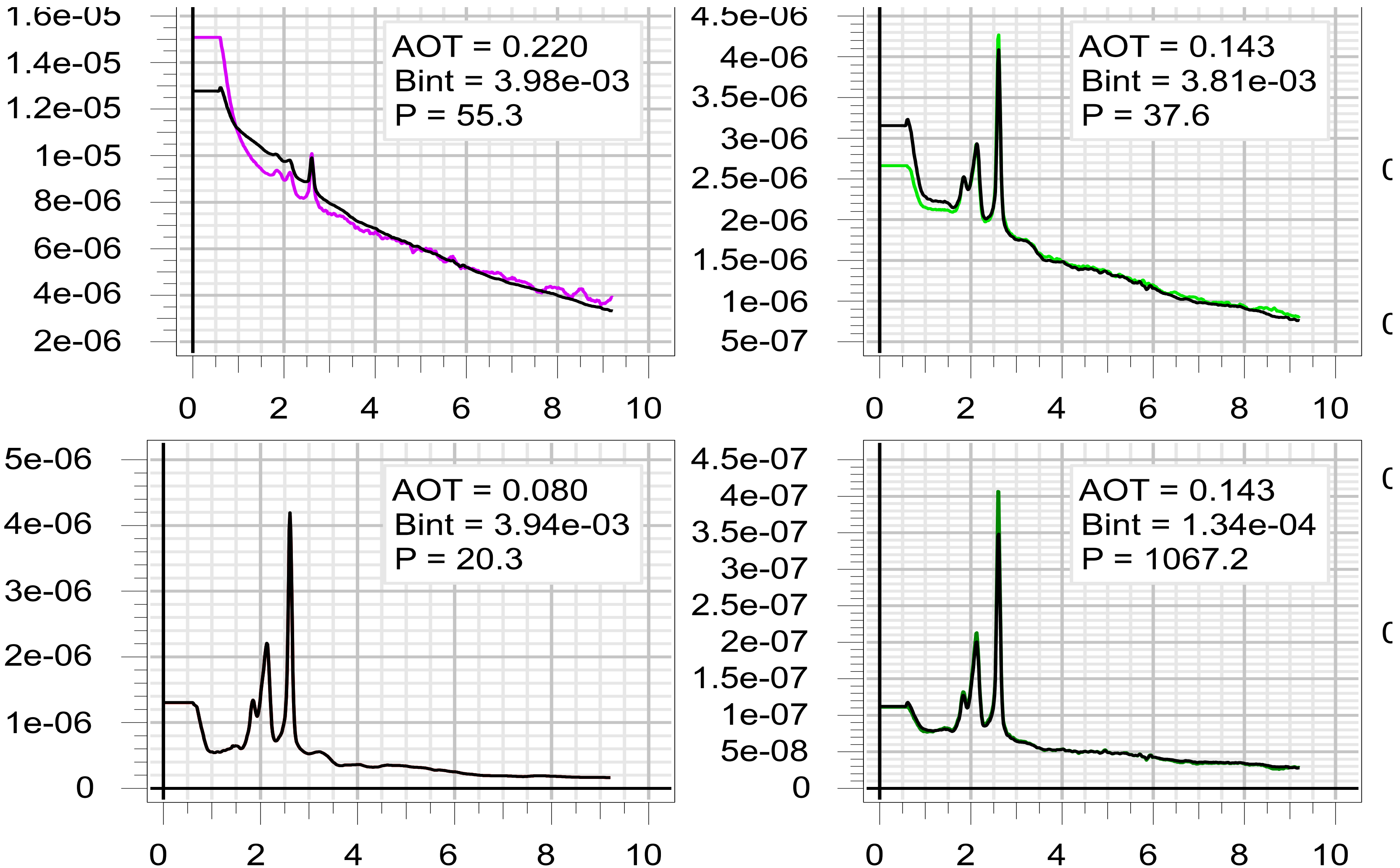
Aerosol parameters retrived, volcano event, 19-05-2010, 07:50, Lille





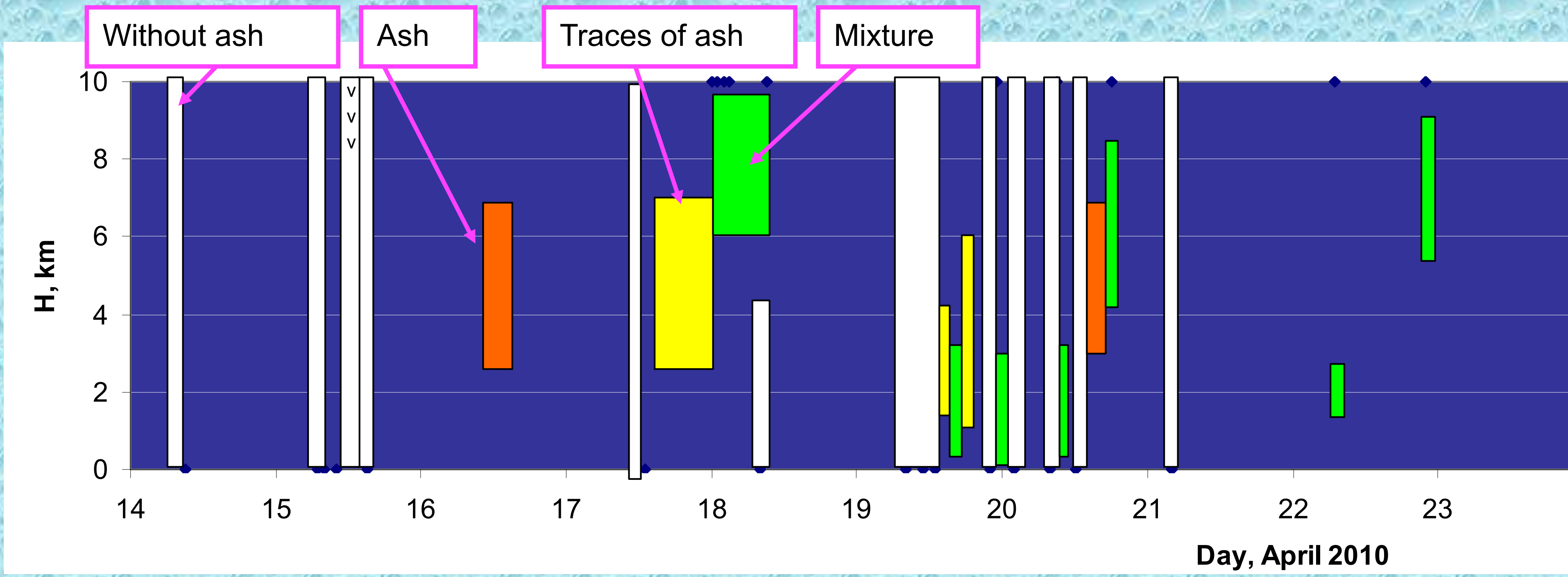


Software for processing data of combined lidar and sun-photometer sounding



Measured and calculated lidar signal for three component aerosol model, volcano event, 19-05-2010, 07:50, Lille

Results of ash identification, Minsk lidar station, Belarus, April 2010



Summary

- Nowadays, we have created software package for processing data of combined lidar and Sun-photometer sounding (***sequential variant, with possibility of polarization lidar data processing),*** adapted to EARLINET (CIS-LiNet) and AERONET data formats and began it application at some joint lidar and Sun-photometer stations.
- We suggest that multiwavelenth polarization lidar data combined with Sun-photometer results in the frame of parallel inversion approach can significantly improve resulted optical aerosol models transforming it into altitude dependent distributions, as well as more objective evaluations of some characteristics of aerosol particles (refractive index, spherisity, backscatter phase function) will be achieved.

Thank you very much for attention