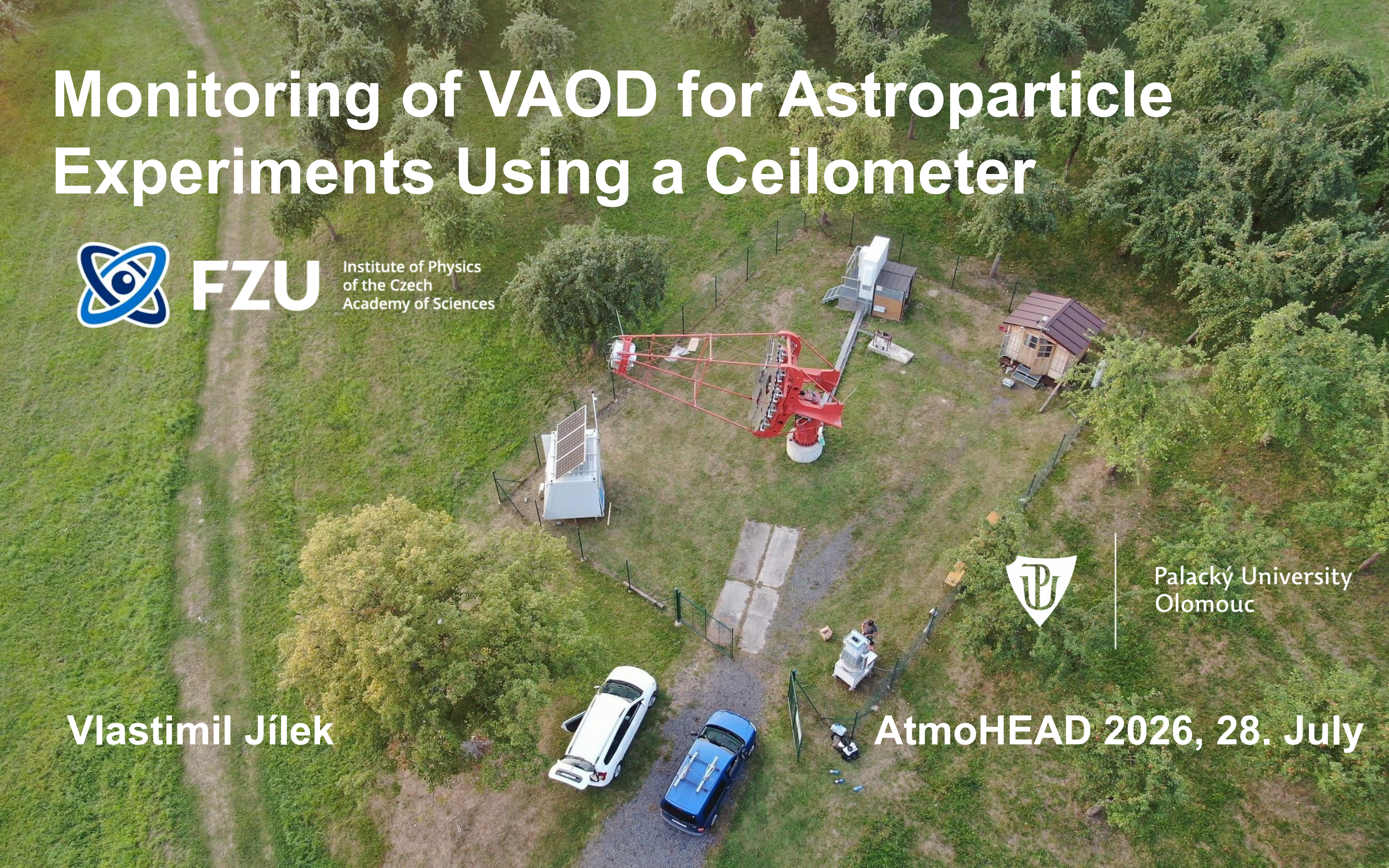
Monitoring of VAOD for Astroparticle Experiments Using a Ceilometer



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AtmoHEAD 2026, 28. July

What is Ceilometer?

- Infrared lidar for commercial use
  - Airports
    - measuring clouds base height and layers, vertical visibility, cloudiness
  - Professional meteorological stations
    - Aerosols and air pollution, structure of the boundary and mixing layer, cloudiness
    - Relation to other meteorological measurements

Ceilometer Luft CHM 15k Nimbus

- Laser
  - Nd:YAG - λ = 1064 nm
  - pulse energy - 7 μJ
  - f = 4-7 kHz
  - beam divergence < 0.5 mrad

- Detector
  - FOV = 0.45 mrad
  - filter bandwidth - 1 nm

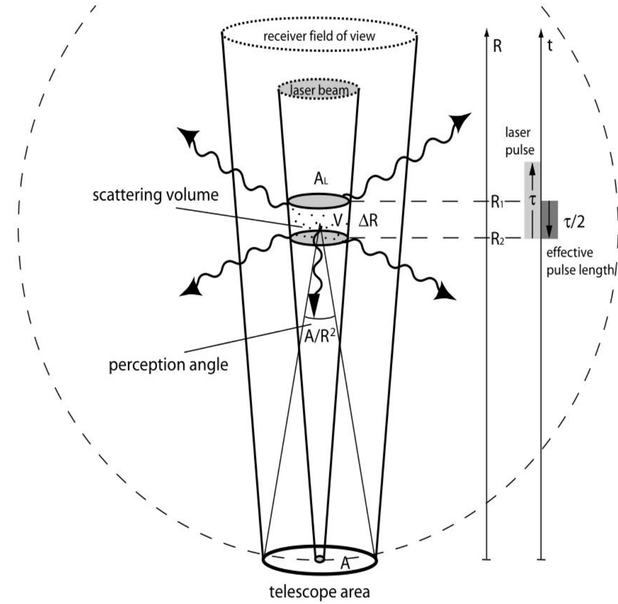
- Measuring parameters
  - Range - 5...15 000 m
  - Range resolution - 15 m
  - Time resolution - 15 s

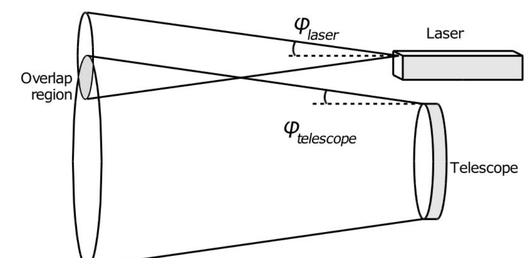
Principle of lidar measurement

- **Measurement of backscatter light**
  - The easiest way - interference filter (Luft CHM 15k)
  - more complicated systems - polarizers,
    grating spectrometers, interferometers, etc.

- **Co-axis FOV of optics and laser**
  - problem with overlapping in low height
    - corrected with overlap function

- **Light attenuation in atmosphere**
  - scattering X absorption (neglectable)
    - scattering on molecules (analytical model)
    - scattering on aerosols
      - dependence on size and shape of particles





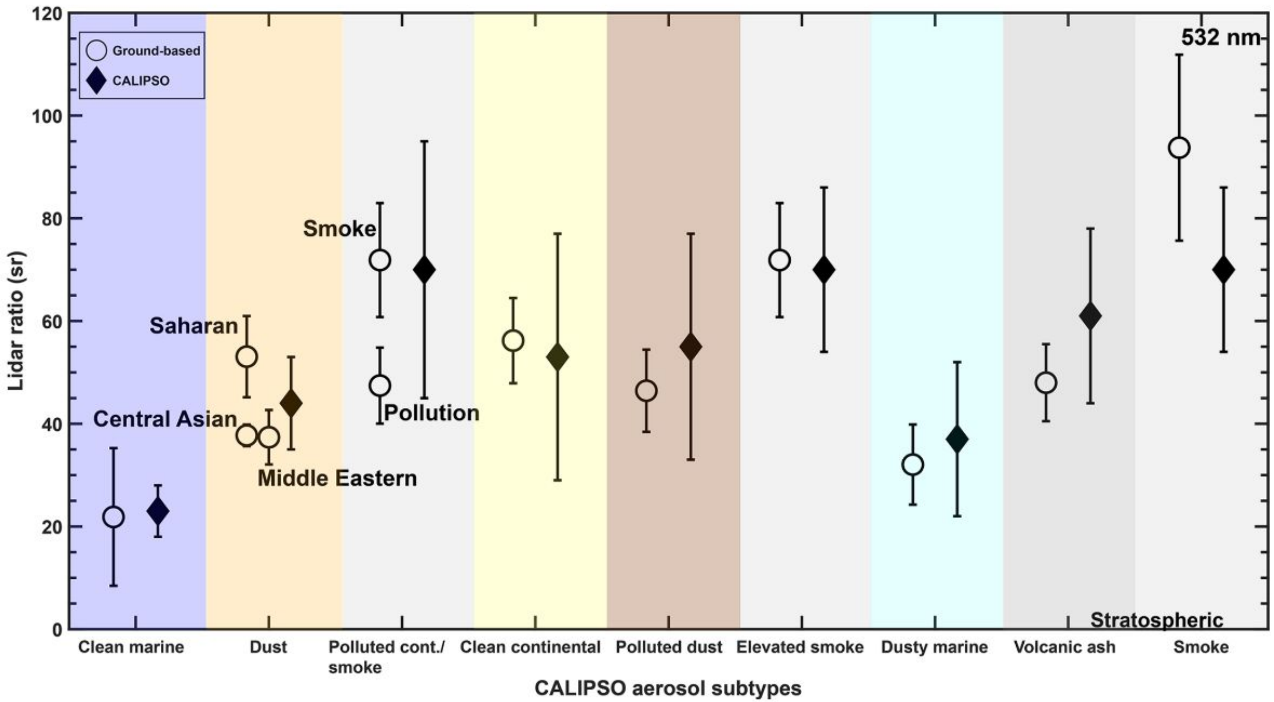
Mathematical theory behind lidar data

- Lidar equation - $P(R) = KG(R)\beta(R)T(R) = P_0 \frac{c\tau}{2} A\eta \frac{O(R)}{R^2} \beta(r) exp\left[-2\int_0^R \alpha(r)dr\right]$
  - lidar constant - $K = P_0 \frac{c\tau}{2} A\eta$
  - Geometry correction - $G(R) = \frac{O(R)}{R^2}$
  - backscattering coefficient - $\beta(r) = \beta(r)_{aer} + \beta(r)_{mol}$
  - attenuation coefficient - $\alpha(r) = \alpha(r)_{aer} + \alpha(r)_{mol}$
  - **Lidar ratio** - $L(R)_{aer} = \frac{\alpha(R)_{aer}}{\beta(R)_{aer}}$, $L(R)_{mol} = \frac{\alpha(R)_{mol}}{\beta(R)_{mol}} = \frac{8\pi}{3}$ sr

Mathematical theory behind lidar data

- Klett-Fernald inversion
    - $$P(R)R^2\ L(R)_{aer} exp\left\{-\ 2\int_0^R \left[L(r)_{aer} - L(r)_{mol}\right]\beta(r)_{mol} dr\right\} =\ KG(R)\,Y(R)\ \ exp\left[-\ 2\int_0^R Y(r)\ dr\right]$$
    - auxiliary function - $$Y(R)\ \ =\ L(R)_{aer}[\beta(R)_{aer} + \beta(R)_{mol}]$$
- Critical parameter - Lidar ratio
    - dependence on aerosol properties
    - change with height
    - normal values for central Europe: 20 - 100 sr

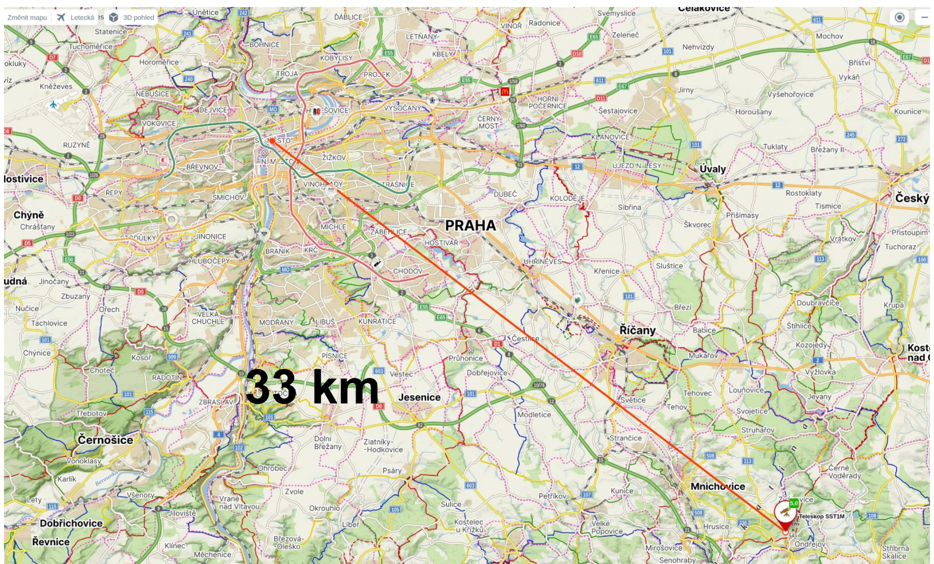
Mathematical theory behind lidar data

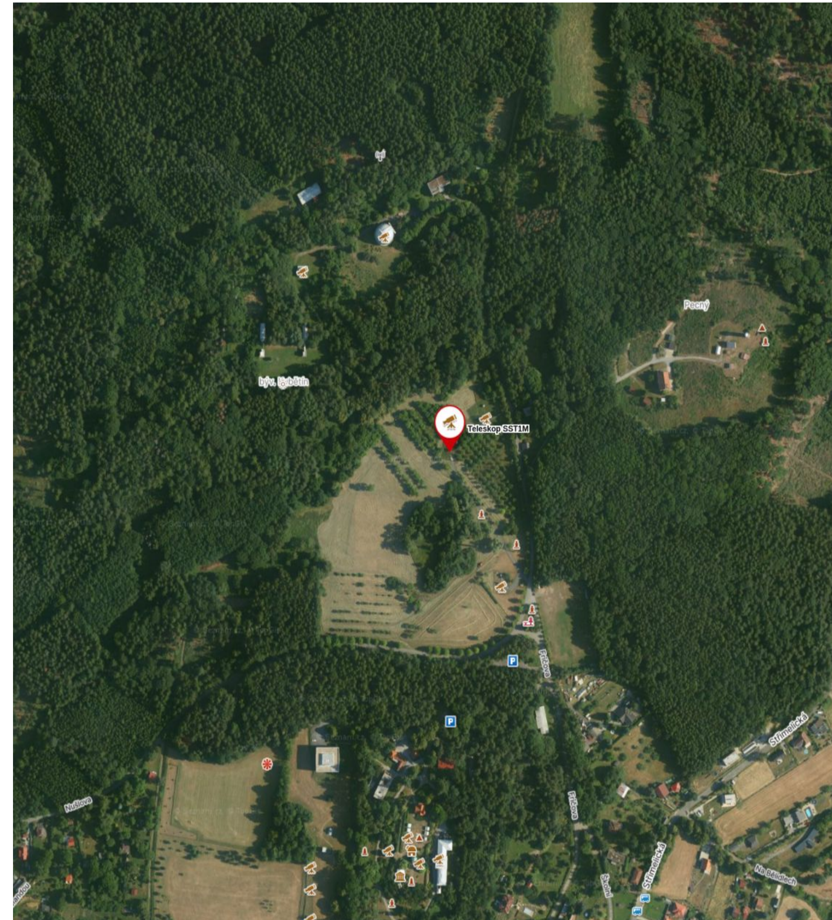


Comparison of the 532 nm lidar ratio as derived from ground-based lidars (white circles) and from the CALIPSO aerosol subtypes.

Data analysis

- Site info
  - Ondřejov, Hvězdárna ASU CAS
  - Altitude: 509 m
  - Meadow and forest around
  - Aerosol type: Rural-industrial mix
    - L_{ar} = 45 - 70 sr





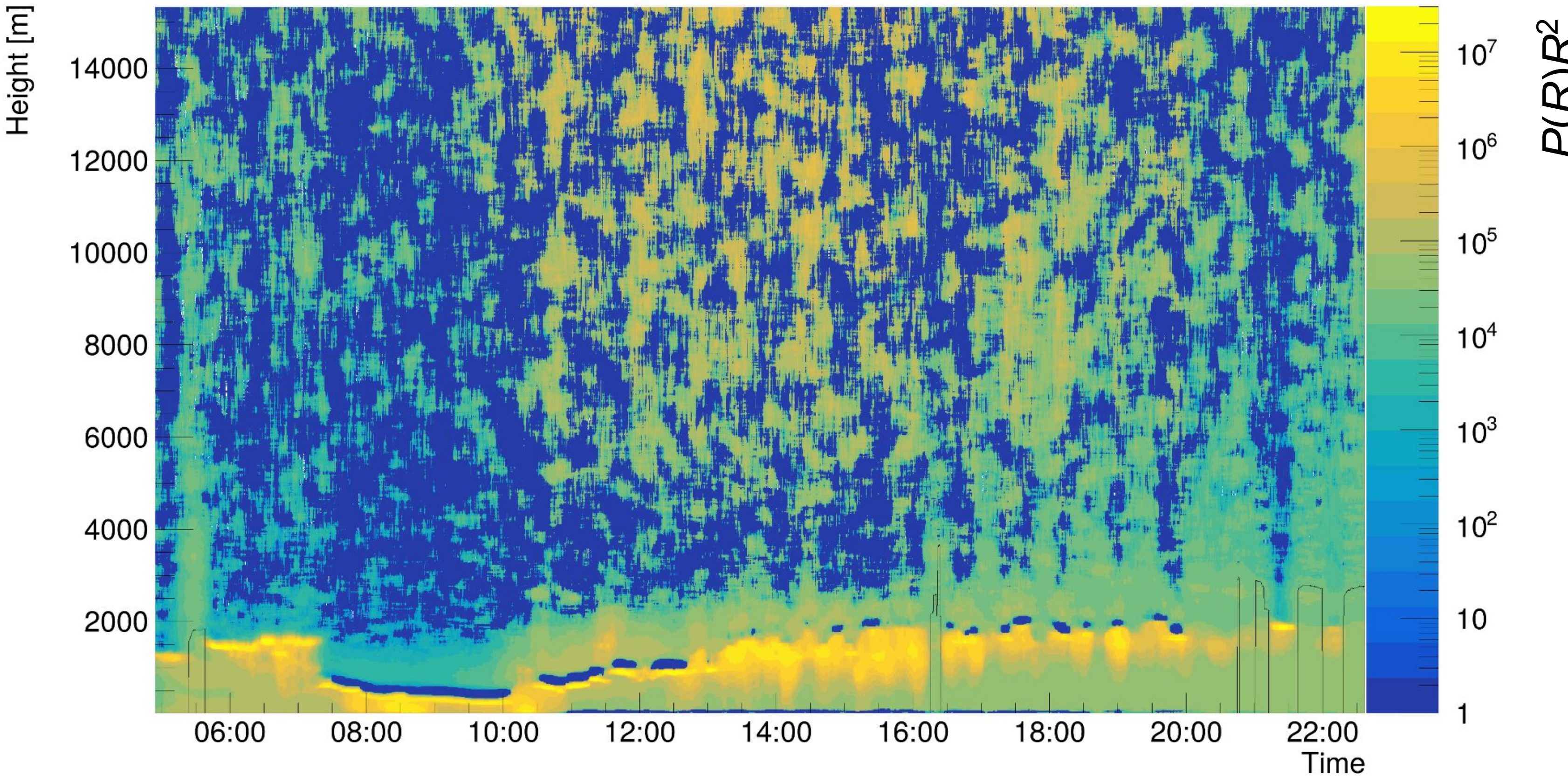
Data analysis

- Atmosphere simulation
  - data from Copernicus ERA 5 - vertical profiles
    - temperature, relative humidity, pressure
    - data from every 3 hours

  - determination of optical properties

- Signal analysis
  - time smoothing - median of 15 min data
  - vertical smoothing - floating window (from 45 m to 500 m)
  - Wavelet Covariance Transform of signal (WCT)
    - $W_f(a,z) = \frac{1}{a}\int_{z_b}^{z_t} f(z') \cdot h\left(\frac{z'-z}{a}\right) dz'$

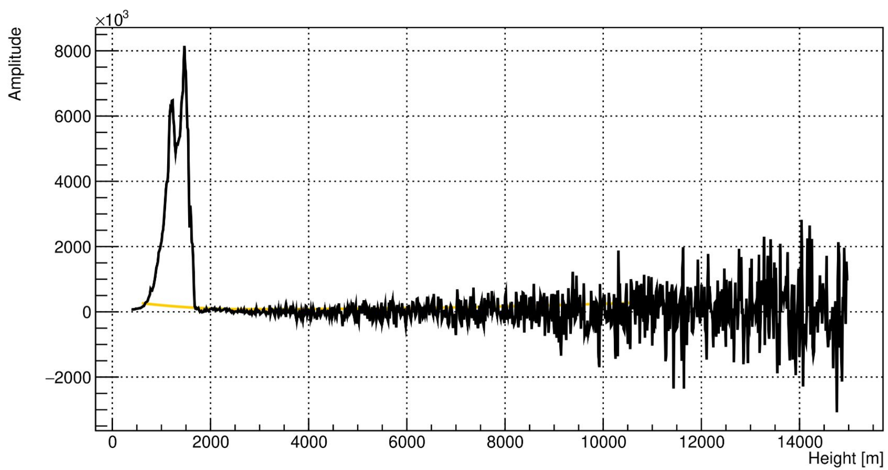
Data analysis

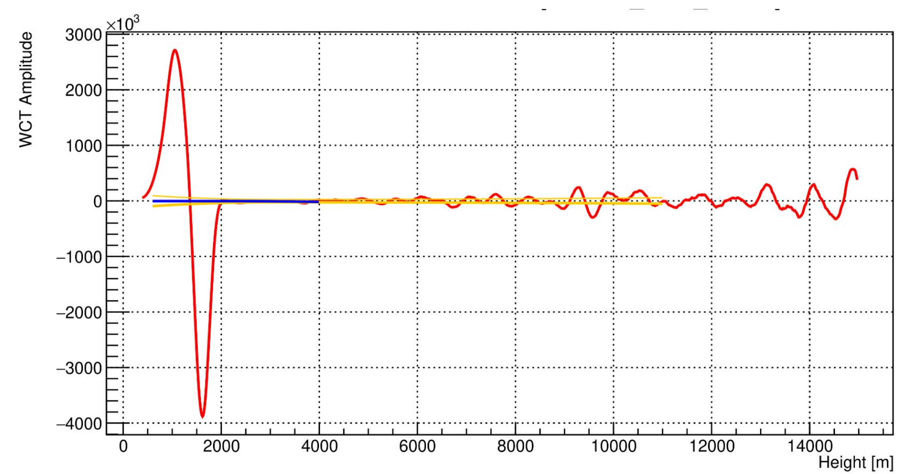


Heat map of lidar signal $P(R)R^2$ from 17.3.2026.

Data analysis

- Clouds detection
  - Close to surface -> absolute signal threshold (overlap problem of ceilometer)
  - scan from bottom to top
    - WCT and absolute signal -> asymmetric thresholds - $a + bx + c(x+d)^2$
    - maximum sensitivity around 3 km

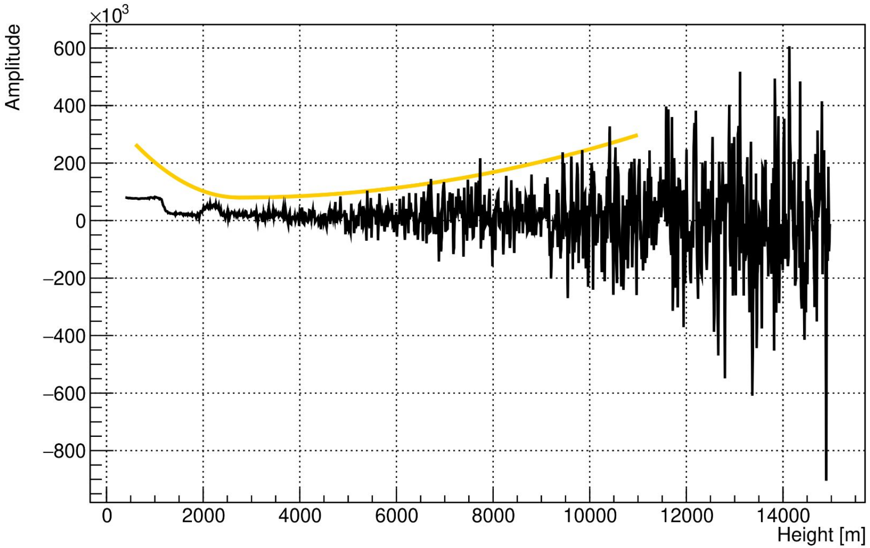


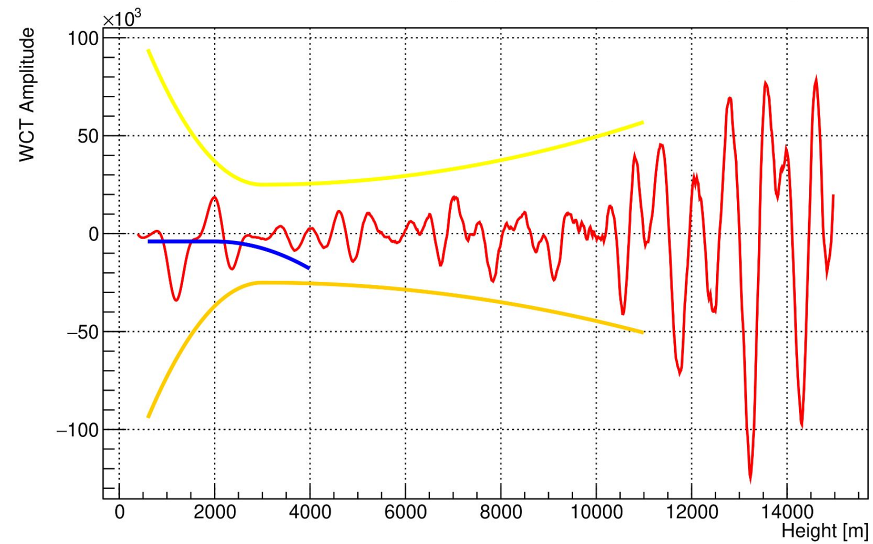


Lidar signal $P(R)R^2$ and Wavelet Covariance Transform of signal from 17.3.2026, 14:00.

Data analysis

- Aerosol layer estimation
  - scan top-bottom from 4 000 m
  - WCT asymmetric thresholds $a + bx + c(x+d)^2$ - highest layer of aerosol
  - Beta signal - find the precise edge of aerosols layer

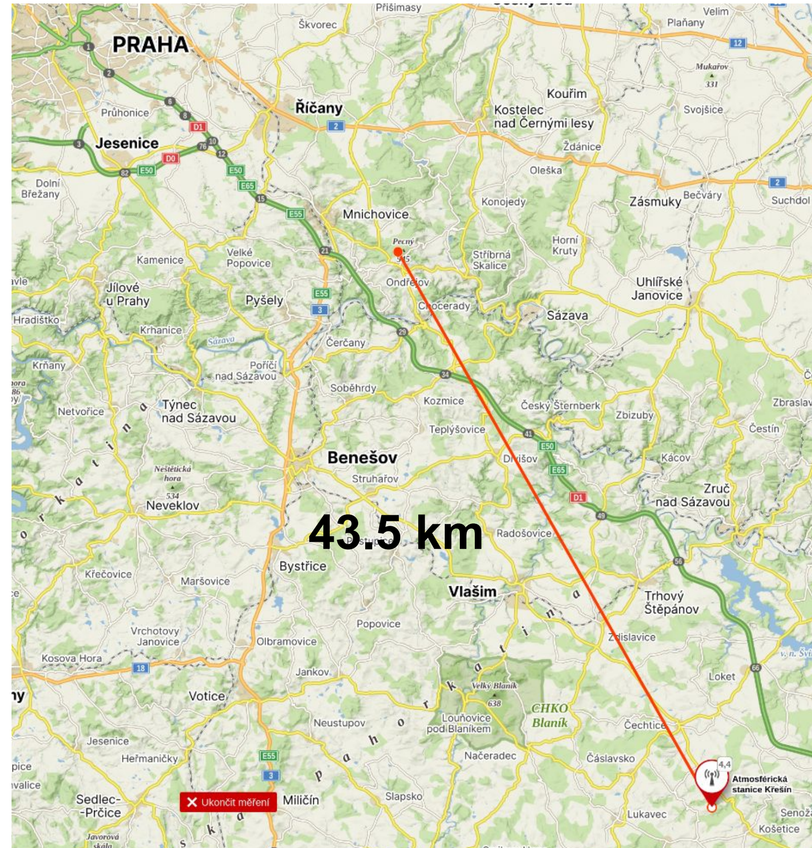




Lidar signal $P(R)R^2$ and Wavelet Covariance Transform of signal from 18.3.2026, 16:00.

Results

- AOD calculated by Fernald-Klett methode
  - 3 results for different values L_{aer}
    - 18 sr, 45 sr, 70 sr
- Comparison of data with AERONET station Košetice
  - calibration of Lidar
  - correlation of data

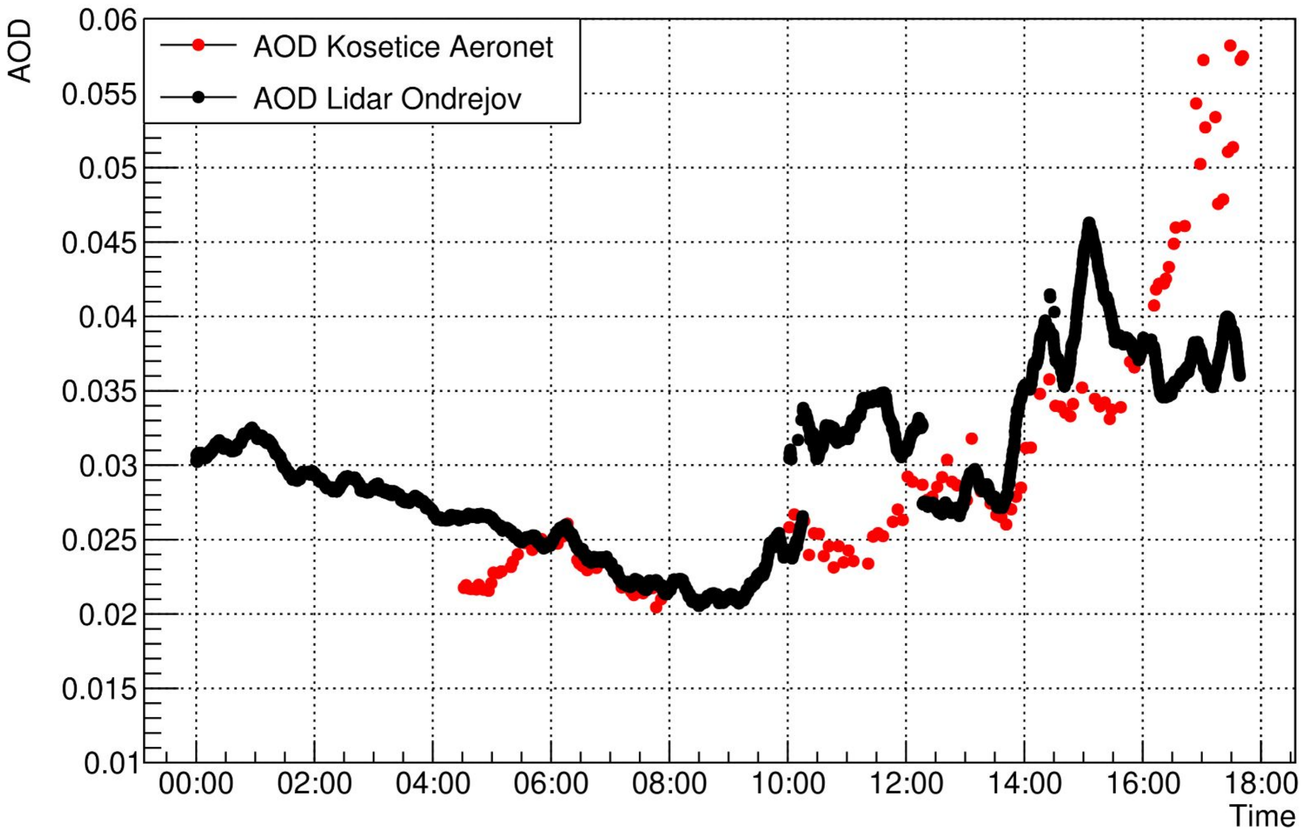


Results

- Same environment like around ceilometer at Ondřejov Observatory.

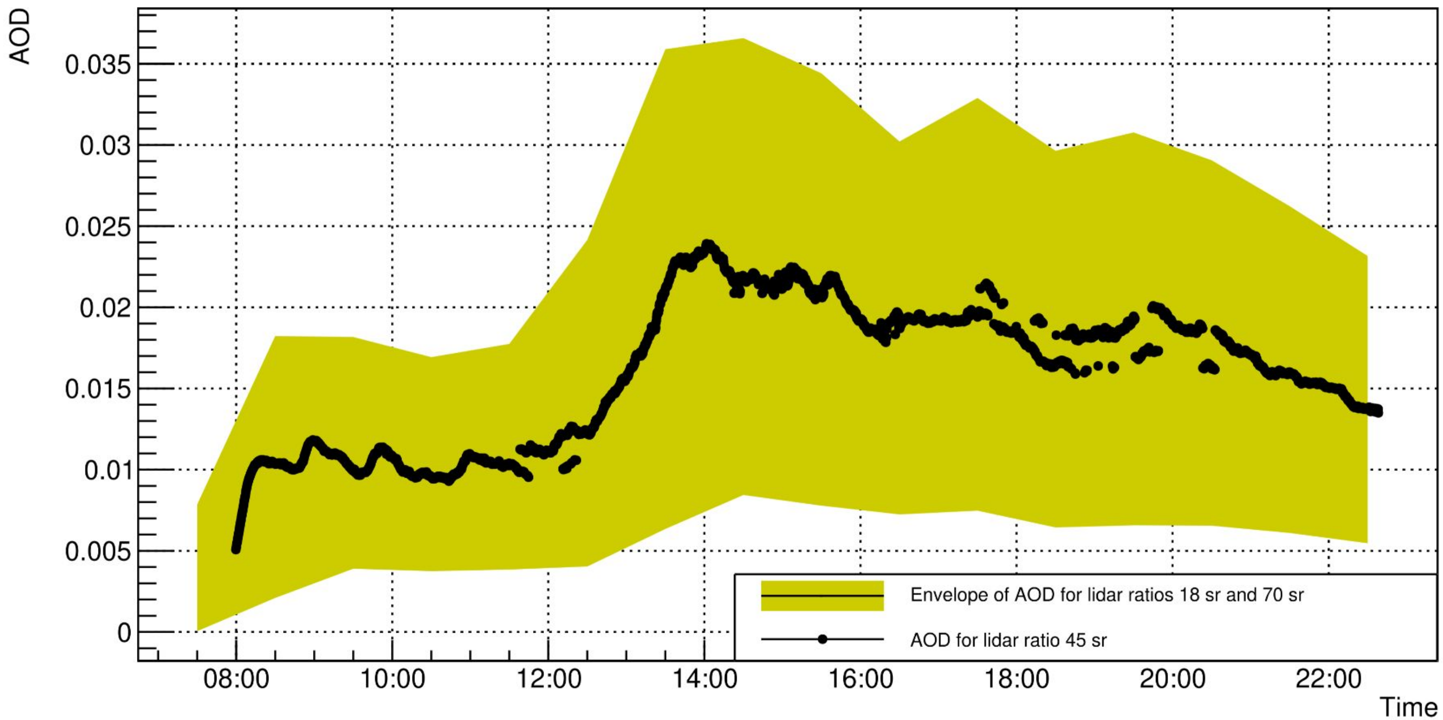
Košetice AERONET station and environment around. Altitude is 530 m.

Results



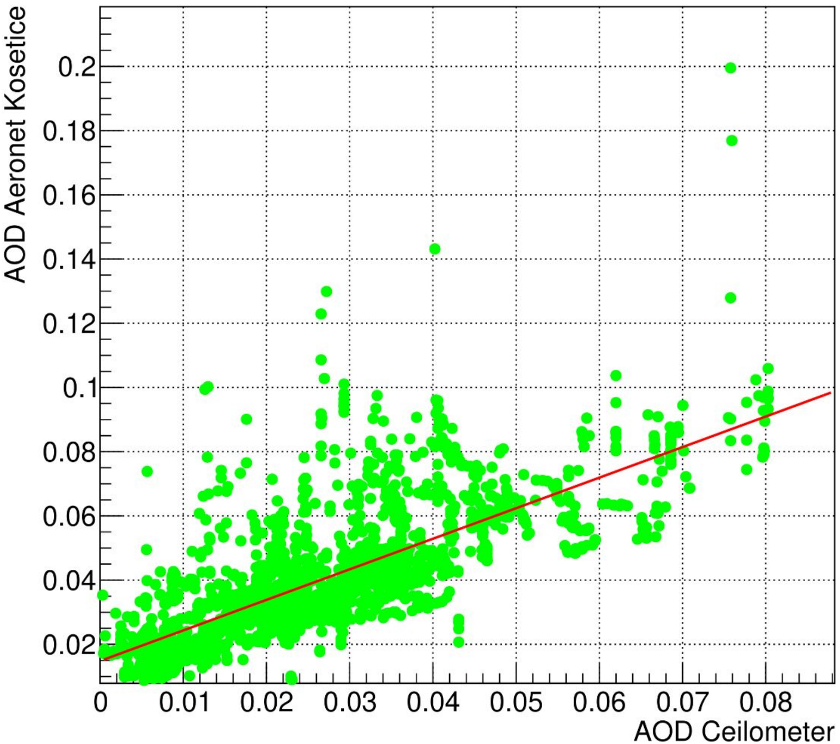
Comparison of data between Košetice AERONET station and ceilometer. Data from 30.7.2024.

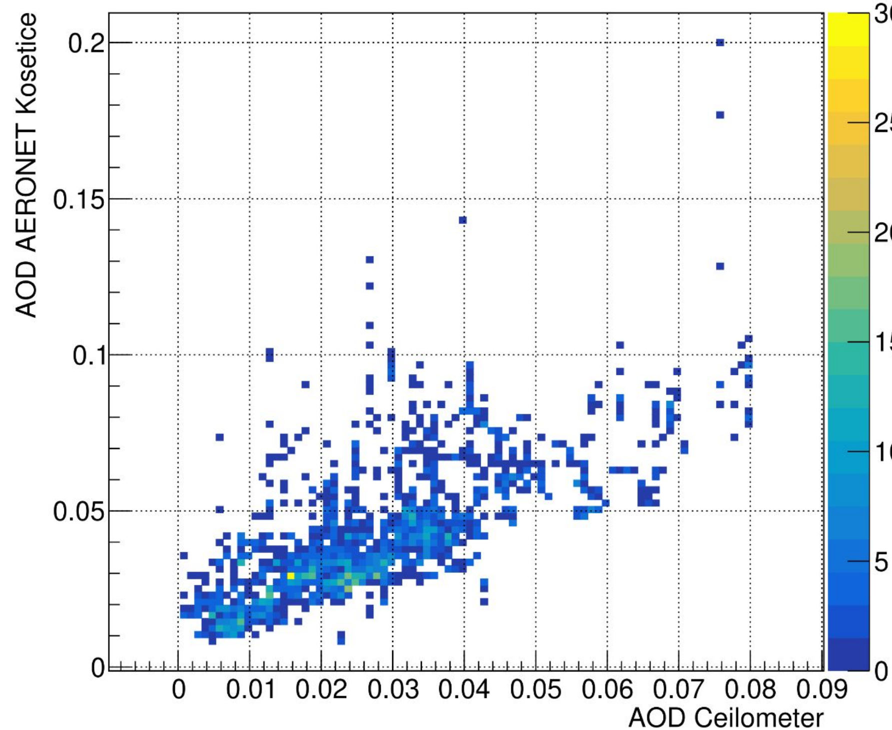
Results



Results from 18.3.2025.

Results





Correlation of AOD data from AERONET station photometer Košetice (1020 nm) and Ceilometer. Left figure shows linear fit with slope 0.95, right figure shows heatmap of correlation. Data from July 2024 to April 2026.

Conclusion

- Data from ceilometer can by use for estimation of aerosol optical depth
- Good correlation with AERONET photometer station
- Future plans:
    - using AOD for SST1-M data
    - comparison measurement with all-sky camera at Ondřejov
    - measure AOD at different zenith and elevation angles

Acknowledge

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Literatura

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[2] Lufft, *User Manual Lufft CHM 15k Ceilometer*, https://www.lufft.com/fileadmin/lufft.com/07_downloads/1_manuals/Manual_CHM15k_EN_R19.pdf

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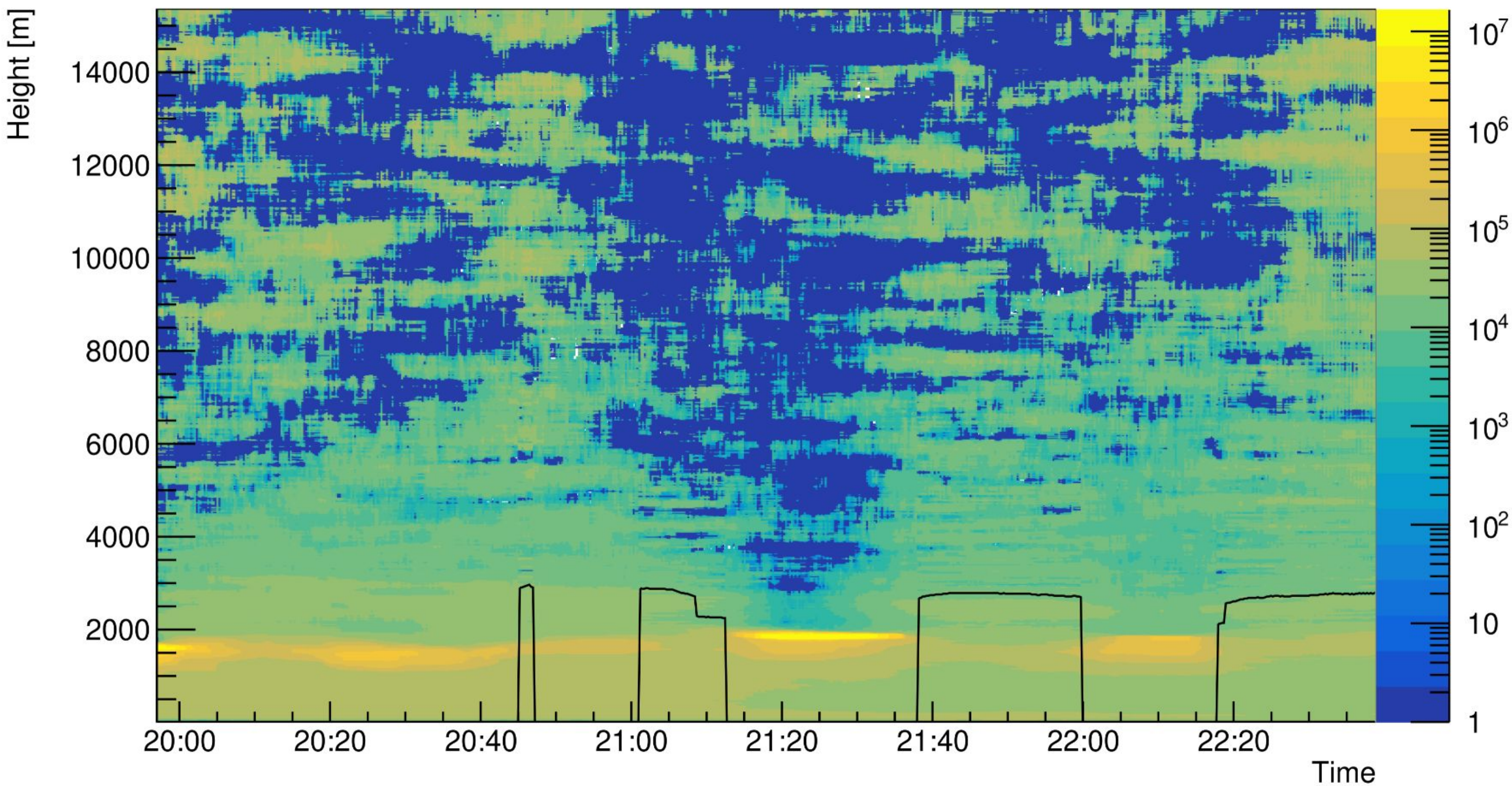
Clouds and aerosol detection detail



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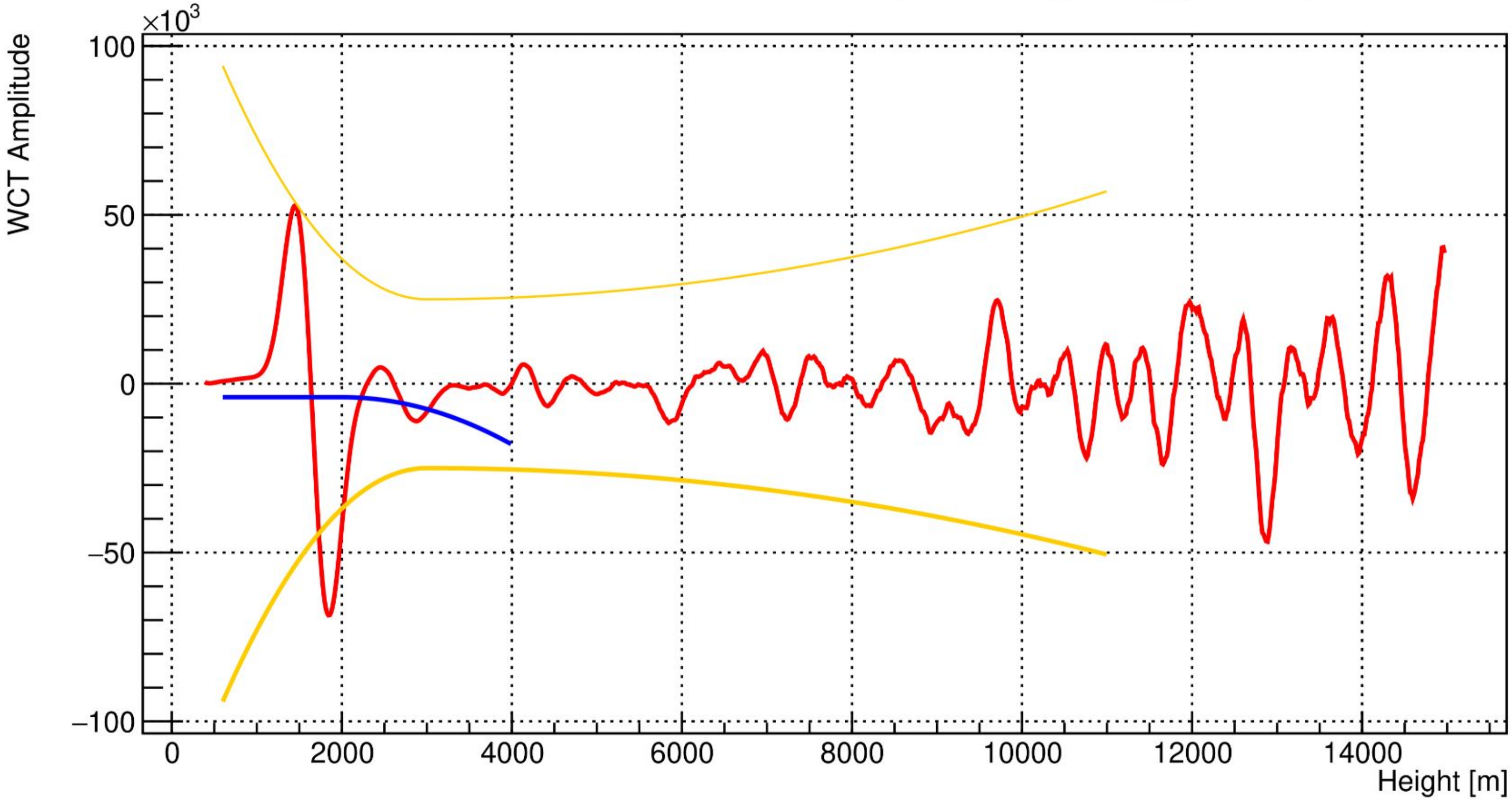
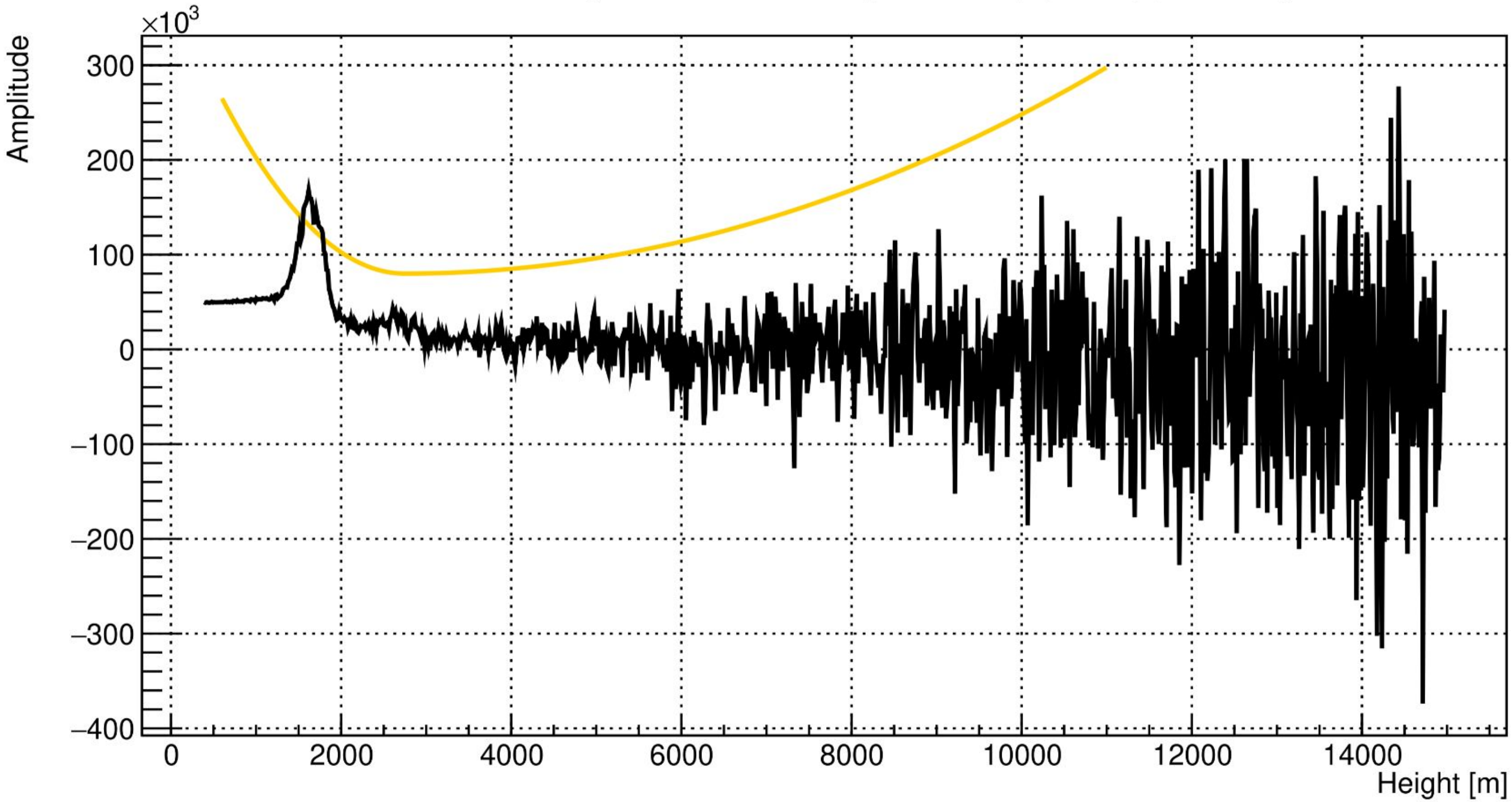


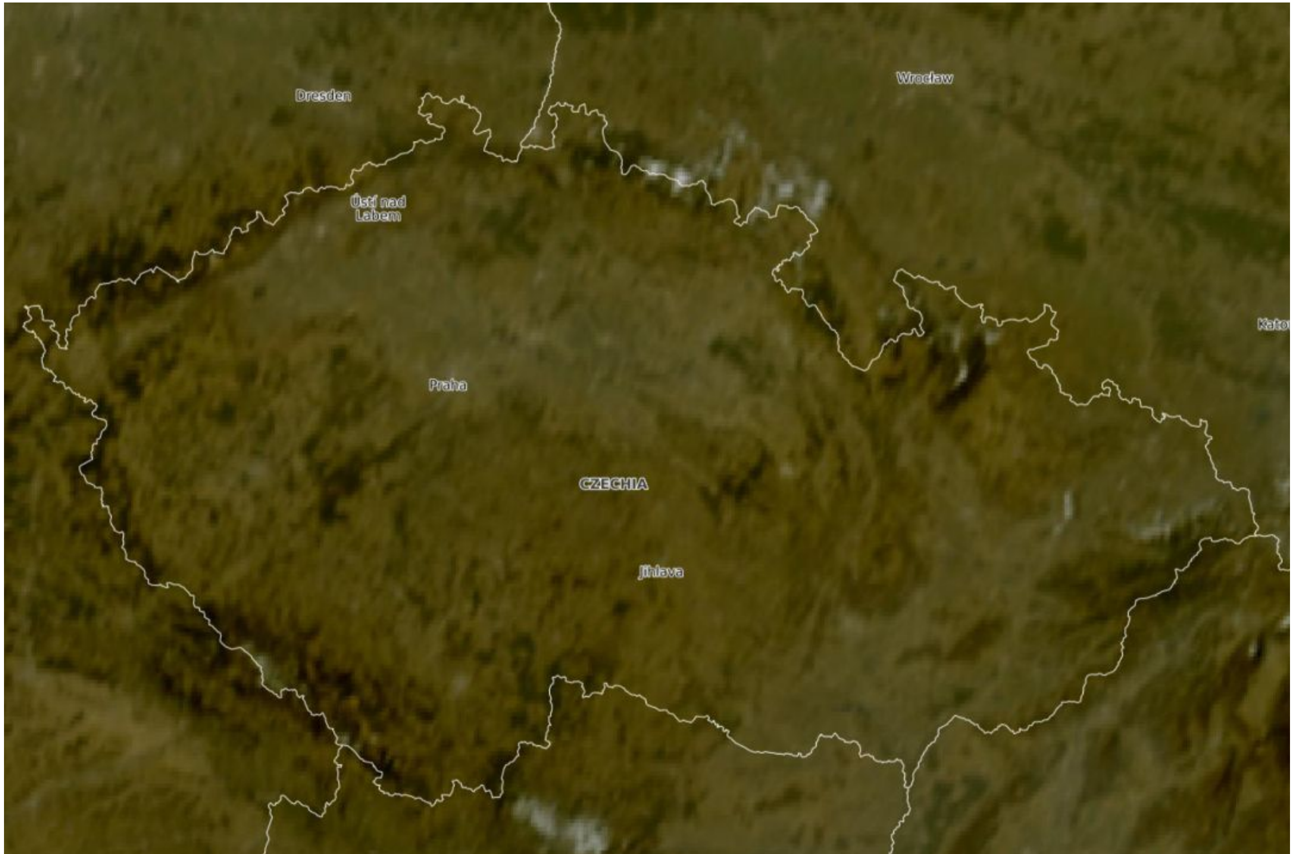
Wavelet Covariance Transform of signal from 17.3.2026, 14:00.

Clouds and aerosol detection detail



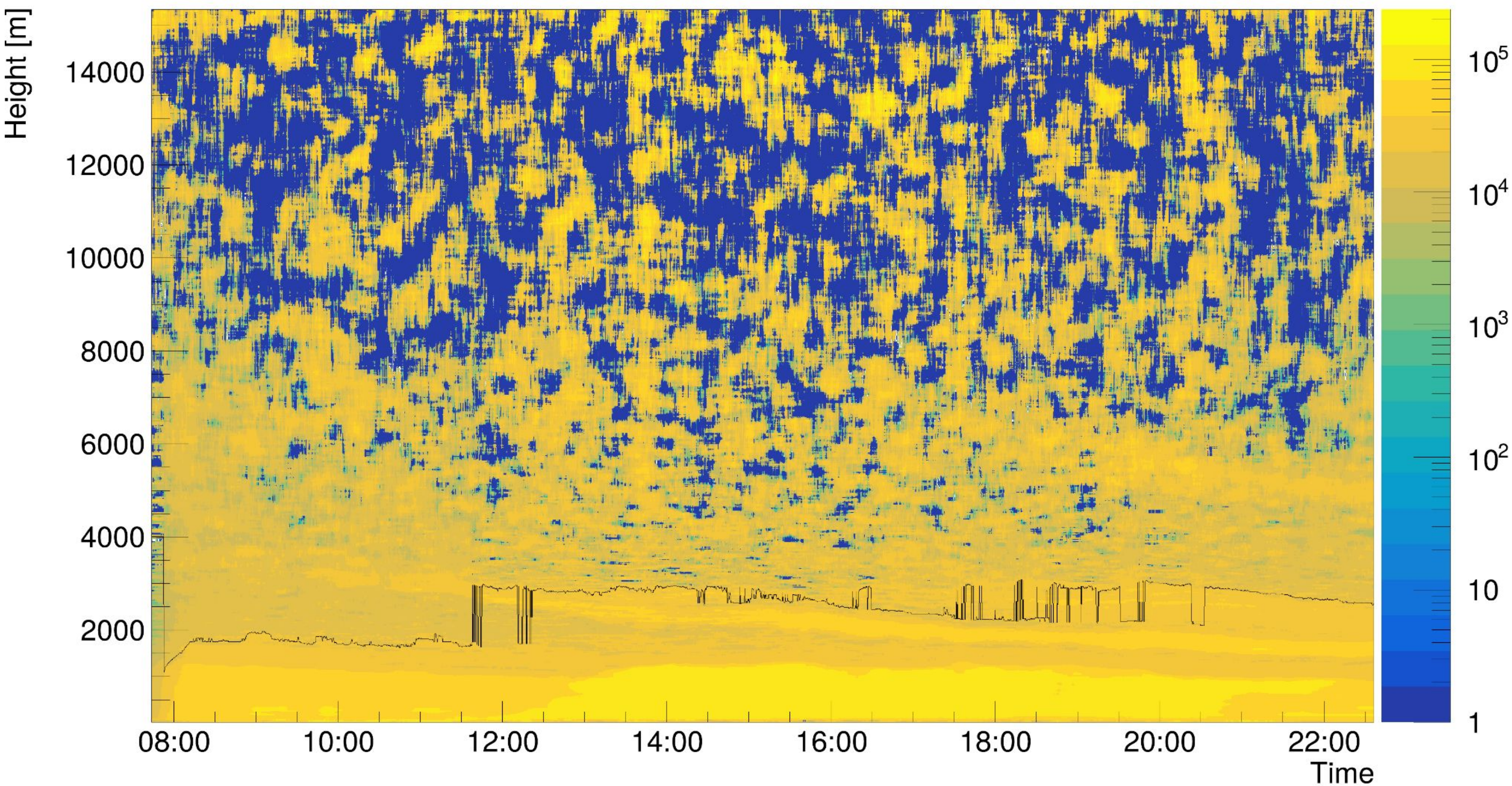
Lidar signal $P(R)R^2$ from 17.3.2026, 21:00.

Satellite images and data comparison



Satellite image of Czechia from 18.3.2025, 16:00.

Satellite images and data comparison



Satellite images and data comparison

Satellite image of Czechia from 17..3.2025, 16:00.

Satellite images and data comparison