Validation of ATLID extinction and lidar-ratio of cirrus clouds using airborne measurements with the research aircraft HALO during the PERCUSION campaign: assessment of the multi-scattering correction

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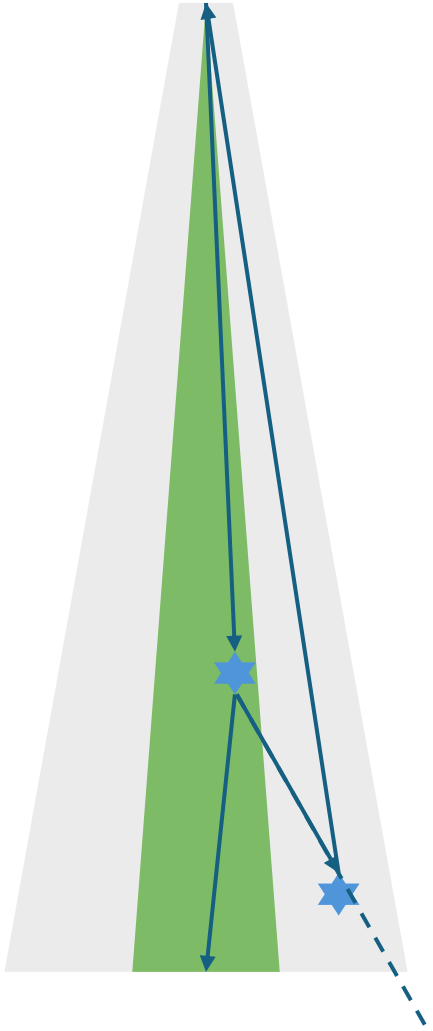
Small Angle Forward Scattering in Cirrus Clouds I



- Ice crystals can become large which results in a very narrow forward scattering peak ($\Theta = \lambda/(\pi r) \approx 1.7$ mrad for $r = 100$ µm)
- Part of the scattered light stays within the laser beam and appears to the lidar as un-scattered
- Another part of the scattered light takes some distance until is has left the receiver field of view giving rise to tails in the signal
- Standard retrieval without MS underestimates the optical thickness/extinction of the cirrus cloud
- Backscatter coefficient is much less affected for a HSRL-Lidar since by taking the ratio of two MS-affected signals most of the effect cancels out (besides some possible backward scattering peak smoothing…)

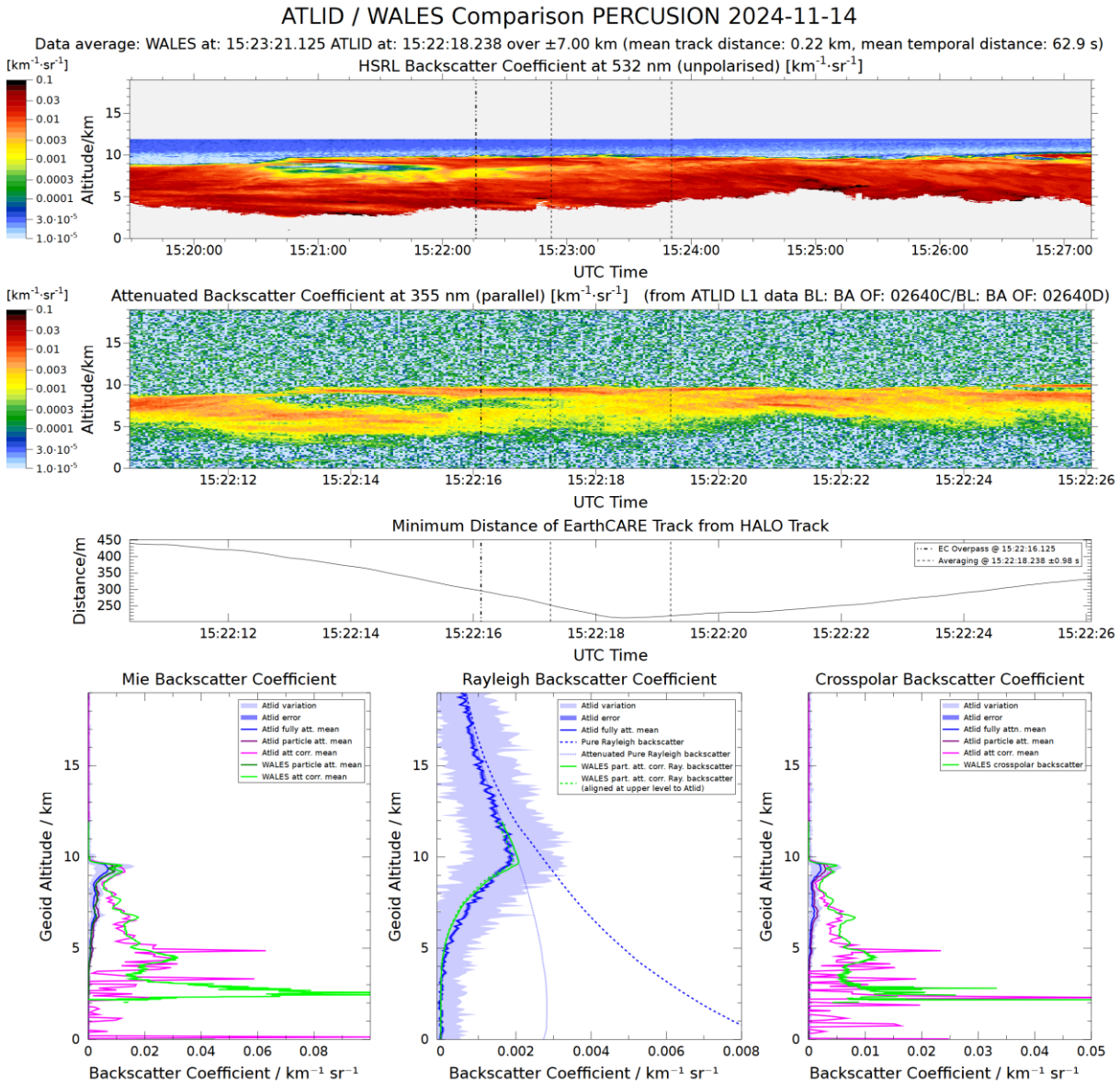
Small Angle Forward Scattering in Cirrus Clouds II

Several correction methods have been suggested in the literature:

- Single photon Monte Carlo scattering simulations: need a phase function and are very slow but the most accurate (Platt 1980, Wang et al. 2005 etc.)
- Simple empirical approximations: correction factor for extinction. Has to be *calibrated* with other methods. No tail correction. (Platt 1979)
- More sophisticated analytical solutions: Eloranta 1998, Hogan 2006/2008, Donovan 2024 (ATLID-algorithm)

All of them need the phase function or at least the **area equivalent radius** of the ice particles!

Case 1: Thick Cirrus on 14. November 2024



Case of an optically thick cloud system

Level 1 signal comparison:

- Signals are not corrected for MS
- Very good agreement of L1 co- and cross-polar backscatter
- Rayleigh backscatter of ATLID slightly higher than WALES which should result in higher extinction coefficients for WALES
- Averaging region slightly shifted away from the best match to a more homogenous region

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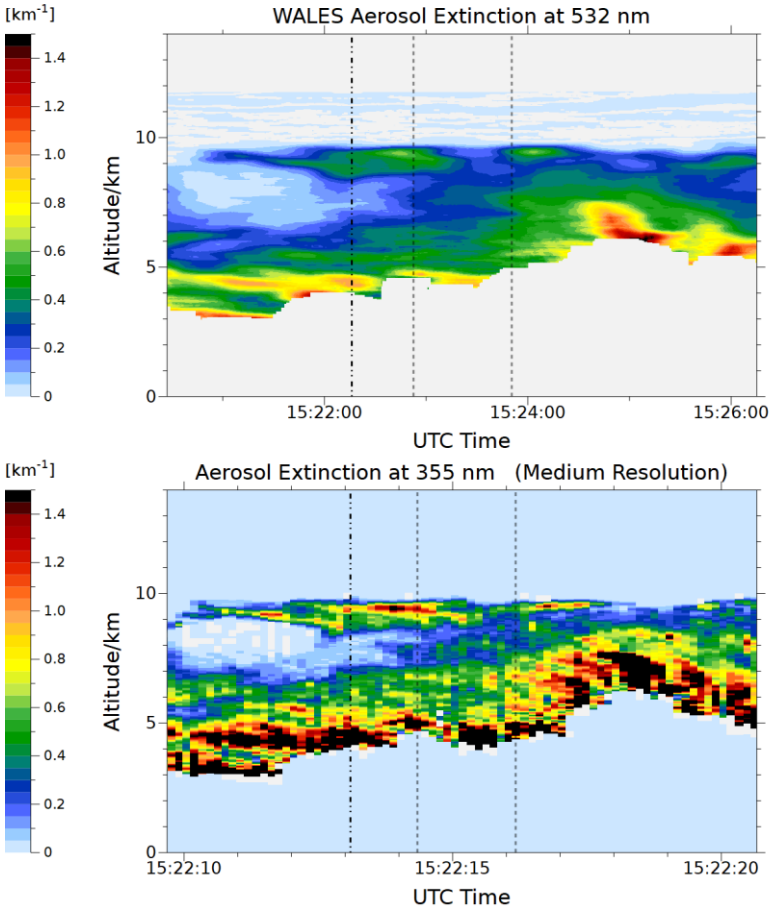
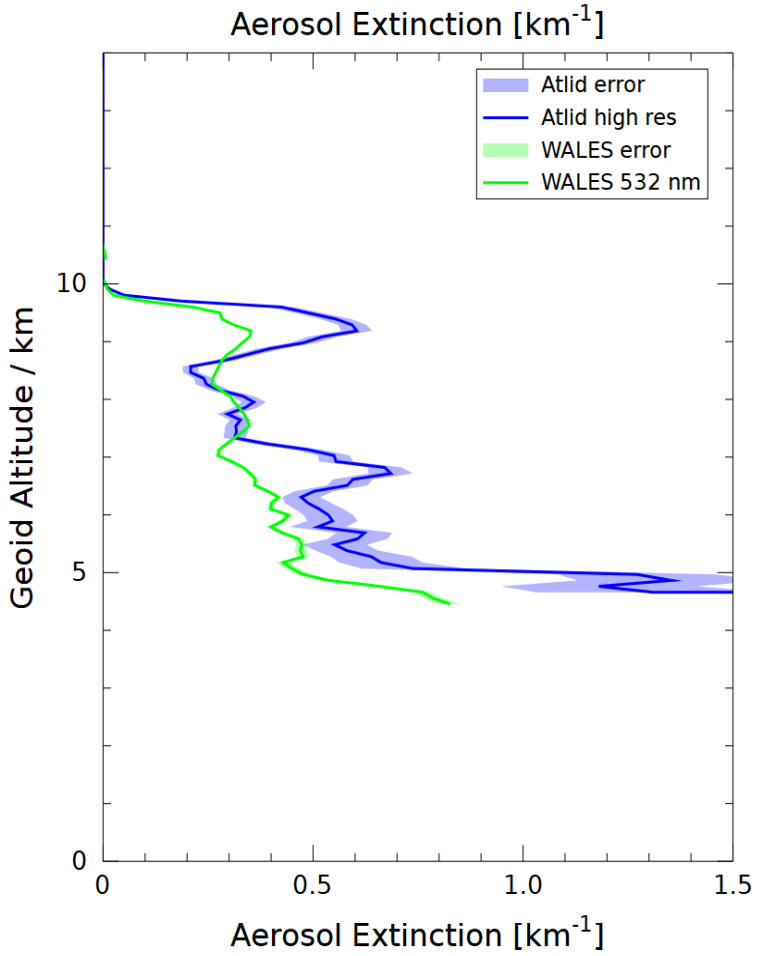
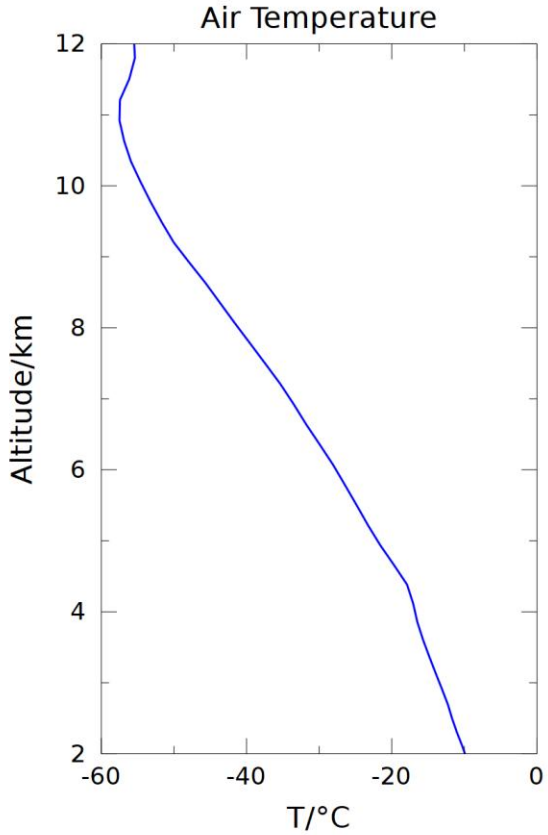


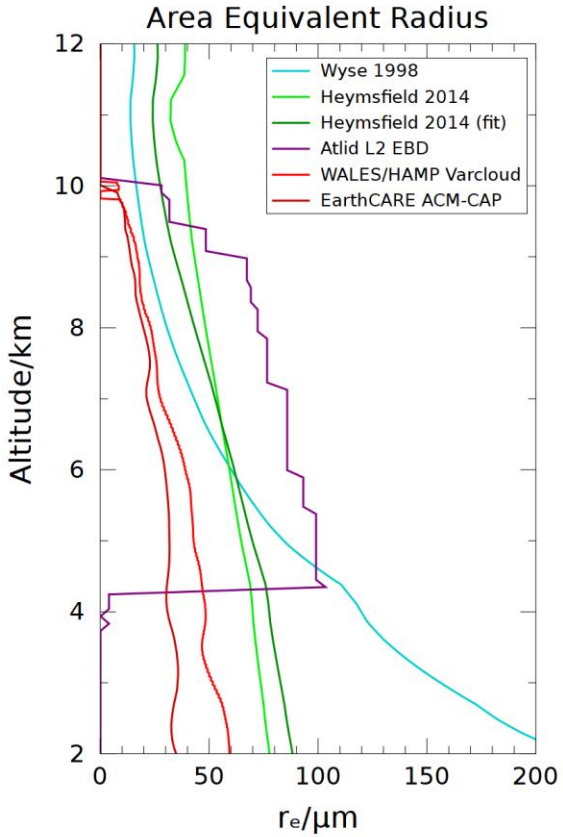


Level 2 EBD data comparison:

- ATLID is MS corrected, WALES **not**
- Good agreement of the 2d geometrical structure
- WALES uncorrected extinction is lower at the top and the bottom of the cloud
- All three resolutions in EBD show (nearly) the same data
- ***Next step***: Apply MS correction to WALES data

Effective Radius Data Sources



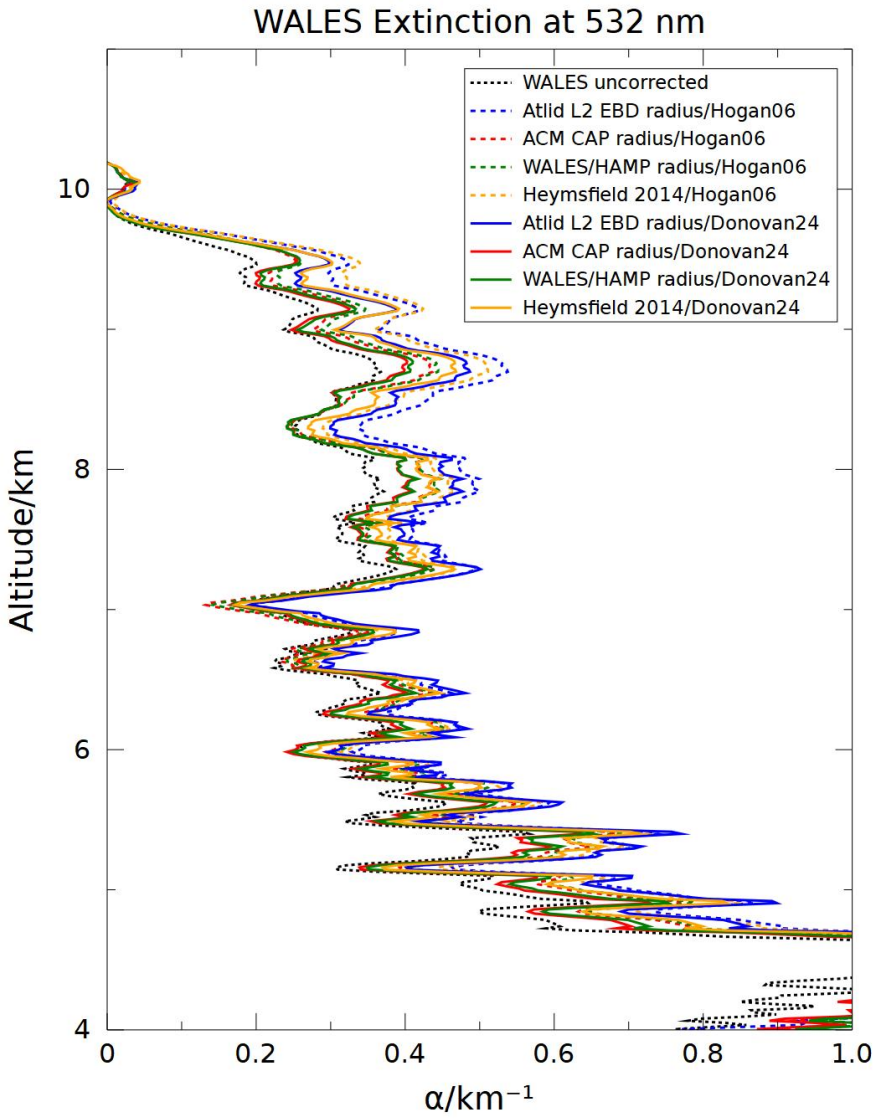


Possible sources for the effective radius of cirrus particles:

- Correlations between radius and temperature and/or extinction: e.g. Wyse et al. 1998, Heymsfield et al. 2014 (fits to empirical data from particle counters)
- Output of synergistic Lidar/Radar retrievals

- **There is a factor of 2-3 spread between different sources, leading to significant differences in forward scattering corrections!**
- **Additional uncertainty by conversion from effective radius to area equivalent radius** ($C^{1.5}$ with C = 0.7 used here)

Selection of Radius Profile and Algorithm



Comparison of two algorithms:

1. Hogan 2006, supposed to be more accurate, but slower (dashed lines)
2. Donovan 2024, ATLID algorithm (solid lines)

And four radius profiles:

a. ATL EBD 2A data (blue)

b. ACM CAP 2B data (red)

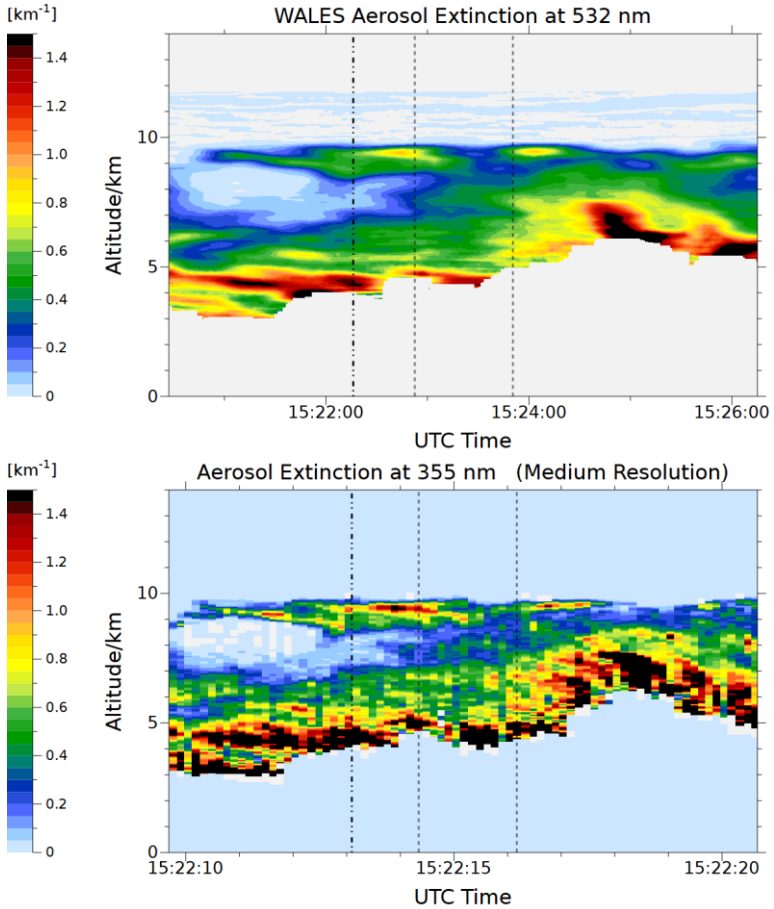
c. Varcloud WALES/HAMP data (green)

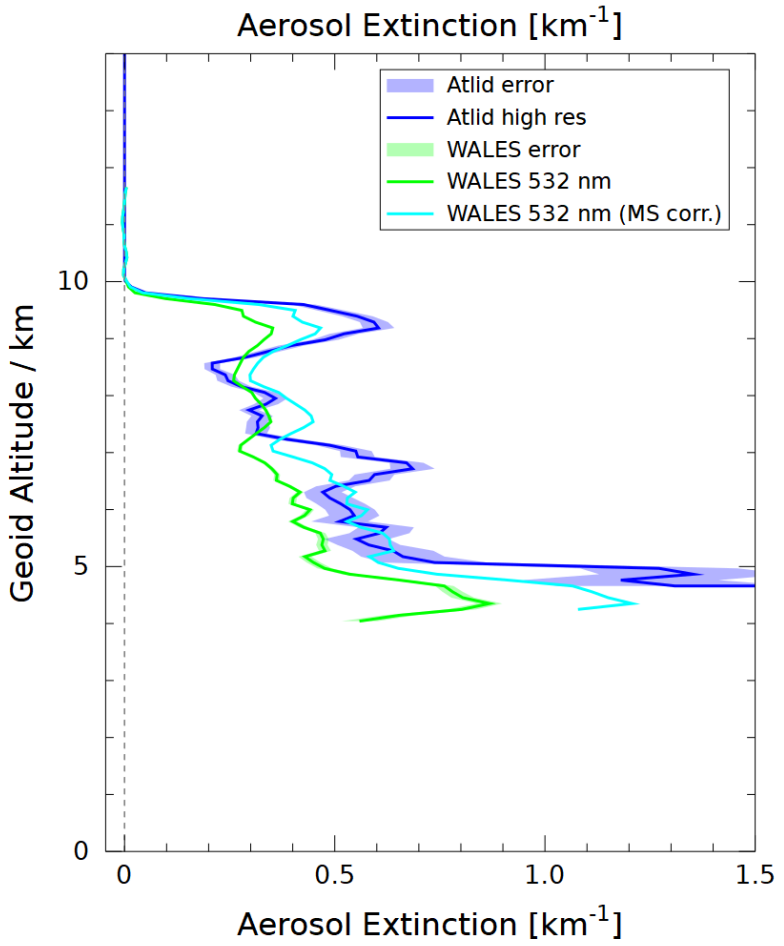
d. Heymsfield 2014 parametrisation (orange)

- **Largest difference between algorithms at upper part of the cloud. No significant Difference deeper within the cloud**
- **Largest impact from radius selection, as expected**

Case 1: Thick Cirrus on 14. November 2024

Radius from ATLID EBD and Donovan 2024 algorithm



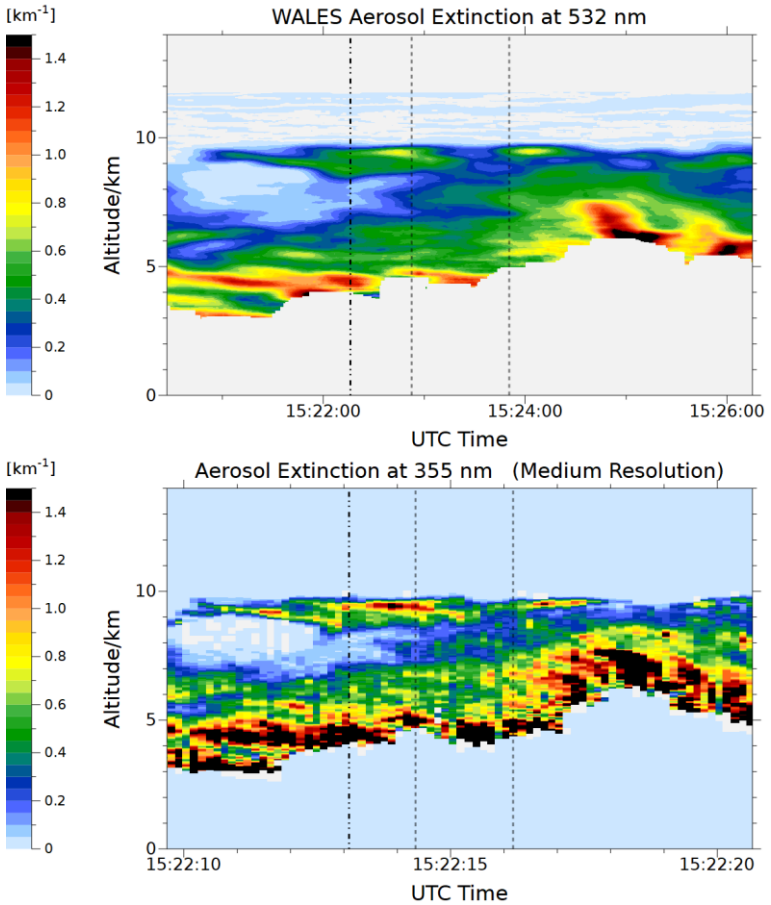


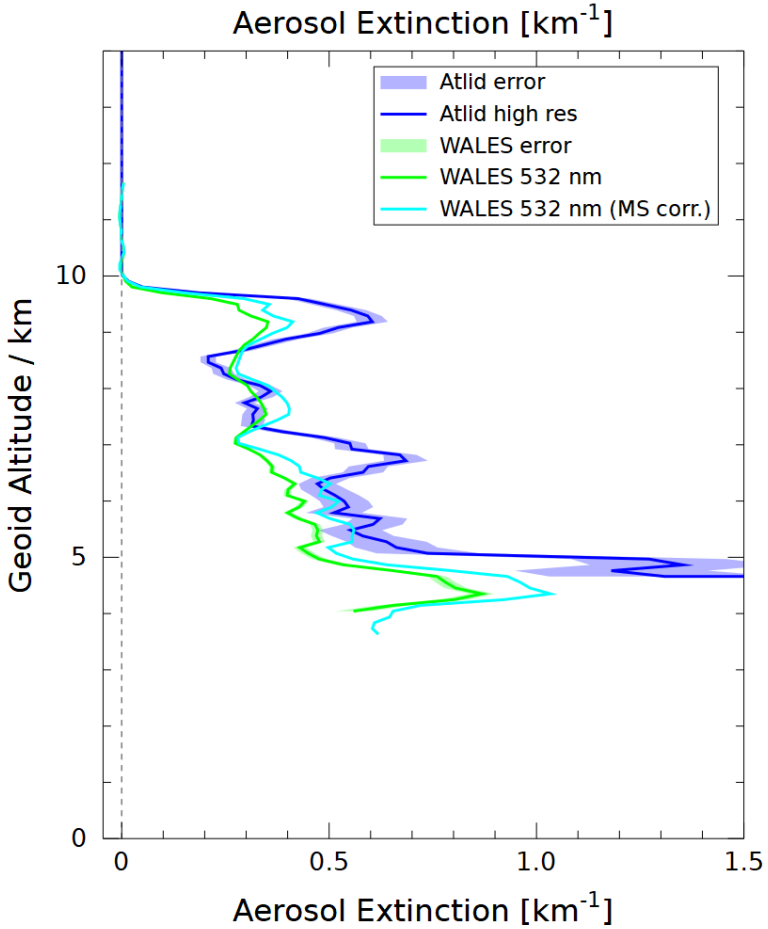
Level 2 EBD data comparison:

- Good agreement in the mean (same optical thickness)
- Largest relative correction a cloud top
- Extinction much smoother in for WALES. ATLID profile follows backscatter coefficient, i.e. constant lidar-ratio, while for WALES the lidar-ratio is anti-correlated to the depolarisation (like known from literature for smaller ice crystals…)

Case 1: Thick Cirrus on 14. November 2024

Radius from ACM CAP and Hogan 2006 algorithm

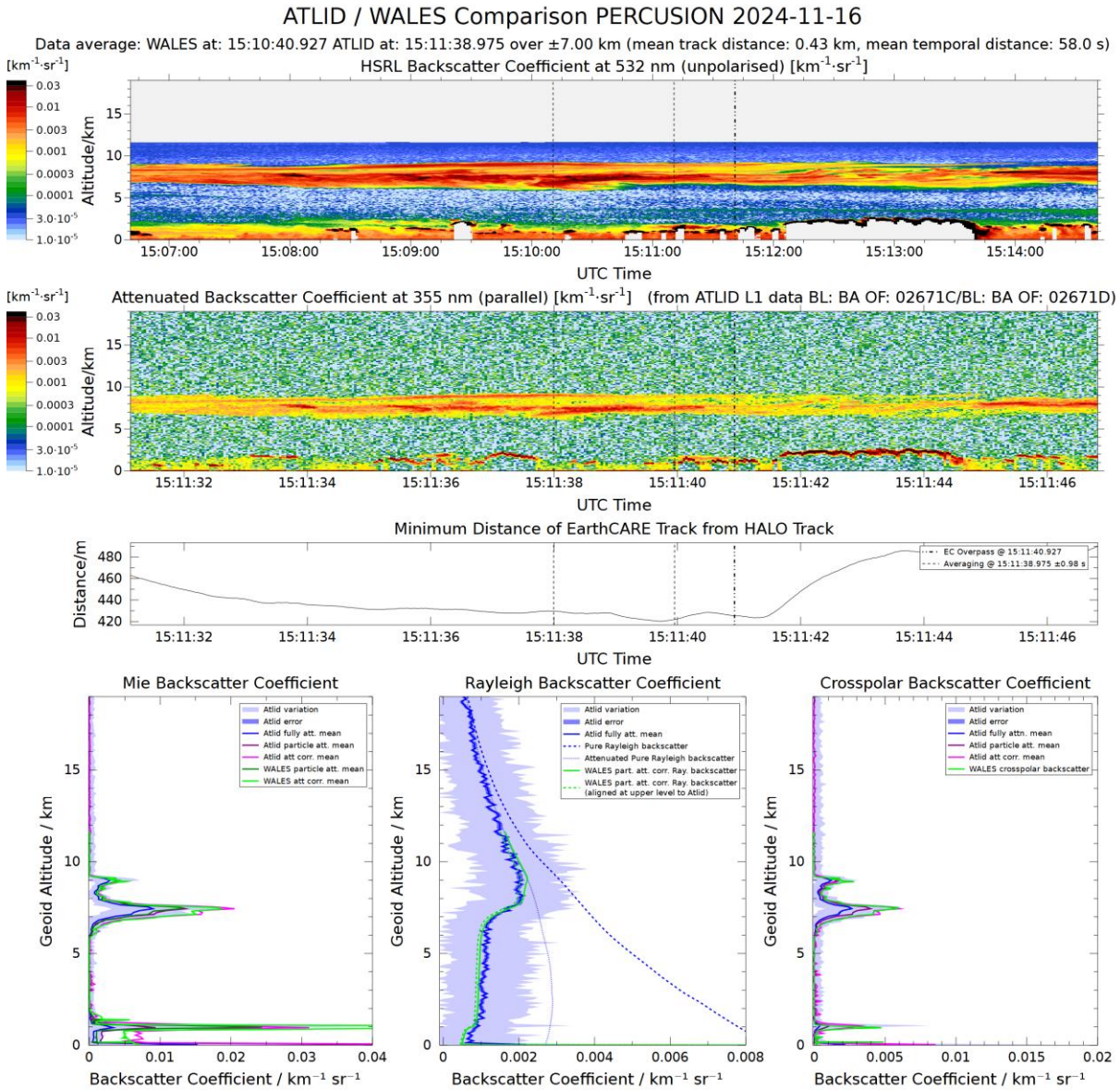




Level 2 EBD data comparison:

- Correction lower than with ATLID radius and algorithm
- If it is assumed that radius data and algorithm are more accurate for this case the ATLID data seems to be overcorrected, especially given the fact that for L1 the extinction of ATLID seems lower than WALES

Second Case Study 16. November 2024



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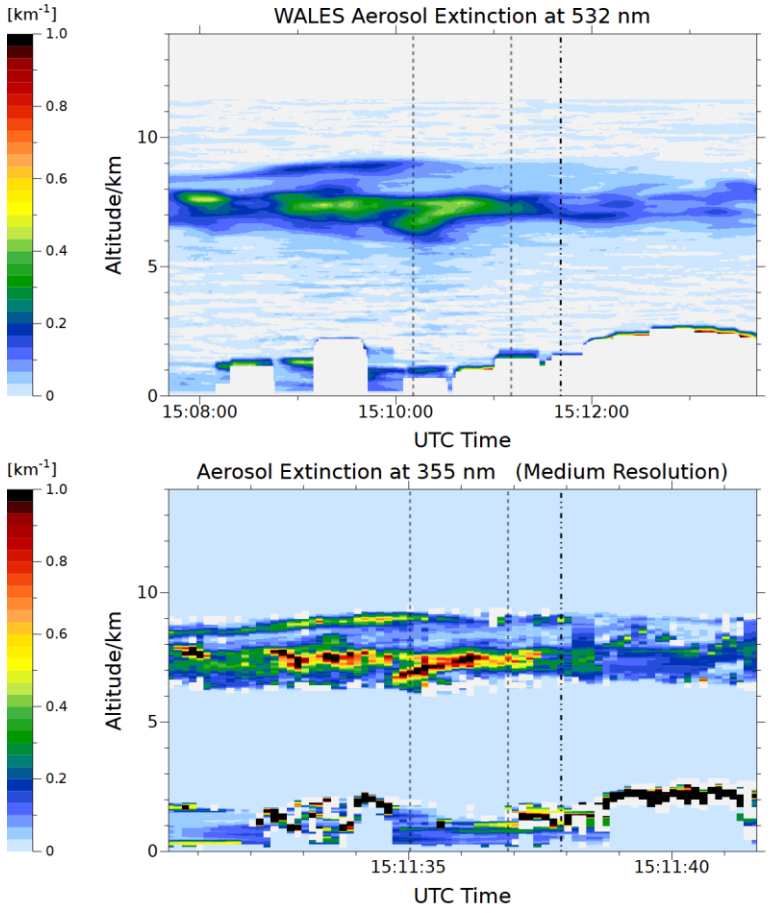
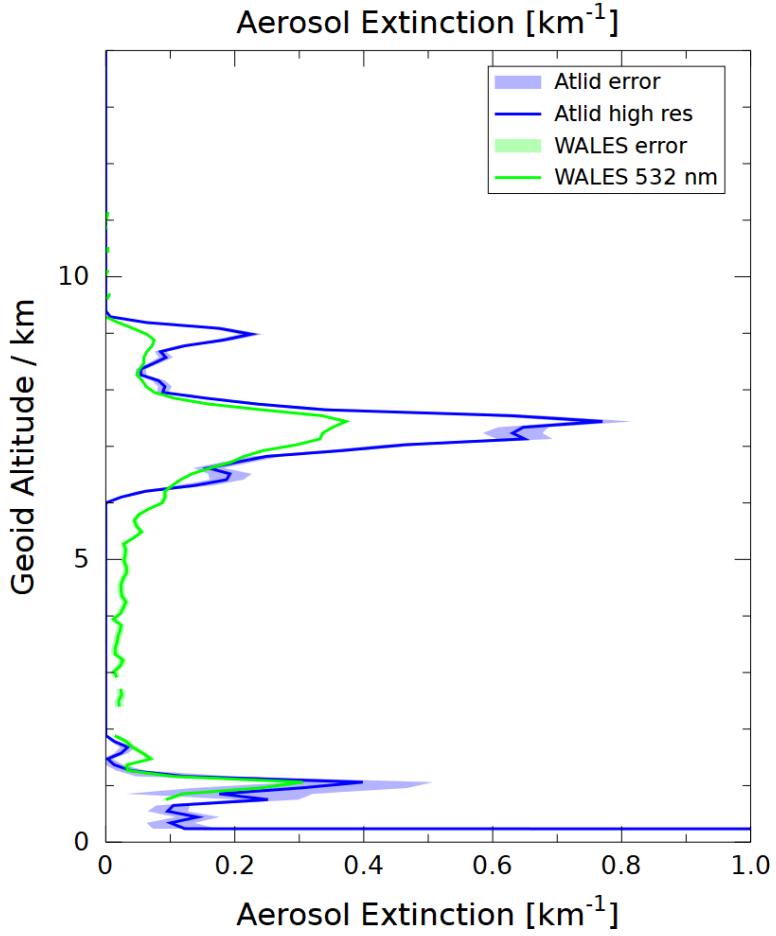
Case 2: Thin Cirrus on 16. November 2024





Level 2 EBD data comparison:

- ATLID is MS corrected, WALES **not**
- Good agreement of the 2d geometrical structure
- WALES uncorrected extinction is lower at the top and the bottom of the cloud
- WALES profile shows tail below the cloud typical for MS
- All three resolutions in EBD show (nearly) the same data

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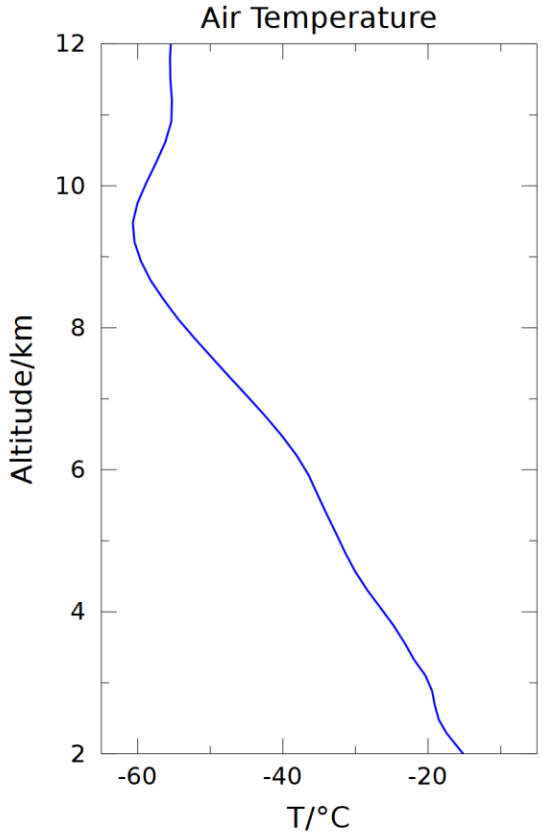
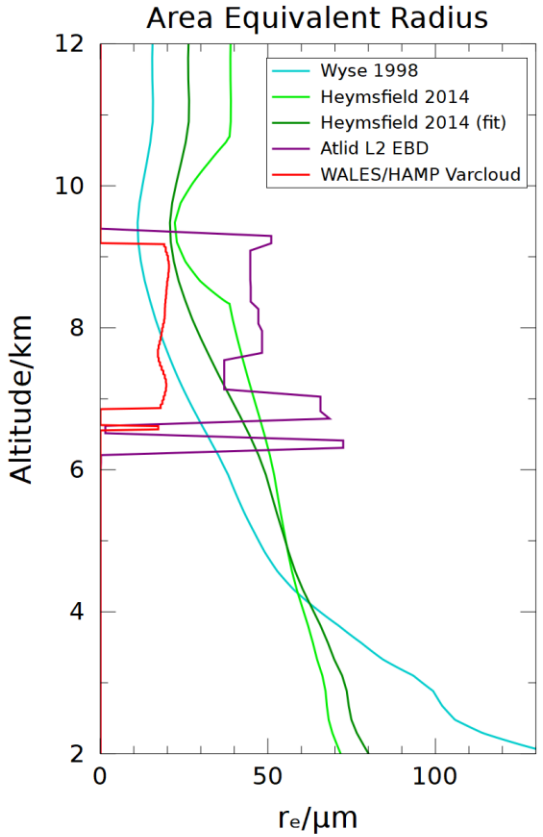


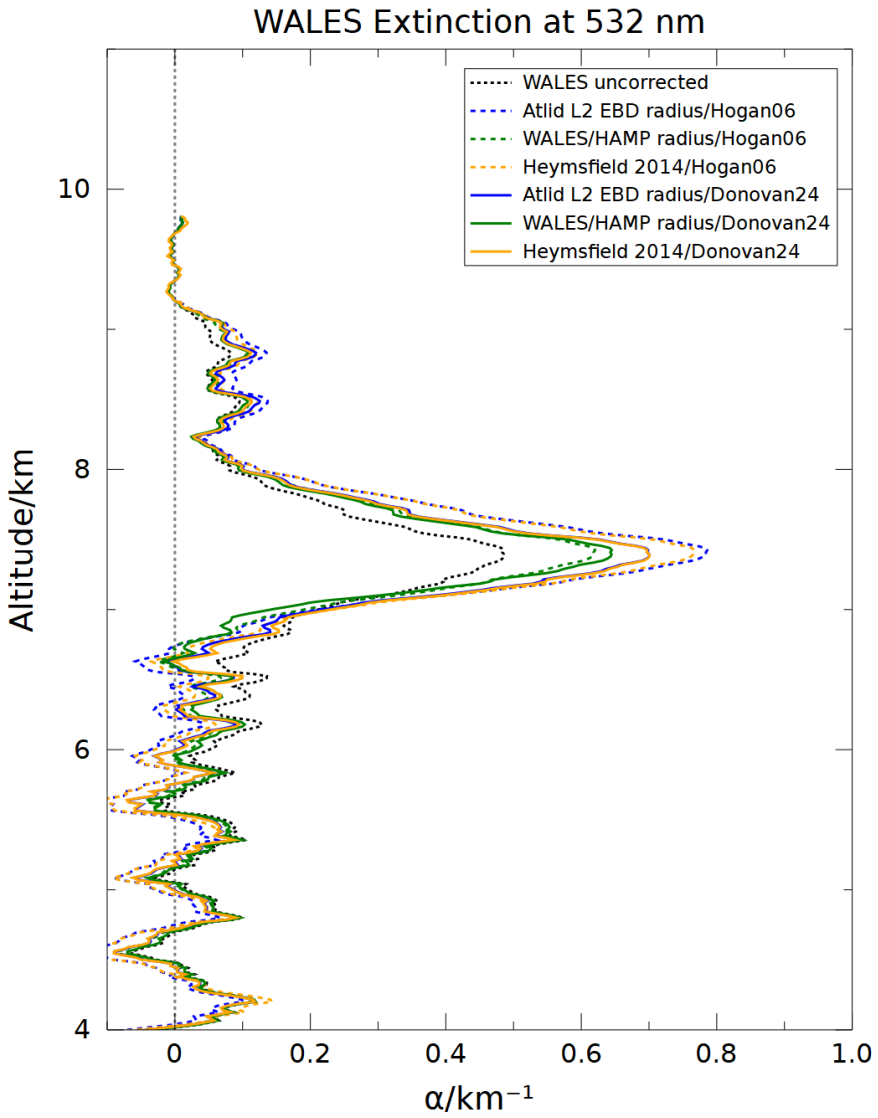


Possible sources for the effective radius of cirrus particles:

- Radius relatively constant at about 50 µm for ATLID EBD, VARCLOUD with similar profile shape, but lower
- Temperature correlations show much stronger vertical dependence

No ACM CAP data for this case on the server!

Case 2: Thin Cirrus on 16. November 2024



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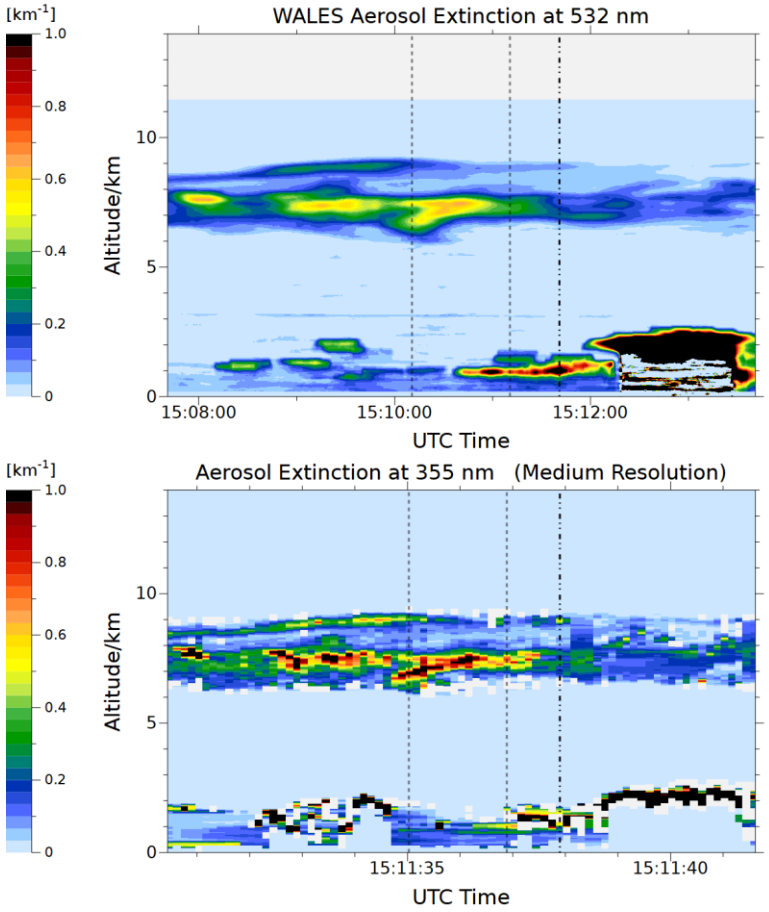
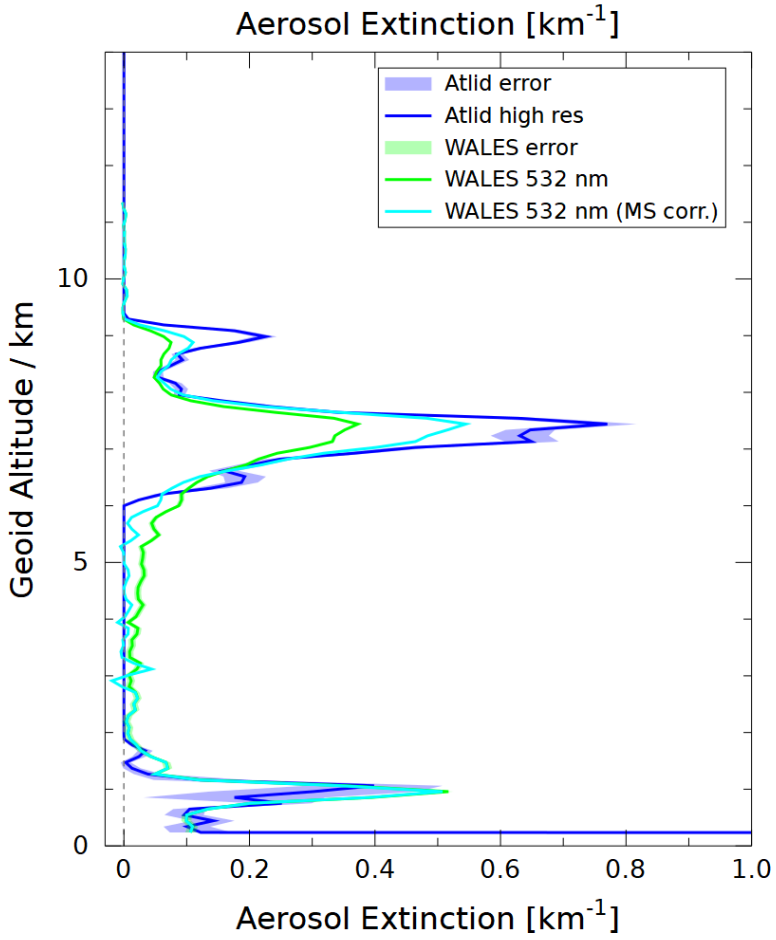
- **Hogan 2006 shows higher corrections for same radius profile and slightly better tail correction**

Case 2: Thin Cirrus on 16. November 2024

Radius from ATLID EBD and Donovan 2024 algorithm



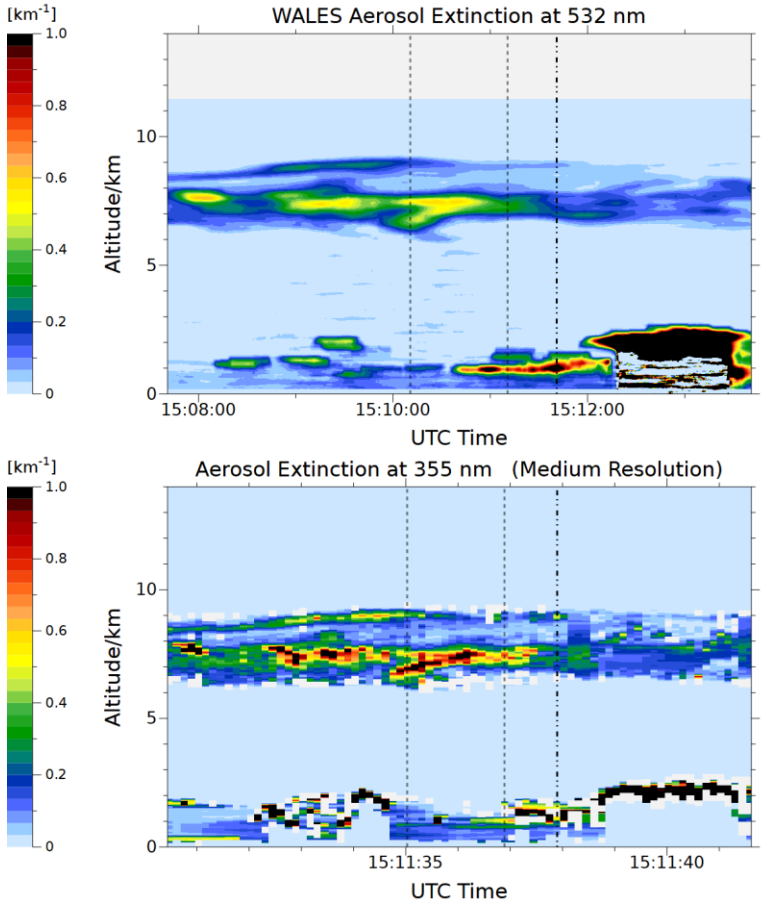


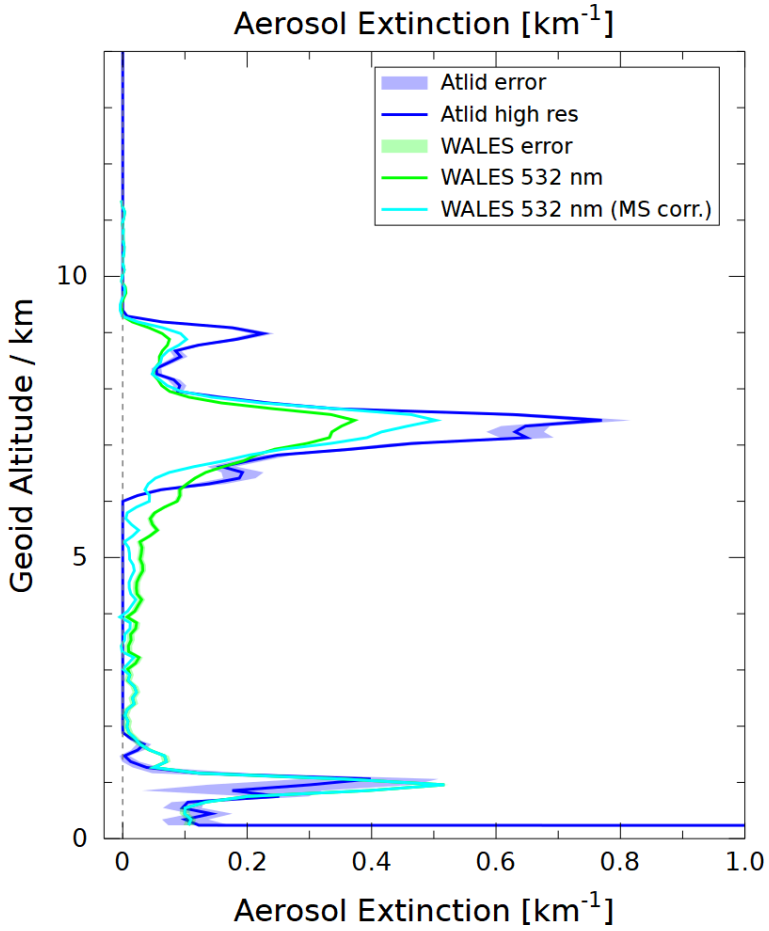
Level 2 EBD data comparison:

- Correction too small in general
- Good Tail correction

Case 2: Thin Cirrus on 16. November 2024

Radius from VARCLOUD (WALES/HAMP) and Hogan 2006 algorithm



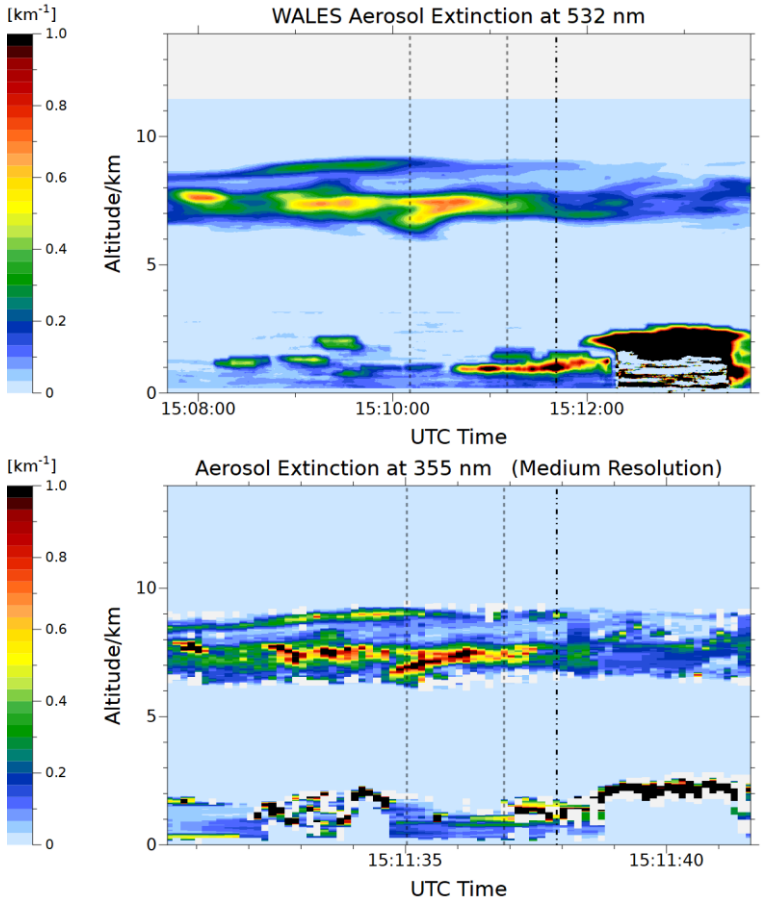


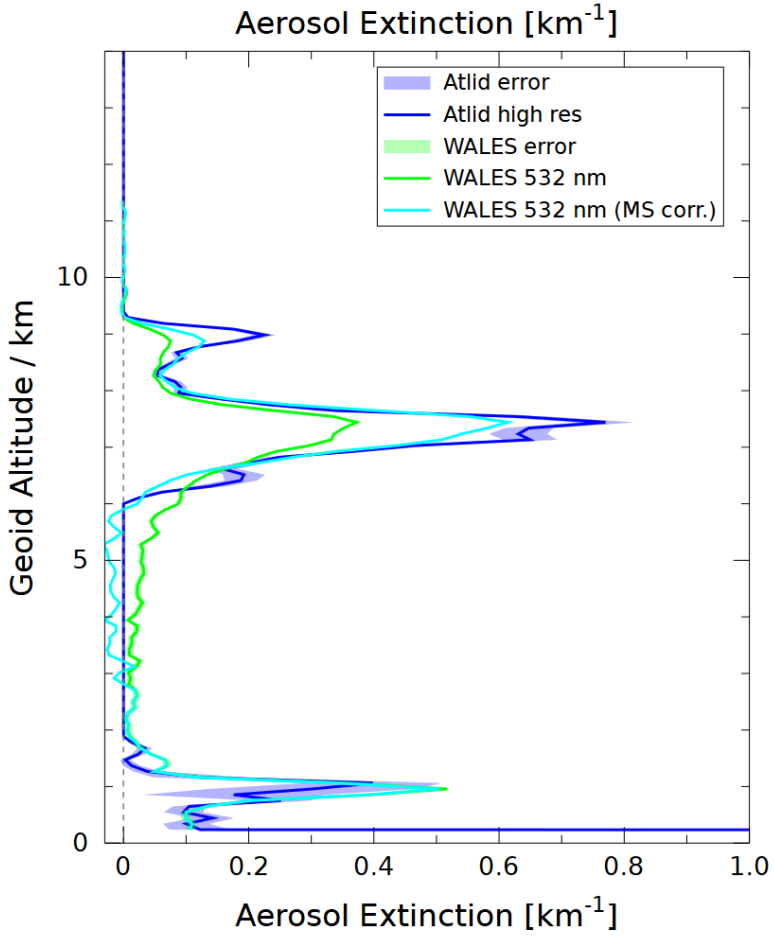
Level 2 EBD data comparison:

- Correction too small
- Tail correction too low (because of to small radii?)

Case 2: Thin Cirrus on 16. November 2024

Radius from ATLID EBD and Hogan 2006 algorithm





Level 2 EBD data comparison:

- Correction much closer
- But tail correction too high

Conclusions

- All in all the multiple scattering correction in ATLID EBD products seem sound and of high quality
- Compared to the aircraft data the ATLID extinction seems to be overestimated, probably linked to too large r_{eff} values
- For thin/cold cirrus the Hogan 2006 algorithm seems to provide better agreement if the same radii are used, but the ATLID values are still larger then the corrected WALES extinctions
- The ATLID retrieval tends to keep a constant lidar-ratio S while HSRL and Raman-lidar profiles typically show some variation of S for in-homogenous clouds
- **Suggestions for the retrieval**: revisit the r_{eff} values used: ATL-EBD values seem to be on the high side while ACM-CAP values seem to be a bit too low. Use the Hogan 2006 algorithm which makes a difference especially at cloud top and shows a slightly faster settling for the tail correction. Make the LR more variable in the optimal estimate (use higher a priory error).