Validation of ATLID extinction and lidar-ratio of cirrus clouds using airborne measurements with the research aircraft HALO: extend case study on the multi-scattering correction

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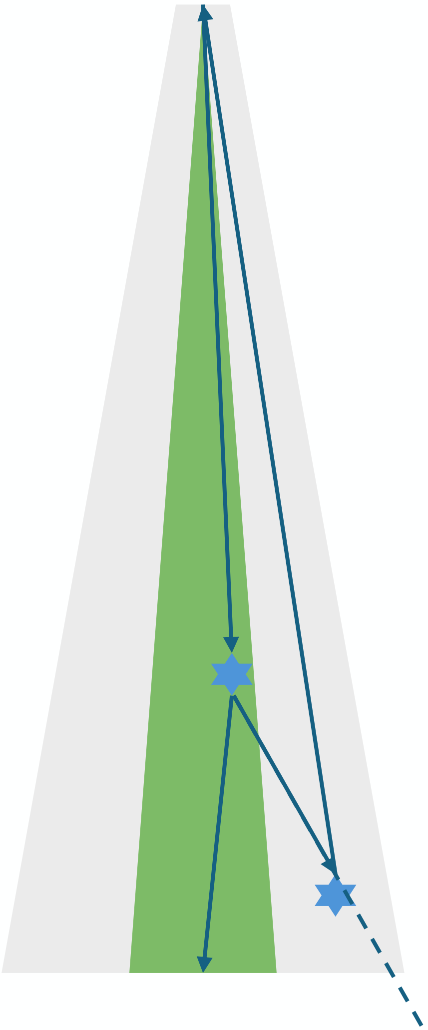
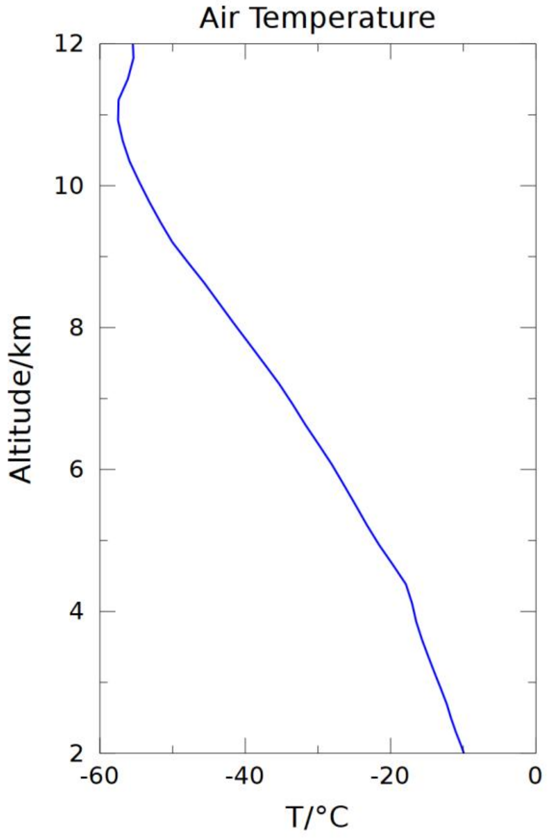
Small Angle Forward Scattering in Cirrus

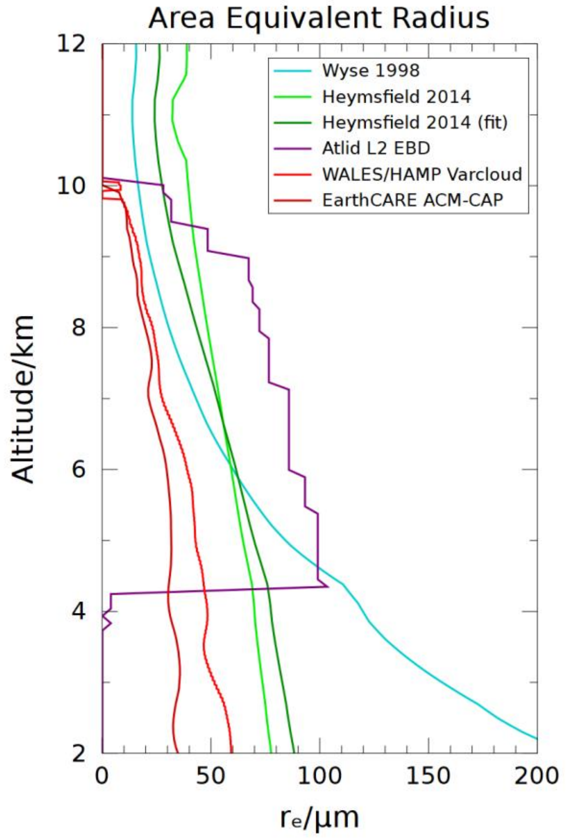


- Ice crystals can become large which results in a very narrow forward scattering peak ($\Theta = \lambda/(\pi r) \approx 1.7$ mrad for $r = 100$ µm)
- Part of the scattered light stays within the laser beam and appears to the lidar as un-scattered
- Another part of the scattered light takes some distance 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

All fast correction algorithms need an **area equivalent radius** of the ice particles!

Area Equivalent Radius? Which one?





Recap from Tokio workshop:

- Classical area equivalent radius definition results in insufficient MS tail correction
- r_{aeff} profile from A-PRO provides good correction (maybe even slight overcorrection), but has much larger values than other sources, esp. radar-lidar retrievals

- ▶ **Revisit definition of Area Equivalent Radius wrt. forward scattering – is there a better definition than the mean area radius?**
- ▶ **What's the best parametrisation for the effective?**

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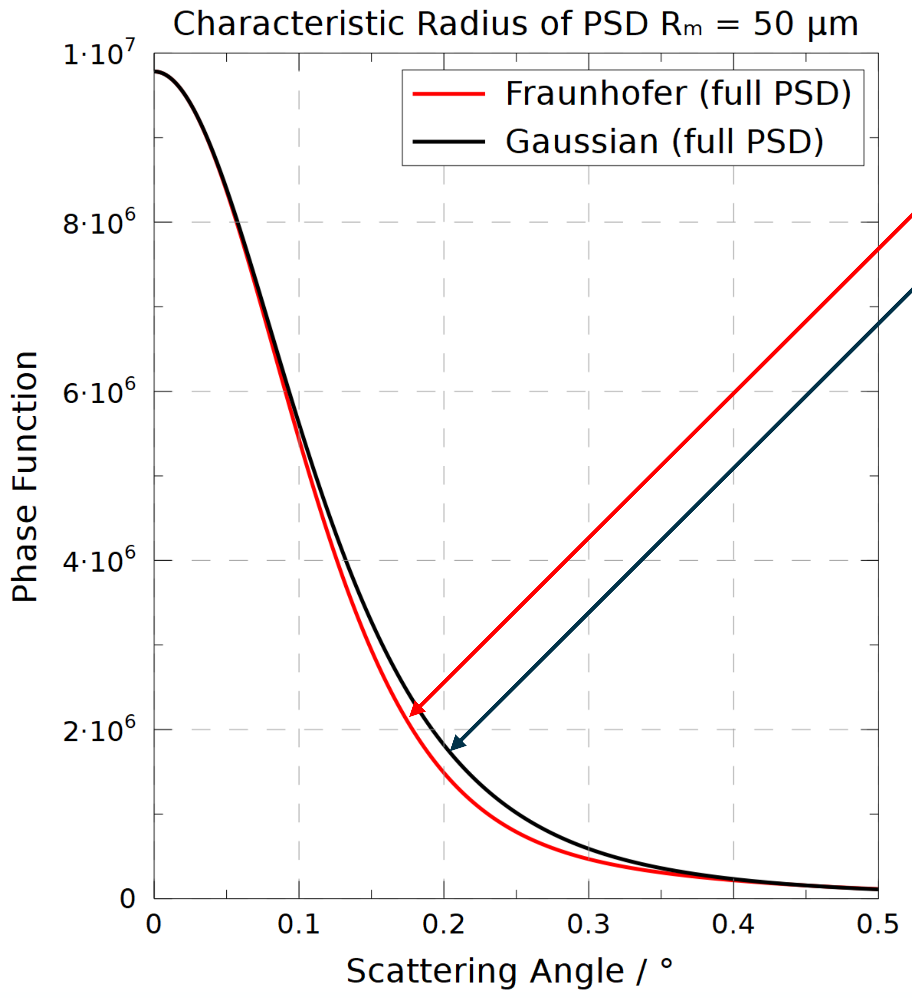

Modelling of the forward scattering peak of a realistic ice particle ensemble (Field et al. 2005 PSD with Brown&Francis $r_a(D)$ relation)

Fraunhofer scattering (Bessel functions) summed over PSD

Equivalent Gaussians summed over PSD

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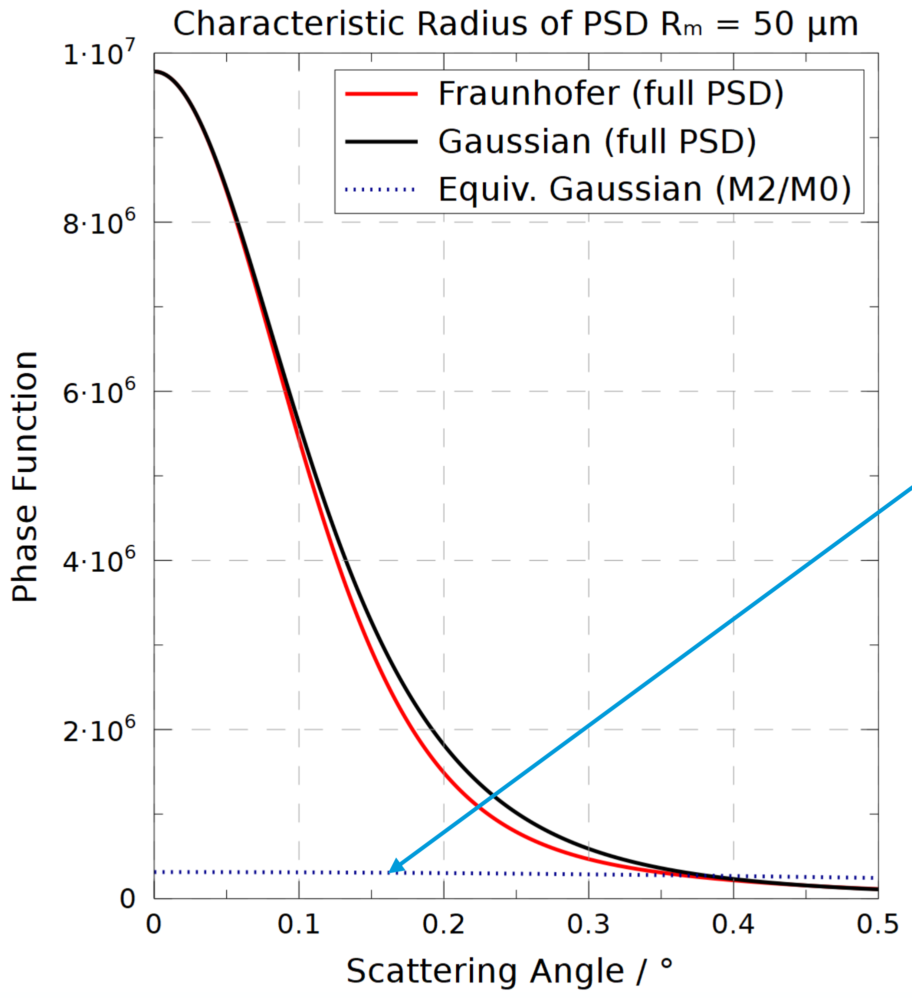

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$$r_{a,eff} = \sqrt{\frac{\int N(D) r_a^2(D) dD}{\int N(D) dD}} = \sqrt{\frac{M_{2,a}}{M_{0,a}}}$$ Classical area equivalent radius

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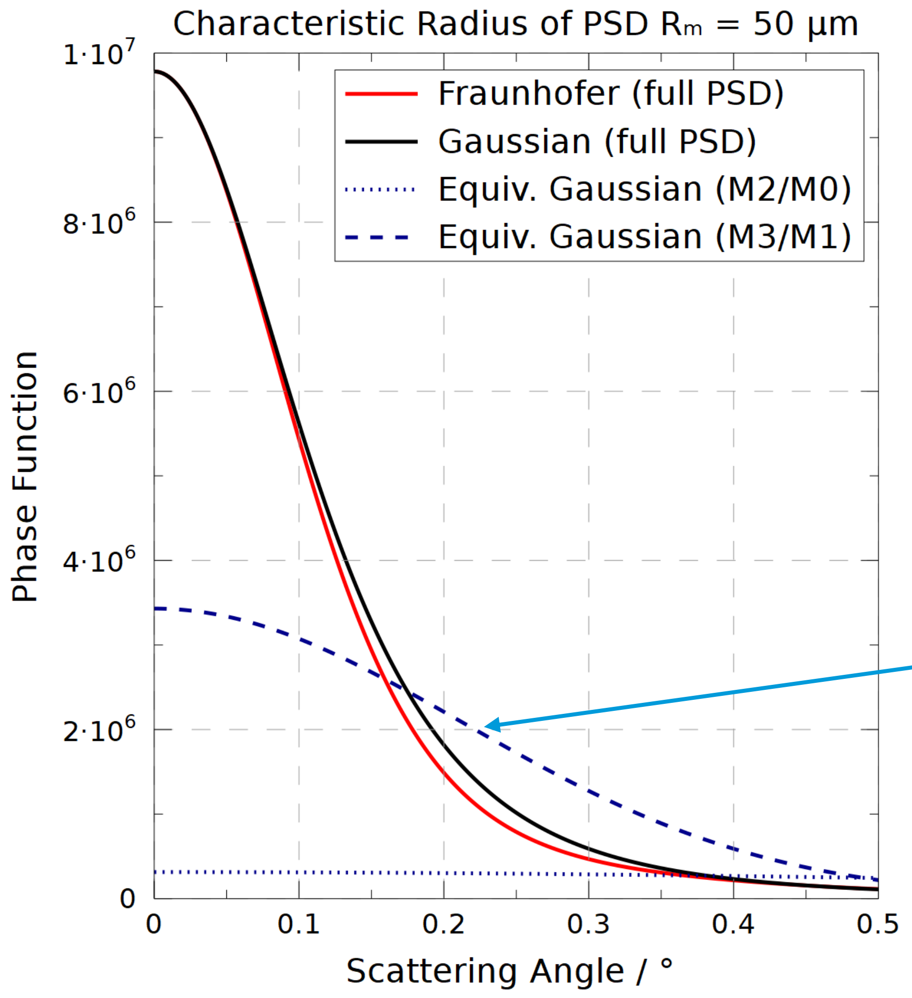

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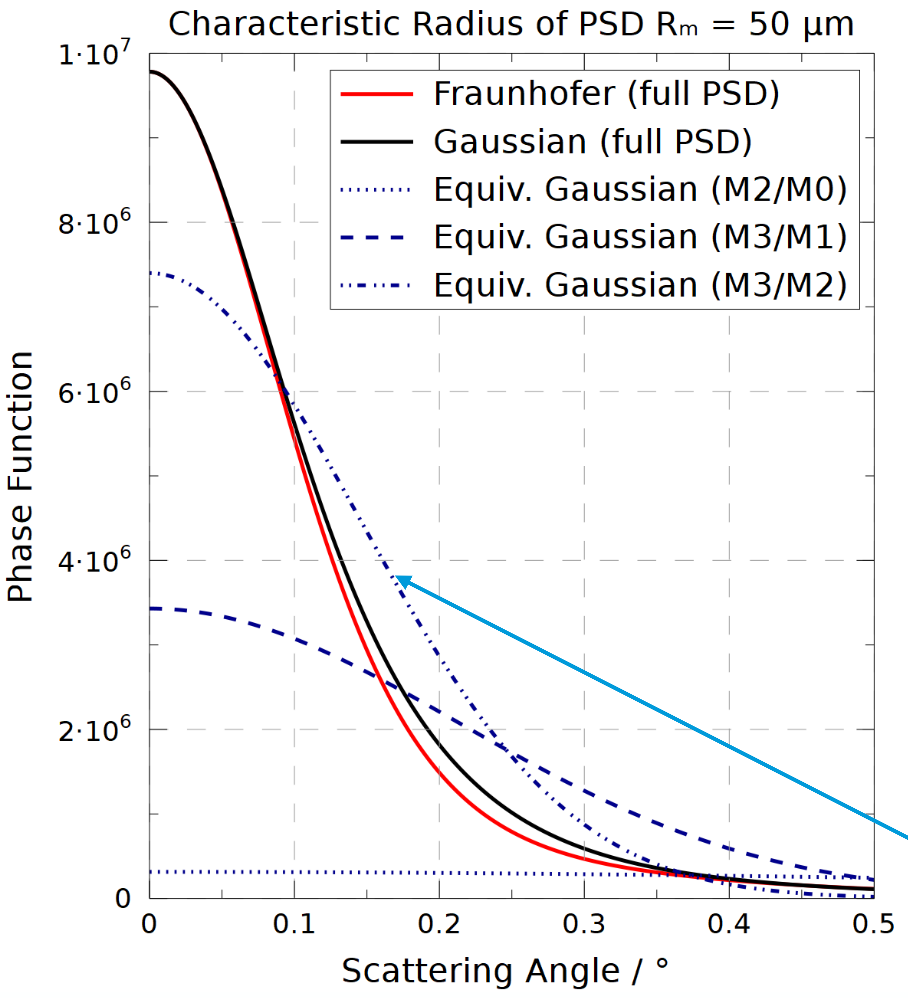

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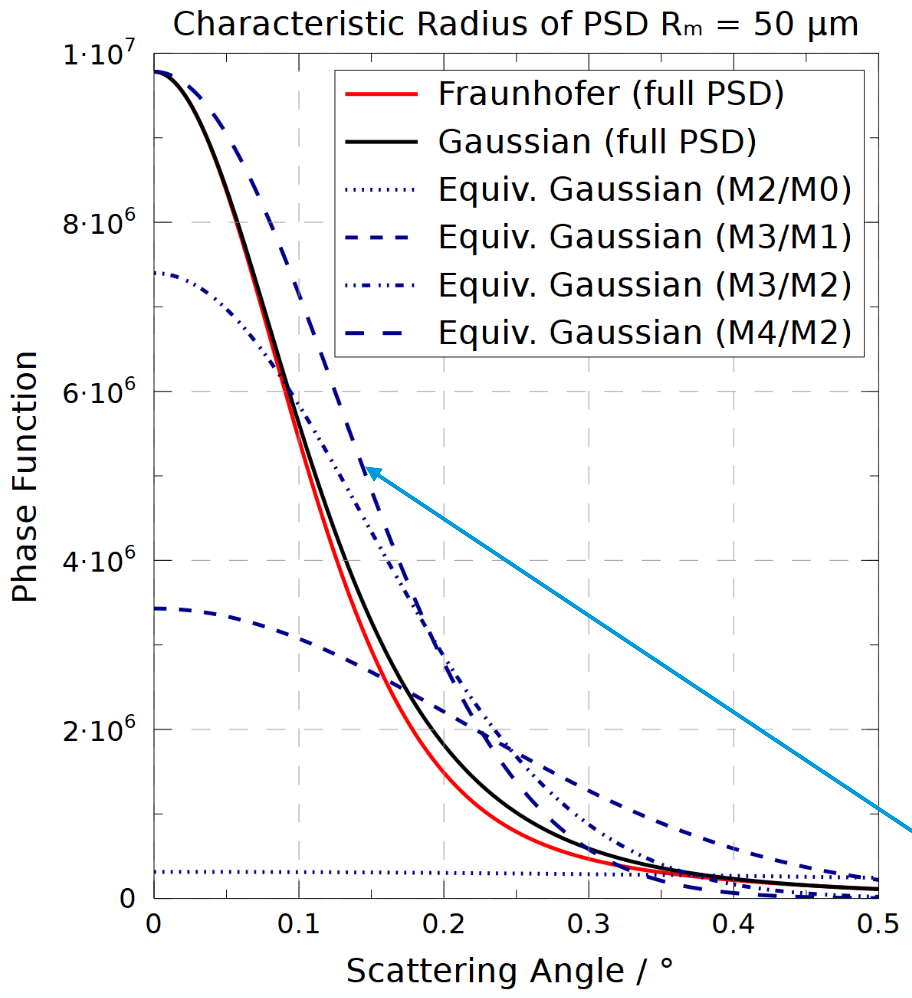

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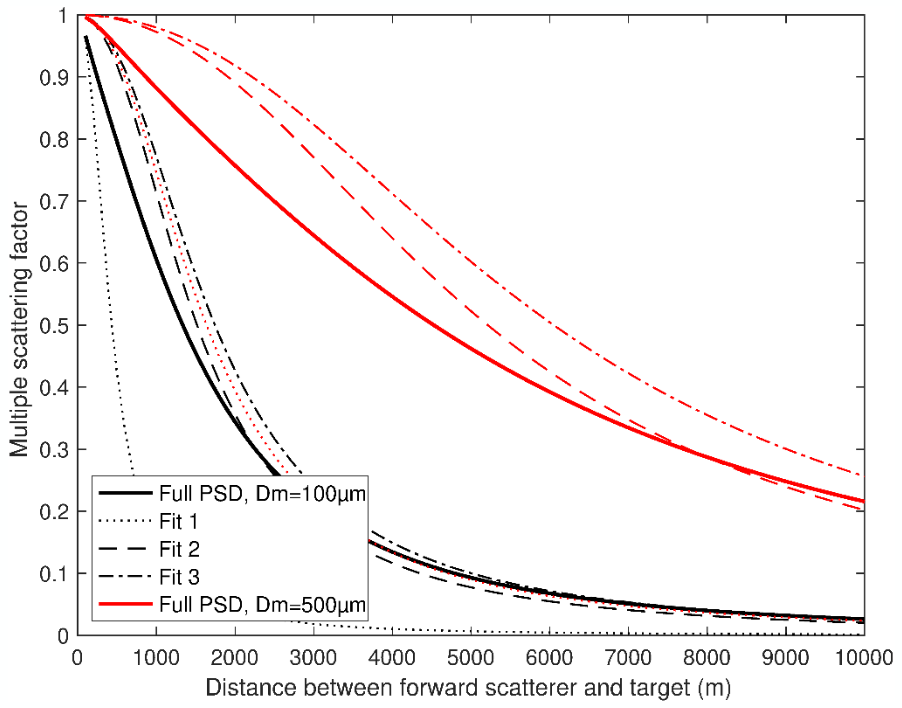
$$r_{a,eff} = \sqrt{\frac{\int N(D) r_a^4(D)\, dD}{\int N(D) r_a^2(D)\, dD}} = \sqrt{\frac{M_{4,a}}{M_{2,a}}}$$ Peak preserving (future A-PRO definition?)

No definition is completely satisfying! But which one is the best?

Area Equivalent Radius? Which one?

Modification of the Hogan 2006 Algorithm to use a PSD Averaged Multiple Scattering Factor



The Multiple Scattering Factor is the basic building block of correction algorithms and describes how fast the forward scattered light leaves the field of view of the lidar

- Replace the version with one effective radius by sum over PSD:

$$\exp\left(-\frac{\rho_t^2}{\rho_l^2+\left(\frac{\lambda}{\pi r_{a,eff}(r)}\right)^2\left(\frac{R-r}{R}\right)^2}\right)\alpha(r) \rightarrow \sum_i N_i \cdot \exp\left(-\frac{\rho_t^2}{\rho_l^2+\left(\frac{\lambda}{\pi r_{a,i}(r)}\right)^2\left(\frac{R-r}{R}\right)^2}\right)\alpha_i\,(r)$$

$$\text{with } \alpha_i = \frac{r_{a,i}^2}{\sum_j N_j r_{a,j}^2}\alpha$$

- Use a lookup-table to gain back performance
- **Note:** this is used for first order forward scattering, higher orders still use a single area equivalent radius
- The A-PRO algorithm could also be adapted to use a PSD averaged MSF (not done yet)

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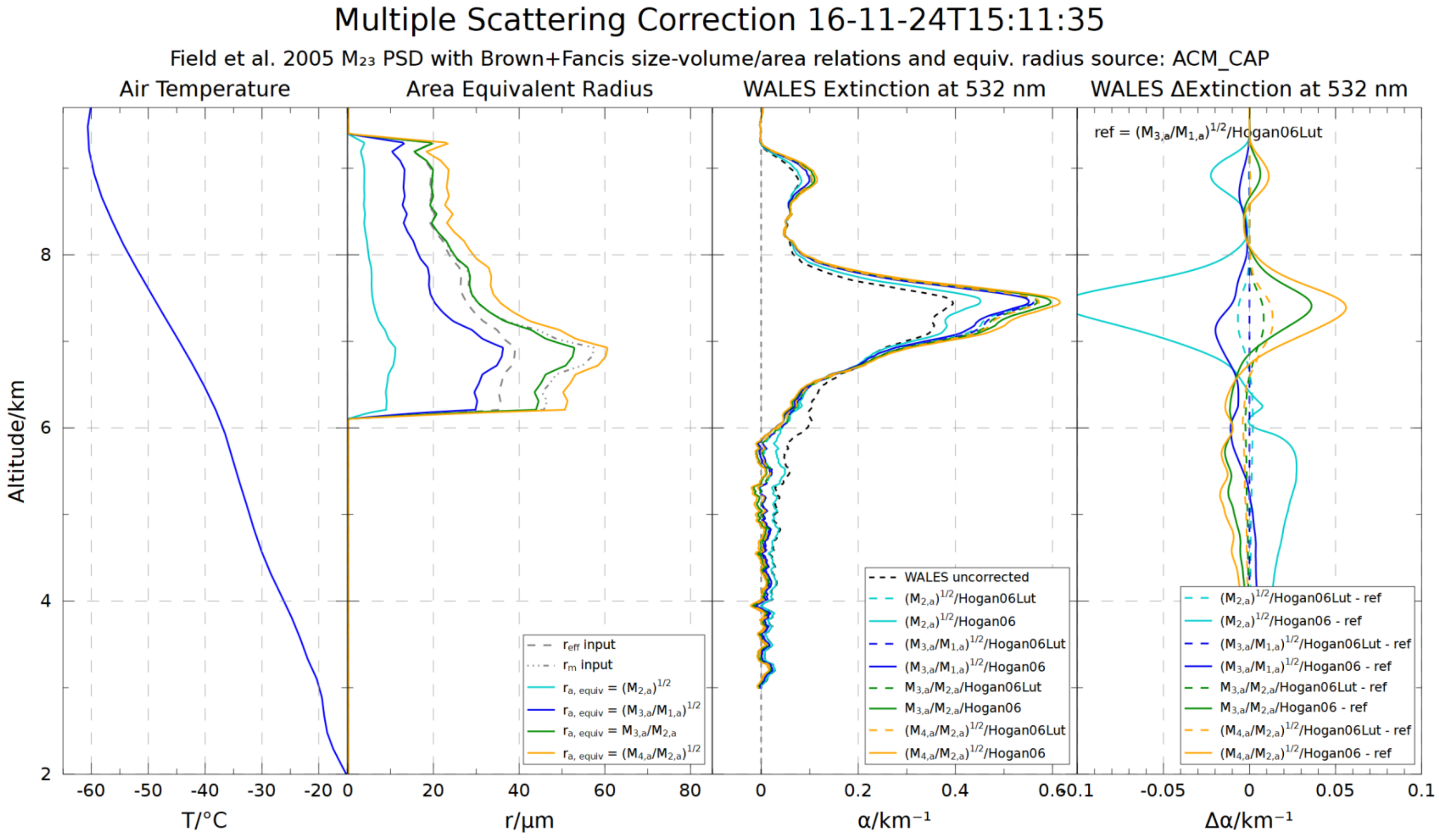
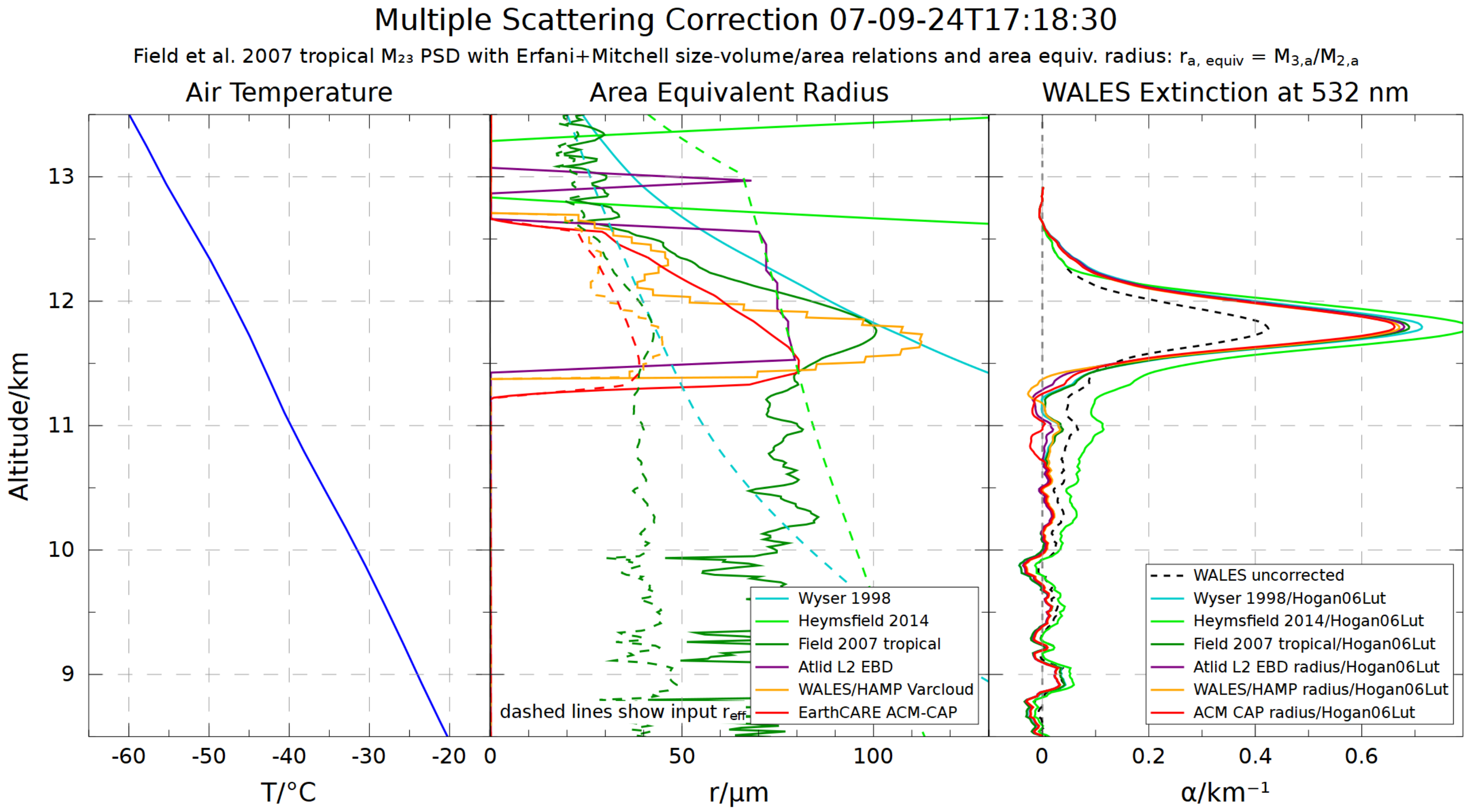


Example of cirrus over the northern North Atlantic

- Enhanced Hogan 2006 algorithm (dashed lines) shows very weak dependence on area effective radius definition (as expected for moderately thick cirrus)
- Standard algorithm performs comparatively best with "variance equivalent" radius or current CAPTIVATE definition
- Peak preserving radius tends a bit to overestimation
- Comparable results for two other cases (not shown here)

► **Current CAPTIVATE definition seem to be a good middle ground**

Effective Radius: Best a-priory choice?

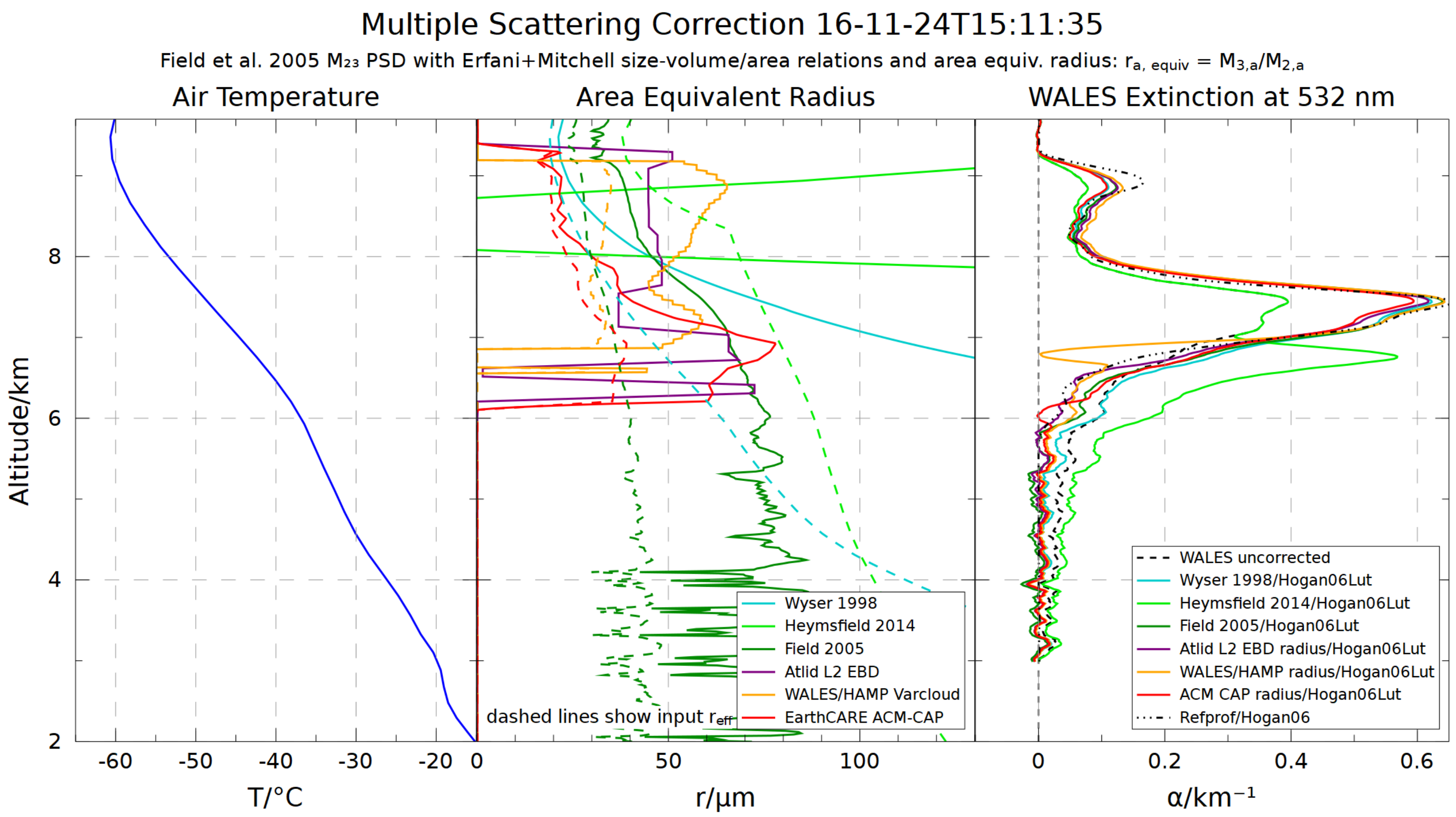


Example of tropical cirrus

- Field based a-priory profile comparable to the two synergistic profiles
- Heymsfield 2014 parameterisation results in much to large radii and wrong correction
- Wyser 1998 works in this example but has much too large radii lower down in altitude
- A-PRO BA values work also well, but only due to a lucky bug…
- MS tail correction equally good for all but Heymsfield

► **Field et al. based r_{eff} come closest to synergistic profiles**

Effective Radius: Best a-priory choice?



Example of cirrus over the northern North Atlantic

- Field based a-priory profile comparable to ACM-CAP, but Varcloud radius is much to large at the cloud top
- Heymsfield 2014 parameterisation results again in much to large radii and wrong correction
- Wyser 1998 does not work here as the cirrus is much lower in this case and the radii are too large
- A-PRO BA values again work well, but…
- MS tail correction equally good for all but Heymsfield, Wyser and Varcloud

► **Again Field et al. based r_{eff} seems to give the best results among the a-apriory profiles**

Conclusions and Open Points

Conclusions

- The classical definition of the area equivalent radius is unsuitable do describe foreword scattering properly
- Area equivalent radius definitions based on higher moments of the particle size distribution provide better correction results when compared to an enhanced algorithm.
- The current CAPTICATE definition seems to be a good middle ground among the investigated schemes
- The Heymsfield 2014 effective radius parametrisation, which is used up to the present A-PRO baseline generally gives much too high r_{eff} values, but due to a bug which resulted in the fact that actually no conversion from r_{eff} to the area-equivalent-radius took place, the results were actually quite good!

Still open points

- Which size-mass/size-area relationship is the best to use? (three different investigated so far which show significant differences – unclear how to decide on this…)
- The Field-type PSD parametrisations seem to work well, but are based only on measurements of large particles (D > 100 µm). The small particle mode is “guessed”. Are there better, more recent models?

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This talk was only on methodological aspects, but how does ATLID compare to WALES if this all is applied?

Comparisons of extinction for 23 Cirrus cases at direct under flights during the PERCSUION, ASCCI and NAWDIC airborne campaigns

No MS correction for WALES | No MS correction for WALES | **With MS correction for WALES**