Response to Reviewer #1

We thank the reviewer for their careful and insightful reading of our manuscript and for highlighting important areas for clarification and improvement. We provide detailed responses below, with the reviewer's comments shown in **dark blue**.

Major Comments

Reviewer: This is an interesting study of considerable merit for its measurements of an important single scattering parameter of cirrus in a location where few measurements have previously been made. The asymmetry parameter is of secondary importance to the optical depth for calculating cloud reflectivity. It is nonetheless important to get right, as existing uncertainties can lead to errors of up to a factor of two.

I have some rather deep concerns about the analyses however, generally with regards to the aspect that the measurement techniques seem insufficiently justified, and also the reported results appear to be implausible.

We thank the reviewer for their positive assessment of the scientific relevance of our work. In response to the reviewer's concerns, we have revised the manuscript to provide a clearer and more detailed discussion of the asymmetry parameter retrieval method, including a more detailed discussion of the uncertainties in the retrieval. We believe these additions improve the transparency and scientific robustness of our methodology.

Line 116

Reviewer: A threshold of 0.1 ms is applied to remove "shattering events". Some justification seems necessary here. Is there a distinct mode in the interarrival times that would suggest there is a shattering mode? How can it be known that such events are not a result of natural turbulent clustering of particles, a well known phenomenon in clouds? If such events were included, would it affect the calculated values of g, optical depth, and all the other microphysical parameters? What I suggest here is plotting a spectrum of interarrival times, logarithmically binned, on a log-log plot (i.e. d n/dlog(tau)). If the spectrum has the property of scale invariance, namely the slope is nearly constant across interarrival times, including 0.1 ms, then the physics governing interarrival times at 0.1 ms should be anticipated to be the same at any other scale. If there is a scale break or distinct mode, then a better argument can be made that such filtering is justified.

The reviewer is correct that the 0.1 ms threshold was selected based on inspection of the interarrival time distributions. Figure 1 shows a log-log plot of interarrival times from all CIRRUS-HL research flights. While the main mode of the distribution typically lies between 1 and 1000 ms, several flights exhibit a distinct secondary mode at much shorter timescales. This secondary mode appears consistently at interarrival times shorter than 0.1 ms, corresponding to spatial separations of less than approximately 20 mm (assuming an aircraft speed of $200\,\mathrm{m\,s^{-1}}$).

Such short separations are unlikely to be maintained for a long periods of time, as electrostatic interactions tends to lead to rapid aggregation, forming a single aggregate particle rather than a temporally separated sequence of distinct ice crystals. Therefore, this distinct population at very short interarrival times is interpreted as resulting from shattering events, consistent with earlier studies. Field et al. (2006) reported a similar break in interarrival time distributions and used a comparable threshold to separate cirrus particles from shattering artefacts in optical array probe data. Our interarrival time filtering approach follows this established methodology.

We will include this interarrival time spectrum in the Supplementary Information along with annotated identification of the threshold. Importantly, please note that the interarrival threshold correction was only applied when constructing particle size distributions and calculating bulk properties (N, IWC), not for the asymmetry parameter g. Values of g were retrieved solely from manually classified intact particles and were unaffected by the interarrival filtering.

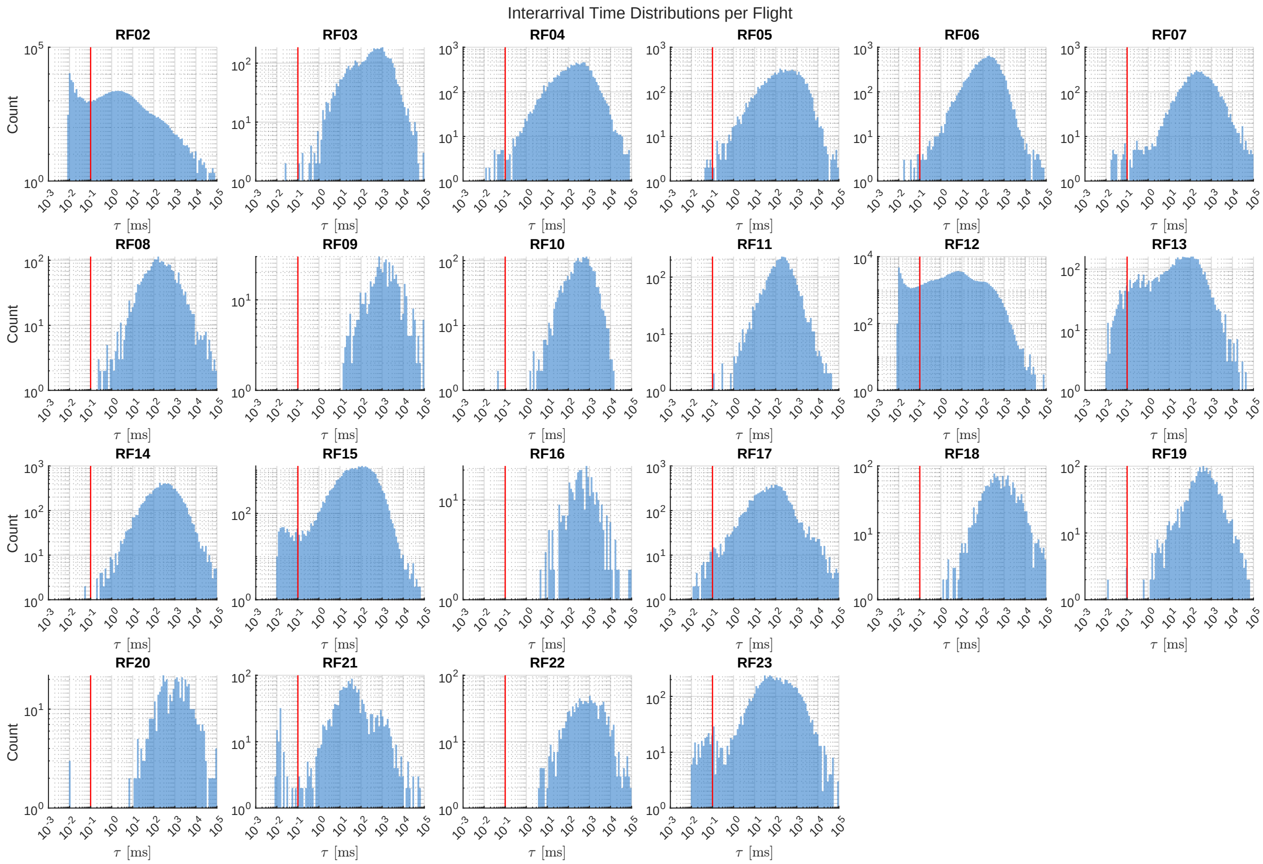


Figure 1: Log–log distribution of interarrival times (τ) for detected particle triggers during CIRRUS-HL research flights (RF02-RF23). For some flights a distinct second mode is visible for interarrival times below 0.1 ms (highlighted with red vertical line), which is attributed to shattering events.

Line 131

Reviewer: Baker and Lawson (2006) focused on mid-latitude clouds, not Arctic clouds. The premise of this submission here is to consider latitudinal variations in microphysical and optical properties. What justification is there that the power-law behavior identified here for relating mass to area, obtained at mid-latitudes, can be applied to the Arctic?

We acknowledge the reviewer's concern regarding the use of an area-to-mass relationship derived from mid-latitude cirrus for our Arctic data. It is well established that different mass-dimensional relationships can lead to significant uncertainties in retrieved ice water content (IWC) and, consequently, in the effective radius. We deliberately chose to use an area-to-mass relationship rather than a conventional diameter-to-mass parameterisation because linking particle mass to projected area has been shown to reduce mass estimation errors by approximately 50% Baker and Lawson (2006). Since particle cross-sectional area is directly measured in our dataset — unlike particle maximum dimension, which often relies on assumptions about shape and orientation — this method offers a more accurate basis for mass retrieval.

To our knowledge, no studies currently provide area-to-mass relationships specific to Arctic cirrus, making the Baker and Lawson parameterization the most suitable option available. In response to the reviewer's comment, we will explicitly note in the manuscript that this relationship is based on mid-latitude observations to ensure full transparency.

Line 154
Reviewer: The data is stated to be "manually cleaned" based on "intact" imaged particles. This sounds very unscientific. Can a more objective justification be described for what is being done to what?

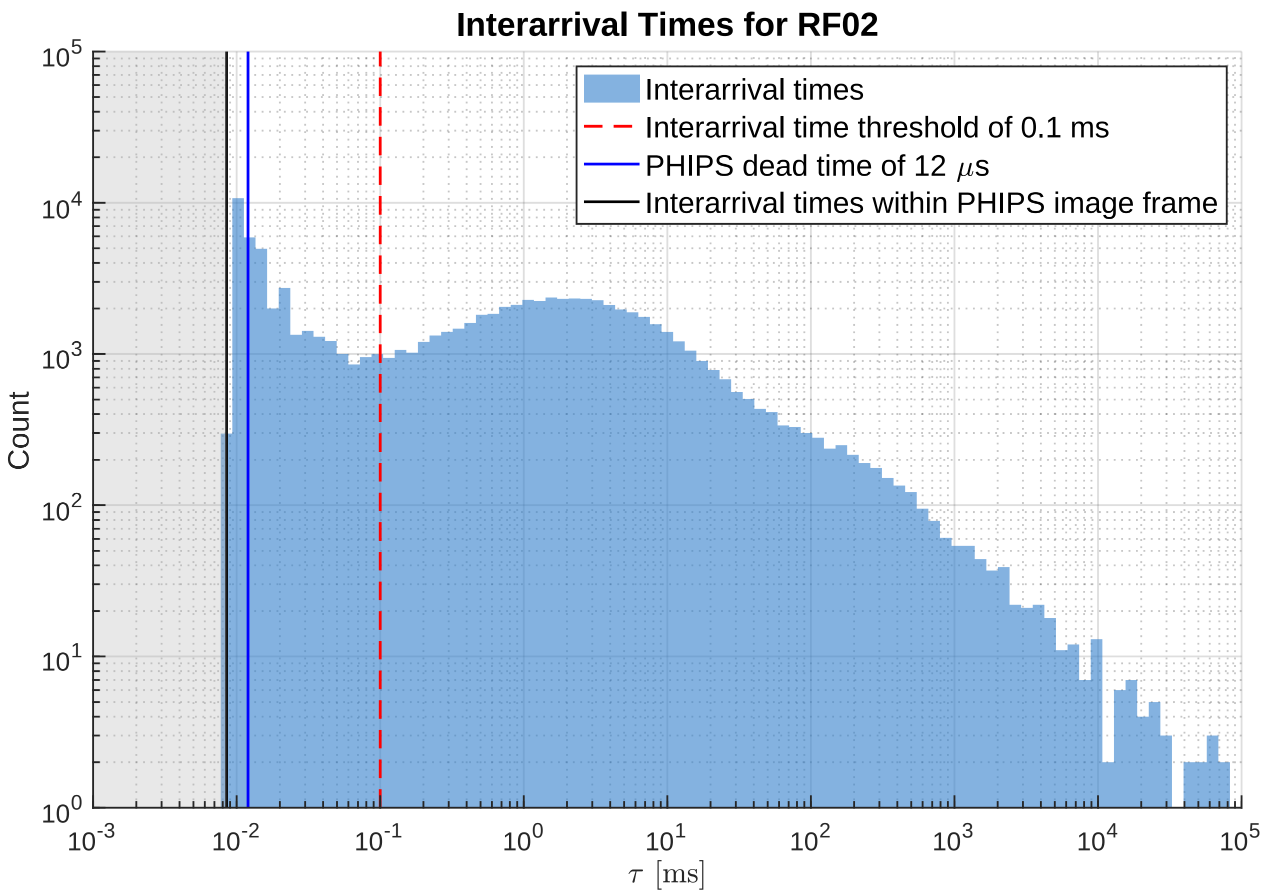


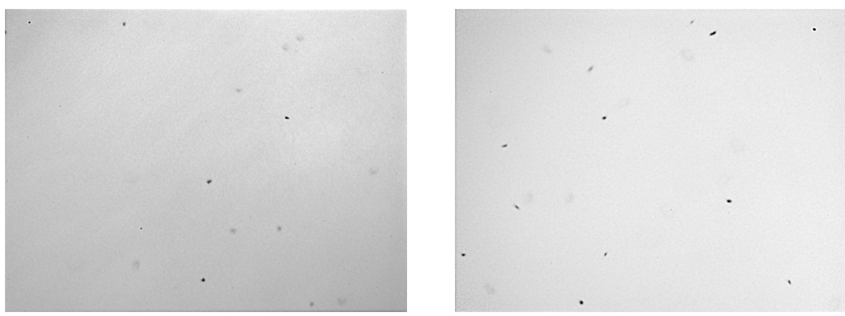
Figure 2: Log–log distribution of interarrival times (τ) for detected particle triggers during CIRRUS-HL research flight RF02.

We emphasize that manual screening of the dataset is necessary, as the inter-arrival time method alone cannot identify all shattering events. Figure 2 illustrates this limitation using the inter-arrival time histogram from research flight 2. The red dashed line marks the threshold of 0.1 ms, which separates the main particle population (longer inter-arrival times) from the shattering mode (shorter inter-arrival times). The shattering mode abruptly ends near 10 μs, corresponding to the electronics dead time of the PHIPS system—that is, the minimum temporal separation required to register two distinct trigger events. This dead time translates to a spatial separation of approximately 2 mm at typical jet aircraft speeds.

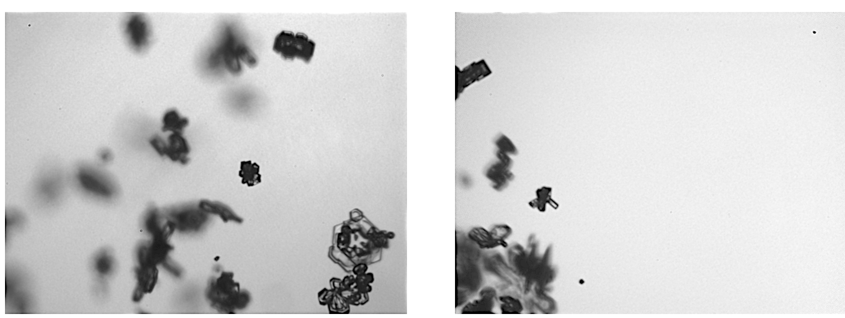
However, the PHIPS image frame covers an area of roughly 1.1 mm $\times$ 1.5 mm, which converted into inter-arrival times is shown as the shaded grey region in Fig. 2. Shattering fragments arriving within these distances—at spacings below the dead time limit—cannot be detected by the inter-arrival algorithm alone. Visual inspection of the stereo images is therefore an important and practical complementary method to identify such events. As illustrated in Fig. 2 of the main text, manual classification using the stereo images is essential to reliably remove residual shattering artifacts.

However, we acknowledge the reviewer's concern and have clarified both the reasoning behind this shattering correction as well as the procedure. Manual inspection refers to the visual classification of individual trigger events using stereo-microscopic images from PHIPS to identify likely shattering events. Shattering is identified when multiple small fragments (typically smaller than 100 µm) appear simultaneously on one or both stereo image frames. Given that each image covers an area of approximately 1.5 mm × 1.1 mm, the presence of several unconnected particles within this small field of view is highly unlikely under natural cirrus conditions, where ice crystal number concentrations and clustering tendencies are generally low. In addition, possible shattering of larger crystals is identified when the particle morphology shows clearly broken or truncated shapes, e.g., when expected hexagonal facets are missing or irregular, or when boundaries appear jagged rather than smooth.

In order to convince the reviewer that shattering events are identifiable from the stereo-images, we have added below two examples of shattering events (Fig. 3), which together with more examples, will be added to the Supplementary information.



(a) Example with small fragments



(b) Shattering of a larger aggregate

Figure 3: Stereo-image examples from PHIPS illustrating different particle shattering events. Each row shows the stereo-image pair separated by 120°: (a) small fragments and (b) shattering of a larger aggregate. The inter-fragment spacing in these examples is significantly below the threshold limit of 2 mm that is calculated from the electronics dead time of 12 µs (the blue vertical line in Fig. 2). Each image covers a field of view of approximately 1.5 mm × 1.1 mm.

Section 2.2.3

Reviewer: This section needs much more detail. A point of particular concern regards the validity and uncertainty related to the assumption stated in Xu et al (2022) that about the assumption lying behind the "mean" statement on l. 174 that "This is achieved by exploiting the assumption that the forward diffraction and the refraction - reflection energies are asymptotically equal." First, it's worth considering the rant in Bohren and Clothiaux about how there is no refraction, reflection or diffraction - only scattering and interference. The distinctions between the three are entirely artificial. But more importantly from a measurement standpoint, per Jarvinen et al (2023), the polar nephelometer only measures scattering at angles between 18 degrees and 170 degrees, which for any conceivable cloud particle encompasses quite a lot less than half the total scattered energy justifying a straightforward mean of forward and side/back scattering. Perhaps this all makes sense. I'm not sure I understand the need for a Legendre series expansion as described in Xu et al (2022). But at the very least, a full justification, with error analysis, should be presented of this measurement that is core to the article.

Thank you for pointing this out. We are aware that the separation of scattering into diffraction, refraction, and reflection is not fundamental from the perspective of electromagnetic theory. As Bohren & Clothiaux (2006) emphasize, all scattering results from the interaction of electromagnetic waves with matter, and the distinction into separate components is introduced only within the geometric optics (GO) framework. However, in atmospheric particle optics, this decomposition is still widely used and practically useful. For particles with large size parameters $x = 2\pi r/\lambda > 100$, geometric optics becomes increasingly accurate in describing the angular distribution of scattered light and the partitioning of energy. At the same time, rigorous electromagnetic methods such as DDA or T-matrix become computationally unfeasible for such large and complex particles. We therefore rely on the GO-based separation in our analysis, as it allows us to reconstruct the full angular scattering function from the limited angular range covered by PHIPS, following the approach described by Xu et al. (2022).

We have expanded Section 2.2.3 significantly. The retrieval of g from the polar nephelometer follows the method described by Xu et al. (2022), where full scattering phase functions are reconstructed from measurements at angles 18°–170° using a Legendre polynomial expansion. In this approach, the basic assumption is that at scattering angles greater than 18°, the measured signal is dominated by geometric optics (GO) contributions, namely refraction and reflection, with only minor contributions from diffraction. The unmeasured forward angular range below 18° is assumed to contain the majority of the diffraction peak. Based on this separation, the GO part of the angular phase function can be reconstructed over the full angular range using the measured data and the Legendre polynomial expansion.

The accuracy of the retrieval algorithm is primarily determined by the integration error, which largely depends on the characteristics of the phase function, such as if peaks or sharp changes in the intensity appear that cannot be well captured by the limited angular range. To investigate the smoothness of the measured phase function, Xu et al (2022) introduced the C_p parameter. This parameter reflects the decay rate of Legendre expansion coefficients and can be directly calculated from the measured angular intensity. When $C_p > 0.4$, the phase function is sufficiently smooth for the Legendre expansion to converge rapidly, and the error in the retrieved asymmetry parameter remains below 0.001. This has been validated by numerical ray-tracing simulations for orientation averaged hexagonal columns and plates with different aspect ratios and with varying degrees of distortion. In our dataset, 96% measured averaged angular scattering function profiles had C_p values above this threshold, indicating that the error introduced by the expansion is negligible compared to other sources of uncertainty, such as the instrumental uncertainty.

The instrumental uncertainty arises from variations in optical transmission and from differences in the individual channel responses of the multi-anode photomultiplier tube (MAPMT). These differences were characterised by performing calibrations using glass beads with known phase function (Wagner et al., 2025) and the resulting maximum uncertainty in g is 0.008. We have added this discussion to the manuscript and now provide a more complete justification and error analysis for the asymmetry parameter retrieval.

Table 1:

Reviewer: The microphysical measurements presented appear implausible for what they would imply for the reflectivity based on the thin cloud expression given by Eq. 8. Taking the reported median microphysical values of 3 mg/m3 for the IWC, 37 um for the effective radius, the mean optical depth for a cloud 1 km thick would be 0.12. If, much more generously the cloud were 3 km thick, then it would be 0.36. From Eq. 8, this quite thick cirrus, taking g = 0.727, would have a reflectivity of 0.05. From the ground, such physically thick clouds would be barely visible. Mostly one would see blue sky. This seems implausible given cirrus are certainly very visible in the Arctic in satellite measurements, with reflectivities I would guess 10 times as high.

We appreciate the reviewer's effort to place our in situ microphysical results in the context of bulk radiative visibility and remote sensing observations. To assess consistency, the optical depths implied by our measured ice water content and effective radius can be compared to independent Arctic remote sensing observations. Using representative cloud geometries (1.4–2 km thickness) reported for Arctic cirrus over Ny-Ålesund (Nakoudi et al., 2021), the same microphysical values yield optical depths of roughly 0.19 to 0.27. These are in line with ground-based lidar climatologies: Campbell et al. (2020) report that cirrus in the Alaskan subarctic generally have optical depths below 0.5, and Nakoudi et al. (2021) find median values between 0.08 and 0.2 at Ny-Ålesund. Thus, the optical depth range we infer is comparable to established Arctic measurements.

The derived reflectivity of order 0.05 for such optically thin cirrus (using Eq. 8 with g=0.727) is physically plausible. Cirrus with these properties can appear faint from the ground, yet still be detectable, especially under favorable contrast conditions (e.g., against a darker sky or when the sun is at a non-zenith angle). While we acknowledge the reviewer's skepticism regarding the visual detectability of these clouds, we note that the concern is based on qualitative reasoning without quantitative comparison to observed reflectivity. Our estimates, in contrast, are now supported by published optical depth observations.

We agree with the reviewer that comparing our in situ results with bulk optical properties is valuable. Importantly, PHIPS directly measures projected particle area from two separate views, which can be used to estimate extinction coefficients under the geometrical optics assumption (i.e., extinction efficiency of 2). To strengthen the connection to remote sensing metrics, we will include the median, mean, and percentile values of the extinction coefficient in Table 1, along with a discussion of corresponding optical depth estimates..

Lines 412–421:

Reviewer: This paragraph risks being a bit misleading as global climate models are dynamic. It could well be that a value of g that is too high means a low bias in reflectivity with substantial instantaneous radiative forcing impacts. But there is a feedback. With less reflected, more sunlight is transmitted, which by heating the ground could destabilize the atmosphere to create more clouds, offsetting the low reflection bias that is discussed here.

We thank the reviewer for pointing this out. We will revise this paragraph to clarify that besides tuning the GCMs, the potential bias could lead to dynamic feedbacks within the GCM that can potentially offset or amplify the original error. We will bring the example of more sunlight reaching the surface, which in turn can lead to increased convection and potentially to more low-level cloud formation.

References

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