Response to reviewer #1

We would like to thank the referee for the valuable comments on our manuscript, in particular also for providing many relevant references. Please find below the answers. We report in blue the comments by the reviewer, and our answers can be found below each comment in black.

General Comments:

This work presents a remote sensing technique that utilizes multi-angle polarization information to retrieve cloud fraction and cloud optical depth. Numerical experiments using 1D radiative transfer are presented to demonstrate the technique along with an extremely welcome field validation. The paper is well suited to publication in AMT. The technique is an important contribution as it provides a means to mitigate the weakness of coarse resolution that upcoming space-borne multi-angle polarimeters will have to deal with.

There are, however, several aspects of the paper that should be expanded before publication to give a more complete accounting of the technique. These include a discussion of the applicability to ice phase clouds, the definition of cloud fraction, and the issues inherent to the application of the retrieval to clouds with 3D geometries. The 3D nature of the cloudy atmosphere is an inextricable component of multi-angle retrievals such as this one and should be addressed within this paper, even if only with a combination of qualitative and idealized quantitative arguments. I therefore recommend major revisions to this paper to address the specific comments listed below.

Specific Comments:

1. Exactly which of the instruments listed in the introduction is this technique applicable to? It seems to me that for general solar zenith angles, only hyperangular measurements will be able to provide the simultaneous scattering angles required, and HARP2 is focused on for what appears to be this reason. If this is the case then this should be made clear when the polarimeters are introduced in Lines 51 to 65. Will there be limitations in the regional coverage of this technique applied to HARP2 because of this due to scattering geometry requirements?

   Thank you for the comment. It is correct that the scattering angles should be provided nearly simultaneously, therefore HARP2 is ideally suited. The regional coverage needs to be investigated, but this is out of the scope of this publication. The applicability to SpexOne and 3MI also requires further investigation. We demonstrated for specMacs, which does not observe the two scattering angles simultaneously, that the cloud fraction retrieval still provides good results. We therefore believe that the method could also be applied to SpexOne and 3MI.

   We have included the following in the introduction to clarify that HARP2 is the ideal instrument for our method:

   “Since cloud structures change rapidly, observations at the two suggested scattering angles should ideally be taken nearly simultaneously. HARP2 is designed to provide such observations, so it is ideally suited for our proposed method. For SPEXone and 3MI, further investigations on the collocation of the observations would be required.”

And in the outlook we included the following statement on the regional coverage:

“When applied to satellite observations, it also needs to be investigated for which regional coverage measurements at scattering angles in cloudbow and glint can be delivered nearly simultaneously.”

2. I also wonder whether the choice of wavelength is based on HARP2’s hyperangular channel or whether there would be some other more optimal wavelength for this technique.

   Yes, we have indeed chosen the wavelength of 667 nm, because HARP2 provides the multi-angle observations that are needed. We clarified this in the introduction.

   We have now put the focus of the paper on cloud fraction retrieval over the ocean, for which 667 nm is well suited. For cloud fraction retrievals over land, shorter wavelengths are more appropriate, because the retrieval over land requires Rayleigh scattering between the clouds.

3. The technique is stated to retrieve cloud fraction. I am left wondering exactly how this cloud fraction is defined. The definition will tend to depend on the purpose of the product, which is not made clear. If the purpose is to retrieve the geophysical variable of cloud fraction for model evaluation, then that is typically defined based on the projected area of clouds onto a space oblique plane. On the other hand, if the point is to identify the presence of clouds within pixels in an image, then that is a completely different target for the retrieval when non-nadir views are considered, as they are here. The definition of the target/truth will determine how the output of the retrieval is validated and also guide how a potential product is used and so this should be made clear. Perhaps the goal is to produce a resolution-independent estimate of cloud fraction due to the potential to provide a continuous output? This would certainly be an important contribution as most moderate-resolution satellite cloud masking products are not necessarily designed to explicitly estimate cloud fraction but rather to mask pixels for a variety of purposes.

   We present a method that does not depend on spatial resolution and does not require any threshold values for cloud detection. It yields a continuous cloud fraction estimate that could be used for climate and weather model validation. We clarified this in the abstract and in the introduction.

   A clearer target and application for the retrieval may help to focus the introduction which, in its present form, is very close to just a listing of different retrieval methods and instruments. Ideally, this section should present a problem to which the proposed technique is a solution. For example, how bad is the problem of unresolved clouds at 2-4 km resolution vs. 1 km? Why can’t we just tune threshold algorithms to retrieval pixel-by-pixel cloud fraction at coarse resolution? Just a few of many relevant references: (Stubenrauch et al., 2024; Dutta et al., 2020, Wielicki, B. A., and L. Parker, 1992)

We thank the reviewer for these important references. In the introduction, we included an outline on the problems related to the definitions of cloud and cloud fractions, in particular the dependence of cloud fraction on the spatial resolution of the observations when the cloud fraction is just defined as the ratio of cloudy pixels to total number of pixels in a given domain. When we derive the cloud fraction only from the reflected radiation at two angles, we overcome the problems related to spatial resolution of the observation.

If the choice of target is a pixel-by-pixel cloud fraction, then which pixel is it? Is it the pixel observing at 140 degrees or the one observing at 90 degrees? For general cloud geometries, observations at these two scattering angles will not observe the same fractional coverage of their field of view (and both will be distinct from the vertically projected cloud fraction). This may seem relatively minor relative to the precision of the technique (which is evaluated using specMACS) but will introduce an instability of the algorithm (i.e., a systematic error) to the target cloud type and the solar zenith angle which will alias into regional and seasonal variability and may be quantitatively significant. This is a fundamental and unavoidable aspect of the technique (as it is proposed here) and should be discussed especially as to how it will affect the use of the product to measure its target.

We retrieve the cloud fraction for the pixel observing the sun-glint. We found in our sensitivity studies that P(140°) over the ocean is almost insensitive to cloud fraction (see left panels in Fig. 6, only for very small optical thicknesses, P(140°) depends on cloud fraction). For shallow cumulus clouds, which are the focus of this paper, this difference is not extremely large.

In section 3.3 we included the following sentence for clarification:

“Note that, since the cloud fraction is derived from the observation in the sun-glint, the retrieved cloud fraction corresponds to the cloud fraction of the pixel observing the glint.”

4. The same issues apply to the retrieval of cloud optical depth. For a model, optical depth is precisely defined as a vertical integral. Exactly how is this retrieved quantity defined here?

   Vertical optical thickness (definition as in RT) shall be retrieved, and this is input to radiative transfer simulations to produce the lookup table. Since the lookup-table is produced for the specific sun-observation geometry, the slant path through the cloud layer is correctly taken into account.

   Of course there are other systematic errors: as we show in the additional 3D simulations, the retrieved optical thickness is generally too small, which is due to the fact that 3D clouds are less reflective than 1D cloud layers. In 3D, photons are scattered through the cloud sides towards the surface. This problem is well-known in all cloud optical thickness retrieval algorithms.

5. Due to the required choice of scattering geometry the observation at 90 degrees or 110 degrees will tend to observe regions of the surface that are shadowed by the

cloud (i.e. when compared to near-backscatter). The technique seems to rely on observations of polarized surface reflection to determine cloud fraction. The shadowed regions of the surface will not provide this strong polarization signal despite being clear. It seems that this will induce a systematic error in the technique that varies with the shadow fraction of the fields of view (which will also differ between the two views). Shadow fraction will vary with cloud geometry such as area, spacing and cloud-base height and aspect ratio. While I appreciate and support the stated intention to examine the retrieval using 3D radiative transfer with complex cloud fields derived from Large Eddy Simulations in a subsequent study, this does not preclude the need to present and explain these basic features of the retrieval within this paper, perhaps with simple idealized clouds such as cuboids. It would also be interesting to see whether there is any detectable signals of these effects in the specMACS data, though this would require development of a pixel-by-pixel shadow mask.

We included a new section with 3D simulations to demonstrate the basic 3D effects (shadowing and in-scattering) impacting the retrieved cloud fraction in opposite directions.

Also we studied randomly generated simple shallow cloud fields, for which the cloud fraction is overestimated due to cloud shadows.

We agree that it would be interesting to look for the cloud shadow effects in specMacs data, but this is out of the scope of this paper.

6. The authors state on Line 218 that the technique will deliver accurate cloud fraction and cloud optical thickness over the ocean. This statement seems overly strong in the case of cloud optical depth even in the highly simplified case of plane-parallel atmospheres. The estimation of the cloud optical depth from the cloud-bow degree of polarization will have a correlated error with the determination of the droplet effective radius and droplet effective variance. For example, the magnitude scaling parameter in the least squares fit for the shape of the cloudbow polarization pattern is implicitly sensitive to both cloud fraction and optical depth. It seems that to properly understand the error characteristics, all four parameters should be jointly retrieved.

   Yes, we agree. In the cloud retrieval algorithm for e.g. HARP2, as many parameters as possible should be jointly retrieved. We investigated how much the retrieval results for specMacs change when we combine the retrieval with the cloud microphysics retrieval from the cloudbow and we find significant impacts on the optical thickness retrieval as to be expected from the sensitivity study shown in Fig. 6. The retrieval results for the selected scenes are listed in Table 1, for the retrieval assuming constant reff and veff values and for the retrieval using reff and veff from the cloudbow retrieval. The impact on the retrieved cloud fraction is relatively small.

7. There is no mention of ice within this paper. Some discussion of whether this technique works for ice phase clouds or mixed phase clouds should be included. Due to the coarse resolution, there will also be a further lack of uniqueness in the cloud phase in the actual data when compared to moderate resolution (1 km) imagers. This possible limitation should be discussed but even if the technique relies on liquid

scattering signals, this technique will still be a valuable contribution because most small clouds (and hence partially cloudy pixels) originate from low-level liquid clouds.

Ice clouds do not produce a cloudbow, so this method is only applicable for liquid water clouds. This is now discussed in the introduction:

“In order to obtain the global cloud cover, the method needs to be extended to ice clouds and to observations over land surfaces. Since ice clouds do not produce a cloudbow, the methodology can not directly be applied. However, it would be possible to replace the degree of linear polarization in the cloudbow region by an intensity observation at the same angle to retrieve the ice cloud optical thickness. …”

The discussion of non-oceanic surfaces appears slightly incomplete. The authors mention that for brighter unpolarized surfaces the technique is impossible but do not come to a conclusive statement about dark unpolarized surfaces, simply stating that the retrieval will be more uncertain. For the case with the unpolarized surface, the retrieval is reliant on the molecular polarization signal and there will be an ambiguity about whether the polarization signal is due to cloud top height or cloud fraction. This sensitivity to cloud top height is not examined for a dark unpolarized surface. It would be helpful to reference the accuracy with which the DoLP can be measured so that the relative statements about uncertainty are translated to actual retrieval uncertainties.

Yes, we agree. For this paper we now limited the methodology for liquid clouds over the ocean. For land, shorter wavelengths would be advantageous to have more Rayleigh polarization caused by molecular scattering between the clouds and to have less signal from the surface. But for sure this method would become far more complicated, because trace gas and aerosol vertical profiles will matter.

8. I am also curious as to whether the retrieval concept presented is overly simplified and doesn’t fully exploit the observational information content. There are some dependences of the retrieval on wind speed and aerosol optical depth documented within the paper. For the purposes of reducing systematic errors and ensuring proper uncertainty propagation, the more variables that are explicitly retrieved (even if with strong priors), the better. Given the hyperangular observations from HARP2 and other multi-spectral observations, is it not possible to jointly retrieve wind speed/surface roughness and aerosol optical depth (e.g., Knobelspiesse et al., 2021) in combination with cloud fraction using this information and some prior information on aerosol composition? I think it would be valuable for the authors to discuss the feasibility of this as a possible extension to their work.

   Yes, we agree. This method should be combined with the overall retrieval methodology. Ideally AOD and wind speed should be retrieved simultaneously. The operational algorithms for PACE are of course more advanced, and rather than extending our method, we would suggest that the PACE team adds the cloud fraction retrieval as an addition to their methodology.

   The following text has been added to clarify that it is advantageous to combine the retrieval with other algorithms: “For the selected scenes, we generated lookup-tables using the cloud size distribution parameters from the cloudbow retrieval in addition. Of course, it would make sense to combine the method with further retrieval algorithms, e.g., with the simultaneous aerosol and ocean glint retrieval by \citet{knobelspiesse2011}. When accurate a priori information about wind speed and aeorosol optical thickness is included, one should also take into account the filter function of the instrument rather than running monochromatic simulations to generate the lookup-table. These improvements are not necessarily needed to demonstrate the method for a few specific cases, which is the purpose of this study."

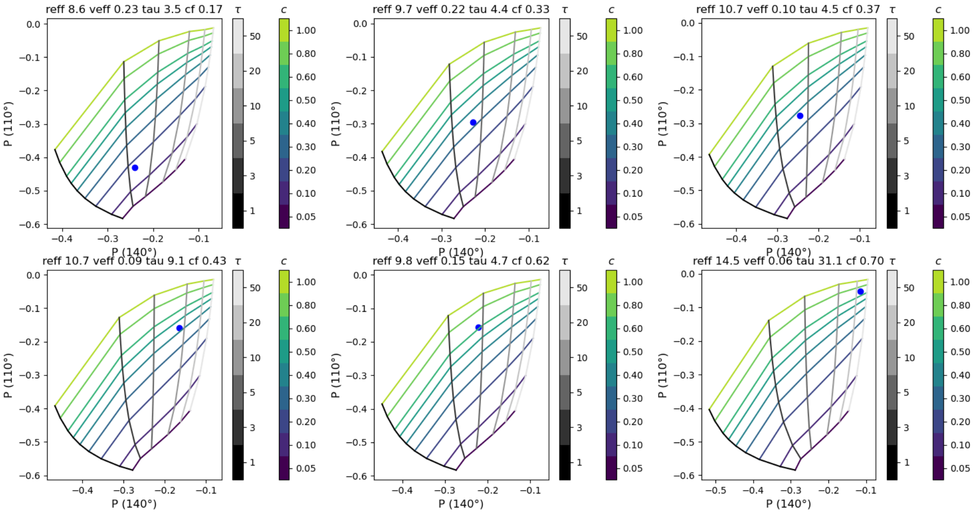
9. The validation of the technique against field data is an extremely valuable component of the paper. Some greater discussion of the threshold-based cloud mask that the technique is being compared against is warranted. The features used in the cloud mask are listed but the tuning of the thresholds is not. Is the cloud mask clear-conservative or cloud conservative? Or is it designed to optimally estimate cloud fraction over 2.5 km regions? This is important for understanding any agreement or lack thereof between the coarse resolution technique proposed here and the high-resolution threshold-based technique. As I understand it, the high-resolution reference mask also makes use of polarization features to separate sunglint and from non-sunglint. Perhaps this point, and the ambiguity of masking in sunglint regions with just intensity measurements should be more emphasized as a strength of the technique

   We have added a paragraph describing the cloud detection algorithm:

   "We also employed the cloud detection method outlined in \citet{poertge2023} on the images of the selected scenes to determine the geometrical cloud fraction of the scenes at the original (high) resolution of the images. The method is based on the algorithm described in \citet{otsu_1979} which determines a threshold to seperate the pixels of an image in two classes (here: cloudy versus non-cloudy) based on a brightness histogram. Such threshold based cloud detection algorithms often struggle with the bright sun-glint reflection. Our algorithm uses the parallel component of polarized light in which the reflectance of the sun-glint is reduced which in turn reduces the number of incorrect classifications in (cloud free) sun-glint areas. The algorithm distinguishes between cloud-free, low to medium cloud coverage and high cloud coverage. For cloud-free scenes it uses the data of the blue channel, for scenes with low/medium cloud coverage the data of the red channel, and otherwise the normalized red (r) to blue (b) ratio ($\text{nrbr} = (b-r)/(b+r)$). This procedure was found by tuning the cloud mask for many different scenes (both over land and over water)."

10. For the specMACS data, I would appreciate seeing retrievals that used the cloudbow reff/veff as input as this is the best guess for the retrieval and would reduce any possible error compensation in the validation.

    We agree that the reff/veff from the cloudbow retrievals should be used as input to the cloud fraction and optical thickness retrieval. It is obvious from Fig.6 that the effective radius impacts the polarization at 140° scattering angle because the angular pattern of the scattering phase matrix, in particular in the cloudbow region, depends on the effective radius. However, the intention of our paper is to demonstrate the methodology and for this purpose it is nice to plot all observational points in one lookup table. For the discussed scenes we have now computed lookup-tables using the correct microphysics as input, these are shown in the following Figure (not included in the paper):



The title of the figure includes the effective radius and the effective variance obtained from the cloudbow retrieval and the retrieved optical thickness (tau) and cloud fraction (cf).

In the paper we have included two additional columns in Table 1 including the retrieved optical thickness and the cloud fraction using the microphysics retrieved from the cloudbow. As expected, we find the largest deviation for the scene where the effective radius deviates most from 10 μm (s6).

Technical Comments:

Line 93: I was a little confused on a first read by the statement that all simulations had a liquid cloud layer located from 2-3 km and same droplet effective radius. It would be helpful to note that this restricted setup is just to illustrate the main sensitivity to cloud fraction and optical depth and that more sensitivity tests are performed later.

ok. Included a note here.

Line 304: Sun-glint

ok.

Relevant References:

Wielicki, B. A., and L. Parker (1992), On the determination of cloud cover from satellite sensors: The effect of sensor spatial resolution, *J. Geophys. Res.*, 97(D12), 12799–12823, doi:10.1029/92JD01061.

Stubenrauch, C.J., Kinne, S., Mandorli, G. *et al.* Lessons Learned from the Updated GEWEX Cloud Assessment Database. *Surv Geophys* (2024). https://doi.org/10.1007/s10712-024-09824-0

Dutta, S., Di Girolamo, L., Dey, S., Zhan, Y., Moroney, C. M., & Zhao, G. (2020). The reduction in near-global cloud cover after correcting for biases caused by finite resolution measurements. *Geophysical Research Letters*, 47, e2020GL090313. https://doi.org/10.1029/2020GL090313

Knobelspiesse, K., Ibrahim, A., Franz, B., Bailey, S., Levy, R., Ahmad, Z., Gales, J., Gao, M., Garay, M., Anderson, S., and Kalashnikova, O.: Analysis of simultaneous aerosol and ocean glint retrieval using multi-angle observations, Atmos. Meas. Tech., 14, 3233–3252, https://doi.org/10.5194/amt-14-3233-2021, 2021.