Reply to comments by referee #2

We thank the referee for carefully reviewing the manuscript and for the valuable suggestions and comments, which are addressed below. The referee's comments are highlighted in blue.

1) More context would help the reader to appreciate the value of this work. Indeed, the global scope of this work should be given in introduction. Advantages (and eventually drawbacks) of ice crystal characterization in cirrus clouds by the HaloCam system compared to others instruments could also be given.

We appreciate your suggestion and expanded further on the motivation for a calibrated camera for halo observations and comparison with other instruments. Referee #1 raised a similar concern. We extended/re-wrote the introduction as follows:

"The use of camera imaging methods for documentation and analyis of halo displays dates back to the 1980s and 90s (Lynch and Schwartz, 1985; Sassen et al., 1994). Probably the first attempt to retrieve information about ice crystal microphysical properties was reported by Lynch and Schwartz. They used an image of a 22° halo taken with a Kodak Plus-X camera to infer ice crystal properties by comparing their observations qualitatively with scattering phase functions. The camera was later calibrated by taking pictures of calibrated intensity wedges and grids with several exposures. However, no further details on the calibration method or its application were provided.

Sky imaging methods in general have been widely used to infer information about sky and cloud properties from the ground. Examples are the Whole-Sky Imager (WSI) (Feister and Shields, 2005; Shields et al., 2013), Total-Sky Imager (TSI) (Long et al., 2001; Pfister et al., 2003), all-sky imager (ASI) (Long et al., 2006; Cazorla et al., 2008), and University of San Diego Sky Imager (USI) (Urquhart et al., 2015, 2016) for short-term solar energy forecasting. All-sky imagers are usually equipped with a fish-eye lens or, in the case of TSI, a spherical mirror that captures the whole upper hemisphere down to the horizon. Applications range from cloud detection and classification to determination of cloud fraction, and cloud base height estimation. To protect the all-sky imagers from direct sunlight and to reduce straylight effects, a shadow band (WSI) or sun-blocking strip (TSI) is usually employed. These strips, however, cover a significant part of the 22° halo (Boyd et al., 2019).

Forster et al. (2017) presented HaloCam, a weather-proof camera system for the automated observation of halo displays, using a sun-tracking mount. This allows replacing the hemispheric fish-eye lens by a lens with smaller field of view (FOV), improving the spatial resolution in the relevant region and limiting optical distortion. Furthermore, this setup allows using a fixed circular shade which can be optimized to cover only a small region up to 10° scattering angle around the sun. As discussed in Forster et al. (2017) the sky region around the sun up to a scattering angle of 46° contains the most important information about ice crystal microphysical properties: While 22° and 46° halos provide information about shape and surface roughness for randomly oriented ice crystals, sundogs and upper tangent arcs allow quantification of the fraction of oriented plates and columns, respectively. The brightness slope in the circumsolar radiance also contributes important information about the microphysical properties of the ice crystals (Haapanala et al., 2017). Thus, for a quantitative retrieval of ice crystal properties from observations close to the sun are desirable.

The all-sky camera presented by Dandini et al. (2018) is equipped with a small sun-tracking shadow disk, which also allows access to the important sky region close to the sun. However, strong optical distortion and the large FOV of the fish-eye lens call for more advanced geometric calibration methods relying on tracking of stars and planets (Schumann et al., 2013; Urquhart et al., 2016; Dandini et al., 2018). Due to the smaller FOV, HaloCam can be calibrated using the simple "chessboard method" (Zhang, 2000; Heikkilä and Silvén, 1997) as described in Forster et al. (2017). Secondly, finding a source of uniform illumination for flat-field calibration of all-sky imagers is challenging (Urquhart et al., 2015; Dandini et al., 2018).

So far, camera observations of halo displays only used relative intensity measurements to retrieve information about ice crystal properties. However, observations of halo displays can not be directly linked to these properties due to the effect of multiple scattering and the contribution of aerosol below the cirrus cloud (Forster et al., 2017). To disentangle these effects and to retrieve ice crystal microphysical properties, the observations have to be compared with radiative transfer simulations. For such a comparison, calibrated measurements of sky radiance are required and thus the camera must be accurately characterized both geometrically and radiometrically.

This paper presents $\mathrm{HaloCam_{RAW}}$, an extension of the HaloCam observation system described in Forster et al. (2017). To the authors' knowledge, $\mathrm{HaloCam_{RAW}}$ is the first weather-proof camera system specifically designed for automated observation and radiometric analysis of halo displays. After describing the HaloCam system including $\mathrm{HaloCam_{RAW}}$ in Sec. 2, methods for geometric (Sec. 3) as well as absolute radiometric calibration (Sec. 4) of this camera will be presented. SpecMACS, an extensively calibrated and characterized (but not weather-proof) hyperspectral imager (Ewald et al., 2016), serves as a reference for the absolute radiometric calibration of $\mathrm{HaloCam_{RAW}}$. The radiometric characterization is inspired by the procedure and notation in Ewald et al. (2016). Section 5 demonstrates the application of the geometric and radiometric characterization to observations of a 22° halo which are compared to radiative transfer simulations. ”

2) Line 2 p.19, the authors write "a method could be developped to retrieve ice crystal properties". Is that method supposed to be automated to make a "long-term database" (line 22 p.20) ? In that case, what are the difficulties to overcome for this purpose? It would be interesting to discuss about that point. For instance, halo cases with quite different sets of parameters might lead to the same radiance response using the libRadtran model, hence the inversion of the operator will not be possible if no additional information or constraint is added.

Thank you for addressing this important point. We added some more discussion at the end of Section 5:

“The brightness contrast of the halo contains valuable information about ice crystal properties, such as shape and surface roughness (van Diedenhoven, 2014; Forster et al., 2017). However, multiple scattering by aerosol and cirrus cloud particles introduces ambiguities. Additional observations of aerosol and cirrus optical thickness, for example from sunphotometer measurements, must therefore be included in the retrieval to reduce the ill-posedness of the problem. The development of such a retrieval will be the focus of a future publication.”

References

Boyd, S., Sorenson, S., Richard, S., King, M., and Greenslit, M.: Analysis algorithm for sky type and ice halo recognition in all-sky images, Atmospheric Measurement Techniques, pp. 4241–4259, doi:10.5194/amt-12-4241-2019, 2019.

Cazorla, A., Olmo, F., and Alados-Arboledas, L.: Development of a sky imager for cloud cover assessment, JOSA A, pp. 29–39, 2008.

Dandini, P., Ulanowski, Z., Campbell, D., and Kaye, R.: Halo ratio from ground based all-sky imaging, Atmospheric Measurement Techniques Discussions, 2018, 1–30, doi:10.5194/amt-2018-3, https://www.atmos-meas-tech-discuss.net/amt-2018-3, 2018.

Ewald, F., Kölling, T., Baumgartner, A., Zinner, T., and Mayer, B.: Design and characterization of specMACS, a multipurpose hyperspectral cloud and sky imager, amt, 9, 2015–2042, doi:10.5194/amt-9-2015-2016, 2016.

Feister, U. and Shields, J.: Cloud and radiance measurements with the VIS/NIR daylight whole sky imager at Lindenberg (Germany), Meteorologische Zeitschrift, 14, 627–639, 2005.

Forster, L., Seefeldner, M., Wiegner, M., and Mayer, B.: Ice crystal characterization in cirrus clouds: a sun-tracking camera system and automated detection algorithm for halo displays, Atmos. Meas. Tech., 10, 2499–2516, doi:10.5194/amt-10-2499-2017, 2017.

Haapanala, P., Räisänen, P., McFarquhar, G. M., Tiira, J., Macke, A., Kahnert, M., DeVore, J., and Nousiainen, T.: Disk and circumsolar radiances in the presence of ice clouds, Atmos. Chem. Phys., 17, 6865–6882, doi:10.5194/acp-17-6865-2017, https://www.atmos-chem-phys.net/17/6865/2017, 2017.

Heikkilä, J. and Silvén, O.: A four-step camera calibration procedure with implicit image correction, in: Proceedings of IEEE Computer Society Conference on Computer Vision and Pattern Recognition, pp. 1106–1112, Washington, DC, USA, doi:10.1109/CVPR.1997.609468, 1997.

Long, C., Slater, D., and Tooman, T.: Total Sky Imager model 880 status and testing results, ARM TR 006, Atmospheric Radiation Measurement Program (ARM), 2001.

Long, C. N., Sabburg, J. M., Calbó, J., and Pages, D.: Retrieving cloud characteristics from ground-based daytime color all-sky images, Journal of Atmospheric and Oceanic Technology, pp. 633–652, 2006.

Lynch, D. K. and Schwartz, P.: Intensity profile of the 22° halo, J. Opt. Soc. Am. A, 2, 584–589, doi:10.1364/JOSAA.2.000584, 1985.

Pfister, G., McKenzie, R., Liley, J., Thomas, A., Forgan, B., and Long, C.: Cloud coverage based on all-sky imaging and its impact on surface solar irradiance, J. Appl. Meteorol., 42, 1421–1434, 2003.

Sassen, K., Knight, N. C., Takano, Y., and Heymsfield, A. J.: Effects of ice-crystal structure on halo formation: cirrus cloud experimental and ray-tracing modeling studies, Applied Optics, 33, 4590–4601, doi:10.1364/AO.33.004590, 1994.

Schumann, U., Hempel, R., Flentje, H., Garhammer, M., Graf, K., Kox, S., Lösslein, H., and Mayer, B.: Contrail study with ground-based cameras, Atmospheric Measurement Techniques, 6, 3597–3612, doi:10.5194/amt-6-3597-2013, https://www.atmos-meas-tech.net/6/3597/2013, 2013.

Shields, J. E., Karr, M. E., Johnson, R. W., and Burden, A. R.: Day/night whole sky imagers for 24-h cloud and sky assessment: history and overview, Applied optics, pp. 1605–1616, 2013.

Urquhart, B., Kurtz, B., Dahlin, E., Ghonima, M., Shields, J. E., and Kleissl, J.: Development of a sky imaging system for short-term solar power forecasting, Atmos. Meas. Tech., 8, 875–890, doi:10.5194/amt-8-875-2015, 2015.

Urquhart, B., Kurtz, B., and Kleissl, J.: Sky camera geometric calibration using solar observations, Atmospheric Measurement Techniques, 9, 4279–4294, doi:10.5194/amt-9-4279-2016, https://www.atmos-meas-tech.net/9/4279/2016, 2016.

van Diedenhoven, B.: The prevalence of the 22° halo in cirrus clouds, J. Quant. Spectrosc. Radiat. Transfer, 146, 475–479, doi:10.1016/j.jqsrt.2014.01.012, 2014.

Zhang, Z.: A flexible new technique for camera calibration, IEEE Transactions on Pattern Analysis and Machine Intelligence, 22, 1330–1334, 2000.