Reply to comments by referee #1

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) The introduction is a bit short and lacks a good motivation for such a camera. Please elaborate more on why a calibrated halo camera is useful for cloud, atmospheric and climate physics.

> We appreciate your suggestion and expanded further on the motivation for a calibrated camera for halo observations. Referee #2 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 HaloCam$_{\mathrm{RAW}}$, an extension of the HaloCam observation system described in Forster et al. (2017). To the authors' knowledge, HaloCam$_{\mathrm{RAW}}$ is the first weather-proof camera system specifically designed for automated observation and radiometric analysis of halo displays. After describing the HaloCam system including HaloCam$_{\mathrm{RAW}}$ 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 HaloCam$_{\mathrm{RAW}}$. 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) The application described in section 5 assumes randomly oriented crystals only. Please state this in the text.

Thank you for pointing this out. We added this information on

p. 3, l. 19

"Section 5 demonstrates the application of the geometric and radiometric characterization to observations of a 22° halo which are compared to radiative transfer simulations assuming randomly oriented ice crystals."

and p. 17, l. 22

"Figure 12 displays radiative transfer simulations with libRadtran (Mayer and Kylling, 2005; Emde et al., 2016) using the DISORT solver (Stamnes et al., 1988) and ice crystal optical properties based on the parameterization of Yang et al. (2013), which assumes randomly oriented crystals."

Please add some discussion on how this type of analysis would possibly be affected by the presence of oriented crystals. In particular, parts of the supralateral arc by oriented columns are very close to the 46-degree halo. Thus, the analysis might be biased if a supralateral arc is present instead of the more rare 46-degree halo. The distinction between the 46-dgeree halo and supralateral arc is discussed on this website: https://www.atoptics.co.uk/halo/46orsup.htm.

The referee is raising a very important point. We added more discussion about the possibility to retrieve information about oriented ice crystals and the possible overlap of halo displays formed by oriented and randomly oriented crystals. The main focus of the present study is on the characterization of HaloCam$_{\mathrm{RAW}}$ including a simple demonstration assuming randomly oriented crystals. The actual development of a quantitative retrieval method will be the focus of a future study, where it will also be necessary to discuss the separate treatment of halo displays formed by randomly oriented and oriented crystals in more detail. We added the following paragraph at the end of Section 5:

"While this study focuses solely on randomly oriented crystals, halo displays caused by oriented crystals, such as sundogs, upper tangent arcs as well as the rare Parry and supralateral arc (e.g. Greenler, 1980; Tape, 1994) can also be observed within HaloCam$_{\mathrm{RAW}}$'s FOV and contain important information about the fraction of oriented plates and columns. Depending on the solar elevation, halo displays formed by oriented and randomly oriented crystals overlap in certain image regions, as for example upper tangent arc and 22° halo or supralateral arc and 46° halo (Cowley). For the future development of a quantitative retrieval method, care must be taken to treat those image regions appropriately."

Moreover, I am wondering whether the camera has the resolution and accuracy to, in principle, detect and distinguish other arcs caused by oriented crystals (many are described on the atoptics website).

In principle, HaloCam can distinguish between features with an inter-pixel resolution of 0.1° (for each color channel with 608x968 pixels; p. 6, l. 12) and a pointing accuracy of about 0.5° (p. 4, l. 25). This is a very interesting question and motivates an in-depth discussion about the analysis of more infrequently observed halo displays caused by oriented crystals such as e.g. Parry arcs. Since the application in this study only focuses on randomly oriented crystals, we will leave this discussion for a future publication but added a short sentence on p. 20, l. 14:

> "Halo displays caused by oriented ice crystals, such as sundogs, upper tangent arcs as well as the rare Parry and supralateral arc (e.g. Greenler, 1980; Tape, 1994), could also be observed within HaloCam$_{\mathrm{RAW}}$'s FOV and add important information about the fraction of oriented columns and plates."

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