

Response to Referee #3

Referee comments are in grey.

Author response is in blue.

Changes are in bright red

We would like to thank the Reviewer for their thoughtful comments on this paper.

This paper discusses the design, development, and operation of a high dynamic range camera (the USI), with a close-to full sky field of view, to be used for cloud measurements for assisting solar power plant operations. The camera is designed to be sufficiently fast to enable useful insolation forecasting over the following 30 minute period after an observation.

The paper is well written and includes many details and discussions which clarify the issues involved with imaging day-time skies in the presence of the high intensity solar disc. More generally, this paper should also serve as a useful introduction to many practical sky imaging and calibration issues for those new to the field.

Thank you kindly for these comments. This was our goal.

There are perhaps a few issues not discussed, but which could be considered as further topics to be included or commented on:

Were there any initial design criteria identified in the project? 16 bits and the quoted dynamic range are interesting numbers but what are actually necessary? The following issues relate to this basic thought.

The primary considerations going in from a practical standpoint were to obtain the best images possible using a commercially available camera system components. The dynamic range required to obtain on scale measurements of the sun while still obtaining measurements of the sky can exceed 150 dB (computed for our camera/lens combination). To measure just outside the solar disc requires a dynamic range of approximately 125dB (again for the USI). Assuming a read noise of 1 count, for a single exposure this would require at least 25 bits to measure direct normal irradiance, and 21 bits to capture on scale measurements just outside the solar disc. I am not aware of reasonably priced cameras with this capability. Additionally, the sensitivity would have to be low enough to not saturate at extremely short exposure times. Many cameras are built with high sensitivity for low-light conditions, but for the sun, this causes pixels to quickly saturate.

The question of necessity is a challenging one, because this depends also on the algorithms using the data. We did not test performance of specific algorithms as a function of dynamic range, but the idea is an interesting one. For our design we sought a CCD camera for more uniform measurement, a high dynamic range to measure as close to the sun, and a moderate system cost to keep things practical. We have had several groups request us to build this system for their research purposes, and the moderate price has made it possible for them to afford it.

The camera is intended for long term use in the field, but there is no discussion of any possible long term degradation issues in this 16 bit system. I wondered how the sensor array will respond to daily repeated exposure to the solar intensity over a limited part of its sensitive area.

This was definitely a concern for us. From what I have read about this subject, newer sensors are more resilient to degradation from high intensity light, however the sun is a very high intensity source and can wear even resilient equipment over time. The camera already has an IRC30 infrared cutoff filter which blocks light >660nm. To be cautious, we have taken additional steps to minimize degradation: a) a UV hard-coat applied to the dome to reduce UV transmission (the shorter the wavelength, the more damaging the light, in general); b) reduction of incoming light using neutral density ND3.0 filter or smaller aperture. The aperture lets about 17 times more light in than the ND filter, but does not have as large of a spectral impact (the Kodak Wratten 2 neutral density filters are not entirely neutral). We suspect that the largest impact of direct solar exposure will be to the dyes used in the Bayer filter.

We have had cameras in continuous operation since 2011 without any noticeable ill effects. Because of the system resolution, the solar disc only passes the same pixel perhaps for only 5 consecutive days and covers a given pixel for less than 5 minutes per day, thus a single pixel gets direct exposure for about 25 minutes, twice a year (these numbers are valid near the equinox). This of course depends on the solar declination (some pixels are passed only once a year).

Is it expected that the uniformity checks discussed in the paper will be repeated at some regular interval? – What interval would be suggested?

Using the uniformity correction to also assess sensor degradation is a good idea and we will include this as a suggestion. As a preventative diagnostic, this check would likely only be necessary a few times a year, perhaps biannually.

In any case, at what level would degradation affect the ability of analysis algorithms to quantify aerosol scattering, and will that level be reached with this non-occluding system?

Currently we do not quantify AOD levels with the USI regularly. We have used a TSI to quantify AOD (see Ghonima et al., Atmos. Meas. Tech., 5, 2881-2892, 2012, <http://www.atmos-meas-tech.net/5/2881/2012/amt-5-2881-2012.html>).

If the system did see degradation due to the sun, it would certainly impact cloud detection. If the on-chip color dyes were to fade (Bayer mosaic providing spectral information), we would expect to see a spectrally uniform streak (a white streak) which would limit the application of RBR for cloud detection. Any change noticeable to the eye would considerably impact the cloud detection algorithm, and because errors in cloud detection directly translate into forecast errors when those pixels are used in the forecast algorithm, a low severity level degradation would cause a forecasting performance impact.

Experience tells me that, in an exposed environment, such as 'hot and dusty deserts' which will be common for solar systems, there is likely to be surface damage to the acrylic dome optics through wind-carried particulates (as opposed to a cleaning issue mentioned on page 26). Do the authors have comments on long term degradation from their experience? Such damage has

the effect of scattering the incoming sunlight into a large area of the image, again making faint cloud and aerosol effects difficult to image.

This is a very insightful question, and is indeed a concern, however to date, we have not deployed a USI in a dusty location, only very hot ones. We have found that birds actually cause issues as well. Birds like to land on one of our systems quite regularly, and peck at it. Between the talons and the beak, the dome gets damaged to the point of considerable degradation, and has been changed a few times. One issue with cleaning is that debris on the surface, when rubbed with a cleaning cloth, causes small scratches. Our current method is to iteratively pour water on then lightly sweep away dust until the cleaning condition is satisfactory.

As you noted, small scale scratches on the dome cause subtle intensity increases over local areas of the image, and larger scale scratches are actually visible features in the image, particularly when the sun is near the scratches within the image. When using a plastic dome, degradation is expected, and we have had to change a few domes of our longer operating systems. **Comments added regarding concerns with acrylic and scratching for both dust and birds, as well as the requirement for more careful system cleaning.**

Regarding the impact on forecasting performance, the small scale scratches do not cause too much of an impact, but larger ones do. Yang et al. 2014 used USI 1.2 which had the bird problem, and forecasting errors were found to be more dependent on issues of cloud detection near the sun. Scratches only make this problem worse, but it is just really difficult to detect clouds near the sun, with or without scratches. We are actively trying several different methods to improve cloud detection near the sun. We are now testing a dynamic method which uses several image frames to determine the cloud state for pixels near the sun. The results look very promising but require more extensive testing. A publication on this topic is expected.

Minor typographical issues have already been identified by another referee.