Response to Referee #2

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 gives a very good account of the details of a camera suitable for sky imaging and would be a useful addition to the literature.

The stated goal of the paper is to provide details on the USI system and its imaging performance to help making informed design decisions. However, given that the paper does include a review of other cameras available, it does not make clear what the shortcomings of these cameras are and why the authors saw the need to design and build a new one. There is a single statement indicating shortcomings of the TSI camera, but no discussion of what they were and how the USI design overcomes these. It would be extremely useful if section 1.2 included some mention of where each of the designs discussed failed to meet the requirements summarized in section 1.1, and what exactly the problem is that the current camera attempts to solve. In short: the technical and scientific objective of the design work in view of existing technology.

> **The goal of section 1.2 is to give the reader a background on whole sky imaging hardware. We do agree that the review is lengthier than one might expect in a 'regular' paper (as opposed to a 'review' paper), but this was not to suggest that some of the camera systems would not also be suitable for forecasting. Some of the systems described might work quite well for forecasting (e.g. the HDR-ASIS). A quantitative inter-comparison of cameras would be a significant undertaking as it would have to go significantly beyond reporting documented specifications, and is beyond the scope of this work. Without doing such a thorough inter comparison, it is not fair to say a particular camera is not suitable. Before deciding to develop the USI in 2010, we did survey commercial options which were very limited at the time. The only commercially available continuous outdoor operation system without an occultor that we could find was the Santa Barbara Instrument Group (SBIG) system, but the product demonstration had considerable vertical smearing when the sun was present. This appears to have improved since then.**
>
> **We developed our forecasting methods using the TSI and can indeed make comments about this system. To better illuminate the problems we encountered, the following changes were made:**
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> **1. Addition to section 1.1 which discusses the physical size of cloud element covered by a single pixel as a function of camera resolution, and how this translates into shadowmap resolution.**
>
> **2. Statement regarding calibration of catadioptric system. Imprecise translation and rotation of the camera body w.r.t. the mirror and rotation of mirror itself makes calibration more challenging. Additionally, the mirror is often slightly warped in**

shape and is not perfectly spherical, and the surface is covered in small scale imperfections that produce local distortion.

3. Sentence indicating that inclusion of a sky imaging systems in section 1.2 does not necessarily imply it is not usable for forecasting.

Additionally, for the reviewer's consideration, we have prepared some additional results highlighting the differences between the TSI and the USI.

The spectral content of TSI images is impacted by the jpeg compression used for storing the images. This makes the use of the red-blue ratio for cloud detection more prone to errors. Figure 1 shows the red-blue ratio (RBR) along with the RBR gradient magnitude and phase (the x and y gradients were computed with a 5 point stencil, with their sum in quadrature being the magnitude and the arctangent of their ratio being the phase).

The shadowband on the TSI was one of our largest problems in solar power forecasting. The impact on cloud observation and its use for subsequent deterministic forecasting is shown in Figure 2. While the missing data due to the shadowband is interpolated, the forecast resulting from this missing data is not valid. Regions directly near the shadowband have reduced constrast and increased brightness, making cloud detection in the vicinity of the shadowband less accurate. The ray tracing of the cloud obstruction is shown in the bottom portion of Figure 2, where it can be seen that the missing data due to the shadowband covers about half of the plant. Additionally, the regions of poor contrast and increased brightness near the shadowband can be identified in the shadowmap by inspection, increasing the portion of the plant covered by no or poor observational data. The cloud height here is 3,000 meters. The projected area of coverage scales with the square of the cloud height, thus at larger heights, the shadowband covers more of the plant.

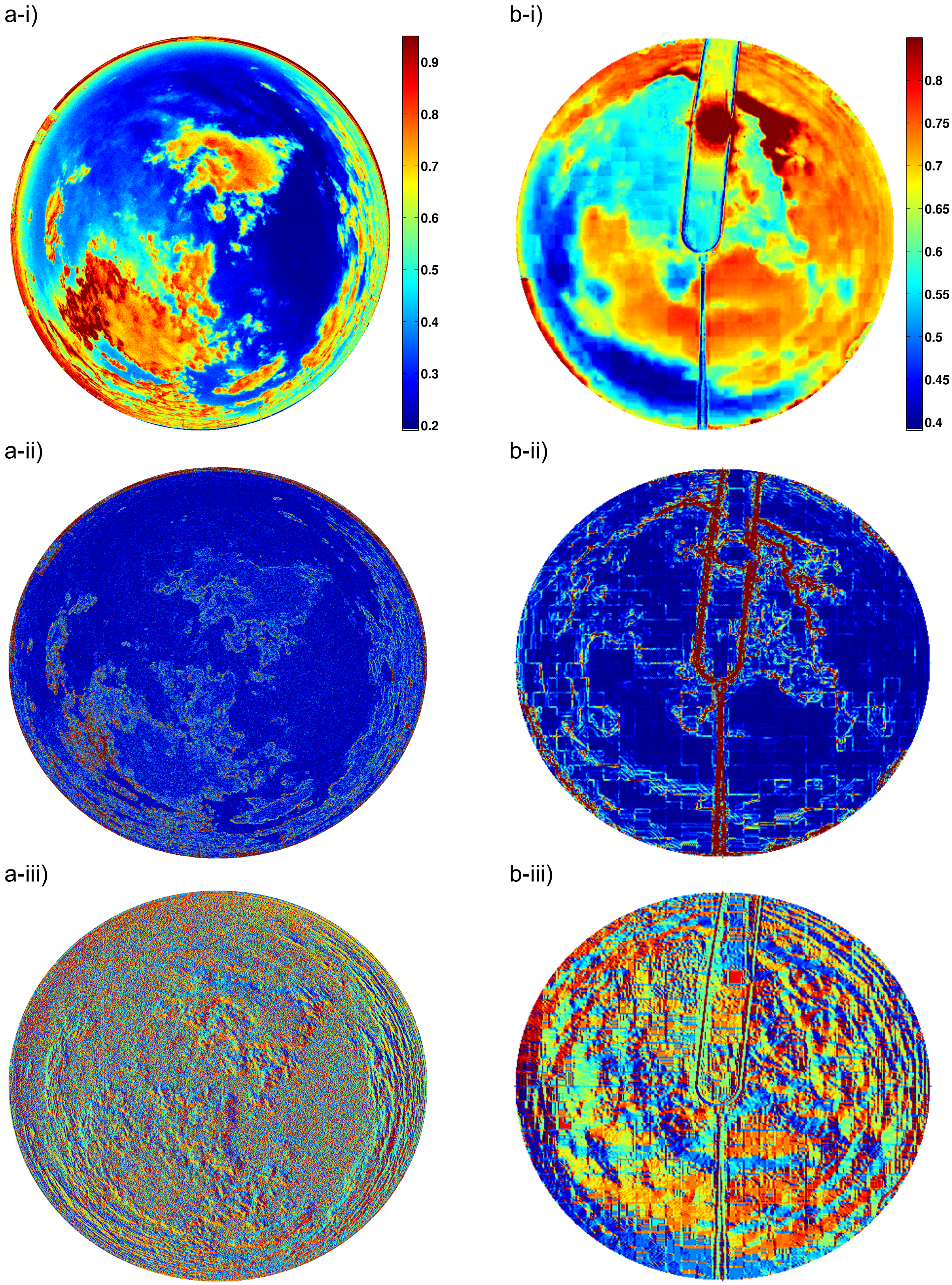

Figure 1 A comparison of the red-blue ratio between the (a-i) USI and the (b-i) TSI. The magnitude of the gradient is given in (ii) and the phase in (iii). The tiling effects of jpg compression can clearly be see in all three TSI images.

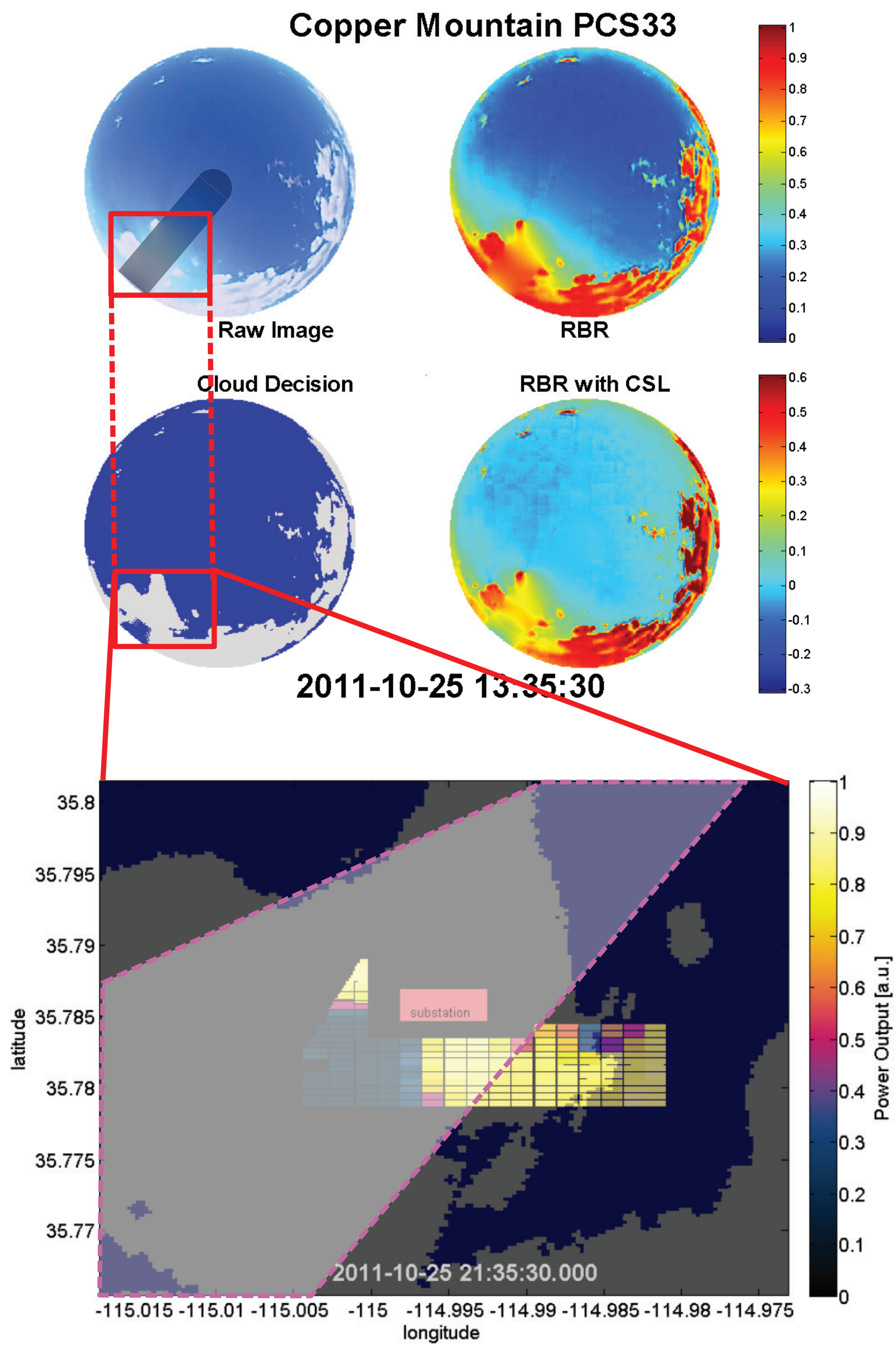

Figure 2 A comparison of a raw TSI image, the cloud map, and the shadow map over the power plant footprint. The shadowband was removed by interpolation, however the interpolated data cannot be considered as valid (it is just a guess based on the static image). The approximate extent of the shadowband is given by the dashed line (by inspection) The relative power output from different sections of the plant is indicated by the color bar (arbitrary units).

Section 2 has a good description of the camera design, but the figures are small and difficult to read (eg fig 2) and Fig 1 does not add useful information: : :especially when combined with Fig 4. A simple sketch and optical configuration would help.

Figures text size have been increased relative to image size for better readability.

Figure 1 updated to remove Fig. 1b and 1c. Figure 4 was merged with Figure 1a (to form a new Figure 1).

I was also surprised that measured dynamic range of 61dB was significantly lower that the camera spec of 72dB, with no mention of attempts to improve it, given the requirement of a very large dynamic range, and the effort described to "live with " the reduced range (eliminations of pixels with low counts: : :a process which could lead to distorted images unless done very carefully, and more discussion of this issue would be helpful)

We would like to thank the reviewer for this comment, as investigating this issue highlighted an error in the paper. The specification sheet for the CCD does give 72 dB, however this was achieved when operating the CCD at 10 MHz. The operating frequency in our case is set by the camera manufacturer and cannot be changed, even though the CCD itself could accommodate the change. In order for the camera manufacturer to achieve 15fps, a higher frequency is required, which in dual output mode (the mode used by the camera manufacturer) is approximately 35.8 MHz. Because the charge to voltage conversion output amplifier has a limited throughput of electrons per unit time, a higher clock frequency means that the allowable charge capacity of each pixel is limited such that the output amplifier slew rate is not exceeded. Our estimate of the allowable charge capacity per pixel at 35.8MHz is 22,392. This was obtained by using the maximum output amplifier voltage swing of 640 mV per cycle, the charge to voltage conversion of 31 μV/e-, a frequency of 35.8 MHz, a frame rate of 15 fps, and 2072 × 1062 pixels per amplifier (includes edge pixels which are not part of the active image area). This per pixel electron capacity gives a gain of 0.1829 counts per electron (or 0.1810 when accounting for the bias). The RMS read noise that we have measured on the sensor is about 3.8 counts, which translates to 20.8 e-. The camera manufacturer has measured both the read noise and the maximum capacity of the pixels (with a set frequency of about 35.8 MHz to achieve 15 fps), and has obtained 21 e- RMS and 23,600 e-, respectively. Their dynamic range comes out to be 61.04 dB, whereas ours was measured at 60.65 dB (or 60.56 dB after making a correction for a bias of 41.7 counts). We have corrected the paper to reflect the dynamic range as specified by the camera manufacturer using the EMV1288 test data.

Low count (or high count) pixels are eliminated only in the HDR construction process, which does not affect the single frame dynamic range. If we are not careful about which pixels to eliminate, then we will indeed observe undesirable artifacts in the HDR images. The linearity criteria we have outlined, however is a means to avoid this from occurring and has worked very well for us in practice. While we have experienced HDR compositing issues which ruin the images, it is generally because there was a delay in the capture of two successive frames, and something in the scene moved considerably in the intervening time. After we noticed this occasionally occurring, we had to carefully implement the capture algorithm with the camera API

so that it did not slow down during the frame capturing process. This is absolutely necessary or the assumption that all frames used in the HDR image were obtained at approximately the same time is not valid (and thus the resulting HDR image will be garbage).

The dynamic range of an HDR image, constructed as we describe, is a subject we did not cover in the paper. We have updated the paper with a short discussion on the dynamic range of HDR imagery.

The discussion about baffles and stray light is very interesting and highlights the difficulties of having a camera looking directly at the sun. While a shade is being used , there is no discussion of an optimization of the shade: : :(is it the best one possible?).

The shading experiment was manually performed. A student stood next to the instrument for several hours shading and un-shading the instrument every 30 seconds with a handheld shade (pg. 4883, lines 11-12) so that we could have a continuous cycle shaded/un-shaded imagery for analysis. Because we do not use a shading mechanism during normal operations, we did not make a noteworthy attempt to optimize the handheld shade. During the experiment, we did attempt to make the shade not much bigger than the dome so the optics were completely covered. We also held it as far away as possible using a long wooden rod so as to minimize the number of pixels covered by the shade. To indicate the shading process more clearly, the following sentence has been added:

The shade used was not much larger than the dome and was held at a considerable distance so as to sufficiently shade the entire optical assembly while minimizing the number of pixels occupied within the image.

Furthermore, the spectral variation of the stray light and its practical consequences (whether sunlight scattered from clouds or from internal camera components) are mentioned but not discussed in detail : : :with some results "omitted due to inconsistency". This is worrying.

We have added an additional discussion on the spectral variation of stray light which was missing from the paper.

The specific results that were inconsistent were correcting the stray light intensity using a zenith by sun-pixel-angle lookup table. The work was performed by a master's student and was not well polished, and thus was not suitable for publication. We are still working to address the stray light issue, however, we are now using a different approach that may be more promising. We are investigating a combination of an automated sun shade and 3D radiative transfer model to obtain stray light free and simulated a clear sky images, respectively. The radiative transfer model does not have obstructions due to a shading device. Corrections derived from both of these imagery sources are currently being tested and are expected to appear as part of a later publication.

Given these problems it would be a welcome addition to the conclusion to have a statement evaluating how well the camera performed as compared with other cameras and techniques available for this purpose, and what the key issues for further development are.

The title of Section 6 has been changed to "Conclusions and Future Work", and several comments in line with the reviewers suggestions have been added.

Minor comments include:

1. The need to differentiate between "principle" and "principal" in section 2.1
   Corrected. Should be "principal" everywhere.

2. page 4861, line 22, omit "a" in "provide details"
   Corrected.

3. page 4862 line 19, change "This" to "The"
   Corrected.

4. Fix page 4886 line 15 : : :.Suggest: " site is fitted out with ", or the site includes...
   Changed to "The site includes ...".