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University of California, San Diego (UCSD) Sky Imager Cloud Position Study Field Campaign Report

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ARM
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Executive Summary

During the University of California, San Diego (UCSD) Sky Imager Cloud Position Study, two University of California, San Diego Sky Imagers (USI) (Figure 1) were deployed the U.S. Department of Energy(DOE)'s Atmospheric Radiation Measurement (ARM) Climate Research Facility Southern Great Plains SGP) research facility. The UCSD Sky Imagers were placed 1.7 km apart to allow for stereographic determination of the cloud height for clouds over approximately 1.5 km. Images with a 180-degree field of view were captured from both systems during daylight hours every 30 seconds beginning on March 11, 2013 and ending on November 4, 2013. The spatial resolution of the images was 1,748 × 1,748, and the intensity resolution was 16 bits using a high-dynamic-range capture process. The cameras use a fisheye lens, so the images are distorted following an equisolid angle projection.

This report describes the USI and the experimental setup in detail, and also provides cloud height results of the stereography with a comparison to the collocated Vaisala Ceilometer. Dense maps of cloud height are shown for selected image pairs. The method to geometrically calibrate the sky imagers, and the method applied to determine cloud position, are given in other works.

We would like to thank the ARM Climate Research Facility and the SGP staff for making this experiment possible. The data collected have been valuable to our research on cloud position, cloud motion, and cloud optical depth determination. Only the work regarding cloud height is reported here.

Figure 1. A UCSD Sky Imager deployed in the field.

Acronyms and Abbreviations

ARM	Atmospheric Radiation Measurement Climate Research Facility
CAD	computer-aided design
CCD	charge-coupled device
CFA	Color Filter Array
DOE	U.S. Department of Energy
ftp	file transfer protocol
GB	gigabyte
GHz	gigahertz
HDR	high dynamic range
MB	megabyte
PNG	Portable Network Graphics file format
SGP	Southern Great Plains, an ARM megasite
TSI	Total Sky Imager
UCSD	University of California, San Diego
USB	Universal Serial Bus
USI	University of California Sky Imagers
UV	ultraviolet
VPN	virtual private network
W	watt

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1.0 Introduction

With increasing penetration of variable generation onto the grid, power forecasting has become vital for the integration of these variable resources into the electric grid. By using forecasts of solar power production, grid and solar power plant operators can agree to and follow schedules that better reflect the actual solar power that will be produced. This allows the grid operators to use the solar power when it is available, or to schedule the most economical alternative on the market. Without accurate solar power forecasts, additional reliability resources must be procured in capacity markets, which is more expensive than power procured in energy markets.

University of California, San Diego (UCSD) has been at the forefront of developing and improving forecasting technology for short-term (<15minutes) solar power forecasts. The basis for the short-term forecasting technology is sky imagery, which informs a deterministic cloud position forecast. The goal is to use high spatial and temporal resolution cloud imagery to predict the future cloud coverage, and with this information, estimate the surface irradiance. Initial research was performed using a Total Sky Imager (TSI) (Chow et al. 2011). Experience using the TSI to forecast at a large solar power plant in the Nevada desert indicated that the system, while it could reliably record sky conditions, had a number of limitations for solar power forecasting (Urquhart et al. 2012, Urquhart et al. 2013). The key issues with the TSI are the difficulty in accurate geometric calibration, the missing sky condition information due to the shadowband, the inability to programmatically control the unit (it has a simple user interface), and the high level of glossy compression applied to the images. The TSI has served the community well, but advances in computing and imaging technology offer superior image quality for nearly the same budget.

In late 2010 UCSD began developing a sky camera system using high-quality camera equipment. The UCSD Sky Imager (USI) was designed and built entirely by a team of students under the guidance of Professor Jan Kleissl. Over 30 (mostly undergraduate) students have contributed to the project in the course of its development. The average experience of the contributing students was very limited, but a consistent dedication to high-quality work (along with many revisions) resulted in a reasonably well designed and rugged system. Over 10 systems have now been built and deployed across the United States (Table 1).

Table 1. USI locations in the United States and deployment time ranges.

USI No.	Longitude [deg]	Latitude [deg]	Altitude [m]	State	City	Start Date	Stop Date
1.1	-117.233088	32.881090	120	California	La Jolla	2012-04-21	-
1.2	-117.240987	32.872136	135	California	La Jolla	2012-06-06	-
1.5	-117.243111	34.076355	347	California	Redlands	2012-10-18	2014-03
1.6	-117.209333	34.079822	384	California	Redlands	2012-05-45	2014-03
1.7	-97.478766	36.618377	304	Oklahoma	Billings	2013-03-11	2013-11-04
1.8	-97.484871	36.604094	318	Oklahoma	Billings	2013-03-11	2013-11-04
1.9	-117.238378	32.707122	15	California	San Diego	2013-04-19	2014-03
1.10	-156.479136	20.890549	20	Hawaii	Kahului	2013-08-21	-

The primary observational goal of our solar power forecasting research is to determine the cloud position and velocity using a camera system. The nature of clouds makes knowing their position and velocity for observation system validation a significant challenge. The best way to validate the cloud position and velocity estimates is cross-validation with other instruments, particularly the information obtained from active sensors. The U.S. Department of Energy Atmospheric Radiation Measurement (ARM) Climate Research Facility has several measurement sites with a high density of cloud observations from a multitude of instruments. These sites are ideal for testing new instrumentation and algorithms, and a field campaign for deploying two cameras was requested for ARM's Southern Great Plains (SGP) research facility near Billings, Oklahoma. This report details the experimental setup of the work that was performed, along with results from cloud height estimation using the stereo pair of sky imagers.

2.0 Cloud Position Experiment

2.1 Research Team and Funding

Principal Investigators	Jan Kleissl,	jkleissl@ucsd.edu
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	Felipe Mejia	fmejia@ucsd.edu

The team members listed above conducted the research using the sky imagers, in addition to their design and development work. Numerous students looking for laboratory work at the university helped with the design, fabrication, and assembly of the UCSD Sky Imager: Caspar Hanselaar, Edmundo Godinez, William Gui, Prithvi Sundar, Dan Erez, Scott Kato, Amy Chiang, Jessica Traynor, Kristen Ostosh, Tyler Capps, Sebastian Schwarzfischer, Sebastian Pangratz, Christian Faltermeier, Nick Truong, Salil Kektar, Jeff Yeh, Max Twogood, Alex Turchik, Danielle Donnely, Emily Davis, and, last but not least, the Victors, Fung (1) and Piovano (2). We also appreciate funding from the Panasonic Corporation, the Department of Energy High Solar PV Penetration Award Number EE-0004680, and the California Energy Commission contract 500-10-060.

2.2 USI General Information

The USI is an outdoor camera system with an onboard computer, microprocessor, and thermal monitoring and regulation system (Figure 2). The USI uses an Allied Vision GE-2040C camera that contains a 15.15 × 15.15 mm, 2048 × 2048 pixel Truesense KAI-04022 interline transfer charge-coupled device (CCD) sensor. The lens is a Sigma 4.5 mm focal length fisheye lens with an equisolid angle projection. Specific lens customizations for this experiment are given in section 2.4. A 1/16th-in.-thick, neutral-density acrylic dome provides environmental protection while giving the lens a 180° field of view of the sky. The dome has an ultraviolet (UV) hard coat applied to minimize transmission of high-energy solar radiation. The measured dome transmissivity is 46%. The camera is connected to the computer with a gigabit Ethernet interface, and control is achieved by using the PvAPI for Linux provided by Allied Vision. The computer is a 1.8 gigahertz (GHz) dual core (Atom D525) embedded computer running Linux Ubuntu 12.04. Images can be stored locally on a set of internal and Universal Serial Bus (USB) hard drives, or can be transferred across a network connection. Using an embedded computer gives the system flexibility for customizing the configuration per deployment, and the capture software can easily be reconfigured, reprogrammed, or debugged remotely. Remote access to the system is obtained through an outbound virtual private network (VPN) connection initiated by the USI to a USI server at UCSD. The VPN is used to transfer images and system status text files.

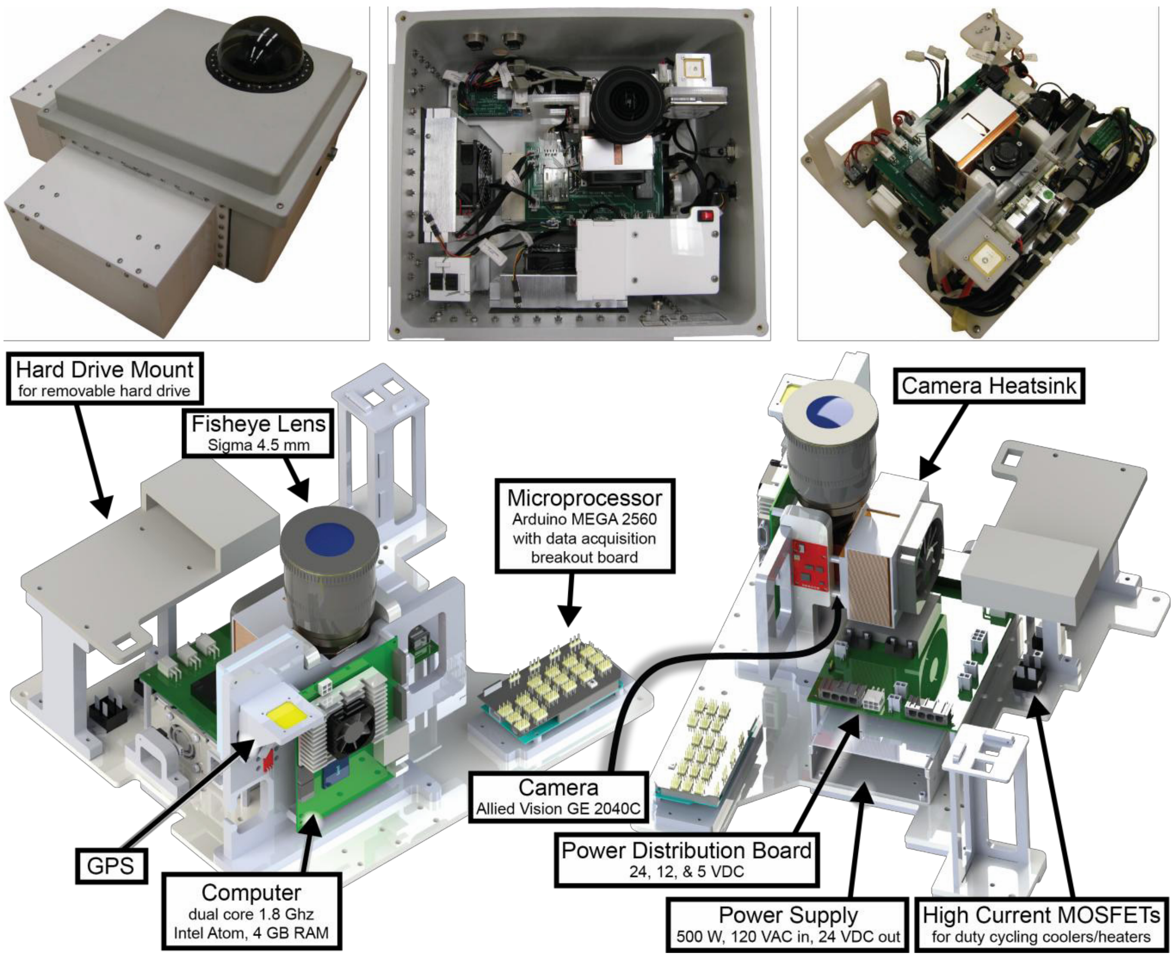


Figure 2. The UCSD Sky Imager enclosure (top) and a computer-aided design (CAD) model (bottom) showing the layout of system components.

Images are received from the camera as uncompressed single-channel 12-bit images with per-pixel color determined by the Bayer Color Filter Array (CFA). Three exposures are composited in a high dynamic range (HDR) imaging process (Urquhart et al. 2015). The combined image is 16-bit-per-pixel, single-channel image, i.e., color information is still defined by the CFA. Images are compressed and stored in a lossless 16-bit PNG format as a single-channel image. A single pixel contains information about only one color of red, green, or blue light. To produce a full-color image from the pixel array suitable for processing, linear demosaicing is applied prior to use. Image sizes are around 3 megabytes (MB) per image, which when capturing images every 30 seconds during daylight hours requires between 3 and 6 gigabytes (GB)/day depending on the time of year.

The maximum frame rate of the USI system in single exposure mode is 15 fps. In HDR mode, which is the standard USI operational mode, three images are captured sequentially in 160ms, which is a frame rate of 18.8 fps (or HDR frame rate of 6.3 fps). This increase in frame rate is possible because a smaller 1748 × 1748 region of interest, extracted from the center of the 2048 × 2048 pixel array, is transferred off the camera. After subsequent HDR compositing and PNG image compression, the effective frame rate drops to 0.77 fps (i.e., 1.3s per HDR image).

The USI has a light-colored exterior to reduce shortwave absorption and has two 80-watt (W) thermoelectric coolers with a NEMA 4X rating. A set of temperature and relative humidity sensors measure camera, power supply, internal and external ambient, and dome conditions. The internal enclosure walls are all insulated to reduce thermal conductivity of the enclosure, which with the use of active thermal control, keeps it cooler on hot days and warmer on cold days. Internal water condensation was initially found to be an issue. Improved system sealing and thorough water testing was found to be necessary. The entire enclosure with external connectors installed is submerged in water for over 24 hours to verify it is completely waterproof and airtight prior to deployment. Three 20 W resistive heating strips are installed on the base of the dome to reduce condensation on the exterior dome surface. Extensive details of the USI can be found in Urquhart et al. 2015a.

2.3 Purpose and Scope

The primary goal of the UCSD Sky Imager Cloud Position Study was to collect sky imagery data from two sky imagers separated by a 1-2km baseline at a site with active cloud position measurement equipment to evaluate and validate a stereoscopic cloud height measurement algorithm. A secondary goal was to collect imagery at a site with several solar radiation sensors and cloud remote-sensing equipment for future research yet to be explored, e.g., estimating cloud optical depth (Mejia and Kleissl, in preparation). The other secondary goal was to field the USI in a non-University setting to demonstrate operational stability and system robustness.

The scope of the campaign was limited to collecting imagery from two USIs for the purposes of determining cloud position by means of stereography. This required a trip to deploy the two cameras at the locations indicated in section 2.4, regular dome cleaning by SGP staff to remove dust and other debris, and a trip to collect the instruments at the completion of the campaign. Hardware configuration changes and moving of equipment were not required during the course of the campaign. SGP staff provided power connections for both instruments and a wired network connection for one of the units. Regular manual data recovery was required for the second unit, which involved swapping a set of USB hard drives, a courtesy provided by SGP staff. The data was then uploaded to UCSD via file transfer protocol (ftp). Power cycling of the units by SGP staff was occasionally required.

2.4 Experimental Setup

2.4.1 Experiment Location and Time Period

Two USIs were deployed at the DOE ARM Climate Research Facility SGP megasite from March 11, 2013 to November 4, 2013. The longitude, latitude, and altitude of USI 1.7 was 97.478766°E, 36.6183435°N, 304.5 m, and for USI 1.8 was 97.484856°E, 36.604043°N, 318 m Figure 3). The instruments were 1.7 km apart.

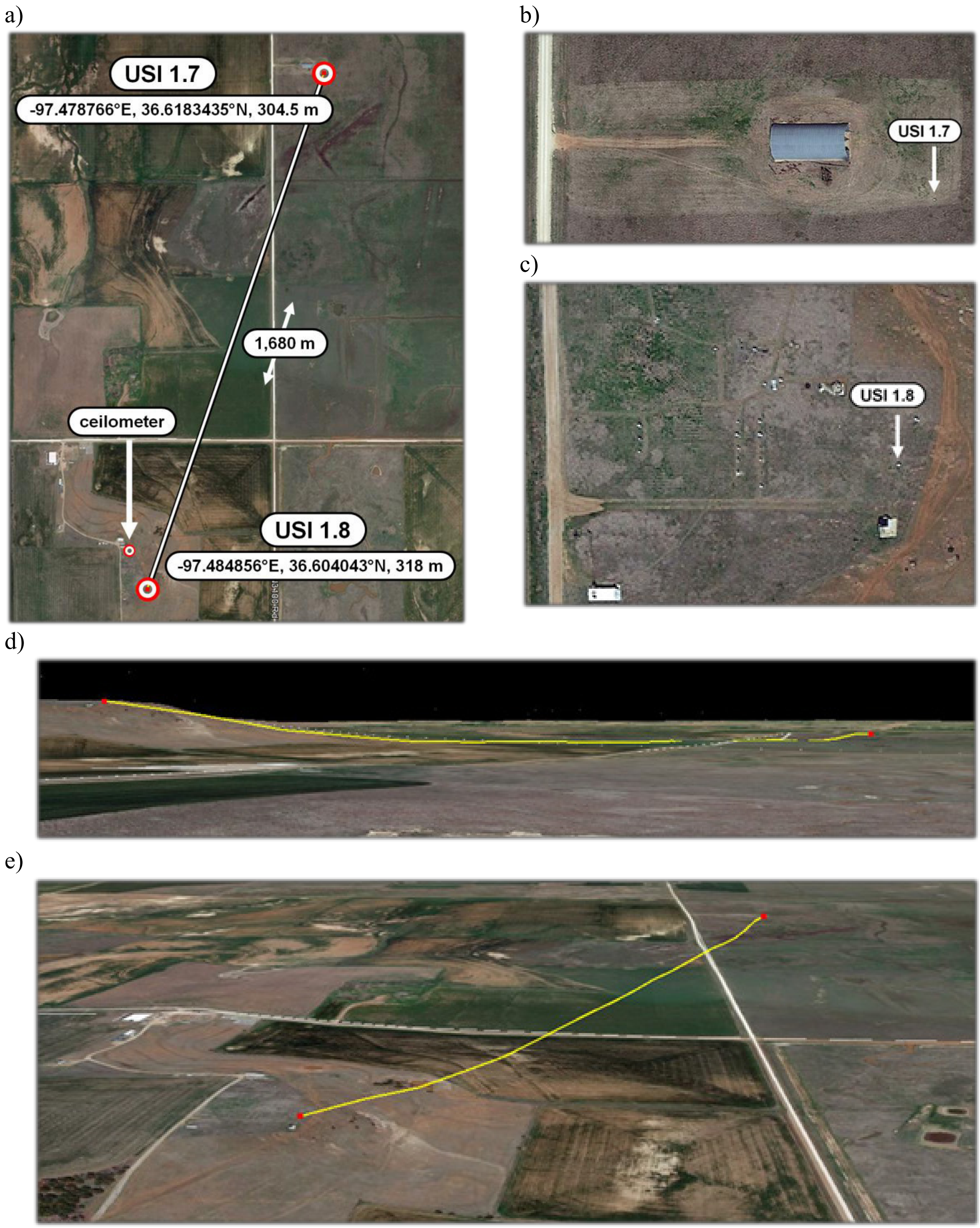
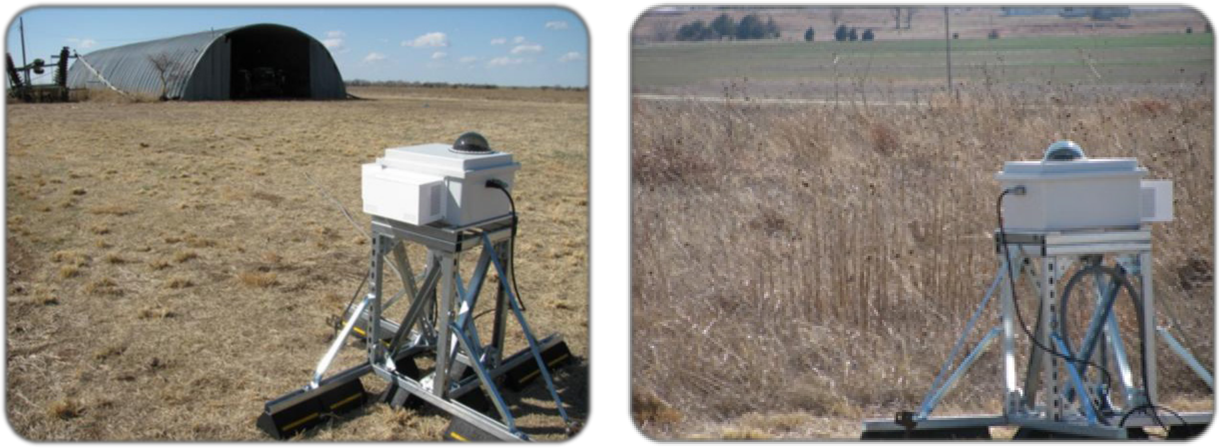


Figure 3. (a) Satellite image showing the camera and ceilometer locations, along with geographic coordinates. Close-ups of the locations for (b) USI 1.7 near the Bobbit roundtop and (c) USI 1.8 in the ARM SGP instrument field. Angled views showing (d) the height of the instrument field relative to the roundtop and (e) a north-south looking view.

USI-1.7



USI-1.8

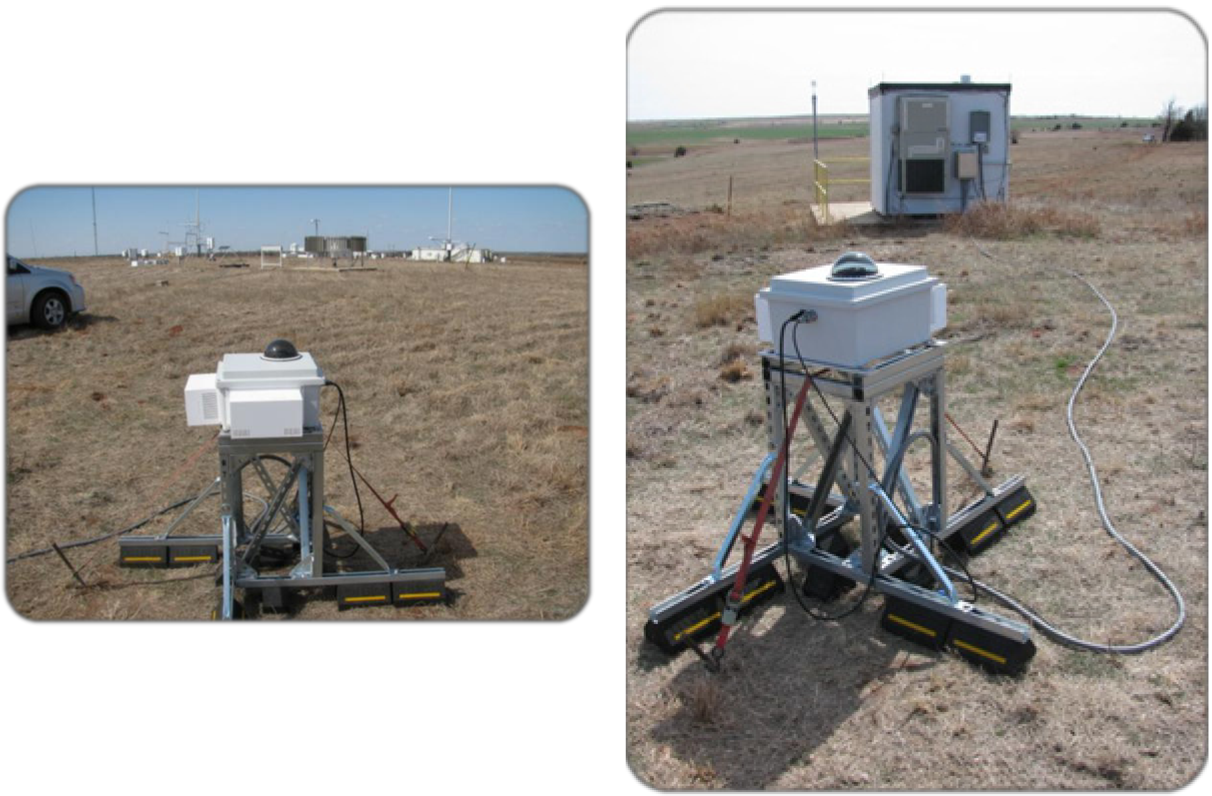


Figure 4. Photographs of USI 1.7 and 1.8 after deployment on March 11, 2013.

2.4.2 Camera System

For the duration of this campaign, the two USIs used three exposures at integration times of 3, 12, and 48 ms to generate a composite 16-bit HDR image. The final sky images have an effective spatial resolution of 1748 × 1748 and radiometric resolution of 65,536 levels per color channel. A fixed circular aperture was added to the lenses of both units: USI 1.7 had a 700 ± 5 µm aperture and USI 1.8 had a 1,000 ± 5µm aperture. The aperture had a black oxide coating to reduce internal reflection in the lens.

Mechanical drawings for the modified aperture are available upon request, and provide information about centering and perpendicularity. Both cameras were geometrically calibrated using the method described in Urquhart et al. 2015b using solar position data on March 31, 2013.

2.4.3 Ceilometer

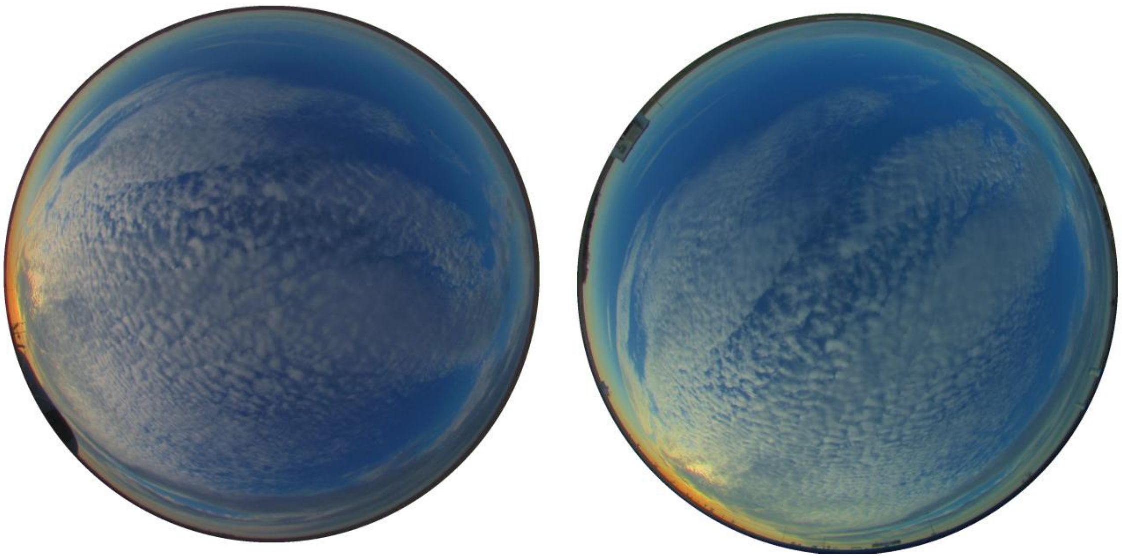
A Vaisala Ceilometer Model CL31 (hereinafter “ceilometer”) was used for cloud height validation. The ceilometer emits pulses of near-infrared light, and detects the backscattered near-infrared signal within an 18.7 deg field of view. It can detect up to three cloud layers and has a 7,600 m vertical range. The ceilometer was located at a longitude, latitude, and altitude of -97.485516°E, 36.605128°N, 316 m, which is 1,590 m from USI 1.7 at 202 deg azimuth (SSW), and 134 m from USI 1.8 at 334 deg azimuth (NNW).

3.0 Results

3.1 Sky Imagery

A selection of sky imagery from the campaign is given in the next several pages.

altocumulus-01, 2013-04-13 T 00:15:00



broken-02, 2013-04-09 T 00:04:00

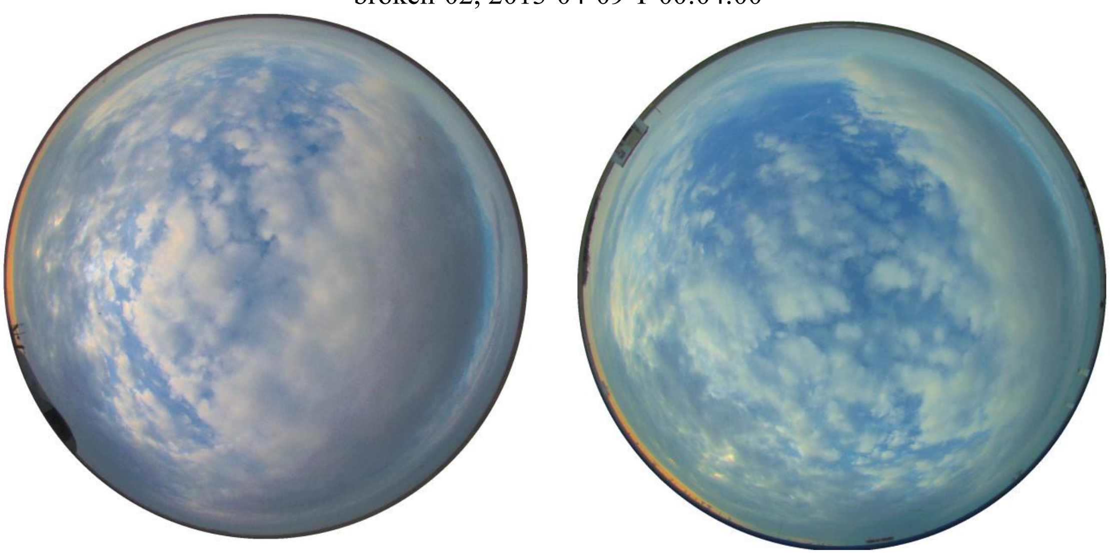
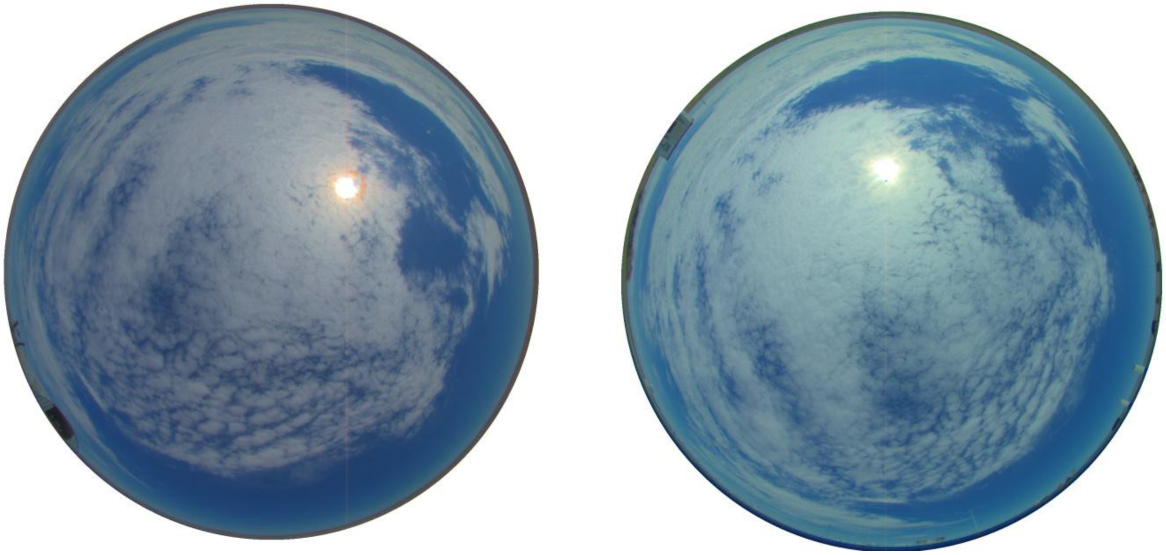


Figure 5. Image pairs for which a dense estimation of cloud position was performed. Images on the left are from USI 1.7 (note Farmer Bobbit's roundtop barn), and images on the right are from USI 1.8. All images are color corrected HDR with a logarithmic intensity rescaling (similar to gamma correction). (*continued*)

cirrocumulus-03, 2013-04-12 T 16:52:00



cirrus-04, 2013-04-06 T 14:47:30

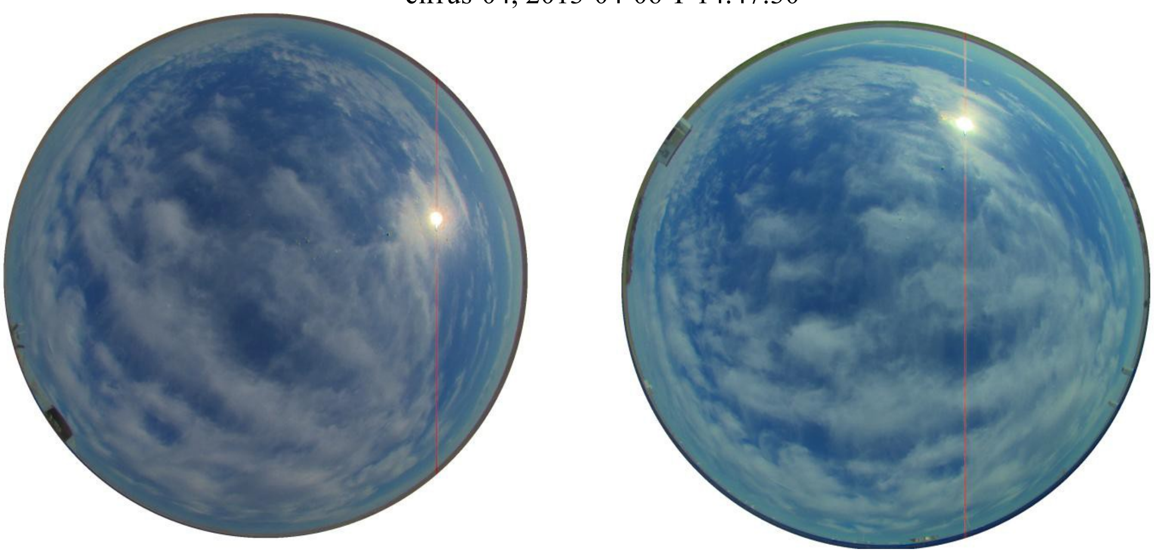
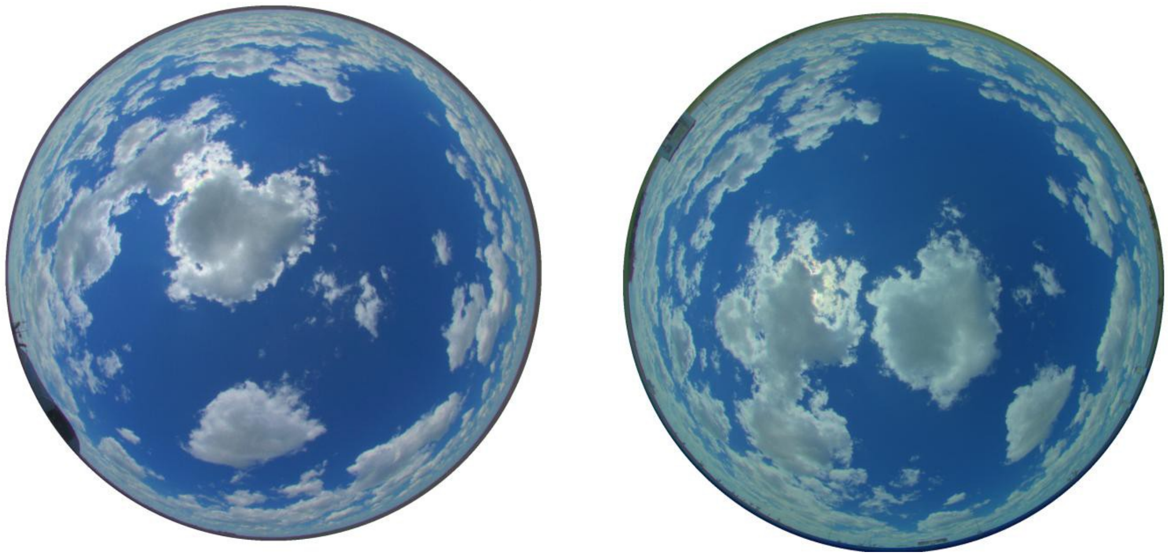


Figure 6. Image pairs for which a dense estimation of cloud position was performed. Images on the left are from USI 1.7 (note Farmer Bobbit's roundtop barn), and images on the right are from USI 1.8. All images are color corrected HDR with a logarithmic intensity rescaling (similar to gamma correction). (*continued*)

cumulus-05, 2013-05-03 T 19:33:30



cumulus-06, 2013-04-04 T 22:30:30

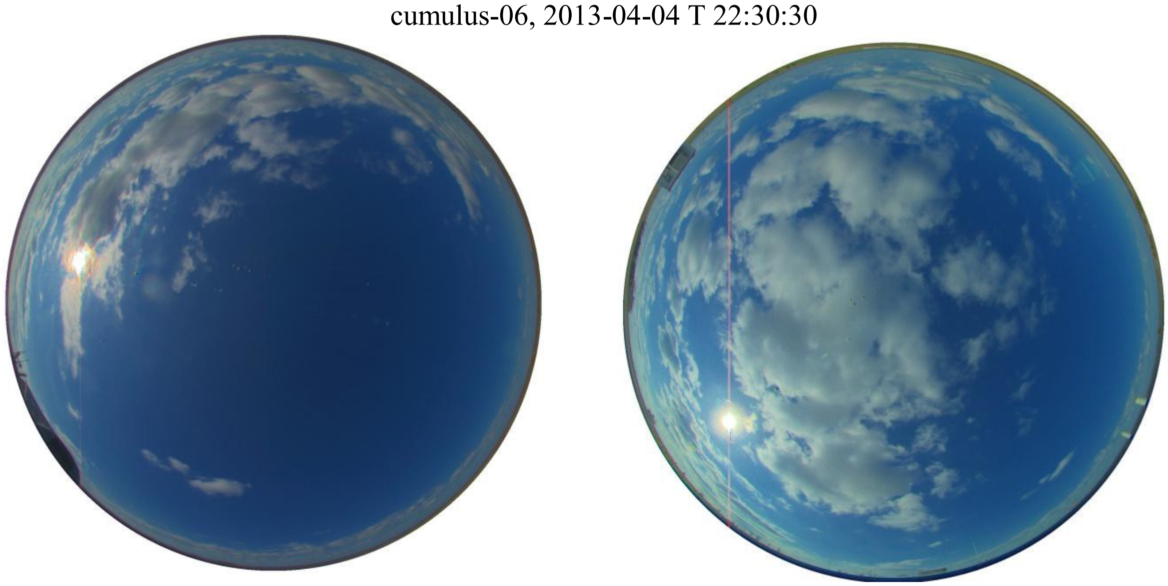
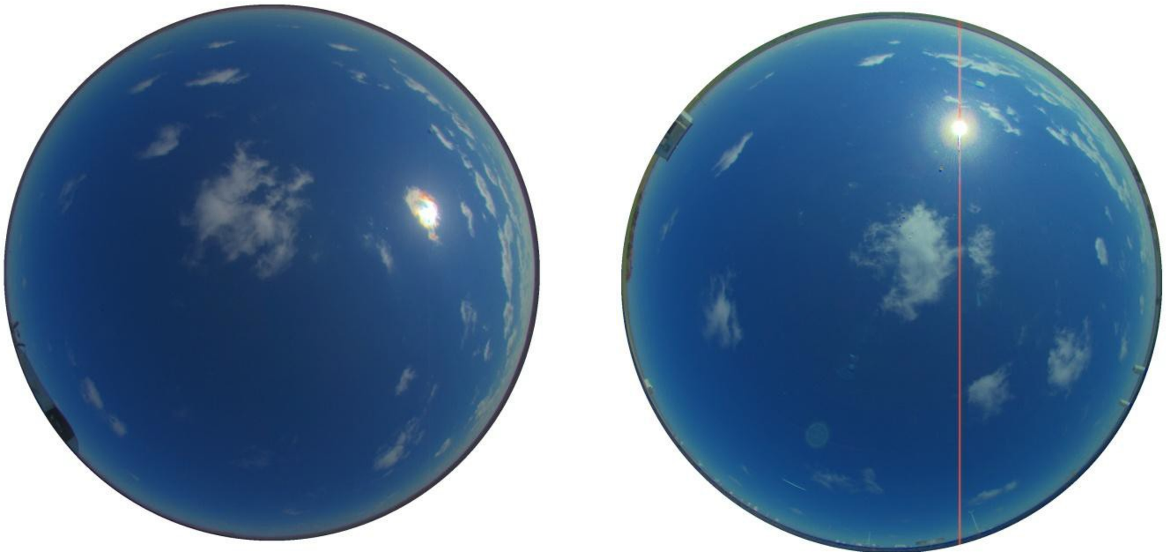


Figure 7. Image pairs for which a dense estimation of cloud position was performed. Images on the left are from USI 1.7 (note Farmer Bobbit's roundtop barn), and images on the right are from USI 1.8. All images are color corrected HDR with a logarithmic intensity rescaling (similar to gamma correction). (*continued*)

lowsparse-07, 2013-04-11 T 15:08:00



lowsparse-08, 2013-04-11 T 21:03:30

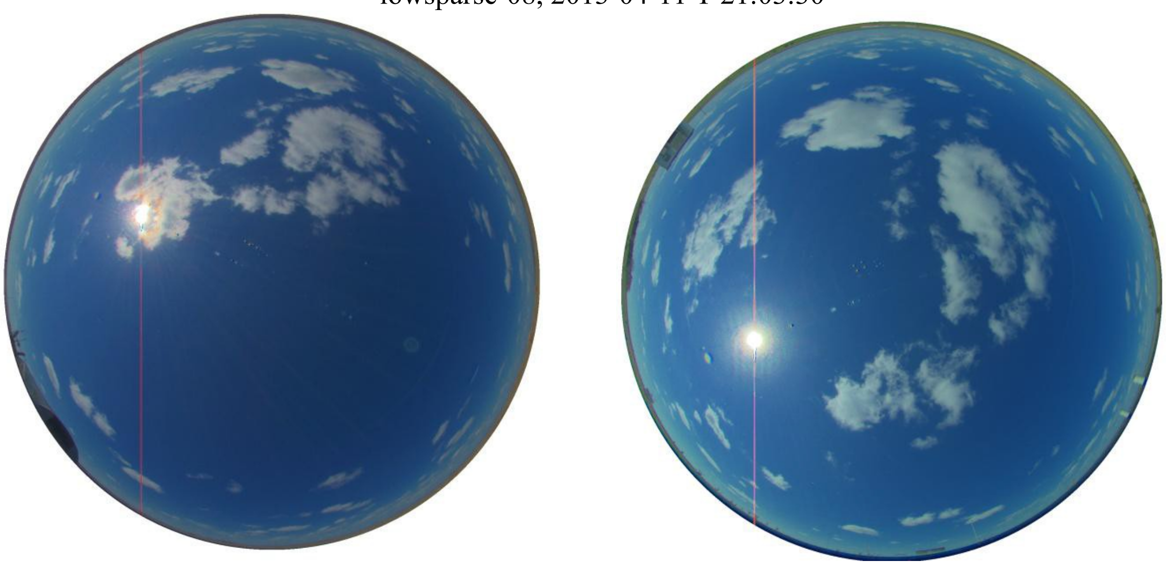
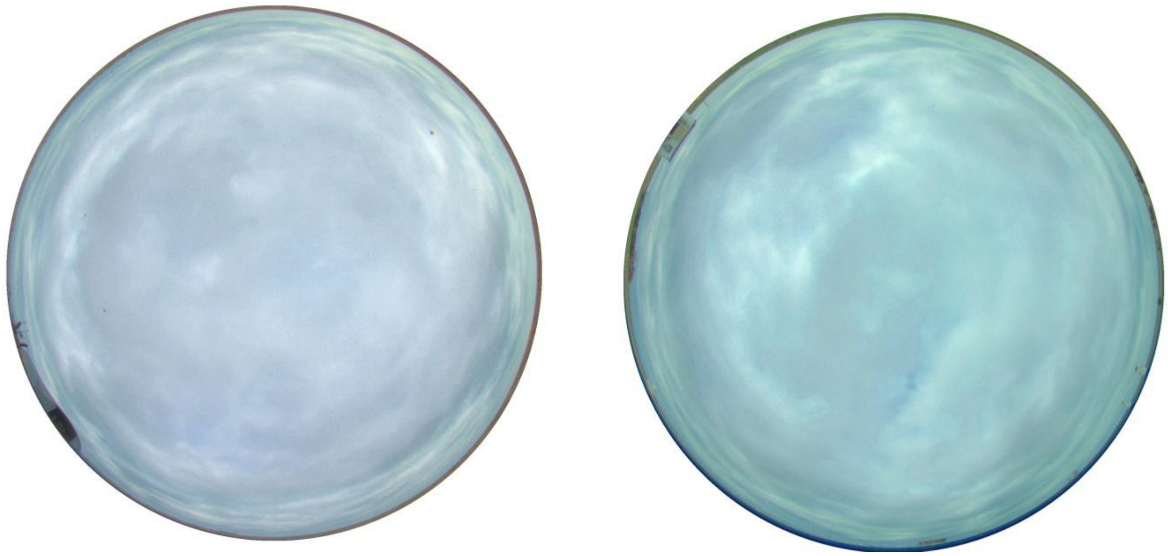


Figure 8. Image pairs for which a dense estimation of cloud position was performed. Images on the left are from USI 1.7 (note Farmer Bobbit's roundtop barn), and images on the right are from USI 1.8. All images are color corrected HDR with a logarithmic intensity rescaling (similar to gamma correction). (*continued*)

overcast-09, 2013-04-07 T 17:41:00



twolayers-10, 2013-04-14 T 16:08:00

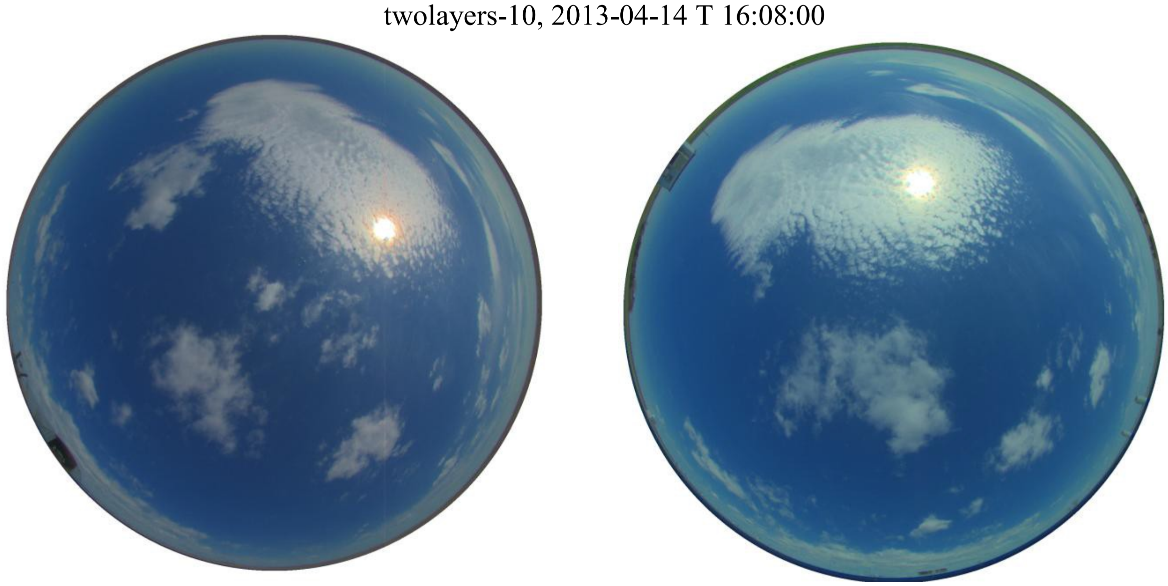


Figure 9. Image pairs for which a dense estimation of cloud position was performed. Images on the left are from USI 1.7 (note Farmer Bobbit's roundtop barn), and images on the right are from USI 1.8. All images are color corrected HDR with a logarithmic intensity rescaling (similar to gamma correction). (*continued*)

3.2 Cloud Position using Stereography

Dense maps of cloud position were computed for each of the above pairs. Only selected results are given here. The method to compute cloud height is thoroughly described in Urquhart and Kleissl (2015). In summary, the two images are rectified so that epipolar lines lie along image columns, and that corresponding columns are in correspondence. A matching procedure is then used to identify which rows are in correspondence. A triangulation procedure is then applied. The result is a position vector for each pixel that gives the position in space relative to the reference instrument, which in this case was USI 1.7. Only the third coordinate of the position vector can be evaluated because the ceilometer only reports cloud height.

Dense cloud maps for cumulus-05 and twolayers-10 are given in Figures 10 and 11. Subfigure i shows the original image images along with the region that was matched (defined by selecting a pointing direction and field of view). Subfigure ii shows the rectified region to be matched. Subfigure iii shows a dense map of cloud height (maps for distance to the north and east are not shown). Subfigure c shows the ceilometer backscatter profile with a dotted border giving the time window in which the image was taken. The dense map of cloud height was reduced into Table 2 for each case. It is difficult to compare the instruments one to one because of the nature of the measurement processes, but overall the stereography method gives cloud heights similar to the ceilometer.

Table 2. Cloud heights measured by the ceilometer and the pair of sky imagers. Ceilometer height statistics are derived from the time-height data in a ±10 minute window about the image capture time. The mean ceilometer height is a backscatter-weighted height of a filtered data set (filtered to remove noise). The sky imager data is unfiltered. The 20th, 50th (median), and 80th percentiles are given as P20, P50, and P80, respectively. The bias between the P50 USI and mean ceilometer measurements is given.

	ceilometer			sky imager			
Case	mean [m]	P20 [m]	P80 [m]	P50 [m]	P20 [m]	P80 [m]	P50 - mean [m]
altocumulus-01	4,360	4,095	4,545	4,575	4,464	4,670	215
broken-02	1,295	615	1,335	1,408	1,369	1,438	113
cirrocumulus-03	3,805	3,465	4,035	3,996	3,945	4,073	191
cirrus-04	5,656	5,385	5,895	5,988	5,525	6,455	332
cumulus-05	2,353	2,235	2,655	2,486	2,318	2,680	133
cumulus-06	955	825	1,095	996	909	1,090	41
lowsparse-07	-			808	521	11,096	
lowsparse-08	1,380	1,275	1,485	1,411	1,326	2,112	31
overcast-09	558	225	645	636	575	826	78
twolayers-10	1,318 5,014	1,155 4,695	1,425 5,145	1,369 5,190	1,283 5,106	1,456 5,539	51 176

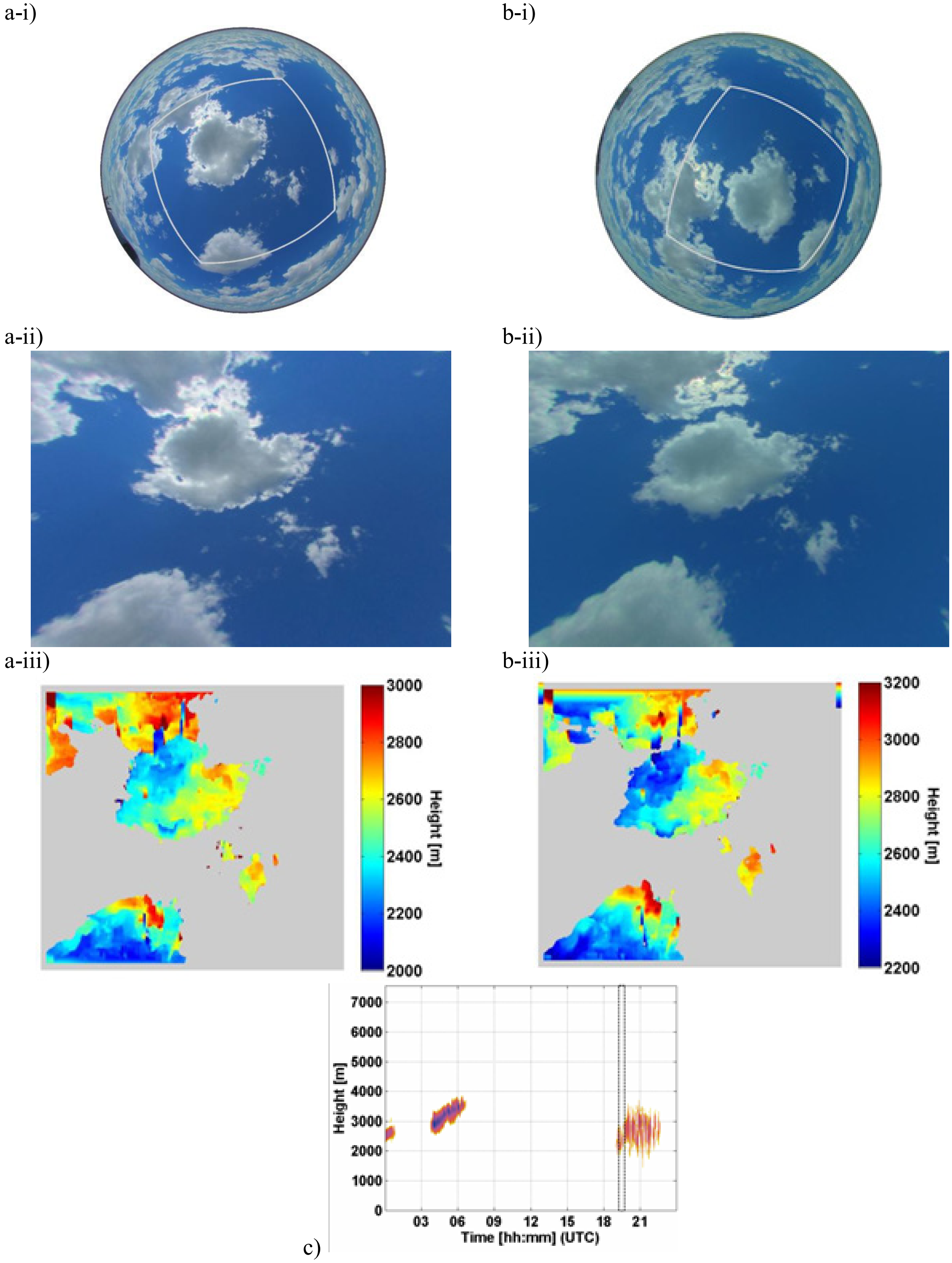


Figure 10. Stereography output for case cumulus-05 for (a) USI 1.7 and (b) USI 1.8. (i) Input images with field of view bounds; (ii) rectified images; (iii) cloud height map. Ceilometer returns are shown in (c) with image capture time indicated by dashed lines.

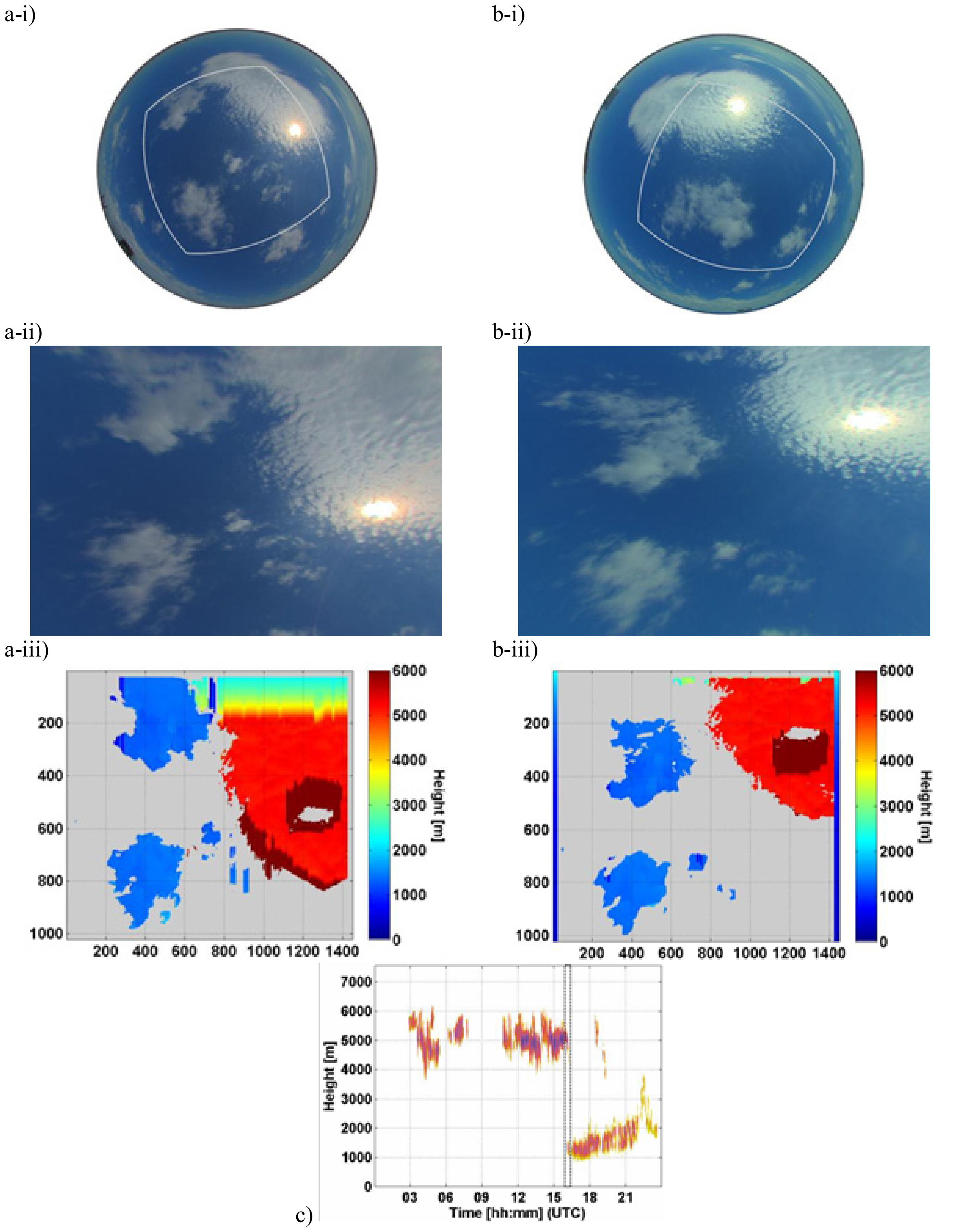


Figure 11. Stereography output for case twolayers-10 for (a) USI 1.7 and (b) USI 1.8. (i) Input images with field of view bounds; (ii) rectified images; (iii) cloud height map. Ceilometer returns are shown in (c) with image capture time indicated by dashed lines.

3.3 Conclusions and Future Work

A method to generate dense cloud position estimates was evaluated using data gathered during the UCSD Cloud Position Study at the DOE ARM Climate Research Facility SGP field site. The method performs well for higher clouds containing a reasonable amount of texture with which to determine correspondence. Due to the 1.7 km baseline, the matching results for lower clouds yielded poorer results than the high clouds, in general. Multiple cloud layers were successfully distinguished and the heights determined for each layer were consistent with ceilometer measurements. Improved cloud position information will benefit geometrically based, deterministic solar power forecasting with sky imagers by allowing more accurate shadow position estimation.

The data gathered at the field campaign are not limited to cloud position estimation. Several periods of higher-frequency data acquisition were performed with the expectation to compute the optical flow of the clouds (Chow et al. 2014). Because the imagers do not adjust any gain settings, all imagery is captured on the same scale, and with the multitude of radiometers at the site this opens the possibility for exploring what radiometric quantities can be derived from the imaging system. Readers interested in additional information about this campaign are encouraged to contact the authors.

4.0 UCSD Sky Imager Cloud Position Study Publications

4.1 Journal Articles/Manuscripts

Mejia, F, and J Kleissl. "Cloud optical depth estimates from sky images." In preparation.

Urquhart, B, and J Kleissl. 2015. "Dense cloud stereo photogrammetry using dynamic programming." In preparation.

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