Infrared Cloud Imager

Cloud cover is an important but poorly quantified component of our environment. The ground-based Infrared Cloud Imager (ICI) provides continuous quantified cloud measurement. The ICI observes the Long Wave Infrared emission from clouds and clear sky to produce an image of the overhead clouds independent of sunlight. The isolated cloud emission is used to observe cloud amount, cloud optical depth, cloud optical attenuation, and cloud spatial distribution. These instruments have seen operation from have seen operation from the high mountain environment at the Haleakala Observatory in HI, the cold arctic in Barrow AK, and the hot desert at the Goldstone Deep Space Communication Complex in CA.

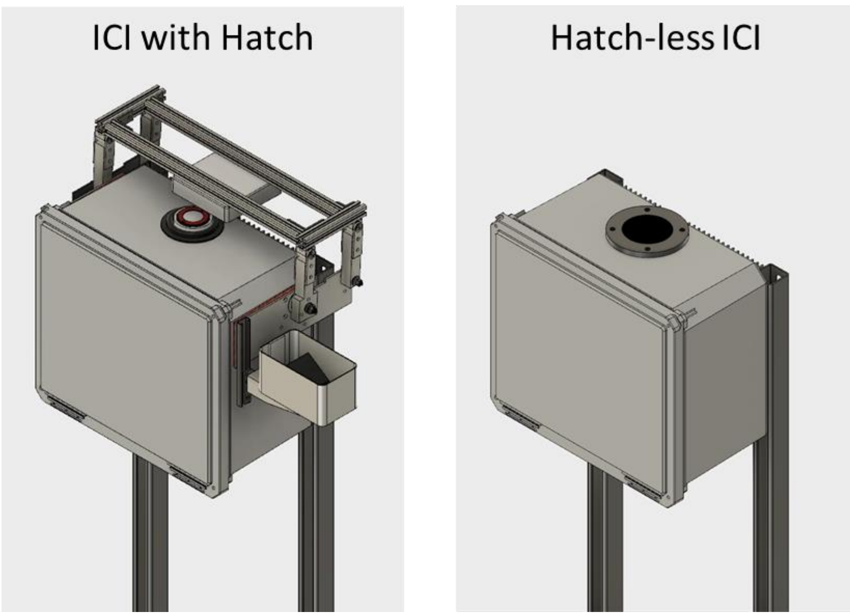


Figure 1. Renderings of two models of the ICI systems, a fish-eye system with a hatch and rain sensor on the left and a hatch-less system with a germanium window and no rain sensor on the right.

High-Accuracy Cloud Measurement

- Accurate quantified cloud measurement
- Equal sensitivity during day and night
- Classification of cloud optical properties (attenuation or optical depth)
- Detection of cirrus down to an optical depth of 0.1 (0.43 dB)
- Advanced image processing routines
- Clock-synchronized image acquisition for operation of multiple ICI’s or synchronization with other instruments.
- Calibrated azimuth and elevation of detected clouds
- Imagery based calibrations an alignment.

Method of operation

The ICI observes the Long Wave Infrared (LWIR) emitted radiance from clouds and clear sky to produce an image independent of sunlight. Clouds and clear sky are separated by modeling of the expected sky emission and observing how the image deviates from the model over time. Once detected the emission from the cloud is isolated and the optical properties of the cloud can be constrained. Resulting images provide classification data including probability a pixel is cloudy, cloud optical depth, cloud attenuation, and long-term cloud cover statistics.

The Instrument

The instrument consists of two enclosures, 1) a temperature-controlled enclosure that contains the camera and 2) a non-temperature-controlled enclosure that contains the power electronics and communication hardware. Both enclosures use the same housing, as shown in Figure 1. Standard configurations have the enclosures connected by up to four meters of cabling. The main enclosure has either a mechanized and automated hatch through which the camera views the sky, or as an option for non-fish-eye ICIs a germanium window.

Example Cloud Data

Cloud Data with a moderate field of view Instrument

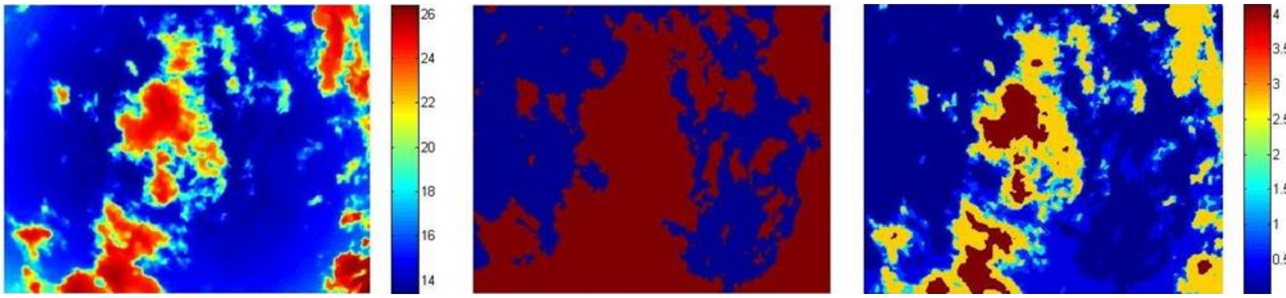


Figure 2 Example images from an ICI deployed at the NASA Table Mountain Facility in California: (left) calibrated sky radiance in W m-2 sr-1, (center) cloud/no cloud map with blue=clear and red=cloud, (right) cloud optical depth.

Example Cloud Data Series (2 days & nights)

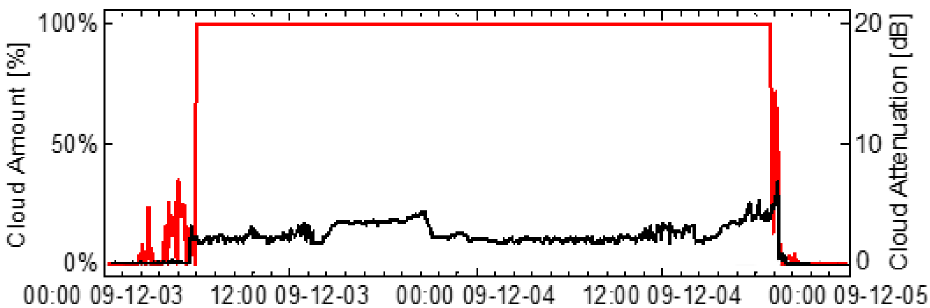


Figure 3. The average cloud fraction and cloud attenuation for a 48-hour day/night period. The red line shows the percentage of sky covered by clouds; the black line shows cloud attenuation. Although the sky was cloudy, these clouds had low attenuation.

Fish-eye Cloud Imager

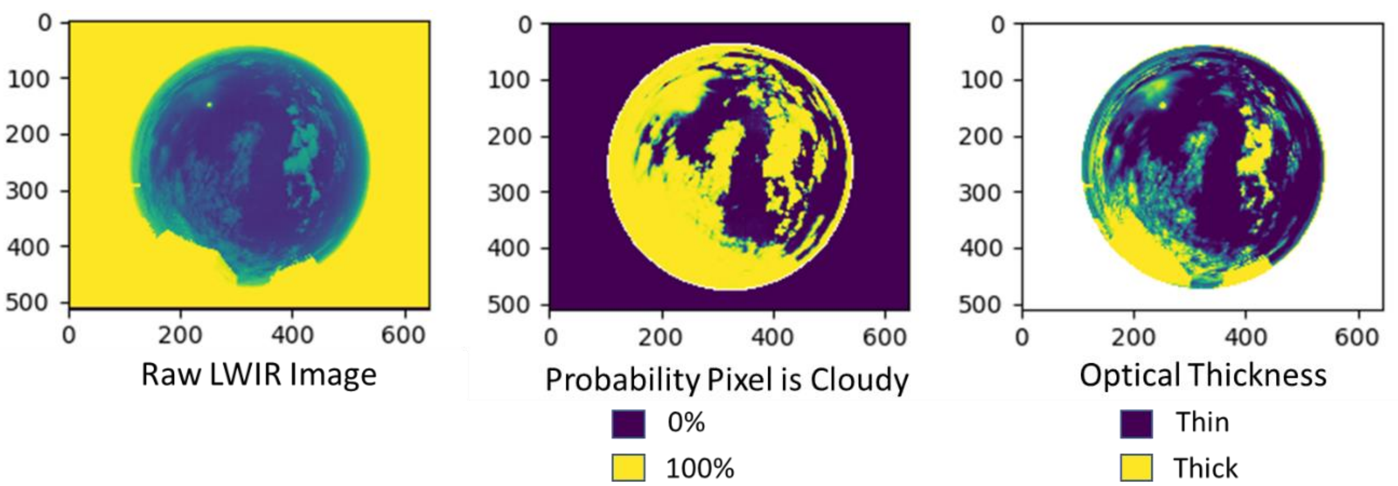


Figure 4. Example images from a full fish-eye ICI deployed in Bozeman, Montana: the left frame shows calibrated sky radiance in $W/(m^2 sr)$, the center from shows cloud probability map with blue=clear and yellow=cloud, and the right frame shows cloud optical depth.

Instrument Capabilities

Instrument Specifications	
Camera	LWIR uncooled microbolometer
Electrical	Standard: 50/60 HZ 120V/240 AC (DC only options and solar power available)
Pixel Resolution	640x480 or 1024x768
Pixel Size	17 µm
Temporal Resolution	User-configured period between images: 10 s or longer
Instrument Interface	Ethernet
Instrument control	Serial over Ethernet
Camera Auxiliary Data	Focal Plane Array Temperature Camera Body Temperature
Non-camera Auxiliary Data	Enclosure Temperature and Relative Humidity
Depending on Options)	Hatch Open/Closed Wind speed Rain External Air Temperature, Relative Humidity, Pressure Precipitable Water Vapor (estimated)
Operating Temperature	-20 °C to 60 °C standard (-40°C to 70°C extended)
Camera Enclosure	Temperature Controlled 22.5°C ±2.5°C
Power Enclosure	Ambient Temperature -40°C to 60°C Temperature control options available

Rugged Design

- NEMA 4X mechanical components
- iP67 exterior optical and electrical components
- Industrial -40°C to 70°C internal electrical components
- Hard-carbon diamond-like coated germanium front optics

Ease of Maintenance

Designed for long term automated operation by a team with experience maintaining instruments. The ICI systems have been designed to make periodic maintenance quick and easy for onsite technicians. All components are easy to access, and maintenance is fully documented.

Instrument Sensitivity Specifications	
Noise Equivalent Temperature Difference (NETD)	40 mK
Minimum Resolvable Cloud Radiance	0.08 W/(m^2 sr)
Minimum Resolvable Cloud	Optical Depth 0.115 Attenuation 0.5 dB

640x480 Moderate Resolution Instrument Field of View (FOV)								
Lens	Fish-eye*		8 mm f/1.2		19 mm f/1.2		25 mm f/1.2	
Detector	x-axis FOV	y-axis FOV	x-axis FOV	x-axis FOV	y-axis FOV	y-axis FOV	x-axis FOV	y-axis FOV
640x480	180°	180°	68°	51°	32°	24°	24°	18°

1024x768 High Resolution Instrument Field of View (FOV)								
Lens	Fish-eye*		9.6 mm f/1		25 mm f/1.2		50 mm f/1.2	
Detector	x-axis FOV	y-axis FOV	x-axis FOV	x-axis FOV	y-axis FOV	y-axis FOV	x-axis FOV	y-axis FOV
1024x768	180°	180°	86°	40°	30°	64°	20°	15°

*Fish-eye systems are a full circular image with a diameter of the vertical pixel dimension of the detector. The pixels outside this circle are not imaged.

Instrument Options

Hardware Options	
Hatch Required for fish-eye system Optional on all systems	Automated Mechanical hatch, closes when not in operation or during times of rain. Requires: Rain Sensor Optional: closure during high wind
Germanium Front Window Required for hatch-less systems	Rather than a hatch non-fish-eye systems can use a hard coated germanium front window to protect the lens.
Pixel Resolutions	640x480 or 1024x768
Field of View Options	See field of view options on page 3
Rain Sensor Required for hatched systems	Detect when it is raining: closes the hatch on hatched systems, alerts user on non-hatched systems
Wind Speed Sensor Optional	Ultrasonic anemometer to measure wind speed: close the hatch to protect optics when blowing debris is a concern, close during extreme wind events.
Fiber Optic Interface Optional	Optional when preferred over Ethernet
Cold Environment Deployment Optional	Increases insulation and heating systems when instrument is planned for cold environments routinely colder than -20°C.
Hot Environment Deployment Optional	Increased insulation and cooling systems when instrument is planned for hot environments routinely warmer than 45°C.

Service Options

Services	
Instrument Recalibration Recommended	It is recommended that the LWIR camera in the ICI be recalibrated on an annual or bi-annual basis. This requires returning the camera to NWB Sensors where the camera is calibrated and returned to the site.
Optics Recoating Recommended	The hard carbon coating on the front optics can become degraded over time. It is recommended these options be recoated after three or more years of operation.
Installation Service and Support	NWB Sensors can provide services to support onsite installation of the instrument.
Instrument Tuning and Alignment	After collection of seven or more days of continuous data NWB Sensors can provide data processing services to tune and validate both the atmosphere removal algorithms and instrument geographic alignment.
Custom Data Analysis	NWB Sensors can provide data post processing services to derive customer specific data products. These can be performed at NWB Sensors or could be custom software developed and distributed to the customer.

Infrared Cloud Imager Software

The ICI image collection and processing software ***ici.exe*** runs on a Windows PC and operates the full ICI instrument over an Ethernet network. The software can be configured to launch on system startup, or may be run by launching ici.exe. This software requires the LabVIEW 2016 runtime environment as well as Python 2.7, both of which are installed with the ICI software Installer.

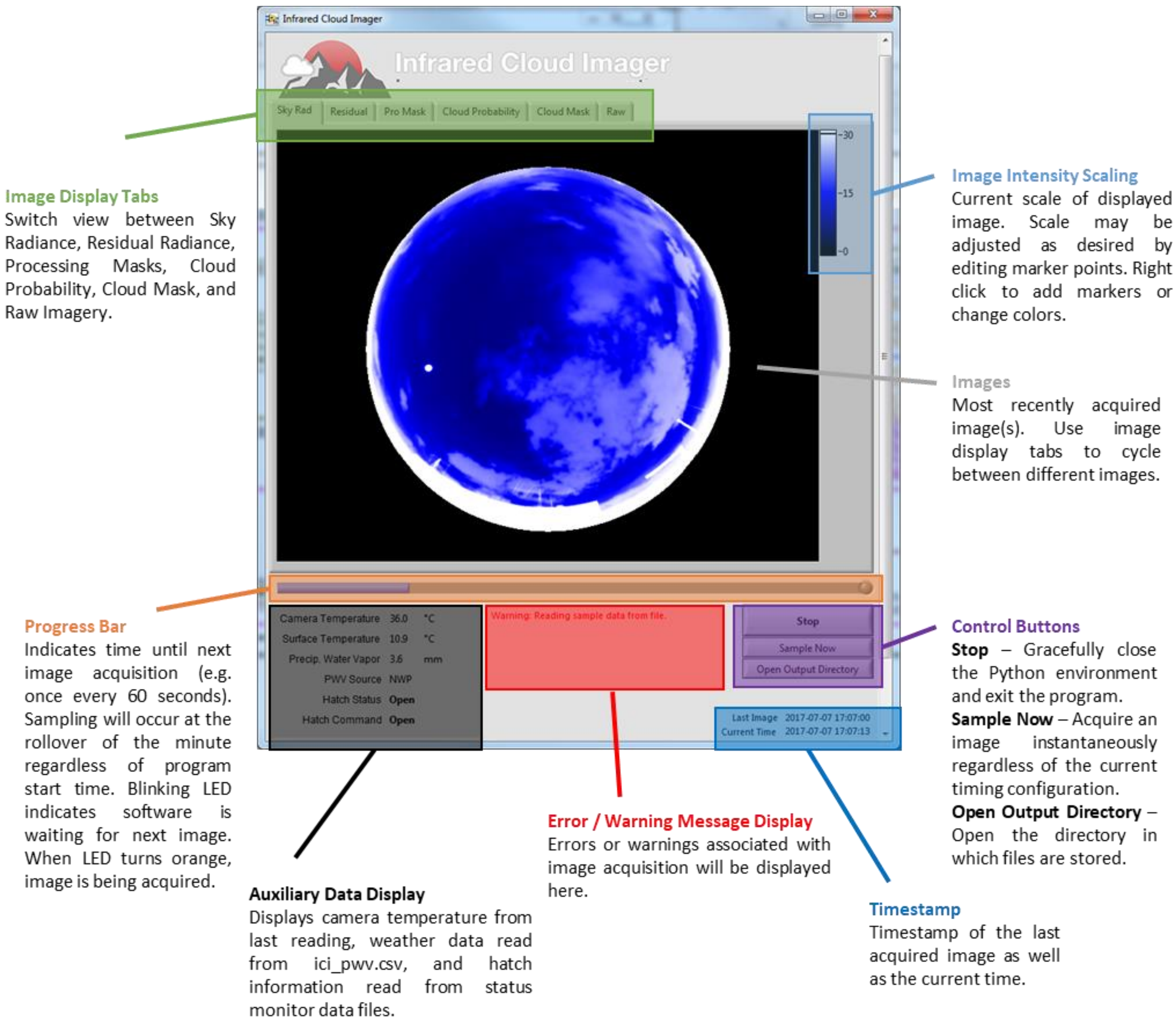
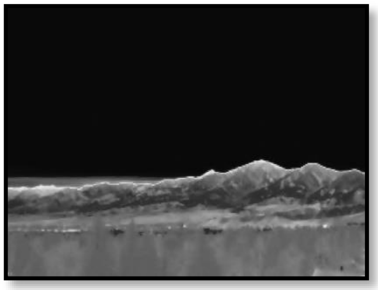


Figure 5. The Infrared Cloud Imager GUI showing the main components of the GUI

Contact Information



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Heritage of the Instrument

The infrared cloud imager has its origins in the work conducted at Montana State University that was licensed in 2017 by NWB Sensors. The following publications demonstrate the long heritage of this instrument and can be seen a reference of the systems abilities. The algorithms used for cloud detection by NWB Sensors have their foundation in those described in this literature but have been significantly enhanced during our internal development.

J. A. Shaw, P. W. Nugent, N. J. Pust, B. Thurairajah, and K. Mizutani, "Radiometric cloud imaging with an uncooled microbolometer thermal infrared camera," *Opt. Express*, vol. 13, no. 15, pp. 5807–5817, 2005.

B. Thurairajah and J. A. Shaw, "Cloud statistics measured with the Infrared Cloud Imager (ICI)," *IEEE Trans. Geosci. Remote Sens.*, vol. 43, no. 9, pp. 2000–2007, 2005.

P. W. Nugent, "Wide-Angle Infrared Cloud Imaging For Cloud Cover Statistics," *Master Thesis Depart of Electrical Engineering*, Montana State University, 2008

P. W. Nugent, J. A. Shaw, and S. Piazzolla, "Infrared cloud imaging in support of Earth-space optical communication," *Opt. Express*, vol. 17, no. 10, pp. 7862–72, May 2009.

J. A. Shaw, P. W. Nugent, B. J. Redman, and S. Piazzolla, "Cloud optical depth measured with ground-based, uncooled infrared imagers," in Proc. SPIE 8523, Remote Sensing of the Atmosphere, Clouds, and Precipitation IV, 2012, vol. 8523, pp. 1 – 7.

P. W. Nugent, J. A. Shaw, and S. Piazzolla, "Infrared cloud imager development for atmospheric optical communication characterization, and measurements at the JPL Table Mountain Facility," IPN Prog. Rep. 42, pp. 1–31, 2013.

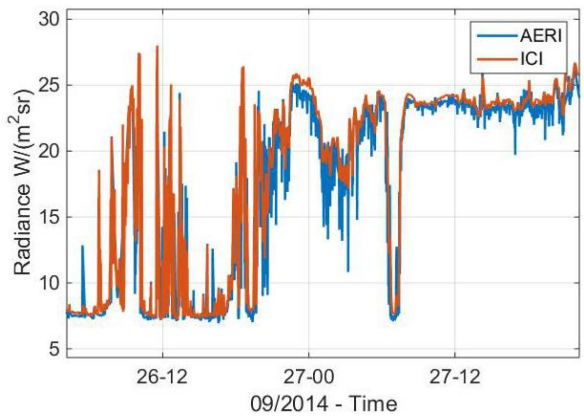
J. A. Shaw and P. W. Nugent, "Physics principles in radiometric infrared imaging of clouds in the atmosphere," *Eur. J. Phys.*, vol. 34, no. 6, pp. S111–S121, Nov. 2013.

P. W. Nugent, "Deployment of the Third-Generation Infrared Cloud Imager, a Two-Year Study of Arctic Cloud at Barrow Alaska," *Doctoral Thesis College of Engineering*, Montana State University, 2016

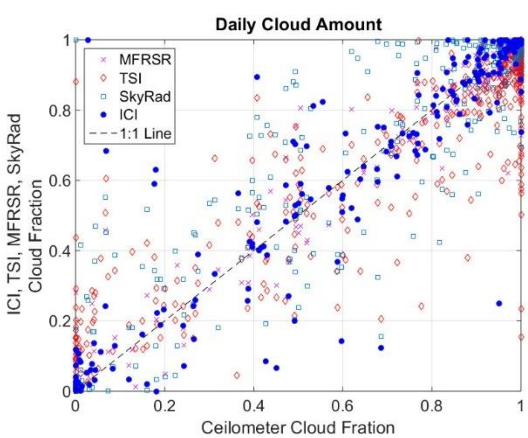
Comparisons with Other Cloud Detectors

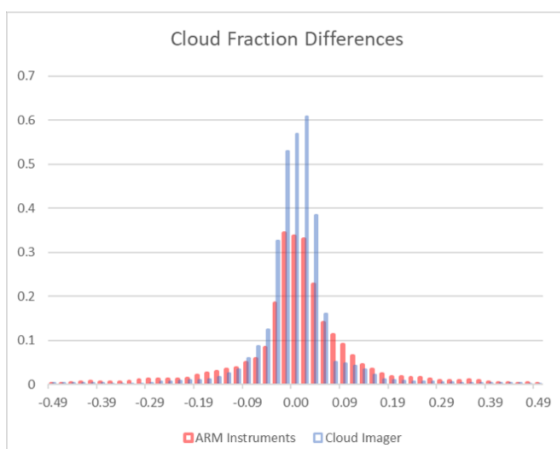
An ICI developed while Dr. Nugent was a student at Montana State University was deployed at the Department of Energy Atmospheric Radiation Monitoring (ARM) site in Barrow, AK from 2012 through 2014. This system was a low-resolution 324x256 LWIR imager with an 80-degree horizontal field of view. At this site the ICI was co-located with other world class cloud detection instruments. This allowed for a comparison of the ICI's performance with these instruments over the two-year deployment. The following figures present the results of these comparisons.

Co-located with the ICI at the Barrow ARM site was the Atmospheric Emitted Radiance Interferometer (AERI). This instrument produces highly accurate measurement of long wave infrared spectral radiance at the zenith. By integrating the AERI data over the spectral response of the ICI camera comparison of the two instruments could be made. With the advanced calibration on the ICI it showed good comparison to the AERI as shown in a time series of AERI integrated radiance and calibrated ICI radiance on the right. During the two-year deployment the ICI was within ±1 $W/(m^2sr)$ of the AERI.



The Barrow ARM site also has multiple cloud measurement sensors that operated during the deployment of the ICI. This allowed for an intercomparing of the ICI and these instrument during the two-year deployment. The co-located instrumented included the cloud Ceilometer, Micropulse Lidar (MPL), Total Sky Imager (TSI), Sky Radiometer (SkyRad), and Multifilter Shadowband Radiometer (MFRSR). In the following comparison the ARM instrument and the ICI are compared to the Ceilometer. (excluding the MPL which only observed high altitude clouds). The daily cloud amounts of the ARM instrument had a correlation of 0.92, 0 mean error and a standard deviation of 0.13 with the ceilometer, during this period the ICI showed similar performance with a correlation of 0.95, 0 mean error and a standard deviation of 0.12.





These comparisons were conducted using a cloud/no cloud decision for the ICI set at optical depth of one, meaning thinner clouds were called clear sky. Decreasing this cloud/no decision allows the ICI to report thinner high clouds, similar to those reported by the MPL. Increasing the ICI sensitivity and comparing with a combination of the Ceilometer and the MPL demonstrated that the ICI observed clouds not reported by the other systems. Using an optical depth of 0.5 as the cloud/no cloud decision the ICI and the combined MPL+Ceilometer showed a correlation of 0.93, 0 mean, and 0.12 standard deviation of daily cloud amounts.