12A.5

ASOS PRODUCT IMPROVEMENT CEILOMETER REPLACEMENT TESTING

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1. INTRODUCTION

The National Weather Service (NWS), Federal Aviation Administration (FAA), and Department of Defense (DoD) jointly participate in a Product Improvement (PI) Program to improve the capabilities of the Automated Surface Observing Systems (ASOS). ASOS has been in existence for almost 20 years and is currently the primary observing system at over 1000 airports nationwide (NOAA 1998).

The current standard cloud height indicator (CHI) for the Automated Surface Observing System (ASOS) is the National Weather Service (NWS) CT12K laser ceilometer. This ceilometer detects clouds to a height of 4000 meters. In late 1998, the manufacturer discontinued production of the CT12K. The vendor agreed to maintain the existing ASOS ceilometers through 2007, with the NWS having enough stock of spare parts on hand to maintain the system through 2008. New ceilometers will need to be deployed to the ASOS network accordingly. On January 05, 2007, upon conclusion of a Commercial-Off-The-Shelf sensor evaluation, the NWS awarded a contract for development of a CT12K replacement ceilometer to Vaisala Inc. of Woburn, Massachusetts. The replacement ceilometers were required to measure clouds to 8000 meters.

2. PURPOSE

The purpose of this test was to determine if the Pre-Production Vaisala CL31ASOS (CL31) laser ceilometer meets the requirements of specification number NWS-S100-CHI-SP1000 (the NWS specification) as determined by comparisons to human observations, and the Sigma Space MicroPulse Lidar (MPL). Under conditions with uniform, non-ragged cloud bases, statistical analysis of reported cloud heights were performed to ensure definition of lowest cloud bases in terms of rate-of-extinction are comparable between the instrument and the references being utilized.

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3. ASOS CEILOMETERS

The CT-12K will measure clouds to 4000 meters (NOAA, 1990). The ceilometer that will replace it, the CL31 measures clouds to 8000 meters. Both are manufactured by Vaisala Inc., based in Woburn, MA.

3.1Vaisala CT12K Laser Ceilometer

The CT12K laser ceilometer (Figure 1) is the standard ASOS ceilometer and was used as a comparison sensor for this performance evaluation. It was not used as a reference, however, since the similarities in the two sensors would likely lead to similarities in performance even when an objective observer might not be in agreement. The “reference”

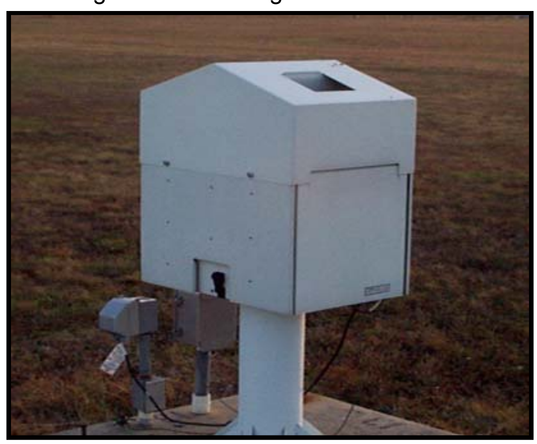

Figure 1. National Weather Service ceilometer model K220 (range 4000 meters)

criteria for this evaluation are explained in section 5.

The CT12K uses a dual lens arrangement to determine cloud base height; one optical path for the transmitter and a separate optical path for the receiver. The operating wavelength of the Gallium Arsenide pulsed laser diode transmitter is 904 nm. The CT12K is equipped with a heater and blower housing to prevent snow and ice accumulation on the windows of the instrument cover. The model CT12K has an advertised maximum reportable cloud base detection range of

4000 meters above the surface. The CT12K was certified for use by the NWS as a result of testing in 1989-1990 (NWS 1990).

3.2Vaisala CL31 Laser Ceilometer

The CL31 Cloud Height Indicator, shown in figure 2, uses single lens technology to detect cloud bases (Ravila 2004). The single lens is shared by both the transmitting and receiving units. The transmitter is an Indium Gallium Arsenide (InGaAs) pulsed laser diode, operating at a wavelength of 910nm (±10nm). The receiving unit is a Silicon Avalanche photodiode with an interference filter centered on 915nm. The sensor is equipped with a heater/blower device to keep the window clear of obstructions. The model CL31 has an advertised maximum reportable cloud base detection range of 8,000 meters above the surface. The test installation included two sensors oriented vertically, and, for a portion of the test period, two tilted 12 degrees from vertical.

Figure 2. National Weather Service ceilometer model CL31 (range 8000 meters)

4. MICROPULSE LIDAR (MPL)

The MPL-4B-527 MicroPulse Lidar (Figure 3) uses a single lens arrangement to detect cloud bases. The single lens is shared by both the transmitting and receiving units. The transmitter is a neodymium yttrium lithium fluoride (Nd:YLF) pulsed laser diode, operating at a wavelength of 527nm. The receiving unit is a 178mm diameter Maksutov Cassegrain telescope with a focal length of 2400mm which collects received energy to a Silicon Avalanche photodiode for photon counting. The sensor is installed in an environmentally controlled enclosure (Figure 4) containing the laser, the laser controller, and the data acquisition systems. A climate control system (HVAC) is mounted externally and connected by a duct to provide heating and cooling to maintain an operationally acceptable temperature range. The HVAC unit and electronically controlled Kapton® strip heaters, mounted to the interior of the window glass, are used to reduce fogging and moisture build-up on the glass. The ASOS PI team added an external blower to assist in clearing the window glass of dust, remnant precipitation, and other environmental debris. The MPL-4B-527 has an advertised maximum range of 60,000 meters.

Figure 3. MicroPulse Lidar inside conditioned housing

The MPL can also be operated in two different polarization modes (Flynn, 2007). Adding an actively-controlled liquid crystal retarder provides the capability to identify depolarizing particles by alternately transmitting linearly and circularly polarized light. This represents a departure from established techniques, which transmit exclusively linear polarization or exclusively circular polarization. Polarization-sensitive detection of elastic backscattered light is useful for detection of cloud phase and depolarizing aerosols. The implementation of this capability provides greater insight into the nature of the cloud or obscuring phenomena and the presence of depolarizing aerosols. The MPL was used as a supporting reference sensor in this evaluation, primarily as an aid to a human observer for determination of cloud height.

Figure 4. MicroPulse Lidar with blower and air conditioner

5. PURPOSE

The purpose of this test was to determine if the Pre-Production Vaisala CL31ASOS (CL31) laser ceilometer meets the requirements of specification number NWS-S100-CHI-SP1000 (the NWS specification) as determined by comparisons to human observations, and the Sigma Space MicroPulse Lidar. Under conditions with uniform, non-ragged cloud bases, statistical analysis of reported cloud heights were performed to ensure definition of lowest cloud bases in terms of rate-of-extinction are comparable between the instrument and the references being utilized.

The metrics described in Section 6 were used to help answer the following questions:

- How often do the CL31 ceilometers report comparable cloud heights to the independent reference reported cloud heights? (Layer Height Comparability)
- How often do the CL31 ceilometers report a comparable percentage of cloud cover to the independent reference reported percent cloud cover? (Percent Cloud Cover Comparability)
- How often do the CL31 ceilometers reports indicate a clear sky condition (CLR) when the independent references report apparent cloud bases? (Missed Layers)
- How often do the CL31 ceilometers reports indicate a non-clear condition when the independent references report CLR? (False Layers)

6. TEST APPROACH

Cloud bases detected by the Vaisala CL31 laser ceilometer's cloud detection algorithm were compared to cloud bases reported by all references (defined in Section 7.2) as a means to validate the CL31 for use as a cloud height detection sensor for ASOS. Cases were collected in all conditions with particular attention to periods with consistent and uniform cloud base reports. Data were separated into 30-minute blocks of time for analysis.

6.1 Ceilometer Performance Requirements

The CL31 was tested to determine comparability using a human observer as the primary reference. The observer was aided by automated cloud detection from the MPL. Comparability was assessed using the criteria defined by the NWS specification. During conditions which persisted for a minimum of one hour, the specification stipulates that the ceilometer shall meet the requirements outlined in Table 1 and Table 2.

Table 1. PERFORMANCE REQUIREMENTS DURING CLOUDY SKIES.

CONDITIONS	CLOUD HEIGHT ACCURACY	PERCENT CLOUD COVER ACCURACY
No surface obscuration and no precipitation and visibility > 5 km.	The greater of ± 60 meters or 10% of the reference reported height.	Within 10% of the ratio of "Cloud Hits" from the reference
With surface obscuration and/or light precipitation and visibility ≥1.6 km and ≤ 5 km		Within 20% of the ratio of "Cloud Hits" from the reference
With surface obscuration and/or moderate precipitation and visibility < 1.6 km		Within 30% of the ratio of "Cloud Hits" from the reference

Table 2. PERFORMANCE REQUIREMENTS DURING CLEAR SKIES.

CONDITIONS	REQUIREMENTS
Clear skies with visibility ≥ 11 km.	No more than 3 sensor samples shall be reported as cloud height bases during any 30-minute period.
Clear skies (including partial obscurations) with 0.8 < visibility < 11 km	No more than 5 sensor samples shall be reported as cloud height bases during any 30-minute period.

Table 3 shows the height ranges selected for this test, and the acceptable level of compliance with respect to the NWS specification.

Table 3. HEIGHT RANGES, AND ACCEPTABLE COMPLIANCE CRITERIA.

HEIGHT RANGE	DESIRED SAMPLES	ACCEPTABLE COMPLIANCE CRITERIA
Surface to 150m	Discrete 30-min periods representing all categories are desired, with at least part of the periods coming from heights above 5500 meters.	≥ 90% compliance to requirements in Tables 1 and 2.
150m to 500m.		
500m to 1500m		
1500m to 4000m		
4000m to 8000m		

As defined in the NWS specification, the ceilometer cloud cover percentage was assessed based on the mean lowest reported layer over a 30-minute period. A comparison between METAR code based on the FMH-1, and the percentages of cloud cover from the NWS specification is shown in Table 4.

Table 4. SKY COVERAGE AMOUNTS AND PERCENTAGES.

METAR CLOUD AMOUNT	NWS-S100-CHI-SP1000 PERCENTAGE SKY COVER
CLR	≤ 3 hits or ≤ 5 hits in 30 minutes depending on criteria in Table 2
FEW	N/A
SCT	≥ 32% - < 56%
BKN	≥ 56% - < 89%
OVC	≥ 89% - 100%
VV	≥ 89% - 100% Surfaced Based

N/A Not Applicable or no specific testing requirement in specification NWS-S100-CHI-SP1000

6.2 Test Methodology

All analysis was performed using the verified reference data available for each time period and individual event. Data analysis was performed utilizing standard statistical procedures with available software packages, and post processing software to conduct calculations of the metrics described in section 6.1. Events were grouped based on the criteria described in Table 1, Table 2, and Table 3.

6.3 Field Based Operational Assessment

The ceilometers were closely monitored during the field evaluation period to document all cases of diagnostic warnings or failures. Documentation of these instances includes any available notes made by the on-duty NWS/SAIC observers, as well as photographic archiving of any visually noticeable phenomena.

7. DATA COLLECTION

7.1 Data Collection and Processing

Ceilometers

Cloud base heights were collected every 30 seconds from each of the CL31 ceilometers and the CT12K ceilometers utilizing a custom data acquisition software program developed by SAIC personnel.

MicroPulse Lidar

Cloud base heights were collected approximately every 30 seconds from the MPL-4B-527 Lidar utilizing a software package provided by Sigma Space. The MPL was initially utilized as an observer's aid for cloud heights above 600 meters and up to the maximum range of the CL31. It was determined that the internal cloud detection algorithm in the MPL was insufficient as an automated reference (Poyer 2008) in previous testing; however, concurrent evaluations showed that an alternative evaluation utilizing a modification of the Klett analysis technique was able to detect the height of higher cloud bases well enough for use as a reference to discern heights for cloud layers whose presence was observer verified (Poyer and Lewis 2009).

Human

Human observations were performed at the Sterling, Virginia, test facility in accordance with observing practices described in the Federal Meteorological Handbook (NWS, 1996) for aviation observations. The observers conducted observations prior to entering the observation building or if already at the observation building prior to looking at any of the automated sensors to maintain an independent reference report and to not bias the observations. The observations were collected in all weather (precipitation, no precipitation, etc.) when clouds were present during standard working hours or when observers were on site for other weather events. Observations were taken at a minimum of approximately once per hour for heights greater than 600 meters. During periods with ceilings at or below 600 meters observations were performed at a rate of approximately three times per hour, in roughly 20-minute intervals during slowly changing sky conditions and at roughly 10-minute intervals during rapidly changing skies. Present weather observations were recorded along with the sky condition for reference use.

7.2 References

Observations of cloud layer amount and heights from the surface to 600 meters were made by SAIC and NWS observers. For daylight observations human-reported ceilings were measured at the top of every hour during normal Sterling Field Support Center (SFSC) business hours. During conditions with ceilings at or below 600 meters human-reported cloud base reports were measured at a resolution of three observations per hour with the aid of pilot balloons, in accordance with Federal Aviation Administration order 7900.5B (FAA 2001). The height of cloud layers were determined by using the midpoint between the time (converted to height) when a balloon first began to enter a cloud layer and the time (converted to height) when the balloon completely disappeared into the cloud layer. This method was used as the reference for ceilings between the surface and 600 meters. Observations of vertical visibility (VV) conditions were conducted in the same manner with the time (converted to height) of a balloon completely disappearing into the surface based obscuration designating the height of the VV layer which was then recorded as the height of the ceiling at that time. Observations were recorded at a minimum resolution of one observation every 20 minutes, with the data being compared to ceilometer reports each minute between 10 minutes before and 10 minutes after each human observation. For example, if an observation was taken at 1710LST, the observation was compared to the ceilometer reports from each minute between 1700LST and 1720LST. During rapidly changing skies, observation resolution was increased to one observation every 10 minutes, with data being compared to the ceilometer reports each minute between 5 minutes before and 5 minutes after each human observation. For example, if an observation was taken at 1810LST, the observation was compared to the ceilometer reports from each minute between 1805LST and 1815LST.

Observations of cloud base heights greater than 600 meters up to and including 8000 meters were made by human observers utilizing the capabilities of the MPL's alternating-polarization images of the cloud cover. Comparisons were made utilizing the human reported height and cloud amount for the 30-minute period with assistance in quantifying the heights/amount of cloud cover from the MPL's cloud reports (Poyer 2008 and 2009) in the same 30-minute period. This was performed for periods with stable sky conditions which persisted for a minimum of one hour. These criteria are based on the requirements from the NWS specification.

8. METRICS AND ANALYSIS

8.1 Metrics

All metrics were analyzed utilizing data separated into 30-minute blocks of time. Each block of time was then categorized based on the height range bin as reported by the reference and the weather conditions during that time period. A definition of these criteria can be found in section 6. The metrics used for the analysis follow:

8.1.1 Layer Height Comparability

Metric [1] determines how often the test ceilometers indicate a mean layer height within a 30-minute period that compares to the reference reported mean layer height for that period. This metric uses the allowable height ranges defined in the NWS specification. For example, a reference height of 5500 meters requires the test ceilometer reported height to be within ±20 meters or ±10% whichever is greater, which allows reported heights of ±550 meters to be considered a comparable data point.

$$layer\ ht.comp = \frac{\begin{array}{c}\#30\ min.periods\\ test\ sensor\ ht.in\ spec\end{array}}{\begin{array}{c}\#30\ min.periods\ reference\\ data\ available\end{array}}$$

8.1.2 Percent Cloud Cover Comparability

Metric [2] can also be considered the Cloud Amount Comparability. This metric determines the comparability between the percent cloud cover (%CC) calculated from the number of cloud samples within a 30-minute period from the test sensor and the amount of sky cover calculated for the reference during the same time period. For example, a reference report of

56% CC, which would be a BKN sky in METAR code, with no ground based obscuration or precipitation will yield a reportable range of 56% ±10%, which allows a %CC within the range from 46% to 66% to be considered a comparable data point. The criteria for the comparability range of %CC is dependent on the present weather conditions. The allowed margin of error can be found in Table 1. The cloud cover percentages and their equivalent METAR code are compared in Table 4.

$$\%\, cover\ comp = \frac{\begin{array}{c}\#30\ min.periods\\ test\ sensor\ CC\ in\ spec\end{array}}{\begin{array}{c}\#30\ min.\ periods\ reference\\ data\ available\end{array}}$$

8.1.3 Missed Layers

Metric [3] can be considered as a condition specific enhancement of Metric [2]. This metric will yield greater insight into the differences that make up Metric [2]'s result by determining whether a cloud layer is completely undetected as opposed to the cloud cover percentage merely being reported outside of the specification range. This metric will be used to determine how often the test ceilometer reports CLR when the reference reports a non-clear sky condition.

$$Missed\ layer = \frac{\begin{array}{c}\#30\ min.periods\\ test\ sensor\ CLR\ and\\ Ref\ not\ CLR\end{array}}{\#\ 30\ min.periods\ ref\ not\ CLR}$$

8.1.4 False Layers

Metric [4] determines how often the test ceilometer indicates a non-clear sky when the reference reports CLR. The specification stipulates that a CLR report must contain no more than 3 cloud hits in a 30-minute period during periods with no ground based obscuration and visibility greater than 11 kilometers, or no more than 5 cloud hits in a 30-minute period when ground based obscuration is present and visibility is from 0.8 to 11 kilometers.

$$Missed\ layer = \frac{\begin{array}{c}\#30\ min.periods\\ test\ sensor\ not\ CLR\ and\\ Ref\ CLR\end{array}}{\#\ 30\ min.periods\ ref\ CLR}$$

8.2 Analysis

All analysis was performed using the verified reference data available for each individual event. Data analysis was performed utilizing Microsoft Excel and a custom post processor software package to calculate the metrics described in section 8.1. Events were grouped based on the criteria described in section 6.1. These groups include events from all precipitation types, and events with no precipitation and/or decreased surface visibility, as well as clear atmosphere situations.

All cloud base heights below 600 meters utilized human observations, aided by pilot balloons, as the reference for data comparison. Cloud base heights from 600 to 8000 meters utilized the human reported cloud base layers, with assistance from the MPL, as the reference.

Event logs were kept to note any situations of interest, snow capping, bird perching, etc… and any visible phenomena were photographed when possible. Entries were also made in the logs for events of specific interest and case studies were created. The first hand knowledge of the observer that is noted in these logs was kept for the post event case study analysis of sensor performance.

9. RESULTS

Ceilometers at the Sterling test site were compared to the references and analyzed using the metrics in sections 8.1. The data are separated into five height categories for each of the four sensors. The height categories used are shown in Table 3.

During this period of performance testing the firmware was modified twice to address concerns with detection of false clouds and underreporting of higher clouds.

From December 27, 2007 through March 5, 2008 at Sterling, Virginia, the initial firmware showed compliance results as follows.

- Surface to 150 meters: All sensors passed compliance except one (20 of 25 events compliant, 23 needed for 90% comparability), missed compliance by 3 events. This was one of the tilted units.

- 150 meters to 500 meters: All sensors were compliant.

- 500 meters to 1500 meters: Only one sensor was compliant (21 of 22 events compliant), while three sensors failed to meet compliance by one event (23 of 26 were compliant, 24 needed for 90% comparability).

- 1500 meters to 4000 meters: All sensors passed height compliance with the exception of one which missed compliance by 1 event, (25 of 28 events, 26 needed for 90% comparability). All sensors were non-compliant for percentage of cloud cover.

- 4000 meters to 8000 meters: An insufficient number of events were available to determine compliance (2 events).

- Clear Skies: All sensors were compliant.

From March 6, 2008 through July 15, 2008 updated firmware to address false cloud detections had the following compliance results:

- Surface to 150 meters: All sensors were compliant for all metrics.
- 150 meters to 500 meters: All sensors were compliant for all metrics.
- 500 meters to 1500 meters: All sensors were compliant for all metrics except one (missed compliance on metric 2, percentage of cloud cover, by 1 event).
- 1500 meters to 4000 meters: All sensors were compliant.
- 4000 meters to 8000 meters: An insufficient number of events were available to determine compliance (5 events); however only one sensor was height comparable on all 5 events while the three other sensors were height comparable on 4 of the 5 events. All 4 sensors were non-compliant (compliant on 3 of 5 events) for percentage of cloud cover. All sensors were compliant for missed layers during non-clear conditions except one (compliant 3 of 5 events)
- Clear Skies: All sensors were compliant.

After July 15, the final firmware version test results were as follows:

- Surface to 150 meters: No periods were available during replay data
- 150 meters to 500 meters: All sensors were compliant.
- 500 meters to 1500 meters: All sensors were compliant.
- 1500 meters to 4000 meters: All sensors were compliant.
- 4000 meters to 8000 meters: All sensors were height compliant; two of the 4 were non-compliant for percentage of cloud cover and missed layers during non-clear conditions (compliant for 5 of 7 events). Note: this was a small sample set due to the logistics and time required to replay the raw data.
- Clear Skies: All sensors were compliant.

The above results include data from an interim test version that was used to post process data previously collected and replayed to generate results from the upgraded firmware.

10. CONCLUSIONS

During the compliance testing there were two firmware upgrades that corrected performance deficiencies that were identified.

The firmware upgrades led to the CL31 being judged as completely or nearly compliant in all the categories and conditions. Follow-on testing will continue to be performed during the subsequent rounds of development, the limited production and production phases, to verify that the comparability of the CL31 is meeting the compliance specification requirements.

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