ARL-TR-7362 ● JULY 2015

US Army Research Laboratory

Meteorological Sensor Array (MSA)–Phase I, Volume 3 (Pre-Field Campaign Sensor Calibration)

by Gail Vaucher and Robert Edmonds

NOTICES

Disclaimers

ARL-TR-7362 ● JULY 2015

US Army Research Laboratory

Meteorological Sensor Array (MSA)–Phase I, Volume 3 (Pre-Field Campaign Sensor Calibration)

by Gail Vaucher and Robert Edmonds
Computational and Information Sciences Directorate, ARL

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED (From - To)**
July 2015	Final	1 Oct 2013–1 Feb 2015

4. TITLE AND SUBTITLE

Meteorological Sensor Array (MSA)–Phase I, Volume 3 (Pre-Field Campaign Sensor Calibration)

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Gail Vaucher and Robert Edmonds

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

US Army Research Laboratory
Computational and Information Sciences Directorate
Battlefield Environment Division (ATTN: RDRL-CIE-D)
White Sands Missile Range, NM 88002-5501

8. PERFORMING ORGANIZATION REPORT NUMBER

ARL-TR-7362

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Army decisions are strengthened by accurate input. The US Army Research Laboratory (ARL) is developing a Meteorological Sensor Array (MSA) to provide reliable and persistent atmospheric data resources, which allow modelers and sensor developers to validate model and sensor performance with atmospheric observations. Such models and sensor data become a foundation for future, environmentally dependent Army decision aids. As an MSA feasibility study, ARL conducted an MSA-Phase I ("Proof of Concept") field campaign in 2014, which consisted of 5 meteorological towers, more than 25 sensors, and a 5.5-week dataset of 24 h/day–7 days/week (24/7) atmospheric measurements. Before this field campaign could be executed, 2 side-by-side relative calibration exercises were conducted. The first exercise examined the MSA-Phase I dynamic sensors (ultrasonic anemometers); the second assessed the MSA-Phase I thermodynamic sensors (barometers, thermometers, hygrometers, and pyranometers). This report documents the results of a detailed calibration assessment. In short, the results showed that most sensors were within the manufacturer's specifications, confirming the qualitative assessments executed just prior to the MSA-Phase I field campaign execution.

15. SUBJECT TERMS

meteorological sensor array, MSA, sensor calibration, ultrasonic, sonic, barometer, thermometer, hydrometer, pyranometer

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Gail Vaucher
Unclassified	Unclassified	Unclassified	UU	44	**19b. TELEPHONE NUMBER (Include area code)** (575) 678-3237

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Contents

List of Figures v

List of Tables vi

Acknowledgments vii

Executive Summary ix

1. Background 1

1.1 The Meteorological Sensor Array (MSA) Program 1

1.2 MSA-Phase I, Field Campaign Overview 2

1.2.1 Dynamic Sensors 4

1.2.2 Thermodynamic Sensors 6

2. Pre-Field Campaign Sensor Calibration 7

3. Dynamic Sensor Relative Calibration 8

3.1 Dynamic Relative Calibration Design 8

3.2 Dynamic Sensors Calibration Data Analysis 12

3.2.1 Root-mean-square error as a function of distance 12

3.2.2 Calibration Fits 14

4. Thermodynamic Sensor Relative Calibration 15

4.1 Thermodynamic Relative Calibration Configuration 15

4.2 Thermodynamic Sensors Data Analysis 18

4.2.1 Pressure Calibration Data Analysis 18

4.2.2 Thermometer Calibration Data Analysis 19

4.2.3 Relative Humidity Calibration Data Analysis 21

4.2.4 Solar Radiation Calibration Data Analysis 21

5. Discussion 22

6. Summary and Recommendations 23

7. Notes **26**

8. References **27**

List of Symbols, Abbreviations, and Acronyms **28**

Distribution List **29**

List of Figures

Fig. 1 MSA-Phase I tower layout and data acquisition flow: "node" boxes represent tower locations; North Node includes the general tower configuration 3

Fig. 2 MSA-Phase I tower configuration 4

Fig. 3 RM Young 81000 ultrasonic anemometers quantified the dynamic atmospheric attributes 5

Fig. 4 Dynamic sensor side-by-side intercomparisons....9

Fig. 5 Overview of the dynamic side-by-side sensor configuration 9

Fig. 6 Group 1—Dynamic sensor relative-calibration configuration 10

Fig. 7 Group 2—Dynamic sensor relative-calibration configuration 11

Fig. 8 Group 3—Dynamic sensor relative-calibration configuration 11

Fig. 9 RMSE as a function of group and distance from the standard sonic: Linear trend ("best fit") lines for each group are shown as black lines; slope and intercept of each trend line are presented in the table (top left) within the plot....13

Fig. 10 Sonic #637 versus Standard Sonic #1341 u-components: Each measurement comparison is a black dot; best-fit linear is a thin black line....14

Fig. 11 Thermodynamic sensors side-by-side intercomparisons 16

Fig. 12 Thermodynamic sensor side-by-side inter-comparisons layout 17

Fig. 13 Barometric differences compared against Logger 4649 during the 2014 Julian Day (JD) 60 local nighttime hours; logger associated with each sensor is indicated in the legend 19

Fig. 14 Temperature sensor differences: standard was the T107 of Logger 4647; Rotronic sensors are indicated with red lines, T107 sensors are blue lines, and the PRT is indicated by a gray line....20

Fig. 15 RH percentage difference from Logger 4649 RH measurements during the local nighttime of 2014 JD 60 (02 Mar); the logger associated with each non-standard RH sensor is demonstrated in the legend....21

Fig. 16 Pyranometers percent difference from Logger 4649 pyranometer-standard, during the local daytime hours of 2014 JD 61; logger associated with each sensor is indicated in the legend 22

List of Tables

Table 1 MSA-Phase I “Proof of Concept” sensors 3

Table 2 Thermodynamic sensor specifications 6

Table 3 Phase I sonic calibration position assignments. Position #1 was the southern-most position—Position #8 was northern-most. Each number listed represents a specific sonic. 10

Table 4 RMSE relative to standard (Sensor No. 4) anemometer u-measurements. U-measurements were filtered to include only horizontal winds from within 45° of due west. 13

Table 5 Percentage “Diff” of slope from perfect alignment with the sensor standard (i.e., 1); same-color bold values are same sensor 15

Table 6 Line offset (b) in m/s; same-color bold values represent the same sensor 15

Table 7 MSA-Phase I thermodynamic sensors calibration configuration (28 Feb 2014): Tripod No. 1 was on the west edge (left); Tripod No. 5 was located on the east edge (right). 17

Acknowledgments

The authors wish to thank Robert Brice and Michael “Sean” D’Arcy for their contributions in setting up and executing the 2 relative calibration tasks. Thanks also to Manny Bustillos and Dr Teresa Foley for their graphics contributions, and Ed Creegan for his assistance with the spatial measurements. Special thanks also go to the Technical Publishing Branch at White Sands Missile Range, New Mexico, for their consistently high standard of editing, specifically to Jim LeNoir and Martin Kufus.

INTENTIONALLY LEFT BLANK.

Executive Summary

Environmentally dependent Army decisions rely on accurate representation, which often include the atmosphere. The US Army Research Laboratory (ARL) is building an "Army-scale", high-resolution Meteorological Sensor Array (MSA) to provide reliable and persistent meteorological data resources that, in turn, will allow atmospheric modelers and sensor developers to validate and compare model and sensor performance with atmospheric observations at and near the surface and in close proximity to terrain of varying complexity.

In 2014, an MSA "Proof of Concept" (MSA-Phase I) was executed to test the feasibility for such a significant ARL investment. A representative Phase I field campaign was designed. A detailed description of the MSA-Phase I and its preliminary results is documented in ARL publications cited within this report.

Before the field campaign could be confidently executed, all sensors needed to be calibrated. Time and fiscal limitations prohibited the option of submitting all instruments to a certified National Institute of Standards and Technology (NIST) calibration laboratory. Consequently, a side-by-side sensor intercomparison (relative calibration) was designed and conducted. The relative calibration task was subdivided into 2 parts: dynamic and thermodynamic sensor-calibration segments. The dynamic sensors were calibrated first, to optimize the steady, high-wind events of the February–March "windy season" in New Mexico. Aligning the sensors perpendicular to the prevailing wind on top of a "flat" roof, the strong, steady airflow equated that of a calibration wind tunnel. The thermodynamic sensor calibration followed, sampling data from a more protected location. The calibration acquisition period ran from 10 Feb through 06 Mar 2014.

A preliminary, qualitative calibration review showed that the majority of sensors were worthy of the MSA-Phase I field campaign. Those instruments that did not meet the standard were either retested and/or replaced. With a persistent deadline, to complete the MSA-Phase I measurement portion by mid-fiscal year, the sensors passing the calibration assessment were integrated into the field campaign design, which promptly followed the calibration task. A detailed calibration analysis was postponed due to the uncompromising schedule and lack of available personnel. Fortunately, after the successful "Proof of Concept" was completed and MSA-Phase II was underway, a more detailed relative-calibration data analysis has now been executed, with results documented in this report.

The calibration "standard" sensors selected for the analyses were either new or instruments calibrated within the last year. The dynamic calibration configuration and data analyses are described in Section 3. The 20 ultrasonic anemometers

(“Sonics”) calibrated were subdivided into 3 groups of 8 side-by-side Sonics sampling sessions. The “standard” sensor (Sonic #1341) was used in all 3 calibration sessions. Table 3 shows the sonic placements and data-acquisition dates for each group.

Section 4 describes the 24 thermodynamic sensor relative calibration layout, methodology, and analysis. To help identify these sensors, each instrument was correlated with its data logger, which stored the sampled data. Table 7 summarizes the thermodynamic sensor configuration details.

The detailed analyses confirmed the qualitative assessments made prior to the MSA-Phase I field campaign execution. That is, most sensors were found to be within the manufacturer’s specifications. Summarizing the calibration results by sensor type:

1) Sonic Anemometers: Based on the intercomparison root-mean-square error (RMSE) and curve-fitting analyses, there were no significant calibration issues identified. The instrument calibration for each anemometer was good to approximately 0.1 m/s, which was close to the manufacturer-stated accuracy of ±0.05 m/s. Since the results fell within the manufacturer-stated accuracy of ±1% root mean square (rms), no correction curve was suggested.

2) Barometer: Barometer 4607 reported erratic data during the initial calibration assessment and was consequently removed from consideration prior to the field campaign. Based on the more detailed post-campaign review, the remaining barometers were within manufacturer’s specifications. Barometer 4649, however, showed a potential need for an offset correction of about –0.5 mb when used with the other fielded barometers.

3) Temperature sensors: The thermometers were found to be within the general manufacturer specifications.

a) The Rotronic sensors reported values about 0.1 °C higher than the T107 sensors. Note: During the MSA-Phase I field campaign, the Rotronic sensors were mounted at 2 m above ground level (AGL) and the T107s at 10 m AGL. The analyzed results imply that uncorrected MSA-Phase I data may report overly unstable, near-surface, vertical temperature profiles. Since an absolute calibration was not available, the direction of the 0.1 °C correction is debatable. For studies concerned with relative temperature differences only, it is suggested to either correct the T107 measurements by an offset of +0.1 °C or, the Rotronic data by –0.1 °C.

b) The Platinum Resistance Thermometer (PRT) sensor reported values about 0.4 °C colder than the standard. This sensor was ultimately replaced with a new T107, during the MSA-Phase I field campaign. (Note: The process of purchasing a new sensor began during the pre-campaign calibration. The PRT was used as a "placeholder" until the new instrument arrived and could be installed on Tower No. 3, at the 10-m AGL location. The new T107 started data acquisition on 15 Apr 2014 at 0942 Mountain daylight time (MDT).

4) Hygrometers: Relative Humidity (RH) measurements for Loggers 4653, 4607, 4647, and 3405 reported values within 1% of each other. Logger 4649 measurements were on average approximately 1% lower than the other 4 recorded logger values. The sensor variations (excluding Logger 4649 RH sensor) between the 4 RH sensors were within the manufacturer-stated calibration of ±0.8%.

5) Pyranometers: Solar Radiation measurements from Loggers 4607, 4647, and 3405 reported measurements within 1% of each other. Loggers 4649 and 4653 reported 3–9% departures from the 3 sensors. A percentage departure drift was observed over the course of a day. Logger 4649 solar radiation measurements were noted as being potentially too high during the MSA-Phase I field campaign.

This calibration exercise has demonstrated the strengths and weakness of a relative calibration. For the dynamic sensors, where the "standard" instrument was closely aligned to a NIST-standard quality (such as, Sonic #1341), confidence in the measured data was re-enforced. For the thermodynamic sensors, even though the instruments were technically new or calibrated within the last year, the comparison against the standards exposed data limitations. Fortunately, with this analysis, the results will help scientists to use the data in an informed manner. Recommendations gleaned from this project include the following:

1) A sensor with NIST paperwork does not guarantee that the sensor has not been dropped or accidentally hit in a manner that negates the calibration; and

2) When a field project's sensor calibration is postponed or deleted, this sacrifice can reduce the quality and usefulness of the final measurements.

In an ideal world, all meteorological sensors would be calibrated against NIST standards prior to their field installation, rechecked in a side-by-side assessment just before fielding, and then put on a routine recalibration schedule; thus, ensuring the best quality measurements for the data users.

INTENTIONALLY LEFT BLANK.

1. Background

Successful Army decisions can be reached only when the information on which the decisions are made accurately represents the given scenario. Environmental decisions involving the atmosphere rely heavily on detailed meteorological models. “Army-scale” atmospheric models include high-resolution (≤1-km) models. Locating meteorological observations to validate these high-resolution atmospheric models is very difficult. The National Research Council (NRC) recognized this technological gap in 2009 after reviewing the US Weather Research and Researcher-to-Operations progress and priorities (National Research Council 2010). Their assessment prompted numerous NRC conclusions and recommendations.

The US Army Research Laboratory (ARL) has answered the national and military concern by proposing an observational data resource specifically designed to address the “Army-scale”, high-resolution atmospheric model validation and verification issues. This solution is called the “Meteorological Sensor Array (MSA)”. The MSA is intended to provide reliable and persistent data resources that, in turn, allow atmospheric modelers and sensor developers to validate and compare model and sensor performance with atmospheric observations at and near the surface and in close proximity to terrain of varying complexity.

1.1 The Meteorological Sensor Array (MSA) Program

Before the MSA endeavor could be approved as a multi-phased program, a “Proof of Concept” was organized and executed to test the feasibility of success for such a significant ARL investment. The “Proof of Concept” became known as the “MSA-Phase I”. Phase I began with a survey of all potential ARL data users, inquiring what they envisioned gleaning from the MSA data and capability. These multiple, diverse concepts were assimilated and reduced into a handful of practical objectives that could be demonstrated within the 8 months allotted for the Phase I task. A representative field campaign was quickly designed, along with an expandable data-management strategy that would accommodate the initial field requirements and provide a foundation for follow-on MSA phases. A detailed description of the MSA-Phase I and its preliminary results is found in MSA, Volumes 1 (Vaucher et al. 2014) and 2 (Harrison and Vaucher 2014).

Based on the timely Phase I success, the MSA Project advanced into a full MSA Program within the same fiscal year. Phase II was initially designed to be a simple expansion of the Phase I meteorological tower array which incorporated the Phase I lessons learned. However, with added user input from outside ARL, Phase II managers elected to diversify the tower configurations and locations, thus facilitating a larger number of scientific and technical applications for the future phases.

1.2 MSA-Phase I, Field Campaign Overview

The MSA-Phase I field campaign was originally designed as a 5.5-week (17 Mar–25 Apr 2014), 24 h/day–7 days/week (24/7), meteorological data-acquisition event. The intended campaign function was to provide a tangible platform from which high resolution data for multiple scientific and technical objectives could be completed. Specifically, the Phase I objectives included

1) Setting up and testing a model/observation verification process.

2) Acquiring data for wind assessment of the White Sands Missile Range (WSMR) solar photovoltaic (PV) Farm.

3) Acquiring data to assess turbulence impact of the WSMR solar array.

4) Designing, developing, testing, and evaluating integrated Data Acquisition System (DAS) hardware and software.

The field campaign was located at WSMR, New Mexico. A series of relative calibration tests preceded the campaign execution. Preliminary calibration results were included in MSA-Phase I, Volume 1 (Vaucher et al. 2014). A more detailed data analysis of the Phase I relative calibration task is given in this report. The successfully calibrated sensors were used and/or designated as "backup sensors" for the field portion of Phase I.

The Phase I field campaign design consisted of 5 equally separated, 10-m meteorological towers positioned around a large solar PV farm. Three towers were situated west of the solar PV farm, aligned along a north–south axis, with a 100-m separation between towers. Two towers stood east of the solar PV farm, oriented along an east–west axis and separated by 100 m (see Fig. 1).

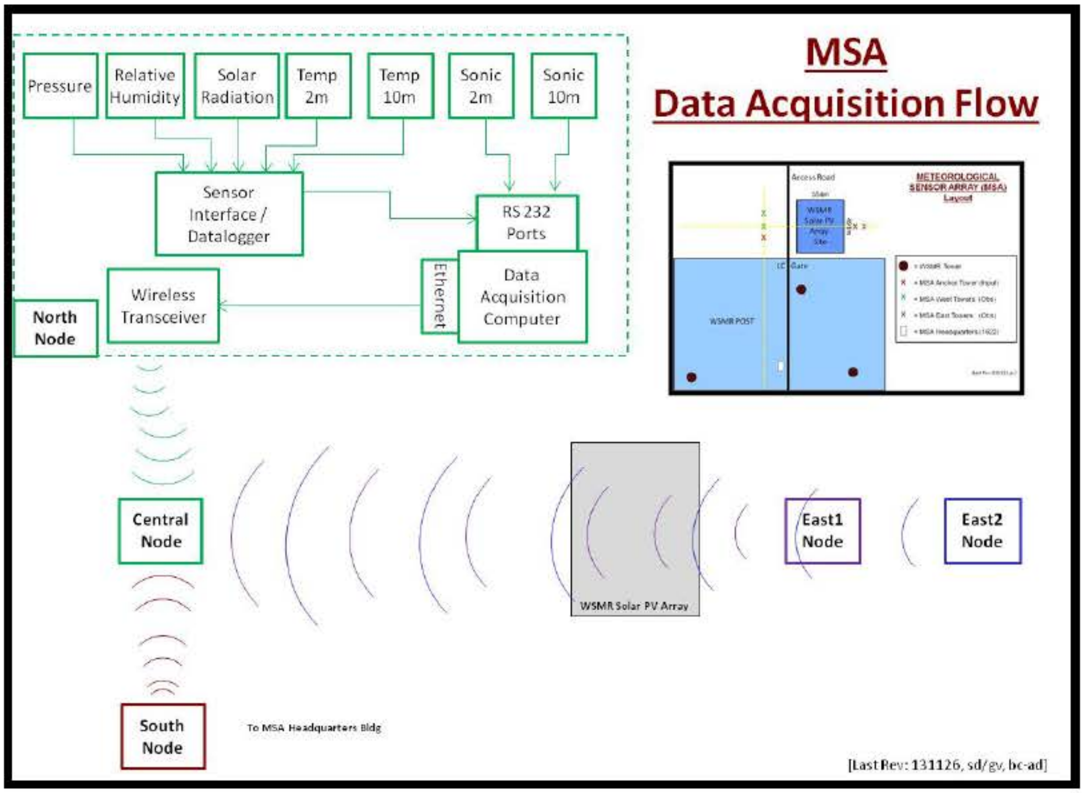

Fig. 1 MSA-Phase I tower layout and data acquisition flow: "node" boxes represent tower locations; North Node includes the general tower configuration

The meteorological tower configuration included 2 data-acquisition systems, based on the 2 data acquisition rates. Dynamic sensors sampled and archived 20-Hz data, after which these data were reduced to 1-min averages for sensor quality-control assessment purposes. Thermodynamic sensors acquired and archived 1-min average samples. Table 1 describes the variables and sensors used for the "Proof of Concept" field campaign.

Table 1 MSA-Phase I "Proof of Concept" sensors

Variable	Sensor	Manufacturer	Model	Units
Pressure	Barometer	Vaisala	PTB-101B/PTB110	Millibars
Temperature	Thermometer	Campbell	T107	Celsius
Temperature/ Relative Humidity	Thermometer/ Hygrometer	Rotronic	HC2S3	Celsius/ Percent
Solar Radiation	Pyranometer	Kipp/Zonen	CM3/CMP3	W/m^2
Micro-logger	ALL	Campbell Scientific	CR23X	. . .
Wind Speed and Wind Direction	Ultrasonic Anemometer	RM Young	81000	m/s and degrees

The dynamic sensors (wind) were mounted at 10 m and 2 m above ground level (AGL). The thermodynamic sensors (pressure, temperature, relative humidity, and solar radiation) were distributed as follows:

- Pressure: about 1 m AGL
- Temperature: 2 m and 10 m AGL
- Relative Humidity: 2 m AGL
- Solar Radiation: 2 m AGL

Figure 2 shows a schematic of the composite MSA Phase I sensor layout on the UT30 flat-based (10 m) mounting towers.

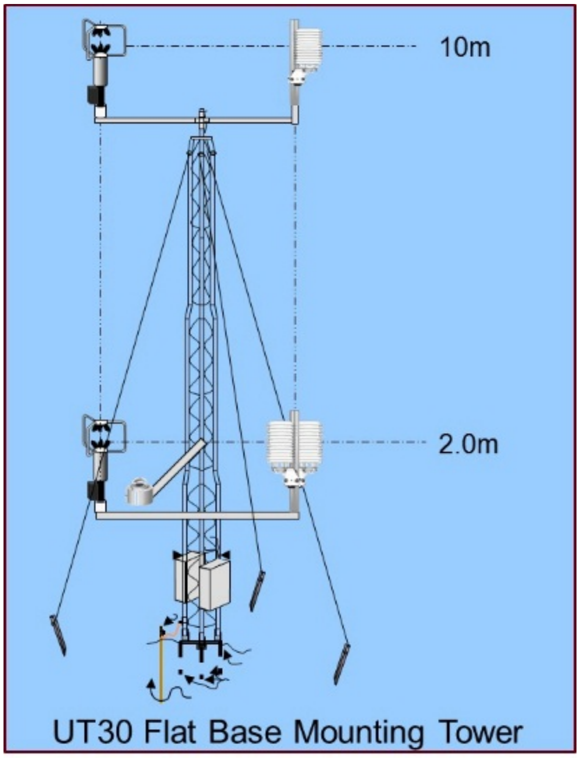

Fig. 2 MSA-Phase I tower configuration

1.2.1 Dynamic Sensors

The dynamic sensors consisted of RM Young Ultrasonic 81000 anemometers (see Fig. 3). This ultrasonic anemometer (sonic) model had no moving parts and sampled wind, sonic temperature, and speed of sound. The wind variable was quantified into u-component, v-component, w-component, wind speed, and wind direction.

Fig. 3 RM Young 81000 ultrasonic anemometers quantified the dynamic atmospheric attributes

The sonic wind velocity magnitudes were based on the time it takes a sound wave, or sonic pulse, to travel through the atmosphere between a fixed pair of transducers. The measurements worked on the principle that sound-wave propagation in a moving medium is equal to the sound-wave velocity, with respect to the medium, plus the medium velocity. Wind velocity vector was determined by a measure of the time required for the sound wave to travel from its origin to 3 points on space. This method presumed that the speed of sound was known for the medium, which can be determined from the medium temperature or from an additional travel-time measurement (Huschke 1970).

With 6 transducers, the sonic anemometer was able to quantify a 3-component wind. The sensor casing to support the transducers was known to impact the sampling, which is why manufacturers include a correction factor in their data-sampling routines. Another known sonic shortcoming was the reduced accuracy during precipitation events. Raindrops can interfere with the speed of sound; thus, distorting the processed sonic wind data results. Since the ultrasonic sampling rate can be 25 Hz (MSA-Phase I used 20 Hz), these sensors are often used to characterize atmospheric turbulence. Sonic anemometers have been used to sample temperature. However, the technology was still being perfected at the time of the MSA-Phase I field campaign, so this capability was not emphasized in the calibration/operational data analyses.

The Ultrasonic 81000 sensor specifications published by RM Young Co. (2004) describe the sensors as having a 0–40 m/s (0–90 mph) range, a sensor resolution of

0.01 m/s, and a threshold of 0.01 m/s. The manufacturer-stated accuracy is ±1% root mean square (rms), ±0.05 m/s (0–30 m/s) and ±3% rms (30–40 m/s).

1.2.2 Thermodynamic Sensors

The thermodynamic measurements utilized sensors linked by 5 Campbell Scientific, Inc., micro-loggers. As mentioned above, the thermodynamic variables sampled included pressure, temperature, relative humidity, and solar radiation. All thermodynamic data were saved in 1-min averaged samples.

The pressure sensor was a Vaisala Barometer, PTB-101B (also known by Campbell Scientific as "CS105"). The sensor was housed in an anodized aluminum case fitted with an intake valve for pressure equilibration. The sensor utilized a silicon capacitive sensor to measure barometric pressure over a 600–1,060 mb range. The general barometer specifications are listed in Table 2, along with all of the other sensor specifications (Campbell Scientific 2001a).

Table 2 Thermodynamic sensor specifications

Sensor	Tower AGL	Model	Range	Accuracy	Comments
Barometer	~1 m	PTB-101B, "CS105"	600–1,060 mb	±0.5mb @ +20 °C ±1.5mb @ 0 to +40 °C ±2.0mb @ -20 to +45 °C ±3.0mb @ -40 to +60 °C	
Thermometer	10 m	T107	–35 °C to +50 °C	±0.4°C (–24 to 48 °C) ±0.9°C (–38 to 53 °C)	
Thermometer	10 m	PRT		~0. 01 °C	"max of 0.02 °F at 98 °F"
Thermometer	2 m	HC2-S3	–50 °C to +100 °C	At 23 °C, ±0.1 °C	
Hygrometer	2 m	HC2-S3	0 to 100%	At 23 °C, ±0.8% RH	Accuracy changes with Temperature (Max ± 1.3%)
Pyranometer	2 m	CM3/ CMP3	0–2,000 W/m^2	±10%	Spectral range (50% pts nm) 305–2,800 nm

The temperature sensors designated for the 10-m AGL position were Campbell T107 probes and a Platinum Resistance Thermometer (PRT). The probes were thermistors encapsulated in an epoxy-filled aluminum housing. Temperature range was from –35 °C to +50 °C; the T107 manufacturer-stated accuracy is ±0.4 °C between –24 °C and 48 °C (Campbell Scientific 2001b) as shown in Table 2. The PRT accuracy was reported to be approximately 0.01 °C.[1]

The Rotronic HC2-S3 measured temperature and relative humidity (RH) at the MSA-Phase I Tower, 2 m AGL. The temperature sensor used a 100-Ohm PRT; the RH was measured with a capacitive sensor. The Rotronic manufacturer stated temperature accuracy is ±0.1 °C at 23 °C; the RH accuracy is 0.8% at 23 °C (Campbell Scientific 2012).

The thermometers and hygrometers were mounted in naturally aspirated radiation shields. Ten and 12 disk radiation shields were used during the calibration data collection. During MSA-Phase I operations, 10 and 12 disk radiation shields were used with the Rotronic sensors and 6 disk radiation shields were used with the T107s. The expected impact of the different radiation shields on the calibration study was minimal.

The solar radiation was quantified by Kipp and Zonen CM3 and CMP3 pyranometers. The primary difference between the 2 models is that the CMP3 includes a snap-on, sun shield around the circular instrument, to reduce sensor temperature. MSA-Phase I used four CM3 sensors and one CMP3. During the calibration exercise, the CMP3 was wired to Logger 4653. These instruments utilize a thermopile sensor that is coated with a black absorbent coating. The radiation is absorbed by the paint and converted into heat. A resultant temperature difference is converted into voltage by a copper constantin thermopile, which has a 180° field of view (fov). The fov provides the angular characteristics needed for the cosine response requirements. The pyranometers are intended to have a flat spectral sensitivity from 305- to 2,800-nm wavelengths (Campbell Scientific 2002b). The worst-case error stated by the manufacturer for both pyranometers is ±10%, with the typical accuracy being ±5% (Campbell Scientific 2002b).

2. Pre-Field Campaign Sensor Calibration

The official start of the MSA-Phase I project was 1 Oct 2013. With less than a year to identify participants, design a multi-phased program, construct and execute a full-scaled “Proof of Concept” project that included a successfully accomplished field campaign justifying this major investment program, and solicit funding resources, timely access to a certified National Institute of Standards and Technology (NIST) calibration laboratory was not an option for the MSA-Phase I. Consequently, a side-by-side sensor intercomparison (a relative calibration) was designed and conducted. The relative calibration task was subdivided into 2 parts: dynamic and thermodynamic sensor-calibration segments. Utilizing the projected high winds of the February–March, New Mexico “windy season”, the dynamic sensors were calibrated first. Steady, high winds were sought to best equate the airflow of a calibration wind tunnel. The thermodynamic sensors followed, using a more protected location. The total acquisition period ran from 10 February to 06 March 2014.

A preliminary, qualitative review of the side-by-side calibration data (reported in Volume 1) showed the majority of sensors as being worthy of the MSA "Proof of Concept" field campaign. Those instruments that did not meet the standard were either re-tested and/or replaced. With a pressing deadline to complete the "Proof of Concept" measurement portion by mid-fiscal year, the sensors that passed the calibration assessment were integrated into the field campaign design, which promptly followed the calibration task. A detailed calibration analysis also had to be postponed due to the uncompromising schedule and lack of available personnel. Fortunately, with the successful "Proof of Concept" completed and MSA-Phase II underway, a more detailed analysis of relative calibration data has now been executed. The results are documented in this report.

3. Dynamic Sensor Relative Calibration

In this section, the dynamic sensor relative-calibration configuration and data analyses are described. Results confirm the qualitative assessment executed prior to field campaign execution. That is, all sensors fell within the manufacturer-stated accuracy.

3.1 Dynamic Relative Calibration Design

The ultrasonic anemometer intercomparisons were conducted on the prevailing-windward side of a "flat" roof on a 2-story building. The anemometers were arranged in a single row, mounted on 4 tripods with 2 sensors per tripod (see Fig. 4). The tripods were approximately 4.4 m from the roof's west-facing edge and aligned in a south–north orientation to optimize the strong, prevailing westerly winds. The sensors were mounted at the ends of the tripod crossbar, with all 8 sensors separated by an even spacing of 1.13 m (see Figs. 4–8).

Fig. 4 Dynamic sensor side-by-side intercomparisons

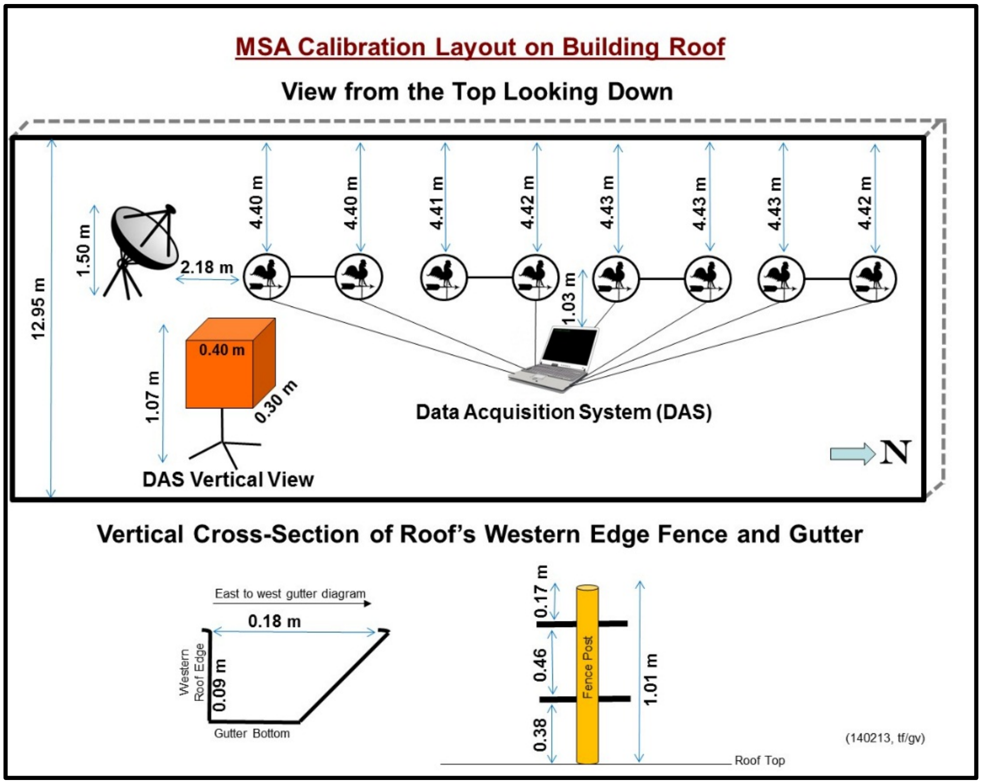

Fig. 5 Overview of the dynamic side-by-side sensor configuration

A total of 20 sonic anemometers were calibrated using 3 intercomparison groups (see Table 3). The same configuration pattern was repeated for all 3 anemometer calibration periods (10–24 Feb 2014), keeping one sensor common to all 3 acquisition periods. Figures 6–8 detail the layouts for all 3 groups.

Table 3 Phase I sonic calibration position assignments. Position #1 was the southern-most position—Position #8 was northern-most. Each number listed represents a specific sonic.

Sonic Calibration Sampling Positions	Group I (2014 Feb 10–13)	Group II (2014 Feb 13–18)	Group III (2014 Feb 18–24)
1 (southern-most position)	#1343	#626	#498
2	#1355	#633	#499
3	#1356	#634	#633
4	#1341	#1341	#1341
5	#1357	#637	#646
6	#1359	#638	#650
7	#1361	#646	#712
8 (northern-most position)	#1370	#1354	#726

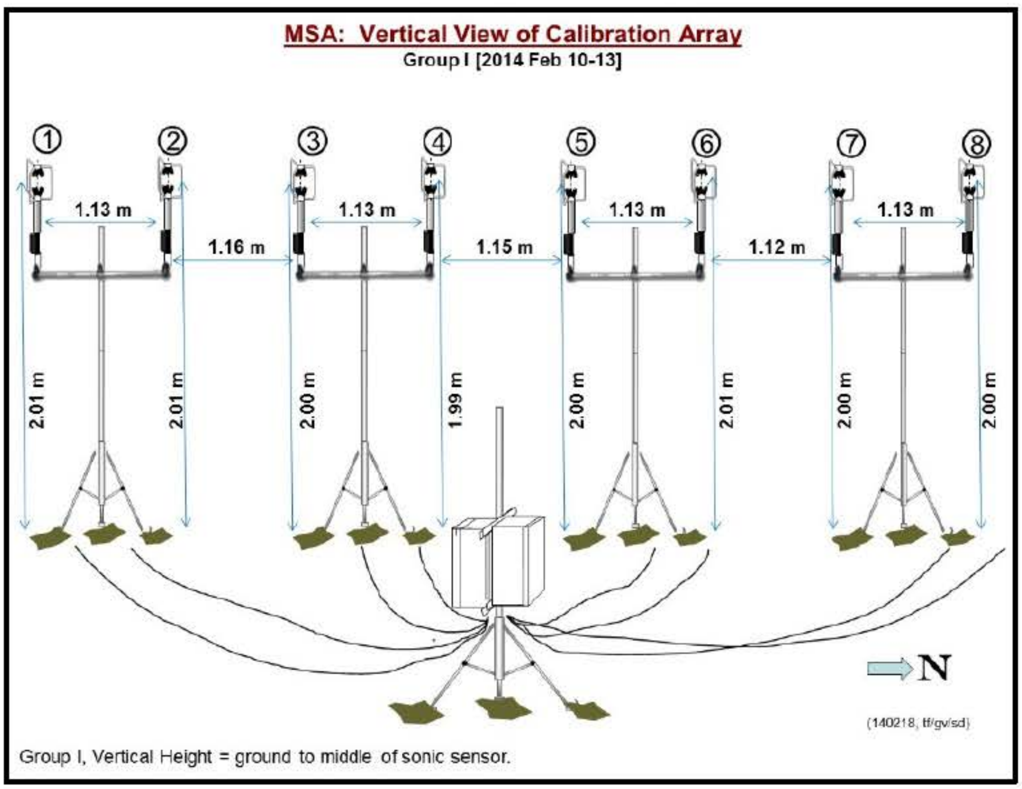

Fig. 6 Group 1—Dynamic sensor relative-calibration configuration

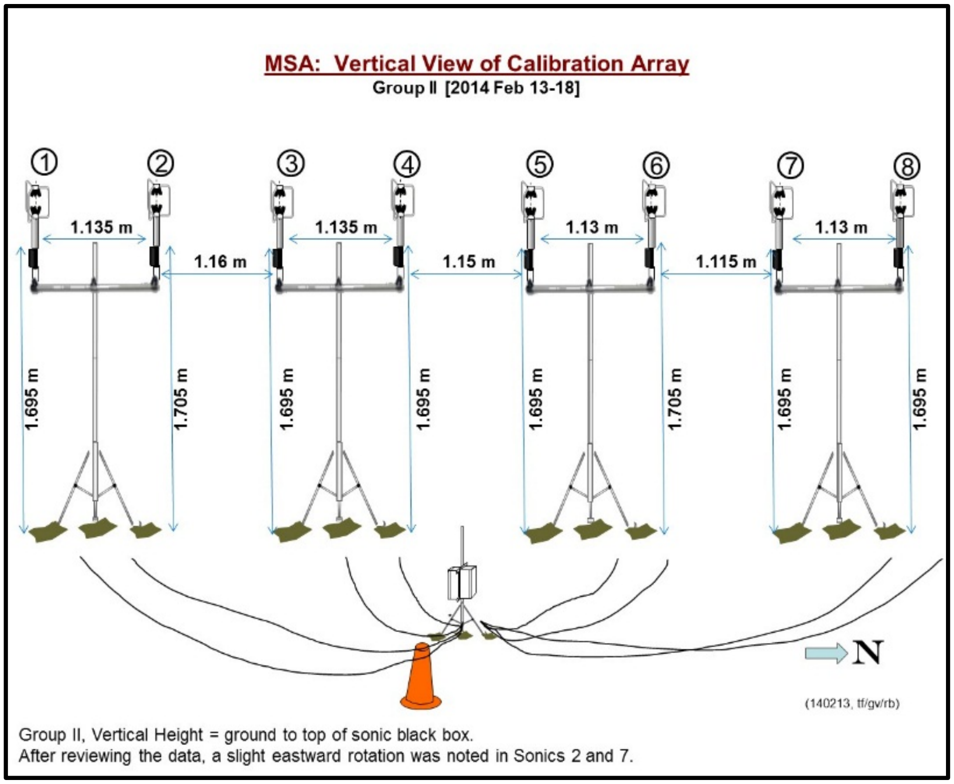

Fig. 7 Group 2—Dynamic sensor relative-calibration configuration

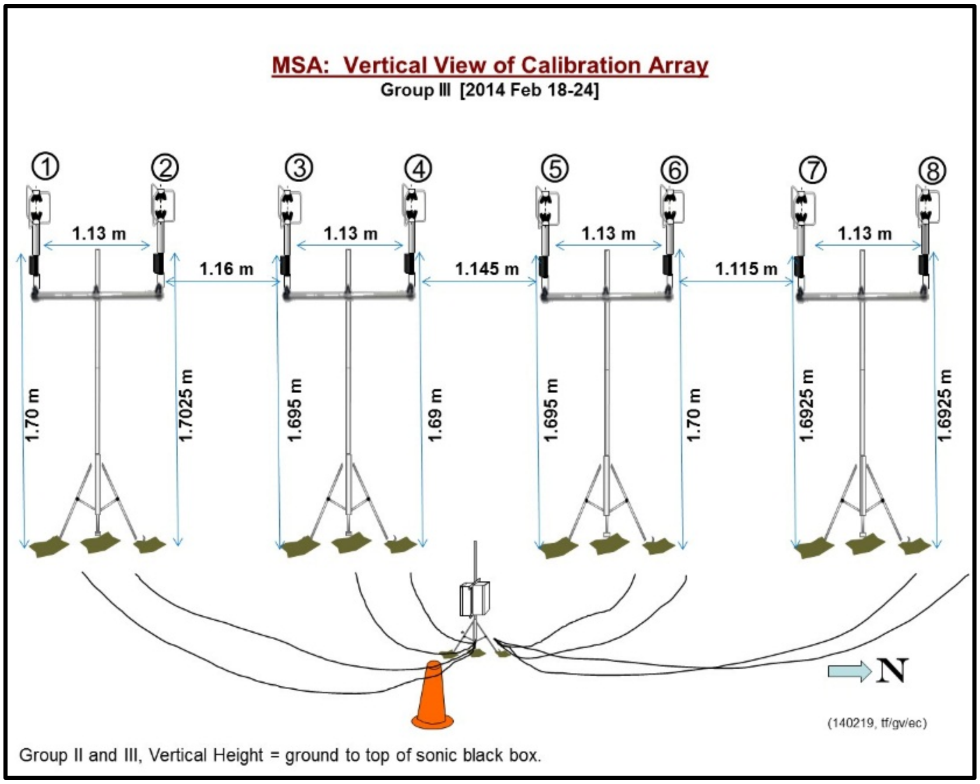

Fig. 8 Group 3—Dynamic sensor relative-calibration configuration

The sonic measurements were acquired on a central data-collection computer, using an 8-port RS232 adapter, and Labview software to collect and time-stamp each reading.

The orientation of the building's western edge was used to minimize flow-variation influences by the local and surrounding building structures. Some upward vertical velocity was noted; however, later analysis confirmed that the u-component of the velocity was on average fairly uniform.

Within each group, toward the spatial center of each group (Position #4), one sonic anemometer was repeatedly used. This sensor was selected based on earlier field study performance, and was defined as the calibration "standard". Two sonic anemometers (#633 and #646) were sampled in 2 group calibration sessions (Groups II and III), due to questionable performance in their initial sampling session. Statistical data analyses and data fitting were used to assess the sensor-calibration quality and to determine if data corrections were required.

3.2 Dynamic Sensors Calibration Data Analysis

The sonic relative calibration data were initially examined by calculating the standard deviation of each sonic anemometer against the Standard. Also examined was whether any linear corrections could be confidently applied to improve instrument calibration of the sonic anemometers. The analysis for each instrument group used all available data where the horizontal wind from the standard sonic was coming from within 45° of due west. To compare measurements taken at similar times, measurements were interpolated to a fixed time grid using 25-Hz temporal grid spacing and nearest-neighbor interpolation, and then time-averaged to a 1-min increment to aid in making the analysis easier to process.

3.2.1 Root-mean-square error as a function of distance

Within each group, ultrasonic anemometer #1341 was utilized as the "standard" sonic anemometer for comparison. This originally NIST-calibrated sonic was selected based on its historical usage as an un-fielded, carefully managed sensor preserved for relative-calibration purposes. Consequently, the sensor was placed toward the center of each group of 8 sonic anemometers (Position #4).

The root-mean-square error (RMSE) or difference of each sonic anemometer 1-min, averaged u-component, measured wind value from the standard sonic anemometer measured value is presented in Table 4. Apparent within Table 4 is that the RMSE generally increases within each group depending on the distance of the anemometer relative to the standard. The RMSE of each anemometer plotted as a function of distance from the standard highlights this issue, and the growth in the

RMSE appears linearly correlated with distance (see Fig. 9). Also noted was that the RMSE was well correlated with the standard deviation of the measurements from the sonic measurements, meaning the RMSE was not due to offset/mean error differences. This effect of RMSE growing with distance was likely due to turbulent fluctuations, and other spatial/temporal deviations in the wind flow (see Fig. 9). If an anemometer significantly deviated from this linear trend, the deviation would suggest that an added source of error was significant, in addition to the turbulent fluctuations potentially from calibration issues. Since no anemometer shows a large deviation from each group's linear trend of the RMSE growing with distance, this suggests no anemometer has a significant calibration issue; and that the primary source of the discrepancy between the measurements is due to turbulent fluctuations/differences in the wind between stations. Backing out this increase in noise/standard deviation, assuming the linear trend, suggests that the instrument calibration for each sensor is good to about 0.1 m/s. This is close to the manufacturer-stated accuracy of ±0.05 m/s.

Table 4 RMSE relative to standard (Sensor No. 4) anemometer u-measurements. U-measurements were filtered to include only horizontal winds from within 45° of due west.

Sensor Position	1 (m/s)	2 (m/s)	3 (m/s)	4 (m/s)	5 (m/s)	6 (m/s)	7 (m/s)	8 (m/s)
Group 1	0.25	0.19	0.12	Standard	0.13	0.20	0.28	0.35
Group 2	0.41	0.27	0.18	Standard	0.18	0.27	0.40	0.45
Group 3	0.51	0.37	0.17	Standard	0.19	0.31	0.43	0.51

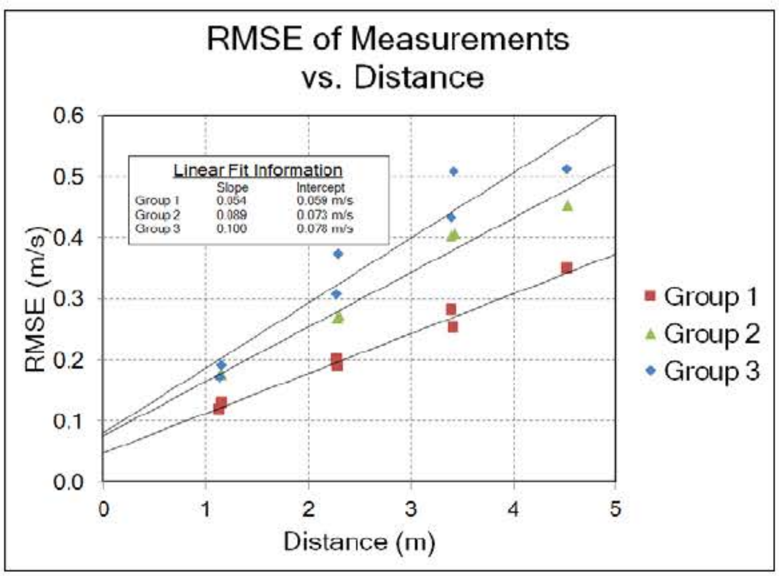

Fig. 9 RMSE as a function of group and distance from the standard sonic: Linear trend ("best fit") lines for each group are shown as black lines; slope and intercept of each trend line are presented in the table (top left) within the plot

3.2.2 Calibration Fits

While satisfied that sensors were within specifications, the sonic-calibration data were also analyzed to see whether any linear corrections should be applied to improve instrument calibration of the sonic anemometers. In this investigation, the u-component of each sonic was plotted against the standard u-component and a linear "best fit" (from a least squares standpoint) was determined using the following equation:

$$u_{\text{sonic}} = m \times u_{\text{standard sonic}} + b, \tag{1}$$

where u_{sonic} is the u-measurement being compared against the standard sonic measurement, $u_{\text{standard sonic}}$; m is the dimensionless slope of the best-fit line; and b is the offset of the measurement, when $u_{\text{standard sonic}}$ is zero. For a perfect fit between the sonic and the standard, the offset/intercept would be zero and the slope of the fit would be unity.

The linear fits were conducted with the Matlab polyfit function. Figure 10 shows an example of this fit using Sonic #637 against Standard Sonic #1341. Note the measurement spread in the y direction is well correlated with the RMSE values presented in Table 4 and Fig. 9.

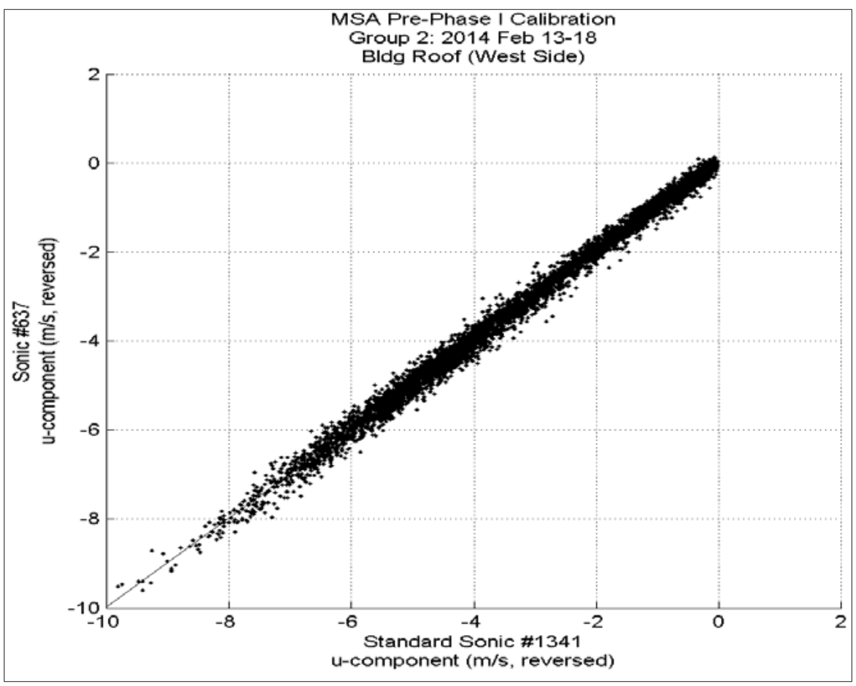

Fig. 10 Sonic #637 versus Standard Sonic #1341 u-components: Each measurement comparison is a black dot; best-fit linear is a thin black line

The resulting sensor fits are tabulated in Tables 5 and 6. Table 5 shows the percentage difference ("Diff") of the slope from the Standard. A perfect alignment would equal 1. Table 6 tabulates the line offset (or "b" from equation 1), for each fit.

Table 5 Percentage "Diff" of slope from perfect alignment with the sensor standard (i.e., 1); same-color bold values are same sensor

Sensor Position	1 (% Diff)	2 (% Diff)	3 (% Diff)	4	5 (% Diff)	6 (% Diff)	7 (% Diff)	8 (% Diff)
Group 1	0.32	–0.49	–0.15	Standard	–3.22	–0.95	–4.04	–6.76
Group 2	2.01	**–1.40**	1.76	Standard	0.06	–0.83	**–5.24**	–3.28
Group 3	5.61	4.12	**–0.44**	Standard	**–2.09**	–2.98	–4.99	–5.13

Table 6 Line offset (b) in m/s; same-color bold values represent the same sensor

Sensor Position	1 (m/s)	2 (m/s)	3 (m/s)	4	5 (m/s)	6 (m/s)	7 (m/s)	8 (m/s)
Group 1	0.007	–0.006	–0.015	Standard	–0.020	–0.024	–0.041	–0.051
Group 2	–0.019	**–0.031**	0.011	Standard	0.032	–0.046	**–0.112**	–0.090
Group 3	0.025	0.020	**0.006**	Standard	**–0.021**	–0.045	–0.065	–0.070

If the difference between the sensor and standard was purely a function of the instrument, then the fit should be similar when the sensor is used in different groups. Sonics #633 and #646 were included in both Groups 2 and 3. Sonic #633 was placed in Group 2, Position 2, and Group 3, Position 3. Sonic #646 was located in Position 7 for Group 2 and Position 5 in Group 3. The reason for the 2-group sampling was due to the need for a physical correction to the sensor alignment. Comparing the results from each group run implies that the source of the numerical differences is not purely a function of the sensor. The results do fall within the manufacturer-stated accuracy of ±1% rms, so no correction curve was suggested.

4. Thermodynamic Sensor Relative Calibration

This section describes the thermodynamic sensors relative calibration layout, methodology, and analysis. The results confirm the original MSA-Phase I field campaign's qualitative assessment.

4.1 Thermodynamic Relative Calibration Configuration

The thermodynamic sensor calibration began once the dynamic calibration was completed; and ran for 10 days, 25 Feb–06 Mar 2015. The side-by-side intercomparison method was similar to the dynamics calibration study. However, all of the thermodynamics sensors were tested at the same time and the measurement location was situated on the south side of a 1-story office building (see Fig. 11).

Fig. 11 Thermodynamic sensors side-by-side intercomparisons

The sensors were grouped into 5 stations and mounted on 5 independent tripods. These tripods were aligned in a west–east orientation.

Each station sampled pressure, 2 temperatures, relative humidity, and solar radiation. Campbell Scientific, Inc., micro-loggers (CR23X) recorded the data in 1-min samples. The loggers were assigned a number, which was then associated with the sensors reporting to that logger. (See Fig. 12 and Table 7.) The center tripod (Tripod No. 3) had sensors that were new or had been calibrated within the last year. The sensors mounted on the tripods to either side of the recently calibrated "standard", had the "unknowns" or instruments for testing. All sensor positions on the individual tripods (height above ground, distance from the tripod or boom) were carefully aligned to within 2 cm of each other. For reference, the wall of the building, which was north of the tripods, was almost exactly aligned on a true west–east line. Tripod No. 1 was positioned on the west (Fig. 11, left side); Tripod No. 5 was on the eastern edge (Fig. 11, right side).

The MSA-Phase I "Proof of Concept" used hardware components from previous field tests. This resource insured that the components had a proven durability and that system development costs would be kept very low. The deviation of measurements from the predetermined "standard" sensor will be examined in the next section.

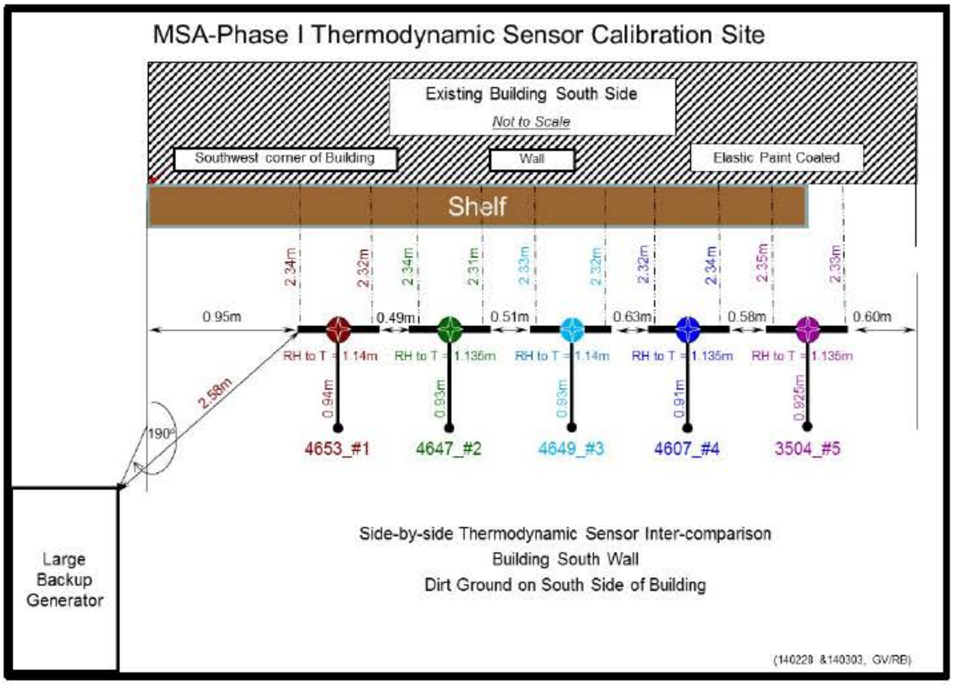

Fig. 12 Thermodynamic sensor side-by-side inter-comparisons layout

Table 7 MSA-Phase I thermodynamic sensors calibration configuration (28 Feb 2014): Tripod No. 1 was on the west edge (left); Tripod No. 5 was located on the east edge (right).

Logger	Pressure (~1 m)	Temp (10 m)	Temp (2 m)	RH (2 m)	Solar Rad (2 m)	Solar Batteries	Sonic (10 m)	Sonic (2 m)
4653 Tripod #1 (MSA – PI, Tower 4)	**X1720009** Vaisala/CSI (PTB101b, CS105)	**4653** CSI (T107)	**61081155** Rotronic	**61081155** Rotronic	**092102** Kipp & Zonen (CMP3)	Four 6v Batteries	**1354 / 499** RM Young	**1343** RM Young
4647 Tripod # 2 (MSA – PI, Tower #2)	**X1720010** Vaisala/CSI (PTB101b, CS105)	**4647** CSI (T107)	**61081276** Rotronic	**61081276** Rotronic	**025277** Kipp & Zonen (CM3)	Four 6v Batteries	**1359** RM Young	**1357** RM Young
4649 Tripod #3 (MSA – PI, Tower #1)	**F1220011** Vaisala/CSI (PTB101b, CS105)	**4649** CSI (T107)	**61085447** Rotronic	**61085447** Rotronic	**014907** Kipp & Zonen (CM3)	Four 6v Batteries	**1370/ 650/637** RM Young	**1361** RM Young
4607 Tripod #4 (MSA – PI, Tower #5)	**X1630015** Vaisala/CSI Bad Sensor (not fielded)	**4607** CSI (T107)	**61053263** Rotronic	**61053263** Rotronic	**014906** Kipp & Zonen (CM3)	Two 6v Batteries	**726** RM Young	**712** RM Young
3405 Tripod #5 (MSA – PI, Tower #3)	No sensor	**3405** PRT*	**61085415** Rotronic	**61085415** Rotronic	**014912** Kipp & Zonen (CM3)	Four 6v Batteries	**1356** RM Young	**1355 / 638** RM Young

*PRT generated questionable data during the relative calibration. Consequently, the sensor was used as a "placeholder" instrument until a new T107 was purchased and installed in Tower No. 3, at 10-m AGL, on15 Apr 2015.

4.2 Thermodynamic Sensors Data Analysis

The calibration data analyses for the barometers, thermometers, and hygrometer sensors focused on the time period: 2014 Julian Decimal Days (JDDs) 61.1–JDD 61.3 Universal Time Coordinated (UTC). The equivalent local time was during the nighttime hours of 2014 JDD 60 (Mar 01), 19.4 hours Mountain Standard Time (MST) through JDD 61 (Mar 02), 0.2 hours MST. The night hours were selected based on an observed, ambient environmental consistency over that time period.

The pyranometer calibration data analysis was centered on JDD 61.7–61.9 UTC (local time: 2014 Mar 02, 0.2–14.6 hours MST), which was during daylight hours. This period was selected based on the persistent atmospheric attributes generated by the cloudless day. Wind measurements were not acquired during the thermodynamic calibration due to limited resources. Consequently, no filtering based on airflow attributes could be utilized. To compare measurements, sampling data were interpolated to a fixed time grid, using 1-min temporal grid spacing and nearest-neighbor interpolation.

The "standard" sensor measurements used for the relative calibration analysis were recorded by Logger 4649 on Tripod No. 3. The instruments mounted on this centrally located tripod were either new or calibrated within the last year, as explained earlier.

4.2.1 Pressure Calibration Data Analysis

Three barometer outputs were compared in the pressure relative-calibration assessment process. A fourth barometer, wired to Logger 4607, showed erratic data time series during the preliminary calibration review. Consequently, that sensor was not included in this analysis. Fiscal and temporal limitations prevented the acquisition of a replacement pressure sensor.

Figure 13 shows the pressure-measurement differences with respect to Logger 4649 during the 2014 JDD 61.1–61.3 time frame. Pressure measurements from the 3 loggers were within 0.8 mb of each other. In general, there was little drift (approximately 0.1 mb) in the typical offset between each sensor. Since there is technically no solid basis for an increased confidence in one sensor over another, only the spread in the measurements can be reported, with no absolute correction to any particular sensor advised. The deviation between sensor measurements is only slightly larger than the sensor manufacturer-stated calibration of 0.3 mb at 20 °C and 0.6 mb at 0–40 °C. While an absolute calibration cannot be determined, for a relative calibration correction an offset correction of about –0.5 mb for the Logger 4649 barometer would be recommended when comparing fielded sensors.

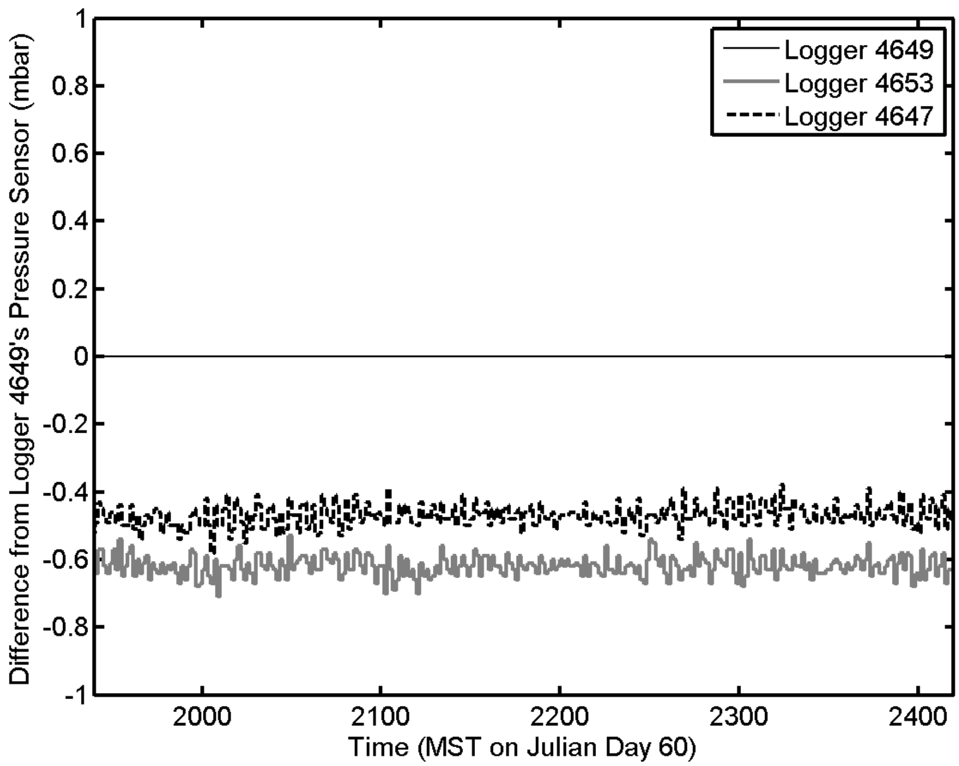

Fig. 13 Barometric differences compared against Logger 4649 during the 2014 Julian Day (JD) 60 local nighttime hours; logger associated with each sensor is indicated in the legend

4.2.2 Thermometer Calibration Data Analysis

Calibration measurements from 9 temperature sensors (3 T107s, 5 Rotronics, and 1 PRT) were examined. The temperature differences were calculated using the Logger 4647–T107 as the standard, over the 2014 JDD 61.1–61.3 UTC time frame. As mentioned above, the equivalent local time was during the night of 01 Mar 2014, 19.4 hours MST through 02 Mar, 0.2 MST. (Results are displayed in Fig. 14.) Most temperature measurements were within about 0.2 °C of each other. An exception was the PRT sensor, which reported values about 0.4 °C colder than the standard. This significant deviation from the expected accuracy of the thermometer was noted during the initial qualitative-calibration assessment. Consequently, this sensor was used as a quasi-placeholder in the MSA-Phase I field campaign until a "new" T107 replacement could be purchased and installed. The replacement sensor was installed on Tower No. 3 at 10 m AGL on 15 Apr 2014. Data ingest for the new sensor began around 0942 MDT (Vaucher and D'Arcy 2014). The need for applying a post-campaign PRT-correction term to the "placeholder" data was noted in the preliminary calibration assessment for the MSA-Phase I field campaign.

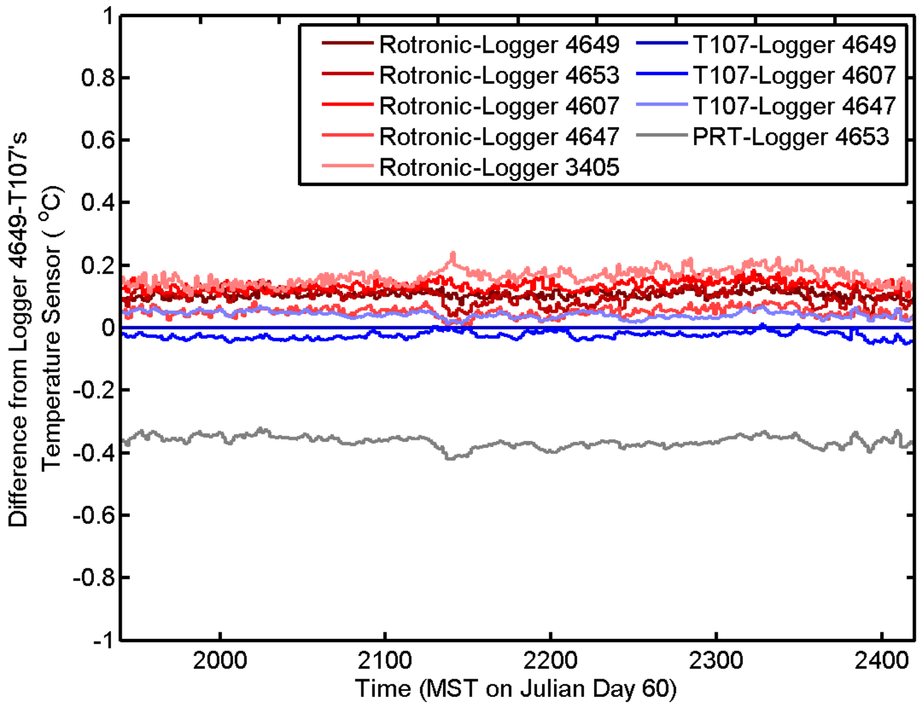

Fig. 14 Temperature sensor differences: standard was the T107 of Logger 4647; Rotronic sensors are indicated with red lines, T107 sensors are blue lines, and the PRT is indicated by a gray line

On average, the Rotronic sensors reported values about 0.1 °C higher than the T107 sensors.

Note: During the MSA-Phase I campaign, Rotronics were used at 2 m AGL and the T107 sensors were used at 10 m AGL. The impact of this observed trend means that during the daytime, if the Rotronics represented accurate readings, then the actual upper-level temperature should be warmer than what was measured by the T107. Likewise, if the T107 sensors were reporting "truth", the actual 2-m surface values should be cooler than what the Rotronic sensors reported.

The net result of this observed trend would imply that the uncorrected MSA-Phase I campaign data may report overly unstable vertical profiles in the near-surface temperature gradients. Since an absolute calibration was not available to confidently distinguish one sensor over another, the direction of the 0.1 °C correction is debatable. For studies concerned with relative temperature differences where absolute calibration is not necessary, it may be appropriate to either correct the T107 measurements by an offset of +0.1 °C or the Rotronic by –0.1 °C.

The calculated sensor differences appear to be within the manufacturer-stated error of 0.4 °C (at –24 to 48 °C) for the T107 sensors and 0.1 °C for the Rotronics.

4.2.3 Relative Humidity Calibration Data Analysis

Five RH sensors were subjected to a relative calibration analysis. The percentage difference of each RH sensor from the Logger 4649 RH-sensor standard were calculated during the JDD 61.1–61.3 time frame (and are presented in Fig. 15). The RH measurements for Loggers 4653, 4607, 4647, and 3405 reported values within 1% of each other. Logger 4649 measurements were on average approximately 1% lower than the average of the other 4 logger-recorded values. The sensor variations (excluding the Logger 4649 RH sensor) between the 4 RH sensors were within the manufacturer-stated calibration of ±0.8%.

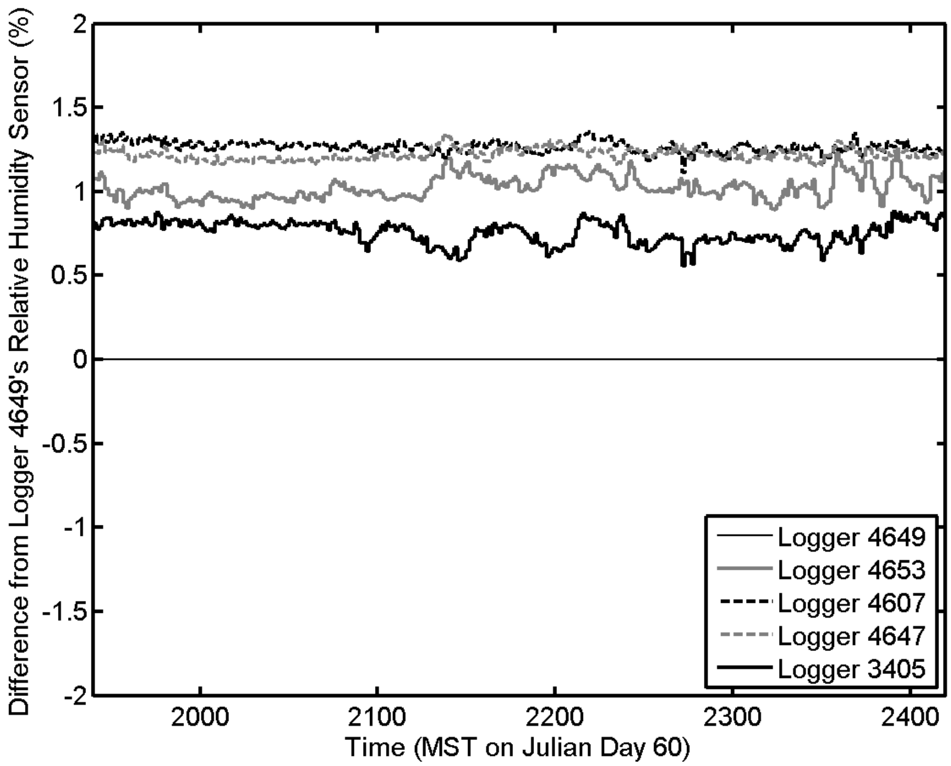

Fig. 15 RH percentage difference from Logger 4649 RH measurements during the local nighttime of 2014 JD 60 (02 Mar); the logger associated with each non-standard RH sensor is demonstrated in the legend

4.2.4 Solar Radiation Calibration Data Analysis

Solar radiation measurements were taken from 5 pyranometers during the daylight hours of JDD 61.7–61.9 UTC (local time: 02 Mar 2014, 0.2–14.6 hours MST). The percent difference between each pyranometer and the Logger 4649–pyranometer standard are shown in Fig. 16. Solar radiation measurements from Loggers 4607, 4647, and 3405 were within 1% of each other. The other 2 instruments reported significant departures (3–9%) from this group of 3 sensors. Drift in the percentage departure was observed over the course of a day. (During the field campaign, Logger 4649 solar radiation measurements were noted as being potentially too high, considering the location/latitude of where the measurements were obtained. Despite the departure of several percent, the results were still within the expected accuracy determined by the manufacturer for daily sums of ±10%.)

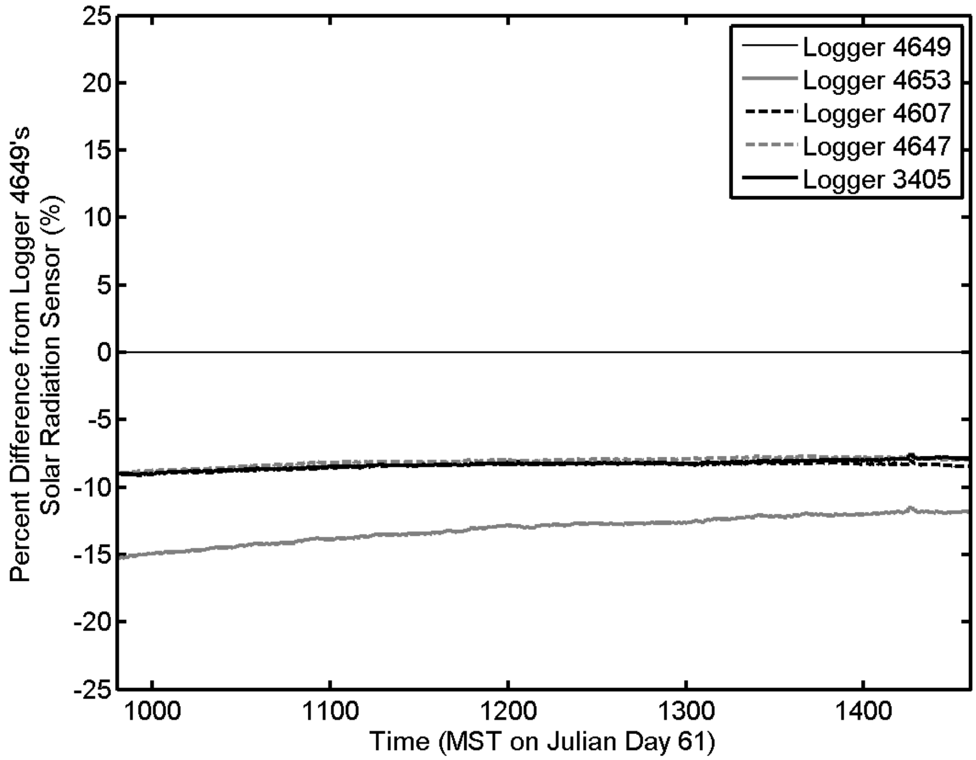

Fig. 16 Pyranometers percent difference from Logger 4649 pyranometer-standard, during the local daytime hours of 2014 JD 61; logger associated with each sensor is indicated in the legend

5. Discussion

Relative calibration assessments work well if the "standard" by which the comparisons are made is NIST approved. This relative calibration assessment demonstrated both the strength and weakness of a relative comparison. For the dynamic sensors, whose "standard" was closely aligned to a NIST standard, confidence in the measured data was re-enforced. For the thermodynamic sensors, the comparison against the standard did not entirely enhance the data confidence, even though the instruments were technically new or calibrated within the last year. Fortunately, the thermodynamic-sensor intercomparison results have preserved the data value by defining how to use these measurements in an informed manner.

When time and funding run short, sensor calibration tends to become a "low" priority. Unfortunately, this sacrifice can reduce the quality and usefulness of the final measurements. In an ideal world, all sensors would be calibrated against NIST standards prior to their field installation, rechecked in a side-by-side relative calibration before fielding, and then put on a routine recalibration schedule.

This study showed that 1) a sensor's NIST paperwork does not guarantee that the sensor has not been dropped or accidentally hit in a manner that negates the calibration; and 2) all sensors need some calibration before being fielded, so that the data user can employ the sensor output in an informed manner.

6. Summary and Recommendations

Successful Army decisions rely on accurate representation. Environmental decisions involving the atmosphere rely heavily on detailed meteorological models. The ARL is building an "Army-scale", high-resolution MSA to provide reliable and persistent data resources that, in turn, allow atmospheric modelers and sensor developers to validate and compare model and sensor performance with atmospheric observations at and near the surface and in close proximity to terrain of varying complexity.

In 2014, the MSA "Proof of Concept" (MSA-Phase I) was organized and executed to test the feasibility of success for such a significant ARL investment. With limited time and funds, a representative Phase I field campaign was designed along with an expandable data-management strategy that would accommodate the initial field requirements and provide a foundation for follow-on MSA phases. (A detailed description of the MSA-Phase I and its preliminary results is found in publications mentioned in Section 1.)

Before the field campaign could be executed all sensors needed to be calibrated. Since timely access to a NIST-certified calibration laboratory was not an option for the MSA-Phase I, a side-by-side sensor intercomparison (a relative calibration) was designed and conducted. The relative calibration task was subdivided into 2 parts: dynamic and thermodynamic sensor-calibration segments. Utilizing the projected high winds of the New Mexico, February–March "windy season", the dynamic sensors were set up first for calibration. Steady, high winds were sought to best equate the airflow of a calibration wind tunnel. The thermodynamic-sensor calibration followed using a more protected location. The acquisition period ran 10 Feb–06 Mar 2014.

A preliminary, qualitative review of the calibration data showed that the majority of sensors were worthy of the MSA "Proof of Concept" field campaign. Those instruments that did not meet the standard were either re-tested and/or replaced. With a pressing deadline to complete the MSA-Phase I measurement portion by mid-fiscal year, the sensors passing the calibration assessment were integrated into the field campaign design, which promptly followed the calibration task. A detailed calibration analysis also had to be postponed due to the uncompromising schedule and lack of available personnel. Fortunately, with the successful “Proof of Concept” completed and Phase II underway, a more detailed relative-calibration data analysis has now been executed, with results documented in this report. The standard sensors selected for the relative-calibration analyses were either new or had been calibrated within the last year.

The dynamic sensor relative calibration configuration and data analyses were described in detail in Section 3. Section 4 described the thermodynamic sensors relative-calibration layout, methodology, and analysis. In short, the results confirmed the qualitative assessments executed prior to the MSA-Phase I field campaign execution. That is, the more detailed analysis showed that most sensors were found to be within the manufacturer specifications.

Looking at each sensor group individually:

1) Sonic Anemometers: Based on the intercomparison RMSE and curve-fitting analyses, there were no significant calibration issues identified. The instrument calibration for each anemometer was good to about 0.1 m/s, which was close to the manufacturer-stated accuracy of ±0.05 m/s. Since the results fell within the manufacturer-stated accuracy of ±1% rms, no correction curve was suggested.

2) Barometer: Barometer 4607 reported erratic data during the initial calibration assessment and was consequently removed from consideration prior to the field campaign. Based on this more detailed post-campaign review, the remaining barometers were within manufacturer specifications. Barometer 4649, however, showed a potential need for an offset correction of about –0.5 mb when used with the other fielded barometers.

3) Temperature sensors: Thermometers were found to be within the manufacturer-general specifications.

a) The Rotronic sensors reported values about 0.1 °C higher than the T107 sensors. Note: During the MSA-Phase I field campaign, the Rotronic sensors were mounted at 2 m AGL and the T107 at 10 m AGL. The analyzed results imply that uncorrected MSA-Phase I data may report overly unstable, near-surface, vertical temperature profiles. Since an absolute calibration was not available, the direction of the 0.1 °C correction is debatable. For studies concerned with relative temperature differences only, it is suggested to either correct the T107 measurements by an offset of +0.1 °C or, the Rotronic data by –0.1 °C.

b) The PRT sensor reported values about 0.4 °C colder than the standard. This sensor was replaced with a new T107 during the MSA-Phase I field campaign. The new T107's data acquisition started on 15 Apr 2014 at 0942 MDT.

4) Hygrometers: RH measurements for Loggers 4653, 4607, 4647, and 3405 reported values within 1% of each other. Logger 4649 measurements were on average approximately 1% lower than the average of the other 4 recorded logger values. The sensor variations (excluding the Logger 4649 RH sensor) between the 4 RH sensors were within the manufacturer-stated calibration of ±0.8%.

5) Pyranometers: Solar radiation measurements from Loggers 4607, 4647, and 3405 reported measurements within 1% of each other. Loggers 4649 and 4653 reported significant departures (3–9%) from the 3 sensors. Drift in the percentage departure was observed over the course of a day. Logger 4649 solar radiation measurements were noted as being potentially too high during the MSA-Phase I field campaign.

This relative calibration exercise has provided insights into the quality of the MSA-Phase I field campaign data, as well as ideas for future data sets. For the dynamic sensors, whose "standard" was closely aligned to a NIST-standard quality, confidence in the measured data was re-enforced. For the thermodynamic sensors, even though the instruments were technically new or calibrated within the last year, the comparison against the standards exposed the data limitations. Fortunately, these analyses provide results that will help scientists use the data in an informed manner. As part of the recommendations, the following observations were noted:

1) A sensor's NIST paperwork does not mean that the sensor has not been dropped or accidentally hit in a manner that negates the calibration; and

2) When a field project's sensor calibration is postponed or deleted, this sacrifice can reduce the quality and usefulness of the final measurements.

In an ideal world, all meteorological sensors would be calibrated against NIST standards prior to their field installation, rechecked in a side-by-side relative calibration before fielding, and then put on a routine recalibration schedule; thus, ensuring the best quality measurements for the data users.

7. Notes

Personal communication between Tim Chavez of BAE Systems and Robert Brice of ARL, 2015 Jan 26.

8. References

Campbell Scientific, Inc. Barometric pressure sensor, model CS105. Logan, (UT): Campbell Scientific, Inc.; 2001a.

Campbell Scientific, Inc. Temperature probes, models 107 and 108. Logan, (UT): Campbell Scientific, Inc.; 2001b.

Campbell Scientific, Inc. CMP3 pyranometer, instruction manual. Rev. 2002 Oct. Logan, (UT): Campbell Scientific, Inc.; 2002b.

Campbell Scientific, Inc. HC2S3 temperature and relative humidity probe, instruction manual. Rev. 2012 Oct. Logan, (UT): Campbell Scientific, Inc.; 2012.

Harrison S, Vaucher G. Meteorological sensor array (MSA)–phase I, volume 2 (data management tool: "proof of concept"). White Sands Missile Range (NM): Army Research Laboratory (US); 2014 Oct. Report No.: ARL-TR-7133. Also available at http://www.arl.army.mil/www/default.cfm?technical_report=7251

Huschke R, editor. Glossary of meteorology, AMS. Boston (MA); 1970. p. 525.

National Research Council (US). When weather matters, science and service to meet critical societal needs. Washington (DC): National Academies Press (US); 2010.

RM Young Company. Meteorological instruments, instructions, ultrasonic anemometer, model 81000; 2004 Dec [accessed 2015 Apr 13]. www.youngusa.com/Manuals/81000-90(I).pdf.

Vaucher G, D'Arcy S. MSA daily data and tower report, (MSA_DailyTowerDataRpt_140415a) internal document; 2014 Apr 15.

Vaucher GT, Swanson J, Raby J, Foley T, Harrison S, Brice R, D'Arcy S, Creegan E. Meteorological sensor array (MSA)–phase I, volume 1 ("proof of concept" overview). White Sands Missile Range (NM): Army Research Laboratory (US); 2014 Sep. Report No.: ARL-TR-7058. Also available at http://www.arl.army.mil/www/default.cfm?technical_report=7179.

List of Symbols, Abbreviations, and Acronyms

24/7	24 h/day–7 days/week
AGL	above ground level
ARL	US Army Research Laboratory
DAS	Data Acquisition System
fov	field of view
JD	Julian Day
JDD	Julian Decimal Day
MDT	Mountain Daylight Time
MSA	Meteorological Sensor Array
MST	Mountain Standard Time
NIST	National Institute of Standards and Technology
NRC	National Research Council
PRT	Platinum Resistance Thermometer
PV	photovoltaic
RH	relative humidity
rms	root mean square
RMSE	root-mean-square error
UTC	universal time coordinated
WSMR	White Sands Missile Range

1 (PDF) DEFENSE TECHNICAL
INFORMATION CTR
DTIC OCA

2 (PDF) DIRECTOR
US ARMY RSRCH LAB
RDRL CIO LL
IMAL HRA MAIL & RECORDS
MGMT

1 (PDF) GOVT PRINTG OFC
A MALHOTRA

2 (PDF) US ARMY RSRCH LAB
ATTN RDRL CIE M
BLDG 1622
WSMR NM 88002
T JAMESON
D KNAPP

6 (PDF) US ARMY RSRCH LAB
ATTN RDRL CIE D
BLDG 1622
WSMR NM 88002
R BRICE
S D'ARCY
R EDMONDS
S HARRISON
R RANDALL
J SWANSON

10 (5 CD, 5 HC, 1 PDF) US ARMY RSRCH LAB
G VAUCHER
ATTN RDRL CIE D
BLDG 1622
WSMR NM 88002

1 (PDF) US ARMY RSRCH LAB
P CLARK
ATTN RDRL CIE
2800 POWDER MILL RD
ADELPHI MD 20783-1138

1 (PDF) US ARMY RSRCH LAB
S O BRIEN
ATTN RDRL CIE D
BLDG 1622
WSMR NM 88002

1 (PDF) DR J MCLAY
NAVAL RESEARCH LABORATORY
7 GRACE HOPPER AVE STOP 2
MONTEREY CA 93943

1 (PDF) R CRAIG DAF CIVILIAN
HQ AFWA 2WXG 16WS/WXN
101 NELSON DRIVE
OFFUTT AFB NE 68113-1023

1 (CD) ARMY JOINT SUPPORT TEAM
SFAE IEW&S DCGS A
ATTN H CARTER
238 HARSTON ST BLDG 90060
HURLBURT FIELD FL 32544

1 (CD) J STALEY
ARMY WEATHER PROPONENT
OFFICE
INTEGRATION
SYNCHRONIZATION AND
ANALYSIS (CDID)
US ARMY INTELLIGENCE
CENTER OF EXCELLENCE
550 CIBEQUE ST BLDG 61730
FT HUACHUCA AZ 85613

INTENTIONALLY LEFT BLANK.