(2)

DOT/FAA/W/92-1
DOT-VNTSC-FAA-92-6

Surveillance and
Sensors Division
Washington, DC 20591

1991 LLWAS Anemometer Test Program

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Research and
Special Programs
Administration
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Cambridge, MA 02142-1093

Final Report
September 1992

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U.S. Department
of Transportation
**Federal Aviation
Administration**

127 P6

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	September 1992	Final Report - Nov. 1990-Sept. 1991

4. TITLE AND SUBTITLE
1991 LLWAS Anemometer Test Program

5. FUNDING NUMBERS
A1236/FA195

6. AUTHOR(S)
Charles O. Phillips, David Burnham, Leo Jacobs and David Hazen

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Department of Transportation
Research and Special Programs Administration
Volpe National Transportation Systems Center
Cambridge, MA 02142-7093

8. PERFORMING ORGANIZATION REPORT NUMBER
DOT-VNTSC-FAA-92-6

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Department of Transportation
Federal Aviation Administration
800 Independence Avenue, S.W.
Washington, DC 20591

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
DOT/FAA/W/92-1

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
This document is available to the public through the National Technical Information Service, Springfield, VA 22161

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Performance tests of anemometers under icing and snow conditions were conducted during 1990-1991 on the test field at Rochester, MN and in icing chambers and wind tunnels at Sterling, VA. These tests were done for the FAA LLWAS program to test sensors for the next phase of LLWAS.

Sensors from ten manufacturers were accepted into the test program from the respondents to the Commerce Business Daily. These sensors were required first to pass an icing chamber test in order to be field tested. The field tests lasted from November 1990 to July 1991. Afterwards, all sensors were sent to Sterling, VA for wind tunnel tests in September 1991.

All units from the eight manufacturers that passed the icing chamber test were in the field test. A propeller/vane sensor that failed the icing chamber test was put in the field as a reference. All the units that passed were not affected by icing during the field test although a mechanical unit was affected by snow during one event. The propeller/vane was affected by icing during one event. Wind tunnel tests were done to check starting thresholds and calibration anomalies found in the field.

It was concluded that there is no one "winning" technology that could be found from the tests.

14. SUBJECT TERMS
Low Level Windshear Alert System, Windshear, Microbursts, Anemometer, Thunderstorms

15. NUMBER OF PAGES
112

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

PREFACE

This study was sponsored by the U.S. Department of Transportation, Federal Aviation Administration (FAA), ANW-150, and was performed by the U.S. Department of Transportation, Volpe National Transportation Systems Center, in support of the Low Level Windshear Alert System-Expanded Network (LLWAS-EN) procurement.

Over the past ten years, the Volpe Center has conducted a program to test and evaluate weather sensors for the FAA, the National Weather Service (NWS), and other government agencies. The tests reported here were conducted in Rochester, Minnesota to evaluate anemometers under icing and snow conditions for the FAA LLWAS program. In addition, icing chamber tests and wind tunnel tests were conducted at the NWS Sterling Research & Development Center in Sterling, Virginia.

This test program was dependent upon the contributions of the following organizations:

1) Rochester Municipal Airport: The airport manager gave permission for the tests and helped with test arrangements.

2) McGhie & Betts, Rochester, Minnesota: Provided office space at Rochester test site. Provided shipping assistance for sensor boxes. Provided personnel to help with sensor installation and removal.

3) H&H Electric, Rochester, Minnesota: Installed and removed power and signal cabling.

4) NWS Rochester office: Provided surface observations and photographs of sensors after icing events. Reset computer or sensor power on request.

5) NWS Sterling Research & Development Center: Provided their laboratory test facilities and patiently taught us how to operate them. Provided shipping assistance for the large number of sensor boxes.

Editorial support was provided by Arthur H. Rubin of EG&G/Dynatrend.

METRIC / ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2) = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2) = 0.09 square meter (m^2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectares (he) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gr)
1 pound (lb) = .45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

$[(x - 32)(5/9)]$ °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2)
1 hectare (he) = 10,000 square meters (m^2) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gr) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg) = 1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

$[(9/5) y + 32]$ °C = x °F

QUICK INCH-CENTIMETER LENGTH CONVERSION

INCHES	0			1			2			3			4			5			6			7			8			9		10
CENTIMETERS	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25					25.40

QUICK FAHRENHEIT-CELSIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and/or other conversion factors, see NBS Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50. SD Catalog No. C13 10 286.

TABLE OF CONTENTS

Section	Page
1. INTRODUCTION	1-1
1.1 Scope	1-1
1.2 Background	1-1
1.3 Test Chronology	1-2
1.4 Objectives	1-2
1.5 Sensor and System Specifications	1-3
2. SENSORS	2-1
2.1 Wind Sensors Accepted	2-1
2.2 Theory of Operation of the Sensor Types	2-2
2.3 Wind Sensor Descriptions	2-3
2.4 Reference Sensors	2-4
3. LABORATORY ICING CHAMBER TEST	3-1
3.1 Procedure	3-1
3.2 Results	3-2
4. FIELD TESTS	4-1
4.1 Site Description	4-1
4.2 Data Collection	4-1
4.3 Field Test History	4-3
4.4 Results	4-3
4.4.1 Icing/Snow Events	4-4
4.4.2 Analysis Method	4-7
4.4.2.1 Scatter Plots	4-7
4.4.2.2 Time Plots	4-7
4.4.3 Analysis of Selected Events	4-10
4.4.3.1 11/27/91 Event	4-10
4.4.3.2 3/12/91 Icing Event	4-16
4.4.3.3 3/12/91 Snow Event	4-16
4.4.4 Sensor Performance: All Events	4-17

Section **Page**

5. WIND TUNNEL TEST 5-1

5.1 Wind Tunnels 5-1

5.1.1 High-Speed 5-2
5.1.2 Low-Speed 5-2

5.2 Test Description and Results 5-2

5.2.1 Reference Standards 5-2
5.2.2 Calibration Accuracy of Other Sensors 5-4

5.2.2.1 Hot-Film Sensors 5-4
5.2.2.2 Pressure Sensors 5-5
5.2.2.3 Cup S ors 5-6

5.2.3 Hot-Film Contamination Effects 5-6
5.2.4 Starting Threshold Test 5-7

6. CONCLUSIONS 6-1

6.1 General 6-1
6.2 Icing/Snow Performance 6-1

6.2.1 Propeller/Vane 6-1
6.2.2 Cup/Vane 6-2
6.2.3 Hot Film 6-2
6.2.4 Pressure Sensor 6-2

6.3 Speed Accuracy 6-2

6.3.1 Propeller/Vane 6-2
6.3.2 Cup/Vane 6-2
6.3.3 Hot Film 6-3
6.3.4 Pressure Sensor 6-3

7. RECOMMENDATIONS 7-1

APPENDIX A - TEST SPECIFICATIONS A-1

A.1 LLWAS ANEMOMETER TEST HARDWARE SPECIFICATION A-1

Section **Page**

A.2 LLWAS ANEMOMETER ACCEPTANCE REQUIREMENTS A-1

APPENDIX B - LLWAS-EN PRELIMINARY SENSOR SPECIFICATION B-1

APPENDIX C - LIST OF MANUFACTURERS PARTICIPATING IN LLWAS ICING TESTS C-1

APPENDIX D - PHOTOGRAPHS D-1

APPENDIX E - RESULTS OF ICING CHAMBER TESTS E-1

APPENDIX F - DATA COLLECTION SYSTEM F-1

F.1 INSTALLATION F-1
F.2 DATA ACQUISITION SYSTEM F-1

F.2.1 Hardware F-1
F.2.2 Software F-1
F.2.3 Data Format F-2
F.2.4 Watchdog Timer F-3

APPENDIX G - SENSOR FIELD TEST HISTORY G-1

APPENDIX H - SUMMARY OF SAO WEATHER REPORTS OF ICING EVENTS - WINTER OF 1990-1991 . . . . H-1

REFERENCES R-1

LIST OF FIGURES

Figure **Page**

FIGURE 4-1. LLWAS TEST SITE LAYOUT 4-2

FIGURE 4-2. DETAIL OF ANEMOMETER TEST SITE 4-2

FIGURE 4-3. LLWAS WIND SENSOR EXPOSURE HISTORY 4-3

FIGURE 4-4. SCATTER PLOT OF CL1 VERSUS ST1. SLOPE = 0.889
OFFSET = 2.88 4-8

FIGURE 4-5. WIND SPEED DATA ON 3/11/91, UNCORRECTED 4-9

FIGURE 4-6. WIND SPEED DATA ON 3/11/91, CORRECTED 4-9

FIGURE 4-7. CL1 WIND DIRECTION ON 11/26-29/90 4-11

FIGURE 4-8. COMPARISON OF CL2 AND CL1 WIND SPEED ON 11/26-29/90 . . . 4-12

FIGURE 4-9. COMPARISON OF ST2 AND CL1 WIND SPEED ON 11/26-29/90 4-13

FIGURE 4-10. COMPARISON OF RS1 AND CL1 WIND SPEED ON 11/26-29/90 . . . 4-14

FIGURE 4-11. COMPARISON OF RS2 AND CL1 WIND SPEED ON 11/26-29/90 . . . 4-15

FIGURE 4-12. CL1 WIND DIRECTION ON 3/11-14/91 4-18

FIGURE 4-13. COMPARISON OF YG1 AND CL1 WIND SPEED ON 3/11-14/91 . . . 4-19

FIGURE 4-14. COMPARISON OF YG2 AND CL1 WIND SPEED ON 3/11-14/91 . . . 4-20

FIGURE 4-15. COMPARISON OF VS1 AND CL1 WIND SPEED ON 3/11-14/91 . . . 4-21

FIGURE 4-16. COMPARISON OF VS2 AND CL1 WIND SPEED ON 3/11-14/91 . . . 4-22

FIGURE 5-1. R. M. YOUNG CALIBRATION 5-3

FIGURE 5-2. CLIMATRONICS CALIBRATION (S/N 011) 5-3

FIGURE 5-3. SUTRON CALIBRATION (S/N 90SC1) 5-4

FIGURE 5-4. ARMTEC CALIBRATION (S/N 171) 5-4

LIST OF FIGURES (Cont.)

Figure **Page**

FIGURE 5-5. BELFORT HOT-WIRE CALIBRATION (S/N 10066) 5-5

FIGURE 5-6. ROSEMOUNT CALIBRATION (S/N LLWAS1) 5-5

FIGURE 5-7. ROSEMOUNT CALIBRATION (S/N LLWAS2) 5-6

FIGURE 5-8. HYDRO TECH CALIBRATIONS (S/N 131, 132) 5-6

FIGURE 5-9. R. M. YOUNG: LOW SPEED 5-8

FIGURE 5-10. CLIMATRONICS: LOW SPEED 5-8

FIGURE 5-11. VAISALA: LOW SPEED 5-8

FIGURE 5-12. BELFORT CUP: LOW SPEED 5-8

FIGURE 5-13. HYDRO TECH: LOW SPEED 5-8

LIST OF TABLES

Table **Page**

TABLE 2-1. LLWAS ICING TEST ANEMOMETERS 2-1

TABLE 3-1. ICING CHAMBER TEST RESULTS 3-3

TABLE 4-1. SUMMARY OF SAO WEATHER REPORTS FOR NOVEMBER 27, 1990 ICING EVENT 4-6

TABLE 4-2. SUMMARY OF SAO WEATHER REPORTS FOR MARCH 12, 1991 ICING AND SNOW EVENTS 4-6

TABLE 4-3. SLOPE AND OFFSET ADJUSTMENTS FOR DATES OF SELECTED EVENTS 4-8

TABLE 4-4. SLOPE AND OFFSET ADJUSTMENTS FOR DATES OF SELECTED EVENTS 4-8

TABLE 4-5. SUMMARY OF CASE STUDIES 4-10

TABLE 5-1. RELATIVE DEGRADATION OF WIND SPEED RESPONSE (%) DUE TO CONTAMINATION 5-7

LIST OF ACRONYMS

AR - Armtech
BC - Belfort Cup and Vane
BH - Belfort Hot Wire
CL - Climatronics
DAS - Data Acquisition System
HY - Hydrotech
IC - Ice Crystals
IP - Ice Pellets (sleet)
L - Drizzle
LLWAS - Low Level Windshear Alert System
MTBF - Mean Time Between Failures
NWS - National Weather Service
QL - Qualimetrics
R - Rain
RS - Rosemount
S - Snow
SAO - Surface Aviation Observation
SG - Snow Granules
S/N - Serial Number
ST - Sutron
SW - Snow Shower
VS - Vaisala
YG - R. M. Young
ZL - Freezing Drizzle
ZR - Freezing Rain

EXECUTIVE SUMMARY

This report describes the laboratory and field tests that were conducted to determine the performance characteristics of icing resistant anemometers required for the next generation of Low Level Windshear Alert System (LLWAS) installations. The decision to deploy icing resistant anemometers was made in response to field reports of system outages caused by ice storms. The Volpe National Transportation Systems Center, Surveillance and Sensors Division, DTS-53, conducted these tests during FY-90 and FY-91 under the sponsorship of the FAA LLWAS Project Office ANW-150.

The goals of this evaluation were threefold:

1) To encourage the development by industry of icing resistant anemometers,

2) To aid in establishing a sensor specification for the Federal Aviation Administration (FAA) Low Level Windshear Alert System Expanded Network (LLWAS-EN) procurement, and

3) To provide information to potential system contractors and to proposal evaluators concerning the performance of the different sensor technologies.

These steps were intended to reduce the sensor risks associated with the LLWAS-EN procurement. The tests were *not* designed to qualify sensors for LLWAS-EN since they did *not* cover many critical system requirements such as reliability.

Test participation requirements were formally advertised and all qualified responses were accepted into the test program. Ten sensor types utilizing five different technologies were accepted for testing:

1) Four mechanical cup/vane types,

2) Three hot-film types,

3) One pressure-sensing type,

4) One heat-sensing type, and

5) One mechanical propeller/vane type.

Before sensors were deployed for field testing, they had to pass an icing chamber test. The results of the icing chamber tests were the following:

1) A number of manufacturers redesigned and/or increased the de-icing heat in order to pass the icing test.

2) The heat-sensing type was eliminated.

3) Although the propeller/vane anemometer failed the icing chamber tests, it was included in the subsequent field and wind tunnel tests as a reference during non-icing conditions.

4) The icing chamber was demonstrated to be a valid test method for determining a sensor's icing susceptibility.

The field tests were conducted from November 1990 through July 1991 at the Rochester Municipal Airport in Rochester, Minnesota. All eight units that passed the icing chamber tests were unaffected by the relatively light icing conditions encountered during the winter of FY91. One mechanical cup/vane type, however, was affected by snow. The mechanical propeller/vane type which failed the chamber tests was also slowed by ice during one event.

A wind tunnel test was conducted after the field test to study observed field anomalies in the sensor calibrations and to measure directly the starting thresholds for the mechanical sensors. The wind-tunnel measurements were more precise than the field measurements, but the results were consistent. All laboratory testing was carried out at the NWS Sterling Research & Development Center.

No clear "winner" resulted from these tests. Before the tests, it was hoped that the sensors with no moving parts would provide the best hope for meeting the reliability and maintenance requirements of LLWAS-EN. Mechanical sensors, however, turned out to provide the best combined icing and accuracy performance. Each of the four sensor technologies that passed the icing chamber tests had its strengths and weaknesses:

- Mechanical cup/vane anemometers performed well (except for one unit which slowed down in snow) but their reliability may be inadequate. For example, some units provided power to sensor heaters through slip rings, which could pose reliability problems.

- Hot-film anemometers can resist icing but are susceptible to contamination from jet exhaust, salt spray, natural fibers, dust, etc. that can significantly degrade their accuracy. A proposed new "self-cleaning" hot-film anemometer design, however, may be worth further testing.

- The pressure-sensing units tested had inadequate dynamic range for LLWAS (in contrast to previously tested units). Some laboratory accuracy testing may be worthwhile for another pressure-sensing type that has recently become available on the market.

- The thermal-sensing units were damaged in shipment, and therefore, never properly tested. Because this sensor concept appears to be quite compatible with the concept of the LLWAS integrated remote system, laboratory icing and wind-tunnel accuracy testing of this concept would be worthwhile.

Reliability and maintainability studies should be performed to evaluate tradeoffs between alternative sensor technologies to reduce risk in the LLWAS-EN specification.

1. INTRODUCTION

1.1 SCOPE

This report describes the laboratory and field tests that were conducted to determine the performance characteristics of icing resistant anemometers required for the next generation of Low Level Windshear Alert System (LLWAS) installations. This evaluation is intended to aid in establishing a sensor specification for the Federal Aviation Administration (FAA) Low Level Windshear Alert System-Expanded Network (LLWAS-EN) procurement in order to reduce the risk associated with sensing wind changes under adverse weather conditions. The Volpe National Transportation Systems Center, Surveillance and Sensor Division, DTS-53, conducted these tests during FY90 and FY91 as part of the support to the FAA LLWAS Project Office ANW-150.

1.2 BACKGROUND

The Low Level Windshear Alert System (LLWAS) program is an element of the FAA Integrated Windshear Program Plan issued in April 1987. The integrated plan was developed by the FAA in cooperation with the aviation industry, the meteorological research community, and other governmental agencies. It encompasses ground and airborne sensors, as well as aircrew education and training.

The FAA LLWAS measures wind speed and wind direction from sensors located on or around the periphery of airports, computes whether hazardous windshear or microbursts are present, and displays the information to air traffic controllers. A warning of the hazard is then passed to the pilots.

The FAA LLWAS program has resulted in the scheduled installation of systems with a minimum of six sensors each at 110 airports throughout the nation. The installation is now complete and a two-step enhancement program is underway to upgrade the present systems. The upgraded systems have already proven themselves effective. The most dramatic event occurred at Denver in the fall of 1989 when the enhanced LLWAS system installed there detected a violent microburst and prevented the loss of a Continental flight on final approach.

Because of the increased awareness of the importance of the LLWAS system and the mounting logistic costs of the expanded systems, the FAA is planning to replace the existing systems with a new Low Level Windshear Alert System-Expanded Network (LLWAS-EN). This system will include improved sensors, communications, processors, and displays.

Prior to LLWAS-EN, eight of the existing systems will be upgraded to the LLWAS - Network Expansion configuration which is functionally equivalent to LLWAS-EN. Both of these systems will increase the density of sensors, eliminate wind sensor sheltering and provide runway-oriented windshear alerts.

Over the past ten years, the Volpe Center has had an ongoing program to test and evaluate weather sensors for the FAA, NWS, and other government agencies. In 1987 through 1989, tests were conducted at three airports in Massachusetts to evaluate anemometers under icing and snow conditions for the FAA LLWAS program. The results of these tests are published in the following two FAA Project Memoranda: DOT-TSC-FA915-PM-88-28, *Evaluation of Wind Sensors for the FAA Low Level Windshear Alert System* and DOT-TSC-FA015-PM-89-24, *Evaluation of Sutron Wind Sensors for LLWAS.* Although certain sensors were significantly better than others in handling ice and snow, no sensor met all the LLWAS requirements.

As a result, the FAA requested the Volpe Center to continue the tests in Rochester, Minnesota to provide better information for the LLWAS-EN sensor specification and to help insure the successful implementation of the next generation LLWAS-EN system. Rochester, Minnesota showed the highest incidence of icing at LLWAS airports in a climatological study covering 26 years of data.[1]

1.3 TEST CHRONOLOGY

The test program was formally advertised in the Commerce Business Daily (CBD) on June 19, 1990 and July 27, 1990; the requirements for test participation were sent to all interested parties. The responses to the test requirements were evaluated and ten sensor types were accepted into the program. The Volpe Center leased ten pairs of anemometers for test and evaluation over a one-year period. Icing chamber tests were conducted at the National Weather Service (NWS) Sterling Research & Development Center in Sterling, Virginia. Anemometers that successfully passed these tests were then installed at the field test site in Rochester, Minnesota. The first group of sensors was installed in November 1990 and the last group was installed in late February, 1991. Upon completion of the field tests in July 1991, all anemometers were returned to Sterling, Virginia for wind tunnel tests which were completed in September 1991.

1.4 OBJECTIVES

The objectives of this test program were as follows:

- Reduce Risk for LLWAS-EN Procurement
- Alert Industry to the Requirement for Icing Resistant, Low Maintenance, High Reliability, Long Life Anemometers
- Develop Sensor and System Specifications
- Develop Test Procedures

- Provide Data That Will Enable Both the Government and Industry to Select the Best Sensor Technology

Note that this program was not complete enough to be a sensor qualification test. For example, the critical areas of reliability and maintainability were not addressed.

1.5 SENSOR AND SYSTEM SPECIFICATIONS

Appendix A lists the test sensor performance specification and requirements released with the Commerce Business Daily announcement. It was based on the understanding of the LLWAS performance requirements at that time and was also intended to describe the interface requirements to allow communication with the test data acquisition system. Appendix B lists the preliminary LLWAS-EN system specification that is intended to be updated as a result of the test activities and associated studies.

2. SENSORS

2.1 WIND SENSORS ACCEPTED

The ten wind sensor types selected for evaluation from the CBD responses are listed in Table 2-1. Two units of each type were tested to assess performance consistency and to permit sensor failures to be distinguished from performance deficiencies. Five different sensor technologies were represented:

1) Mechanical cup/vane (four types),
2) Mechanical propeller/vane (one type),
3) Pressure sensing (one type),
4) Hot-film (three types), and
5) Thermal sensing (one type).

The first two technologies use moving parts; the last three do not, and hence, might be expected to be more reliable. The mechanical anemometers measure wind speed by means of a structure which rotates at a rate proportional to the wind speed. The pressure anemometer measures the wind speed as an induced pressure that is proportional to the square of the wind speed. The hot-film and thermal anemometers measure the cooling effect of the wind.

The tested anemometers and their characteristics are listed in Table 2-1. The codes in the first column of this table are used as a short way of identifying the sensors in plots and other situations in this report. The names, addresses and telephone numbers of the manufacturers are listed in Appendix C. Photographs of the sensors are presented in Appendix D.

TABLE 2-1 LLWAS ICING TEST ANEMOMETERS

CODE	TYPE	MFG	MODEL	HEAT	WATTS	PHOTO
YG1,YG2	PROP & VANE	R.M. YOUNG	1774MS	RADIANT/EXTERN	600 W	D-5
HY1, HY2	CUP & VANE	HYDROTECH	WS3, WD3	RADIANT/INTERN	1000+ W	D-11
CL1, CL2	CUP & VANE	CLIMATRONICS	TACHMET	RADIANT/EXTERN	1000+ W	D-8
BC1, BC2	CUP & VANE	BELFORT	2000	CONDUCTIVE	110 W	D-9
VS1, VS2	CUP & VANE	VAISALA	WAA 15A	CONDUCTIVE	20 W	D-9
ST1, ST2	HOT FILM	SUTRON	8600	DIRECT	100 W	D-10
BH1, BH2	HOT FILM	BELFORT	270	DIRECT	100 W	D-6
AR1, AR2	HOT FILM	ARMTEC	200	DIRECT	500 W	D-13
RS1, RS2	PRESSURE	ROSEMOUNT	1774MS	CONDUCTIVE	150+ W	D-12
QU1, QU2	THERMAL	QUALIMETRICS	3056	DIRECT	50+ W	NONE

The Qualimetrics heat sensors did not pass the Sterling icing chamber tests and were not installed at the Rochester Field Site because of damage in shipment and the manufacturer's failure to resubmit them for further tests. The Young propeller/vane sensors also failed the Sterling icing chamber tests, but a decision was made to include them in the Rochester field tests for comparison with earlier icing tests and LLWAS field experience (the Young type is used in the Climatronics LLWAS).

2.2 THEORY OF OPERATION OF THE SENSOR TYPES

1) Mechanical Vane - The weather vane is the oldest wind instrument. The modern versions of the vane sense the wind direction with several different types of angle transducers: a) potentiometer (YG, BC), b) optical encoder (VS, BC), or c) synchro.

2) Mechanical Cup - The cup anemometer is likely the oldest wind speed instrument. It operates on the difference in drag between the convex and concave sides of a cup. Three cups rotate around a vertical axis at a rate proportional to the wind speed. The cup rotation rate can be measured by an electric tachometer (YG, HY) or a light chopper (VS, BC). A vane can be combined with a cup anemometer in two configurations: coaxially (CL) or separated (VS, BC, HY).

3) Mechanical Propeller - A propeller operates on the lift principle and is designed to rotate on an axis pointed into the wind at a rate proportional to the wind speed. The rotation rate of the propeller can make use of a generator, tachometer (YG), or light chopper. The propeller is mounted on the front of a wind vane to keep it pointed into the wind.

4) Pressure Sensing - A pressure-sensing anemometer (RS) consists of a vertical cylindrical sensing probe containing four pressure chambers. Differential pressure sensors measure the difference in pressure between the chambers on opposite sides of the cylinder. Orifices connecting the chambers to the outside atmosphere are located around the cylinder. The orifice design is intended to provide a differential pressure that is proportional to the square of the wind component in the direction of the two opposite chambers. The component sign is determined by the sign of the pressure difference. The sensing probe is strongly heated to prevent icing.

5) Hot Film - A hot-film anemometer (ST, AR, BH) measures the wind-induced cooling on a horizontal element consisting of an insulating rod covered with a platinum thermal-resistive film (TRF). The film serves both to heat the element and measure its temperature. The element temperature is kept at a constant offset above ambient (e.g., 100 degrees C) and the wind cooling is sensed as the power required to maintain this offset, which is related to the wind speed by King's law. A complete wind sensor consists of two perpendicular elements that measure the two components of the horizontal wind. The film on each element is split so that the side of the element experiencing the most cooling can be sensed and used to

determine the sign or direction of the wind component. The two elements are covered by a protective cap to keep rain off the elements. Ambient temperature and pressure are monitored by the anemometer to compensate the wind measurements for changes in air density. The cap and base of the unit are heated to prevent icing.

6) Thermal Sensing - A thermal field anemometer (QL) measures both wind speed and direction using a vertical cylindrical sensing element that is much larger than a hot-film anemometer, and hence, should be less affected by contamination. The sensing element contains a heater surrounded by eight temperature sensors. The cylinder is maintained at a constant average temperature. With no wind, the thermal field of the cylinder is uniform and all temperature sensors read the same value. When the wind blows, the thermal field changes, becoming cooler on the side facing the wind. Because the transducer is cylindrical, the thermal field forms a symmetrical parabolic shape. The eight measured temperatures are processed to determine the parabolic form: the depth of the parabola related to the wind speed and its orientation to the wind direction. The anemometer monitors ambient temperature and pressure to compensate and correct the wind measurements. The unit is covered with a cap to prevent rain from hitting the sensing element. The cap and base are heated to prevent icing.

2.3 WIND SENSOR DESCRIPTIONS

The last section described most sensor characteristics. Only those sensors requiring further discussion will be included in this section.

VAISALA MODEL WAA 15A & BELFORT MODEL 2000 CUP/VANE ANEMOMETERS

These two cup/vane anemometers used similar heating methods. The vertical bearing shafts were heated with internal heaters. The cups and vanes, which are fabricated of metal, were heated with stick-on electrical heating elements that were powered through slip rings.

CLIMATRONICS MODEL TACHMET 102059 CUP/VANE ANEMOMETER

The Tachmet sensor has two types of heaters: a heater on the area around the bearings to prevent any icing on the bearings proper, and the balance of the heat provided by eight radiant heaters located on a one-foot diameter around the metal cup and vane assembly.

HYDRO-TECH MODEL WS-3, WD-3 CUP/VANE ANEMOMETER

In this unit, the conventional cup and vane design was significantly modified (see Figure D-11) to greatly increase the thermal conductivity to all exposed surfaces of the unit. The basic design is similar for both cup and vane and consists of a heavy aluminum rotor 3 in. high and 12 in. in diameter. The rotor is heated internally with a 1500 Watt "Cal Rod" stove-top element which is controlled by a sensing element close to the top of the rotor. The rotor temperature at that point is normally maintained at 90 degrees F. The "cup" wind speed unit is constructed by welding a number of aluminum half cylinders to the edge of the rotor. A large vane is welded to the wind direction unit.

R.M. YOUNG MODEL 05103 PROPELLER & VANE WIND MONITOR

The main housing, nose cone, propeller, and other internal parts are injection molded U.V. stabilized plastic. The de-icing system (Model 15203) consists of four heat lamps (See Figure D-5) which are powered when the ambient temperature is between -7 degrees C and 2 degrees C.

2.4 REFERENCE SENSORS

No reference wind sensor was installed. The consensus of the test sensors was used as the best estimate of the wind at the test area.

The weather conditions during the test were determined from the NWS surface observations (SAO). The wind for these observations comes from the center field anemometer, located about one mile from the test area.

Two additional sensors were installed in the test area to augment the SAOs with minute-by-minute data on icing, temperature, visibility, precipitation type, and precipitation amount:

1) A Rosemount icing sensor measured the amount of ice building up on a one-inch vertical rod (detection threshold of 0.01 inches of ice). The data acquisition system was programmed to de-ice the Rosemount sensor in accordance with the NWS icing sensor algorithm of that time. Essentially the sensor was de-iced whenever ice stopped building up. In most icing events, this algorithm resulted in a series of sensor de-icing cycles.

2) An HSS present weather sensor measured temperature, visibility (forward-scatter), precipitation type (rain, snow, drizzle), and precipitation amount. The HSS precipitation algorithm detects precipitation particles in the sensor scatter volume and compares forward and backward scattering to assess the type and amount precipitation. It generally works well for precipitation rates above 0.01 inches/hour (liquid water content). For lower rates, when it cannot distinguish the precipitation type, it simply reports "precipitation." The HSS algorithm is not very sensitive to drizzle and/or to rain mixed with fog.

3. LABORATORY ICING CHAMBER TEST

According to the test plan, the anemometers submitted by the manufacturers were required to undergo individual laboratory tests before being considered for installation at the field test site in Rochester, Minnesota.

The laboratory testing was performed by Volpe Center personnel in the Tenney cold test chamber at the NWS Sterling Research & Development Center in Sterling, Virginia. Upon receipt, the sensors were unpacked, set up and interfaced to a simplified version of the Rochester data acquisition system (DAS) described in Appendix F. After the sensor was observed to operate correctly and log data onto the DAS, it was mounted in the Tenney cold chamber. One or two sensors of each type were installed depending upon their space requirements. Sensors were then subjected to the controlled icing test described in the next section.

The sensors that passed the icing test were shipped to the Rochester test site for installation. The sensors that failed the icing test were returned to the manufacturer for possible improvement. When satisfactory improvements were made, the sensors were accepted for further testing.

3.1 PROCEDURE

To carry out the icing test, the following equipment was installed in the Tenney cold chamber:

1) A rain/drizzle nozzle operating with water and compressed air. The water passed through an ice bath before entering the chamber. To prevent freeze up, the water line was kept empty until the spraying began and the nozzle was heated with an electric wrap-around heater.

2) A large blower fan capable of generating winds greater than 10 meters-per-second.

3) An EG&G temperature/dew-point sensor used to monitor the chamber temperature in degrees Fahrenheit.

4) The anemometer(s) to be tested were mounted on a suitable fixture. The anemometer was positioned so that it was exposed to both the rain/drizzle from the nozzle and the wind from the blower fan.

The icing tests performed on the candidate LLWAS anemometers were derived from a procedure used by the NWS for freezing rain testing in the Tenney cold chamber. Sensor failure due to icing was determined by visual inspection. The output of the sensors was displayed on the DAS.

The chamber icing test consisted of the following steps:

1) The temperature of the chamber was lowered to -30° F, with the fan turned on and off intermittently to see if the sensor(s) responded properly.

2) When the chamber temperature was attained and stable at -30° F, a cold soak was begun. The cold soak continued for one hour to cool off all of the equipment.

3) Upon completion of the one-hour cold soak, the temperature of the chamber was raised to +20° F. This transition was monitored to make sure it took at least 30 minutes.

4) After the chamber has been at +20° F for five minutes, the spraying began. The rain/drizzle nozzle was operated with as fine a spray as possible for at least one hour or until the sensor was seriously iced up (whichever occurred first). The blower was turned on intermittently after the first fifteen or twenty minutes of spraying to verify that the sensor was still operating satisfactorily.

5) If within the hour of spraying, the anemometer had failed or exhibited decreased performance outside of the LLWAS specification, the sensor will have failed the chamber icing test. The failed sensor would then be removed from the chamber and returned to the manufacturer with the results of the testing and suggestions for improvements that should be made before further testing.

6) If after the hour of spraying the anemometer had not exhibited decreased performance outside of the LLWAS specification, the sensor would have passed the chamber icing test. The passed sensor was removed from the chamber and shipped to the Rochester test site for installation.

7) The output of the anemometer was recorded on the data acquisition computer throughout the test period.

8) A log of all testing was maintained by the test engineer.

3.2 RESULTS

The anemometer laboratory tests were performed on four separate occasions as the sensors became available. The first three anemometer(s) tested were subjected to a more severe criteria of spraying at a temperature of +10° F rather than at +20° F as mentioned in the procedure above. This alteration in the procedure to spraying at +20° F was adopted after +10° F was found to be too extreme for the desired testing.

A summary of the test results is contained in Table 3-1. More details may be found in Appendix E.

TABLE 3-1 ICING CHAMBER TEST RESULTS

MANUFACTURER	*SENSOR TYPE*	*TEST DATE*	*QTY*	*RESULTS*	*COMMENTS*
ROSEMOUNT	PRESSURE	10/18/90	2	PASSED	SPRAYED AT +10 DEG F
BELFORT	HOT WIRE	10/18/90	1	FAILED	SPRAYED AT +10 DEG F
BELFORT	HOT WIRE	11/30/90	1	PASSED	INCREASED HEAT POWER
SUTRON	HOT WIRE	10/23/90	2	FAILED	SPRAYED AT +10 DEG F
SUTRON	HOT WIRE	10/24/90	2	PASSED	INCREASED HEAT POWER
ARMTEC	HOT WIRE	11/30/90	2	PASSED	
CLIMATRONICS	CUP & VANE	10/25/90	2	PASSED	
BELFORT	CUP & VANE	11/27/90	1	PASSED	
HYDRO TECH	CUP & VANE	12/01/90	1	PASSED	
VAISALA	CUP & VANE	02/20/91	1	PASSED	
R.M. YOUNG	PROPELLER	01/11/91	1	FAILED	INSTALLED IN FIELD AS REFERENCE
QUALIMETRICS	THERMAL	11/28/90	2	FAILED	
QUALIMETRICS	THERMAL	02/21/91	2	FAILED	DAMAGED IN SHIPPING

4. FIELD TESTS

4.1 SITE DESCRIPTION

The test site was located at the Rochester Municipal Airport near the two-story building housing a branch of the National Weather Service. The data acquisition system was located in a first-floor office of the building. The test sensors were located in the front yard of the building (to the northeast) about 150 feet away. Figure 4-1 shows the location of the test area with respect to the three nearby buildings, the NWS building, and two large hangars. These buildings affect winds blowing from south through northwest.

Figure 4-2 shows the detailed layout of the test area. The sensors were mounted on twenty-one 10-foot poles which were installed in three rows of seven. Each pole was equipped with a power and signal junction box. The seven poles in each row were spaced 10 feet apart and the three rows of poles were spaced 20 feet apart. The rows were oriented toward the northwest so that interference between adjacent sensors would occur for winds from the same direction already affected by the nearby hangar.

4.2 DATA COLLECTION

Appendix F describes the data collection system in detail. Its characteristics will be summarized here. The data acquisition system (DAS) was controlled by a configuration file that specified the data collection parameters for each sensor. The DAS recorded one-minute averages of the sensor measurements and had to generate the one-minute averages for those few sensors that did not provide averaged data. A new data file was generated for each day. The data and configuration files were compressed after the daily data collection was completed. The compressed files were then downloaded daily to the Volpe Center for processing.

The Rochester NWS office provided copies of the surface weather observations to assist in the data analysis.

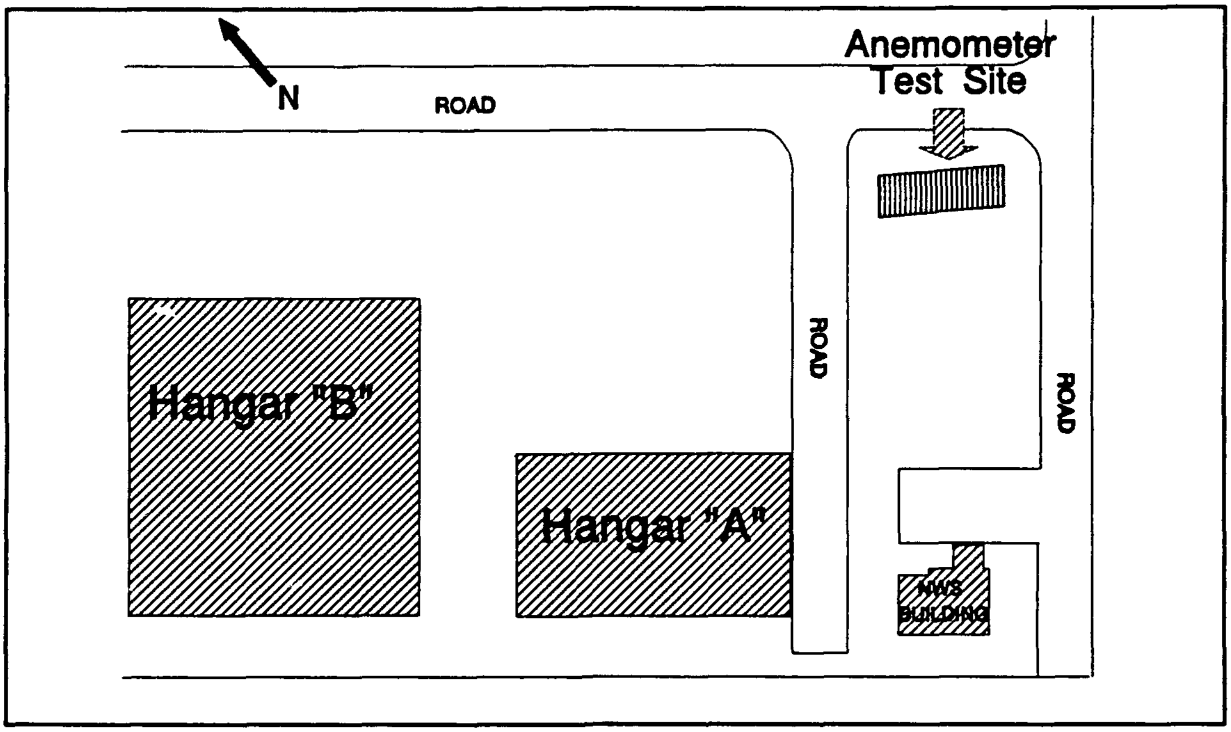
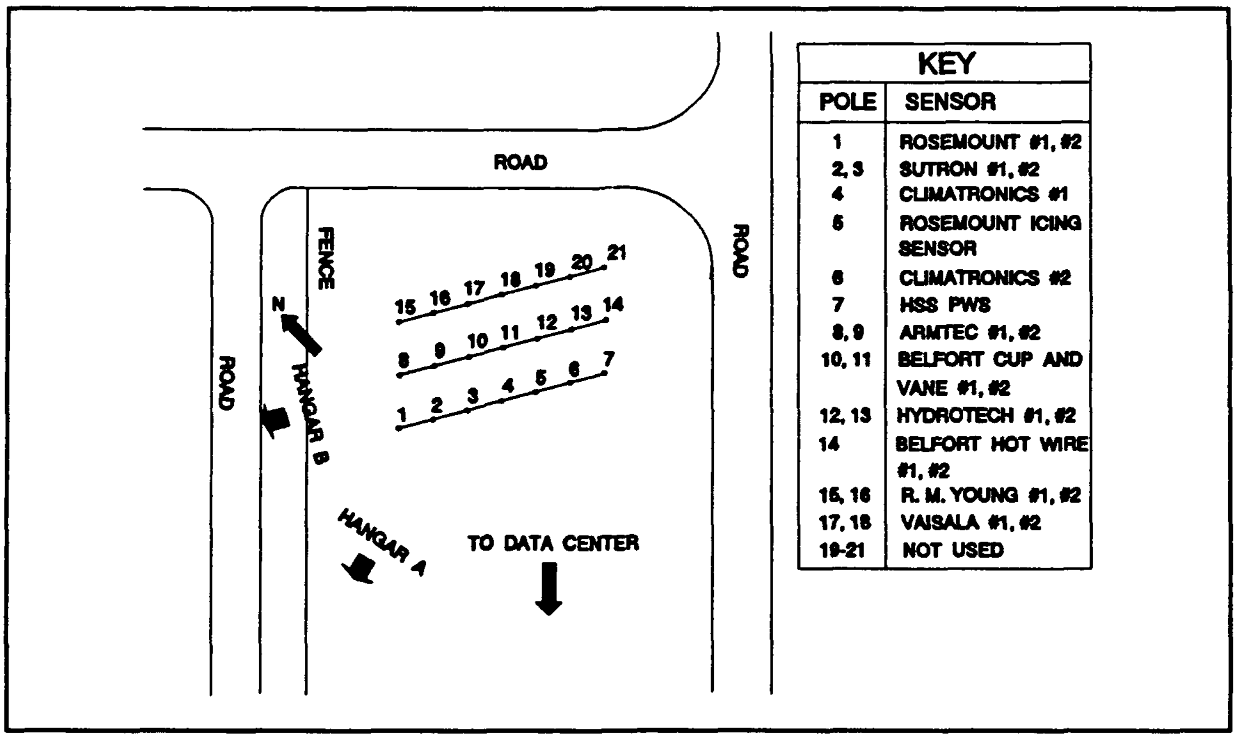


FIGURE 4-1. LLWAS TEST SITE LAYOUT



KEY

POLE	SENSOR
1	ROSEMOUNT #1, #2
2, 3	SUTRON #1, #2
4	CLIMATRONICS #1
5	ROSEMOUNT ICING SENSOR
6	CLIMATRONICS #2
7	HSS PWS
8, 9	ARMTEC #1, #2
10, 11	BELFORT CUP AND VANE #1, #2
12, 13	HYDROTECH #1, #2
14	BELFORT HOT WIRE #1, #2
15, 16	R. M. YOUNG #1, #2
17, 18	VAISALA #1, #2
19-21	NOT USED

FIGURE 4-2. DETAIL OF ANEMOMETER TEST SITE

4.3 FIELD TEST HISTORY

Figure 4.3 summarizes the percentage of time each sensor was operating and reporting useable data. Particulars of the maintenance history of each sensor are found in Appendix G. The first sensors were installed during the first week of November, 1990. The last installation date was February 28, 1991 for the Vaisala sensors. The sensors were removed from the test site on August 1, 1991.

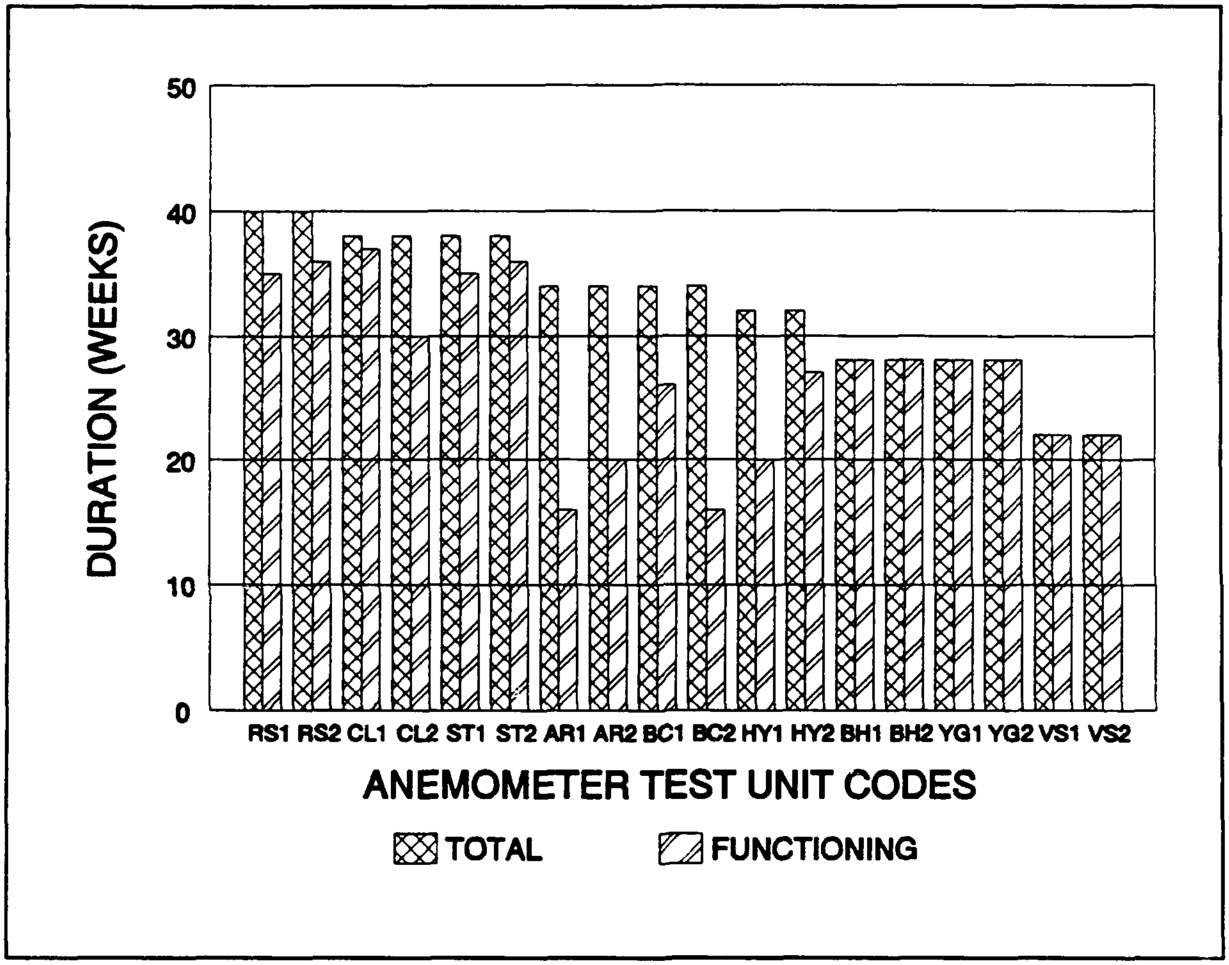


FIGURE 4-3. LLWAS WIND SENSOR EXPOSURE HISTORY

4.4 RESULTS

The results of the field tests are presented in the following sections.

4.4.1 ICING/SNOW EVENTS

All icing events occurring during the test period were analyzed. Thirty-three events were identified during the winter of 1991. The descriptions of the icing events may be found in Appendix H. Events were included if noted in the National Weather Service Surface Observations (termed SAO in the tables) or detected by the Rosemount icing sensor. Tables 4-1 and 4-2 describe the two events of the case study days of 11/27/90 and 3/12/91.

The columns in Tables 4-1, 4-2 and in Appendix H contain:

Column 1 EVENT DATE is the date of the icing event.

Column 2 PRECIP TIMES (SAO) are the times of precipitation according to the SAO report.

Column 3 PRECIP TYPE (SAO) is the precipitation type reported during each time range in Column 1 according to the SAO report. The precipitation codes used in the SAO report translate as follows:

IC	ice crystals
IP	ice pellets (sleet)
L	drizzle
R	rain
S	snow
SG	snow granules
SW	snow shower
ZL	freezing drizzle
ZR	freezing rain

A minus sign after the precipitation code means light precipitation, no sign is moderate precipitation.

Column 4 ROSEMOUNT ICING - Indicates whether or not the Rosemount Icing sensor registered a change in icing thickness according to the strip charts during the precipitation time range reported.

Column 5 TEMP RANGE - Temperature range in degrees Fahrenheit during each precipitation time range in Column 2, according to the SAO report.

Column 6 GLAZE TIME (HH.H) - Glaze time in decimal hours. The glaze time is defined as the time after the end of the last freezing precipitation time interval of the icing event day in which the temperature stayed below 32 degrees Fahrenheit, up to a maximum of 48 hours or until the start of the next icing event.

Column 7 WIND SPEED (SAO) - The wind speed range in knots reported from the SAO report during the precipitation time interval in Column 2.

Column 8 WIND GUSTS (SAO) - The wind gust speeds in knots reported from the SAO report during the precipitation time interval in Column 2.

Column 9 WIND DIRECT (SAO) - The wind direction range in degrees according to the SAO report reported during the precipitation time interval in Column 2.

Column 10 COMMENTS - Comments about the icing event. ICING SENSOR EVENT means an event in which the Rosemount icing sensor registered a thickness other than zero. SAO EVENT means an event in which freezing precipitation was recorded in the SAO report. Other comments from the SAO report or from notes attached relevant to the field test analysis are also given.

In addition to the SAO reports, precipitation rate and type (L,R,S) data from the HSS Present Weather sensor were also looked at in the analysis of events as a check.

Section 4.4.3 presents a detailed analysis of two selected icing events (11/27/90 and 3/12/91) and a snow event (3/12/91).

Snow events were not studied so systematically. After the Vaisala sensor was observed to be affected by snow, all the snow events that occurred after it was installed were examined.

TABLE 4-1. SUMMARY OF SAO WEATHER REPORTS FOR NOVEMBER 27, 1990 ICING EVENT

EVENT DATE	PRECIP TIMES (SAO)	PRECIP TYPE (SAO)	ROSE-MOUNT ICING	TEMP RANGE (SAO)	GLAZE TIME (HH.H)	WIND SPEED (SAO)	WIND GUSTS (SAO)	WIND DIREC (SAO)	COMMENTS
11/27/90	0210-0528	L-	N	32-34	39.1	10-14	18	290-300	ICING SENSOR/SAO EVENT
	0528-0722	*ZL-*	*N*	*31*		*10-15*	-	*300-320*	
	0722-0948								
	0948-1250	*ZL-*	*Y*	*29-30*		*7-11*	-	*300-340*	
	1250-1412								
	1412-1740	*ZL-*	*Y*	*30-31*		*6-12*	-	*350-30*	
	1740-1748	*ZL-,ZR-*	*Y*	*31*		*9*	-	*360*	
	1748-1830	*ZR-*	*Y*	*31*		*6-7*	-	*330-10*	
	1830-1847	*ZL-*	*Y*	*31*		*6*	-	*330*	
	1847-1922	*ZR-,ZL-*	*Y*	*31*		*10-12*	-	*310*	
	1922-2147	*ZR-,S-*	*Y*	*26-30*		*12-16*	-	*310*	
	2147-2225	S-	N	24-26		16	23	290-310	

TABLE 4-2. SUMMARY OF SAO WEATHER REPORTS FOR MARCH 12, 1991 ICING AND SNOW EVENTS

EVENT DATE	PRECIP TIMES (SAO)	PRECIP TYPE (SAO)	ROSE-MOUNT ICING	TEMP RANGE (SAO)	GLAZE TIME (HH.H)	WIND SPEED (SAO)	WIND GUSTS (SAO)	WIND DIREC (SAO)	COMMENTS
3/12/91	0237-0525	R-	N	33	31.1	18-19	23-26	100-110	ICING SENSOR/SAO EVENT
	0525-0540								R. M. YOUNG UNIT
	0540-0647	*ZR-*	*Y*	*33*		*17-20*	*24-27*	*100-110*	SLOWED SLIGHTLY FROM
	0647-0726	R-	Y	32-33		17-19	-	100	0400-0500 AND 0600-1030
	0726-0742	IP-	Y	31-32		19-20	-	90-100	
3/12/91	0742-0947	IP-,S-	Y	30-31		17-20	-	90-100	SAO SNOW/ICING SENSOR EVENT
	0947-1740	S-	N	27-30		16-24	24-30	60-100	VAISALA UNIT 1 SLOWED FROM
	1740-1839								1230-1800 AND UNIT 2 FROM
	1839-1935	S-	N	29-30		15-17	-	60-70	1100-1800 IN SNOW AND
									BLOWING SNOW

4.4.2 ANALYSIS METHOD

This section outlines the method used to assess the effect of icing or snow on the sensor wind speed performance. The same methodology was used for the earlier studies at Worcester, MA and Otis AFB, MA.[2,3] The goal of the methodology is to recalibrate all sensors so that they agree during non-icing conditions. A lower wind speed will then be observed for any sensor slowed down by icing or snow.

4.4.2.1 SCATTER PLOTS - The first step of the analysis was to compare each test sensor to a reference sensor. The first Climatronics unit was normally used as the reference sensor since it operated successfully throughout the test. Figure 4-4 shows a sample scatter plot comparing the first Sutron sensor and the Climatronics reference sensor. Each data point represents a 30-minute average. If the two sensors agreed exactly, the data points would lie on the diagonal line. In fact, the data points show a consistent offset. The scatter plot software also generates a least-square straight-line fit to the data which determines a slope and an offset which characterize the relationship between the two sensors. The data in Figure 4-4 are for three days before or after the 3/12/91 event.

4.4.2.2 TIME PLOTS - The icing analysis is based on plots of wind speed vs. time. Figure 4-5 shows a sample plot for a number of sensors on the day before the 3/12/91 event. There is considerable scatter in the readings for the different sensors. Figure 4-6 shows how the agreement of the sensors is improved when the sensors have been corrected using the slopes and offsets obtained from scatter plots like Figure 4-4.

Tables 4-3 and 4-4 show the slope and offset corrections that were used in the analysis of the two selected events. The first column of each table is the date of the event. For each sensor, a pair of numbers is given. The first number is the slope adjustment and the second number is the offset adjustment. Blank values for a particular sensor mean that the sensor was not in service.

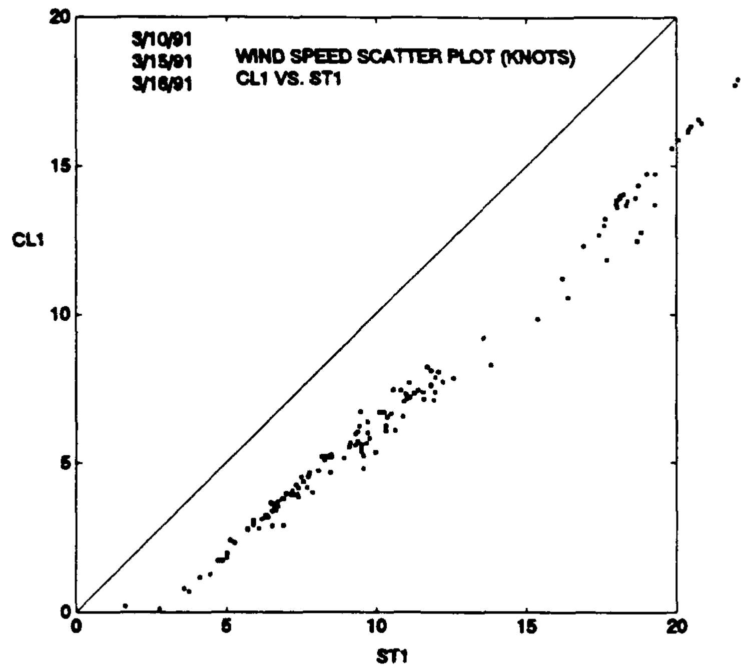


FIGURE 4-4. SCATTER PLOT OF CL1 VERSUS ST1. SLOPE = 0.889 OFFSET = 2.88

TABLE 4-3. SLOPE AND OFFSET ADJUSTMENTS FOR DATES OF SELECTED EVENTS

DATE	RS1	RS2	CL2	ST1	ST2	AR1	AR2	BC1	BC2
11/27/90	1.16,-2.30	1.06,-2.62	0.96,+0.14		0.79,-1.59				
3/12/91		0.92,+0.08		0.89,-2.88	0.90,-2.44	1.07,-2.64	1.34,-1.9	1.05,-0.81	0.99,-2.24

TABLE 4-4. SLOPE AND OFFSET ADJUSTMENTS FOR DATES OF SELECTED EVENTS

DATE	HY1	HY2	YG1	YG2	BH1	BH2	VS1	VS2
11/27/90								
3/12/91	0.95,-0.46	0.94,-0.32	0.99,-0.57	0.99,-0.57	0.76,-0.13	0.90,+0.34	0.96,+0.40	0.96,+0.45

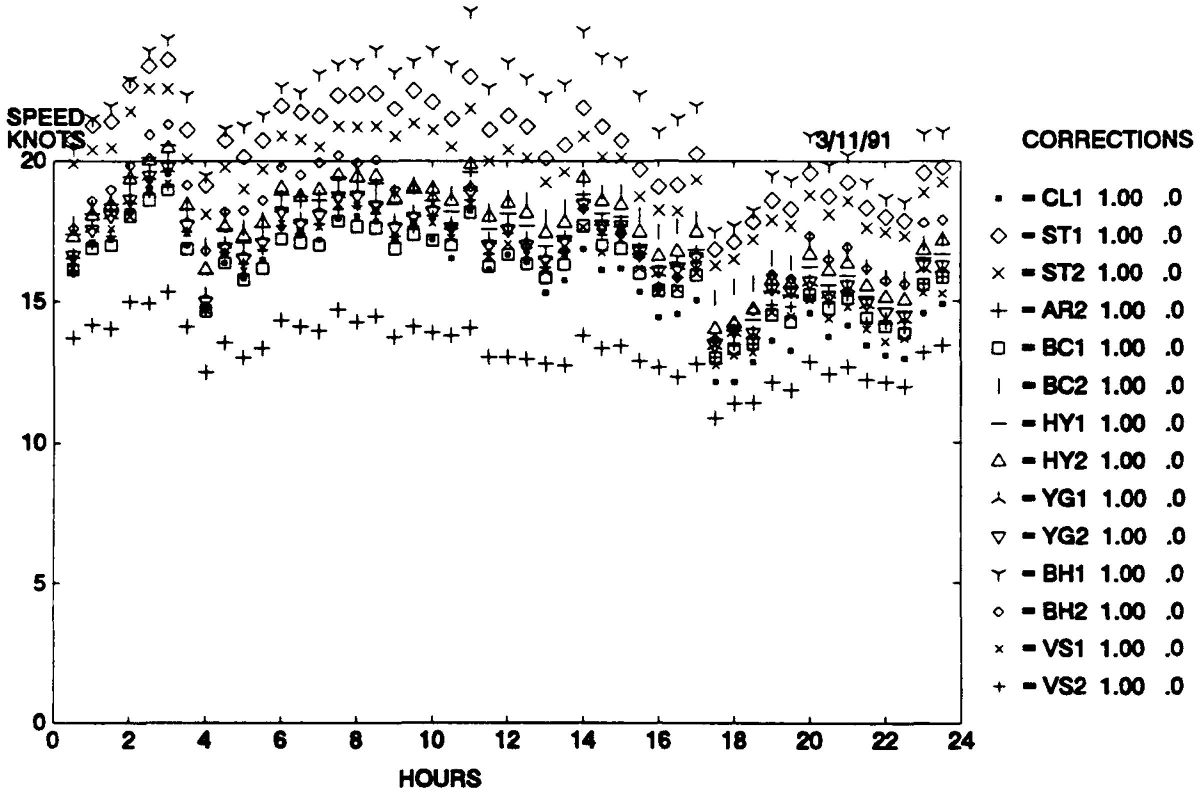


FIGURE 4-5. WIND SPEED DATA ON 3/11/91, UNCORRECTED

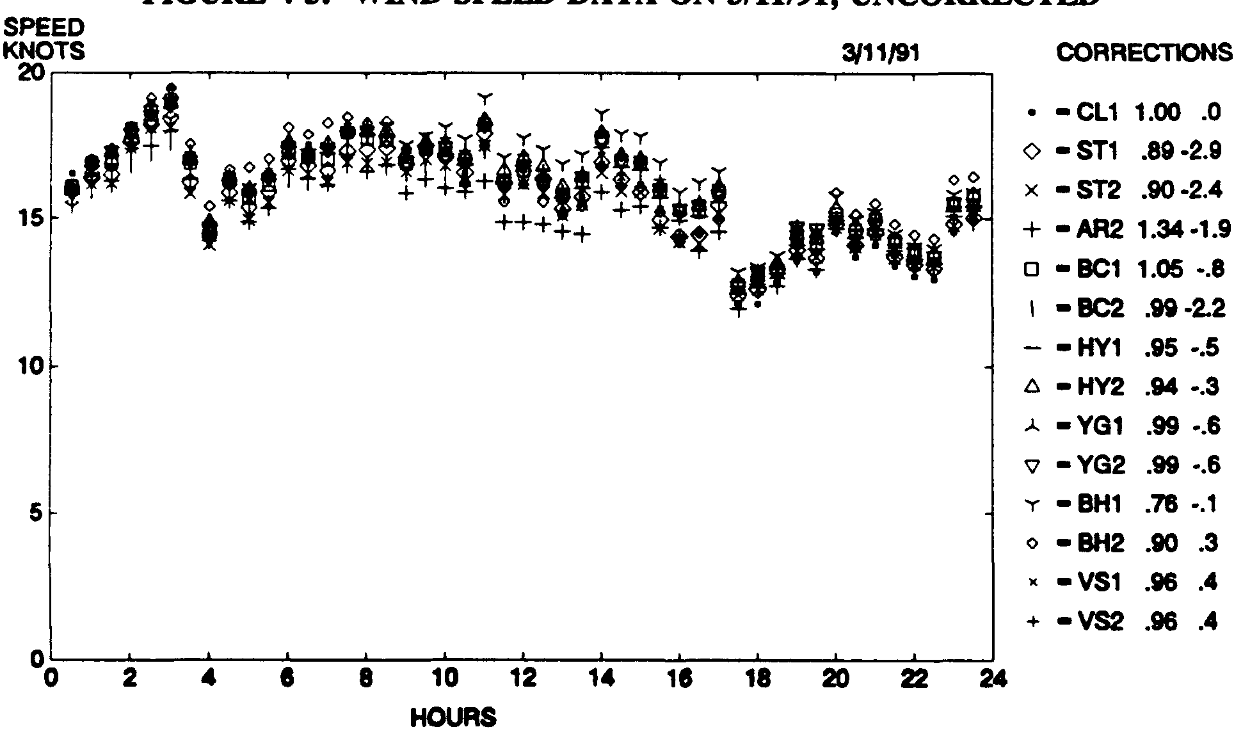


FIGURE 4-6. WIND SPEED DATA ON 3/11/91, CORRECTED

4.4.3 ANALYSIS OF SELECTED EVENTS

The events in Table 4-5 will be analyzed in further detail.

TABLE 4-5. SUMMARY OF CASE STUDIES

EVENT DATE	EVENT TYPE	PURPOSE
11/27/90	ICING	EXAMPLE OF MAJOR ICING EVENT
03/12/91	ICING	EFFECTS ON R. M. YOUNG INSTRUMENT
03/12/91	SNOW	EFFECTS ON VAISALA INSTRUMENTS

4.4.3.1 11/27/91 Event - This icing occurrence was a fairly major event; the SAO weather observer reported freezing drizzle and freezing rain for much of the day (See Table 4-1). There was a changeover to snow toward the end of the day. The Rosemount icing sensor was indicating ice build-up during much of the event. The temperatures were near 30°F during much of the icing period, but cooled slightly during the changeover to snow. The temperature remained below freezing until 11/29/91. It should be noted that only a few sensors were installed at the time of this event, and that the sensors that did show effects from icing and snow were not yet installed.

Figure 4-7 shows the wind direction for the day before the event and the two days after the event. The wind direction varied from 310° to 20° during the icing period. The wind blew much of the time around the side of the large hangar (see Figure 4-1); and therefore, some wind speed gradients across the test site could be anticipated.

Figures 4-8 through 4-11 show wind speed plots for all the sensors operating during this event, which occurred very early in the test period. Figure 4-8 shows that the two Climatronics sensors tracked well through the event; CL2 was not in service after the event. Figure 4-9 shows agreement to within 1.5 knots between ST2 and CL1 through the event and for the following day. Larger disagreements were noted on the day before and the second day after the event when the wind direction was southerly. Figures 4-10 and 4-11 show variable agreement between the two Rosemount sensors and CL1; the errors are larger at low wind speeds, as would be expected for the pressure-sensing Rosemount units.

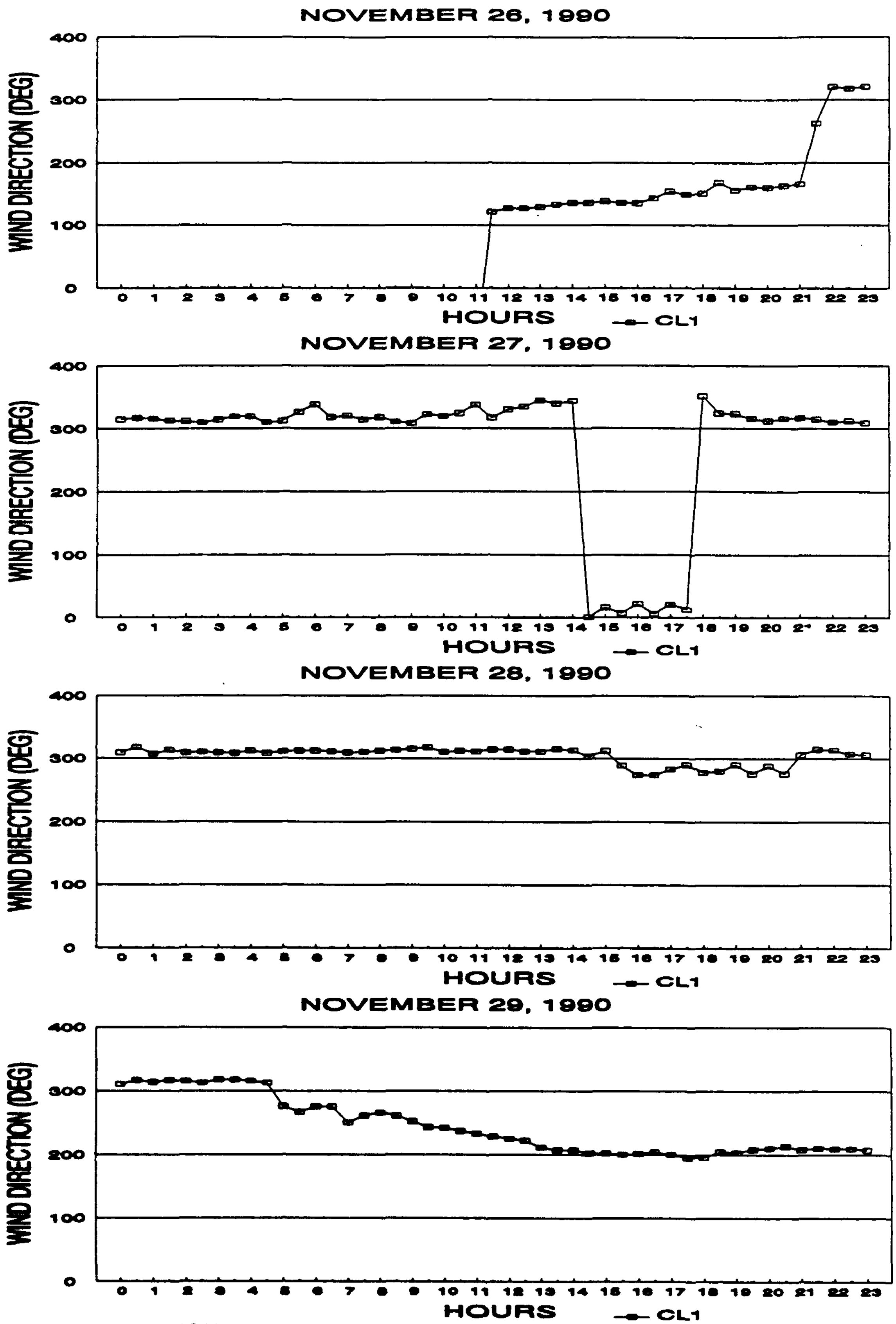


FIGURE 4-7. CL1 WIND DIRECTION ON 11/26-29/90

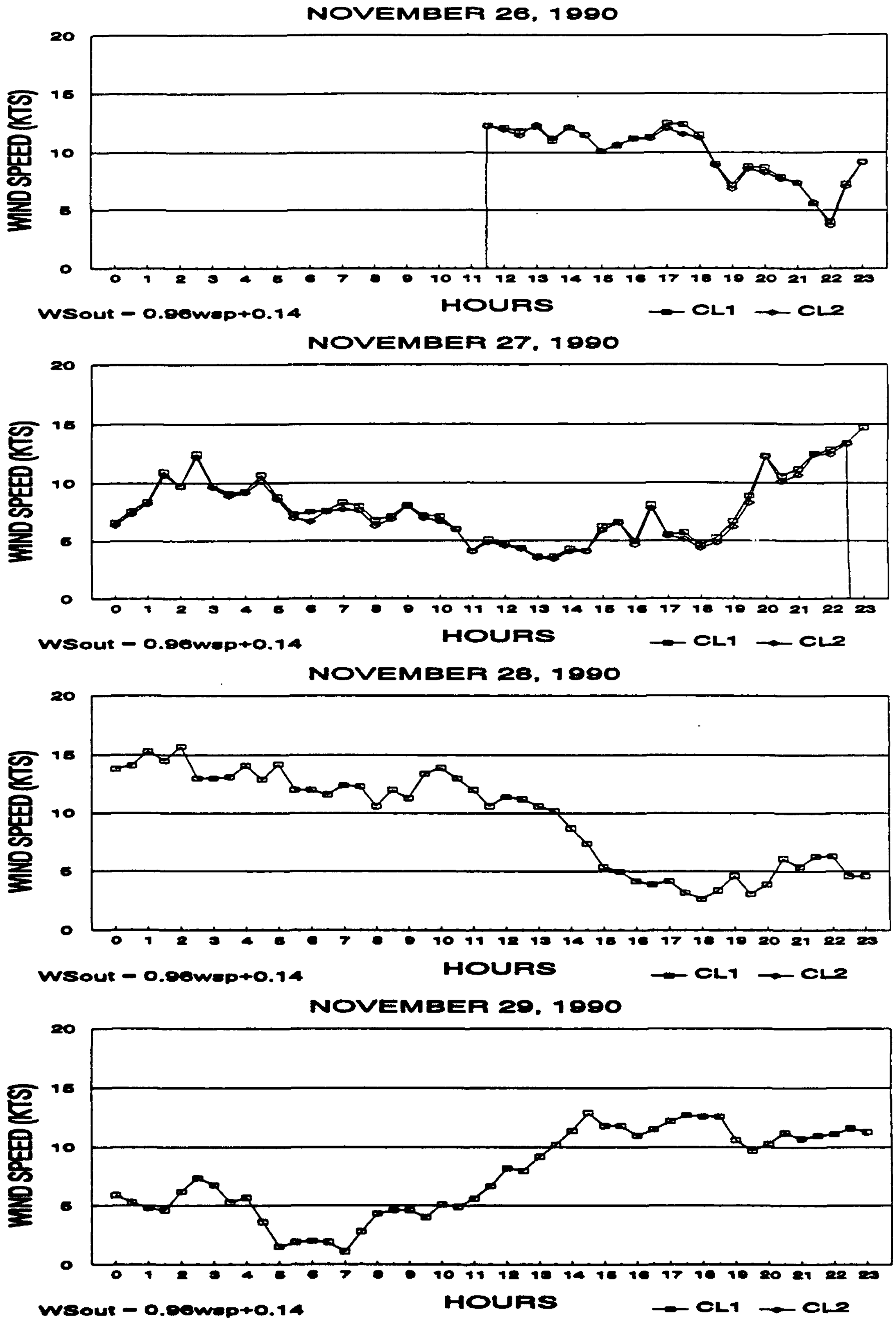


FIGURE 4-8. COMPARISON OF CL2 AND CL1 WIND SPEED ON 11/26-29/90

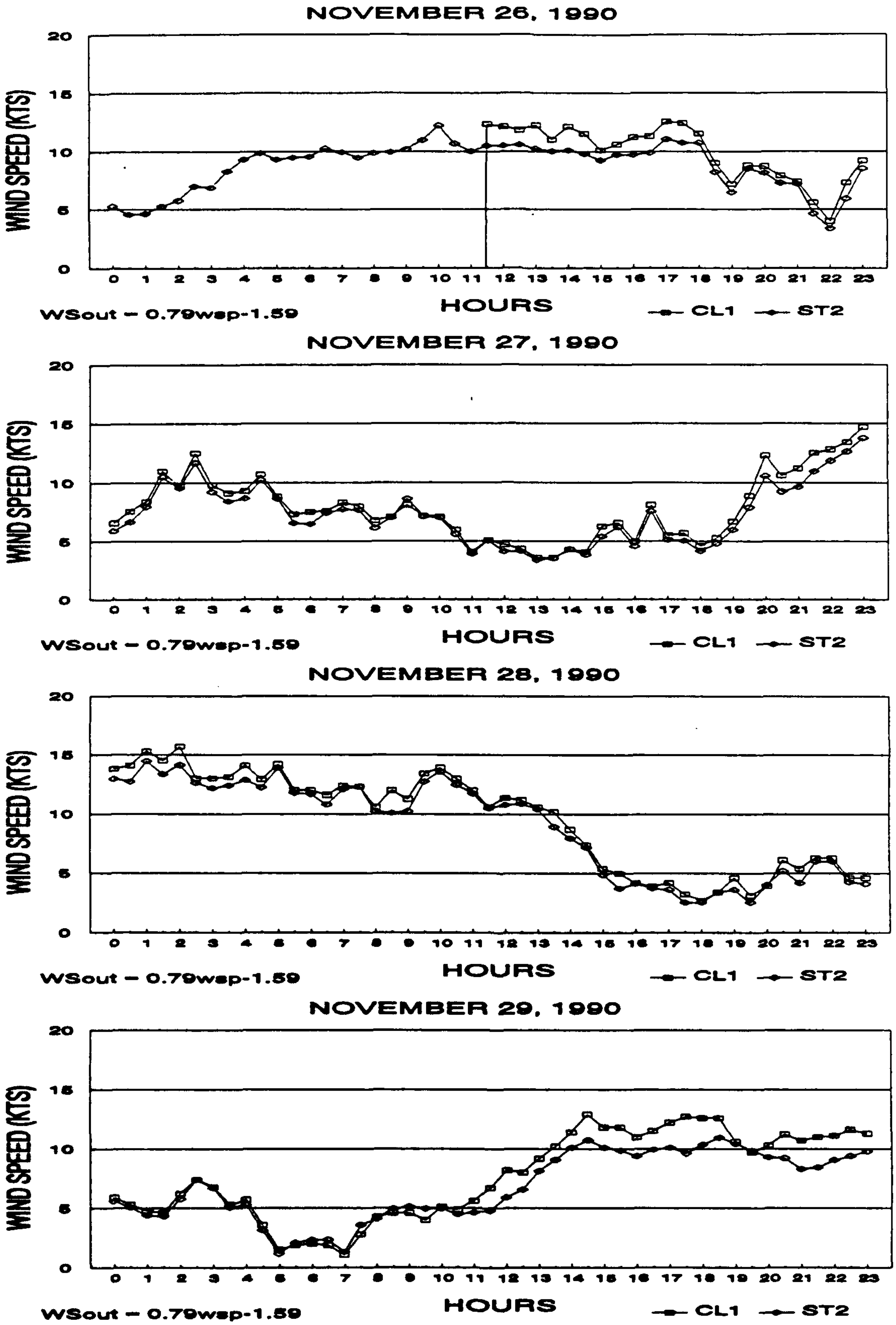


FIGURE 4-9. COMPARISON OF ST2 AND CL1 WIND SPEED ON 11/26-29/90

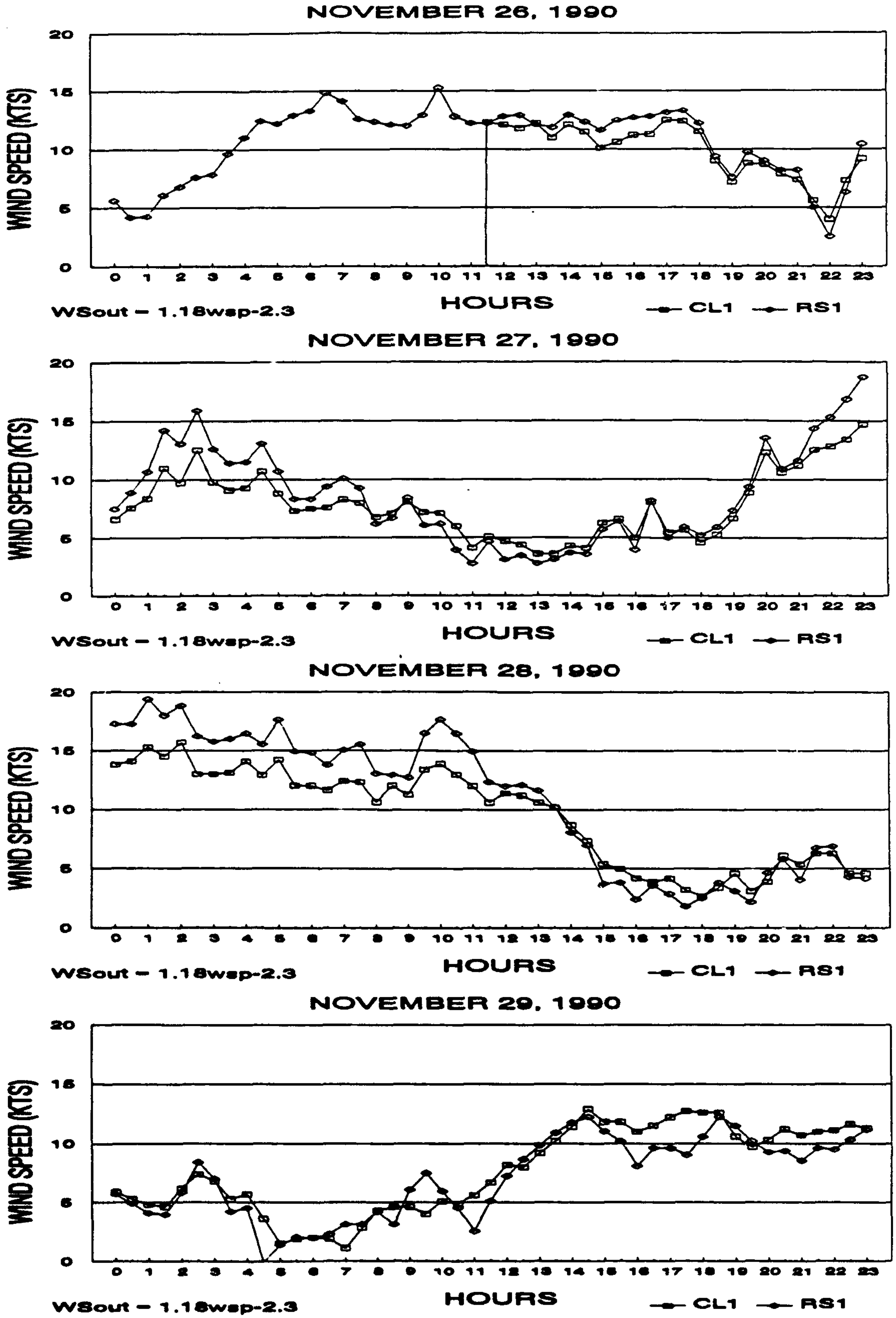


FIGURE 4-10. COMPARISON OF RS1 AND CL1 WIND SPEED ON 11/26-29/90

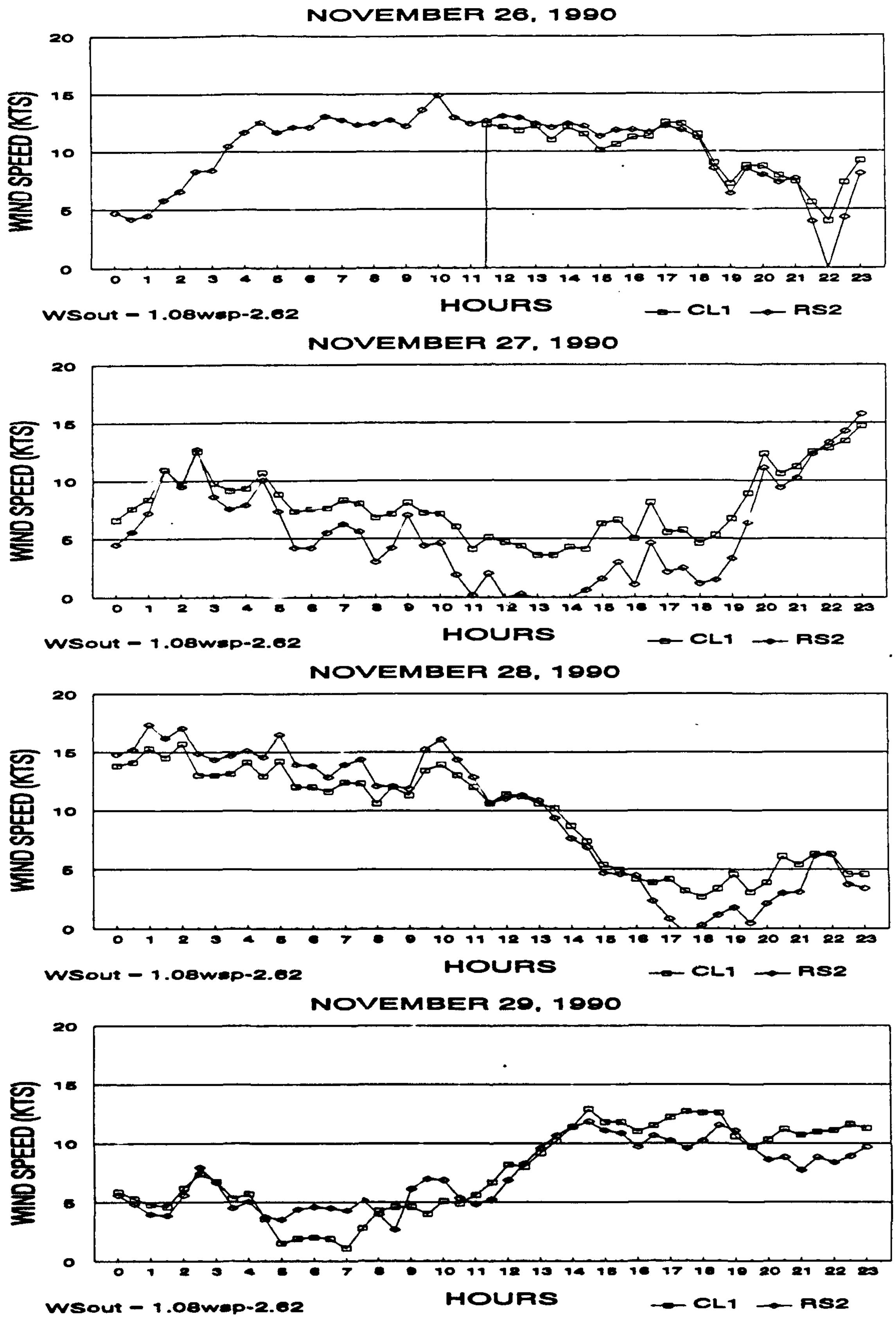


FIGURE 4-11. COMPARISON OF RS2 AND CL1 WIND SPEED ON 11/26-29/90

4.4.3.2 3/12/91 Icing Event - The March 12, 1991 icing event is an interesting case study because there is some evidence that the R. M. Young 1 sensor slowed down slightly during the icing period and early in the subsequent glazing period.

Figure 4-12 shows the wind direction (CL1) for the days around the event. Throughout this period, the wind direction was not affected by the direction of buildings near the test site (see Figures 4-1 and 4-2). Thus, building shadowing effects can be ruled out for this event. Table 4-2 lists the precipitation periods for this event, which included light freezing rain and ice pellets.

Figures 4-13 and 4-14 show wind speed plots for the two R. M. Young sensors (YG1 and YG2). In Figure 4-14, YG2 agrees well with CL1 throughout the event. In Figure 4-13, however, YG1 slowed down by 1.5-2 knots during 0400-0500 hours and during 0600-1030 hours. The maximum speed reduction was reached by 0430 and 0700 hours. The second speed reduction period corresponded to the observer's report (see Table 4-2.) of light freezing rain, icing indications from the Rosemount icing sensor, and a temperature near freezing (33 degrees). Neither the observer nor the Rosemount icing sensor indicated any icing during the first speed reduction period.

Interestingly enough, the two Hydro Tech sensors were tracking above the reference sensor by up to 2 knots, and up to 3-4 knots for units 1 and 2, respectively. This occurred at roughly between 1200-1800 hours, during the glaze period of the icing event. The Hydro Tech difference may be due to the averaging effect of turbulence on slowly responding wind sensors. Because the force on anemometers is proportional to the square of the wind speed, the acceleration forces exceed the decelerating forces so that the average rotation rate of the cups in turbulence is higher than that given by the average wind.

Most of the other sensors tracked within 3 knots or less of the Climatronics #1 reference sensor during the time period indicated in Figure 5-12. It should be noted that all the sensors were a few knots slower than the SAO's center field anemometer about a mile from the test site.

4.4.3.3 3/12/91 Snow Event - The March 12, 1991 snow event is an interesting case study because there is evidence of effects on the two Vaisala cup anemometers, probably due to blowing snow. The snow event follows the icing period in Section 4.4.3.2. The wind conditions were similar (Figure 4-12) and the same comments on the other sensors pertain.

Figures 4-15 and 4-16 show wind speed plots for the two Vaisala sensors (VS1 and VS2). VS1 and VS2 began to indicate lower wind speeds than CL1 at 1230 and 1100 hours, respectively. They both reached a maximum reduction at 1530-1600 hours and recovered by 1800 hours. The maximum speed loss for VS1 and VS2 was 4 and 5 knots, respectively, out of a wind speed of 17 knots; the speed loss was thus 24 and 29 percent, respectively. According to Table 4-2, this loss of speed occurred during the first segment of light snow when the temperature was not very far below freezing (minimum of 27 degrees). The sensors recovered when the snow stopped and were not affected by the next snow segment (when the Vaisala units actually read higher than the Climatronics reference).

4.4.4 SENSOR PERFORMANCE: ALL EVENTS

The averaged wind speed and direction for each anemometer under test was compared with the reference anemometer for each of the icing events by adjusting the plots to overlay each other by the process described in Section 4.4.2.2. The overlaid plots were visually inspected for differences in response between the units. The results of this evaluation are as follows.

1) With the qualifications noted below, excluding the special case studies of Section 4.4.3, all of the units that passed the icing chamber tests did not fail or demonstrate detectable reduced performance because of icing.

2) The proximity of buildings to the test area created variations in wind speed of up to three knots when the wind direction was 220 to 330 degrees (See Figure 4-1).

3) The icing events encountered during the winter of 1991 were not severe. The National Weather Service anemometer stopped due to icing only on the 24th and 26th of January.

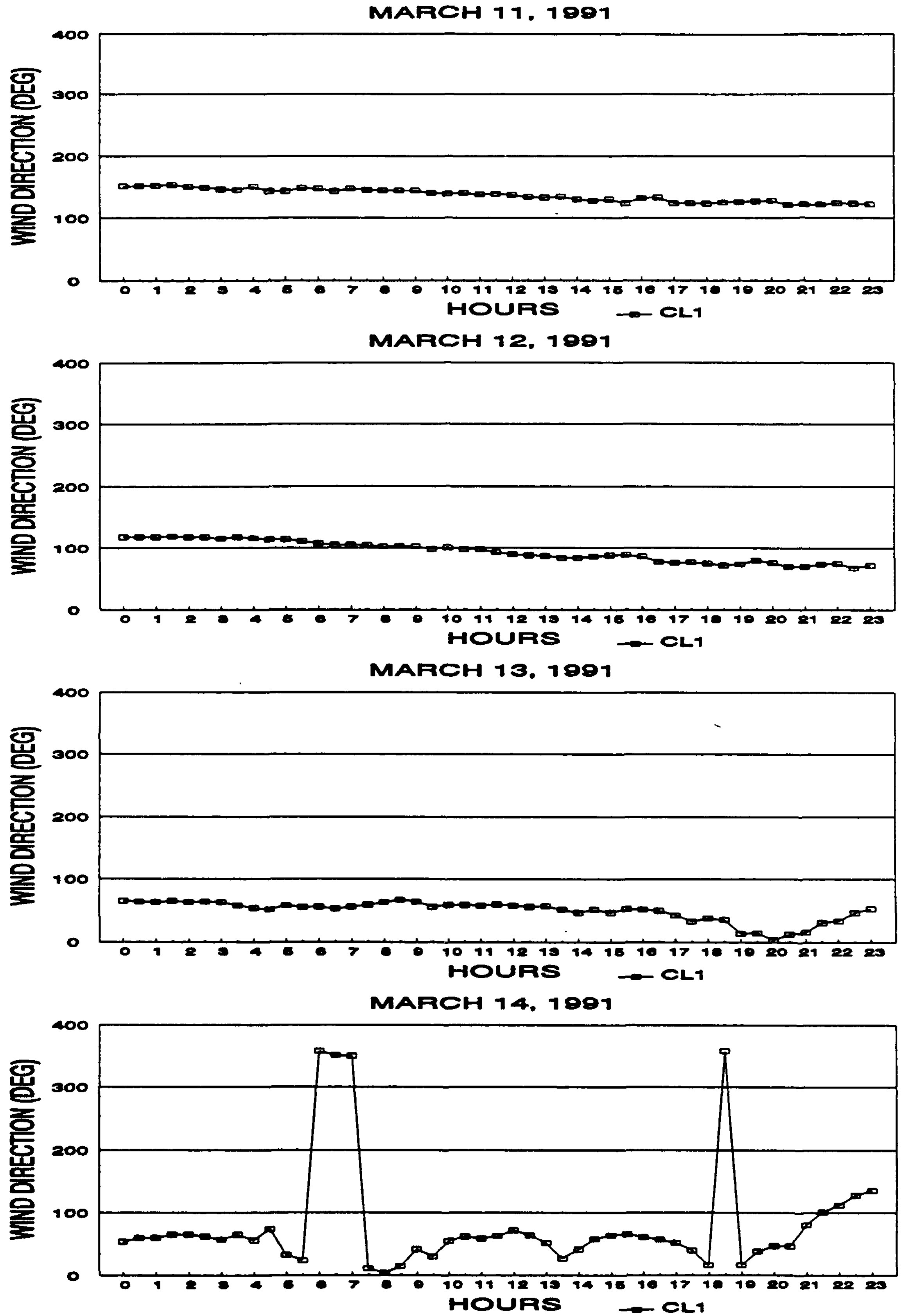


FIGURE 4-12. CL1 WIND DIRECTION ON 3/11-14/91

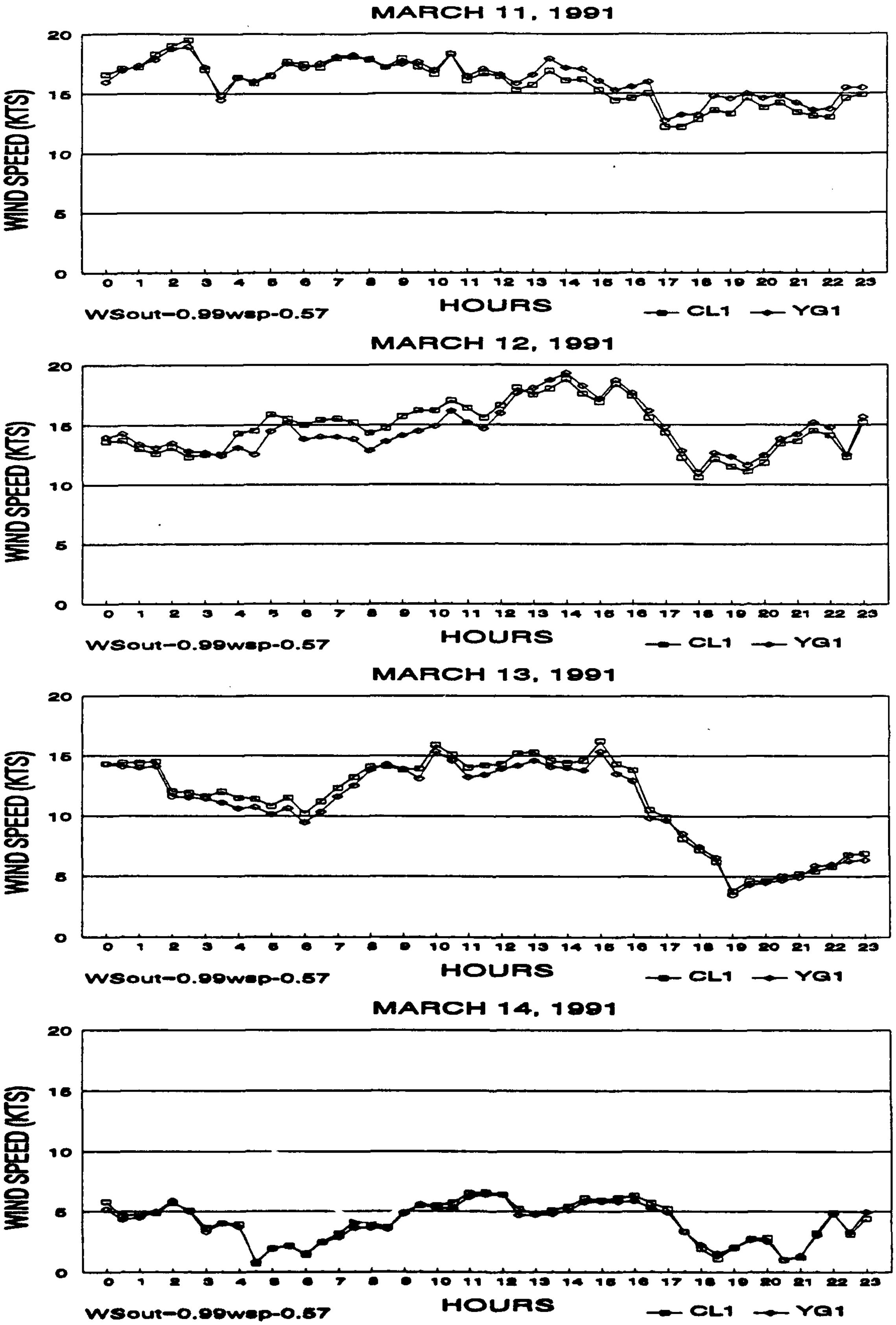


FIGURE 4-13. COMPARISON OF YG1 AND CL1 WIND SPEED ON 3/11-14/91

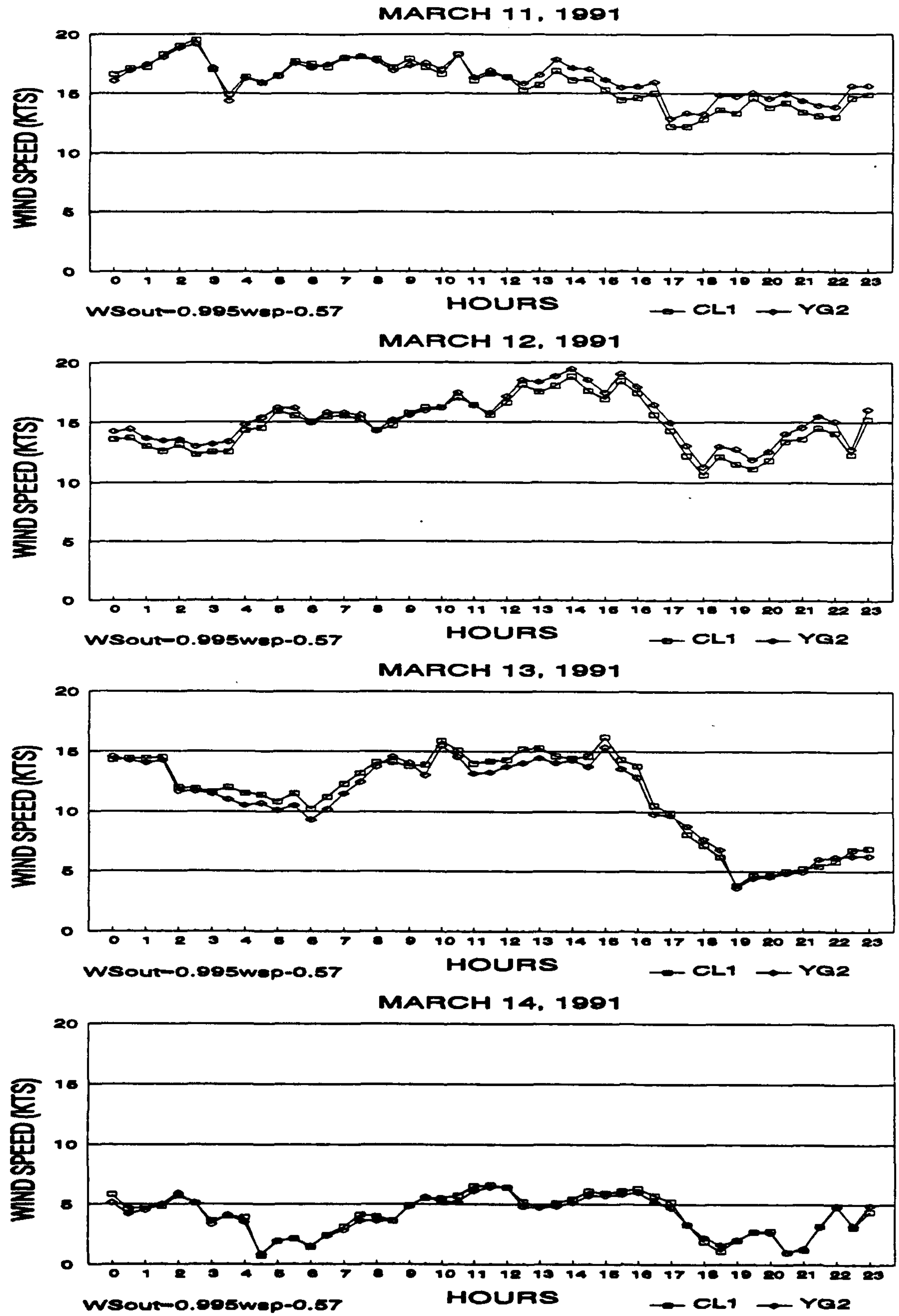


FIGURE 4-14. COMPARISON OF YG2 AND CL1 WIND SPEED ON 3/11-14/91

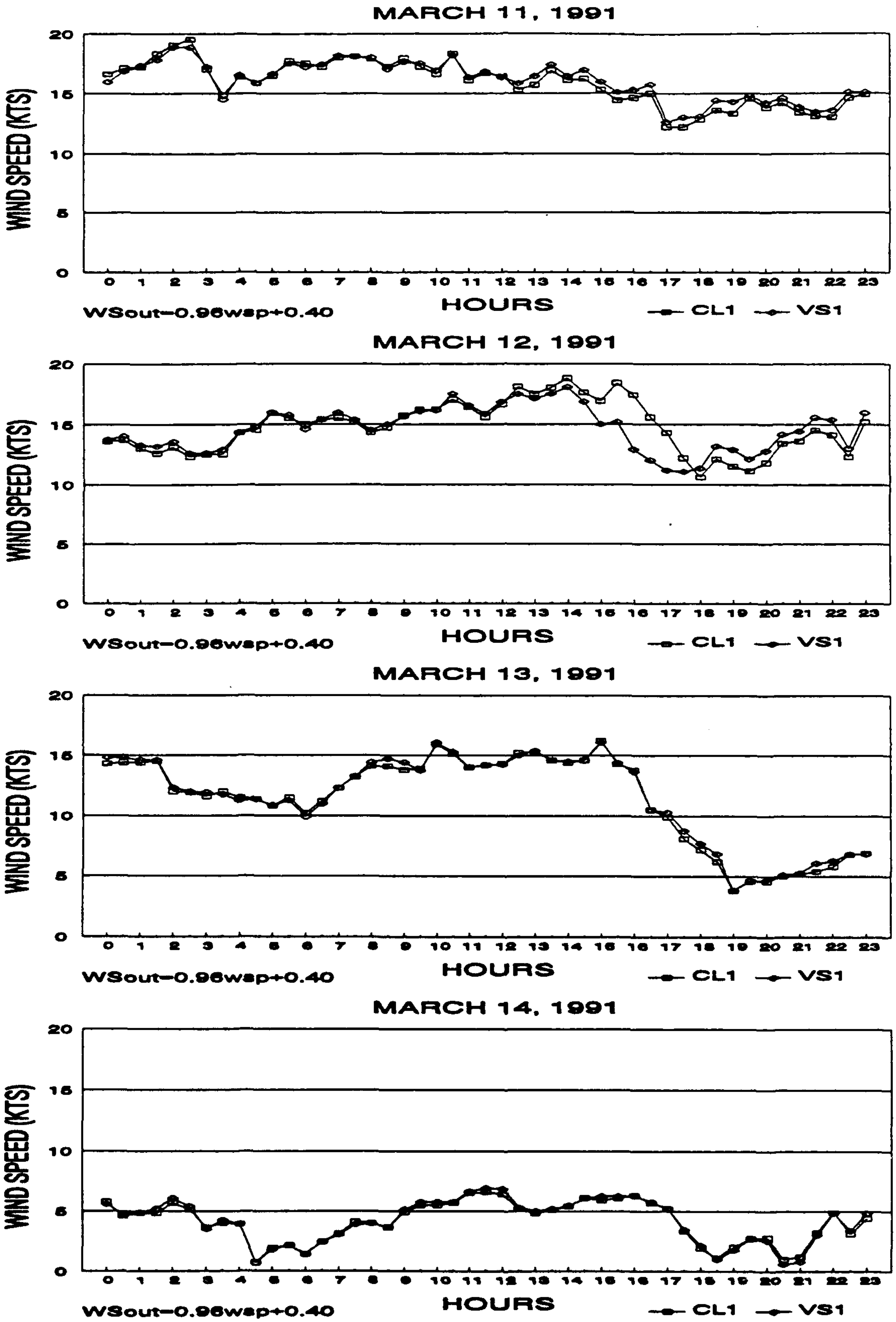


FIGURE 4-15. COMPARISON OF VS1 AND CL1 WIND SPEED ON 3/11-14/91

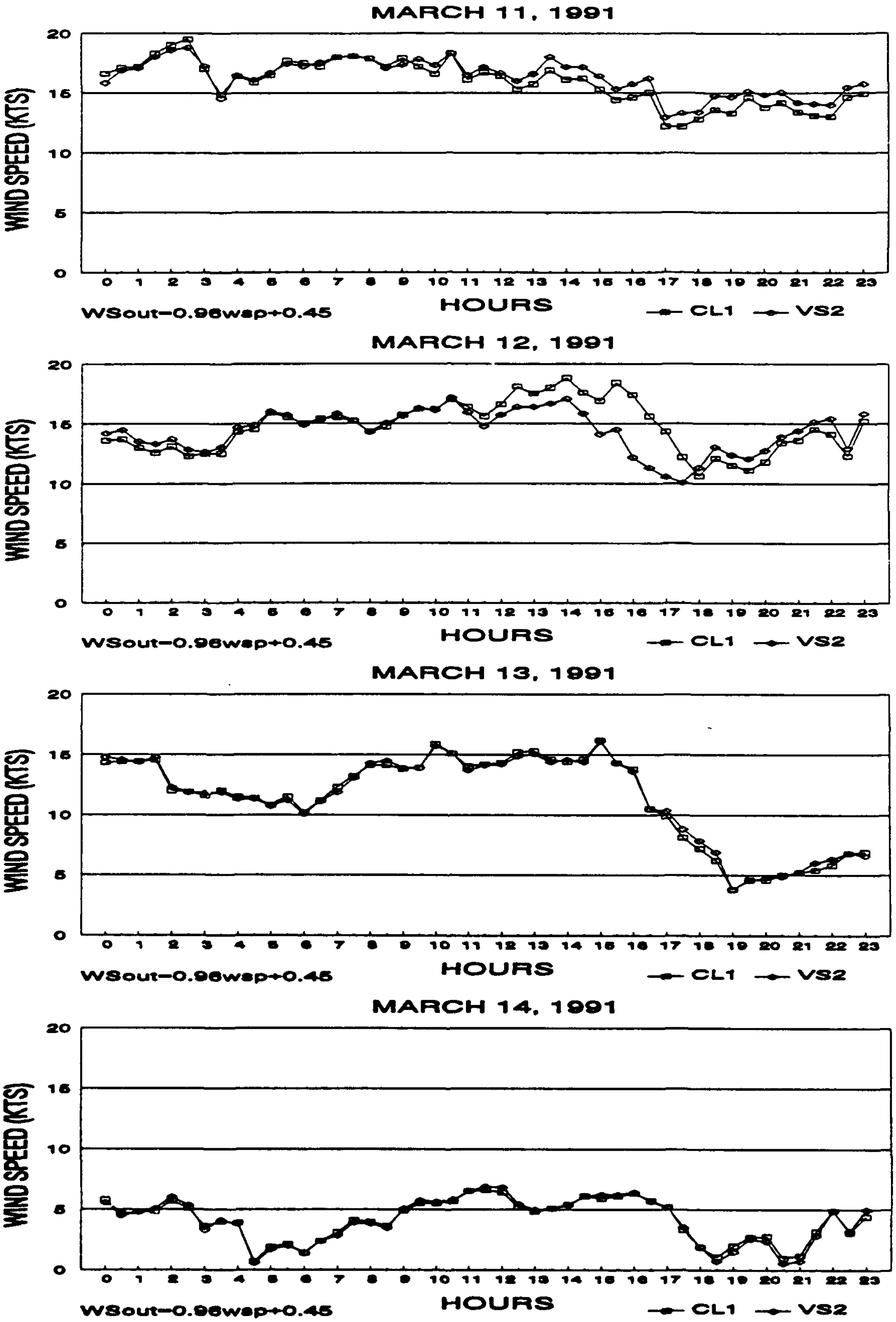


FIGURE 4-16. COMPARISON OF VS2 AND CL1 WIND SPEED ON 3/11-14/91

5. WIND TUNNEL TEST

Upon completion of the LLWAS anemometer field test in Rochester, Minnesota, all the anemometers were subjected to laboratory wind tunnel tests. The field tests indicated some discrepancies between different sensors and raised a number of questions concerning sensor performance. The wind tunnel tests were designed to help interpret the results of the field tests.

The following issues were identified:

1) The Sutron and Armtec (but not Belfort) hot-film anemometers consistently read about two knots higher than all the other sensors. This was most notable at low wind speeds.

2) When the sensors were removed, there were some hint of contamination on the Sutron, and possibly, the Belfort hot-film anemometers. Both Sutron units showed a brown deposit on the side of the film facing south, toward the middle of the air field. The Armtec anemometers were replaced by the manufacturer near the end of the test period, and therefore, had no time to accumulate.

3) The Rosemount pressure anemometer demonstrated poorer low-speed performance than noted in the earlier Worcester tests. Rosemount attributes this problem to insufficient dynamic range for the A/D converter for processing signals that vary with the square of the wind speed. The unit tested at Worcester had an analog linearizing circuit that reduced the dynamic range of the signal.

4) All of the mechanical anemometers showed evidence of higher starting thresholds than the R. M. Young units. For some units, the higher threshold is likely related to drag from the slip rings used to transmit heater power to the anemometer cups.

5) The two Hydro Tech anemometers showed some signs of inconsistency between the two units.

The laboratory testing was performed by Volpe Center personnel utilizing two wind tunnels at the National Weather Service (NWS) Sterling Research & Development Center in Sterling, Virginia. A set of tests was designed to address the sensor performance issues.

5.1 WIND TUNNELS

The NWS Sterling Research & Development Center has two wind tunnels: one tunnel for measuring up to high wind speeds and another tunnel for studying anemometer starting thresholds.

5.1.1 *High-Speed*

The high-speed wind tunnel has two test sections: one 4 ft. x 4 ft. and the other, 6 ft. x 6 ft. The speed range of the 4 ft. x 4 ft. section is about 15 to 120 knots. The 6 ft. x 6 ft. section has a speed reduced by the ratio of the areas (2.25). The wind speed of the high-speed tunnel is calibrated by means of a pitot tube and manometer. The 6 ft. x 6 ft. section was used for most testing for two reasons:

1) The wind speed range is more appropriate for LLWAS.

2) There was room for two anemometers side-by-side in the 6 ft. x 6 ft. test section. The tests were run by placing a reference and test anemometer side-by-side in this test section to avoid the difficult manometer measurements required for an absolute calibration of the wind speed. These manometer measurements were used only to calibrate a reference sensor.

5.1.2 *Low-Speed*

The low-speed wind tunnel has a test section about 2.5 ft. x 2.5 ft. and operates up to about 5.5 knots. It has a nominal calibration as a function of motor rpm.

5.2 TEST DESCRIPTION AND RESULTS

First, the sensors were checked for damage due to shipment and set up for testing. A sensor was then mounted in the appropriate wind tunnel for the particular test. Special efforts were made to center the sensor in the small tunnel and to locate the sensing components of the two sensors in the large tunnel symmetrically with respect to the tunnel walls.

The sensors were interfaced to the same simplified data acquisition system used for the icing chamber tests. The one-minute data was recorded in a disk file and printed out to provide a hard-copy record of the test which could be annotated. The manometer data for calibrating the reference sensor were entered into the wind tunnel computer that also provided a hard-copy record.

Upon completion of the tests, the data were entered into spreadsheets for analysis and plotting.

5.2.1 *Reference Standards*

Before any sensor discrepancy issues could be addressed, a reference standard for the tests had to be established. The most sensitive mechanical anemometer (R. M. Young) was used as the primary reference standard for the wind-tunnel test. One R. M. Young anemometer was mounted in the 4 ft. x 4 ft. section of the high-speed tunnel. Measurements were taken on several cycles between low and high wind speeds. Figure 5-1 plots the differences between the manometer measurements as a function of wind speed. At high wind speeds

(40-50 knots), the R. M. Young measurements matched the readings from the tunnel pitot tube and manometer to better than one knot. The errors became larger for lower wind speeds because of the greater manometer errors, which would be expected to vary inversely with wind speed. (Figure 5-9 shows that the low-speed response of the R. M. Young sensor is accurate with respect to the calibration of the low-speed tunnel.) The R. M. Young sensor could therefore be used with confidence as a reference sensor for subsequent tests over the full wind range.

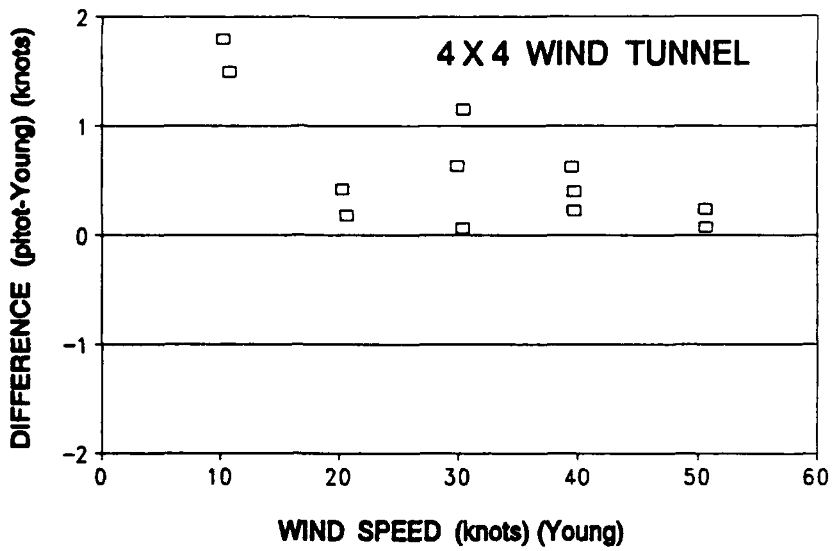


FIGURE 5-1. R. M. YOUNG CALIBRATION

Since the R. M. Young anemometers were not installed until midway through the field tests, a Climatronics anemometer (installed at the beginning of the tests) was used as a secondary standard. Figure 5-2 compares the wind-tunnel measurements of the reference Climatronics sensor (CL1) and the R. M. Young reference sensor mounted in the 6 ft. x 6 ft. test section. The measurements agree to better than 0.5 knots at 20 knots and below and better than 1.5 knots at the highest test wind speed. This test validated the accuracy of the Climatronics secondary field standard.

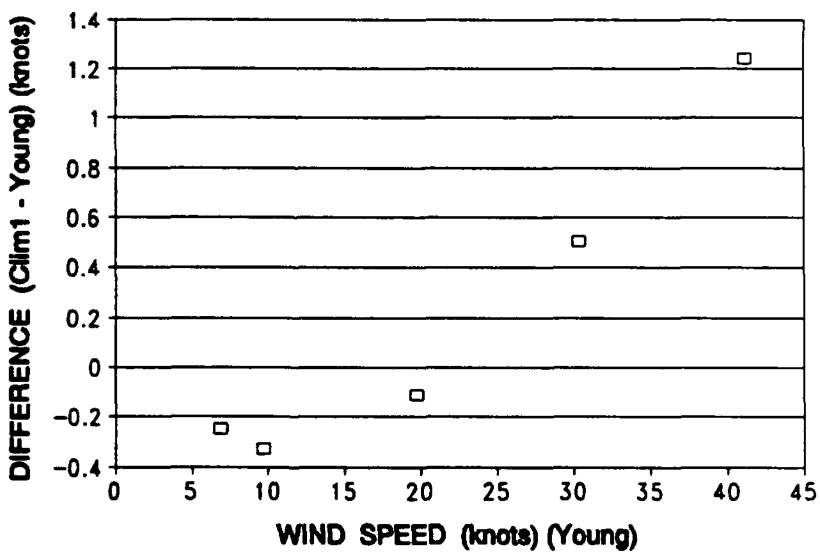


FIGURE 5-2. CLIMATRONICS CALIBRATION(S/N 011)

5.2.2 Calibration Accuracy of Other Sensors

The calibration accuracy of most other sensors was determined by comparison with the R. M. Young reference in the 6 ft. x 6 ft. test section.

5.2.2.1 Hot-Film Sensors

Figures 5-3 through 5-5 present the calibration results for the three types of hot-film anemometers; Sutron, Armtec, and Belfort, respectively. The calibration tests were conducted after the sensors had been cleaned. Data before cleaning will be presented in Section 5.2.3 for Sutron and Belfort. Wind speeds ranged from 5 to 42 knots and in four wind directions (north, east, south, and west). The Sutron units report only integer knot values and therefore produce the steps seen in the upper left corner of Figure 5-3.

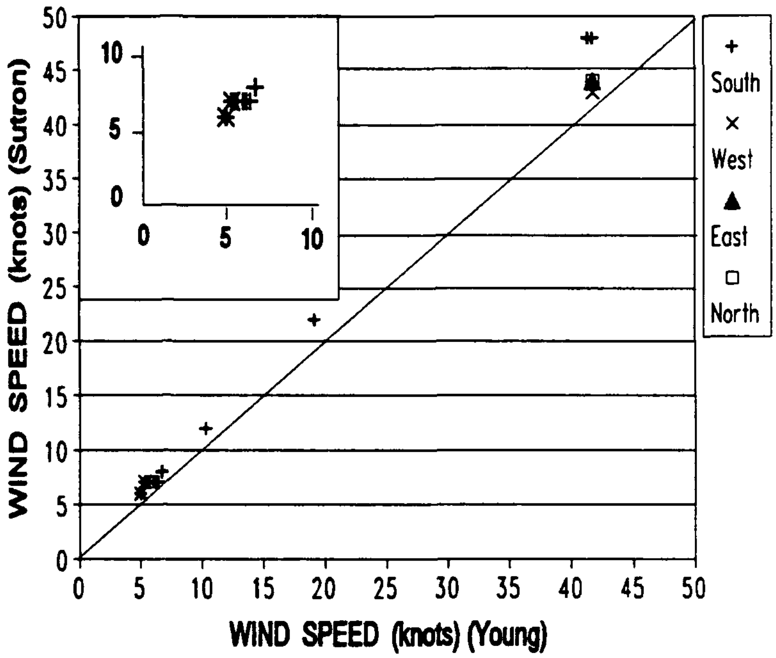


FIGURE 5-3. SUTRON CALIBRATION(S/N 90SC1)

The Sutron and Armtec field test readings of two knots higher than all the other sensors were substantiated for both sensors at low wind speed as shown in Figures 5-3 and 5-4.

Most of the Sutron data was for one direction (south). The Sutron sensor was reading almost 2 knots higher than the R.M. Young reference for winds below 15 knots. The error became larger for higher wind speeds, reaching an error of about 7 knots at a reading of 42 knots. The spread in calibration for different directions at 42 knots was about 5 knots.

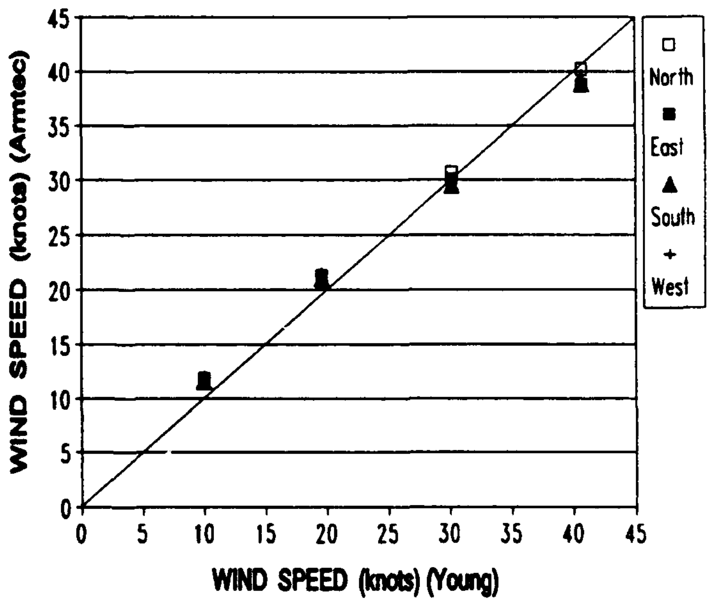


FIGURE 5-4. ARMTEC CALIBRATION (S/N 171)

At 10 knots, the Armtec sensor was also reading almost 2 knots higher than the R. M. Young reference sensor in all four directions. The Armtec sensor readings came into closer agreement with the R. M. Young sensor as the wind speed increased.

Figure 5-5 shows the calibration of one Belfort hot-wire unit. Although the unit was seriously out of calibration, the response appeared to be linear.

5.2.2.2 Pressure Sensors

Figures 5-6 and 5-7 show the calibrations of the two Rosemount sensors. Four wind directions (north, east, south, and west) were tested for most wind speeds. RS1 (S/N LLWAS1) had been modified during the field testing to improve its response at low wind speeds. This modification limited RS1 to measuring wind speeds to a maximum of about 35 knots. RS2 (LLWAS2) was tested at wind speeds over the normal range (up to 42 knots).

Both Rosemount sensors showed somewhat greater differences from the R. M. Young reference sensor at low wind speeds than at high wind speeds, as would be expected for a pressure sensor. Since the signal is proportional to the square of the wind speed, a pressure offset will produce a greater error at lower wind speed. The modified RS1 sensor did show at best, a slight improvement in performance over the other Rosemount unit at the low wind speeds, but the improvement was at the cost of

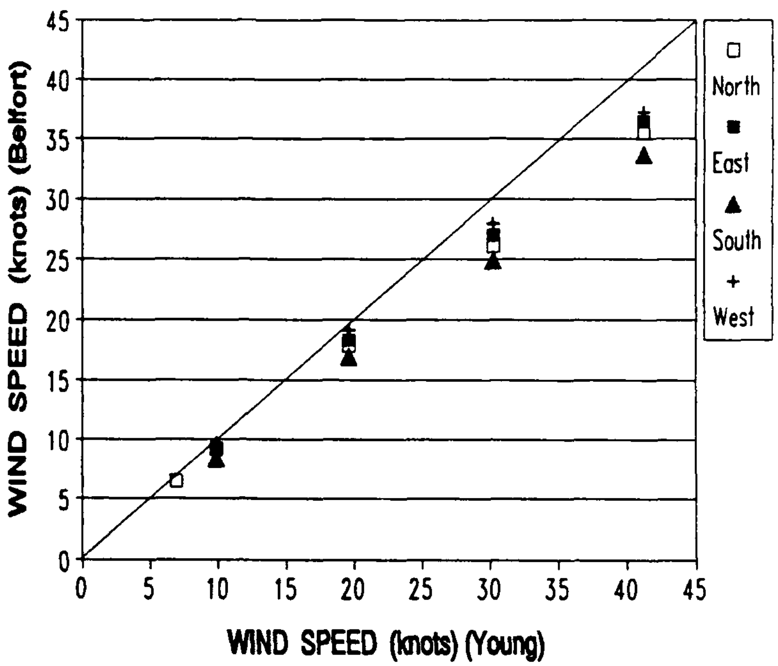


FIGURE 5-5. BELFORT HOT-WIRE CALIBRATION (S/N 10066)

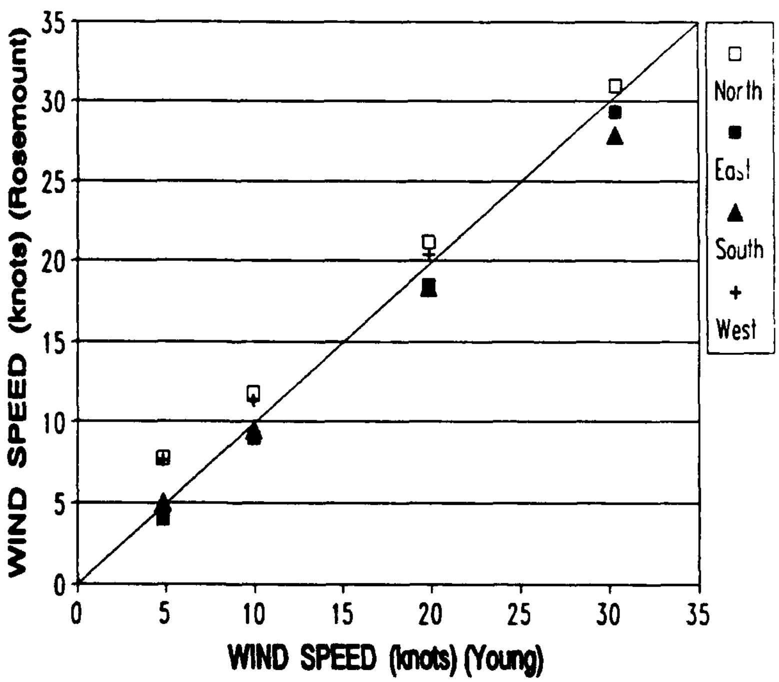


FIGURE 5-6. ROSEMOUNT CALIBRATION (S/N LLWAS1)

reduced dynamic range. The Rosemount sensors also showed significant calibration variations (4 knots) with direction at both high and low wind speeds.

5.2.2.3 Cup Sensors

Figure 5-8 shows the calibration for the two Hydro Tech anemometers. Their response was consistent at high speeds, but somewhat different at low speeds. This difference represents the high starting threshold noted in section 5.2.4.

The Belfort and Vaisala cup anemometers were not calibrated.

5.2.3 Hot-Film Contamination Effects

Contamination produces a percentage loss in the calibration of a hot-film anemometer. The effect is similar to that of increasing the diameter of the film. The hot-film anemometers with a long test exposure (nine months for Sutron, and perhaps, three months for Belfort) were tested before and after cleaning; the wind speed was 40 knots and all four directions were tested. The cleaning was done on-site by the manufacturer's personnel (both are located near Sterling, VA). Both Sutron units and one Belfort unit were tested; the results are shown in Table 5-1. Contamination had reduced the response of the Sutron units by 4 to 17 percent, depending upon

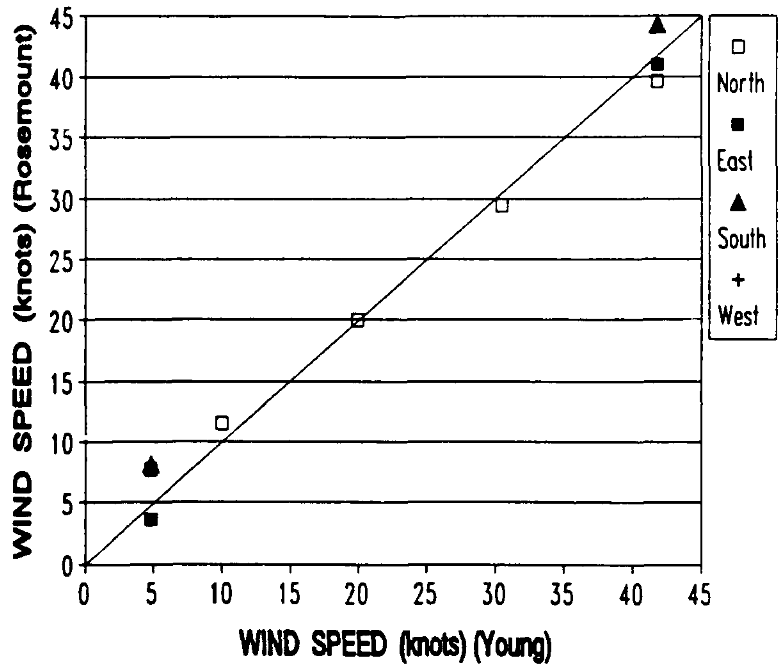


FIGURE 5-7. ROSEMOUNT CALIBRATION (S/N LLWAS2)

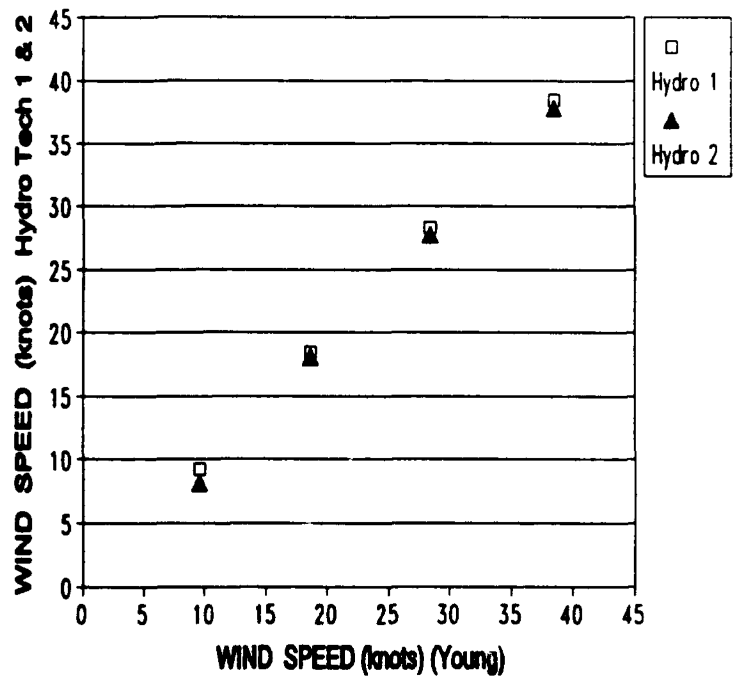


FIGURE 5-8. HYDROTECH CALIBRATIONS (S/N 131, 132)

the direction. The direction dependence was more or less consistent for the two sensors (at least for east and west). The direction (south) that showed the visible brown contamination was not more affected than other directions, e.g., north. The Belfort unit had smaller losses, which ranged from -1 to 5 percent, with the negative change occurring in a southern direction.

TABLE 5-1. RELATIVE DEGRADATION OF WIND SPEED RESPONSE (%) DUE TO CONTAMINATION

SENSOR	MODEL	NORTH	EAST	SOUTH	WEST
SUTRON	#8600 HW, UNIT 1	88.6	86.7	89.1	93.2
SUTRON	#8600 HW, UNIT 2	84.1	88.6	83.3	96.3
BELFORT	#270 HW	95.4	98.0	100.8	97.3

5.2.4 Starting Threshold Test

All of the mechanical sensors were tested to determine starting thresholds. One sensor each of R. M. Young, Climatronics, Vaisala, and Belfort (cup) were tested. Both Hydro Tech sensors were tested because one unit appeared to be reading lower values at low wind speeds. The starting threshold was determined on each unit; then calibration measurements were taken at 0.5 knot increments up to approximately 5.5 knots. The results are presented in Figures 5-9 through 5-13.

The R. M. Young anemometer was indeed the most sensitive and had the lowest starting threshold. Climatronics, Vaisala, and Belfort (cup) had starting thresholds in close proximity to each other. The Hydro Tech anemometer had the highest starting threshold at about 3 knots. Note that this higher starting threshold results in significant measurement errors at wind speeds up to five knots. The second Hydro Tech anemometer was also tested for suspected problems. The starting threshold on the second Hydro Tech was somewhere between 5.5 and 7 knots, probably due to a bad bearing.

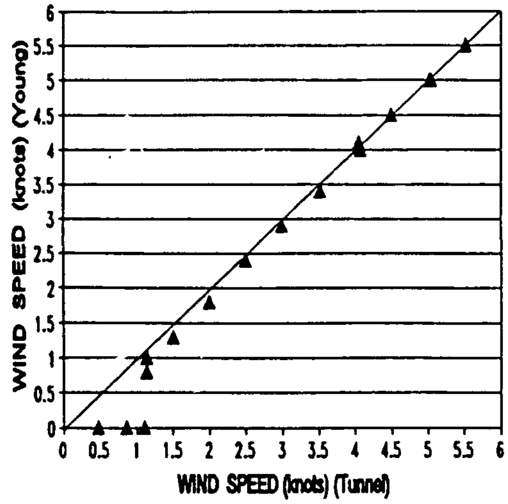


FIGURE 5.9 R. M. YOUNG: LOW SPEED

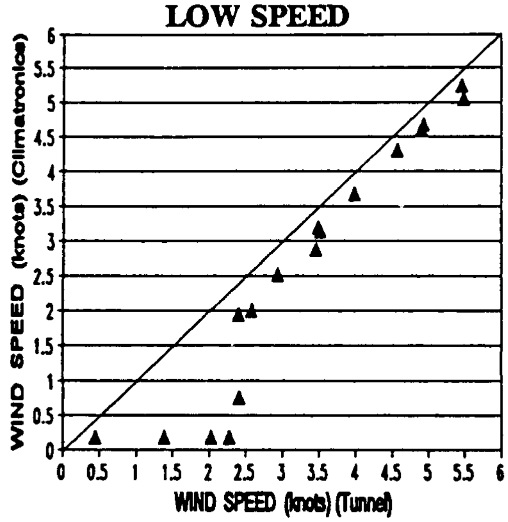


FIGURE 5-10. CLIMATRONICS: LOW SPEED

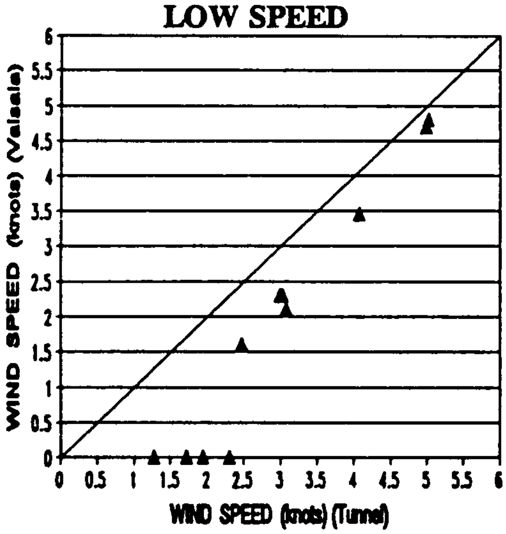


FIGURE 5-11. VAISALA: LOW SPEED

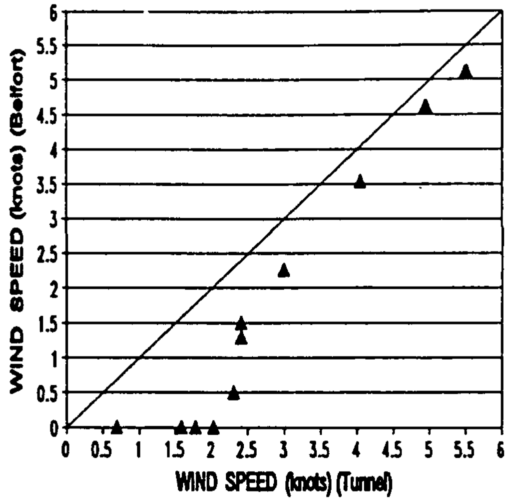


FIGURE 5-12. BELFORT CUP: LOW SPEED

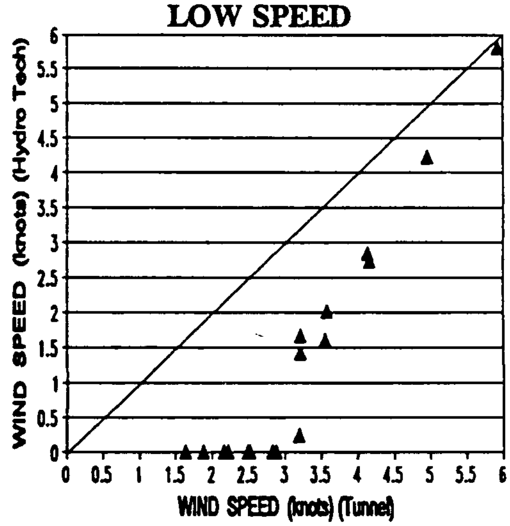


FIGURE 5-13. HYDRO TECH: LOW SPEED

6. CONCLUSIONS

6.1 GENERAL

In response to this test program, industry has demonstrated a variety of icing-resistant wind sensors that may be candidates for LLWAS-EN. Some of these sensors, however, did not meet the LLWAS-EN accuracy requirements. Moreover, the test program was not designed to evaluate other critical LLWAS-EN system requirements such as low maintenance, high reliability, and long life. None of the sensors tested are likely to meet all these additional requirements without further improvements.

The use of laboratory icing tests to qualify sensors for field testing was very successful because:

- Initial failure of sensors in the laboratory icing test prompted a number of manufacturers to increase the amount of heat used to prevent sensor icing.

- None of the sensors that passed the laboratory icing test showed icing problems during the field tests.

- The one sensor model that failed the laboratory icing test was also affected by icing in the field test.

The laboratory icing test was not effective, however, in eliminating sensors sensitive to the buildup of snow (i.e., Vaisala cups).

The year selected for testing was not a severe icing year at Rochester, MN. FAA sector personnel reported that the operational Rochester LLWAS was not seriously affected by icing during the period of the tests. Consequently, the test results cannot be used to quantify the effectiveness of various sensor designs and heat levels in assuring proper sensor operation under the most severe icing conditions. Nevertheless, the authors believe that the laboratory icing test and the icing specification are sufficient to insure wind sensor operation over an adequate range of icing conditions.

6.2 ICING/SNOW PERFORMANCE

Only two sensor models (Vaisala, R. M. Young) exhibited any icing or snow problems during the field tests. All the rest showed no performance degradation during the snow and ice experienced during the tests.

6.2.1 Propeller/Vane

The only propeller/vane sensor used in the tests (R. M. Young, with heat lamps) failed the laboratory test and also exhibited a slow-down during one icing event.

6.2.2 Cup/Vane

The Vaisala cup anemometer, although heated, slowed down during one snow event. The similar, but much larger, Belfort cup anemometer showed no snow problems. Assuming that the amount of heating was similar for the two units, larger cups are apparently more resistant to snow clogging, as might be expected.

6.2.3 Hot Film

No icing or snow problems were noted with the hot-film anemometers. Transient measurement differences in snow and rain (as were observed in previous tests at the Otis Weather Test Facility) were not explicitly studied in this report and were not noted in the events examined in detail.

6.2.4 Pressure Sensor

Although the heaters for the Rosemount pressure anemometers failed on several occasions, no wind measurement errors showed up in the analysis of icing and snow events.

6.3 SPEED ACCURACY

Wind speed accuracy was examined in both field and wind tunnel tests; the latter gave more definitive results. Angle accuracy was not examined, but would also likely be more easily addressed in laboratory tests.

The LLWAS speed accuracy requirements at the time this test was run were:

1) Virtually no accuracy below 4 knots wind speed,

2) Two knots accuracy between 4 and 30 knots, and

3) Ten percent accuracy above 30 knots.

6.3.1 Propeller/Vane

According to the wind tunnel test, the R.M. Young sensor (the only propeller/vane type used) was accurate enough to be used as a wind speed reference in the field tests.

6.3.2 Cup/Vane

All cup anemometers except one Hydro Tech unit were accurate enough to meet the LLWAS requirements. The one Hydro Tech unit had an abnormally high starting threshold. Both Hydro Tech units tended to overspeed on occasion, perhaps because of their higher inertia coupled with rapidly varying winds.

6.3.3 Hot Film

One Belfort sensor had a large calibration error. The other Belfort sensor showed larger than acceptable errors at 30 knots. Both the field tests and the wind tunnel tests showed that the Sutron and Armtec units had a wind speed offset of about two knots. This offset put them outside the LLWAS accuracy requirements. The Armtec calibration was consistent for different directions and improved at higher wind speeds. On the other hand, the Sutron calibration sometimes became worse at higher wind speeds. For one unit, the Sutron calibration error for one direction became about 6 knots at 42 knots, which is clearly unacceptable.

The wind speed measured by hot-film anemometers decreases when the elements become contaminated. The Sutron units, which were operated for the full nine-month test period without cleaning, showed the greatest calibration change. The calibration loss was somewhat greater than ten percent for the north, east, and south directions. Less loss was noted for the west direction. Since the 30-knot measurement accuracy requirement is about seven percent, hot film anemometers at Rochester would have to be cleaned at six-month intervals to meet the LLWAS accuracy requirement. Sites with more contamination (especially ocean shore sites with salt spray) would require more frequent cleaning.

6.3.4 Pressure Sensor

The dynamic range of the Rosemount pressure anemometer was not adequate to meet the LLWAS specification. The early sensor configuration gave very poor low-speed results. The final configuration, with a lower maximum speed (below the LLWAS-EN requirement), gave low speed accuracy that was closer to acceptable. This dynamic range limitation is related to the fact that the sensor signal varies as the square of the wind speed.

The performance of the Rosemount sensors during the FY91 tests was disappointing. Earlier tests at Worcester, MA showed acceptable low-speed performance. The earlier Rosemount unit used a nonlinear analog circuit to reduce the dynamic range of the sensor signal.

7. RECOMMENDATIONS

Since mechanical anemometers were the only sensors meeting both the icing and accuracy requirements of LLWAS-EN, their reliability and maintainability should be studied to assess the feasibility of meeting the LLWAS-EN MTBF requirements. Some of the methods used to meet these requirements, such as slip rings for cup heaters, may make it difficult for a mechanical sensor to meet the stringent LLWAS-EN reliability requirements.

Although the laboratory icing test was successful in predicting the icing performance observed in the field tests, it did not accurately predict the snow performance. It would be worthwhile to develop a laboratory snow test.

The use of heat to prevent icing and snow buildup may induce problems at low temperatures. For example, heat may cause cold snow to stick to a sensor. Consideration should be given to turning off the de-icing heat below a certain temperature to avoid inducing snow problems.

At the beginning of this test program it was assumed that, contrary to the test results, wind sensors with no moving parts would be most compatible with LLWAS-EN requirements. They are generally small and reliable and require little power for de-icing. The three no-moving-parts technologies included in the tests were hot-film, pressure sensing, and thermal sensing. Further testing of these technologies would be warranted if the observed problems could be overcome:

- A self-cleaning hot-film sensor may be ready for testing. The critical test would be contamination buildup in a salt spray environment.

- A pressure-sensing anemometer is being deployed in mountainous locations in Europe. A wind tunnel test of its accuracy would be useful to assess the promise of this technology.

- The thermal-sensing unit is large enough to be less sensitive to contamination than the hot-film anemometers. The units submitted for these tests have been repaired and are available for testing. Icing chamber and wind tunnel testing would be appropriate.

The experience of this test program indicates that most of the useful information about sensor icing performance and accuracy can be obtained from quick laboratory tests.

APPENDIX A

TEST SPECIFICATIONS

A.1 LLWAS ANEMOMETER TEST HARDWARE SPECIFICATION

Proposed test anemometers must meet the following minimal hardware specifications to be eligible for testing.

Cross Section:	< 2.75 sq. ft.
Mounting:	Bracket allowing attaching or clamping to 3 in. pole or cross arm.
Power:	115 V $\pm$ 10% < 1 KW with heaters < 50 W electronics only
Operating Temp:	-50 to +50 deg. C
Storage Temp:	-65 to +70 deg. C
Output:	Digital, asynchronous RS232 (polled preferred), 300-1200 baud, wind speed and direction or wind components. (This output shall be compatible with a government PC compatible computer with a multiport "Digiboard Com/x" or equivalent interface)
Cables:	15 ft. with 5 in. pigtails with #6 spade lugs signal and #8 spade lugs power.
Calibration:	Drift Free

A.2 LLWAS ANEMOMETER ACCEPTANCE REQUIREMENTS

Lease applicants shall provide information to establish that their candidate anemometers are responsive to the following performance requirements. Evaluation of these responses as outlined in Section 7 [of test plan], LLWAS Anemometer Acceptance Criteria shall determine which sensors will be selected for testing.

Environmental

The anemometer shall not be adversely affected by:

1) Freezing rain (0.3 inches/hr), 20-knot wind, temp. -20 to 0 deg. C.

2) Freezing drizzle, 10-knot wind, temp. -20 to 0 deg. C.
(The anemometer shall be unaffected by a buildup of 2 inches of ice on the support.)
(Note: Chemical and radiant heat lamp methods for preventing icing have been unsuccessful in previous tests.)

3) Snow (4 inches/hr), 30-knot wind, temp -20 to 0 deg. C.

4) Pollutants (jet exhaust), natural fibers, salt spray, etc.

Maintainability

Preventative maintenance shall be required once a year for no more than 15 minutes duration. Note: drift-free calibration is a necessary part of this requirement.

Reliability

Mean Time Between Failures: 30,000 hrs required, 100,000 hrs desired. Equipment life > = 15 yrs.

Sensitivity/Accuracy

Maximum Starting Threshold: 1.5 m/s
Maximum Distance Constant (speed & angle): < =25 m desired,
< = 50 m required.
Speed Error: ± 1m/s for 2-15 m/s; ± 10 % for >15 m/s
Angle Error: ± 4 degrees

Power

< = 200 W with heat desired, < = 1000 W permitted.
< = 50 W without heat (including system electronics)

Operational System

Evidence of operational use of manufacture's anemometers is required.

Estimated Production Cost (>1000 units)

< = $3,000 anemometer, desired.

< = $7,000 anemometer plus system electronics as defined in the Appendix, desired.

APPENDIX B

LLWAS-EN PRELIMINARY SENSOR SPECIFICATION

The following specification incorporates the LLWAS sensor requirements as presently understood into a preliminary specification for: (A) The final operational sensor unit including modem and transceiver; and (B) The operational anemometer. It is included here to make a distinction between the test anemometer requirements and the future operational sensor requirements.

A. Sensor Unit

Consisting of:

1) Anemometer
2) Processor
3) Modem
4) Transceiver

The sensor unit will be mounted on top of a 150-foot tower and will have FAA standard remote maintenance monitoring capability.

Cross Section: <=2.75 sq. ft. (excl. antenna and obstr. light)

Maximum Power: 1 KW with heaters
50 W electronics

Reliability: 30,000 Hrs. required, 100,000 desired

Maintenance: Yearly, exterior cleaning on site, <15 min.

Equipment Life: > 15 Yrs.

Operating Temperature: -50 to +50 deg. C

Storage Temperature: -65 to +70 deg. C

B. Anemometer

Maximum Starting Threshold: 1.5 m/s

Maximum Distance Constant (speed & angle): 50 m

Speed Error: $\pm$1m/s for 2-15 m/s
$\pm$ 10 % for > 15 m/s

Angle Error: $\pm$ 4 degrees

No icing of critical sensors components under the following conditions:

1) Freezing rain (0.3 inches/hr), 20-knot wind, temp -10 to 0° C.

2) Freezing drizzle, 10-knot wind, temp -10 to 0° C.

3) Snow (4 inches/hr), 30-knot wind, temp -20 to 0° C.

4) Pollutants, jet exhaust, natural fibers, salt spray etc. Unaffected by 2 in. ice buildup on support.

APPENDIX C

LIST OF MANUFACTURERS PARTICIPATING IN LLWAS ICING TESTS

Ms. Nancy Dyer
Armtec Industries Inc.
3 French Dr.
Manchester, NH 03103-7406
Tel 603-669-0940
FAX 603-669-0931

Mr. Brian Benhaim
Belfort Instrument
727 South Wolfe St.
Baltimore, MD 21231
Tel 301-342-2626
FAX 301-342-7028

Mr. Jeffrey Stern
Climatronics Corp
140 Wilbur Place
Bohemia, NY 11716
Tel 516-567-7300
FAX 516-567-7585

Mr. Philip L. Taylor
Hydro-Tech
4658 N.E. 178th St.
Seattle, WA 98155
Tel 206-362-1074
FAX 206-363-8271

Mr. Theodore Sekula
Qualimetrics Inc.
1165 National Dr.
Sacramento, CA 95834
Tel 916-928-1000
FAX 916-928-1165

Mr. John Campbell
R.M. Young Co.
2801 Aero-Park Dr.
Traverse City, MI 49684
Tel 616-946-3980
FAX 616-946-4772

Mr. Jeff Graupmann
Rosemount Inc.
14300 Judicial Rd.
Burnsville, MN 55337
Tel 612-892-4300
FAX 612-892-4430

Mr. Dave Goodman
Sutron Corp.
2190 Fox Mill Rd.
Herndon, VA 22071
Tel 703-471-0810
FAX 703-450-7872

Mr. Selwyn Alpert
Vaisala Inc.
100 Commerce Way
Woburn, MA 01801
Tel 617-933-4500
FAX 617-933-8029

APPENDIX D

PHOTOGRAPHS

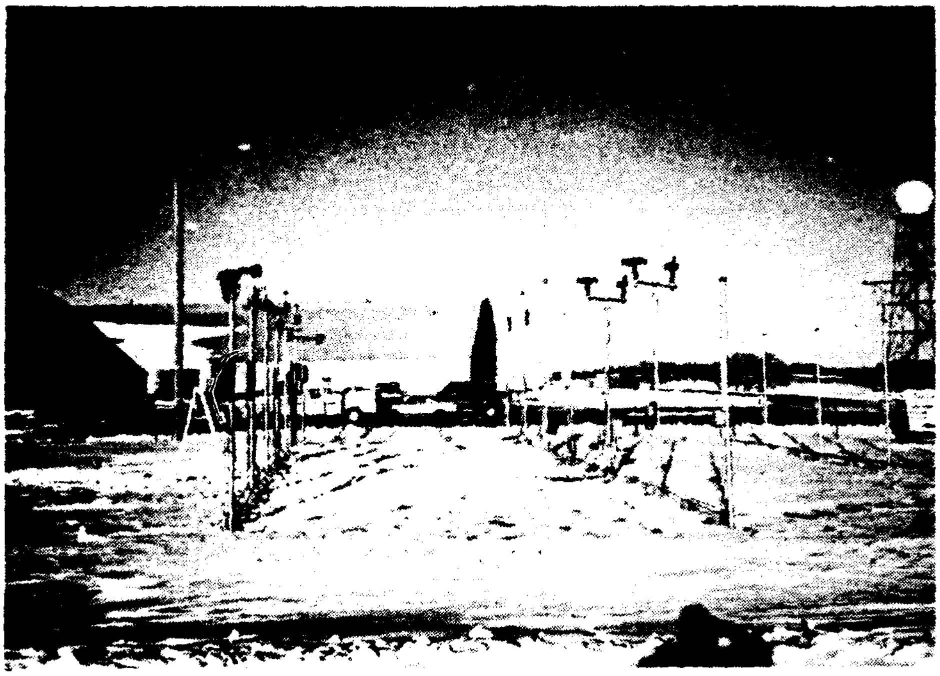


FIGURE D-1. ROCHESTER MN. TEST SITE

FIGURE D-2. SETUP OF TEST SENSORS

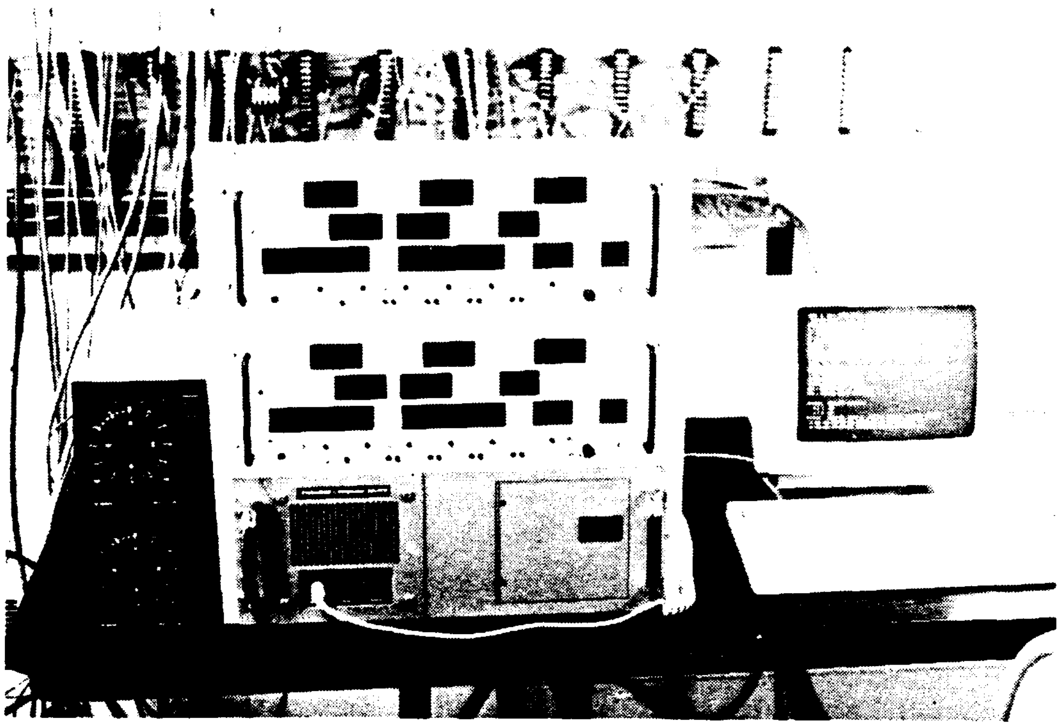


FIGURE D-3. DATA ACQUISITION SYSTEM

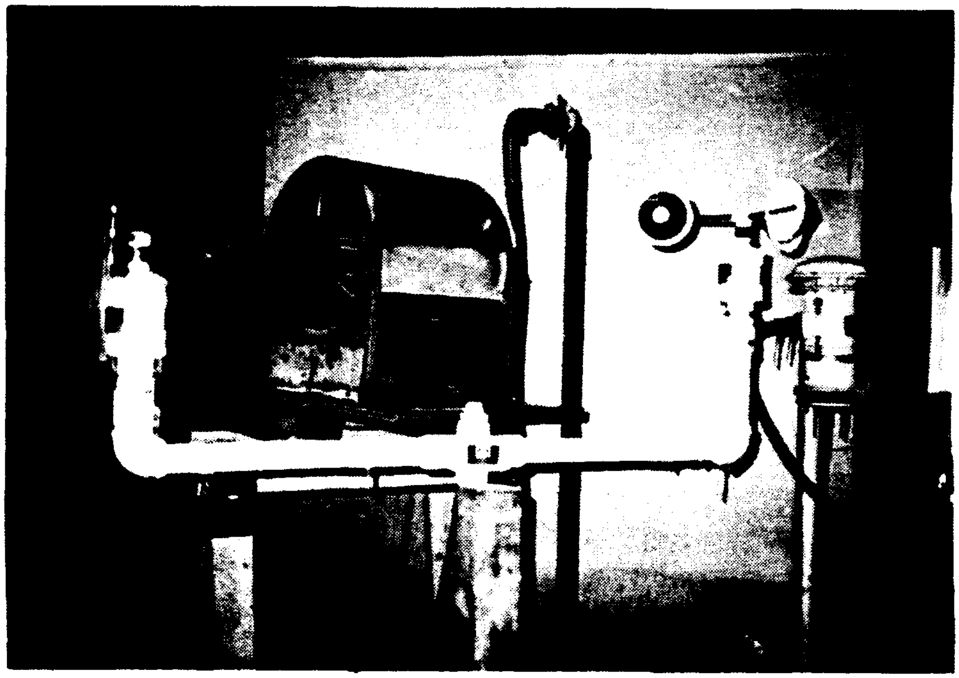


FIGURE D-4. TENNEY ICING CHAMBER
NATIONAL WEATHER SERVICE, STERLING VA.

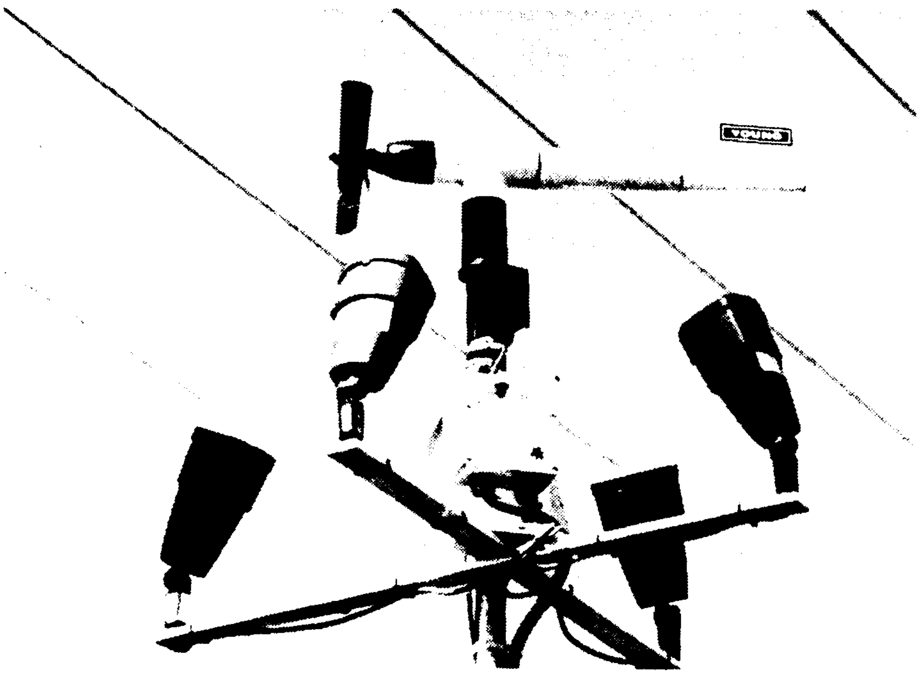


FIGURE D-5. YOUNG PROPELLOR ANEMOMETER

FIGURE D-6. BELFORT HOT WIRE ANEMOMETER

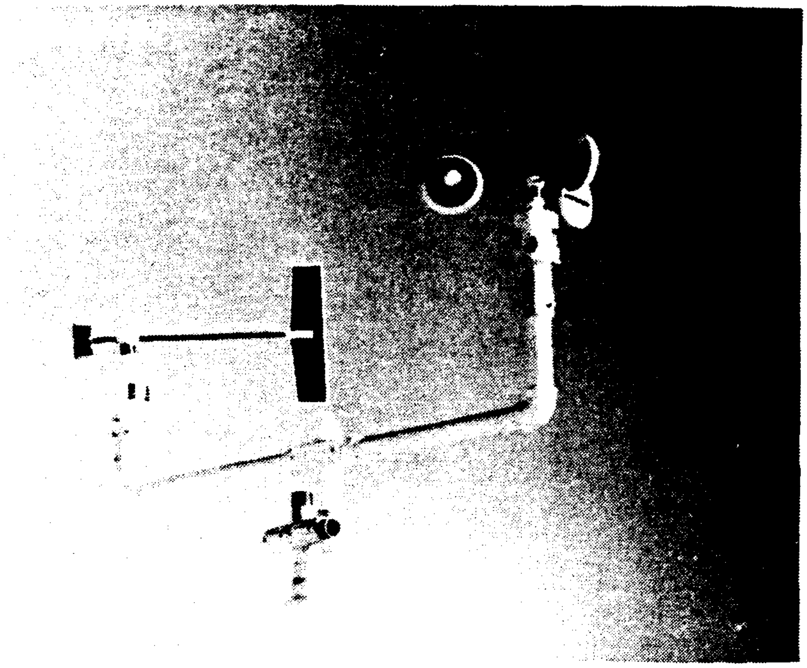


FIGURE D-7. BELFORT CUP & VANE ANEMOMETER

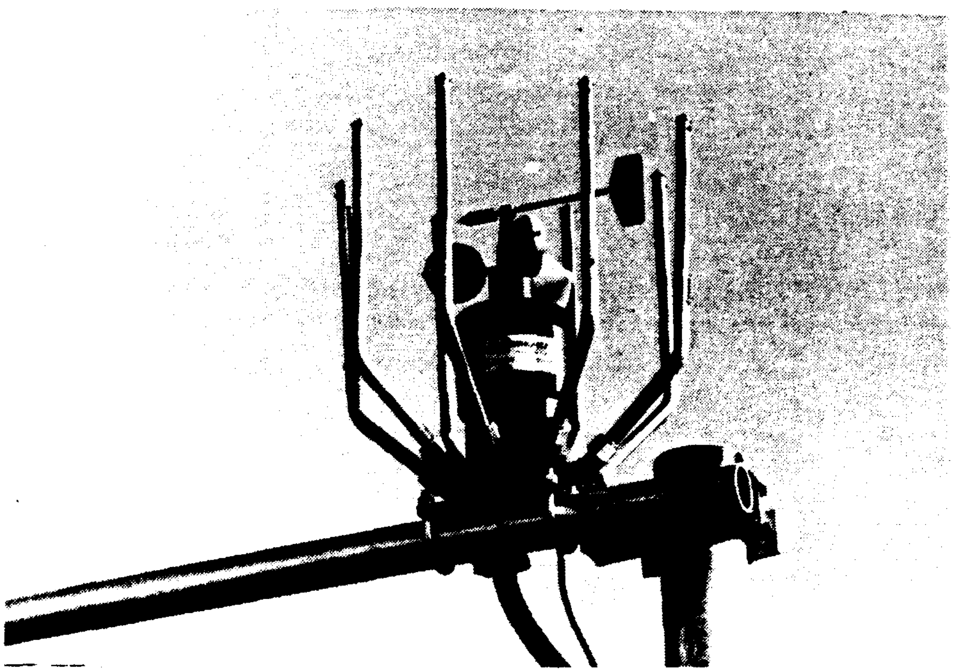


FIGURE D-8. CLIMATRONICS CUP & VANE ANEMOMETER

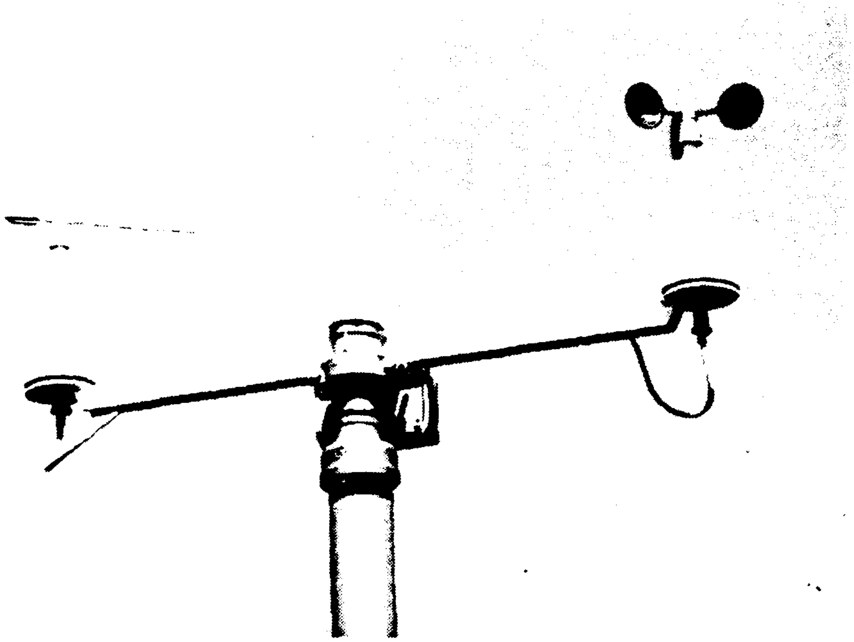


FIGURE D-9. VAISALA CUP & VANE ANEMOMETER

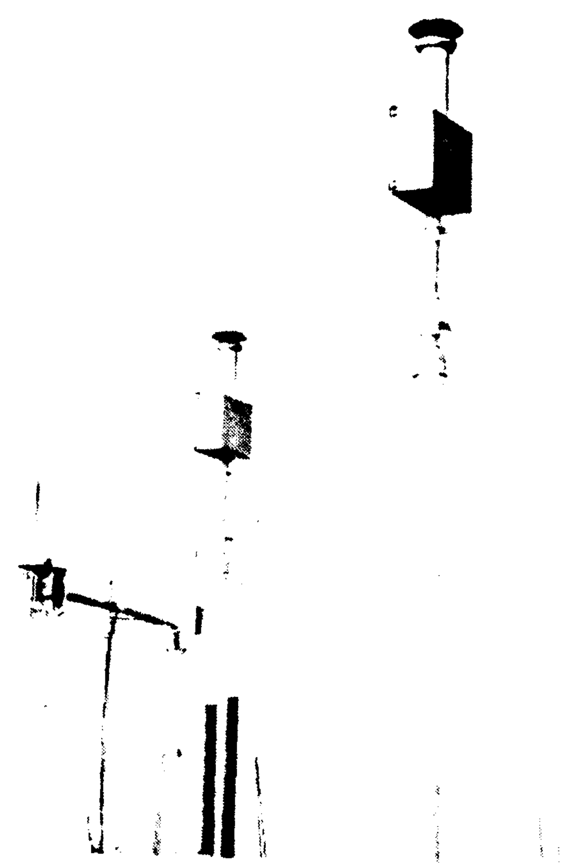


FIGURE D-10.

SUTRON HOT WIRE ANEMOMETER

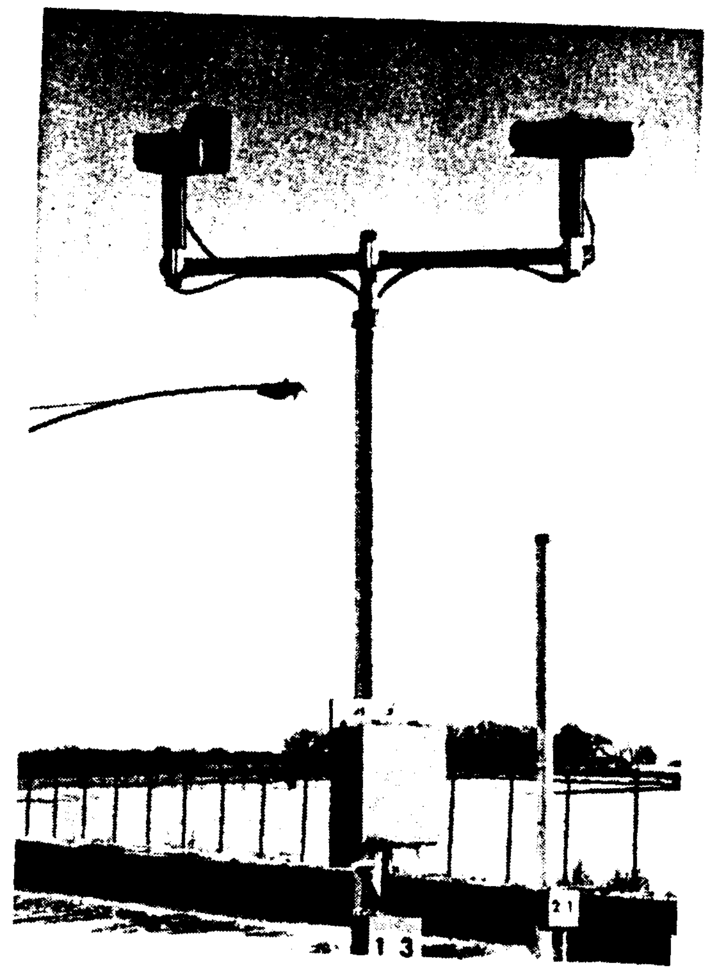


FIGURE D-11.

HYDRO TECH CUP & VANE ANEMOMETER

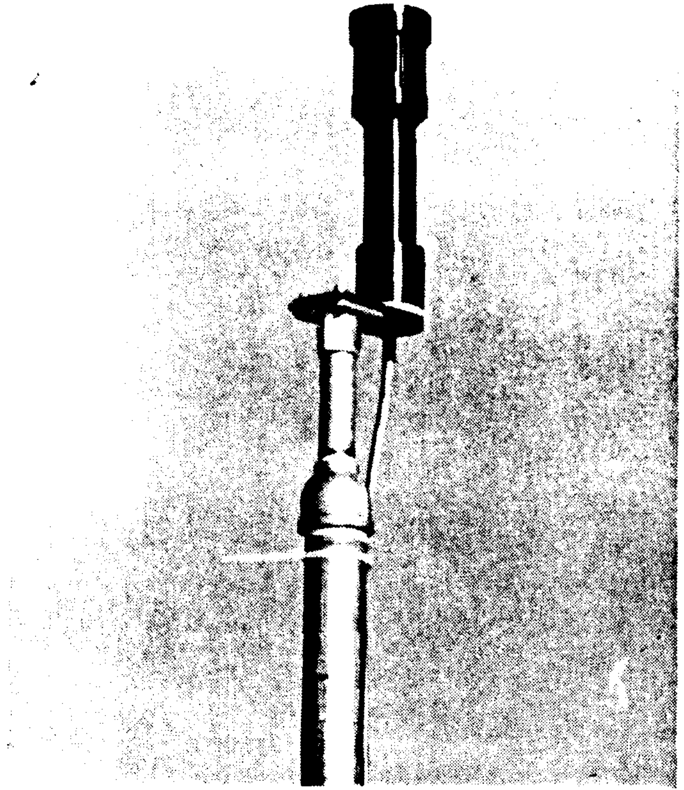


FIGURE D-12.

ARMTEC HOT WIRE ANEMOMETER

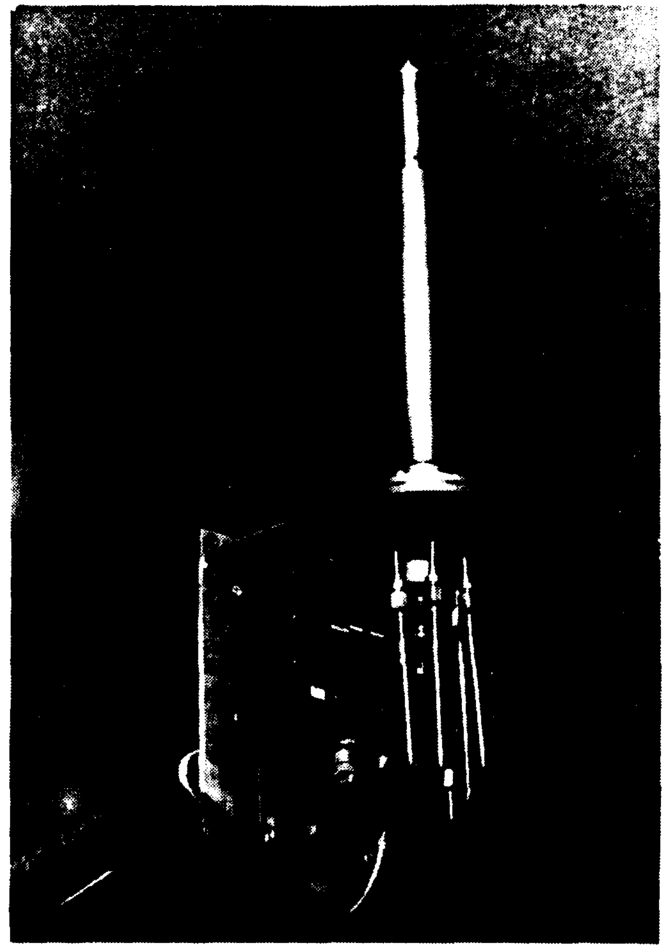


FIGURE D-13.

ROSEMOUNT PRESSURE ANEMOMETER

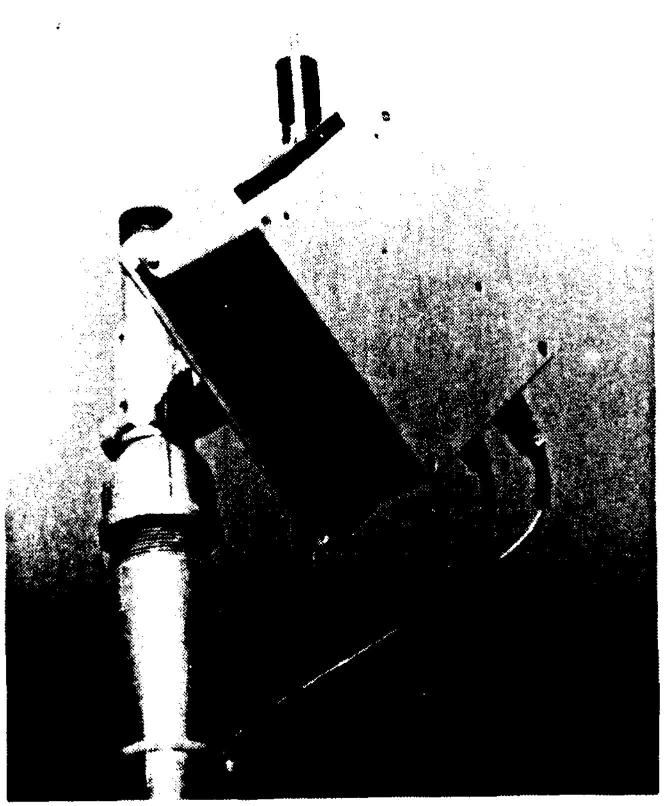


FIGURE D-14.

ROSEMOUNT ICING SENSOR

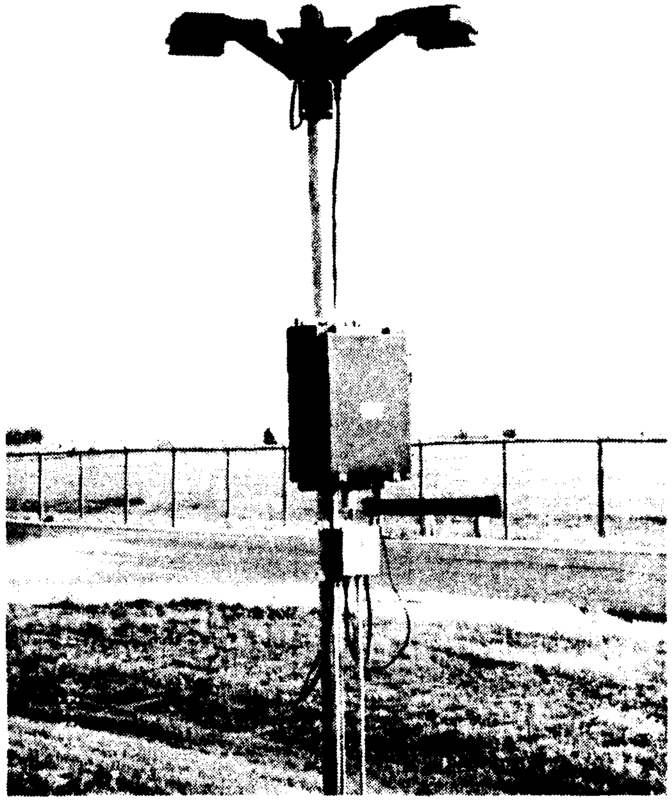


FIGURE D-15.

HSS PRESENT WEATHER SENSOR

APPENDIX E

RESULTS OF ICING CHAMBER TESTS

1) Rosemount (orthogonal system) (pressure) - October 18, 1990

PASSED: Two sensors were tested in the chamber. After being sprayed for forty minutes with the temperature at +7.3°F, a small amount of ice had formed at the top of one of the Rosemount sensors. The ice formed, but then quickly melted. This process repeated itself again near the end of the test; however, the operation of the sensor was never affected by the ice formation. The other Rosemount sensor remained clear of ice during the entire test. Both Rosemount sensors had passed the chamber icing test.

2) Belfort (hot wire) - October 18, 1990

FAILED: One sensor was tested in the chamber. The Belfort sensor was utilizing 30 watts of power on the top heater and 7 watts on a heater in the middle of the sensor head. After just ten minutes of spraying with the temperature at +12°F, the sensor began to have severe ice build-up around the cage and on the top of the sensor head. The testing was terminated at this time due to the rapid severity of the ice build-up. The Belfort sensor had failed the icing test.

3) Sutron (hot wire) - October 23, 1990

FAILED: Two sensors were tested in the chamber. The Sutron sensor was utilizing 50 watts of power on the top heater and 25 watts on the bottom heater. After nineteen minutes of spraying with the temperature at +8.4°F, ice began to form on both sensors. After forty minutes of spraying with the temperature at +8°F, severe ice build-up had formed on the cages and the hoods of both sensor heads. Both Sutron sensors had failed the chamber icing test.

4) Sutron (hot wire) - second test - October 24, 1990

PASSED: Two sensors were tested in the chamber. The Sutron sensor's bottom heater had been increased from 25 watts to 50 watts since the first test. After twenty-four minutes of spraying with the temperature at +19°F, a small amount of ice formed on half of the cage bars on one of the sensor heads. The other Sutron sensor was clear of ice. The effects of the ice on the sensor could be seen in the gradual dropping of the wind speed at the times when the blower fan was turned on.

After fifty-three minutes of spraying, the ice on the affected sensor began to melt. After one hour of spraying with the temperature at +19.4°F, the ice had melted completely from the affected sensor, but had begun to form at the center of four of the cage bars again. The other Sutron sensor remained clear of ice throughout the entire test. One Sutron sensor had passed the chamber icing test more easily than the other.

5) Climatronics (cup & vane) - October 25, 1990

PASSED: Two sensors were tested in the chamber. The Climatronics sensor was utilizing 1000 watts of power on the cup and vane and the eight heating rods that encircle the cup and vane. After one hour of spraying with the temperature at +19°F, both sensors had remained free of ice. After one hour and thirty-three minutes of spraying at the same temperature, the conditions were unchanged. Both Climatronics sensors had passed the chamber icing test.

6) Belfort (cup & vane) - November 27, 1990

PASSED: One sensor was tested in the chamber. The Belfort sensor was utilizing approximately 150 watts of power on the cup and vane external heaters. After one hour of spraying with the temperature at +20°F, both cup and vane showed no signs of problems due to icing. The cups seemed to respond slowly at times when the fan was turned on; however, they operated satisfactorily once inertia was broken. The Belfort sensors had passed the chamber icing test.

7) Qualimetrics - (thermal field variation) - November 28, 1990 Model 3056

FAILED: Two sensors were tested in the chamber. The Qualimetrics sensor was utilizing approximately 50 watts of power in the string of thermistors used as the sensing portion of the unit. No other forms of heating were being used in these units. After ten minutes of spraying with the temperature at +20.8°F, ice began forming on the cylinders and on the rain hoods of both sensors.

At this time, icicles began to form, hanging from the rain hoods of both sensors. After thirty-three minutes of spraying, eleven icicles were hanging from the hood of one unit and three from the hood of the other unit. After forty-five minutes of spraying, icicles covered 290 degrees of the area around the rain hood of one sensor and on one side of the rain hood of the other sensor. The icicles were growing in length and width rapidly. After one hour and five minutes of spraying, the icicles on one sensor had grown into each other becoming meshed and creating walls of ice.

The other sensor had built-up ice underneath the rain hood with the ice extending down on all sides almost reaching the cylinder. The icicles on this sensor had also grown, but continued to be confined to hanging from only one half of the rain hood. Both Qualimetrics sensors had failed the chamber icing test.

8) Belfort (hot wire) - second test - November 30, 1990

PASSED: One sensor was tested in the chamber. The Belfort sensor heaters had been increased since the sensor's first test to 50 watts of power on the top heater, 10 watts to a middle heater, and 50 watts to the bottom heater for a total of 110 watts to the heaters. After one hour of spraying with the temperature at +20°F, no icing had occurred on any part of the sensor. However, after about thirty minutes of spraying, a problem was noted with the sensor's output.

Upon completion of the testing, it was determined that some part of the sensor's electronics had failed. It was noted during the testing that a bubble of water had formed on the bottom plate inside the sensor head. This bubble of water was extending upward high enough to engulf the lower pair of hot wires. The water seemed to be adhering to the plate and would not clear off, even at times when the fan was turned on.

It was speculated that this water formation caused the electronics of the sensor to short out or to be over-driven to the point of failure. Belfort personnel stated they could fix this problem by drilling some small holes in the plate for the water to drain. It was decided that the Belfort sensor had passed the icing requirements of the chamber testing and that when Belfort completed the modification in the plate, the Belfort sensor could be installed in Rochester.

9) Armtec (hot wire) - November 30, 1990

PASSED: Two sensors were tested in the chamber. After one hour of spraying with the temperature at +20°F, both sensors showed no signs of icing or any other anomalies in their outputs. Both Armtec sensors had passed the chamber icing test.

10) Hydro Tech (cup & vane) - December 1, 1990

Heated Rotor Anemometer Model WS-3 & Heated Direction Vane Model WD-3.

PASSED: One sensor was tested in the chamber. The Hydro Tech sensor was utilizing 500 watts of power on the heater in the cup and 500 watts on the heater in the vane for a total of 1000 watts. The heaters are internal on the cup and vane units. The Hydro Tech sensors are variable and for the chamber test were set at 80 percent power. After seventeen minutes of spraying with the temperature at +20°F, some ice formed on the rudder of the vane unit.

It was also noted that when the fan was turned on, a very small amount of ice would form on the outer edge of the cups' unit. The ice that formed on the cups would melt off in less than one minute when the fan was turned off. A small amount of ice remained on the vane unit.

Both units were free moving and responding properly. After fifty minutes of spraying, the vane had a slight increase in the amount of ice on the rudder. The cups only had a small amount of ice appear when the fan was turned on. Both units demonstrated immediate melting of the ice when the fan was off. Both units remained free moving with no ill effects due to icing. The Hydro Tech sensor passed the chamber icing test.

11) R. M. Young Company (propeller) - January 11, 1991

Model 05103 Wind Monitor and Model 5203 De-Icing System

FAILED: One sensor was tested in the chamber. The R. M. Young sensor was utilizing four heat lamps of 150 watts each to de-ice the sensor. The heat lamps are controlled by two thermostats used as high and low temperature controls. After nine minutes of spraying with the temperature at +20°F, a small thin rim of ice formed on the top and front of the vane (fin). After twenty minutes of spraying, a thin layer of ice formed on the fuselage of the sensor.

After thirty minutes of spraying, an occasional small piece of ice formed on the blades of the propeller, but then melted. The layer of ice on the vane was now 1/4- to 1/2-inch thick. After thirty-six minutes of spraying, ice began to outline the lower portion of the vane. After forty-three minutes of spraying, a small icicle formed at the lower corner of the vane. At this time, the fan was turned on. Three minutes after turning on the fan, it was noted that the speed output from the sensor was dropping at an average rate of 2 knots-per-minute.

Ice was forming on the blades of the propeller and effecting the wind speed output. The fan was turned off after seven minutes of running. Large icicles extended off all of the blades of the propeller. One minute later, the propeller had frozen still after a total of forty-six minutes of spray time. The R. M. Young sensor had failed the chamber icing test.

It was decided that in spite of the failure to pass this icing test, an exception would be made for the R. M. Young sensors and that they would be included in the Rochester field test to provide a comparison to the other units based on the longstanding reputation of propeller technology anemometers. This decision reinforces the position that the purpose of the tests is to gather performance data and not to qualify participating units for the LLWAS application.

12) Vaisala (Cup & Vane) - February 20, 1991

PASSED: One sensor was tested in the chamber. The Vaisala sensor was utilizing approximately 50 watts total to heat the cups and the vane. After thirty-eight minutes of spraying with the temperature at +21°F, a small amount of ice formed on the top of the shaft of the cups' unit. After forty-eight minutes of spraying at +21°F, the ice on the top of the cups' shaft had melted off.

After fifty-five minutes of spraying at +21°F, a layer of ice had coated the fin of the vane and ice began to form on the top of the shaft of the cups again. After one hour and six minutes of spraying, six icicles had formed on the vane, but the unit was still very responsive to the air blower. No ice had formed on the cups themselves. The Vaisala sensor had passed the chamber icing test.

13) Qualimetrics - second test - February 21, 1991

Model 3056 - (thermal field variation)

FAILED: Two sensors were tested in the chamber. After the first chamber test, the Qualimetrics sensor had been modified with the addition of a 40- or 50-watt heater to the rain hood of the sensor. This heat is in addition to the 50 watts utilized in the string of thermistors in the sensing portion of the unit just under the center of the rain hood.

Early in the chamber test, it was determined that both sensors were not operating properly. It was suspected that the sensors had either been damaged during shipping or back at the factory during modification. Since the heaters on the rain hoods were still functioning, and this was the crucial portion of the first test of the Qualimetrics sensors, it was decided to go ahead with the spray segment of the test.

After seven minutes of spraying at +20°F, a small amount of ice had formed on the rain hood of one of the sensors. After thirteen minutes of spraying, a thin layer of ice had formed on the cylinder of one sensor, while three or four icicles hung from the same unit's rain hood. After nineteen minutes of spraying, icicles hung from the rain hoods of both units. After twenty-two minutes of spraying, it was noted that the icicles on both units had increased in size.

After twenty-nine minutes of spraying, ice had formed up on one cylinder over the cone and over the sensing portion of the sensor. The icicles on both sensors increased in size in both length and width. After one hour of spraying at +20°F, six or more icicles hung from the rain hoods of both sensors, with some icicles becoming six or more inches long and others becoming meshed together. Ice had formed up on both cylinders over the cones and over the sensing portions of the sensors. Both Qualimetrics sensors had failed the chamber icing test.

APPENDIX F

DATA COLLECTION SYSTEM

F.1 INSTALLATION

The power for the sensors was provided by 100-amp 240 VAC service from a nearby power line. The power panel was centrally located in the array of poles (see Figure 4-2). Each pole was provided with a 10-amp 120 VAC circuit to enforce the 1000-watt sensor maximum power limit. One sensor type was found to trip the circuit breaker and had to be reprogrammed to use less power. The cabling permitted substituting a 15-amp circuit breaker, if needed. One 20-amp circuit was routed back into the data acquisition office to provide a common power ground for the data acquisition system computer.

Each pole was provided with six shielded twisted wire pairs for signal transmission to the data acquisition system. These pairs were connected to terminal strips mounted on the wall above the data acquisition system computer. From there, the signals passed through surge protectors to the computer interface cards.

F.2 DATA ACQUISITION SYSTEM

F.2.1 Hardware

The data acquisition system (DAS) was based on a rack-mounted 16-Mhz 386SX personal computer. Three 8-port RS232 serial interface cards (Digiboard COM/8) were installed. All channels were assigned to interrupt IRQ5, but had different addresses. The channel generating an interrupt was indicated in a status register.

Digiboard software (COMSET) was used to configure the Digiboards as COM3 through COM26 and to specify the baud rate, number of bits, and parity of each channel. A 2400-baud modem permitted remote access to the DAS. The computer was equipped with a watchdog timer that would reboot the computer if the data acquisition software failed.

F.2.2 Software

The DAS software used the MS-DOS operating system and the Desqview multi-tasking environment. Two tasks were operating simultaneously:

1) The data acquisition program (version COLD, i.e., version D) ran in the foreground (assigned three clock ticks).

2) The communication program (Crosstalk XVI) ran in the background (assigned nine clock ticks).

In addition to permitting multi-tasking, Desqview provided a display driver that was not affected by the interrupt service routine, a problem recently corrected.

The data acquisition was controlled by a configuration file that specifies the information for each sensor, including the following:

1) Hardware channel.

2) Required sensor initialization.

3) Type of sensor:

   a) Unpolled: Sensor reports on its own timing. Last message every minute is recorded.
   b) Polled: Sensor responds to poll message each minute.
   c) Continuous: Sensor reports continually. DAS software provides one minute average.

4) Length of sensor message, end-of-message character.

5) Part of message to be saved.

The data collection program COLD consists of the following sections:

1) Initialization section.

2) Sensor status loop. The status of each sensor is checked in turn and any messages received are processed.

3) End-of-minute processing:

   a) Pole polled sensors in turn.
   b) Average continuous sensors and generate message.
   c) Record and display data block.
   d) Initialize data block.

4) Interrupt service routine. Puts character into buffer. Checks for message complete.

F.2.3 Data Format

The data for each minute was stored as an ASCII data block headed by the date and time. The data from each sensor was separated by a carriage return and a line feed so that the data could be readily printed out, if desired. The data block stored to disk was also written to the display screen so that the operator could verify the proper recording for each sensor. A new data file was started each day at midnight. The file was kept closed except when data was being written.

F.2.4 Watchdog Timer

The watchdog timer usage evolved in response to observed problems:

1) The timer was originally reset whenever an interrupt was serviced. This procedure protected against an interrupt latchup that has been noted in the Digiboards. This procedure would not, however, protect against the main program bombing out.

2) A new interrupt service routine was implemented to set a flag every time an interrupt was serviced. The main program reset the timer when it saw this flag and then cleared the flag. Both the main program and the interrupt service routine were thereby protected.

3) The Desqview script was found to malfunction one in ten or twenty starts because of a timing problem. The timing problem was resolved, but watchdog protection was also added to the AUTOEXEC.BAT file, so that Desqview problems would lead to a reboot.

APPENDIX G

SENSOR FIELD TEST HISTORY

The following is a chronology of sensor maintenance for each sensor during the field test at Rochester, Minnesota during the field test period from November, 1990 to July, 1991.

HYDRO TECH I

12/06/90 - Sensor physically installed.

12/18/90 - Sensor communicating with the Data Acquisition System (DAS).

05/03/91 - Data Malfunction. Cause of failure never determined. This was the last time this sensor reported to the DAS.

HYDRO TECH II

12/06/90 - Sensor physically installed.

12/18/90 - **SENSOR FAILURE**. Cause of failure was a bad pulser in the speed unit (cups). Returned to Hydro Tech for repair.

01/17/91 - Speed unit re-installed. Sensor communicating with the DAS.

February - Data Malfunction. Intermittent dropouts of data were experienced in February due to a poor connection.

02/28/91 - The intermittent problem due to a poor connection was corrected. No other failures or drop-outs experienced with this sensor.

VAISALA I

02/22/91 - Vaisala personnel visit site.

02/28/91 - Sensor installed and communicating with the DAS.

03/27/91 - Data Malfunction. Site power failure reported.

03/29/91 - Sensor began reporting to the DAS again. No other failures or dropouts experienced with this sensor.

VAISALA II

02/22/91 - Vaisala personnel visit site.

02/28/91 - Sensor installed and communicating with the DAS.

03/27/91 - Data Malfunction. Site power failure reported.

03/29/91 - Sensor began reporting to the DAS again. No other failures or dropouts experienced with this sensor.

R.M. YOUNG I

01/16/91 - Sensor installed and communicating with the DAS. No failures or dropouts experienced with this sensor for the duration of the test.

R.M. YOUNG II

01/16/91 - Sensor installed and communicating with the DAS. No failures or dropouts experienced with this sensor for the duration of the test.

SUTRON I

11/14/90 - Sensor installed and communicating with the DAS.

03/28/91 - Data Malfunction. Site power failure reported on March 27. Sensor began reporting as straight line. Sensor did not return to reporting to the DAS upon return of power.

04/19/91 - Power on sensor unit itself reset by NWS personnel. Sensor began reporting properly to the DAS again.

06/13/91 - Data Malfunction. Loss of sensor due to lightning strikes in the area.

06/14/91 - Sensor began reporting to the DAS again. No more failures or dropouts experienced with this sensor.

SUTRON II

11/14/90 - Sensor installed and communicating with the DAS.

03/27/91 - Data Malfunction. Site power failure reported.

03/29/91 - Sensor began reporting to the DAS again.

06/11/91 - Data Malfunction. Loss of sensor due to lightning strikes in the area. Sensor did not return on its own.

06/24/91 - Sensor power reset by NWS personnel. Sensor began reporting to the DAS again. No more failures or drop-outs experienced with this sensor.

CLIMATRONICS I

11/02/90 - Sensor installed and communicating with the DAS.

11/23/90 - Data Malfunction. Sensor had popped the circuit breaker.

11/26/90 - Circuit breaker is reset and sensor returned to reporting to the DAS. No other failures or drop-outs experienced with this sensor.

CLIMATRONICS II

11/02/90 - Sensor installed and communicating with the DAS.

11/13/90 - Data Malfunction. Sensor circuit breaker found popped by Volpe Center personnel and was reset.

11/23/90 - Data Malfunction. Sensor circuit breaker popped again.

11/26/90 - Sensor circuit breaker is reset and sensor returned to reporting to the DAS.

11/27/90 - Data Malfunction. Sensor circuit breaker popped again.

12/04/90 - Sensor circuit breaker reset and sensor returned to reporting to the DAS.

12/05/90 - Climatronics personnel changed E-Prom program to limit power to heaters at 1,000 watts. No limit in previous program was reason for the circuit breaker popping.

02/27/91 - Sensor program changed to allow heaters to exceed the 1,000 watt limit. (Circuit breaker replaced with 15 amp breaker.)

02/28/91 - **SENSOR FAILURE.** Errors in the program allowed the heaters to get so hot that they melted the cups.

03/20/91 - Climatronics personnel on-site to replace the sensor and correct the program. Sensor reporting to the DAS again.

04/22/91 - **SENSOR FAILURE.** Sensor found to be missing one of its three cups by Volpe

Center personnel. Sensor also found to have a bad transducer. Sensor was removed and shipped back to Climatronics for repair.

05/09/91 - Climatronics personnel are on-site to install the sensor. The gain on this unit's program was increased. The sensor is again reporting to the DAS. No more failures or drop-outs were experienced with this sensor.

BELFORT HWI

01/18/91 - Sensor installed and communicating with the DAS. No failures or drop-outs experienced with this sensor for the duration of the test.

01/25/91 - Belfort personnel on-site to change the position of the sensors.

04/12/91 - Data Malfunction - Belfort personnel on-site to discover problem with the program in the data logger.

04/18/91 - Belfort personnel on-site to correct the program in the sensor data logger.

BELFORT HWII

01/18/91 - Sensor installed and communicating with the DAS. No failures or drop-outs experienced with this sensor for the duration of the test.

01/25/91 - Belfort personnel on-site to change the position of the sensors.

04/12/91 - Data Malfunction - Belfort personnel on-site to discover the problem with the program in the data logger.

04/18/91 - Belfort personnel on-site to correct the program in the sensor data logger.

BELFORT CVI

12/06/90 - Sensor installed and communicating with the DAS.

12/07/90 - Data Malfunction. Loss of sensor data. Cause not yet determined.

12/18/90 - **SENSOR FAILURE**. Sensor speed unit (cups) moving very slowly. Removed speed unit and shipped to Belfort for repair. New E-Proms installed in sensor. E-Proms had changed baud rate from 1200 to 2400.

01/16/91 - Speed unit re-installed. Sensor reporting to the DAS.

03/27/91 - Sensor Malfunction. Site power failure reported.

03/28/91 - Data Malfunction. Belfort personnel on-site to remove cups and replace bearings.

04/04/91 - Sensor began reporting to the DAS again.

04/12/91 - Data Malfunction. Belfort personnel on-site to change the E-Proms on sensor. E-Proms changed baud rate from 2400 to 1200, however the DAS did not change to accept the different baud rate.

04/22/91 - Sensor baud rate on the DAS changed to 1200 baud. Sensor data now being accepted properly. No other failures or drop-outs were experienced with this sensor.

BELFORT CVII

12/06/90 - Sensor installed and communicating with the DAS.

12/11/90 - Data Malfunction. Loss of sensor data. Cause not yet determined.

03/28/91 - Data Malfunction. Site power failure reported on March 27.

04/04/91 - Sensor began reporting to the DAS again.

04/04/91 - Belfort personnel on-site to re-install cups. Sensor began reporting to the DAS again.

04/12/91 - Data Malfunction. Belfort personnel on site. Change E-proms on sensor. E-proms changed baud rate from 2400 bps to 1200 bps, however the DAS did not change to accept the different baud rate.

04/18/91 - **SENSOR FAILURE**. Problem with speed unit. Slip rings damaged in shipment. Cups were removed by Belfort personnel for repair. Speed unit was never re-installed and this was the last time this sensor reported to the DAS for the remainder of the test.

ARMTEC I

12/06/90 - Sensor installed and communicating with DAS.

12/06/90 - **SENSOR FAILURE**. Problem with wind directions from sensor. Sensor programmed backwards.

12/19/90 - **SENSOR FAILURE CONTINUED.** New E-Proms installed in the sensor to cure direction problem. Direction problem continued, so sensor was removed and shipped to Armtec for repair.

01/19/91 - Sensor re-installed and began reporting to the DAS.

02/28/91 - New E-Proms installed for improved averaging.

03/19/91 - Armtec personnel visit site.

03/27/91 - Data Malfunction. Site power failure reported.

04/05/91 - Sensor began reporting to the DAS again.

04/06/91 - Data Malfunction. Sensor suspected of damage caused by lightning strikes or power outage was removed by Armtec personnel.

07/03/91 - Sensor re-installed by Armtec personnel. No more failures or drop-outs experienced with this sensor for the remainder of the test.

ARMTEC II

12/06/90 - Sensor installed and communicating with the DAS.

12/06/90 - **SENSOR FAILURE**. Problem with wind directions from sensor. Sensor programmed backwards.

12/19/90 - New E-Proms installed in sensor curing the wind direction problem.

02/28/91 - New E-Proms installed for improved averaging.

03/19/91 - Armtec personnel visit site.

03/28/91 - Data Malfunction. Site power failure reported.

04/05/91 - Sensor began reporting to the DAS again.

04/06/91 - Data Malfunction. Sensor suspected of damage caused by lightning strikes or power outage. Sensor was removed by Armtec personnel.

07/03/91 - Sensor re-installed by Armtec personnel. No more failures or drop-outs experienced with this sensor for the remainder of the test.

ROSEMOUNT I

11/02/90 - Sensor installed and communicating with the DAS.

01/17/91 - Data Malfunction. Rosemount sensor heater problem due to welding.

01/23/91 - Sensor again reporting to the DAS.

03/04/91 - **SENSOR FAILURE.** Sensor removed for bad heater by Rosemount personnel.

03/22/91 - Sensor re-installed and reporting to the DAS again.

04/11/91 - **SENSOR FAILURE.** Sensor popped circuit breaker and blew its power supply fuse.

04/18/91 - Sensor reporting again to the DAS system. No other failures or drop-outs were experienced with this sensor for the remainder of the test.

ROSEMOUNT II

11/02/90 - Sensor installed and communicating with the DAS.

12/18/91 - **SENSOR FAILURE.** Sensor found to have bad heater.

12/22/91 - Sensor replaced by Rosemount personnel and reporting to the DAS again.

03/04/91 - Data Malfunction. Sensor removed by Rosemount personnel for bad heater.

03/08/91 - Sensor again reporting to the DAS. Re-installed by Rosemount personnel.

03/25/91 - **SENSOR FAILURE.** Sensor removed by Rosemount personnel.

04/06/91 - Sensor re-installed and reporting to the DAS.

04/11/91 - **SENSOR FAILURE.** Sensor popped circuit breaker and blew its power supply fuse.

04/18/91 - Sensor reporting again to the DAS system. No other failures or drop-outs were experienced with this sensor for the remainder of the test.

APPENDIX H

;UMMARY OF SAO WEATHER REPORTS OF ICING EVENTS - WINTER OF 1990-1991

TABLE H-1. SUMMARY OF SAO WEATHER REPORTS FOR NOVEMBER, 1990 ICING EVENTS

NT TE	PRECIP TIMES (SAO)	PRECIP TYPE (SAO)	ROSE-MOUNT ICING	TEMP RANGE (SAO)	GLAZE TIME (HH.H)	WIND SPEED (SAO)	WIND GUSTS (SAO)	WIND DIREC (SAO)	COMMENTS
l/90	0716-0834	R-	N	36-38	0.0	11-15	-	360-10	ICING SENSOR/SAO (IP) EVENT
	0834-0901	R-,IP-	N	36		12-15	-	340-350	
	0901-0930	R-	N	36		12-14	-	360	
	0930-0947								
	0947-1030	R-,S-	N	36-37		10-14	21	360-10	
	1030-1126								
	1126-1224	R-	N	35-36		16-18	23-26	340-10	
	1224-1248	R-,S-	N	33		13-18	23-24	340-350	
	1248-1630	S-,S	Y	32-33		8-13	-	350-20	
l/90	***1535-1647***	***ZL-***	***Y***	***29***	***7.7***	***19-22***	***24-29***	***170-190***	ICING SENSOR/SAO EVENT
	1647-1744	IP-	Y	29		17-19	24-25	170-190	
	1744-1810	***IP-,ZL-***	***N***	***29***		***16***	***29***	***180-190***	
	1810-1853	IP-	N	29-30		15-16	21-24	180-190	
1/90	***0501-0535***	***ZR-***	***Y***	***33-35***	***28.3***	***11-14***	-	***210***	ICING SENSOR/SAO EVENT
	0535-0606								
	0606-0620	R-	N	35		14	-	220	
	0620-0705								
	0705-0715	R-	N	36		10	-	230	
7/90	0210-0528	L-	N	32-34	39.1	10-14	18	290-300	ICING SENSOR/SAO EVENT
	0528-0722	***ZL-***	***N***	***31***		***10-15***	-	***300-320***	
	0722-0948								
	0948-1250	***ZL-***	***Y***	***29-30***		***7-11***	-	***300-340***	
	1250-1412								
	1412-1740	***ZL-***	***Y***	***30-31***		***6-12***	-	***350-30***	
	1740-1748	***ZL-,ZR-***	***Y***	***31***		***9***	-	***360***	
	1748-1830	***ZR-***	***Y***	***31***		***6-7***	-	***330-10***	
	1830-1847	***ZL-***	***Y***	***31***		***6***	-	***330***	
	1847-1922	***ZR-,ZL-***	***Y***	***31***		***10-12***	-	***310***	
	1922-2147	***ZR-,S-***	***Y***	***26-30***		***12-16***	-	***310***	
	2147-2225	S-	N	24-26		16	23	290-310	

TABLE H-2. SUMMARY OF SAO WEATHER REPORTS FOR DECEMBER 12-17, 1990 ICING EVENTS

EVENT DATE	PRECIP TIMES (SAO)	PRECIP TYPE (SAO)	ROSE-MOUNT ICING	TEMP RANGE (SAO)	GLAZE TIME (HH.H)	WIND SPEED (SAO)	WIND GUSTS (SAO)	WIND DIREC (SAO)	COMMENTS
12/12/90	***0744-1047***	***ZL-***	***Y***	***30-32***	***1.1***	***12-20***	***26***	***310-320***	ICING SENSOR/SAO EVENT TRACE PRECIPITATION
12/15/90	1934,12/14-0742	S-	Y	26-28	20.8	7-14	-	40-150	ICING SENSOR EVENT
	0742-0800								
	0800-1108	S-	N	26-29		8-13	-	350-40	
	1108-1415								
	1415-1620	S-	N	29-30		12-14	-	320-340	
12/16/90	2028-2046	S-	N	28	3.0	15	-	160	ICING SENSOR/SAO EVENT
	2046-2147	***ZR-,IP-, S-***	***Y***	***28***		***15-16***	-	***160-180***	
	2147-2344	S-	N	28-29		15-19	-	180-190	
	2344-0045	IP-,S-	N	29-30		15-18	-	180-190	
12/17/90	***0045-0140***	***ZL-,S-***	***N***	***30***	***10.2***	***15-17***	-	***180-190***	ICING SENSOR/SAO EVENT
	0140-0245	S-	N	30		15-17	25	180-190	BROKE ANNUAL PRECIPITATION RECORD
	0245-0350	S-,IP-	Y	30-31		13-15	-	180	
	0350-0850	S-	Y	31		7-13	-	170-210	
	0850-0941								
	0941-1145	S-,SP-	N	32-34		3-7	-	200-340	
	1145-1236	L-	N	33-34		3-4	-	320-340	
	1236-1251								
	1251-2044	S,S-	Y	21-33		4-13	-	300-360	

)0	0038-0211	L-	Y	32	27.4	16-21	-	140-160	ICING SENSOR/SAO EVENT
	0211-0245	*ZL-*	*N*	*32*		*18-20*	-	*140-150*	
	0245-0316								
	0316-0339	L-	Y	32		19	-	150	
	0339-0424	L-,S-	Y	32		20	-	150	
	0424-0825	L-	Y	30-34		19-20	-	160-170	
	0825-0843								
	0843-1018	*ZL-*	*Y*	*15-26*		*11-15*	-	*280-300*	
	1018-1050	*SG-,ZL-*	*Y*	*12-15*		*13-15*	-	*300-310*	
	1050-1412	SG-,S-	Y	6-12		13-17	-	300-320	
)0	0250-0636	IC-	N	-8--6	35.4	9-11	-	310-340	ICING SENSOR EVENT,
	0636-0730	IC,S-	N	-6		8	-	320-340	ICE CRYSTALS
	0730-0030	S-,S	Y	-1--13		10-17	-	290-10	
)0	-	-	Y	-23--22	48.0	8-9	-	260-270	ICING SENSOR EVENT, 0710-0755
)0	1441-2017	S-	?	-2--3	?	10-12	-	150-180	DAY AFTER CHRISTMAS
)0	*0448-0646*	*ZL-*	*N/A*	*22-24*	*1.2*	*16-20*	-	*180-200*	ICING SENSOR/SAO EVENT
	0646-1248								BLOWING SNOW, FOG
	1248-1542	*ZL-*	*Y*	*26-27*		*8-15*	-	*120-180*	
	1542-1646	*SG-,ZL-*	*Y*	*27-28*		*8-9*	-	*110-140*	
	1646-2244	*ZL-*	*Y*	*28-29*		*6-9*	-	*140-270*	
	2244-2344	*SG-,ZL-,S-*	*N*	*27-29*		*7-8*	-	*280-300*	
	2313-0742	S-	Y	2-27		8-20	-	290-320	
0	2313,12/28-				48.0				BLOWING SNOW
	0742	S-	Y	2-27		8-20	-	290-320	ICING SENSOR EVENT
	0942-1110	S-	N	-2--4		19-20	-	320	

TABLE H-4. SUMMARY OF SAO WEATHER REPORTS FOR JANUARY 5-13, 1991 ICING EVENTS

EVENT DATE	PRECIP TIMES (SAO)	PRECIP TYPE (SAO)	ROSE-MOUNT ICING	TEMP RANGE (SAO)	GLAZE TIME (HH.H)	WIND SPEED (SAO)	WIND GUSTS (SAO)	WIND DIREC (SAO)	COMMENTS
1/5/91	0302-0939	S,S-	N	11-13	4.7#	4-7	-	40-140	ICING SENSOR EVENT: 2305-2335
	0939-1337								# - BASED ON ICING SENSOR
	1337-1534	S-	N	16-18		9-10	-	340-360	
1/6/91	-	-	Y	-4-3	39.6	6-7	-	310-20	HOAR FROST 0215-0944 ICING SENSOR EVENT: 0415-0500
1/8/91	2325,1/7-0520	S-	Y	11-18	48.0	13-15	-	140-180	ICING SENSOR/SAO EVENT
	0520-0709	***ZL-,S-,***	***Y***	***17-19***		***12-13***	-	***180-190***	BLOWING SNOW
	0709-1244	S-,SG-	Y	19-22		11-13	-	180-220	
	1244-1412								
	1412-1448	***ZL-***	***N***	***22***		***10-11***	-	***240-270***	
	1448-1503	***S-,ZL-***	***N***	***22***		***10***	-	***270-280***	
	1503-2325	S-,SG-	N	16-22		8-13	-	280-320	
1/13/91	1645,1/12-0015	S-	N	8-15		6-9	-	210-260	SAO EVENT BLOWING SNOW
	0015-0941								
	0941-1258	S-	N	19-22	11.2	15-20	-	200	
	1258-1311								
	1311-1348	***ZL-,S-***	***N***	***24***		***16-19***	-	***200***	
	1348-1438	***ZR-,IP-, S-***	***N***	***24***		***16-18***	-	***200-210***	
	1438-1507	IP-,S-	N	24		17-19	-	200-210	
	1507-1844	S-	N	24-26		14-19	-	200-230	

TABLE H-5. SUMMARY OF SAO WEATHER REPORTS FOR JANUARY 15-26, 1991 ICING EVENTS

T E	PRECIP TIMES (SAO)	PRECIP TYPE (SAO)	ROSE-MOUNT ICING	TEMP RANGE (SAO)	GLAZE TIME (HH.H)	WIND SPEED (SAO)	WIND GUSTS (SAO)	WIND DIREC (SAO)	COMMENTS
91	0648-0745	S-	N	20-21	23.9	5	-	100-110	SAO EVENT
	0745-0938								
	0938-0947	***ZL-***	***N***	***21***		***6***	-	***160-170***	
	0947-1140								
	1140-1347	S-	N	22-23		5-9	-	70-110	
91	0248-0739	S-	Y	18-20	26.7	7-9	-	340-30	ICING SENSOR/SAO EVENT'
	0739-1912								HOAR FROST HANDWRITTEN ON
	1912-2245	S-	Y	22-24		11-15	-	270-300	SAO REPORT PRINTOUT
	2245-2339	***ZL-,S-***	***Y***	***24***		***11-15***	-	***300***	(GLAZE 2245-CONTIN IN SAO
	2339-0242	S-	N	24-26		11-16	20	290-330	REMARKS)
91	0636-0645	IC	N	16	24.4	11	-	260	ICING SENSOR EVENT
	0645-0846								ICE CRYSTALS (SAO)
	0846-0939	S-	Y	24-26		11	-	250	
91	2035-0044	IC	N	-1--3	22.4	13-17	-	230-240	ICE CRYSTALS (SAO) SAO ANEMOMETER INOPERATIVE DAY BEFORE
91	0948-1030	S-	N	6-9	48.0	14-16	-	250-260	ICE CRYSTALS (SAO) TO 0044 SAO ANEMOMETER INOPERATIVE 1447-1643; T=18-19 F AIRCRAFT ACCIDENT 1210 ACCORDING TO SAO REMARKS

TABLE H-6. SUMMARY OF SAO WEATHER REPORTS FOR FEBRUARY 1991 ICING EVENTS

EVENT DATE	PRECIP TIMES (SAO)	PRECIP TYPE (SAO)	ROSE-MOUNT ICING	TEMP RANGE (SAO)	GLAZE TIME (HH.H)	WIND SPEED (SAO)	WIND GUSTS	WIND DIREC (SAO)	COMMENTS
2/13/91	1515-2048	S-	Y	28-32	48.0	8-18	26	190-310	ICING SENSOR/SAO EVENT
	2048-2137	***ZL-,S-***	***N***	***27-29***		***15-17***	-	***310***	BLOWING SNOW VERY LATE IN
	2137-1101	S-	N	11-27		13-28	25-35	290-360	DAY TO LATE MORNING NEXT DAY
2/18/91	0648-0741	S-	N/A	28	34.4	14	-	90	STRIP CHART BEGAN AT 0847
	0741-0948								
	0948-1007	IP-,S-	Y	29		15-17	-	80-90	ICING SENSOR/SAO EVENT
	1007-1014								
	1014-1123	***ZR-,ZL-,***	***Y***	***30***		***16-18***	***22***	***70-90***	
	1123-1140								
	1140-1250	***ZR-,IP-***	***Y***	***31***		***13-15***	-	***80-90***	
	1250-1330	***ZR-***	***Y***	***31***		***9-13***	-	***70-80***	
	1329-1352	R-,IP-	Y	32		6-9	-	30-70	
	1352-1400	IP-	N	32		6	-	30	
	1400-1417	IP-,SP-	N	32		6	-	30-40	
	1417-1850	S-	Y	30-32		5-8	-	360-50	
	1850-1947	***ZL-***	***Y***	***30-31***		***6-7***	-	***40***	
	1940-2240								
	2240-0027	***ZL-***	***Y***	***29-31***		***10-13***	-	***300-320***	
2/19/91	0237-0615	S-	Y	25-27	34.4	11-15	-	290-300	ICING SENSOR EVENT

TABLE H-7. SUMMARY OF SAO WEATHER REPORTS FOR MARCH, 1991 ICING EVENTS

EVENT DATE	PRECIP TIMES (SAO)	PRECIP TYPE (SAO)	ROSE-MOUNT ICING	TEMP RANGE (SAO)	GLAZE TIME (HH.H)	WIND SPEED (SAO)	WIND GUSTS (SAO)	WIND DIREC (SAO)	COMMENTS
3/2/91	1427,3/1-0145	R-,L-	N	32-38	48.0	8-24	23-30	10-80	ICING SENSOR/SAO EVENT
	0145-0246								
	0246-0333	***ZL-***	***Y***	***28-30***		***21***	***28***	***360-10***	
	0333-0917								
	0917-1040	S-	N	18-21		19-21	26	350-10	
3/6/91	***0054-0125***	***ZR-***	***N***	***29-30***	***48.0***	***18-21***	***29***	***310-320***	SAO EVENT
	0125-0149	IP-,S-	N	28-29		18-22	25	310-320	BLOWING SNOW
	0149-0515	S-	N	23-28		19-22	31-32	310-330	
	0515-0750								
	0750-0845	S-	N	20		20-22	-	320-330	
3/12/91	0237-0525	R-	N	33	31.1	18-19	23-26	100-110	ICING SENSOR/SAO EVENT
	0525-0540								R. M. YOUNG UNIT
	0540-0647	***ZR-***	***Y***	***33***		***17-20***	***24-27***	***100-110***	SLOWED SLIGHTLY FROM
	0647-0726	R-	Y	32-33		17-19	-	100	0400-0500 AND 0600-1030
	0726-0742	IP-	Y	31-32		19-20	-	90-100	
3/12/91	0742-0947	IP-,S-	Y	30-31		17-20	-	90-100	SAO SNOW/ICING SENSOR EVENT
	0947-1740	S-	N	27-30		16-24	24-30	60-100	VAISALA UNIT 1 SLOWED FROM
	1740-1839								1230-1800 AND UNIT 2 FROM
	1839-1935	S-	N	29-30		15-17	-	60-70	1100-1800 IN SNOW AND BLOWING SNOW
3/27/91	0148-0640	R-	N	48-54	48.0	8-16	-	260-40	ICING SENSOR EVENT
	0640-0712	L-	N	48		17	-	20-40	ICE THICKNESS NEGATIVE
	0712-0820								FROM 1529-1535 DUE TO SLUSH
	0820-0950	R-	N	39-44		17-22	-	310-340	
	0950-1002								
	1002-1435	R-	N	34-39		17-22	25	320-20	
	1435-1446	R-,S-	N	33-34		20	-	330	
	1446-1817	S-	Y	29-33		20-28	28-36	310-330	
3/30/91	1645-1715	SW-	N	36	0.0	17-18	-	210-220	ICING SENSOR EVENT

TABLE H-8. SUMMARY OF SAO WEATHER REPORTS FOR APRIL, 1991 ICING EVENT

EVENT DATE	PRECIP TIMES (SAO)	PRECIP TYPE (SAO)	ROSE-MOUNT ICING	TEMP RANGE (SAO)	GLAZE TIME (HH.H)	WIND SPEED (SAO)	WIND GUSTS (SAO)	WIND DIREC (SAO)	COMMENTS
4/12/91	0352-0416	R-	N	37	0.0	16	-	110	ICING SENSOR EVENT
	0415-0535	S-	N	35-38		16-21	25-28	100	ICE PELLETS (SAO)
	0535-0610	R-,S-, IP-	Y	34-35		16-18	25	100-110	
	0610-0652	S-	Y	33-34		18-20	25	100-110	
	0652-0738	S-,IP-	N	33-34		22	-	110	
	0738-0815	S-,L-	N	34		22-24	29-30	110-120	
	0815-0918								
	0918-1004	R-	N	35		12-17	-	100-110	
	1004-1035	R-,IP-	N	35-36		12-14	-	100-110	
	1035-1201	R-	N	36		14-31	39-43	110-130	
	1201-1818								
	1818-1832	R-	N	34-35		16-18	-	100-110	
	1832-1902								
	1902-2243	R-	N	34-35		14-18	23-26	110-130	

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