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WIND SHEAR TEST SITE UPGRADING

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D. W. Beran
Duane Haugen

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16. Abstract

During late 1975 and early 1976 the FAA was faced with the problem of selecting one or two remote sensing techniques from many which might be used to solve the airport wind shear problem. To do this a suitable [illegible] site, along with test personnel were required. The Table Mountain field site [illegible] [illegible]ulder, Colorado, was chosen because it met most of the requirements.

This report describes the field site modifications that were made at ~~for the tests~~. In addition, the results from tests of a commercial acoustic Doppler system, a CW lidar system and a WPL owned FM-CW radar and prototype acoustic Doppler system are summarized. The commercial devices were tested for only a short period of time due to other contracted arrangements and limited resources for maintaining the systems on site. As a result the tests were useful but inconclusive. This limited availability for testing was also a problem with the FM-CW radar. However, it was possible to make the first comparisons of this device with an acoustic Doppler system. Winds measured by the two systems over approximately 5 minute averaging times compared well.

The WPL prototype acoustic Doppler system was operated for a much longer period and we now have a better understanding of its potential. This particular system is limited by surface winds above 10 meters per second and its performance is degraded by other background noises such as thunder. The limiting influence of rain is not as severe as had previously been expected, but it is a serious problem for intense rainfall.

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PREFACE

This work was performed under Inter-Agency Agreement No. DOT FA76WAI-622 by the Remote Sensor Applications Program Area of NOAA's Wave Propagation Laboratory (WPL) in Boulder, Colorado for the Aviation Weather Branch, Airport Division, Systems Research and Development Service, Federal Aviation Administration, U.S. Department of Transportation. The cooperation and participation of many other individuals and groups was also essential to the successful conclusion of the work. The cooperation of personnel from Lockheed Missiles and Space Co., Xonics Co., and the Transportation Systems Center is gratefully acknowledged. Dr. Haugen was ably assisted by Dr. Kaimal and Mr. Newman during all of the field operations. The FM-CW tests and analysis of the WPL acoustic Doppler system was under the direction of Mr. Frank Pratte. Dr. R. Chadwick and Mr. Ken Moran were responsible for operating the FM-CW radar and Mr. B. Willmarth was in charge of the balloon-borne measurements that supported this research effort.

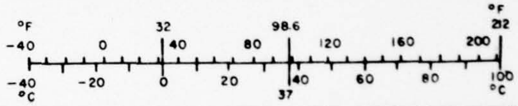
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	*hectares (10,000 m^2)*	2.5	*acres*	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

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LIST OF ILLUSTRATIONS

LIST OF ABBREVIATIONS AND SYMBOLS

WPL	-	Wave Propagation Laboratory
FM-CW	-	Frequency Modulated/Continuous Wave
FAA	-	Federal Aviation Administration
MMOS	-	Mobile Micrometeorological Observation System
AFCRL	-	Air Force Cambridge Research Laboratories
SDS	-	Scientific Data Systems
TSC	-	Transportation System Center
BLP	-	Boundary Layer Profiler
dB	-	decibel

1. INTRODUCTION

In response to the urgent need for methods of alleviating the wind shear problem a number of new and innovative approaches were proposed to the FAA. Many of these involved remote sensing techniques specifically designed to measure a wind profile from which the magnitude of shear could be derived. As a class, these instruments represent an advanced form of measuring device and none have undergone sufficient testing to judge their applicability in an operational setting.

Innumerable performance claims were made by the advocates of various techniques. With little or no supporting data, the FAA was faced with the need to select the most promising system for possible early operational implementation. Field testing to establish performance limits and reliability for these devices was clearly called for. The results from an analysis of the testing problem suggested the following requirements:

a. A test facility where standard _in situ_ sensors could be used to produce a wind profile for comparison with the profile measured by a remote sensor.

b. Data recording equipment which would allow both archiving and "quick look" capabilities for real-time analysis and later detailed statistical comparison of the data sets.

c. Personnel with an intimate knowledge of the systems to be tested and with a background in boundary-layer meteorology and tower operation.

d. A location having a high probability of strong winds and other meteorological conditions which might limit the operation of the devices to be tested.

A survey of potential sites indicated that the Table Mountain field facility, near Boulder, Colorado, came closest to meeting these requirements. This mountain-lee-side location has a high probability of winds greater than 100 knots on at least a few occasions during the winter months. These strong winds and the typically clear air were conditions that could limit acoustic and lidar systems, two of the devices which were being considered as potential wind shear detectors. The site already had a 150-m tower, suitable for mounting _in situ_ instruments and the facility was supported by a sophisticated data collection system which could be programmed to accommodate a wide variety of test conditions. The existing tower had been used for radio propagation work and was fitted with large antennas, but no meteorological instruments. The only major work effort required to upgrade this site involved the removal of existing antennas and some smaller towers and the mounting of meteorological sensors.

The facility is near WPL where experts in all types of remote sensing devices are available for consultation, and the tower and data collection equipment were under the direction of an experienced team of boundary layer meteorologists from the U.S. Air Force Cambridge Research Laboratory.

Following the FAA's identification of remote sensing systems that appeared to have potential, it was WPL's responsibility to contract and arrange with the owners for the necessary tests. WPL controlled the test conditions, analyzed the data and reported the results. The contractors were required to install and operate their own equipment throughout the tests.

Two commercial devices were selected for testing. The first was an acoustic Doppler system, and the second a CW Doppler lidar. In addition to these commercial systems, a prototype of the WPL acoustic Doppler system was employed when possible. Direct side-by-side comparisons of this system and the tower were not feasible, because the fixed installations were separated by about 2 km, however, gross comparisons were made. An additional series of tests compared a newly developed clear air radar system with the WPL prototype acoustic Doppler. The site preparation at Table Mountain, necessary for this experiment, was also included under this contract.

This report deals only with the activity necessary to upgrade the facility to conduct the tests. Existing equipment such as the tower and the data collection and instrument calibration systems are fully documented elsewhere and detailed descriptions do not properly form a part of this report. The essential function of the upgrading task was to modify and bring together the existing facilities for the purpose of providing standard comparison measurements.

2. THE TOWER

The Table Mountain field site has in the past been used primarily for radio propagation research. The array of equipment assembled for this purpose included a 500 ft. tall tower on which was mounted a number of very large Yagi antennas. The tower is near a permanent building which serves as a field laboratory for tower maintenance and experiments. Inspection by qualified engineers demonstrated that the tower was structurally sound. Its only major drawback was the existence of the large Yagi antennas which, if left in place, would have produced sufficient aerodynamic effect to render anemometer data questionable.

In order to eliminate this problem the antennas were removed before mounting the meteorological instruments. This was a major task since the tower was not equipped with an elevator and it was necessary to subcontract the work to professional steeplejacks. In addition, it was necessary to bring in a special high lift crane from the midwest in order to lower the detached antennas and to avoid damaging the tower structure. This effort was complicated by the necessity to work during the winter months, a period characterized by occasional strong winds. Despite these complications the tower was stripped of existing antennas and made ready for the installation of the required meteorological instrumentation well before the first scheduled tests.

3. TOWER INSTRUMENTATION

Great care was exercised in selecting the instruments since they were to serve as the standard for making decisions on the potential future development of various commercial devices. High quality research instruments were desired which had proven themselves during many past measurement exercises and which were manufactured by a firm with an excellent reputation in the field.

All of the systems that were to be tested against this standard were supposedly capable of measuring a vertical profile of the horizontal wind, therefore, it was also necessary to equip the tower at enough levels to insure a good representation of the wind profile. To achieve this, five levels (101, 220, 312, 410 and 485 feet) were instrumented.

The anemometers selected for each of these five levels were manufactured by R. M. Young Company, Traverse City, Michigan. They were propeller vane-type instruments, manufacturer model number 8002 having a low speed threshold of roughly 1.5 ft/sec. A complete description of these anemometers is contained in the literature supplied by the manufacturer which is included as Appendix A of this report. Each instrument was calibrated in accordance with the manufacturer's specifications before and after mounting on the tower. To insure compatibility between the five instruments before mounting them on the tower they were placed in a line at 5 ft intervals 8 ft above the ground and oriented into the wind. They were operated in this configuration for two and a half hours in wind speeds ranging from 5 ft/sec to 42 ft/sec in order to obtain data in naturally turbulent conditions. Ten-minute mean wind speeds were obtained for each anemometer. Differences in the mean speeds observed were small — within 0.3 ft/sec. No systematic bias was observed for any of the anemometers.

The anemometers were mounted on booms extending 8.3 ft north of the tower structural members. This provided sensor exposures with unobstructed air flow except for a 90-degree sector centered roughly on 195 degrees azimuth. During the actual tests it was determined that possible degradation of the wind data due to tower shadow effects became negligible relative to other aspects of the analysis.

The anemometers were considered the primary tower instruments, however in order to provide a more complete data set for post analysis, a set of temperature probes was also installed. Again research quality instruments manufactured by Hewlett-Packard were selected. A complete description of these instruments is contained in the manufacturer's specification documents.

All anemometer and temperature probe outputs were telemetered by signal cable to a computer-controlled data acquisition system located 350 ft north of the tower. Each output was sampled once per second and the data were processed in real time to provide the time-averaged wind and temperature information required for each test.

In addition to the tower equipment described above, special instrumentation was provided as needed for each of the tests. For example, a two-axis sonic anemometer, EG&G Model 198-2, was mounted at a height of 7.5 ft to measure the surface winds, a known limitation of the acoustic Doppler systems. This anemometer was installed in the open area east of the tower where the acoustic equipment was also located, well removed from possible turbulent wake effects induced by buildings or the tower. Precipitation, a second potentially limiting factor for acoustic systems, was monitored by a tipping bucket rain gauge also located in the open area east of the tower.

4. DATA COLLECTION SYSTEM

As noted above, all instrument outputs were transmitted via signal cable to the Mobile Micrometeorological Observation System (MMOS), a computer-controlled data acquisition, processing and recording system, having a total capacity to accept 96 separate channels of information. Developed by the Air Force Cambridge Research Laboratories (AFCRL) of Bedford, Massachusetts before 1965 for micrometeorological observations, this system had only recently been transferred to WPL. Its potential as a highly efficient data collection and processing system had been demonstrated during numerous AFCRL field experiments in the past and its availability for the wind shear detector tests resulted in a substantial saving. It would have been impossible to duplicate such a sophisticated system in the time available and the cost for a similar device would have easily reached a million dollars.

The components of MMOS were selected to insure four basic concepts of system operation. These were: 1) fast data scan to approximate simultaneous sampling of all data channels, with no interruption of any scan sequence or scan repetition rates by any other system function; 2) frequent calibration checks for drift in all the analog input channels; 3) direct digital data recording of all the raw data and, 4) real-time data processing of incoming data for periodic presentation of statistical results. The system was built around a Scientific Data Systems (SDS) 920 computer chosen, at the time, for its compactness, speed and versatility. The block diagram in Figure 1 shows the major components of the system. For a complete and detailed description of the system, its operation, accuracy and resolution see Kaimal et al., 1966.

The fully programmable feature of the system provided great versatility for the wind shear equipment tests. Special programs designed to meet the needs of each test were prepared to meet the unique characteristics of each device that was tested. For example, the data output rate for the test of the acoustic device was slowed to match that of an Acoustic Doppler. The lidar system proved to be effective at only one range at a time so the system was programmed to meet this requirement. A description of one of the special program outputs is provided by Haugen (1976) in the report on the testing of the Xonics acoustic Doppler system.

5. CALIBRATION AND SPECIAL PRECAUTIONS

All instruments were calibrated according to the manufacturer's specification. In addition to the special cross-check of the anemometer output described above, special tests were conducted to determine the effect, if any of terrain irregularities or tower shadow. In any comparison study involving tower instrumentation, one must consider possible contamination of the results when the wind direction is through the tower to the anemometers. In addition, unless the site of the comparison study is horizontally homogeneous, topographical effects can, in principle, produce undesirable bias in the data. To check for this possibility the wind component difference

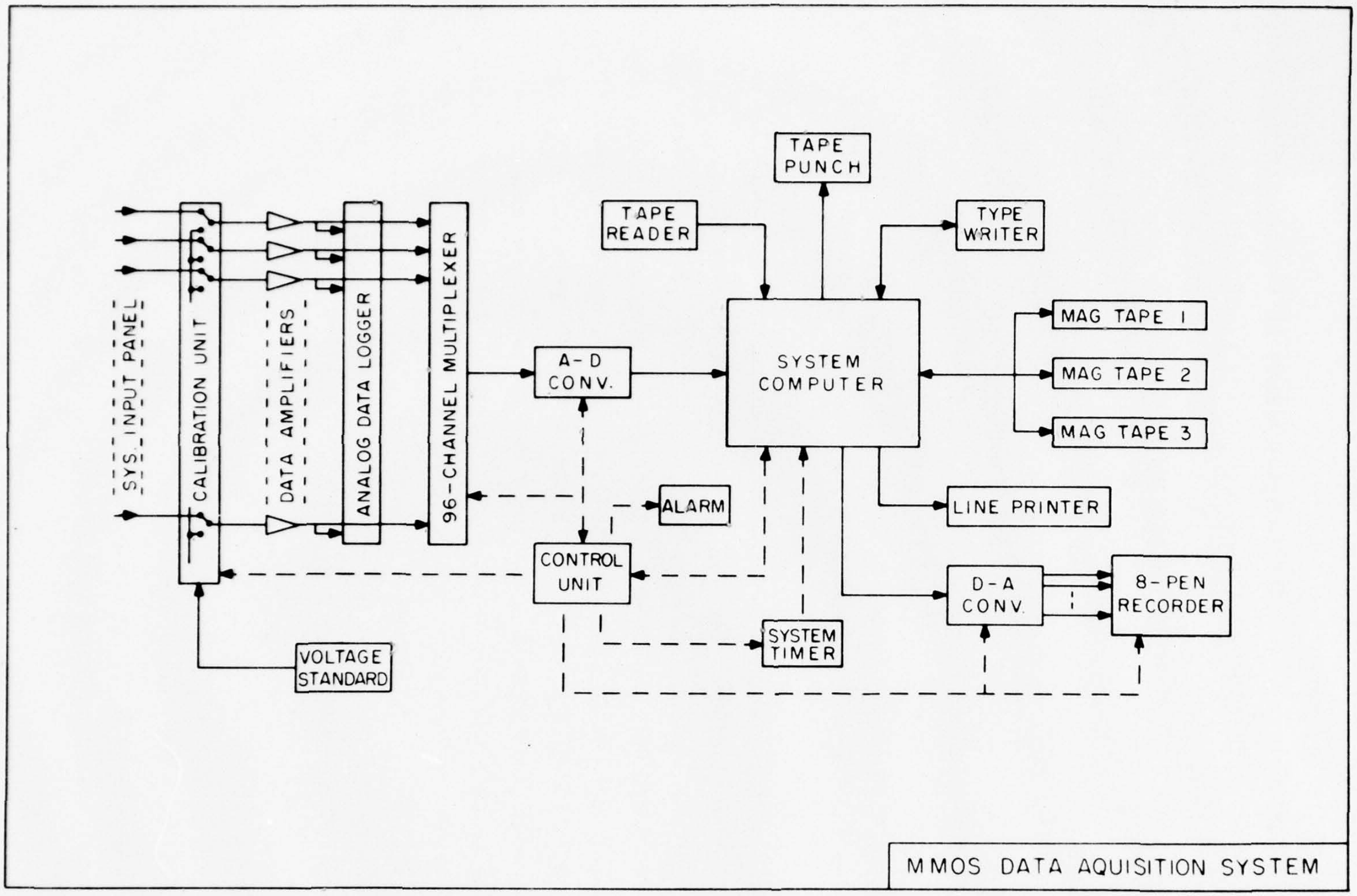


Figure 1. Simplified block diagram of the Mobile Micrometeorological Observation System data acquisition system showing direction of information flow between components. The dashed line distinguishes control signals from data signals.

between the tower and the acoustic Doppler at 220 and 485 ft were plotted against wind directions. No directional sensitivity was evident. The position of the anemometer was such that the two northerly quadrants provided the optimum exposure. The analysis showed no significant bias between northerly and westerly winds and no bias of the results for any other wind direction. Thus, there was no evidence of contamination of the results due to tower shadow effects or to topographical factors.

6. REMOTE PROBE TESTS

An artist's concept of the Table Mountain field site (see Figure 2) shows the tower, along with the general location of the remote probes which have been tested to date. The scale can be judged by noting that the distance from the tower in the background to the single leg WPL acoustic Doppler in the foreground is about 2 km.

Two side-by-side tests were conducted using the tower facility in support of FAA programs. One was to evaluate an acoustic Doppler sounder manufactured by Xonics, Inc., Van Nuys, California. This test was conducted during March and April of 1976. Details of the experiment procedures and the overall performance characteristics of the sounder were reported shortly after completion of the tests. A second series of tests was designed to evaluate a CW laser Doppler wind sensor manufactured by Lockheed Missiles and Space Company, Huntsville, Alabama. The Lockheed personnel and equipment needed for this effort were contracted for by the Transportation System Center (TSC), U.S. Department of Transportation, Cambridge, Massachusetts. A preliminary report on the results obtained was prepared for the FAA upon completion of the tests (see Appendix B).

The comparison of WPL's FM-CW clear air radar and the prototype acoustic Doppler system took place in the proximity of the permanent acoustic installation. The FM-CW radar was moved to this location for purposes of the tests. Operation of the radar in this area was restricted by ground clutter from several small towers. These were dismantled during the tests and replaced

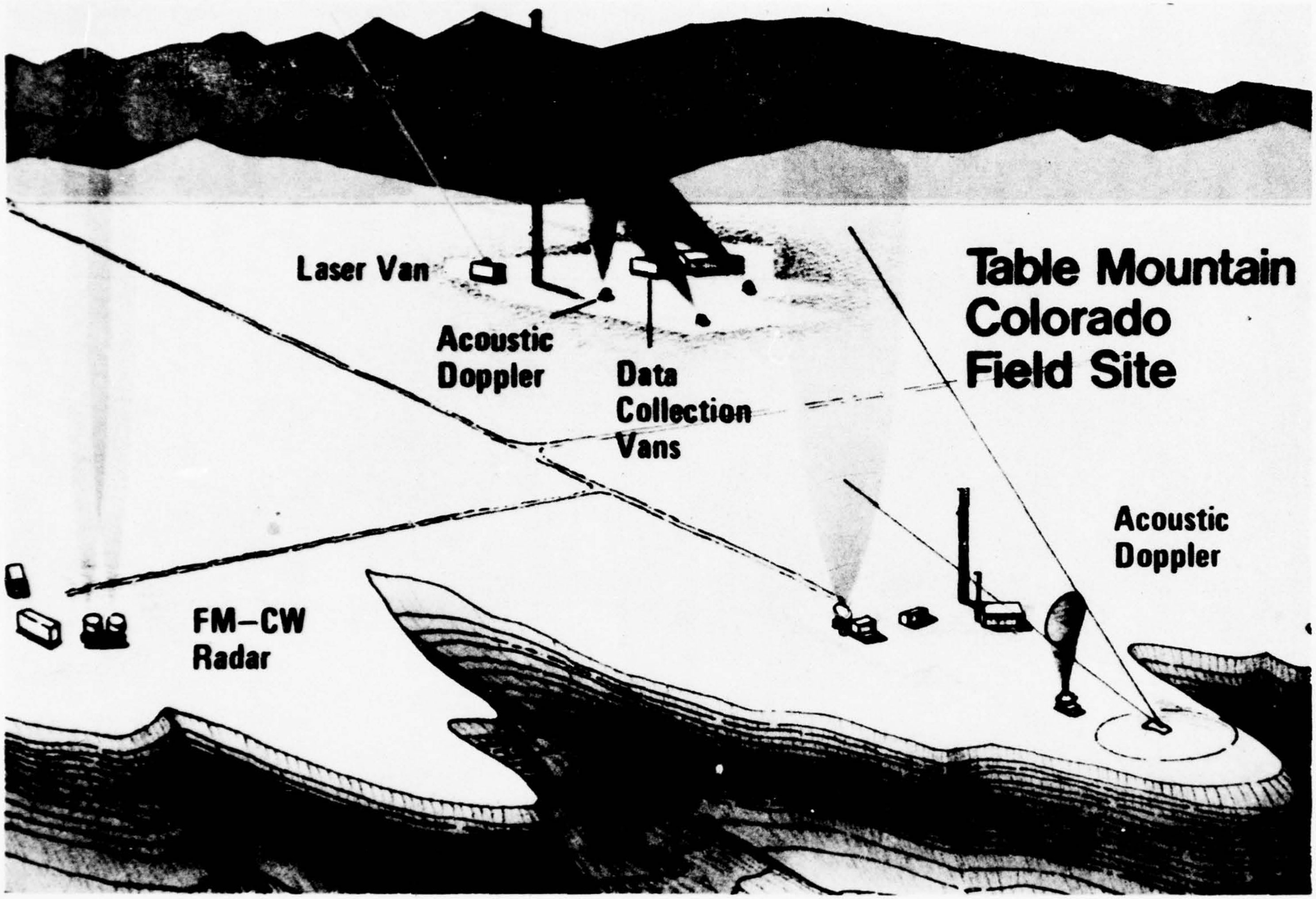


Figure 2. Artist's concept of Table Mountain field site showing the general location of the 150 m tower and the remote sensors which were tested.

on an as-needed basis later. The FM-CW radar-acoustic Doppler tests were conducted during a two-week period during June 1976 and the tests results are contained in Appendix C.

7. SUMMARY AND CONCLUSIONS

These tests and the related upgrading of the Table Mountain field site represent an important part of the overall effort to solve the wind shear problem. It was clear from the outset that the operational limits of the various devices were unlikely to be determined during such short test periods. To establish the full operational potential and limits of these devices would require extensive further field tests. Since limiting conditions are primarily produced by anomalous weather, a minimum one year program would not be out of the question.

The commercial systems had both been advertised as close to an operational configuration that could be used to solve the wind shear problem with minimum delay. The fact that both of the systems did not function well during more than three-quarters of their scheduled time indicates that these claims may have been somewhat exaggerated.

The CW lidar was clearly an experimental device which required manned operation and a large amount of maintenance. It was, however, useful as an instrument to test the concept of using CW lidar as a vertical wind profiling device. It did this well, but questions concerning its capability under conditions of rain or fog were not answered; these conditions simply did not occur during the approximately one week of successful testing.

The Xonics acoustic system was also, clearly, at an experimental prototype stage. This was demonstrated by the nearly 6 weeks of modification and adjustment that were required before the system operated correctly. As is documented by Haugen (1976), the system performed well for about two weeks. Unfortunately, very strong winds which may have established the system limits occurred much earlier during the test and were absent when the system was operating properly. Again, we are left with doubt as to the ultimate performance limits on this system.

The advantage of longer term testing is apparent in Appendix C which contains an analysis of several months data collected by the prototype WPL acoustic Doppler system. This attachment, extracted from the Phase III report under FAA/NOAA interagency agreement No. DOT-FA72WAI-281, also contains the result of the FM-CW radar and acoustic Doppler system comparisons and is included here, because part of the field work for this test was performed under this agreement.

These tests demonstrated that the FM-CW radar wind measurements were in good agreement with those from the acoustic Doppler system. In addition, the advantages of a system which can scan to low elevations (such as the radar) and measure a wind component which is nearer to the horizontal were clearly demonstrated.

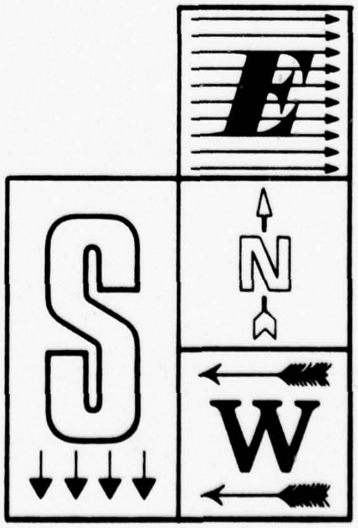
The main conclusion to be drawn from this work is that short-term field tests are unlikely to provide much information on system reliability or operational limits. The tests did help to refine our understanding of the potentially available devices, but extensive operation of a fixed configuration will be essential before the optimum system is identified.

APPENDIX A

PROPVANE

R. M. YOUNG COMPANY

TRAVERSE CITY, MICHIGAN



PROPVANE

GENERAL

The Model 8002 Propvane is a ruggedized and lower cost version of the Gill Propeller Vane. The polystyrene fin used on the Propeller Vane has been replaced with an aluminum fin of reduced area and with a shortened vane shaft. An extended range molded ABS thermoplastic 3 blade propeller has been substituted for the polystyrene propeller. This propeller has a working range from 1 to 120 mph yet still has a threshold well below 1 mph. Distance constant of the propeller is approximately 8 ft. (2.4 meters). The propeller and vane combination exhibits a damping ratio of approximately 0.34 making the instrument suitable for most air pollution studies as well as many other routine wind measurements.

The vane assembly is mounted on a vertical shaft, supported on stainless steel ball bearings, which transmits the angular position of the vane through a pair of gears to a conductive plastic potentiometer in the lower housing of the instrument. The potentiometer requires a regulated excitation voltage from a battery or power supply located external to the instrument. With constant voltage applied to the potentiometer the analog voltage signal output is directly proportional to wind direction.

The 3 blade propeller is molded in the form of a helicoid with 50cm pitch. The propeller shaft is supported on two stainless steel ball bearings and coupled to a miniature d.c. tachometer generator in the anemometer head. The self generated analog voltage output is directly proportional to wind speed and is linear throughout the working range.

The instrument mounts on vertical 1" standard iron pipe and weighs approximately 5½ pounds.

OPERATING PRINCIPLE

With the passage of each wind gust the vane assembly moves from side to side trying to keep the wind pressure equalized on the fin surfaces. The balanced vane assembly rotates freely on a vertical shaft which is supported on two instrument grade stainless steel ball bearings which have double seals to help retain lubricant and exclude dirt. The angular position of the vane is transmitted by the vertical shaft through the gears in the lower housing to the shaft of the 1000 ohm precision conductive plastic potentiometer.

> *The potentiometer is rated 1 watt at 70°C (and derated to 0 watts at 125°C) and care must be exercised not to apply excessive voltage to the element nor to allow excessive current to be drawn from the wiper. Maximum applied voltage should not exceed 30 volts. Maximum wiper current should not exceed 1-1.5 milliamps.*

The potentiometer has an open section (dead band) in the element of 18 degrees. Normally the open section of the potentiometer element is oriented to north and this is made to correspond to the zero level of the recorded signal. Thus rotation of the vane from north to east to south, etc., will cause the azimuth signal to increase to successively higher values until the vane reaches 342° rotation at which position the signal falls to zero. When adjusting the full scale reading on the azimuth recorder or data logger it should be set at 342° or 18° below full scale, rather than a full 360°. This will provide the optium linearity over the 342° active range of the potentiometer.

As an option the Propvane can be supplied with dual azimuth potentiometers which provide an azimuth signal range of 0 to 540°. This eliminates the effect of the potentiometer open section or dead band and is especially valuable when the signal is to be recorded on a strip chart. The 540° range eliminates the continuous switching of the recorder pen from zero to full scale when winds are oscillating across the extremes of the potentiometer element. The 540° range option requires special logic and relay circuitry located external to the instrument for proper operation.

The vane keeps the propeller type wind speed sensor oriented into the wind. The helicoid form of the propeller allows it to slice freely through the passing wind with practically zero drag and with very little turbulence created in the air stream. The propeller makes one revolution per 50 centimeters wind passage for all wind speeds above 3 mph (1.3 m/s). Increasing slippage occurs down to the threshold speed of approximately 0.9 mph (0.4 m/s).

The propeller drives a miniature d.c. tachometer generator through a flexible coupling consisting of a circular bristle disc mounted on the propeller shaft and two pin projections mounted on the generator shaft to engage the bristles. This simplified method of coupling allows the front section of the anemometer to be removed and replaced without bothersome alignment and engagement problems and also eliminates all backlash from the system. The coupling also prevents any side or end loading of the tiny generator bearings. Output of the generator is 2400mV (±10%) at 1800 rpm which is equal to 33.7 mph (15.3 m/s) wind speed. This output signal is linear from zero to full scale.

The two generator lead wires are located inside the vertical shaft and carry the wind speed signal to a slip ring assembly in the lower housing. Four slip rings with double contacts are used, four contacts for each generator lead, to assure that a continuous uninterrupted signal is transmitted from the sensor to the translator.

The wind speed signal carries a ripple voltage which is caused by the miniature brushes riding on the commutator segments of the d.c. generator. This ripple is significant enough that it must be filtered if an analog to digital converter is to be used in the data logging. On the other hand a chart recorder or panel meter will probably not be affected by the ripple (because of the inherent inertial filtering effect of these devices). The amount of filtering required will depend upon the sampling speed of the data logger and the desired, or permissable, time constant of the signal. Generally reasonable filtering is achieved by placing a 1000 mfd (25 vdc) capacitor directly across the signal.

CALIBRATION

When the Propvane is unpacked it should be checked carefully for any signs of physical damage. The instrument is aligned, balanced and calibrated before shipment, however it should be checked both mechanically and electrically before each installation according to the following procedure.

With the Propvane mounted in a room with little air movement, the vane assembly should be checked for balance and freedom of operation. The vertical shaft, and the vane hub assembly on which the vane and anemometer are mounted, should easily rotate the complete 360 degrees in azimuth without friction points. The two plastic gears which drive the azimuth potentiometer should have a very slight clearance throughout the entire 360 degree rotation but without excessive backlash. The engagement of these gears is adjusted by loosening the azimuth potentiometer support bracket and sliding in or out as necessary. The gears should be clean and dry. The gears are self lubricating and the use of lubricants should be avoided so that dust and foreign particles will not adhere to the gear teeth. The gears are intentionally offset so that they are not in full face to face contact in order to reduce the possibility of interference due to edge burrs or flash.

Assuming the vertical shaft rotates freely, the anemometer assembly and the vane assembly, should be attached. The anemometer assembly is held in place on the vane hub assembly by means of two set screws. After attaching the generator lead wires to the mating wires which protrude from the vane hub assembly, the generator housing is slipped into position just over the o-ring so that the after edge of the generator housing is aligned with the leading edge of the taper on the vane hub assembly. The two set screws, located 90° apart nearest the aft edge of the generator housing, are oriented with one downward and one to the side, and tightened securely with an Allen wrench. The propeller hub, propeller, propeller button and nut are then installed. The vane shaft is also inserted into position opposite the anemometer and fastened with the screw provided. Balance of the anemometer and vane assembly can now be checked by simply laying the instrument on it's side. The vane should not have any tendency to raise or fall on either side. When properly balanced it should stay in any position in which it it placed. If balance needs adjustment, add or remove small portions of weight at the extreme end of the vane shaft. A black nylon plug is fitted in the end of the shaft and can be removed easily with a knife edge or a small pliers.

Calibration adjustments are most easily made before the instrument is installed. The Propvane should be connected electrically with the power supply translator and recorders in the laboratory. The recorders should first be adjusted for proper zeroing with no voltage applied to the sensor. This is normally accomplished by means of a zero adjustment located within the recorder. Now with regulated voltage applied to the azimuth potentiometer the output signal can be switched electrically to the end positions of the potentiometer element by alternately connecting to pins F and G if the cable receptacle. This effectively causes the azimuth signal to correspond to the extremes of the azimuth potentiometer element which represents the zero and full scale signals. In this manner wind direction span calibration can be checked easily and quickly at any time during normal operation without disturbing the instrument. With the output signal switched to full scale (Pin G) the azimuth output signal level is adjusted to give the desired reading. For normal operation the azimuth signal is taken from Pin C.

Where studies are made of winds coming from one sector only, the azimuth calibration may be adjusted so that a 180-degree change will provide a full scale signal. This will permit more accurate abstraction of data.

If the complete 360 degrees of azimuth are to be recorded it is customary that 0 scale division correspond to a true north wind; 90 degrees to an east wind, etc. First rotate the vane in a clockwise manner from north to east to south; the azimuth signal should increase steadily toward higher numbers. If the signal moves in the opposite direction interchange the output connections. The element of the conductive plastic potentiometer has an open section of $17-19^{\circ}$. The full scale calibration of the azimuth signal should therfore be adjusted for 342° on the recording rather than a full 360°.

Calibration of the wind speed sensor is accomplished by driving the propeller shaft at a known rpm and adjusting the signal level to give the proper reading for that speed. Remove the propeller and the propeller hub from the anemometer head assembly. The shaft is then driven at 1800 rpm (or some other convenient known speed) by means of the synchronous motor Calibrating Unit or any similar device. After zeroing the recorder the Calibrating Unit is switched on to drive the propeller shaft at 1800 rpm counterclockwise while the wind speed output signal is adjusted to give a reading on the recorder of 33.7 mph (15.3 m/s). Be sure that the direction of rotation corresponds to the propeller rotation when checking calibration.

Calibration points for miles per hour, feet per second, and meters per second at all rotational speeds are indicated on the Propeller Calibration Curves.

EXPOSURE AND ORIENTATION

The exposure of the Propvane to get representative wind direction data is very important. Eddies in the lee of buildings or trees can greatly reduce the value of wind direction observations. Unless it is desired to actually measure the eddy effect of buildings or other structures, it will be desireable to locate the instrument well to windward of such obstructions.

> *As a rule of thumb, the normal flow of air past a building will disturb the air flow about twice the height of the building to windward; six times the height of the building to leeward; and up to twice the height of the building above the ground.*

Installation and orientation of the vane generally requires two people; one located on the tower to adjust the instrument and another at the recorder location to signal when the recorder reading corresponds to the actual vane position. The base plate of the instrument is installed on a vertically mounted 1 inch pipe (standard iron pipe size) and the multiconductor cable attached. The vane is pointed toward a reference point, of known azimuth, on the horizon by sighting directly along the vane shaft. While the vane is held in a fixed position, the housing of the instrument is slowly turned on the mounting pipe until the recorder or data logger gives the proper reading or signal level. It may be easier to sight along the vane shaft from the propeller end toward the fin. In this case the signal should be 180° from the reference point. Once the instrument is properly oriented the two set screws in the mounting plate are tightened to lock the instrument in position. An orientation ring is supplied to provide a means of easily realigning the instrument when it is removed for service or storage. This ring should be installed first on the vertical mounting pipe below the instrument. After alignment of the instrument the orientation ring is raised and the indexing pin is engaged in the slot in the instrument base casting. The two set screws in the ring are then tightened to lock it in place on the mounting pipe. The index slot on the base of the instrument has been aligned with the azimuth potentiometer before shipment so that it will be oriented due south. Changes in the relationship between the vane potentiometer and the instrument housing are made by adjustment of the angular position of the vertical shaft gear.

MAINTENANCE

Adjustment of mechanical clearances and balance is less critical than in most electrical instruments and should not present any particular problems to the average instrument technician.

Since this instrument was designed for recording of low wind speeds it is important that bearing friction be kept very low. Experience has shown that it is impratical to attempt to thoroughly clean these precision bearings and relubricate them satisfactorily without special facilities. Accordingly stainless steel ball bearings lubricated for life and with permanently installed dust shields have been adopted. Life expectancy of these bearings in normal use may vary from 1 to 5 years, depending upon operating conditions. In especially dusty or corrosive atmospheres life expectancy will be reduced. It is intended that when bearing friction becomes noticeable new bearings will be reordered and installed.

The precision potentiometer has a life expectancy of several million cycles, and should last 3-5 years in normal use. The conductive plastic potentiometer element will usually begin to increase in resistance as it becomes worn. When the total resistance increases 10% or more the potentiometer should be replaced.

The miniature tachometer generator has a life expectancy in excess of 750 million revolutions, which represents 2-4 years of normal operation. When the generator voltage output becomes erratic (usually due to brush failure) the entire generator assembly should be removed and replaced. It is usually impractical to attempt to disassemble and recondition the generator.

For bearing and/or tachometer generator replacement, unscrew the propeller nut, and remove the propeller, button and hub as one unit. Unthread the shaft housing from the generator housing by hand. To replace the shaft bearings, remove the red plastic dust shield which covers the front bearing. Remove the retaining ring from the propeller shaft just forward of the front bearing. Loosening the set screw in the shaft collar will allow easier retaining ring removal. Now push the shaft out of the bearings toward the bristle disc end. Do not attempt to remove the bristle disc from the shaft. With the shaft removed, the bearings may be worked out carefully, with the aid of a pocket knife between the bearing flange and the shaft housing edge. The new bearings should fit the 3/8 bore in each end of the housing with very light pressure.

The propeller shaft and bristle disc assembly may then be replaced and the retaining ring installed. Adjust the shaft collar so that the shaft has an end clearance of .003" when the bearings are properly seated, and tighten the collar set screw. Care should be exercised to avoid any undue pressure on the inner race relative to the outer race on the bearings, as they are easily damaged due to the small ball diameter.

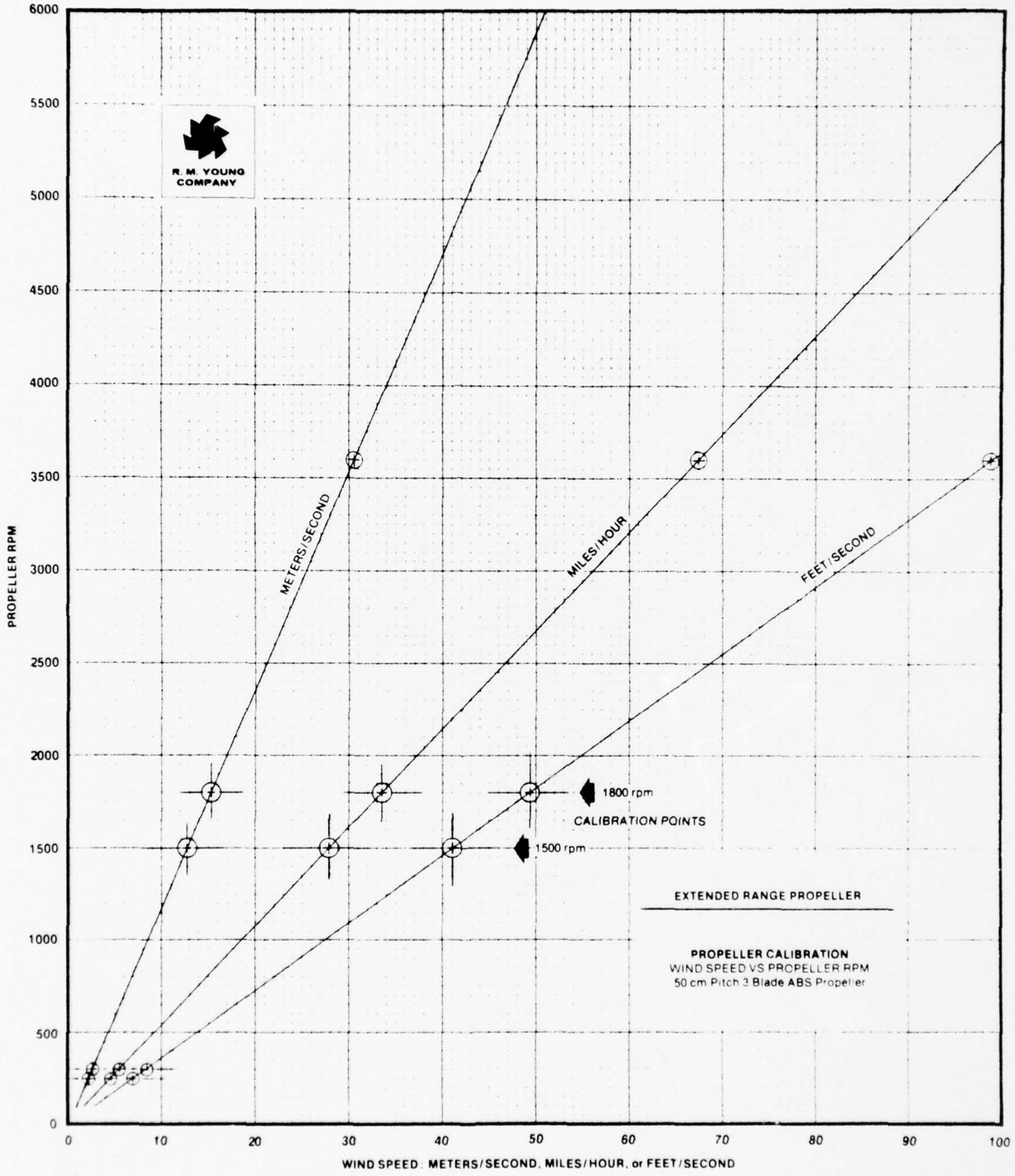
To replace the generator, loosen the forward set screw in the side of the generator housing then pull the generator and cell out of the generator housing with a needle nose pliers. Pull out sufficiently to expose the wire connectors, and then disconnect the generator wires. A bit of tape may be used to keep the wires from slipping back inside, until the new connection is made.

The generator is mounted in the plastic cell with silicone rubber cement. To remove it, twist it gently by hand or with the aid of pliers. The new generator is then re-cemented into place in the cell. Reconnect the wires prior to replacing the cell and generator in the generator housing. There is one male and one female connector on the generator wires to aid in proper connection. The shaft housing assembly is then threaded back in to the generator housing. *For maximum accuracy the wind speed signal should be recalibrated when the generator is replaced.*

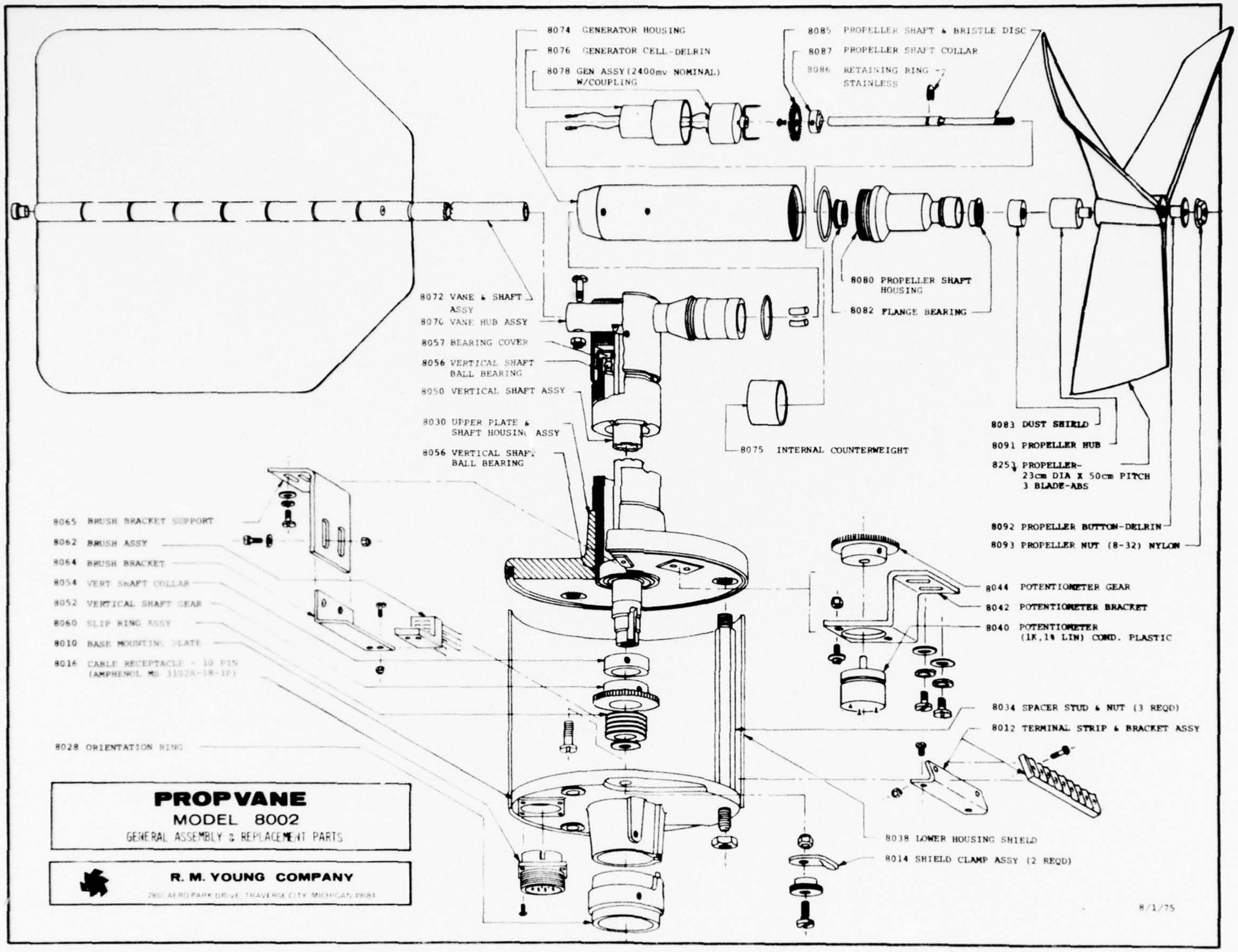
Replacement of the azimuth potentiometer is a fairly obvious procedure, except that care must be taken to avoid a tight gear mesh. Make sure the proper wiring color code is followed as the potentiometer can be damaged by improper connections. The azimuth signal must be realigned with the vane by adjusting the angular position of the vertical shaft gear *after the instrument* is reinstalled.

The slip ring and brush assembly is a critical link in the wind speed signal circuit. Care should be exercised to keep the ring surfaces clean and to maintain proper brush contact. When the brush assembly is removed the individual brush wires should have a separation of ½ inch for proper contact pressure (when assembled). The brush assembly must also be centered carefully so that equal brush contact is maintained on each side of the slip ring.

Given reasonable care this instrument should provide many years of service. We hope it serves you well.


R. M. YOUNG
COMPANY
PROPELLER RPM
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
10
20
30
40
50
60
70
80
90
100
WIND SPEED: METERS/SECOND, MILES/HOUR, or FEET/SECOND
METERS/SECOND
MILES/HOUR
FEET/SECOND
1800 rpm
CALIBRATION POINTS
1500 rpm
EXTENDED RANGE PROPELLER
PROPELLER CALIBRATION
WIND SPEED VS PROPELLER RPM
50 cm Pitch 3 Blade ABS Propeller

8/1/75

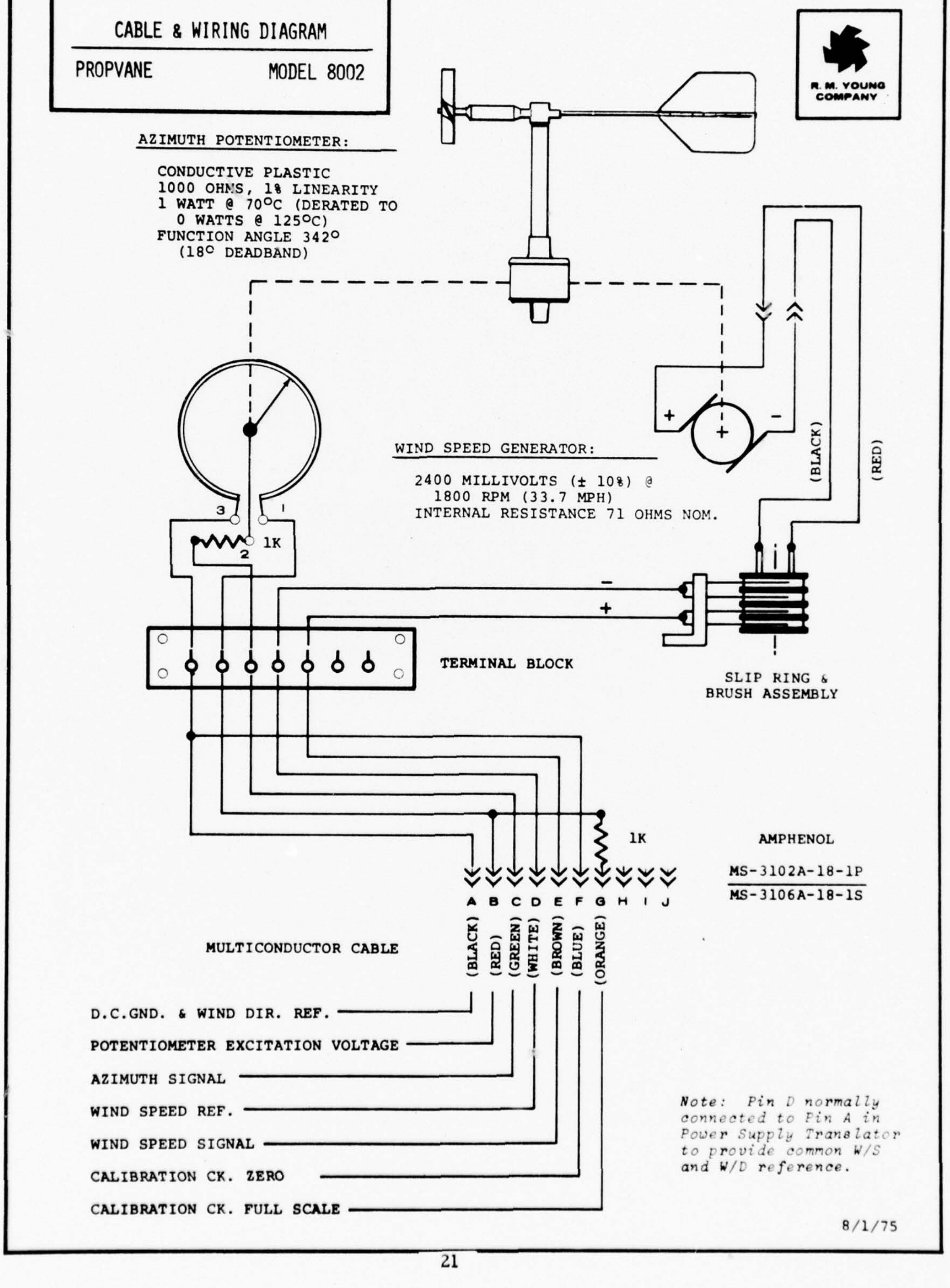


PROPVANE
MODEL 8002
GENERAL ASSEMBLY & REPLACEMENT PARTS

R. M. YOUNG COMPANY
2801 AERO PARK DRIVE, TRAVERSE CITY MICHIGAN 49684

CABLE & WIRING DIAGRAM

PROPVANE MODEL 8002



AZIMUTH POTENTIOMETER:

CONDUCTIVE PLASTIC
1000 OHMS, 1% LINEARITY
1 WATT @ 70°C (DERATED TO
0 WATTS @ 125°C)
FUNCTION ANGLE 342°
(18° DEADBAND)

WIND SPEED GENERATOR:

2400 MILLIVOLTS (± 10%) @
1800 RPM (33.7 MPH)
INTERNAL RESISTANCE 71 OHMS NOM.

D.C.GND. & WIND DIR. REF.
POTENTIOMETER EXCITATION VOLTAGE
AZIMUTH SIGNAL
WIND SPEED REF.
WIND SPEED SIGNAL
CALIBRATION CK. ZERO
CALIBRATION CK. FULL SCALE

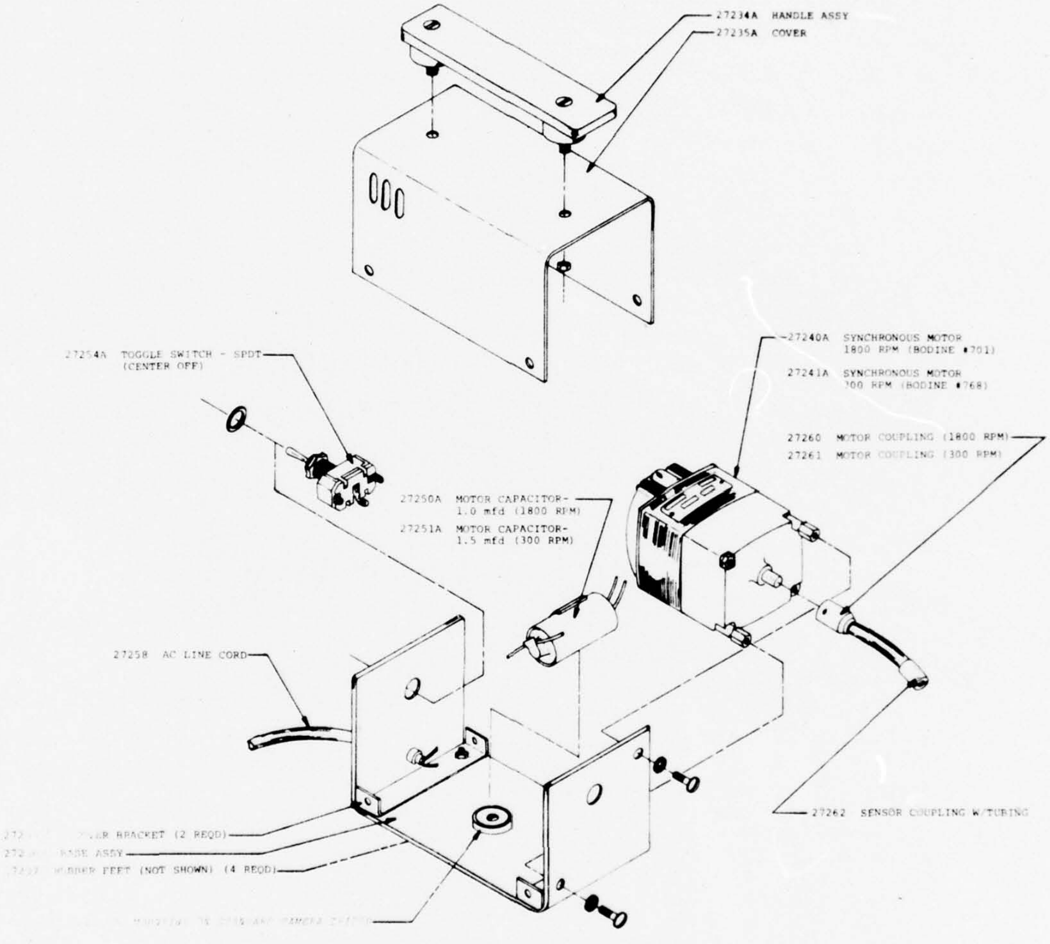
Note: Pin D normally connected to Pin A in Power Supply Translator to provide common W/S and W/D reference.

8/1/75

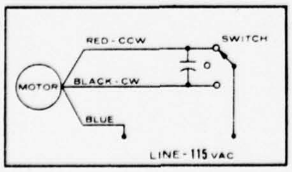
CALIBRATION UNIT
MODEL: 27230 (1800 RPM), 27231 (300 RPM)
GENERAL ASSEMBLY & REPLACEMENT PARTS

R. M. YOUNG COMPANY
2801 AERO PARK DRIVE TRAVERSE CITY MICHIGAN 49684

THE SYNCHRONOUS MOTOR CALIBRATING UNIT IS A HAND HELD DEVICE USED FOR CALIBRATION OF WIND SPEED SIGNALS. THE FLEXIBLE COUPLING ENGAGES THE TWO FLATS ON THE SHAFT OF CUP TYPE OR PROPELLER TYPE ANEMOMETERS (WITH CUP WHEEL OR PROPELLER REMOVED). THE UNIT PROVIDES A KNOWN ROTATIONAL SPEED SO THAT THE OUTPUT SIGNAL CAN BE ADJUSTED TO PROVIDE THE DESIRED METER OR RECORDER READING AS INDICATED ON THE CALIBRATION CURVES SUPPLIED WITH EACH WIND INSTRUMENT.



CONNECTION DIAGRAM



SYNCHRONOUS SPEEDS:

MODEL 27230: 1800 RPM @ 115V/60HZ
1500 RPM @ 115V/50HZ

MODEL 27231: 300 RPM @ 115V/60HZ
250 RPM @ 115V/50HZ

8/1/75

APPENDIX B

PRELIMINARY EVALUATION REPORT ON LOCKHEED LASER ANEMOMETER

by

Duane A. Haugen
Wave Propagation Laboratory
Boulder, Colorado 80302

26 March 1976

Introduction

Between Tuesday, 17 February and Saturday, 13 March, a series of comparison tests between the Lockheed laser anemometer and the WPL instrumented tower were conducted at WPL's Table Mountain site. The tests were incomplete in some respects, conclusive in others. The purpose of this report is to summarize the results and to offer some recommendations for further consideration.

Background

In its present configuration, the Lockheed laser anemometer is not an "operational" system. It does not provide wind information in real time output. The winds must be computed off-line. Furthermore, when used to observe winds at several different heights in order to measure wind shear, its cycle time from one height to another is much too slow to obtain reliable shear estimates. However, both these limitations can be easily removed by straightforward engineering changes. And neither limitation has hidden the promising potential the device displays.

The first limitation led us to agree to write a software package for the WPL data acquisition computer at the field site to analyze the Lockheed data in the field. This was deemed advisable by all concerned in order to measure our progress as the tests were taking place. It should be noted in this regard that writing the software package was a straightforward exercise which demonstrates that the engineering and/or software modifications to the system to provide on-line wind output are certain to be easily accomplished.

There was no way to circumvent the second limitation, however, and this did have unfortunate impact on the test program. The device was set to scan eight altitudes in succession between 31 m and 300 m. Each scan takes five seconds and provides one estimate of the wind speed and direction for that five second period. Thus, in 40 seconds, there is only one estimate of the wind at each altitude. In two minutes, one obtains only three estimates for each altitude with each estimate occurring at 40 second intervals. This is clearly an inadequate sampling rate to measure wind shears accurately in the turbulent winds found in the first 2000 feet of the atmosphere.

Our first attempt to accommodate this problem was to average the winds as observed over a 16-minute period. This gave estimates of the tower winds that were statistically stable and reliable, but provided only 24 estimates of the wind at each level with the laser anemometer. We collected comparison data in this mode starting on 17 February for all periods when the winds were from the NE or NW quadrants. That is, data were collected only when the tower data were not contaminated by tower interference effects.

By 25 February, it was evident to all concerned that this scan mode was going to accomplish only one purpose: demonstration that the sampling rate was inadequate to measure winds and wind shears reliably. It was then agreed in a conference involving TSC, WPL, and Lockheed personnel that further testing should be done with the laser ranging held to only one altitude for an hour or so in order to obtain an adequate data sample for comparison purposes. Three altitudes were chosen, 30, 90, and 150 m, with the idea that long data samples would be obtained independently for each altitude in the time remaining for the comparison test period. Unfortunately, this decision came too late to permit thorough testing of the laser anemometer through a wide range of wind speeds.

From 26 February to 1 March, the winds were southerly, through the tower. From 2 March to 6 March, the Lockheed device was down because of a compressor problem on the laser cooling system. Between 7 March and 12 March, we obtained only 14 hours of northerly winds. On 13 March, it was necessary for Lockheed to pack up their equipment for shipment to Cleveland, Ohio, in order to meet a NASA contractual obligation.

Results

It is to be expected that given the above sequence of events, the test results are inconclusive. No wind speeds have been sampled above 7 m/sec. This is extremely unfortunate since the behavior of the device in strong and/or gusty winds is of paramount interest. However, for those wind speeds sampled, the agreement between the laser anemometer and the tower is excellent, within ± 30 cm/sec. It should also be noted that roughly 8 of the 14 hours noted above were with light to moderate snowfall. The device operates admirably under such conditions.

At the present time, Lockheed personnel are processing their data with software packages written for their own computer facilities. Graphical summary of the results must therefore await completion of their analysis.

Recommendations

It is abundantly clear that further testing is required to permit a more nearly complete data sample. At the moment, it is not clear whether other demands on the system, by TSC and others, will permit such testing to be scheduled in the near future. Any action that can be taken to clarify this situation should be vigorously pursued.

In this regard it should be noted that WPL has now instrumented the tower at two levels (30 and 150 m) to permit data collection for comparison purposes regardless of wind direction.

It should also be clear from the foregoing that the engineering development work to remove the limitations cited should be encouraged. There is every reason to believe that once those limitations are removed, the device will indeed be a prototype operational system ready for extensive testing under operational conditions.

APPENDIX C

WPL PROTOTYPE ACOUSTIC DOPPLER AND FM-CW RADAR PERFORMANCE

INTRODUCTION

In order to learn as much as possible about the wind measuring capabilities and meteorological limitations of the WPL acoustic Doppler system, selective analyses of regularly archived data from the prototype Table Mountain system and a comparison test with other wind sensors were performed. A discussion of some of the experimental problems and a summary of results follows.

The Table Mountain system has been collecting data in unattended mode since early May 1976, whenever the system has been healthy and design changes were not being implemented. For this system, time-averaged data is recorded on digital magnetic tape including such items as signal and noise spectra, derived wind profiles, reliability figures, and surface meteorological parameters (wind, temperature, relative humidity and rain rate). In addition to the normal unattended operations, a special test period was arranged during the second half of June during which comparisons were attempted with another remote wind sensor, the FM-CW Doppler radar. A boundary layer profiler (BLP) tethered balloon, a monostatic acoustic echo sounder, and a 150 m instrumented tower were also in operation during the tests.

The goal of the field program is to obtain information about the Table Mountain system in four categories: system reliability, meteorological operational limits, wind measurement accuracy and availability of acoustic scatterers all under a wide range of conditions. The information obtained from this program facilitates design improvements of the experimental system. Complications involving ongoing system changes, coordination of various groups, and the meteorological limitations of the comparison sensors, have made the analysis of the data somewhat difficult. However, results of the data post-analysis suggest that the acoustic Doppler wind sensor is accurate to design criteria as measuring conditions permit and that it maintains reliability during adverse weather better than previously expected. The effort has been made to present statements and general observations about the system rather than firm conclusions. This tactic is warranted because of the nature of the measuring problem and the relatively small size of useable data sets containing the significant events.

COMPARISON TESTS

On June 24 and 25, 1976, data from several closely spaced sensors were gathered at Table Mountain. Besides the acoustic Doppler, an FM-CW Doppler radar, a tethered balloon (BLP), a monostatic acoustic sounder, and ground based meteorological instruments were operating. Figure 3 illustrates the sensor layout. The test setup was located near the eastern edge of the mesa which is Table Mountain, and the site lies about 15 km north of Boulder and 5 km east of the first range of mountains. A 150 m instrumented tower was also in operation during the tests about 2 km to the WNW of the test site on the western edge of the mesa.

Long term wind comparisons between the acoustic and FM-CW radar systems were the primary goal of the intercomparison tests. The BLP balloon was expected to provide "ground-truth" wind measurements, and the monostatic sounder to give qualitative information about boundary layer stability.

Wind conditions on the two test days were nearly ideal. June 24 was marked by a moderate surface pressure gradient giving reasonably steady easterly winds in the boundary layer. Cool, dry, very clear conditions prevailed with relative humidities near 30%. June 25, on the other hand, was characterized by a weak pressure gradient; but downslope flow yielded occasionally strong westerly winds at the surface and very low humidities. Monostatic sounder records indicated weak thermal plume activity during the daytime on June 24 and well mixed conditions on June 25.

The acoustic Doppler and FM-CW radar were located along an east-west road about 400 meters apart. Both systems measured only an east-west wind component. The comparable sensed volumes were separated by about 200 meters at an altitude of about 200 meters.

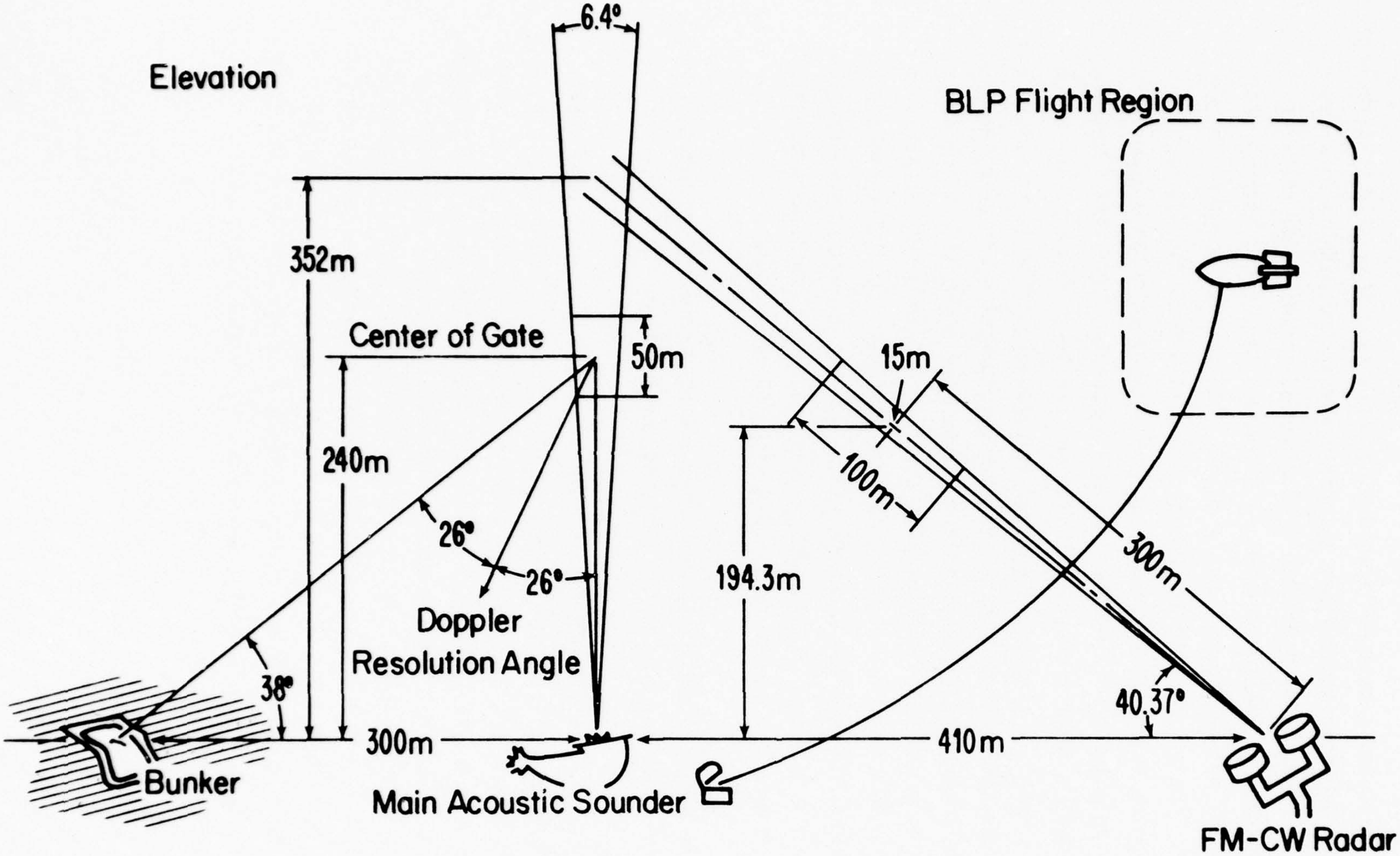


Figure 3. Schematic diagram of remote sensor wind comparison test setup at Table Mountain during June 76. Acoustic sounder and FM-CW radar were positioned along an east-west road. BLP was tethered near main acoustic sounder and flies downwind.

The estimates of a measured quantity, in this case the speed of turbulent scatterers, from remote sensors are necessarily averaged both in time and space. Spatial averaging is related to the sensed volume size; the sizes of volumes for different remote sensors are in general quite different. The acoustic Doppler volume is about 2.5×10^4 m^3, and the FM-CW volume, about 1.2×10^4 m^3. The orientation of the volumes will affect the degree of spatial averaging in any given wind field not aligned with the volumes. Naturally an in situ sensor, such as the BLP anemometer, does its measuring within a volume at least 5 orders of magnitude smaller. Temporal averaging for various sensors is also different and is somewhat difficult to assess due to instrumental differences, but the following information can be given. The acoustic Doppler sampled the wind in its volume once every 15 sec and these measurements were exponentially averaged during the test with a 30 sec time constant. The FM-CW samples every 50 ms (milliseconds) and its estimates were averaged with a 12.8 sec time constant. The BLP anemometer was sampled every 15 seconds for about 1 min. Both mechanical and electrical exponential averaging of unknown value are included in the BLP measurement.

Remarks should be made about the influence of separation distance of sensors on the cross correlation of two wind measurements.

Correlation at low frequencies is normally good, however it drops off rapidly as the scale of phenomena measured approaches the separation distance. Using Taylor's hypothesis ("frozen turbulence") to convert time scales into space scales, the dropoff commences rapidly as the wavelength of the phenomena becomes smaller than 2π times the separation distance. Using this information, the minimum time scale (T), or maximum frequency, at which significant correlations will be found can be estimated from the separation distance (d) and the mean wind speed ($\bar{u}$): $T = 2\pi d/\bar{u}$. For the comparison test, using a typical mean wind speed of 5 ms^{-1} and separation distance of 200 to 300 meters, $T \approx 4$ to 6 minutes. Good correlations may be found, but should not be expected for time scales smaller than these.

The BLP tethered balloon presented unique problems due to the instability of the measuring platform. The BLP consists of a helium-filled, dirigible-shaped plastic bag, tethered by a light dacron cable. The instrument package, suspended directly from the balloon, measures wind speed with a cup anemometer and wind direction by a compass-controlled potentiometer. Maximum flight-time is limited by available batteries to less than 3 hours. Under typical conditions a balance between free lift, aerodynamic lift, and wind drag on the tether line, all varying, determines the maximum useable altitude and the stability.

During good flight conditions at Table Mountain the sensor package can be expected to fluctuate ± 50 m in altitude and ± 25^0 in azimuth with occasional excursions of greater magnitude. This behavior puts some difficulty in the way of achieving a good wind comparison with other devices.

Certain additional experimental problems limited the wind comparisons between the acoustic and FM-CW radar systems. Some of the lesser difficulties can be categorized under the heading of data management. These difficulties were reasonably ironed out with considerable processing. However, two related problems developed due to the layout of the sensors and the meteorological conditions. The low relative humidities both days precluded strong signal returns for the FM-CW radar which depend primarily on moisture inhomogenities. Furthermore, a short metal tower located just east of the acoustic transmitter proved to be within the beam of the radar and required a substantial reduction in receiver gain to avoid overload. This tower could not be moved. The necessary reduction in gain prevented accurate measurement of winds many times due to the low signal to noise ratio. Comparisons between remote sensors should include the specification that all sensors measure in the same volume in space. It was not possible to achieve this requirement either, because of receiver overloading from the metal tower.

RESULTS

Comparison results herein presented consist primarily of time series of wind data from sensors spaced several hundred meters or more apart in the horizontal and up to a hundred meters or so in the vertical. The differences in measured wind by each sensor is a result of several factors listed below:

1. The separation distance as well as the variation in separation distance in three dimensions. The correlation of wind fluctuations drops off as the scale of the phenomena (eddies, gusts, etc.) approach the separation distance.

2. The remote sensors actually measure different, off-horizontal components of the speed of the scatterers. The acoustic Doppler and FM-CW radar measured about 70° and 40° respectively off horizontal in this experiment. The wind values presented in the following figures are horizontal wind values computed from the diagonal components of scatterer speeds by simple geometry, under the assumption of zero vertical velocity. Though this assumption is rarely met in nature, over averaging times of the order of 10 minutes or so zero mean vertical velocity is probably attained for most times and places. Based on careful post analysis of data for consistency and continuity, it appears that false wind shear indication at high gates due to vertical velocity fluctuations may be prevented by averaging for at least 6 minutes.

3. Differences in size and orientation of sensed volumes and different degrees of instrument inertia.

4. Possible errors in the design, or theory of operation, or miscalibration of the various sensors.

Despite these constraints, quite reasonable comparisons were obtained between sensors for periods during which simultaneous data exist. The cases illustrated here show both east and west winds, in one instance above 10 m sec^{-1}, at "fixed" height. (See Figures 4 and 5). Wind correlations between sensors at the test site were consistently good for scales larger than the separation distance. The best correlating time series with the instrumented tower 2 km distant (shown in Figure 6) was found with easterly winds. Under westerly downslope wind conditions less correlation, as expected, was found. At distances of this magnitude in mountainous terrain one should not in general expect to find good correlations for time scales less than an hour, unless meteorological conditions are ideal.

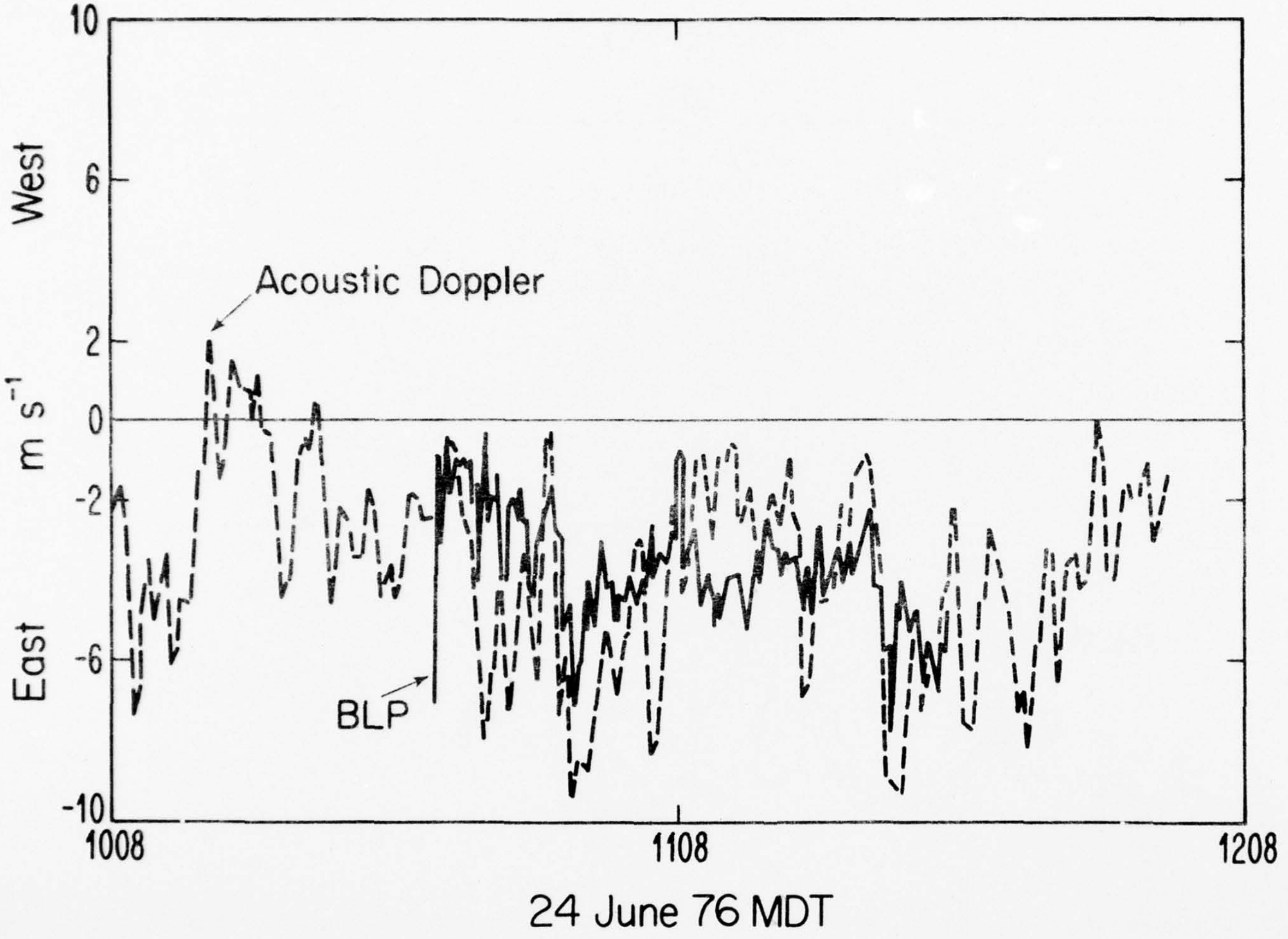


Figure 4. Comparison of westerly horizontal winds between BLP and acoustic Doppler. Acoustic Doppler winds were lagged by mean wind speed to improve correlation. 2 min time constant on acoustic winds. Altitude was about 150 m above ground level.

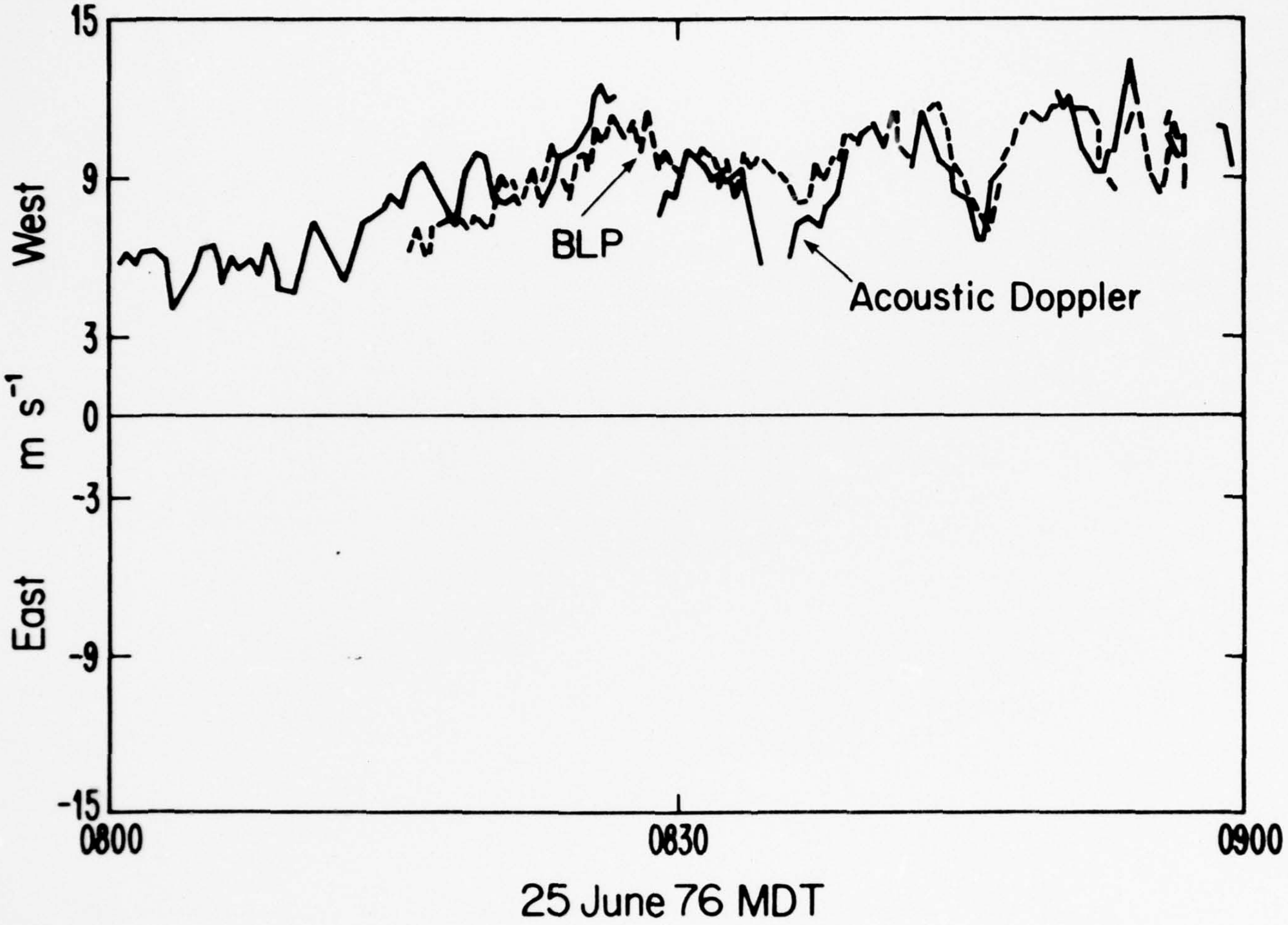


Figure 5. Comparison of easterly winds between BLP and acoustic Doppler. Acoustic Doppler winds were lagged by mean wind speed to improve correlation. 2 min time constant on acoustic winds. Altitude was about 210 m above ground level.

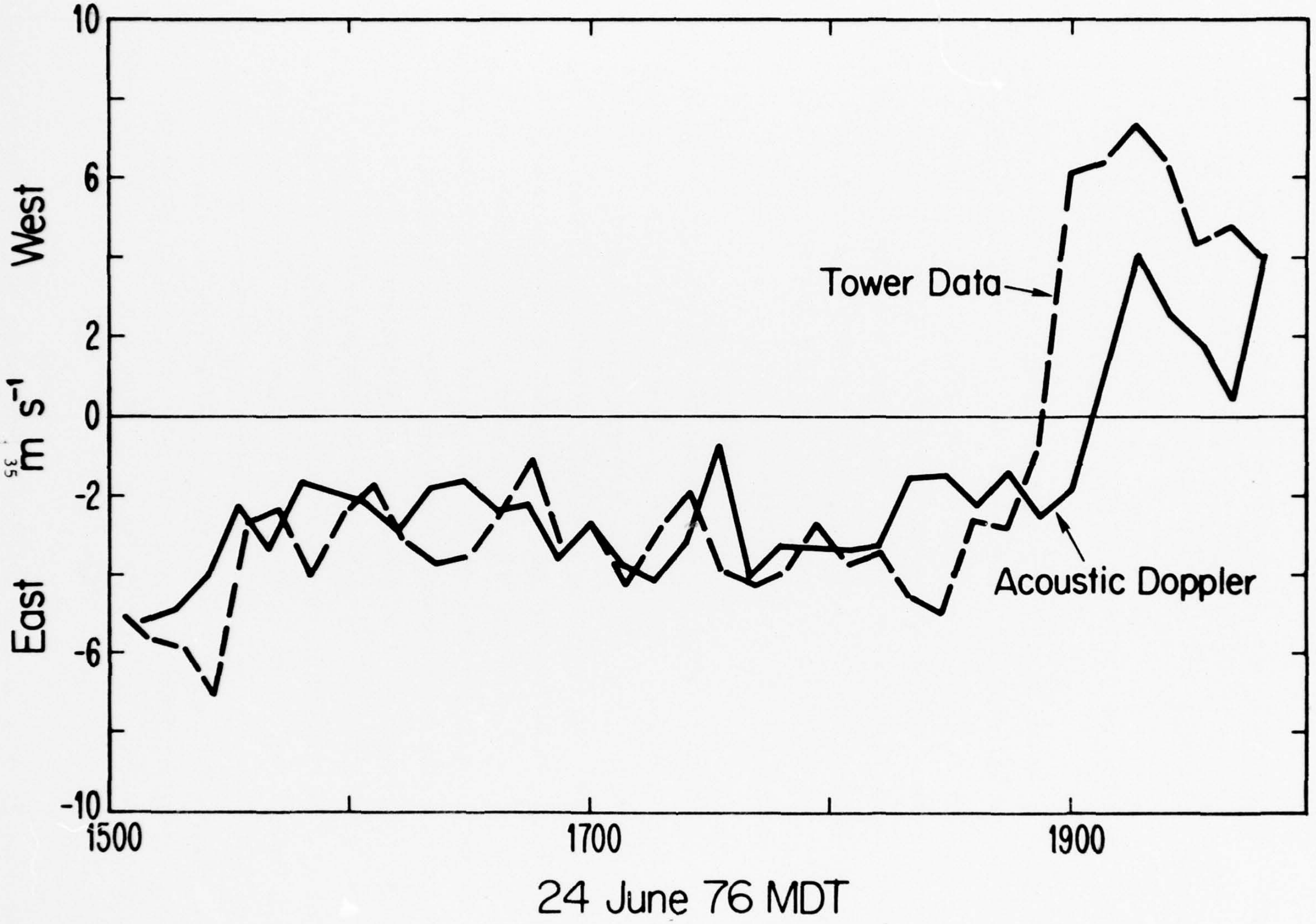


Figure 6. Comparison of horizontal wind speeds (east-west component) between acoustic Doppler and tower (approx. 2 km separation) (8 min block averages of east-west component) altitude was about 150 m above ground level.

Figure 7 shows comparisons among the three co-located sensors under an easterly wind regime, with the data averaged in 5 minute blocks. Note that the calculated horizontal wind speeds differ by 1 m/s or less among sensors.

PERFORMANCE UNDER EXTREME CONDITIONS

The limiting factor in the current acoustic Doppler system appears to be audible noise. Noise has been classified as near field (from wind, rain, birds, and insects) and far field (from traffic, thunder and turbulence). The near field noise, particularly that generated by wind or rain on the bunker cover, is a category over which we have some limited design control. Empirical selection of the best cover material is a goal of these Table Mountain tests. Cover materials installed so far have been different types of acoustically transparent foam or matting.

Wind generated noise often occurs without other adverse phenomena and is a function of wind speed. In Figure 8 noise power in decibels is plotted against the logarithm ground wind speed, measured about 2 meters above the bunker cover. Different cover materials yield different noise powers for a given wind speed. Rough surfaced materials are noisier than those with smoother textures. All noise sources are included in this diagram (the scatter is very large at low wind speeds) but the wind noise at higher speeds completely overshadows noise from other sources. The noise power was found to be about 3 dB greater for the lowest-looking transducers than for the highest. At the higher wind speeds the slope of the best-fit line varied from about +4.5 to +8 depending on meteorological conditions and cover material. These values do not agree well with theoretical and experimental studies of noise generated by wind blowing over rough surfaces, which indicate a 4th power relationship. Thus, there may be an additional source of noise, under windy or highly turbulent conditions, beyond that generated directly on bunker cover material by the wind. This noise could be generated aerodynamically in the turbulent flow itself.

This phase of the tests also have shown that the noise power due to wind blowing directly into the bunker is about 3 dB greater than that from wind

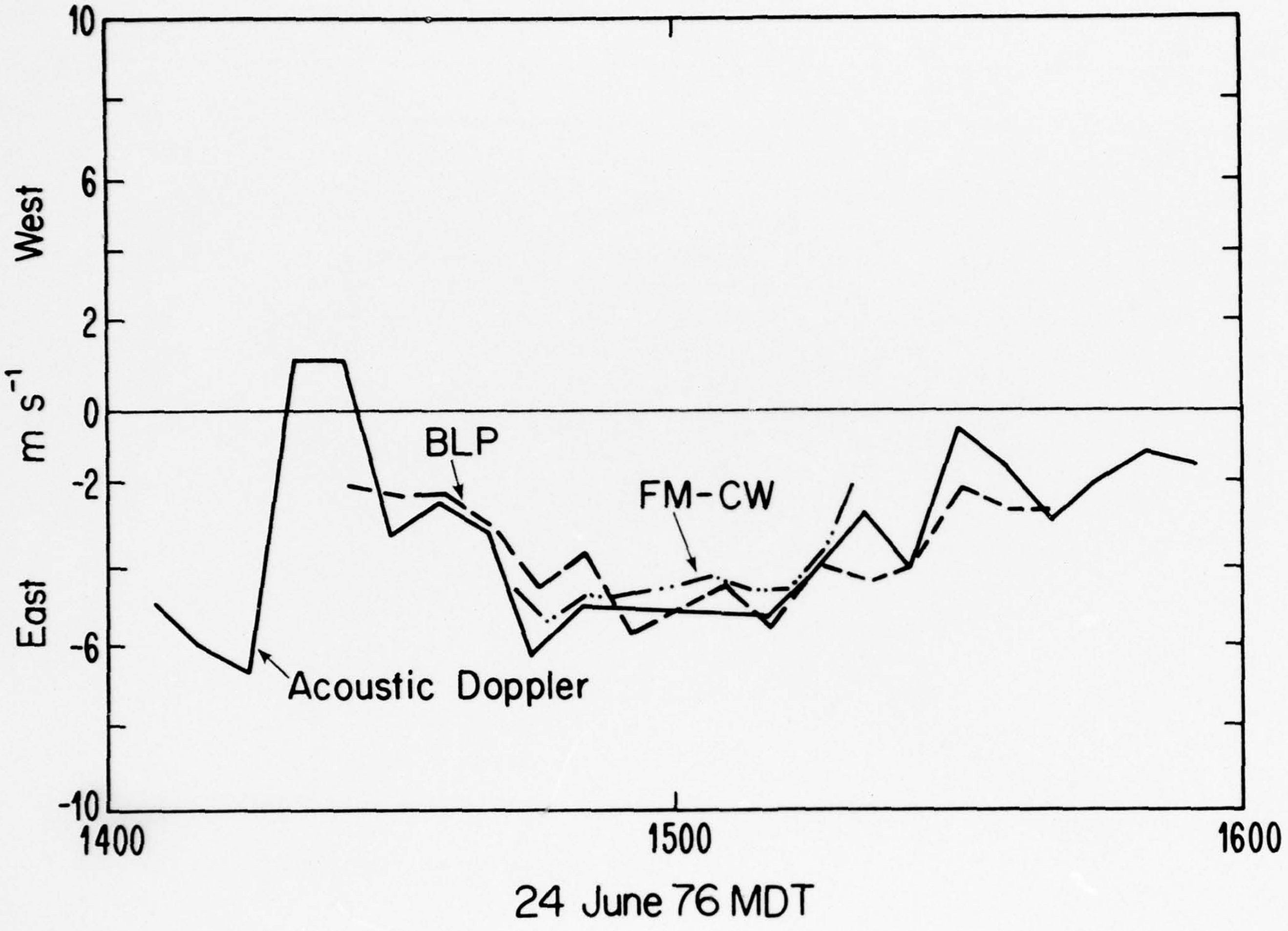


Figure 7. Comparison of horizontal wind estimates from acoustic Doppler, FM-CW radar and BLP tethered balloon. (5 min block averages of east-west component) altitude was about 210 m above ground level.

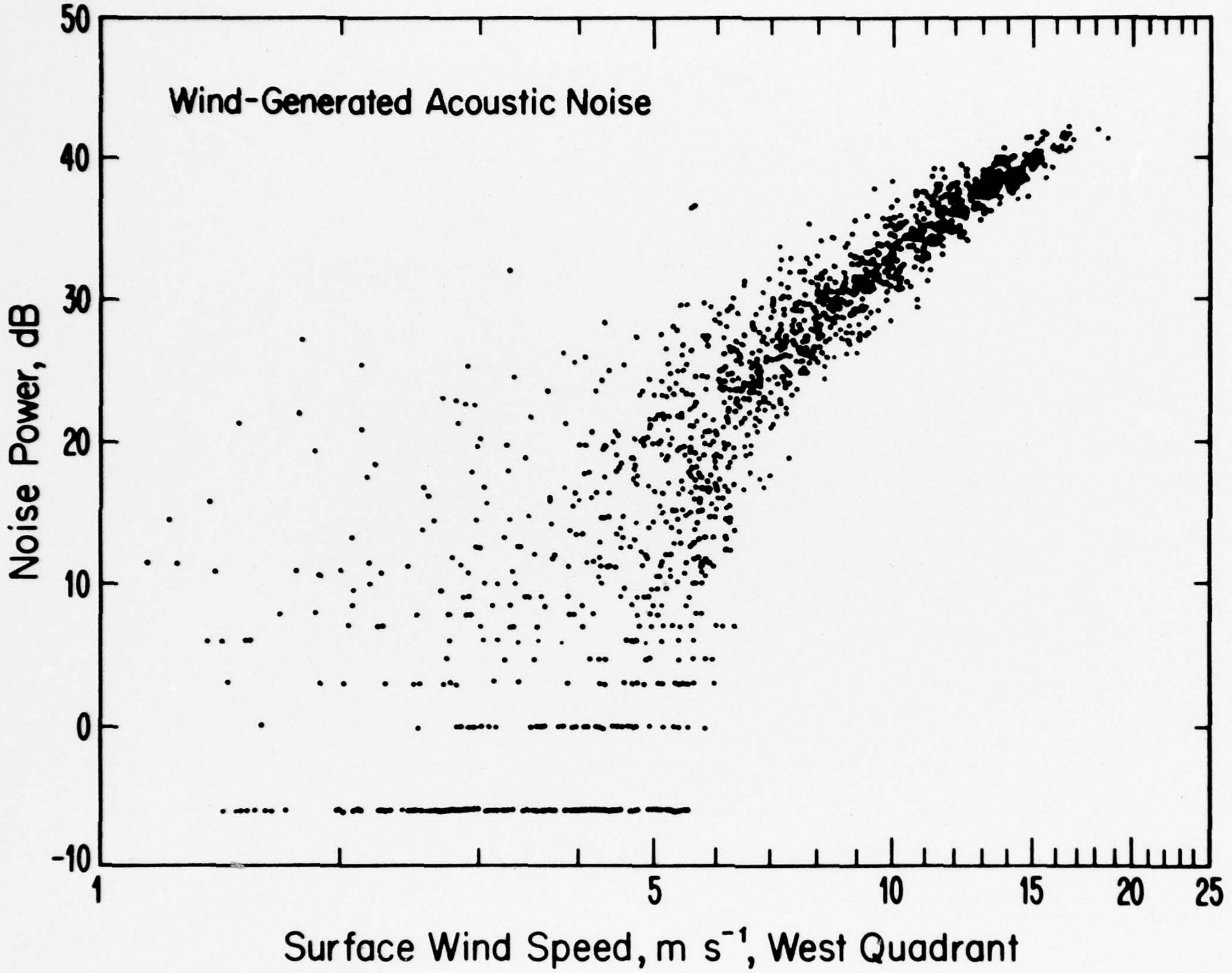


Figure 8. Noise power as a function of westerly surface wind speed on logarithmic plot. Data taken at Table Mountain between 8 June and 21 June 76.

blowing from behind the bunker. Rain generated noise has been found to be less strong than that from other sources. In fact, during thunderstorm conditions, it is difficult, with the data collected so far, to separate the amount of degradation due to rain noise from that due to other limiting factors. It was observed on several occasions when heavy precipitation commenced abruptly, that system outage did not occur for several minutes. A wind profile measured during intense rain (about 13 cm hr^{-1}) shows reliable operation up to 400 meters. It was hypothesized that the noise of water dripping inside the bunker, which starts after cover saturation, is the primary cause of system degradation during rain. Bunker design improvements were then made to substantially reduce the dripping, but nature has not since provided appropriate heavy rain conditions. Thus, no reasonable rain limitation figures can yet be assigned to the Table Mountain system.

PERFORMANCE UNDER AVERAGE CONDITIONS

In order to summarize the field operating reliability of the acoustic Doppler system, one must include the combined effects of many degrading factors: noise from various sources, inexact beam alignment for particular wind conditions, and distribution of acoustic scatterers. Since wind noise appears to be the primary cause of limiting conditions at Table Mountain, scatter diagrams were constructed to present system reliability as a function of wind speed. Figure 9 summarizes a collection of diagrams from different days. Performance is shown for three power settings. The horizontal axis is wind speed and the vertical axis the height of the highest gate at which a 75% or greater reliability was achieved. System reliability figure is determined by self-diagnosis of signal to noise ratio, overload, and minimum signal criteria failure rates. (A 75% to 80% minimum system reliability figures for the Table Mountain system is based on extensive real-time observations and post analysis of events for internal consistency and continuity.) It is evident that under westerly surface wind conditions (worst case, with wind blowing down the bunker throat) good performance cannot be expected with surface winds much above 10 m/s. Increased system reliability can be obtained with longer averaging times since each average contains more samples of the wind. This increase in performance can be seen in

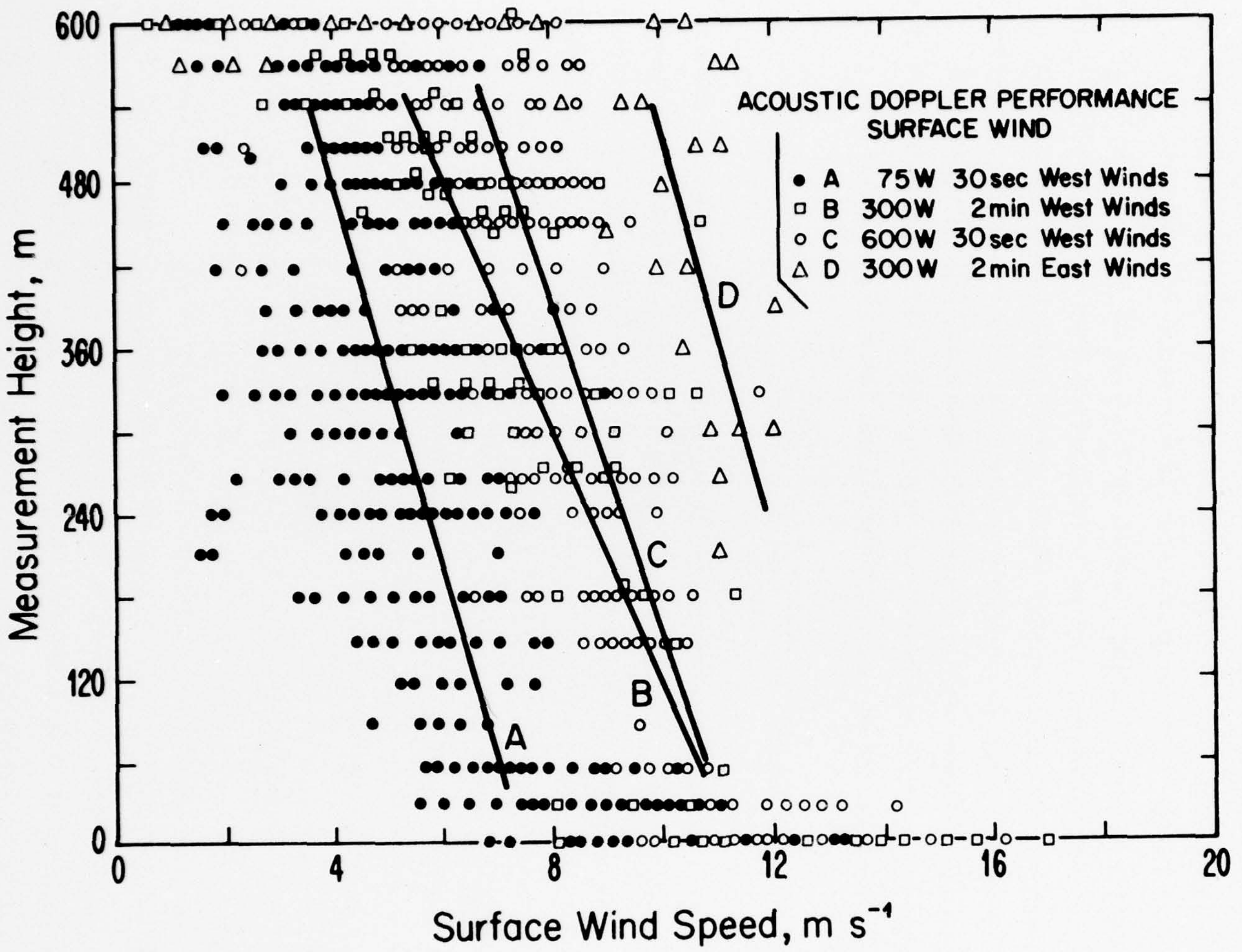


Figure 9. Height of highest reliable measurement (system reliability of 75%) as a function of surface wind speed. a) westerly winds, 30 sec system data averaging, 75 w main transmitter power. b) westerly winds, 2 min averaging, 300 w. c) westerly winds, 30 sec averaging, 600 w. d) easterly winds, 2 min averaging, 300 w.

Figure 9 by comparing curves b and c. Note that these figures also include the effects of variability of acoustic scatterers and the effect of wind blowing the transmitted/scattered acoustic beams away from the maximum lobe in the receiver pattern.

The cause of system outage from wind noise is more complex than the one to one relationship suggested above. Reliable wind measurements over 400 meters have been obtained with ground wind averaging about 15 m sec^{-1}. These situations may have been blessed with extremely strong acoustic scattering. From several cases examined, there seems to be greater scattering and/or less noise during wind shear events than during high wind situations when the boundary layer is well mixed.

Overall, the system operates reliably most of the time up to 300 m, about 75% of the time up to 400 m and about 40% of the time up to 600 m.

Note also that the rapid degradation with increasing wind speed starts at a speed of about 6 mps. This speed corresponds to the onset of significant wind generated noise (see Figure 8). Speeds below about 6 m/s produce noise which is not significantly higher than other noise sources (traffic, insects, birds, etc.)

By plotting many of these reliability versus wind speed scatter (Figure 9) diagrams at various transmitter power settings, a feeling can be obtained for the improvement in system reliability as a result of increasing the transmitted acoustic power. The Table Mountain system seemed to operate to the same altitude with a surface speed increase of 8 m sec^{-1} to 11 m sec^{-1} by increasing the transmitted power from 75 watts to 600 watts. However, atmospheric variability from day to day often obscured this simple formula, and occasions were discovered when the system would perform at nearly its best with much less power than 600 W. As noted earlier, strong easterly winds degrade the system less than strong westerly winds.

Since a small increase in wind speed yields a great increase in noise power, merely doubling or quadrupling the transmitter power will likely not result in a comparable increase in performance.

The archived data was also investigated to answer questions about the availability of acoustic scatterers. The most direct approach seemed to be a look at the temporal variation in received signal power. An estimate of the signal power at any height was obtained by integrating the received power spectra, corresponding to that height, over a narrow band 50 Hz wide, centered on the Doppler shifted signal peak. Besides variations in the scattering parameters of interest (C_V^2 and C_T^2, the wind and temperature structure parameters, respectively), fluctuations in the signal power estimates can be due to temporal variations in attenuation along the path of the beam, in ray bending, in translation of the beam by the wind across the receiver beam pattern, and in noise power in the narrow band. A sample time series of this received signal power estimate is shown in Figure 10. Note that the received power from 600 m is typically 18 dB less than that from 210 m. From several sets of time series for several altitudes, some general statements can be made about variations in received signal power. The narrow band power decreases by as much as 30 dB at a height of 210 m from daytime to nighttime. Sometimes the changes are abrupt steps which correlate with abrupt changes in the wind speed/direction on the ground as well as aloft. Short-term fluctuation in received power by this method appears to be about 6 dB. Furthermore, the variation in signal power at high gates is much greater than near the surface. Received power decreases aloft, but not in a simple manner and there appears to be more power received during periods of easterly winds than westerly winds.

The wind measurement accuracy of the atmospheric heights serviced by the satellite transmitter has been a subject of some concern also. For the two week test period long time series of wind speed were plotted for altitudes immediately above and below the satellite-main transmitter cross-over. Though the series cannot be expected to be extremely similar, no gross differences were seen among all the main and satellite gates inspected. The satellite volume is separated from the main transmitter volume by more than 250 meters.

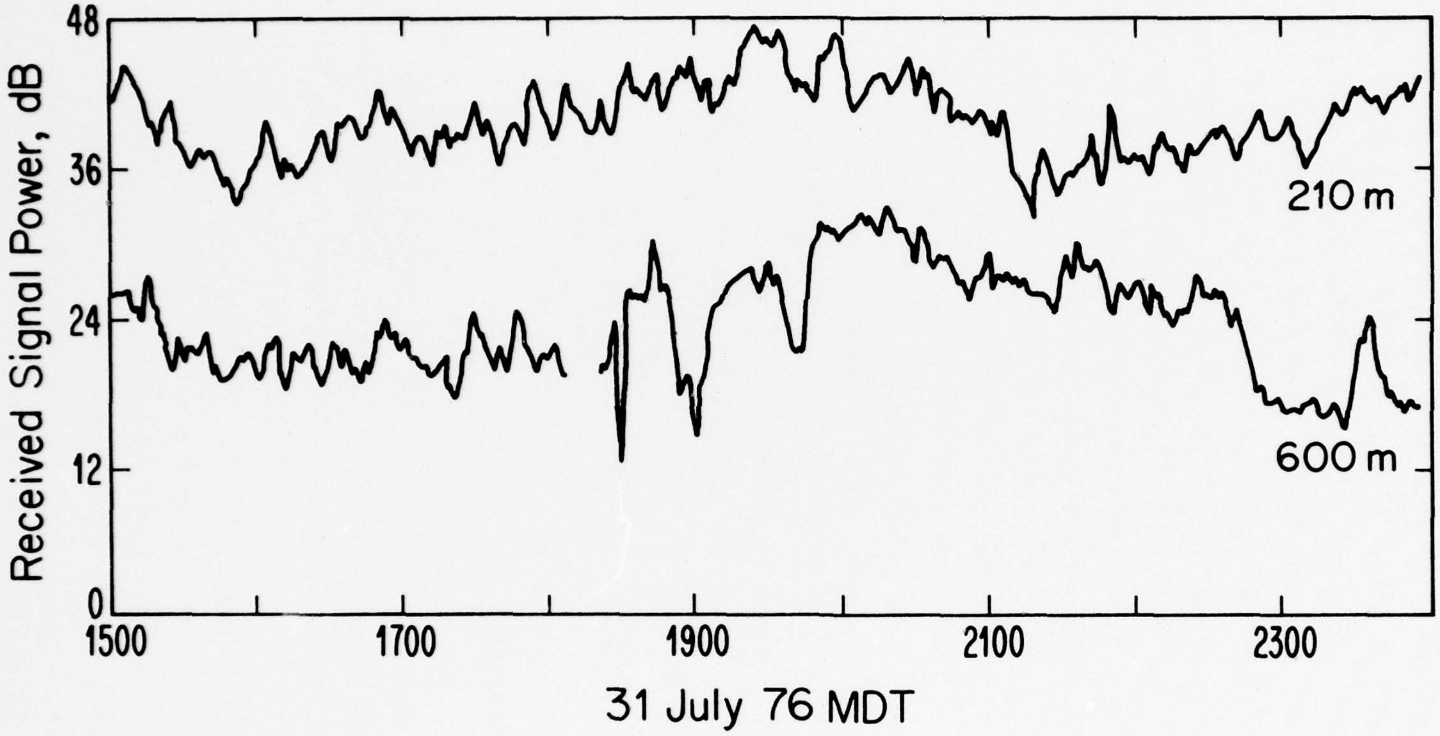


Figure 10. Temporal variation of received signal power for two heights (210 m, 600 m). System averaging time constant was 2 min.

WIND SHEAR EVENT

An interesting case of a gust front passage as measured by the Table Mountain system is illustrated in Figure 11. This depiction describes part of the thunderstorm development on 31 July 76 which preceeded the Big Thompson flood. Some of the strongest low-level easterly winds ever detected in Eastern Colorado occurred on this day. As the site was unattended no specifics can be given regarding the thunderstorm cell pattern surrounding Table Mountain. It seems reasonable, however, that the cell(s) which produced the observed downdraft was somewhere to the west of the site, at least a few kilometers distant.

Fairly strong easterly winds eventually gave way to a good vertical E-W speed shear as the low level winds dropped off. Intrusion of low-level westerly flow is seen about 1/2 of the way through the sequence. It is interesting to note that the wind shear value measured at the strongest point is almost as great as that inferred during the DC-10 crash at Boston in 1973. The shear value seen here is only one component and reaches nearly 25 m/s over the 600 meter depth. Eventually the strong easterly component returns throughout the profile.

CONCLUSION

System Performance

The primary limiting factor in the current prototype acoustic Doppler system is audible noise. The exact causes of system degradation appear to be more complicated than one would expect; more complex and interesting than just wind or rain noise or other easily classifiable parameter. Very good results have been obtained, on occasion, with strong surface wind and heavy rain. Poor results have been observed under apparently favorable conditions. The distribution or climatology of acoustic scattering is an important aspect which has not been fully investigated. Under most circumstances, the maximum westerly surface wind under which the Table Mountain system can operate is about 10 m/s. This figure may be raised only slightly

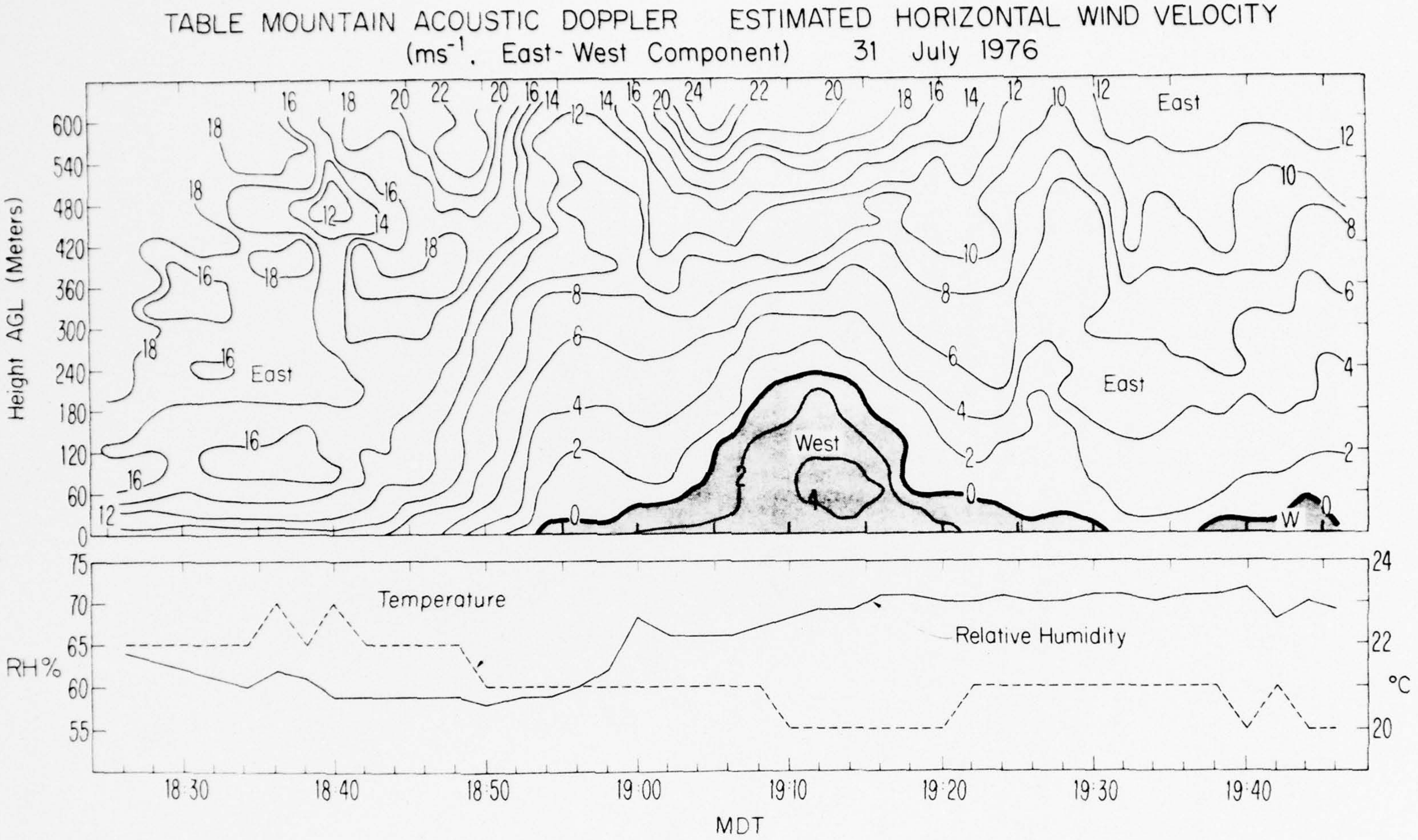


Figure 11. Time-height section of east-west estimated horizontal wind velocity from Table Mountain acoustic Doppler system on 31 July 1976. Westerly winds shaded. Contour interval, 2 m s^{-1} surface temperature and relative humidity progression is shown along the time axis.

by "fine tuning" the current design or significantly by improving both hardware and software design.

Wind Measurement Accuracy

Within the experimental and atmospheric limitations previously described, the acoustic Doppler system seems to measure the horizontal wind speed to within its design criteria of 1 m sec^{-1}. The time averaging of data needed to establish this conclusion is justified under the condition of synoptic scale wind shear measurements. Vertical motions measured by the sounder significantly affect the estimate of horizontal winds, especially at the higher levels; it is recommended that raw estimates be averaged for 10 minutes. Whether the system accurately measures the wind fluctuations down to its small scale limit, and the establishment of this limit, are questions of significant research interest, but have not yet been pursued.

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