

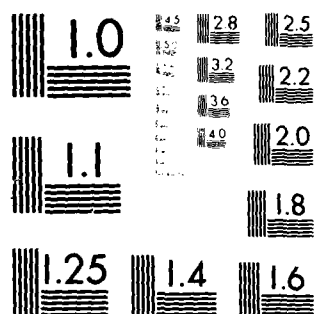
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EVALUATION OF A TETHERED KITE ANEMOMETER.(U)

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EVALUATION OF A TETHERED KITE
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**US Army Electronics Research and Development Command
ATMOSPHERIC SCIENCES LABORATORY
White Sands Missile Range, NM 88002**

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A kite anemometer which can obtain windspeed and wind direction in the range of 3 to 40 ms ⁻¹ up to heights of 500 m has been tested for potential Army applications. It has been found to be inexpensive, portable, easy to use, and able to operate under strong winds (up to 40 ms ⁻¹). Wind profiles using the kite anemometer were measured at a mountaintop location. These profiles demonstrate the ability of the kite to obtain windflow characteristics in rugged terrain. Possible Army applications of the anemometer include wind		

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20. ABSTRACT (cont)

measurements to: (1) support electro-optical and high energy laser testing, (2) determine windflows in complex terrain, and (3) detect dangerous, low-level wind shears at military airports.

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1. INTRODUCTION

Wind information is a necessary input to determine how a variety of Army systems will operate in a field environment. Examples of Army systems sensitive to the wind are high energy laser (HEL) systems where crosswind ventilation is essential to prevent excessive heating of the atmosphere along the beam path and other electro-optical (EO) devices where the windfield can determine the distribution of obscurants. It is often necessary in research efforts and in operational support situations to obtain vertical profiles of windspeed and wind direction to substantial heights. To obtain these profiles, use of either tall towers or remote sensors is required. In many cases, these options are not satisfactory because of lack of mobility, high cost, or the complexity of data reduction. For these reasons, there is an ongoing Army interest in alternative methods of wind measurements.

One new instrument for obtaining vertical wind profiles is a kite anemometer named TALA* (tethered aerodynamically lifting anemometer) manufactured by Approach Fish, Incorporated.** This device obtains winds by measuring the force on a kite caused by the wind. It is capable of measuring winds up to altitudes of about 500 m over the range of 3 to 40 ms⁻¹.

The purpose of this research effort was to evaluate the potential usefulness of this kite anemometer to obtain wind profile information for Army applications. The kite was then used to measure wind profiles at a mountaintop location.

2. DESCRIPTION OF THE KITE ANEMOMETER

2.1 Physical Principles

The principle of operation of the kite anemometer is quite simple. The wind exerts a force F on the kite. The force is transmitted through the tether to the ground and then measured at the ground. The windspeed is determined from the force. Theoretically, the force on a flat plate due to a windflow normal to the plate is given by

$$F = 1/2 C_D \rho A V^2, \quad (1)$$

*US patent no 4,058,010 and 4,152,933

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where C_D is a drag coefficient, ρ is the density of air, A is the area, and V is the windspeed. Kite calibration data are very close to the $F \propto V^2$ dependence.¹ These data are described in more detail in section 3.

The altitude z of the kite must be calculated from the length of the tether L and the elevation angle γ of the kite with respect to the ground observer. With measurement of these two parameters, the height of the kite can be calculated from

$$z \approx L \sin \gamma . \quad (2)$$

This formula is only approximate because there is a bow or catenary in the tether. However, Shieh and Frost² used a computer model to show that the errors are insignificant. Equation (2) is useful when the ground observer visually measures γ . However, for the purposes of an automated system, the angle that is measured is the angle θ at which the tether intersects the ground. Because of the catenary, $\theta \leq \gamma$. The altitude of the kite is then expressed as

$$z = G(L) L \sin \theta , \quad (3)$$

where $G(L)$ is a catenary correction (≥ 1) which is a function of line length. $G(L)$ was empirically determined by the manufacturer and can be significant. For instance, at a line length of ~ 350 m, $G(L) \sim 1.2$.

2.2 System Components

Figure 1 is a block diagram of the TALA system used in this study. The system used is the most sophisticated (and most expensive) system that is available. The manufacturer offers much less sophisticated (and less expensive) TALA systems.

The heart of the system is the kite which is a very simple airfoil design and is made of Tyvek, a strong but lightweight material. The kite is available in two sizes (1500 cm² and 3000 cm²). A tail is attached to the kite for stability. The smaller kite is able to reach altitudes of 300 m and can withstand winds up to 40 ms⁻¹. The larger kite can reach up to 500 m and

¹J. C. Kaimal, H. W. Baynton, and J. E. Gaynor, 1980, The Boulder Low-Level Intercomparison Experiment, Preprint of World Meteorological Organization report, National Oceanic and Atmospheric Administration/Environmental Research Laboratories, Boulder, CO

²C. F. Shieh and W. Frost, 1979, "Tether Analysis for a Kite Anemometer," Wind Engineering, 4:80-86

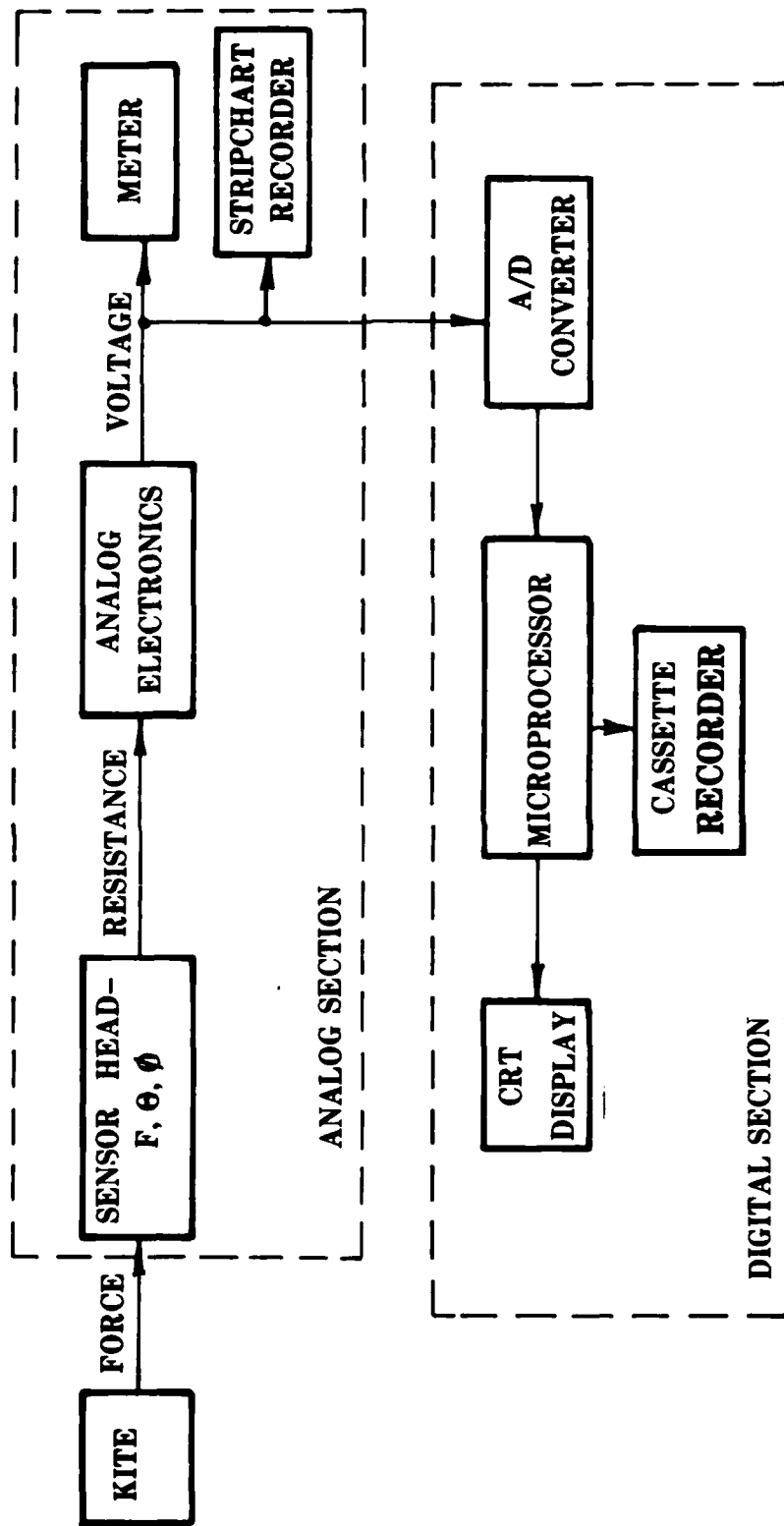


Figure 1. Block diagram of TALA kite anemometer system.

withstand winds of about 25 ms^{-1} . The tether for the kite is made of Kevlar which also is a lightweight (0.25 mm thick) but very strong (30 lb test) material. The tether does not stretch; therefore, the transmission of forces is essentially instantaneous. The tether is attached to a fishing reel which has an attached motor to assist reeling in the kite during high winds.

At the ground, there are a number of options available from the company for measuring the force and recording the data. The most sophisticated option is described here and is labeled as the "analog section" in figure 1.

The force F on the tether is measured by a strain gauge attached to the tether. The strain gauge is mounted on an apparatus (sensor head) which can rotate both in the elevation and the azimuth direction. Potentiometers measure the elevation θ and azimuth ϕ angles of the tether. The azimuth potentiometer is used to sense the horizontal direction of the wind. The elevation potentiometer output together with the length of tether that has been let out is used to calculate the altitude of the kite from equation (3). Two different methods can be used to measure the length of line that has been let out. In one method, a reel counter monitors the number of rotations of the reel. A manufacturer's calibration curve is then used to relate that number to the length of the line. In the second method, a yard counter attached to the tether directly measures the length of line.

Since the strain gauge and potentiometers are resistance elements, analog electronics are used to convert the resistance to electrical voltages. The signals are displayed on a meter and recorded on a strip chart. Power for this analog sensing and recording unit is either an internal Gel cell or an external 12 V dc power supply (for example, car battery).

Data can be measured and recorded with the analog section alone. However, additional sophistication is provided by a digital acquisition system. This system consists of an analog to digital (A/D) converter, a field-programmable microprocessor, a cathode ray tube (CRT) display, and a cassette recorder. The electrical signals from the analog section are digitized by the A/D converter at a rate of 1 Hz. The microprocessor computes windspeed, wind direction, and altitude from the digitized numbers and displays the resulting values on the CRT. Average and standard deviations of these quantities over a specified (by the user) averaging period are stored on cassette tape for later reduction and analysis. The digital system is self-contained and can be run either from an external 12 V dc supply or from a standard 110 V ac outlet.

The entire system is portable and can be carried to a potential site by hand if necessary. The analog section weighs 27 lb and the digital section weighs 28 lb.

Since this system was obtained, a number of improvements have been made in the digital acquisition system. These changes should improve the versatility and ease of use of the system. The major changes are:

- a. The cassette recorder has been replaced by a floppy disc drive.
- b. The microprocessor has been replaced with a more rugged unit that has been used on off-shore oil platforms.

c. A thermistor, clock, and barometer have been added. These are automatically sampled by the system. Formerly, temperature, time, and pressure had to be input by hand.

d. A 16-channel multiplexer has been added to the A/D converter. Nine channels are reserved for kite data. However, seven channels are available to the user for other purposes and could be used to sample other instruments.

3. EVALUATION

A number of field measurements were made with the kite anemometer in a variety of situations to evaluate the usefulness of the kite for obtaining wind profiles. The following discussion is based on the experience gained in these field tests.

3.1 Operational Characteristics

The kite anemometer can obtain wind measurements up to heights of about 300 m with the smaller kite and 500 m with the larger version. Therefore, the kite has been evaluated with reference to methods of obtaining winds to equivalent heights. These methods include very tall towers and remote sensors. In comparison with these types of systems, the kite anemometer has a number of significant advantages. These advantages include:

a. The kite anemometer is much less expensive than these other methods. The most sophisticated system (described in paragraph 2) costs around \$14,000, while the simplest version can be obtained for under \$1,000. Constructing tall towers or purchasing remote sensors is much more expensive. In addition, the cost of replacement kites and additional tether line (the parts most likely to be damaged) is very small (for example, \$30 for a kite).

b. The device is conceptually simple with little danger of misinterpretation of data. This characteristic is an advantage over remote sensors where noise can be mistakenly identified as signal, and complex mathematical algorithms are often required to obtain wind measurements.

c. The system is portable. It can be hand-carried to a measurement site by one to two people and can be battery operated. It therefore seems ideal for obtaining profiles in remote locations.

d. It is easy to set up. One person can set up the system and begin wind measurements in about 15 minutes.

e. The kite can operate under very windy conditions--up to 40 ms^{-1} for the smaller kite and 25 ms^{-1} for the larger kite.

The disadvantages of the system include:

a. It can obtain only a single point measurement. Therefore winds at different heights cannot be obtained simultaneously. To obtain a wind profile, the kite must be reeled in and out to different heights. Each time the height is changed, the kite must be detached from the sensor head, reeled to a new height, and then reattached to the sensor head--a somewhat cumbersome

process. Approximately 30 min are required to obtain a complete profile. This time requirement can result in ambiguities in the interpretation of the resulting profile if the windflow is not stationary. In any experiment, it is suggested that several profiles should be obtained at each location so that nonstationary situations can be identified.

b. The kite will not fly at speeds less than 3 to 4 ms^{-1} . This characteristic requires that the kite be manned at all times since if the wind falls below 3 ms^{-1} the kite will lose altitude and, if left untended, become tangled in surface obstacles such as trees and power lines. In marginal wind situations the kite may not remain at a height long enough to obtain statistically reliable wind averages for that height. The manufacturer claims that balloons attached to the tether can be used to launch the kite under light winds at the surface. Once the desired height is reached, the balloon can be released from the line. However, this is not a general solution since the wind can fluctuate about the minimum flying speed and cause the kite to lose altitude after the balloon has been released from the tether. An additional problem occurs in convective situations with marginal winds where the vertical component of the wind can be significant compared to the horizontal. This situation causes large variations in the altitude of the kite because of large changes in the angle θ in equation (3). The resulting wind vector is thus an average over a large altitude range.

3.2 Calibration

The manufacturer calibrated the kite anemometer in a wind tunnel and states that the kite should measure winds in the atmosphere with 2 percent accuracy. Baker et al³ compare kite measurements with tower measurements and show an average difference of 2 percent. A more complete study was done at the World Meteorological Organization (WMO) Intercomparison Test⁴ which was held during the period of 20 August to 6 September 1979 at the Boulder Atmospheric Observatory (BAO) near Boulder, Colorado, and attended by the author. This test was designed to test a variety of remote and in situ meteorological instruments against standard tower instruments. Approach Fish, Incorporated, participated in this experiment with their kite anemometer. Results of this experiment indicated that kite measurements compared favorably with tower measurements. This comparison is shown in figure 2. When the bad data points are ignored, the kite and tower agree to within 1 m/s. Because of the objective nature of the test, the conclusion is that the kite appears to give accurate measurements of winds. The mean difference seems to be somewhat greater than 2 percent, but this is expected in view of the normal spatial and temporal variability of the wind encountered in the real atmosphere.

³R. W. Baker, R. L. Whitney, and E. W. Hewson, 1979, "A Low Level Wind Measurement Technique for Wind Turbine Generator Siting," Wind Engineering, 3:107-114

⁴J. C. Kaimal, H. W. Bayton, and J. E. Gaynor, 1980, The Boulder Low-Level Intercomparison Experiment, Preprint of World Meteorological Organization report, National Oceanic and Atmospheric Administration/Environmental Research Laboratories, Boulder, CO

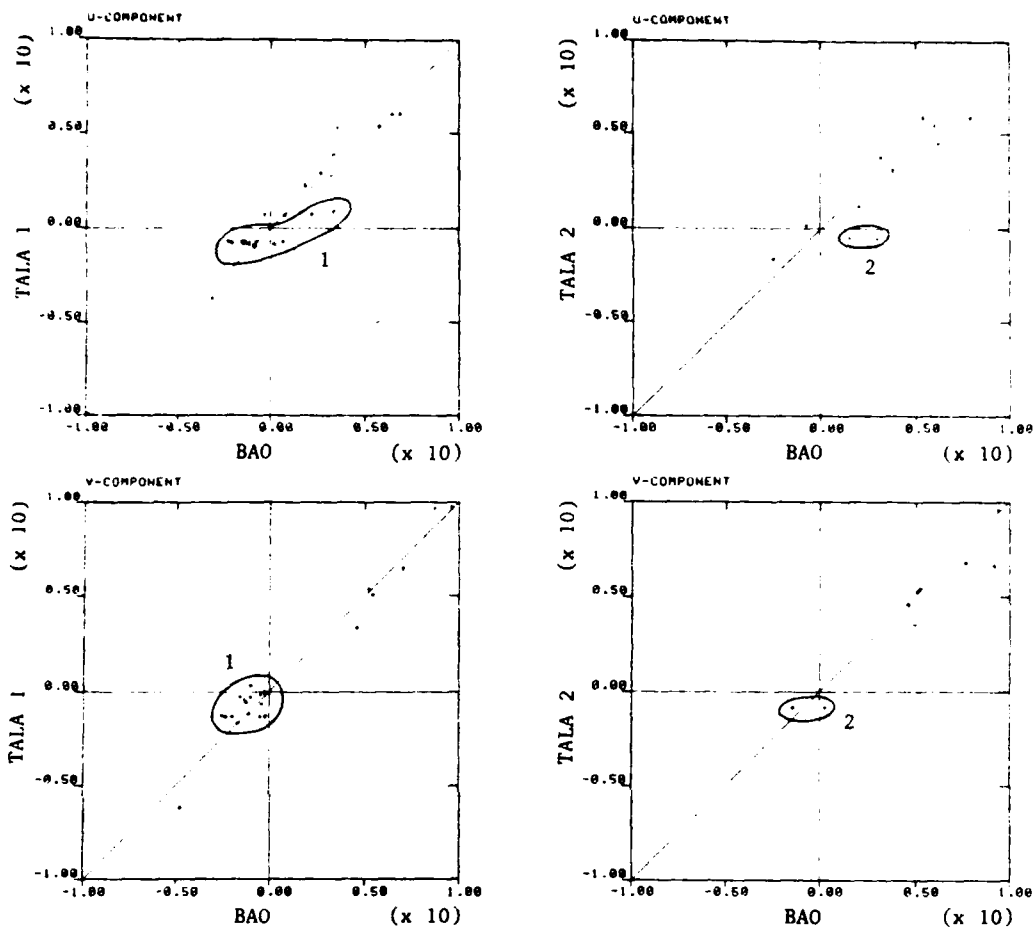


Figure 2. Comparison of TALA winds with tower (BAO) winds. TALA 1 and TALA 2 are similar kites. Data points in group 1 should be discounted because they are only empirical estimates from an uncalibrated lift balloon. Data points in group 2 should be discounted because of equipment malfunction during a thunderstorm (from Kaimal, Baynton, and Gaynor [ref 1]).

The actual calibration of the kite anemometer in a wind tunnel by the manufacturer showed small deviations from the form of equation (1). The following formulas provided a reasonable approximation to the calibration data. The relationship between windspeed and force for the smaller low altitude kite is

$$V = 4.0 \left(\frac{\rho_s}{\rho} \right)^{1/2} F^{0.49}, \quad (4)$$

where F is in newtons, V is in m/s, ρ is the density of air, and ρ_s is the density of air at standard pressure (sea level) and temperature (55°F). The relationship for the larger high altitude kite is

$$V = \left(\frac{\rho_s}{\rho} \right)^{1/2} [-0.092 F - 0.86 F^{1/2} - 2.467]. \quad (5)$$

4. WIND PROFILE MEASUREMENTS

A series of wind profile measurements was taken with the kite anemometer at a mountaintop location. The mountain is part of a ridge line with a north-south orientation. The west side of the mountain is very steep (average slope approximately 45 degrees), while the east side has a much milder slope (average slope approximately 10 degrees). The mountain peak is approximately 1 km above the surrounding plains. These measurements are not in any way meant to be a comprehensive study of mountain flow patterns. However, they are presented to show the kind of information that the kite anemometer can provide.

A single wind profile consisted of measurements at approximately 50-m-height intervals. At each height the winds were averaged for 2 to 4 min. Two to three min were required to change heights. Therefore, a single profile from near the surface to 250 m required approximately one-half hour.

Figure 3 shows a series of average windspeed profiles. Each profile is a 2- to 3-h average consisting of 4 to 6 single profiles. Two of the profiles (6 November 1979 and 6 February 1980) indicate essentially no vertical gradient in windspeed. The other two (6 December 1979) show a substantial gradient. The cause of this difference is not clear. The gradients on 6 December may be due to drag by the mountain caused by convection. Convection would not have been present for the other profiles because the 6 November profile was taken on a cloudy day and the 6 February profile was taken early in the morning before convection began. Although insufficient supporting measurements were obtained to determine the cause of the differences, these profiles illustrate the ability of the kite to obtain wind profiles at a remote site and to provide information about the different flow conditions that can exist from day to day.

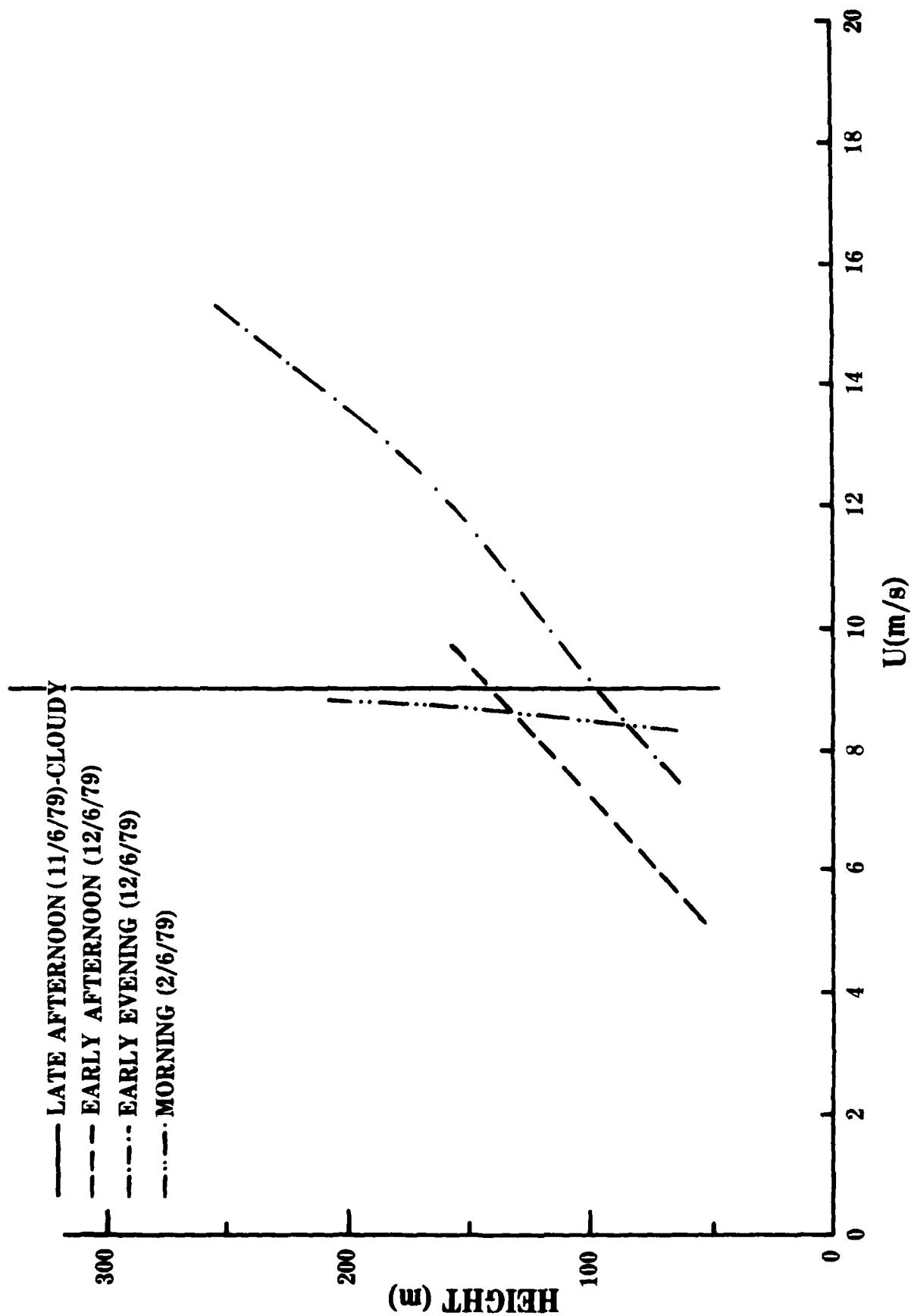


Figure 3. Average wind profiles at a mountaintop location. Each profile is a 2- to 3-h average.

Figure 4 shows the profiles of windspeed and the standard deviation of windspeed for 1500 MST, 24 April 1980. Mostly cloudy conditions were present with strong west winds. The windspeed profile was approximately constant with height with values in the 13 to 16 m/s range. The profile of the standard deviation is quite interesting, showing the large increase in turbulence near the surface. There is an increase of a factor of 3 from the 250-m level down to the 60-m level. This increase corresponds to an increase of a factor of 9 in the turbulent energy of the flow. This difference shows how large an effect a mountain can have on the turbulence in the boundary layer flow. In addition, the standard deviation begins to increase substantially below about 150 m, which suggests that 150 m was approximately the depth of the mountain-induced boundary layer on this day. This profile shows that the kite anemometer can also provide information on the turbulent nature of the flow and on boundary layer depths.

5. POTENTIAL APPLICATIONS OF THE KITE ANEMOMETER

The kite anemometer has been useful in a variety of nonmilitary applications. The most extensive application to date has been its use as a tool in wind power site selection.³* Its portability and ability to operate in rugged terrain and in strong winds have made it an inexpensive method to obtain wind profile information at potential wind power sites. The results of the present study indicate that the kite anemometer is a useful and inexpensive method of wind profiling. The unique characteristics of the kite suggest a few possible Army applications. These applications include:

a. Wind profile measurements in support of testing of EO and HEL devices. Much of the testing to date has been done at temporary field locations without tall towers. Future experiments could benefit from the additional measurements provided by the kite. In fact, the data presented in section 4 are being used to characterize a potential HEL testing site.

b. Wind profile measurements in mountainous terrain. The anemometer's portability make it an ideal instrument to use in this application. In particular, it can augment research efforts to determine flow patterns in complex terrain. Such work may lead to a better understanding of diffusion and dispersion of battlefield obscurants in possible combat zones (for example, West Germany and the Middle East) and therefore to an understanding of the potential usefulness of EO devices in combat situations.

c. Profile measurements in support of military airfields. The kite anemometer provides a cheap and safe method of detecting dangerous, low-level wind shears for incoming aircraft. Once again, its portability makes it attractive for use at temporary airfields. Also, since dangerous wind shears

³R. W. Baker, R. L. Witney, and E. W. Hewson, 1979, "A Low Level Wind Measurement Technique for Wind Turbine Generator Siting," Wind Engineering, 3:107-114

*Personal communication, Steven Keel, sales manager, Approach Fish, Incorporated

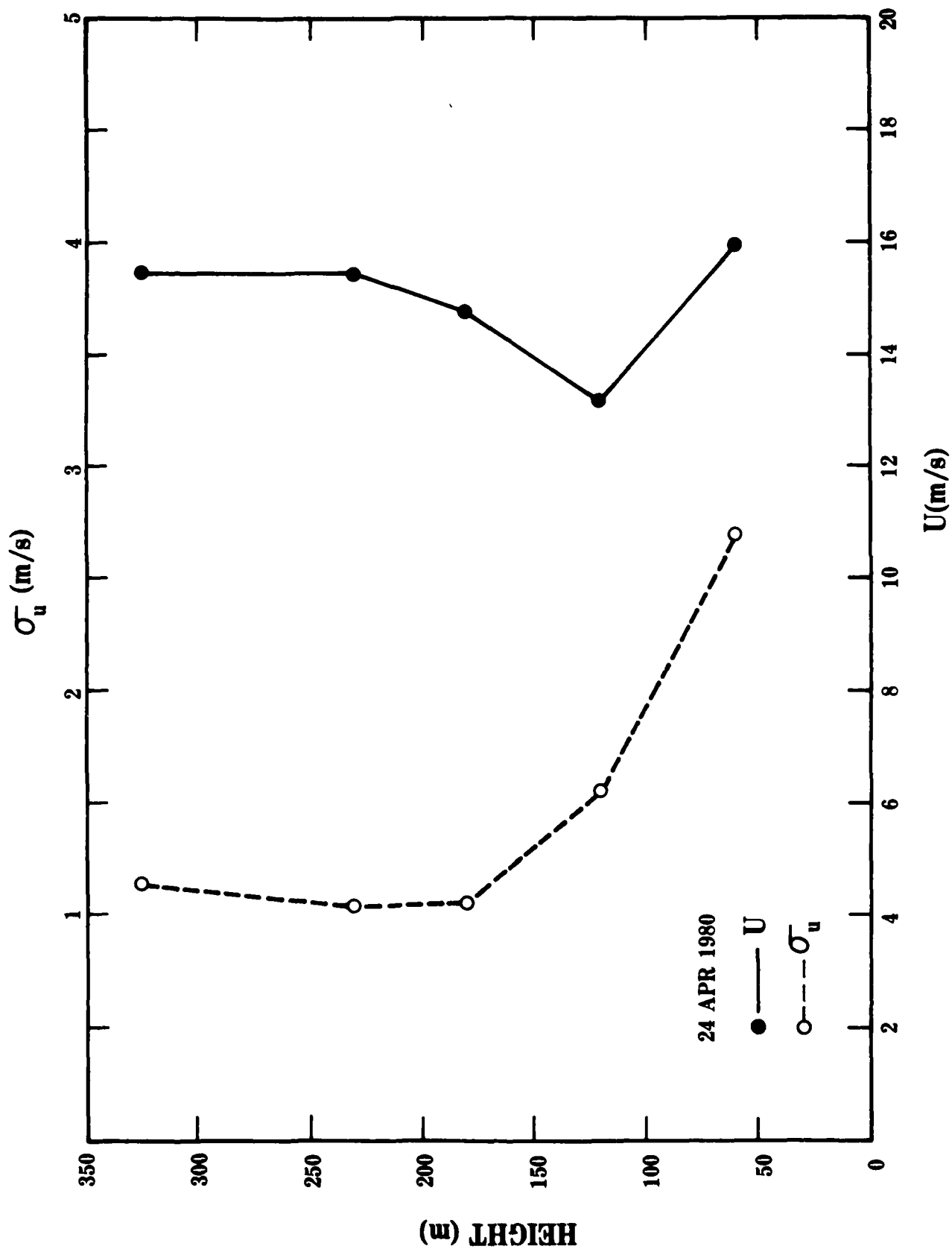


Figure 4. Profiles of windspeed (U) and standard deviation of windspeed (σ_u) for 24 April 1980 at a mountaintop location. The data were obtained at 1500 MST. Each point is an average of 100-200 samples.

occur most frequently under strong wind conditions, the ability of the kite to operate under strong winds is an advantage.

These are just a few of the applications that exist; undoubtedly, the kite anemometer can be useful in a variety of other applications. In general, the kite anemometer may be able to complement or replace tall towers and remote sensors in any Army application where these may be used. The kite anemometer should be considered as an alternative to these other methods because of its economy and other advantages.

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