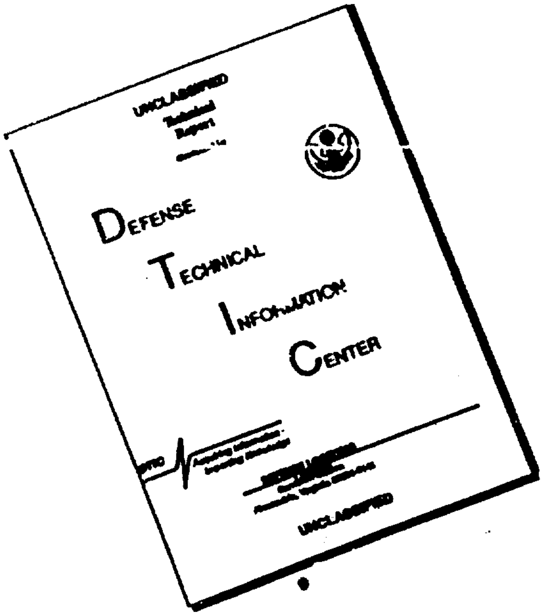

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CHESAPEAKE BAY INSTITUTE
THE JOHNS HOPKINS UNIVERSITY

TECHNICAL REPORT 40

AN EXPERIMENTAL STUDY TO DETERMINE THE UTILITY OF STANDARD COMMERCIAL HOT-WIRE AND COATED WEDGE-SHAPED HOT-FILM PROBES FOR MEASUREMENT OF TURBULENCE IN WATER-CONTAMINATED AIR FLOWS

by

Francis J. Merceret, Jr.

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Director

ABSTRACT

Tests were made to determine the response of hot-wire and wedge-shaped coated hot-film probes to liquid water-contaminated air flow. It was found that conventional hot-wire probes are not suitable for turbulence measurements in such flows, while the hot-film probes are suitable in certain situations. Probe contamination by salt encrustation would prevent effective use of either sort if the contaminating water were saline.

ACKNOWLEDGEMENTS

I hesitate to write this page for fear of omitting mention of one or more of the many people who helped with this work, but without them there would have been no experiment and I will take the risk.

I am grateful to Dr. Frank Champagne, Dr. Blair Kinsman, Dr. Owen Phillips, Mr. Bernard Bertling, Mr. Godfrey Harris, Mr. Albert Kuo, Mr. Mart Peep, and Mr. Stan Wilson of the Johns Hopkins, and to Mr. Ronald L. Humphrey of DISA, among others, for helping me to gather the equipment necessary to carry on the experimental program. Without the often timely and always kindly advice and consultations of Dr. Stanley Corrsin, Dr. Kinsman, and Dr. Phillips, I might well have spent a large part of my effort chasing red herrings. With such expert guidance, it was little trouble to be sure I was hunting where the ducks were. Mr. Yat Hong Lau was of considerable aid during the laborious task of gathering the data. My special thanks, too, to Mrs. Peggy Brougham who, in addition to typing the manuscript, saved me much time and effort by maintaining communication between the DISA Corporation in New Jersey and myself in spite of my continual meanderings in places usually inaccessible to the rest of creation. I would also like to express my appreciation to Mr. R.W. Linfield for his help with the preparation of figures and to Mrs. E.S. Shinn for typing the final copy.

Without the efforts of those above and without the encouragement of many others this paper wouldn't have been.

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INTRODUCTION

The purpose of this investigation was to discover whether the DISA 55D05 constant temperature anemometer and DISA 55A81 hot-film probe form a suitable combination for the measurement of atmospheric turbulence in the presence of heavy rain. Similar studies were made with the DISA 55A25 hot-wire probe using the same anemometer. The response of the hot-film probes to salt water immersion was also studied.

The requirements for a suitable instrument are:

(1) D.C. to 10 KHz bandpass.

(2) Probe size smaller than the smallest scale to be measured and probe area minimized to lessen drop impact probabilities.

(3) Ruggedness.

(4) Reliable calibration for amplitude, frequency, and directional responses.

(5) Fast recovery from drop impact or immersion so that minimum record loss occurs.

(6) Portability.

(7) Calibration stability.

(8) Response to drop impact or immersion distinguishable from response to turbulence.

A. THE ANEMOMETER

The DISA 55D05 is a battery-operated constant-temperature anemometer measuring 62 mm × 210 mm × 220 mm with an internal frequency response from D.C. to above 50 KHz when used with DISA probes. Destruction tests have not been performed, but the unit appears sufficiently rugged to meet the requirements. Additional information may be obtained from Zitzewitz Electronic Laboratories.[1]

B. THE DISA 55A25 (0.0002 in TUNGSTEN WIRE) PROBE TESTS

To examine the reaction of the anemometer and hot-wire probe to raindrop impact on the sensing element a six-inch square plexiglass column three feet long was placed vertically beneath a capillary tube supplied by a reservoir through a flexible hose which was clamped to regulate the flow. (See Figure 1.) The probe was mounted on a laboratory stand and the tip containing the wire inserted in the column through a small access port. The purpose of the column was to minimize flow effects allowing the effects of droplet impact to be isolated.

By varying the size of the capillary and the flow rate it was possible to obtain single drop sizes ranging from that of large raindrops (0.5 cm dia.) to that of medium raindrops (0.3 cm dia.) and a heavy shower of very small raindrops or large drizzle drops (0.04 cm dia.). Laboratory data were compared with measurements made from a five foot tower which rests on the roof of the laboratory building and which has unobstructed exposure to raindrops arriving from all directions in winds slower than 20 meters per second during actual rainstorms.

In all cases the signals from the anemometer were displayed on a Tecktronics type 512 oscilloscope and the traces photographed

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[1] 140 Greenwood Avenue, Midland Park, N.J. 07432.

for analysis. Calibration and flow parameters were recorded. The anemometer bridge ratio was 10:1.

The large drops were allowed to drip down the column and the heated wire was slowly moved toward the path that the drops were taking. The wakes of droplets were observed from varying distances at several overheat ratios. Overheat ratio had little effect on the results of wake or impact studies so most of the measurements were made at Rw/Rc = 1.2 to avoid breaking the wire from thermal shock. Figure 2 shows the wake signal of a large droplet passing the probe in the column about one drop diameter away. The signal from a direct large droplet impact is shown in Figure 3.

The high spike in the signal betraying a direct impact has been noted previously by Goldschmidt and Householder[2] and is a desirable characteristic since it can be readily differentiated from atmospheric turbulence as illustrated in Figure 4. The wake sensitivity proved to be a distinct hindrance, however, since in the small droplet shower in the column (no flow) the wakes produced a turbulence-like output. (See Figure 5.) Observations taken during actual storms indicated that with these probes one could not effectively differentiate among small droplet impact, large droplet wakes, and turbulence. For most atmospheric applications one would expect the contributions from the wakes of droplets to the dynamics of the systems being studied to be negligible. The signals from wakes and from small droplet impacts might be expected to mask more dynamically

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[2] Goldschmidt, V.W. and M.K. Householder, Turbulent Diffusion and Impaction of Aerosol Droplets on Fine Wires, Informal Annual Report, NSF Grant GK00324, Purdue University, September 1966.

significant information. These probes are, therefore, unsuitable for the proposed use.

C. IMMERSION TESTS - DISA 55A81 WEDGE-SHAPED HOT-FILM PROBE

To determine the suitability of these hot-film probes for air flow measurements near a water surface on which waves are running and where temporary immersion is probable, three experiments were performed. To obtain the static recovery time of the probe the heated film was dipped into a beaker of brine (salinity 40 ‰ by weight) and quickly withdrawn. The probe was held vertically and there was no air flow. The overheat ratio was 1.1:1. Spikes from droplets running down the probe after withdrawal show clearly in Figure 6. At a smaller angle to the horizontal such droplets were not evident in the static (no flow) tests nor were they a problem when the probe was operated in the wind-wave tank[3] with a 3 m/s air flow over a wave field. Figures 7 and 8 show static and wave tank results respectively.

To determine whether salt encrustation from the brine would affect the calibration of the probe, microscopic observations of the heated element were made as the probe was repeatedly dipped in the salt solution. The amount of contamination, and the resulting change in heat transfer characteristics, were strong functions of probe angle of attack, immersion and drying times, wind speed, and overheat ratio. This makes it very unlikely that any suitable procedure for field

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[3] A detailed description of the wind-wave tunnel is given by R.I. Hires, An Experimental Study of Wind-Wave Interactions, Tech. Rep. 37, Chesapeake Bay Institute, The Johns Hopkins University, May 1968.

calibration could be developed and that factory calibration would be meaningless. Since it is necessary to have reliable calibration in order to take useful measurements it would be unwise to use this sort of probe to attempt to measure turbulence in the air above salt water if there were any significant probability of immersion.

D. THE DISA 55A81 WEDGE-SHAPED HOT-FILM PROBE TESTS IN AIR

The tests described in section B were repeated for the hot-film probes at various overheats from 1.05 to 1.3 and no variations due to changes in the overheat ratio were observed. The results described here and most of the experimental program data were obtained at an overheat greater than 1.1:1 but less than 1.2:1. Additional measurements were made in the wind-wave tank and a "Windex" spray bottle filled with water was used as a source of smaller droplets equivalent to drizzle or fog (0.005 to 0.02 cm dia.).

Figure 9 shows the response of the probe to a single 0.3 cm dia. drop. Figure 10 shows the response of the probe in the small rain and drizzle shower. Each of these was taken in the column with no flow of air. Note that, in contrast to the response of the wire, the small drops cause distinct spiked traces. There is little or no wake effect. Figure 11 shows the signal from the anemometer with the probe located in the center of the wind channel of the wind-wave tank and pointed into a flow of about two meters per second with no "rain." Figure 12 was made in the same flow with Windex spray rain. It is clear that the turbulence signal is undisturbed except by direct impact and that these impacts are easily separable from turbulence in the signal. Even with the higher turbulence level in the wake of a 0.0374 in wire with a flow nearly 3 meters per second and with a very heavy concentration of water drops less than two inches from the nozzle of the sprayer, the drops remain clearly distinguishable. (See Figure 13.)

Figure 14 shows the signal from the probe on the tower during a light breeze with no rain. Figure 15 is a two minute time exposure taken during heavy rain with a light breeze. There is no difficulty distinguishing the raindrop impact from the turbulence. Since each drop obliterates something slightly less than 200 milliseconds of the record, it would be nice to have some estimate of the number of impacts to be expected per unit time in the field. The following simple calculation may help to demonstrate the difficulty of making such estimates. If V is some volume typical of the raindrops in a storm with rainfall rate R and the area of the probe can be taken as A then roughly N = RA/V is the number of impacts per unit time to be expected, on the average, during rainfall at that rate. For a thunderstorm, a suitable value for V might be the volume of the most numerous drops. In a storm whose rainfall rate R = 0.1 cm/min these drops are roughly 0.03 cm in radius.[4] The sensitive area of the probe is $2 \times 10^{-3}\mathrm{cm}^2$. Instead, I will use the collision cross-section in a shower of the above size drops, $A = 13 \times 10^{-3}\mathrm{cm}^2$. Thus N is nearly 10 drops/min. This simple calculation obviously should provide an

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[4] Dingle, A.N. and K.R. Hardy, Raindrop Size Spectra, Quart. Jour. Roy. Met. Soc. 88, 301 (1962).

underestimate yet experimental results during rains with R >> 0.1 cm/min have never indicated more than one impact per minute. Advance estimates in particular situations should therefore be made with extreme caution. Since droplet spectra vary widely and concentrations may range over three decades of drops per unit volume[5], it may even be impossible to make useful feasibility estimates for necessary record salvage percentages in particular cases.

Microscopic examination of the probes used on the tower indicated that no contamination occurred during several runs longer than two hours in city air which is certainly dirtier than that at most field sites. The DISA 55D05 and 55A81 combination would therefore be satisfactory for most field applications if accurate and reliable calibration could be obtained.

E. THE CALIBRATION OF THE WEDGE-SHAPED PROBES

The usual procedure for calibrating a hot-wire probe system is to plot the square of the output voltage against the logarithm of the speed, which one hopes will be a straight line, and using the "quasi-steady" approximation to obtain the dynamic response over a wide frequency range. Because of the large heat capacity of the backing material this method is useless for hot-film probe calibration. In addition, nonlinearities in the heat flux as a function of airspeed and sensor temperature prohibit calibrating coated probes dynamically

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[5] Ibid., also Murgatroyd and Garrod, Observations of Precipitation Elements in Cumulus Clouds, Q.J.R.M.S. 86, 167 (1960) and Singleton, Aircraft Observations of Rain and Drizzle from Layer Clouds, Q.J.R.M.S. 86, 195 (1960).

from alternating current injection at the probe.[6] The difficulty is compounded by the strong temperature sensitivity of the D.C. calibration. This sensitivity caused some difficulty in studying the directional response of the probes because it was impossible to calibrate them at constant temperature in our apparatus. The curve used had to be drawn using the best "engineering estimate" of the correct curve that I could make from the data as taken. (See Figure 16 and below.)

Since reliable field calibration equipment is out of the question for most operations, I enquired about the reliability of factory calibration of the probes. The manufacturer's representatives assured me that complete static and dynamic calibrations accurate to within less than 5 % from D.C. to 60 KHz are available for the entire pressure and temperature range to be expected in field studies. It has been my experience that DISA is quite candid in evaluating their equipment. We have confirmed their factory directional calibrations during this study, and since reliable field checks could be made at considerably less expense of time and money, I believe that factory calibrations could be trusted within the manufacturer's specifications for most meteorological and oceanographic field studies if periodic checks were performed. Since frequency dependent phase shift between the signal and the flow is introduced by the response of the system it is necessary to correct correlation measurements. Correction techniques are available and are discussed in detail elsewhere.[7] For

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[6] DISA Information No. 4, p. 17, December 1966.

[7] See Ibid., p. 3ff for a detailed presentation of these corrections for both hot-wire and hot-film anemometers.

spectral measurements, phase information is unimportant and calibration alone is sufficient.

F. THE DIRECTIONAL RESPONSE OF THE WEDGE-SHAPED PROBES

The probe used during these experiments was not factory calibrated although directional curves were supplied for the 55A81 type, and it was necessary to attempt our own calibration in the large low-turbulence wind tunnel described by Corrsin and Compte-Bellot[8]. The D.C. directional response tests were run at a constant temperature of 79 degrees F but the calibration was, as mentioned on page 8, performed with the temperature fluctuating. The curve shown in Figure 16 was drawn through points having a temperature of 79 degrees, and above those having higher temperatures, to correct roughly for the variation. While the curve may differ slightly from one which would have been drawn through points taken at truly constant temperature, the error should be small and the qualitative results certainly correct.

The wind speed in the tunnel was maintained at 15 meters per second and the yaw and pitch angles of the probe axis with respect to the airstream were varied independently and jointly. The results from the independent variations are described in detail. The results from the joint variation studies merely served to confirm them. The voltage output from the anemometer was recorded and converted to an equivalent or "sensed" velocity. Figure 17 shows the normalized

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[8] Corrsin, S. and G. Compte-Bellot, The Use of a Contraction to Improve the Isotropy of Grid Generated Turbulence, J. Fl. Mech. 25, IV, 657 (1966).

sensed velocity as a function of attitude. The curious response to the pitch at about 30 degrees and the deviation from the cosine law for yaw were both expected from the factory curves. This strange angular response obviously prohibits the effective use of these probes in any application requiring the directional resolution of the velocity field in three dimensions and in particular, three-dimensional spectra cannot be taken with these probes, nor can Reynolds stress measurements be made by direct cross component correlation.

In order to determine the response to isotropic turbulence of moderate intensity superimposed on a flow with a directionally varying local mean flow an experiment was performed in a turbulent jet. The orifice of the jet was six inches in diameter and the probe was placed 32 diameters downstream on the axis of the flow. The stream temperature was 29 degrees C. The mean speed was maintained at 7.3 meters per second. The probe tip position was fixed (except where otherwise noted) and the yaw and pitch angles were varied independently as before. Previous experience with this jet indicates that the flow is locally isotropic and that the turbulent intensity is greater than 20 %.[9] The signal from the anemometer was passed through a bandpass filter to a true RMS meter whose reading was recorded as a function of orientation and frequency. The results are plotted in Figure 18. It appears that if the deviation of the direction of the local mean flow is less than 30 degrees from the axis of the probe in any direction there will be no sensible change in the response.

In locally isotropic turbulence, therefore, it might be possible

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[9] Stanley Corrsin, private communication.

to obtain one-dimensional spectra at wave numbers sufficiently large that the filtered RMS fluctuations are not comparable with the local mean speed if the direction of the mean velocity varies less than 30 degrees from the probe axis. In the atmosphere these conditions are compatible because we expect local isotropy at large wave numbers where the energy content is small.[10]

G. RECOMMENDATIONS FOR A CONTINUED EXPERIMENTAL PROGRAM

While it appears that the probes tested will allow improved techniques for studies of the atmospheric dissipation range, better directional response could be obtained if a cylindrical probe could be found which would meet the criteria set out at the beginning of this paper. DISA has developed a coated hot-wire probe which might have the desired characteristics. I recommend repetition of the test sequence for these probes in the hope that they will provide the means of making full three-dimensional measurements over the entire spectral range rather than the one-dimensional spectra in regions of local isotropy to which we are presently restricted.

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[10] See the discussion in part II, The Structure of Atmospheric Turbulence, by J.L. Lumley and H.A. Panofsky. New York: Interscience, 1964.

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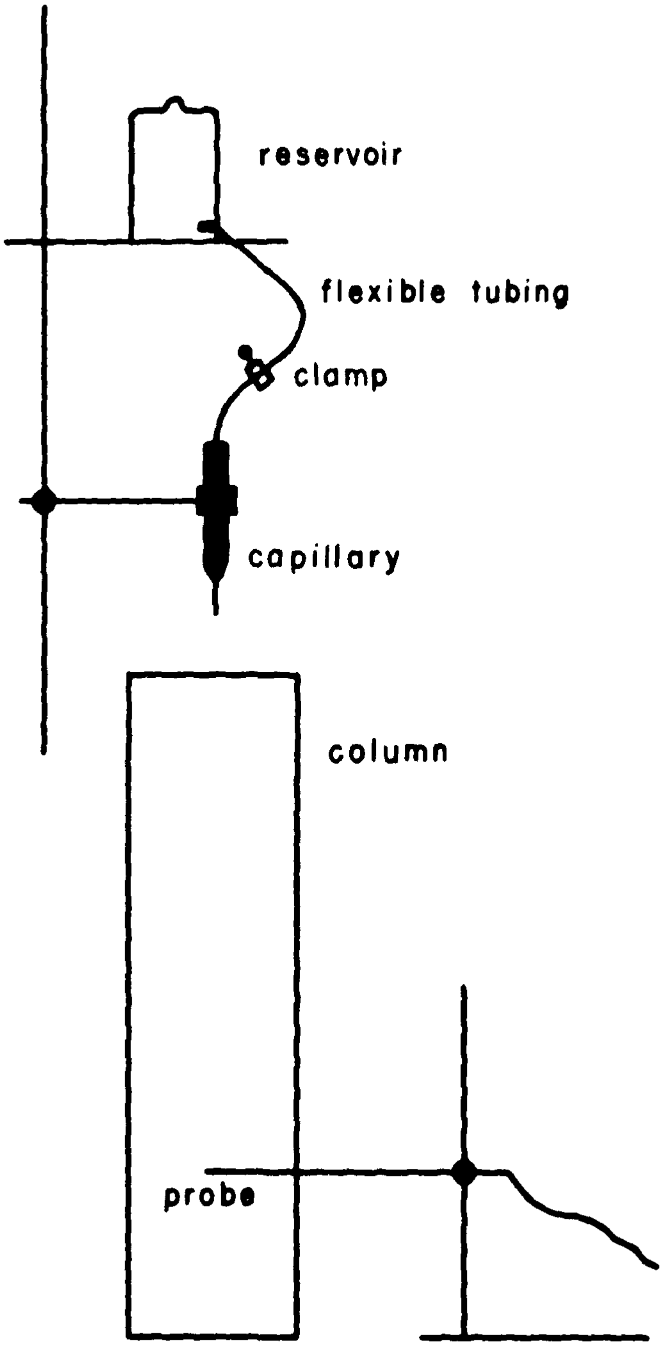

Figure 1. Schematic Diagram of the Test Column.

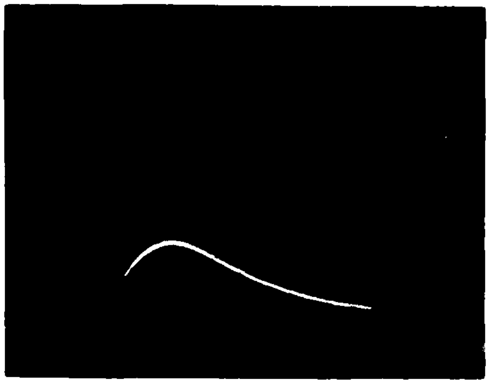

Figure 2
Calibration signal: 20 millivolts
peak to peak
Trace length: 50 milliseconds

Figure 3
Calibration signal: 1.0 volts
peak to peak
Trace length: 50 milliseconds

Figure 4
Calibration signal: 50 millivolts
peak to peak
Trace length: 180 milliseconds

Figure 5
Calibration signal: 20 millivolts
peak to peak
Trace length: 1.0 seconds

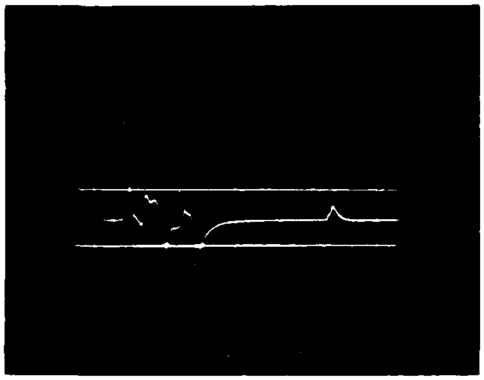

Figure 6
Calibration signal: 1.5 volts
peak to peak
Trace length: 3.0 seconds

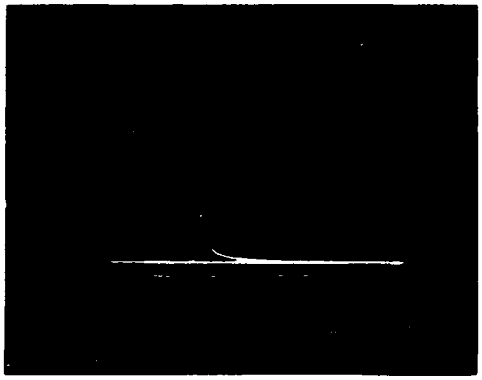

Figure 7
Calibration signal: 1.5 volts
peak to peak
Trace length: 3.0 seconds

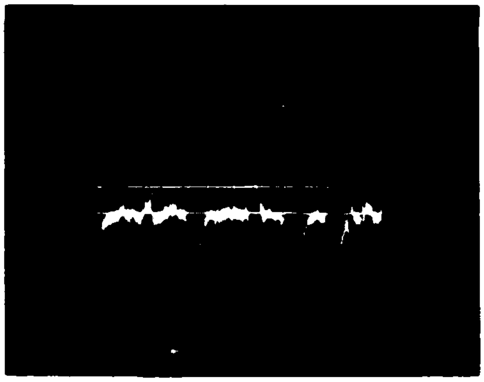

Figure
Calibration signal: 100 millivolts
peak to peak
Trace length: 5.0 seconds

Figure 9
Calibration signal: 1.0 volts
peak to peak
Trace length: 100 milliseconds

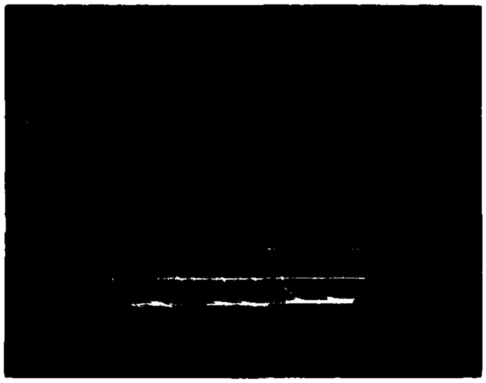

Figure 10
Calibration signal: 1.0 volts
peak to peak
Trace length: 100 milliseconds

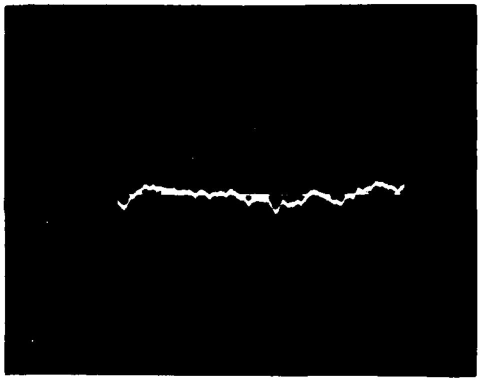

Figure 11
Calibration signal: 50 millivolts
peak to peak
Trace length: 200 milliseconds

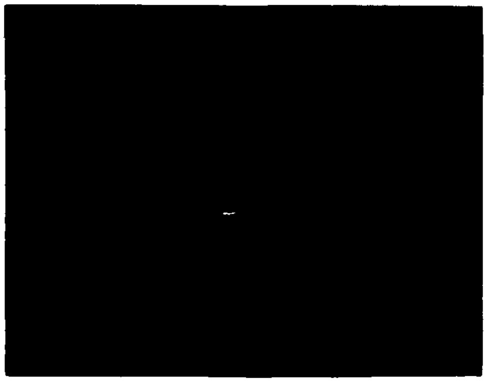

Figure 12
Calibration signal: 100 millivolts
peak to peak
Trace length: 1.0 seconds

Figure 13
Calibration signal: 100 millivolts
peak to peak
Trace length: 1.0 seconds

Figure 14
Calibration signal: 50 millivolts
peak to peak
Trace length: 2.0 seconds

Figure 15
Calibration signal: 50 millivolts
peak to peak
Trace length: 2 seconds, 60
consecutive traces

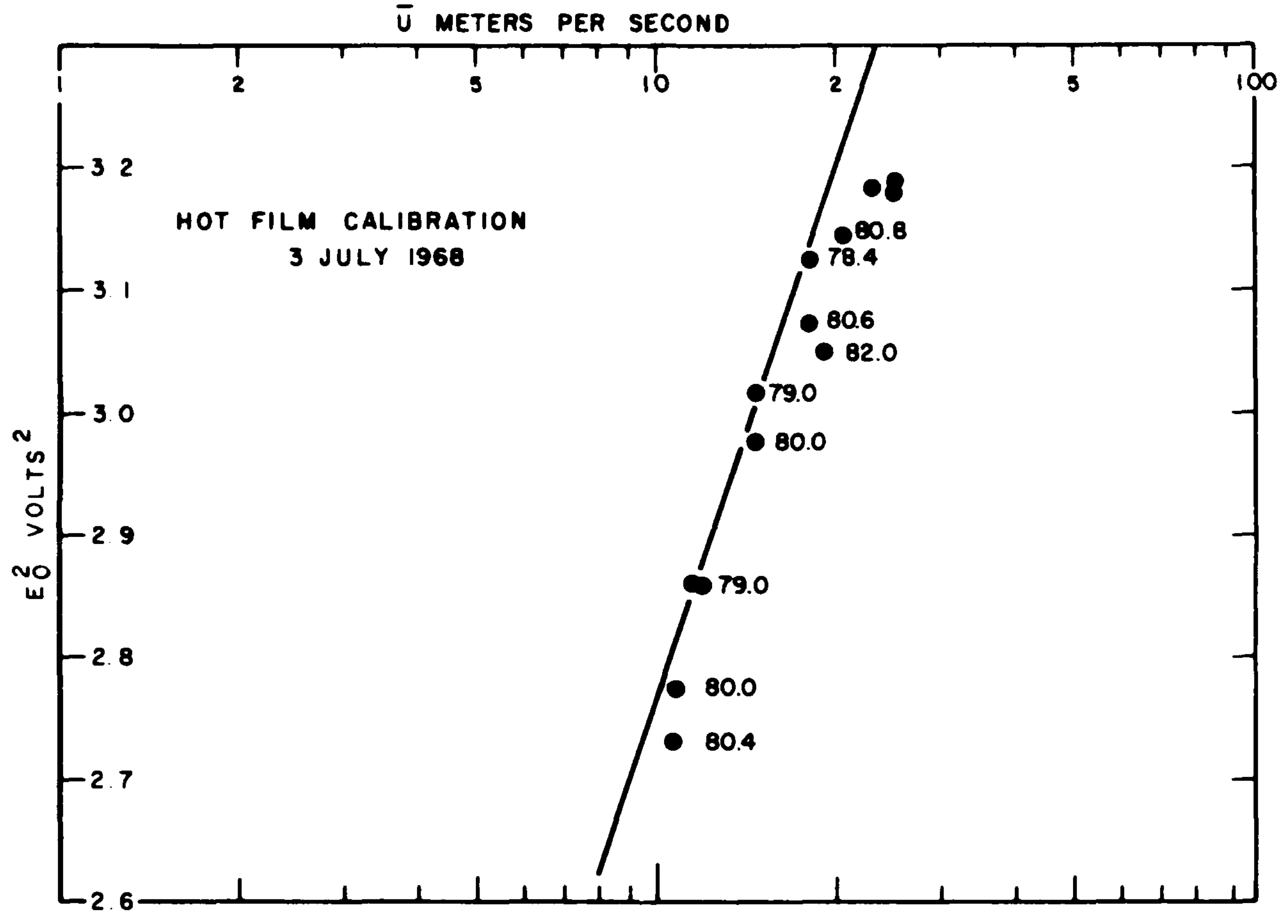

Figure 16. Calibration Curve for the Wedge-Shaped Hot-Film Probe.

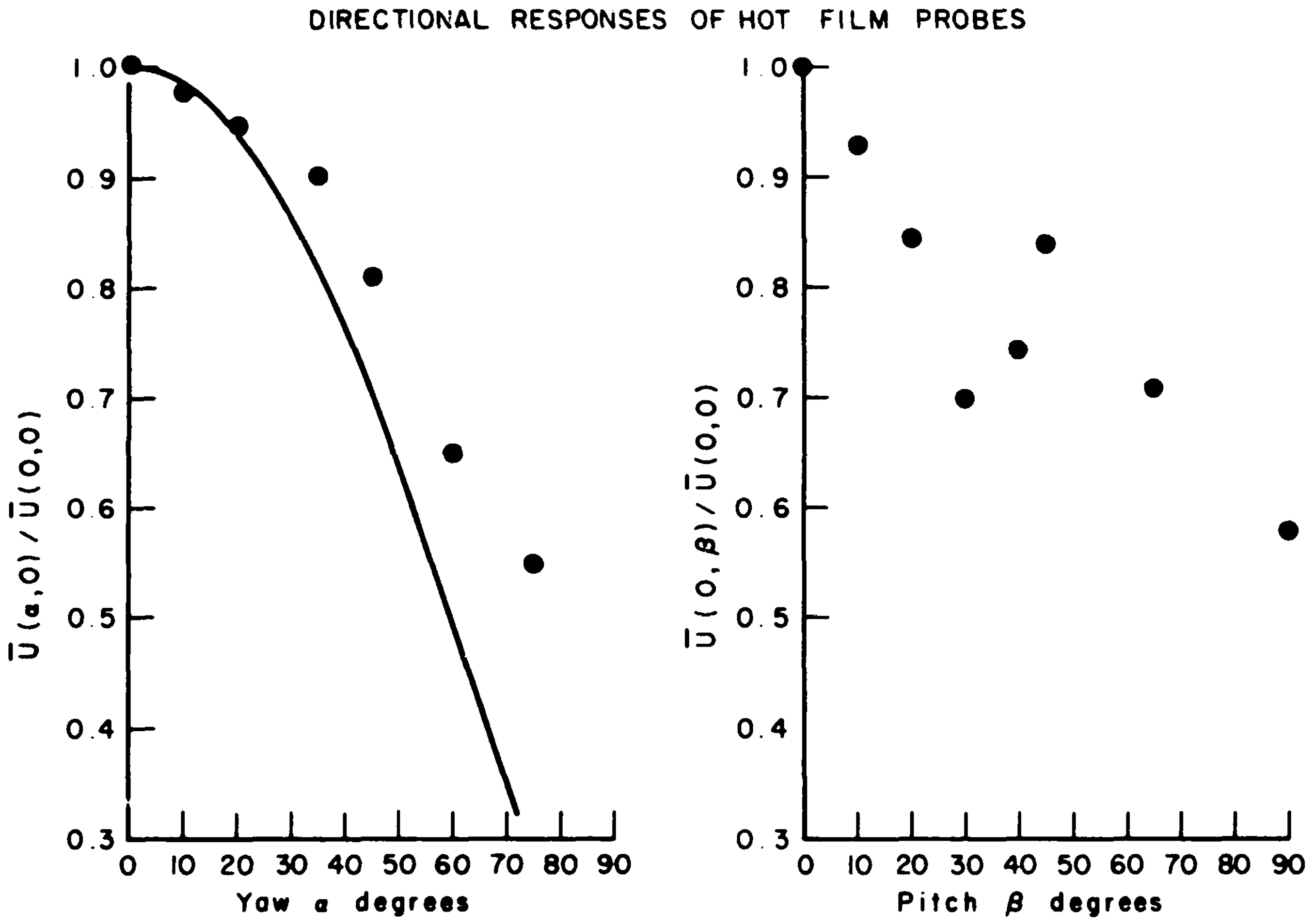

Figure 17. Directional Responses of Hot-Film Probes: Yaw and Pitch.

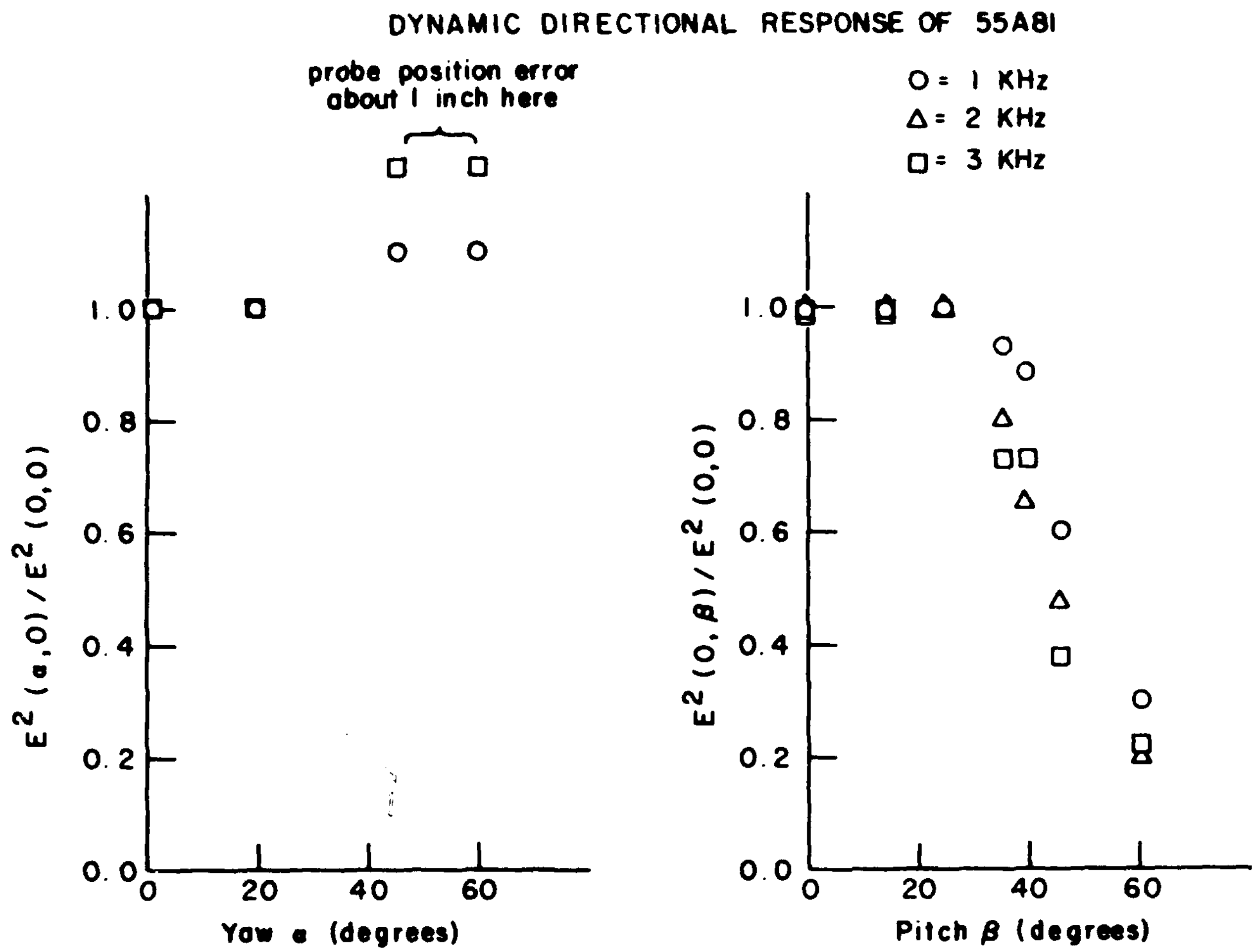

Figure 18. Dynamic Directional Responses of the DISA 55A81 Probe: Yaw and Pitch.

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13. ABSTRACT

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