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APPARATUS FOR ATMOSPHERIC BOUNDARY LAYER MEASUREMENTS OVER WAVES

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Apparatus for Atmospheric Boundary Layer Measurements over Waves

by

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MANAGEMENT PERSPECTIVE

The interchange of energy and matter across the air-water interface plays a key rôle in the dynamics of lake (or ocean) and atmospheric circulations and in the fate of pollutants. This paper describes an apparatus devised to explore the turbulent characteristics of the near surface boundary layer over a water surface. The analysis and interpretation of the data gathered by this apparatus is expected to improve our understanding of the properties and mechanics of the air-water interface.

Dr. J. Lawrence
Director
Research and Applications Branch

PERSPECTIVES DE GESTION

L'échange d'énergie et de matière à travers l'interface air-eau joue un rôle clé dans la dynamique de la circulation dans les lacs (ou les océans) et dans l'atmosphère ainsi que dans le sort des polluants. La présente communication décrit un appareil conçu en vue d'étudier les caractéristiques de turbulence de la couche limite près de la surface au-dessus d'une surface d'eau. On prévoit que l'analyse et l'interprétation des données collectées par cet appareil nous permettront de mieux comprendre les propriétés et la mécanique de l'interface air-eau.

J. Lawrence
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ABSTRACT

This paper describes an apparatus developed for measuring simultaneously, water elevation and static and dynamic pressure, momentum and heat fluxes above waves close to the interface. The apparatus was used successfully at the Lake Ontario wave research tower of the Canada Centre for Inland Waters. The principle and purpose of the various sensors used, calibration procedures and data gathering processes are described. Simultaneous measurements of the atmospheric boundary layer's physical quantities are presented. All the quantities necessary to close the kinetic energy budget in the atmosphere surface layer have been measured.

RÉSUMÉ

La présente communication décrit un appareil mis au point en vue de mesurer simultanément la hauteur, la pression statique et la pression dynamique de l'eau, la quantité de mouvement et le flux thermique au-dessus de vagues à proximité de l'interface. L'appareil a été utilisé avec succès à la tour de recherche sur les vagues du lac Ontario du Centre canadien des eaux intérieures. Le principe et le rôle des différents capteurs utilisés, les méthodes d'étalonnage ainsi que les méthodes de collecte des données sont décrits. Des mesures simultanées des grandeurs physiques de la couche limite de l'atmosphère sont présentées. Toutes les grandeurs physiques requises pour compléter le bilan d'énergie cinétique de la couche de surface de l'atmosphère ont été mesurées.

1. INTRODUCTION

Measurements of flow properties in the atmospheric boundary layer over natural wind-generated waves have been made with varying degrees of accuracy over the last few decades. Generally speaking such measurements have been motivated by one of three goals: (i) estimation of interfacial fluxes of momentum, heat and mass; (ii) exploration of the rate of wave-generation by wind; (iii) investigation of the transmission of electromagnetic radiation in the turbulent near surface layer. The apparatus that is the subject of this work was devised in order to realize the first two of these goals.

Among the many different methods of estimating the interfacial fluxes is the so-called inertial dissipation technique (Fairall and Larsen, 1986). This method, based on the kinetic energy budget, is particularly easy to apply at sea since it is not very susceptible to platform motion. The accuracy of the method hinges on several assumptions regarding the relative sizes of the various terms in the kinetic energy equation. In the near surface boundary layer, under steady and homogeneous conditions, the kinetic energy equation reduces to (Fairall and Larsen, 1986):

$$-\langle uw\rangle\frac{\partial U}{\partial z}+g\frac{\langle\theta w\rangle}{\Theta}-\frac{\partial\langle ew\rangle}{\partial z}-\frac{1}{\rho}\frac{\partial\langle pw\rangle}{\partial z}=\epsilon_e \qquad (1)$$

where u, w are the downstream and vertical velocity components, θ the temperature (°K), e the kinetic energy, p the pressure, ϵ_e the kinetic energy dissipation rate, g the acceleration due to gravity and z the vertical coordinate (positive upwards). Upper case letters denote the mean and lower case, deviations from the mean.

The first two terms are the production of kinetic energy by mechanical shear and buoyancy respectively. Under stable conditions the buoyancy term is negative i.e. a sink for turbulent energy. These terms involve the fluxes of momentum $\langle uw \rangle$ and heat $\langle \theta w \rangle$ and their estimation is a principal goal of air-sea interaction research. Terms three and four are "transport" or vertical flux divergence terms for turbulent kinetic energy and pressure. The last term is the rate of dissipation (to heat) of turbulent kinetic energy.

A similar budget for temperature variance also includes the term $\langle \theta w \rangle$, this time in the form of a heat production term.

$$-\langle \theta w \rangle \left[\frac{\partial \Theta}{\partial z} + \gamma \right] - \frac{1}{2} \frac{\partial \langle \theta^2 w \rangle}{\partial z} + S_\theta = \epsilon_\theta \qquad (2)$$

where γ is the adiabatic lapse rate, ϵ_θ the rate of dissipation of temperature variance and S_θ the radiative flux divergence term.

The first term is the production of temperature variance $\langle \theta^2 \rangle$; the second is the "transport" or vertical flux divergence of θ^2 stuff; S_θ is the radiative transfer term, which is generally negligible at usual measurement heights over waves.

To date no comprehensive attempt to establish the relative importance of the terms in these budgets has been made over water. Direct estimates of the production terms require simultaneous measurement of fluxes and gradients. Very few experiments in which these have been made over water have been published and it is customary to deduce the production terms from measured fluxes using flux-gradient relations Φ_u, Φ_θ derived from data over land:

$$-\langle uw \rangle \frac{\partial U}{\partial z} = \frac{u_*^3}{\kappa z} \Phi_u(\zeta) \qquad (3a)$$

$$-\langle\theta w\rangle\left[\frac{\partial\Theta}{\partial z}+\gamma\right]=\frac{u_*\theta_*^2}{\kappa z}\Phi_\theta(\zeta) \qquad (3b)$$

where κ = von Karman's constant, $u_*=\langle -uw\rangle^{\frac{1}{2}}$ and $\theta_* = -\langle\theta w\rangle/u_*$ are scaling velocity and temperature respectively and $\zeta=Z/L$ is the Monin-Obukhov (1954) stability index.

$$\zeta=\frac{z}{L}=-\frac{zg\kappa\langle\theta w\rangle}{u_*^3\Theta} \qquad (4)$$

The non-dimensional gradients ϕ are assumed to be universal functions of ζ only and, indeed, over land there is substantial experimental support for this (e.g. Businger et al.,1971). In the marine boundary layer the surface characteristics are not prescribed but vary with the development of the waves. Alterations in profile shapes during wave development have been predicted by Stewart (1961) and observed by Merzi and Graf (1985). It may well be that estimates of the shear production term based on land-derived $\Phi_u(\zeta)$ are erroneous over growing or decaying waves. Similar objections to current methods of estimating the production term for θ^2 stuff (equation 3b) may be made. Here the principal differences from boundary layers over land have to do with the unlimited supply of moisture, the bursting of bubbles at the surface and the evaporation of airborne droplets.

The transport terms have also received scant attention. In particular the pressure transport term has never been directly measured in geophysical boundary layers. McBean and Elliott (1975) measured <pw> at one height (5.77m) over prairie grassland, but the divergence $\frac{\partial \langle pw \rangle}{\partial z}$ has not been measured and even <pw> has not been reported over water.

The dissipation terms ϵ_θ and ϵ_θ have been explored and various estimates have been gathered based on the assumption of local isotropy (Champagne et al., 1971):

$$\epsilon_u = 15\nu < \left(\frac{\partial u}{\partial x}\right)^2 > = \frac{15\nu}{U^2} < \left(\frac{\partial u}{\partial t}\right)^2 > B_u \qquad (5a)$$

$$\epsilon_\theta = 3\kappa_\theta < \left(\frac{\partial \theta}{\partial x}\right)^2 > = \frac{3\kappa_\theta}{U^2} < \left(\frac{\partial \theta}{\partial t}\right)^2 > B_\theta \qquad (5b)$$

where ν is the kinematic viscosity, κ_θ the thermal diffusivity and B_u, B_θ (Wyngaard and Clifford, 1977) are corrections to Taylor's "frozen turbulence" hypothesis $\left(\frac{\partial}{\partial x} = \frac{1}{U}\frac{\partial}{\partial t}\right)$.

Estimates of ϵ based on equation 5 are called "direct dissipation" estimates. They place substantial demands on instrument response and recorder capacity and are consequently rare. Instead ϵ_θ and ϵ_θ are usually estimated from the level of the inertial sub-range of the spectrum of downwind velocity fluctuations $[S_{uu}(f)]$ or temperature fluctuations $[S_{\theta\theta}(f)]$ respectively using the Kolmogorov concept of local isotropic turbulence

$$\epsilon_u = \frac{2\pi}{U}\left(\alpha_u^{-1} f^{5/3} S_{uu}(f)\right)^{3/2} \qquad (6a)$$

$$\epsilon_\theta = \frac{1}{\alpha_\theta}\left(\frac{2\pi}{U}\right)^{2/3} \epsilon_a^{1/3} f^{5/3} S_{\theta\theta}(f) \qquad (6b)$$

where α_u and α_θ are the empirical Kolmogorov constants. These have been measured by various authors (see review by Dyer and Hicks, 1982) but an uncertainty of about 20% remains. Nonetheless equation 6 is commonly used to obtain "inertial-dissipation" estimates for ϵ_a and ϵ_θ from the spectra $S_{uu}(f)$ and $S_{\theta\theta}(f)$ in the range of frequencies between 1 and 10 Hz.

In spite of all these unproven assumptions and untested hypotheses (particularly over developing waves) regarding the balance of terms in the budgets of kinetic energy and temperature variance, it is becoming increasingly popular to estimate the fluxes of momentum and heat from the spectral estimates of downwind velocity and temperature. The principal advantage of this "dissipation" method of flux estimation is that it can be readily applied on a moving platform such as a ship or buoy.

In order to attempt to establish the individual terms in the budgets of kinetic energy and temperature variance over water, an apparatus was constructed to support the simultaneous measurement of all the terms of equation 1 and all but one of the terms of equation 2. Furthermore, the correlation of surface slope and pressure (extrapolated to the surface) yield information on the rate of amplification or attentuation of waves by wind. This paper describes the apparatus and the testing and calibration of the instruments where these differ from standard methods. Finally, a few examples of the sort of data collected are shown for illustration. The detailed budgets are analyzed and presented in a companion paper (Donelan et al., 1990).

2. DESCRIPTION OF THE APPARATUS.

In 1976 the Canada Centre for Inland Waters (CCIW) installed a tower (Fig.1) near the western end of Lake Ontario in support of air-water interaction studies (Donelan et al., 1985). The tower stands in 12m of water and is firmly fixed to the bottom by means of piles driven through its 40 cm diameter cylindrical legs. The space between piles and legs was filled with grout under pressure making the structure very stiff --- natural frequency of 1.54Hz (Roy and Der, 1978). The superstructure of the tower was designed to minimize disturbance to both wind and waves.

Wave heights at the tower have been measured in excess of 6m in strong easterly (long fetch) winds, whereas heights of less than 1 metre are typical in strong westerly (1.1km fetch) blows. In order to accommodate near surface measurements of the terms of the turbulent budgets (equations 1 and 2), the support structure for the probes was designed to move 4m along a track parallel to the northeast leg of the tower; i.e., at 10° to the vertical (Fig. 1). The support structure and its instruments --- collectively termed "the wind profiler" --- could be positioned relative to the surface by computer control from a trailer 1.2 km away on the western shore. The northeast leg is actually at a bearing of 25° from tower centre so that the wind profiler, being 2.5m outboard of the leg, commanded an unobstructed view of winds from 250° through north to 160°. The profiler (Fig.2) was 2.5m in height and rotated about a vertical axis in response to wind pressure on a vane. To avoid rapid rotation, and its attendant acceleration, the rate of rotation was damped using a pair of closely-spaced concentric cylinders immersed in silicone oil (Fig.3). In a light (3 m/s) wind its rotational response time constant was about 30 seconds.

The wind profiler supported three levels of wind speed and pressure sensors spaced 1m apart vertically (Fig.2 and 3).

The wind speed sensors were commercial (Airflow Developments) Pitot tubes of 4mm and 1.5mm outside and inside diameters. The differential dynamic pressure signals were sensed by capacitance pressure transducers (MKS Baratron, model 223 AH) of full scale 1 Torr corresponding to a maximum wind speed of about 15 m/s. Regular checks of the zero offset were obtained by covering the Pitot tubes with slightly oversized blind tygon tubes.

The actual pressure was sensed by disc-shaped probes of a design due to Elliott (1972). The rejection of dynamic pressure depends on the disk shape especially near the ports, which are in the centre of each side of the 4cm diameter disk (Fig.4a). The pressure signals from opposite sides of the disk are transmitted via independent paths for a distance of 7cm, after which a common tube carries the combined signal to one side of a capacitance pressure transducer (MKS Baraton, Model 223 AH; full scale ± 1 Torr or 1mm Hg). The pressure signal is also delivered to the resistance port of an RC pneumatic filter. The output of the filter is connected to the other port of the differential pressure transducer. The RC pneumatic filter consists of a 76cm length of 0.4mm I.D. hypodermic tubing (resistance) in an insulated volume (capacitance) of 179cc (Fig.4b). Calculations and step function tests indicate that the time constants for pressure and temperature changes are respectively 38 seconds and 2140 seconds, so that the system functions as a very effective high pass filter for pressure fluctuations and that temperature variations do not contaminate the signal in the pass band of interest (0.01 Hz to 10 Hz). The actual pressure response of the system is determined by careful dynamic calibration (§3).The disk (Fig.4a) was turned from a single piece of stainless steel and its internal plumbing was produced by electric discharge machining. The precise construction methods helped ensure the disk's insensitivity to angle of attack variations of up to ± 8° from the plane of the disk. The vane orients the disks into the wind so that these angles of attack are not exceeded. Symmetry ensures complete rejection of angles of attack variations in the (vertical) plane of the disk of up to ± 120°.

The differential pressures are small (typically $<$ 1 Torr) and the contamination of the orifices in the probes by spray or rain droplets completely invalidates the measurement. Thus a system of back purging of the probe/transducer pneumatic paths was devised. A three-way solenoid valve was included in each pressure probe/transducer pneumatic circuit. When energized a path was open to the pressure transducer from the probe. When de-energized the transducer path closed and dry nitrogen at 3 to 5 psi was applied to the probes to expel moisture. This purging was initiated by computer control from shore and operated on each of the nine paths (2 for each Pitot probe and 1 for each Elliott probe) in turn. This ensured the clearing of each path.

Thermal anemometry/thermometry techniques were used to obtain horizontal and vertical turbulent velocity components and temperature just above the bottom level of actual and dynamic pressure sensors (Fig.5). The velocity components were sensed by an X-film anemometer and temperature by a 1.5 micron platinum wire (Thermal Systems Inc.). In order to maintain the calibrations of these delicate and fast-response thermal probes, a pneumatically actuated shield was withdrawn from the probe only during recordings.

Finally, a capacitance wave wire was attached to the bottom of the wind profiler. Eight meters below the surface the wire passed through an eye and was then attached to a 12kg weight, so that its tension was kept constant whatever the position of the profiler. Thus, this wave staff provided information both on the instantaneous surface elevation and on the mean position of the wind profiler above the surface.

The instruments on the wind profiler were supplemented with measurements of mean water temperature and atmospheric mean and turbulence parameters at the top of the tower, i.e. at a distance of 11m to 12m above mean water level - the variation being due to variations in the lake level. These instruments include: a Gill anemometer-bivane (R.M.Young Co.) yielding all 3 components of the wind vector with distance constants of about 1.3 metres; a small thermistor bead thermometer (time constant of about 0.5 seconds) suspended between the double parallel plates of a simple radiation shield; and a "Humicap" (Vaisala Co.) capacitance relative humidity sensor with a cintered brass protective filter (time constant of about 2 seconds). Thus, the fluxes of momentum, sensible heat and moisture could be estimated from the fixed instruments at the standard height of 10m or so. In addition the instruments provided an extension of the profiles which were obtained from the wind profiler alone.

All systems were sampled at 20Hz after appropriate Bessel (linear phase shift) filtering. Much higher frequencies are required to estimate the dissipation directly (equation 5a) and to this end the X-film signals were recorded in FM mode on two channels of a Hewlett Packard 4-track analog recorder (model 3960) running at 15/16 inches per second. This yielded a bandwidth of 0 to 312 Hz. The differentiated signals were also recorded in Direct mode on the other tracks. This yielded a bandwidth of 50 Hz to 3.75 KHz. Since the highly non-linear bridge output of the anemometer was used the high and low frequency information need to be combined to yield the velocity structure over the entire range of energy containing scales through the dissipation range to the viscous cut-off.

Fig.6 illustrates a short run from a typical time series. The 15 individual sensed variables are graphed minus their means and normalized by their standard deviations. Each time series is allocated 5 standard deviations. The heights of the sensor and means and standard deviations of each sensed variable are listed to the right of the figure. The signs of all the variables follow the usual conventions except the actual pressure signals which are inverted to emphasize their coherence with the surface elevation. The shift of the pressure maximum from the wave troughs is small. However it is just this small shift (usually less than 20°) that provides the wave generating force. Although actual pressure was sensed simultaneously at three separate heights to allow examination of the phase changes in wave-induced pressure with height, vertical velocity was sensed only at the lowest height on the wind profiler. The vertical gradient of the $\langle pw \rangle$ term was therefore obtained by making successive 30 minute measurements of $\langle pw \rangle$ at several heights by moving the wind profiler.

The vertical velocity from the X-film anemometer near the surface and the bivane at 11 m illustrate the characteristic red shift of variance with height. The five horizontal velocity signals show a similar but much weaker tendency. A similar red shift in energetic scales is noted in the temperature traces. Finally the relative humidity and wind direction are shown at the top.

3. CALIBRATION

The capacitance wave staff was calibrated in the laboratory and checked on the tower by raising and lowering it through measured distances with respect to a calm surface. Static calibrations of all six MKS pressure transducers were achieved with a modified Chattock gauge. The X-film anemometer was calibrated in a wind tunnel of cross-section 27cm x 11.5cm and capable of centreline speeds up to 11 m/s. The sensitivity to angle of attack was checked in 5° steps. Temperature sensors were calibrated in precisely controlled temperature baths traceable to national standards at the National Research Council of Canada. The relative humidity sensor was calibrated in a controlled humidity chamber. Finally the bivane's anemometer was calibrated by towing the bivane in still air using the 100m long towing carriage current meter calibration facility. The maximum speed of the carriage was 6 m/s so that the method is only suitable for linear sensors.

Many of the sensors respond sufficiently quickly that their phase and amplitude characteristics are flat at the frequencies of interest here (0 to 10 Hz). The X-film anemometer was recorded in analog form up to 3.75 KHz but its frequency cut-off is still well above this. On the wind profiler only the Pitot tubes and Elliott pressure sensors introduce appreciable phase and amplitude response variation in the passband (0 to 10 Hz). The high frequency roll-off is affected by the displacement volume of the MKS transducers (about 1.3 cc) and the resistance to air flow through the probe and associated tubing. For the Elliott probes the low frequency roll-off is determined by the pneumatic filter. In order to match response as closely as possible each transducer/probe pair was fitted with the same length of tubing. All the transducers, pneumatic filters, and excess tubing were housed in the flat box upstream of the vane in the top half of the wind profiler (Fig.2).

The amplitude and phase responses (dynamic calibration) of the Pitot tubes and Elliott actual pressure sensors were obtained by placing each probe in turn in a closed chamber which could be subjected to oscillating pressure.

In previous dynamic calibrations the oscillating pressure was generated mechanically. Young (1984) used a modified bicycle pump by replacing the pump bucket with a piston to provide oscillating pressure signals. Papadimitrakis (1982) and Snyder et al. (1974) generated the pressure signal by the reciprocal motion of a piston-cylinder assembly. Finally, Elliott (1972) generated a sinusoidally varying pressure by oscillating a latex rubber diaphragm stretched over one end of a cylindrical pressure chamber. All these techniques, involving mechanical linkages for generation of pressure signals, have some disadvantages such as nonlinear effects of the system, air leakage around the piston, and presence of vibrations.

In order to overcome the shortcomings of the previous techniques, in the present technique the pressure signals were generated in a pressure chamber by a radio speaker driven by an amplifier connected to a signal generator. The cylindrical pressure chamber was 31cm long with a 7.6cm inner diameter. The chamber was filled with steel wool, the heat capacity of which ensures an isothermal change of pressure, Snyder et al.

(1974). A radio speaker was placed at one end of the cylinder. The inner surface of the speaker was covered with Elmer rubber glue and Saran wrap was placed on it when it was still wet, providing a nearly perfect and flexible seal of the cardboard diaphragm. The other end of the cylindrical chamber had a screen to keep the steel wool from obscuring the probe orifices and a cylindrical cap was fitted to the chamber with an O-ring seal. This cap had two openings for directly attaching pressure transducers to the chamber as well as a third opening designed to accept the Elliott and Pitot tubes in their field configuration. The pressure probes were connected to the pressure transducers by a 2m long and 1.6mm inside diameter stiff wall tubing.

The schematic of the experimental apparatus is shown in Fig.7. A Wavetek signal generator and a frequency counter were used to provide signals at different frequencies. A Neff DC amplifier was used to amplify the signal and drive the radio speaker and a six channel Brush recorder monitored the signals. A computer system comprising a PDP 11/40 and an A/D converter was used for digitization and processing of the signals.

The frequency range of interest covers three decades from 0.01 to 10 Hz. Nineteen frequencies, six to seven in each decade, were used with an amplitude of approximately 0.1 Torr. The digitized time series were the input sinusoidal signal (voltage applied to the speaker) and the three output signals from the pressure transducers: (i) the probe-tubing-transducer (MKS Baratron) system as used in the field; (ii) another identical MKS Baratron transducer connected via a short (30 cm) 6mm I.D. tygon tube; (iii) a much faster response, but less sensitive, transducer (Validyne model DP45 - a variable reluctance type). The response of these transducers to an input square wave form is shown in Fig.8. Since the response of the speaker is not precisely known we have used the fast response Validyne as a reference. Independent tests show its response to be flat to 100 Hz.

The sampling rate was selected to yield an integer number of cycles (3 to 10) in 2^{10} samples and an FFT algorithm was employed to deduce the spectral estimates and the phase and amplitude ratio.

Fig.9 shows the results of the pre-and-post-calibration at 20°C as well as the post-calibration at 4°C for the Elliott probe installed at the lowest level on the wind profiler. This temperature range covers the ambient temperature range of the field data. The agreement is very satisfactory overall (± 2° in phase and ± 4% in amplitude) and in the range relevant to wave generation and decay in these data (0.1 Hz to 2 Hz) the phases of the calibrations are within ± 1° of each other. Thus both time and temperature stability are adequate to the tasks at hand. The calibrations were applied in the form of a 5th order polynomial in the logarithm of frequency against amplitude ratio and phase. All calibration points (pre and post at both temperatures) were included in computing the least squares regression coefficients of the polynomials.

4. <u>SUMMARY</u>

An apparatus has been devised to enable a frontal attack on the resolution of two long-standing issues in air-sea interaction, viz. (i) balancing the atmospheric boundary layer budgets of kinetic energy and θ^2 stuff, (ii) measuring the direct amplification or attenuation of waves over a wide range of wave development. We have described the design criteria, experimental method and special calibration procedures that are a necessary part of the struggle to improve the data quality significantly and thus allow a clear statement to be made about these questions. The results of the analysis of our extensive data set will be reported on elsewhere.

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LIST OF FIGURES

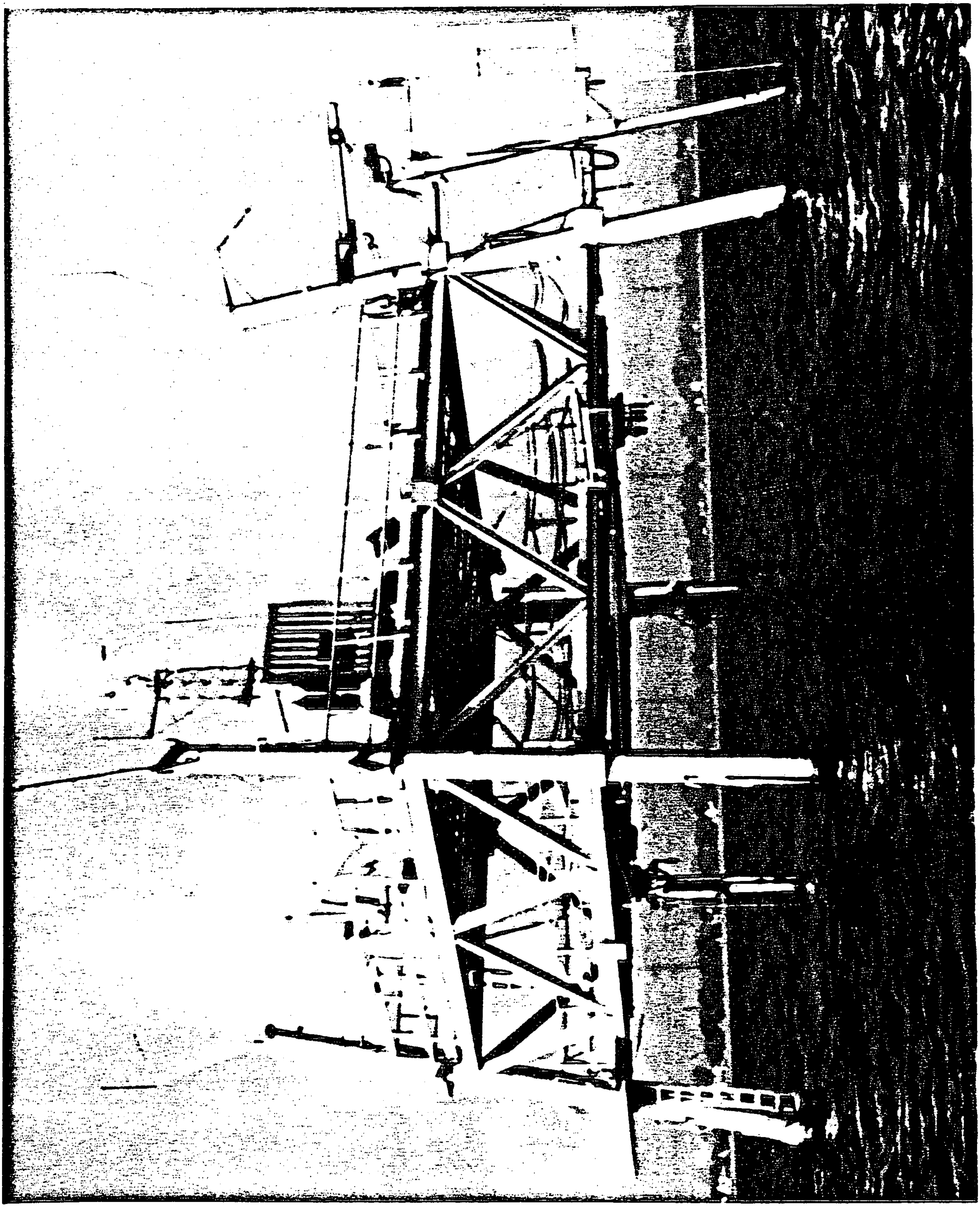


Fig.1

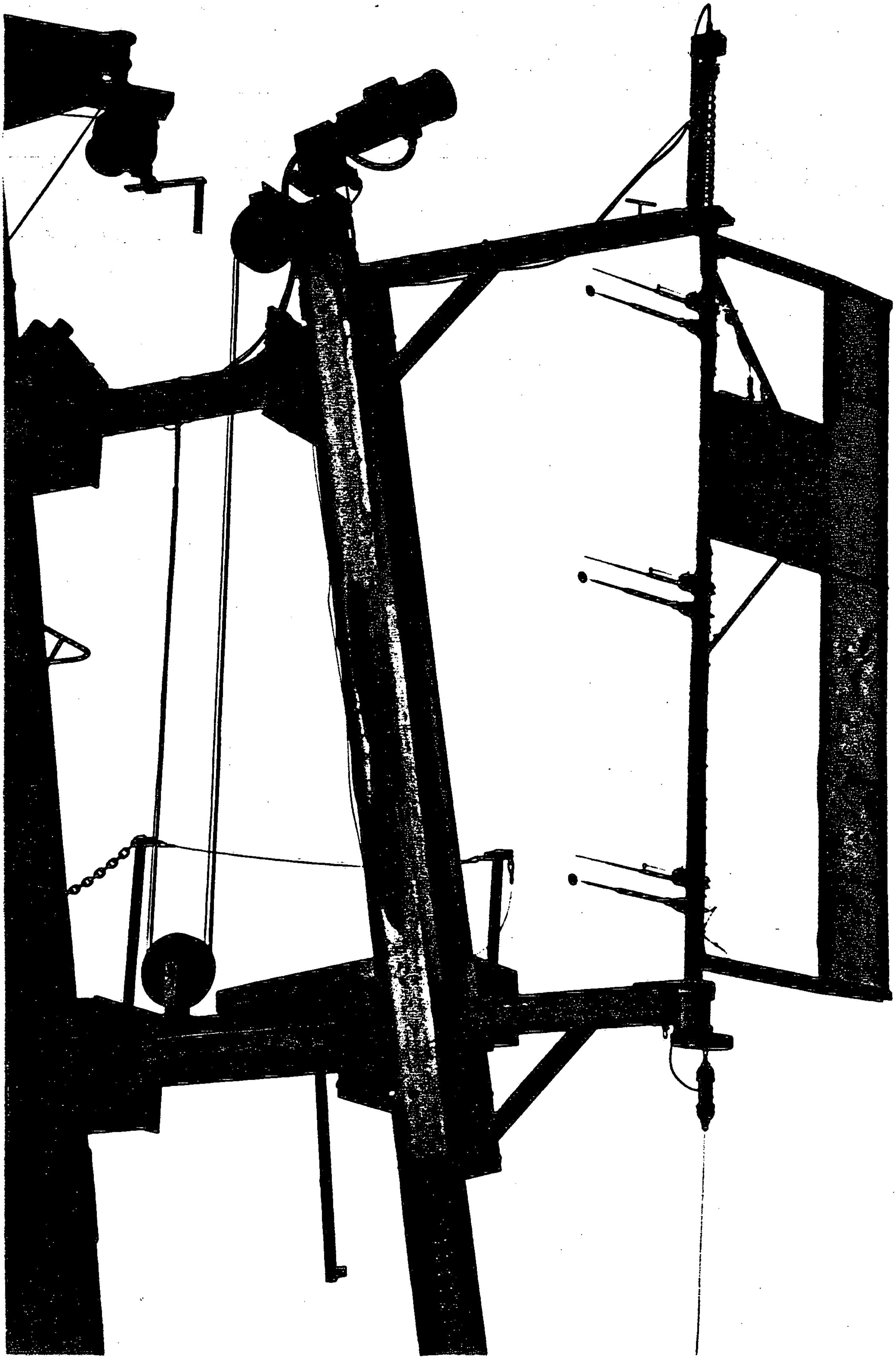
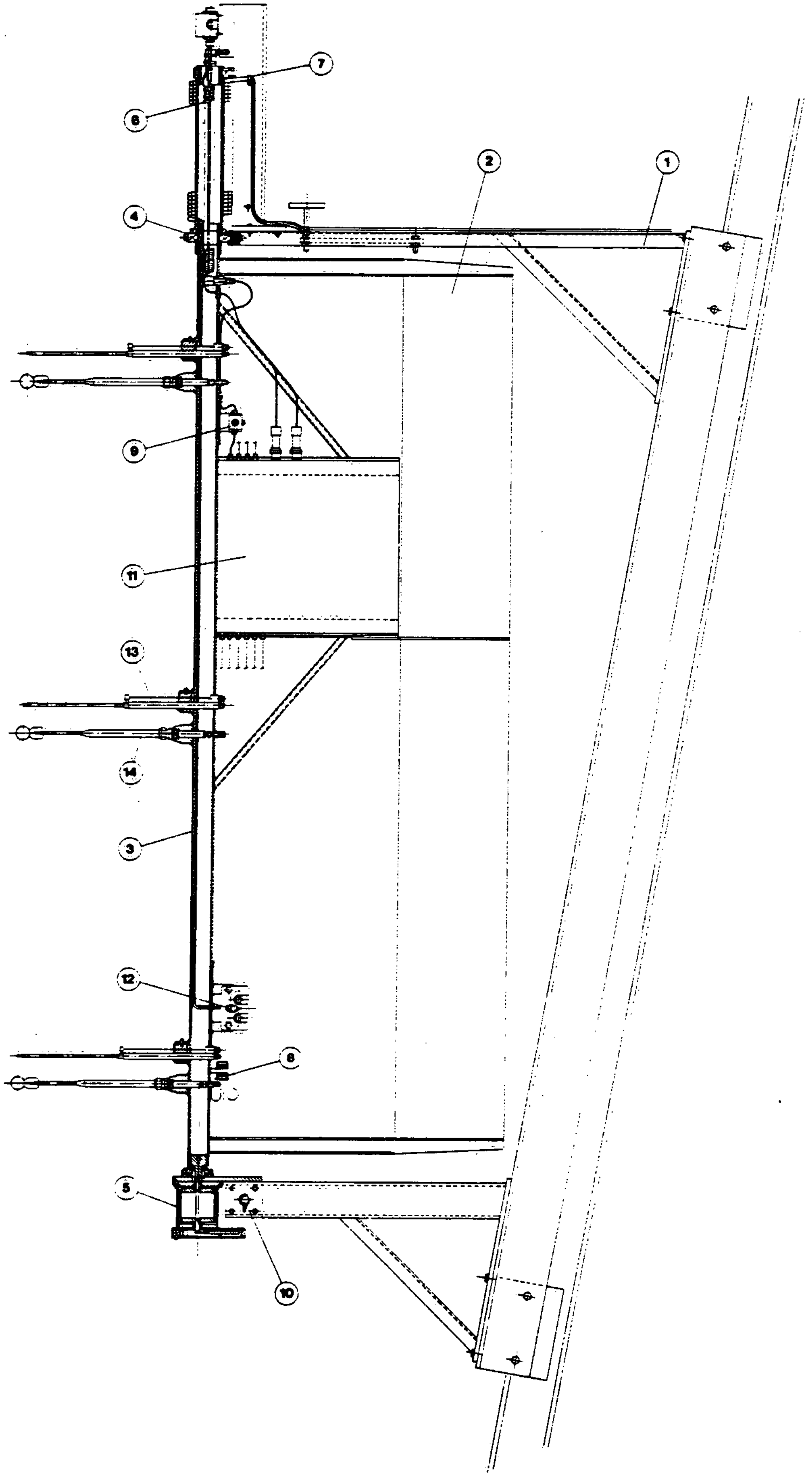
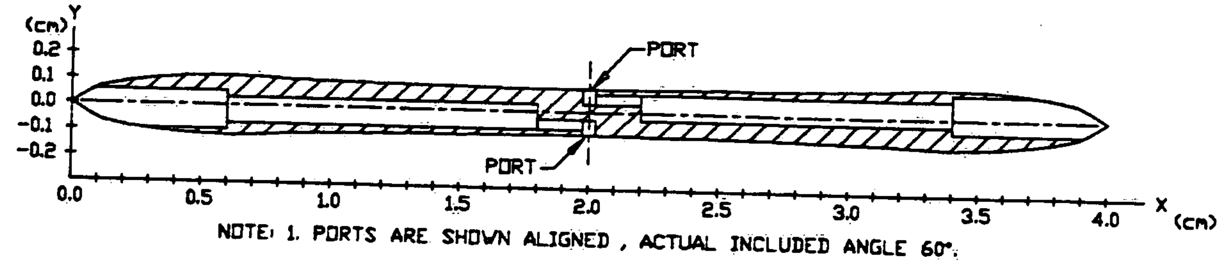


Fig.3



(1) CARRIAGE FRAME	(6) 6 CONDUCTOR RETRACTILE CABLE	(11) INSTRUMENT BOX ASSEMBLY
(2) WIND VANE	(7) FLEXIBLE CABLE RETAINER	(12) HOT WIRE ANEMOMETER
(3) VANE MAST	(8) SOLENOID VALVE AND CAN	(13) PITOT-STATIC TUBE ASSEMBLY
(4) SPLIT BEARING	(9) AIR REGULATOR	(14) PRESSURE PROBE ASSEMBLY
(5) DAMPER ASSEMBLY	(10) WAVE STAFF BRACKET	

Fig.4(a)


(cm) Y
0.2
0.1
0.0
-0.1
-0.2
PORT
PORT
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
X (cm)
NOTE: 1. PORTS ARE SHOWN ALIGNED, ACTUAL INCLUDED ANGLE 60°.

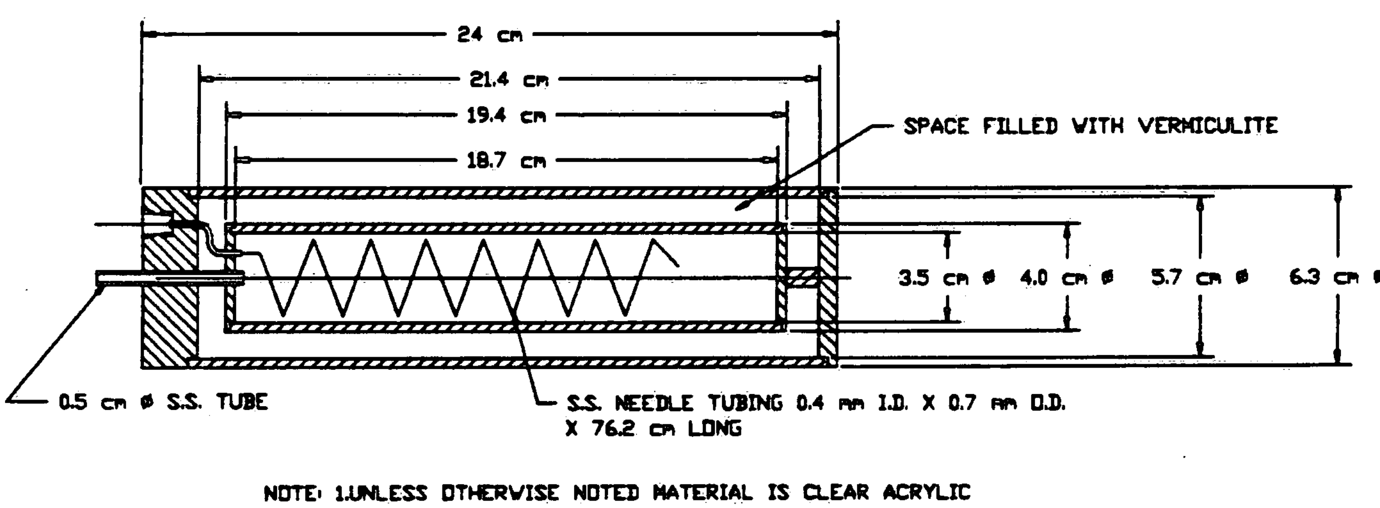

24 cm
21.4 cm
19.4 cm
18.7 cm
SPACE FILLED WITH VERMICULITE
3.5 cm ø
4.0 cm ø
5.7 cm ø
6.3 cm ø
0.5 cm ø S.S. TUBE
S.S. NEEDLE TUBING 0.4 mm I.D. X 0.7 mm O.D. X 76.2 cm LONG
NOTE: 1.UNLESS OTHERWISE NOTED MATERIAL IS CLEAR ACRYLIC

Fig.4(b)

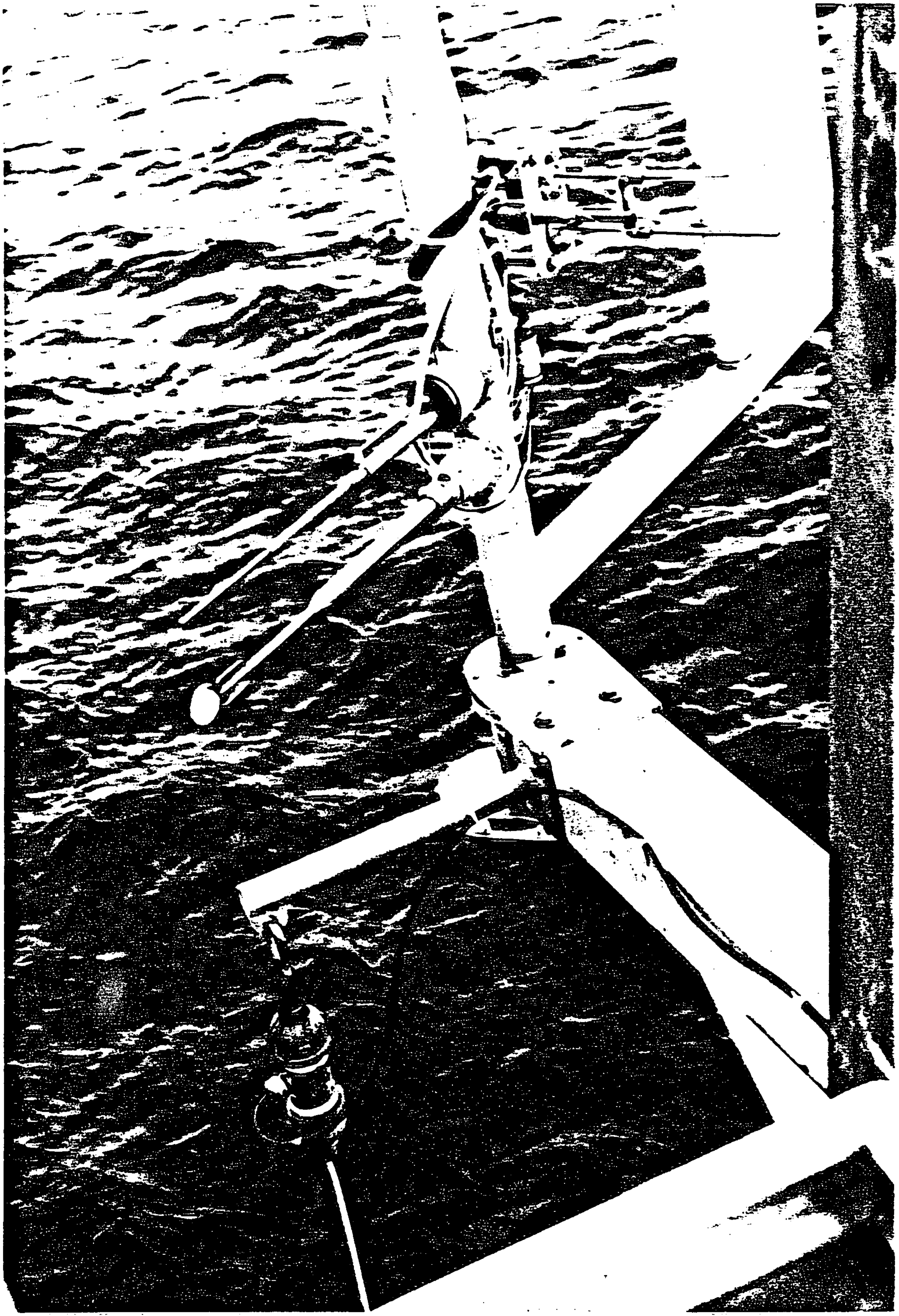
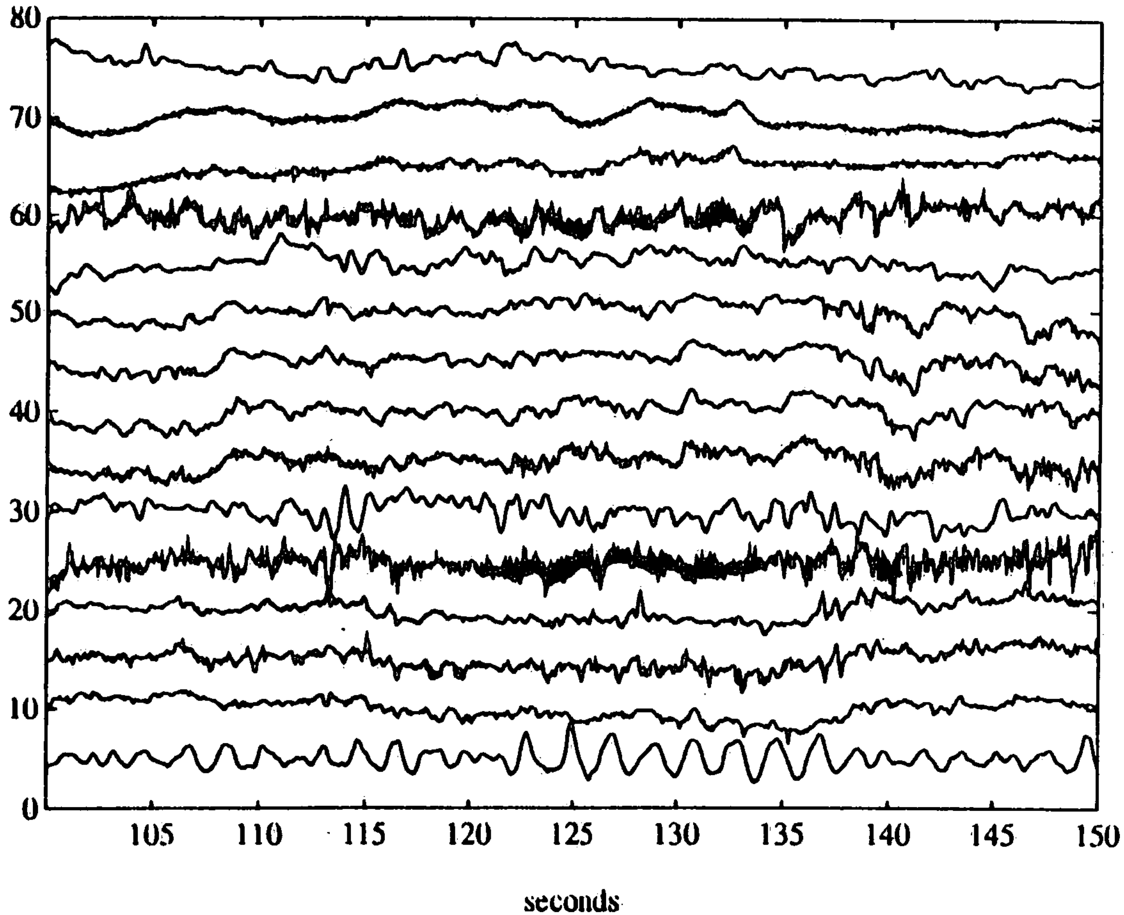
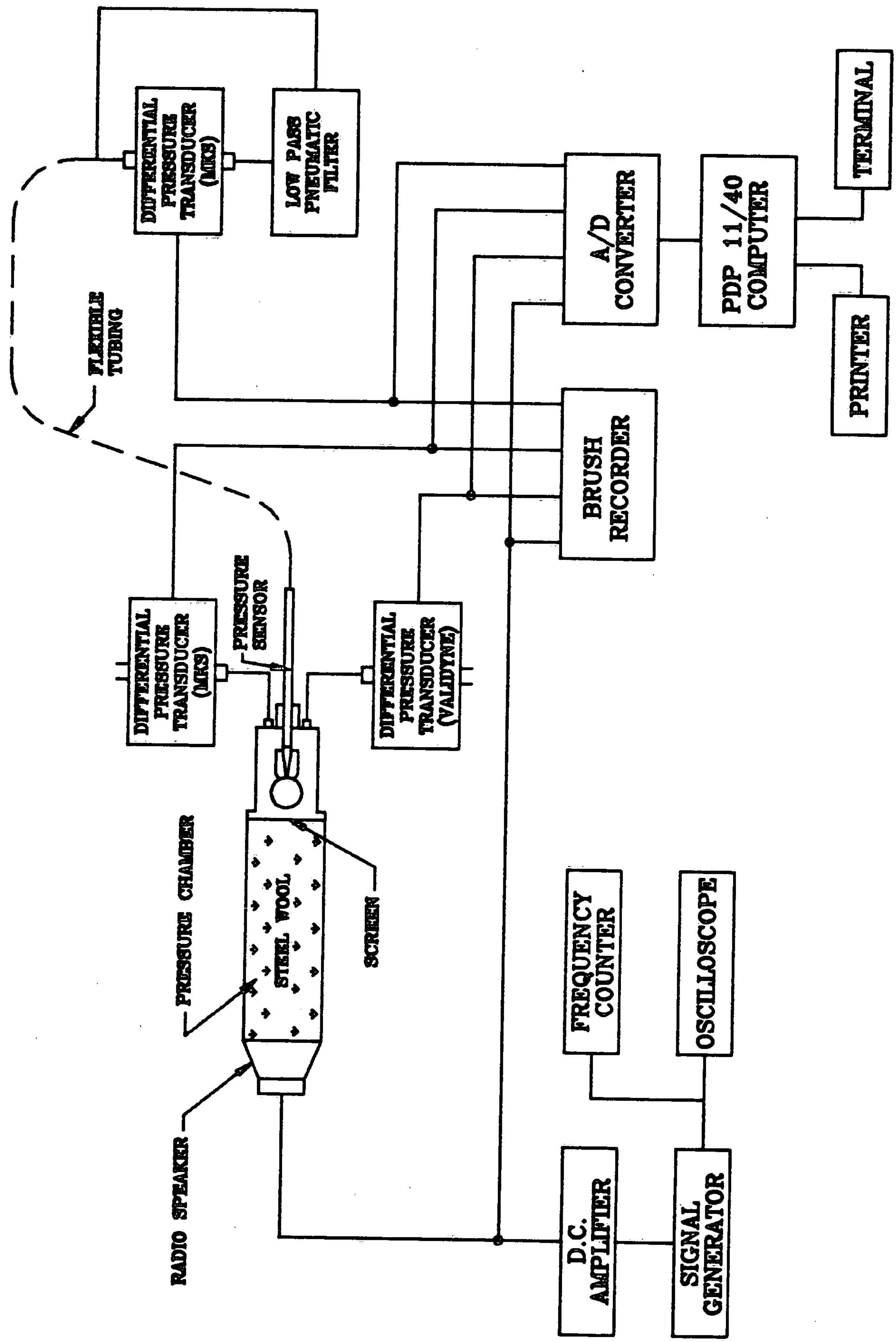


Fig.5



Variable	Height (m)	Mean	Std. Dev.	Units
Wind direction	12.0	265	5.05	degrees
Rel.Humidity	11.1	78	0.58	%
θ	11.6	4.63	0.03	°C
θ	1.4	-	0.08	°C
u (propeller)	12.0	8.22	0.61	m/s
u (Pitot)	3.4	8.15	0.94	m/s
u (Pitot)	2.4	8.13	0.91	m/s
u (Pitot)	1.4	7.61	0.81	m/s
u (X-film)	1.5	7.68	1.12	m/s
w (vane)	12.0	-0.13	0.79	m/s
w (X-film)	1.5	0.00	0.39	m/s
p	3.3	-	3.47	pascals
p	2.3	-	3.35	pascals
p	1.3	-	3.31	pascals
η (wave staff)	-	-	0.08	m

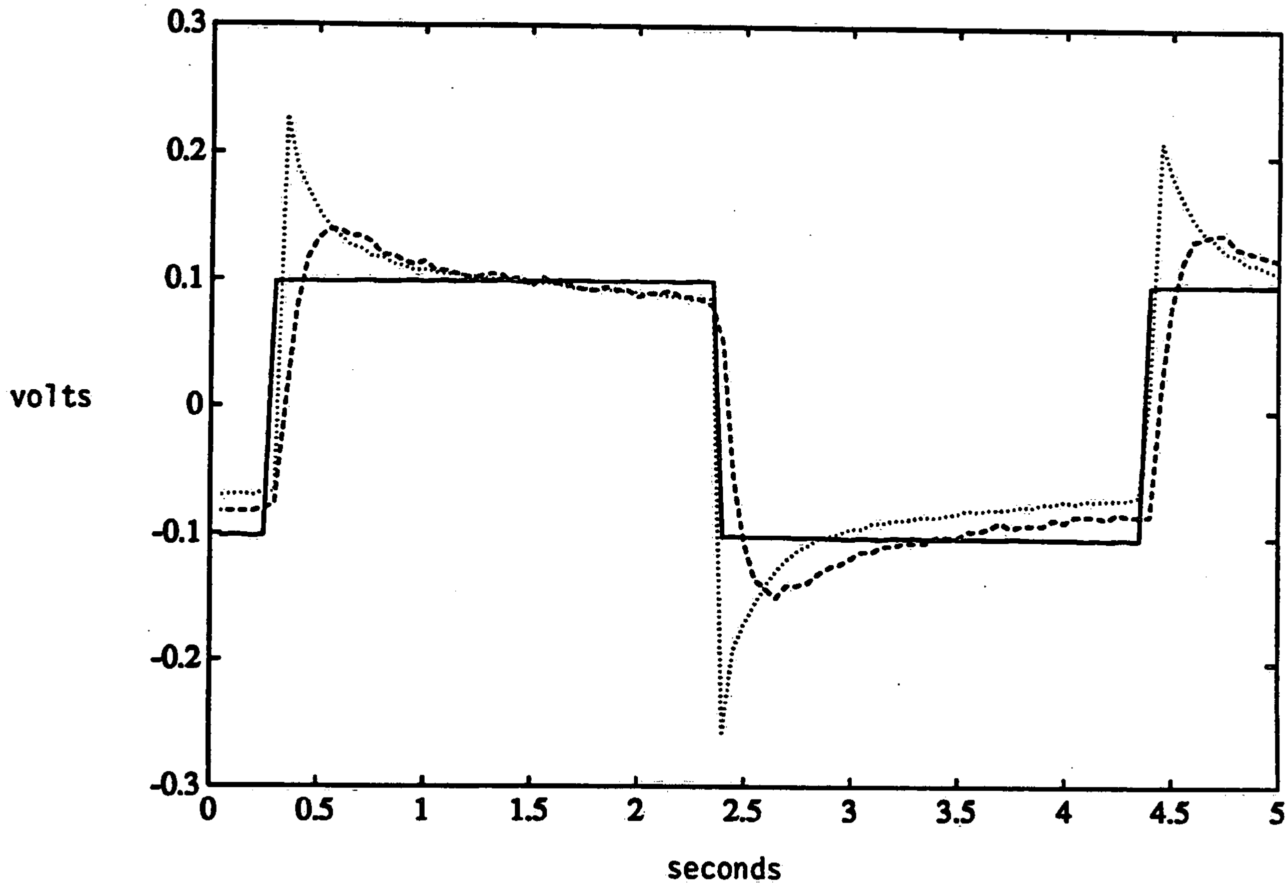
Fig.6

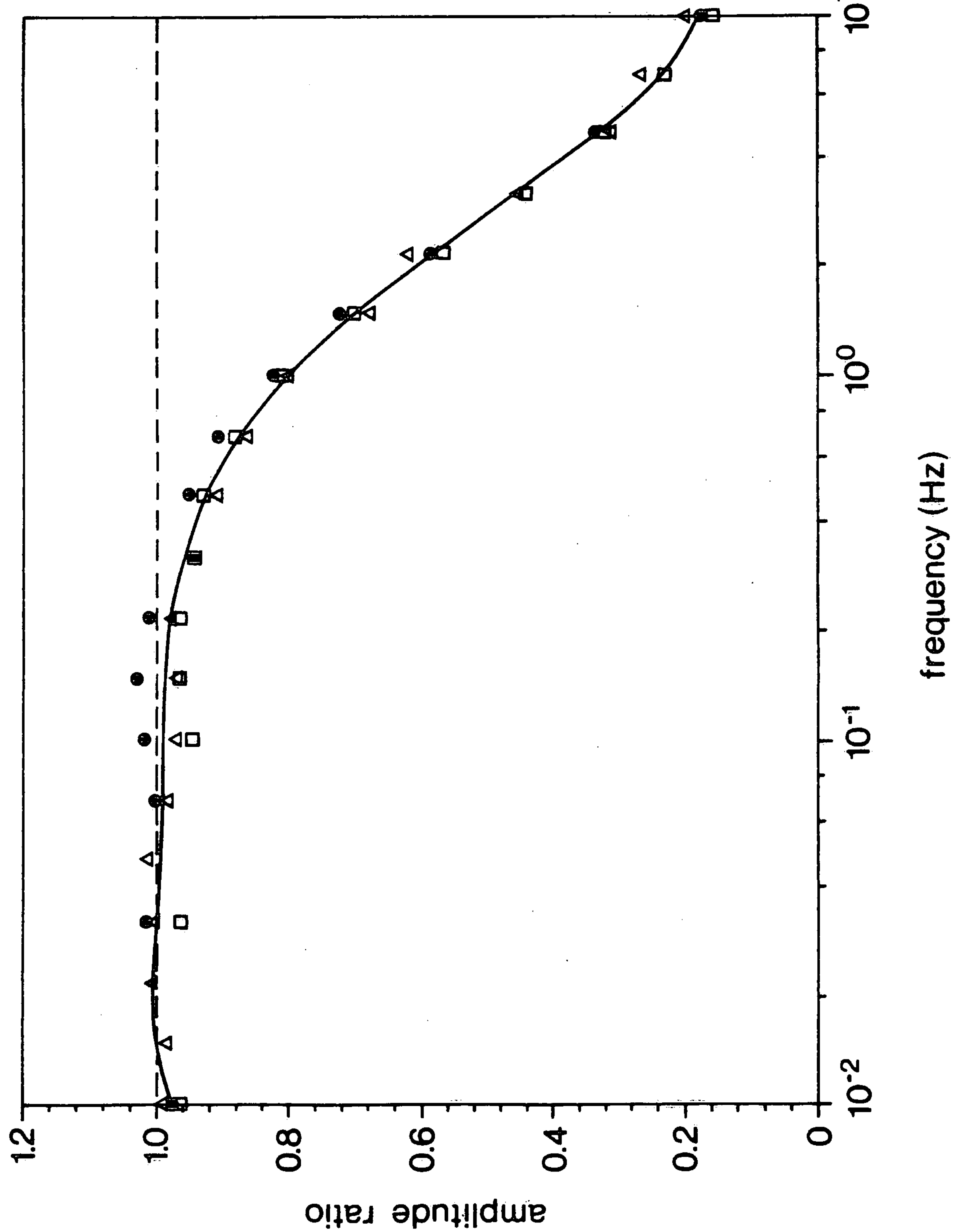


DIFFERENTIAL PRESSURE TRANSDUCER (MKS)
LOW PASS PNEUMATIC FILTER
FLEXIBLE TUBING
A/D CONVERTER
PDP 11/40 COMPUTER
TERMINAL
PRINTER
BRUSH RECORDER
DIFFERENTIAL PRESSURE TRANSDUCER (MKS)
PRESSURE SENSOR
DIFFERENTIAL PRESSURE TRANSDUCER (VALIDYNE)
PRESSURE CHAMBER
STEEL WOOL
SCREEN
RADIO SPEAKER
FREQUENCY COUNTER
OSCILLOSCOPE
D.C. AMPLIFIER
SIGNAL GENERATOR

Fig.7

Fig.8





amplitude ratio
0
0.2
0.4
0.6
0.8
1.0
1.2
frequency (Hz)
10^{-2}
10^{-1}
10^{0}
10^{1}

Fig.9(a)

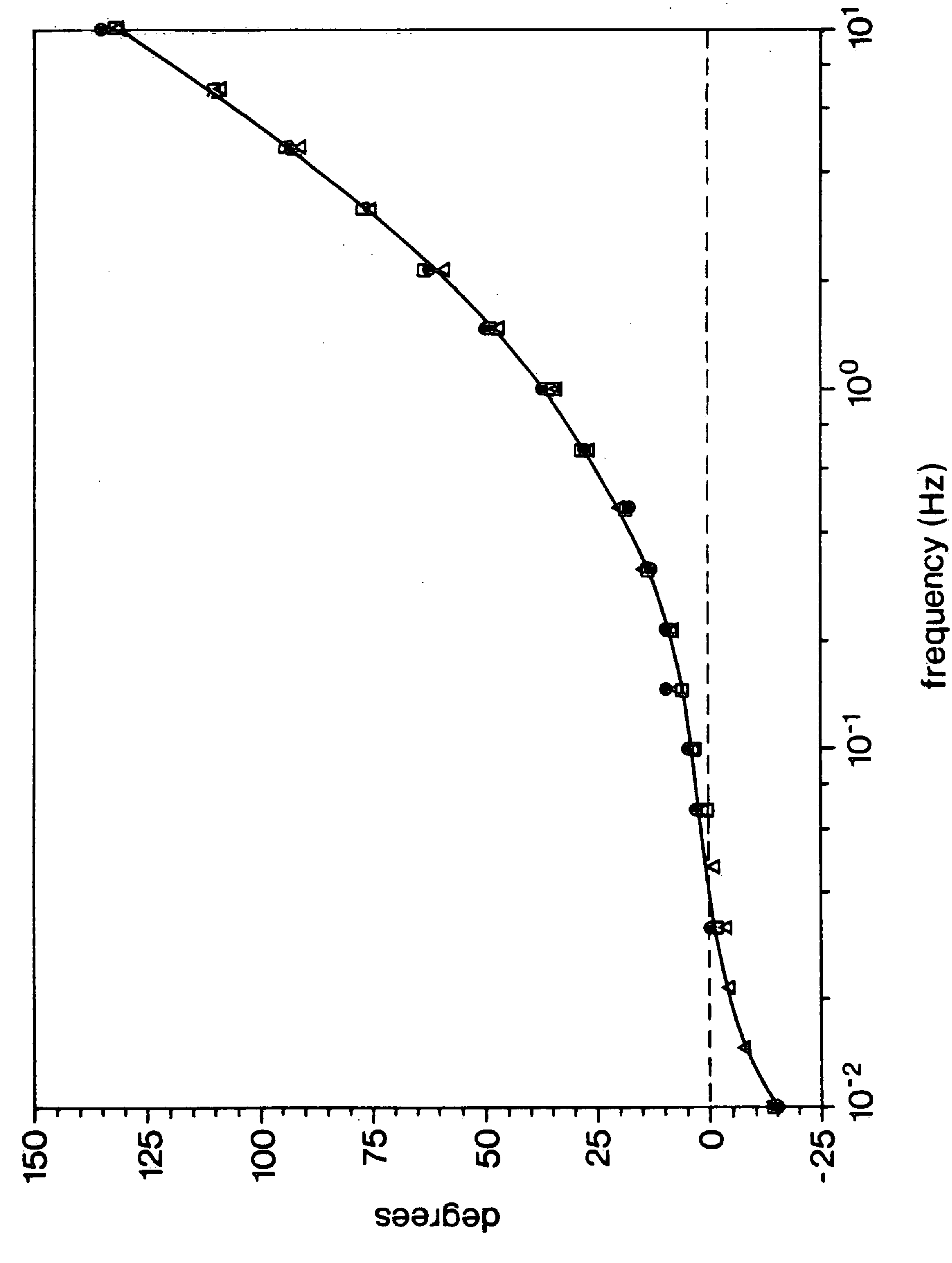


Fig.9(b)

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Environment Canada Environnement Canada

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