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PROPOSED SEA SURFACE METEOROLOGICAL INSTRUMENTATION SYSTEM FOR THE U.S. GARP ATLANTIC TROPICAL EXPERIMENT

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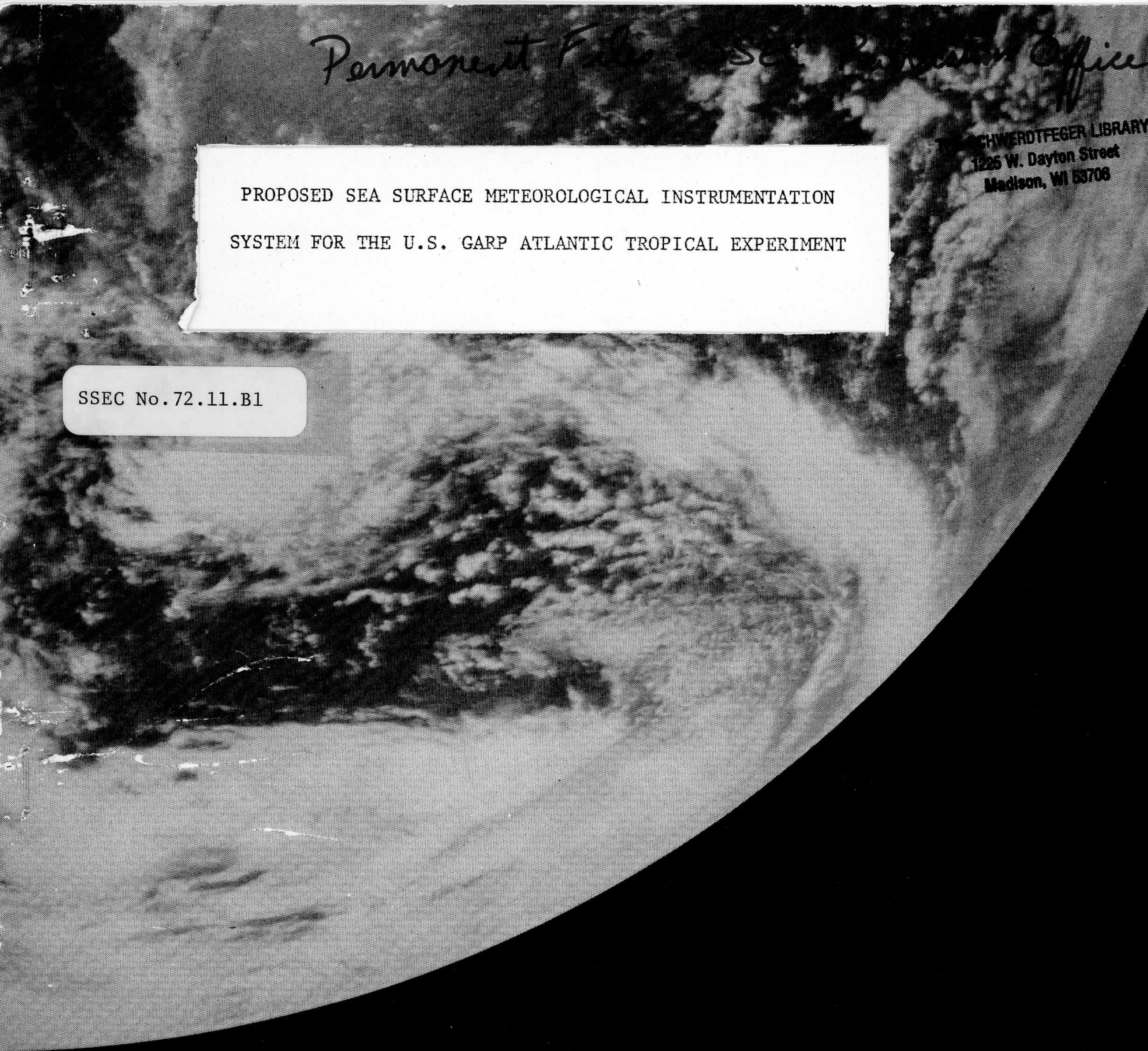

A REPORT

from the space science and engineering center
the university of wisconsin-madison
madison, wisconsin

PROPOSED SEA SURFACE METEOROLOGICAL INSTRUMENTATION SYSTEM FOR THE U.S. GARP ATLANTIC TROPICAL EXPERIMENT

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Report on a Sea Surface Meteorological Sensing System

Task 2 to STAG Contract 2-35116

November 1972

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I. Introduction

This report recommends a design approach for a Sea Surface Meteorological Instrumentation System (SMIS). The system proposed herein is our best estimate of providing a system which meets the basic requirements within probable resource limitations.

The purpose of the instrumentation is to obtain those observations needed at the air-sea interface of the boundary layer. As such, they need to be considered along with the entire Boundary Layer Instrumentation System (BLIS) and not as an isolated set of observations to be carried out by themselves. The scientific requirements specify a need for flux estimate of moisture, heat, and momentum; however, the relevant GATE documents (1, 2) hint that one need not attain exceptionally high accuracy in these observations.

This is the third report produced under Task Number 2 to STAG Contract 2-35116. The first preliminary requirements report by D. W. Martin and V. E. Suomi dated 1 May was followed by the final requirements report on 30 June. The second report established the scientific requirements for a sea surface measurement system for the GARP Tropical Experiment. The final requirements report is attached to this report as Appendix A and serves as a basic reference of design objectives. Table 1 of the report summarizes ideal SMIS requirements.

II. Theoretical Considerations

To accomplish the scientific objectives needed for GATE, it is proposed that a modified bulk aerodynamic method is to be used. That is, the mean vertical temperature and vapor pressure gradients will be measured and the drag coefficient C_D will be calculated from wind fluctuation data by the dissipation technique instead of using handbook values.

TABLE 1

SEA SURFACE MEASUREMENTS FOR GATE

PARAMETER	PURPOSE	ACCURACY	SAMPLING FREQUENCY	REMARKS
horizontal wind speed	fluxes	±3% (abs)	1 sec^{-1}	
	divergence	±.5m/sec (abs)*	1 hr^{-1}	
wind direction	fluxes	2-3° (abs)	1 sec^{-1}	
	divergence	3° (abs)*	1 hr^{-1}	
moisture	moisture flux	0.1°C (dewpt) (abs)	1 sec^{-1}	same level as wind
air temp	heat flux	0.1°C (abs) 0.02°C (rel)	∿ 10 sec^{-1}	same level as wind
sea surface temp	boundary layer dynamics	0.01°C (rel)	∿ 10 sec^{-1}	aircraft mounted radiometer; simultaneous with aircraft spectral measurements of w', T', q'; occasional basis
	fluxes; oceanographic program	0.05°C (abs) 0.02°C (rel)	1 sec^{-1}	
pressure	stress non-geostrophic pressure forces	.1 mb (abs)	.02-.04 sec^{-1}	long sampling frequency smooths high frequency ship-oscillations
rain	heat budget	.5 mm	8 day^{-1} or more	

*based on ship spacing of 150 km, disturbance divergence of 10^{-5} sec^{-1}, 10% accuracy in the measurement of divergence, and an error of .2 - .3 m/sec resulting from platform drift.

Fast response (1/sec.) performance is required in the proposed technique for only the wind vector measurement. This assumes that the variational component of the wind, temperature, and moisture are similar. This is not strictly so, but it is felt that determination of C_D locally using the dissipation technique is better than the use of a handbook value and should result in determinations useful for GATE objectives; albeit, not what is possible from a more elaborate air-sea interface experiment such as was used during BOMEX.

With good data, and in some cases redundant information, the following can be obtained.

ε, the dissipation, is obtained from the structure function using

$\Phi(k) = K\varepsilon^{2/3} k^{-5/3}$ where

K = constant,

k = wave number, and

$\tau = \rho K^{-1} (\kappa z)^{2/3} k^{5/3} \Phi(k)$,

κ = von Karman constant.

Since U^2 is a quantity easily measured on the buoy and ship, C_D can be obtained by using

$$\tau = \rho C_D U^2.$$

The moisture flux can be obtained from

$Q = \rho C_D \Delta Q \, U^2$ where ΔQ is the vertical moisture gradient and the heat flux can be obtained by using

$H = \rho c_p \, C_D (\Delta T) U$ where ΔT is the vertical temperature gradient.

Since C_D is determined locally, we call this approach a modified bulk aerodynamic approach. The recent literature indicates that good estimates using this technique are possible. (3,4)

III. Mode of Operation

Other GATE observational activities require quasi station keeping of the ship at the B and A scale network positions. The ships cannot be held strictly on station because of operational efficiency limitations. Therefore, the ships will be allowed to drift with the current and wind for some 10 km and then brought back to station at a moderate speed. Thus, we have a drift mode and a steaming mode. Typical times might be as much as 75% in the drift mode and 25% of the time used to return to station.

Offhand, one might think that the best time to obtain the sea surface observations is in the drift mode and to use steam time to obtain the sea surface profile values. It may come as a surprise, but an investigation of the disturbance factor shows a considerable imbalance in favor of a space average obtained when the ship is underway back to station. Of course, the mean velocity of the ship will have to be removed from the observations; but this seems to be a much easier task than overcoming the many disturbances which exist in the drift modes. Therefore, we strongly recommend that some observations be taken when the vessel is underway--headed more or less into the prevailing wind back to station.

When a ship is underway, all observations suffer some disturbance--the degree being dependent on the position of the ship. Since the air tends to flow around the ship and over the ship, a major disturbance will arise in the wind direction. This air and water flow pattern is illustrated in Figure 1. This disturbance was also true for FLIP used during BOMEX. Unfortunately, the surface wind is a key measurement in the boundary layer. So, this measurement must be obtained away from the ship on a small spar buoy.

To obtain the required accuracies for the sea surface wind and moisture measurements, the supporting platforms for the wind velocity and humidity

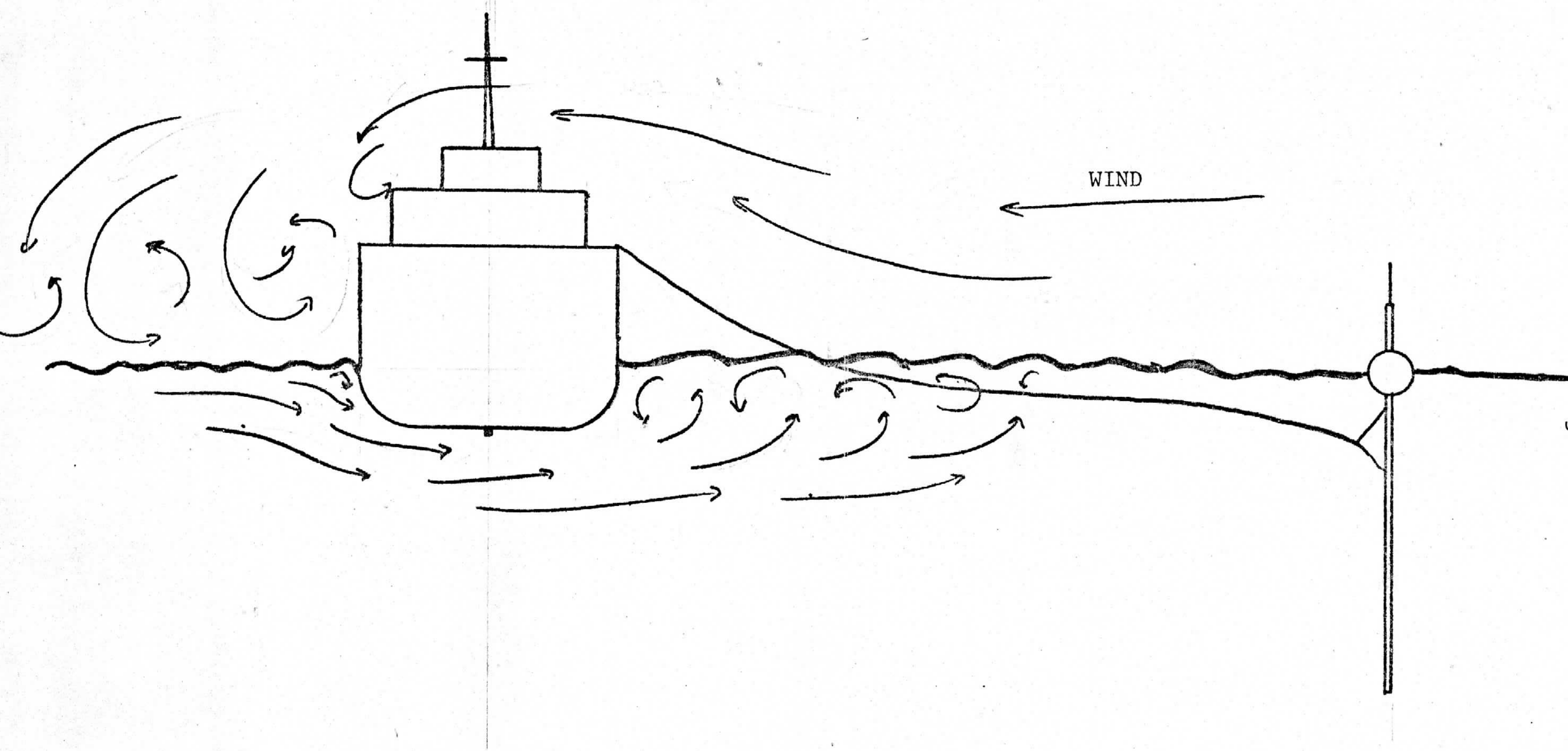


Figure 1   Water and Wind Movement Relative to Ship Hull

sensing instruments should be located as far from the ship as practicable and these sensors should produce minimal disturbance in the air and water movement.

Avoiding the effect of the ship forces consideration of a buoy located up-wind from the ship, or at sufficient distance down-wind so that the ship effect is negligible. The design of a suitable buoy is in itself a formidable problem, which because of time and dollar limitations cannot be undertaken by the Space Science and Engineering Center in developing SMIS. We have accepted the serious constraint of using a small spar buoy upon advice from the NOAA GATE Office.

Survival of the platforms in high breaking seas is a major concern, since the purposes of GATE require extended periods of deployment, and conditions of particular meteorological interest exist during rough weather. Occasional wave heights of eight meters are to be expected; and, thus, the instrumentation and platform must occasionally withstand the impact of a mass of water breaking from a wave crest and falling down the steep advancing face of the broken wave with a kinetic energy per unit mass which could be as high as 78 joules per kilogram.

The wind produced drift to be expected on ships like the Discoverer, Oceanographer, and Gillis will be a minimum of 1 1/2 knots (5) which will require frequent operation under power to return to the initial coordinates. Since it is desired to obtain a continuous record of sea surface measurements, the deployed platforms must be towed. Because of vibration and carbon formation problems in the ship diesel engines, a minimum towing speed of six knots is indicated (6). Vertical orientation of the platforms must be maintained at this towing speed or alternate observing means must be provided for use when steaming. Corrections for platform velocity must be applied to data taken while under power, which will be on the order of 25% of the total time.

IV. Design Approach

Tables II and III summarize the overall instrumentation for the ship and buoy. The buoy is assumed to be a small spar configuration normally tethered to the ship so as to float upwind of the ship at distances on the order of one to two kilometers when the ship is in a drift mode. It is expected that the ship will drift more rapidly than the buoy, but that the towing speed during drift will be low enough as not to cause the buoy to heel. When the ship must steam back to station, the buoy is expected to heel and will fall into the ship's wake so that it will no longer provide a satisfactory measurement platform. Sensors are carried aboard ship to provide data during steaming. It is expected that some wind data collected during steaming will be degraded, but still useful. These limitations are discussed in greater detail below for each measurement.

As discussed in Appendix A, the SMIS design is based on collection of data of sufficient accuracy to permit calculation of flux from C_D by the dissipation technique. Impact of this design approach is especially apparent in the recommended instrumentation for moisture flux measurement.

TABLE II

S M I S

SHIP MOUNTED INSTRUMENTATION

PARAMETER	ACCURACY	SAMPLE RATE	INSTRUMENTATION TECHNIQUE
PRESSURE	± 0.1mb (relative)	1/4 SEC	ANEROID, CAPACITOR, TYPE DEVICE SIMILAR TO THE BLIP
VAPOR PRESSURE GRADIENT (AVERAGE MOISTURE CONTENT AT 3 LEVELS)	$\pm \frac{0.05\text{mb } H_2O}{\text{METER}}$	1/MIN	WET BULB DETERMINATION USING INTEGRATING CHAMBERS. 3 LEVELS: 1.5, 3, 6 METERS. BOOM FROM SIDE OF SHIP.
AIR TEMPERATURE	± 0.1°C (abs) ± 0.02°C (rel)	1/4 SEC	CALIBRATED THERMISTOR CONFIGURATION SIMILAR TO VAPOR PRESSURE APPARATUS.
RAIN GAUGE	± 0.5mm	8/DAY	GIMBAL MOUNTED STANDARD RAIN GAUGE--MANUALLY READ AND EMPTIED
RADIATION BOOM (1)UP RADIATION SHORT WAVE	± 3%	1/MIN	PYRANOMETER--GLASS WINDOW
(2)DOWN RADIATION SHORT WAVE	± 3%	1/MIN	PYRANOMETER--GLASS WINDOW
(3)NET	± 3%	1/MIN	NET PYRADIOMETER--POLYETHYLENE WINDOW LONG AND SHORT
(4)SEA SURFACE TEMPERATURE	± 0.01°C (rel)	1/4 SEC	RADIANT ENERGY SENSING
HORIZONTAL WIND SPEED	± 3% (abs) ± 0.5 m/sec (abs)	1/SEC	SONIC VELOMETER ON BOOM

TABLE III

S M I S

BUOY MOUNTED INSTRUMENTATION

PARAMETER	ACCURACY	SAMPLE RATE	INSTRUMENTATION TECHNIQUE
PRESSURE	± 0.1mb (relative)	1/4 SEC	ANEROID, CAPACITOR, TYPE DEVICE SIMILAR TO THE BLIP
AIR TEMPERATURE	± 0.1°C (abs) ± 0.02°C (rel)	1/4 SEC	CALIBRATED THERMISTOR CONFIGURATION SIMILAR TO THE BLIP. 2 LEVELS
WET BULB TEMPERATURE	± 0.1°C (abs) ± 0.02°C (rel)	1/4 SEC	CALIBRATED THERMISTOR CONFIGURATION SIMILAR TO THE BLIP. 2 LEVELS
RAIN GAUGE	± 0.5mm	1/MIN	DIELECTRIC CHANGE IN A CAPACITOR, BELL LABORATORY CAPACITOR CONTROLLED OSCILLATOR RAIN GAUGE
HORIZONTAL WIND SPEED	± 3% (abs) ± 0.5 m/sec (abs)	1/SEC	SONIC VELOMETER WITH VECTOR DECOMPOSITION FOR PART OF RELATIVE DIRECTION INFORMATION OR SMALL CUP ANEMOMETER
WIND DIRECTION	± 1° (abs)	1/4 SEC	MOTOR DRIVEN EARTH INDUCTOR COMPASS TO SUPPLY A REFERENCE DIRECTION FOR THE SONIC VELOMETER. BLIP WINDAV TYPE CIRCUIT.
SEA SURFACE TEMPERATURE	± 0.01°C (abs) ± 0.01°C (rel)	1/4 SEC	FLOAT THERMISTOR
DEEP WATER TEMPERATURE (10 to 50 METERS (AVERAGE)	± 0.001°C (rel)	1/SEC	BRIDGE CIRCUIT USING A DISTRIBUTED RESISTANCE THERMOMETER

V. Recommended Design

A. Wind Velocity

Wind velocity observations must be made at a rate of at least one per second to meet the requirements of flux determination by the dissipation technique. To meet this requirement and the severe operating environment, a sonic anemometer of the pulse phase locked type developed by John Stichman (7) at the University of Wisconsin is recommended. A horizontal array of sonic sources and receivers, or a wind vane mounted single source and receiver pair, will be used to provide information on direction and speed. The system is to be mounted on the buoy about four meters above the mean sea surface. The sonic sources and receivers are to be hermetically sealed and rigidly mounted to resist the occasional exposure to a large breaking wave. This buoy mounted instrumentation can be made much more resistant to the harsh environment than any form of sensitive moving vane or small cup anemometer.

It is recommended that the direction reference for the buoy mounted horizontal sonic transducer array be a rotationally driven earth inductor-magneto diode compass related to that developed by SSEC for the tethered balloon Boundary Layer Instrumentation Package (BLIP). The buoy and masts must be of nonmagnetic construction. The rotating iron-nickel alloy earth inductor arm is driven by an electric motor. The wind vane is referenced to the magnetic north zero crossing of the rotating magneto-diode. The instrument is protected from water and weather deep inside of the nonmagnetic buoy.

The arrangement schematically given in Figure 2 will yield the vector wind components with respect to some reference (the magneto-diode

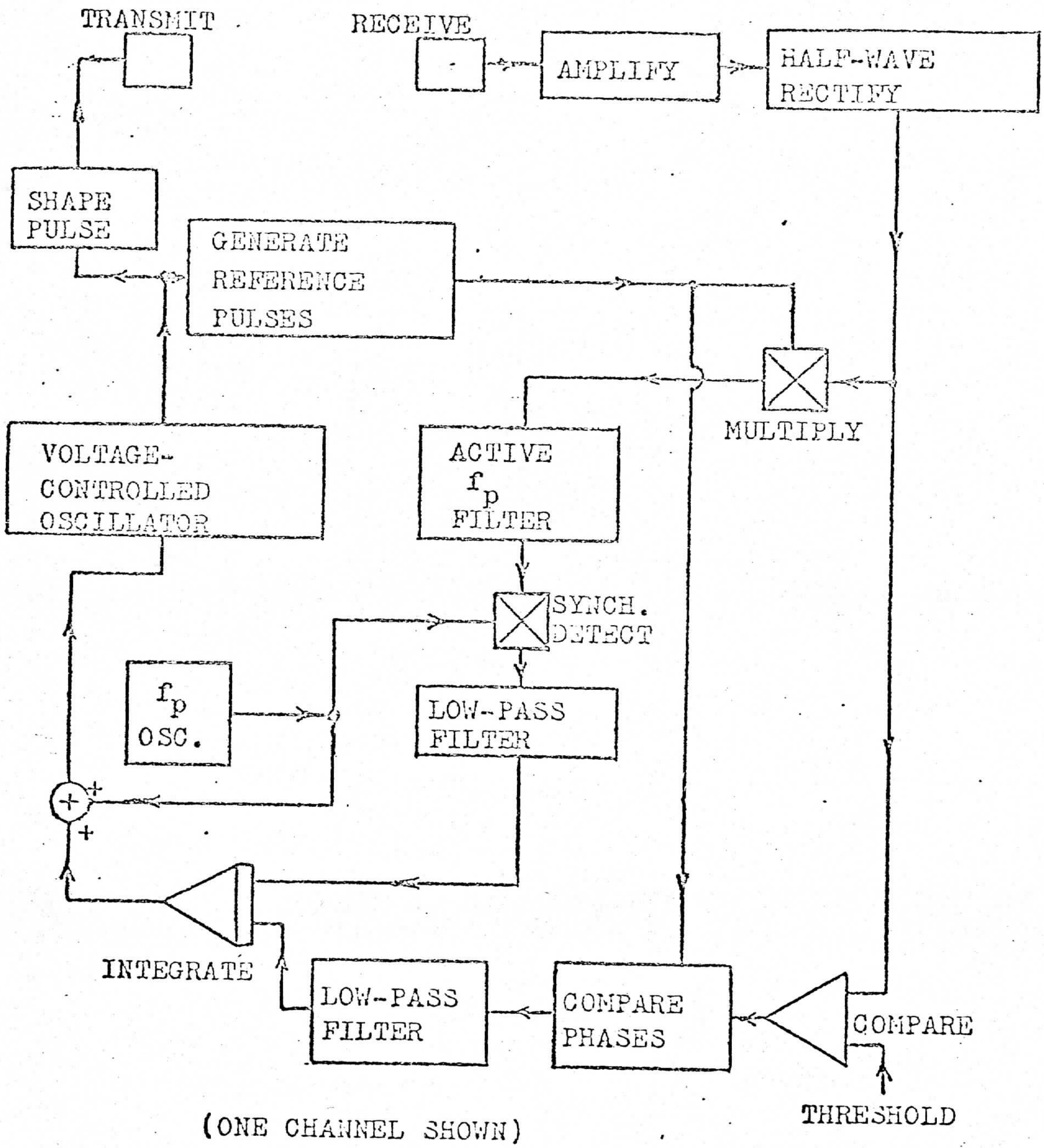


Figure 2 Sonic Anemometer Block Diagram

compass) by measuring the transit times of ultrasonic pulses in air. As mentioned earlier, the use of only one transducer pair mounted on a moving vane which keeps it continually aligned with the direction of an air flow is also being considered. It is conceivable that angular displacement from the vertical could be obtained by use of the gray code tilt indicator developed for the BLIP.

The single sonic velometer mentioned above is proposed for shipboard use to obtain wind data during steaming. During the drift mode data from this instrument should be ignored.

B. Moisture Content

We recommend that the average moisture content of the air at the 1.5 meter, 3 meter, and 6 meter levels above the undulating 1 second mean sea level be determined by the humidity gradient measurement system illustrated in Figure 3.

The three air intake openings are mounted on a pivoted rigid arm from the side of the ship as illustrated in Figure 4. The distance from the ship's side must be so as to provide minimum air flow perturbation.

Three hoses bring air drawn from the three levels to integrating mixing tanks aboard the ship as shown in Figure 3. From the propeller stirred integrating chambers the air is drawn through three parallel copper tubes which are in close thermal contact. The three air streams are at the same temperature when they each pass by wet bulb temperature sensing thermocouples. After the wet bulb temperature of each sample

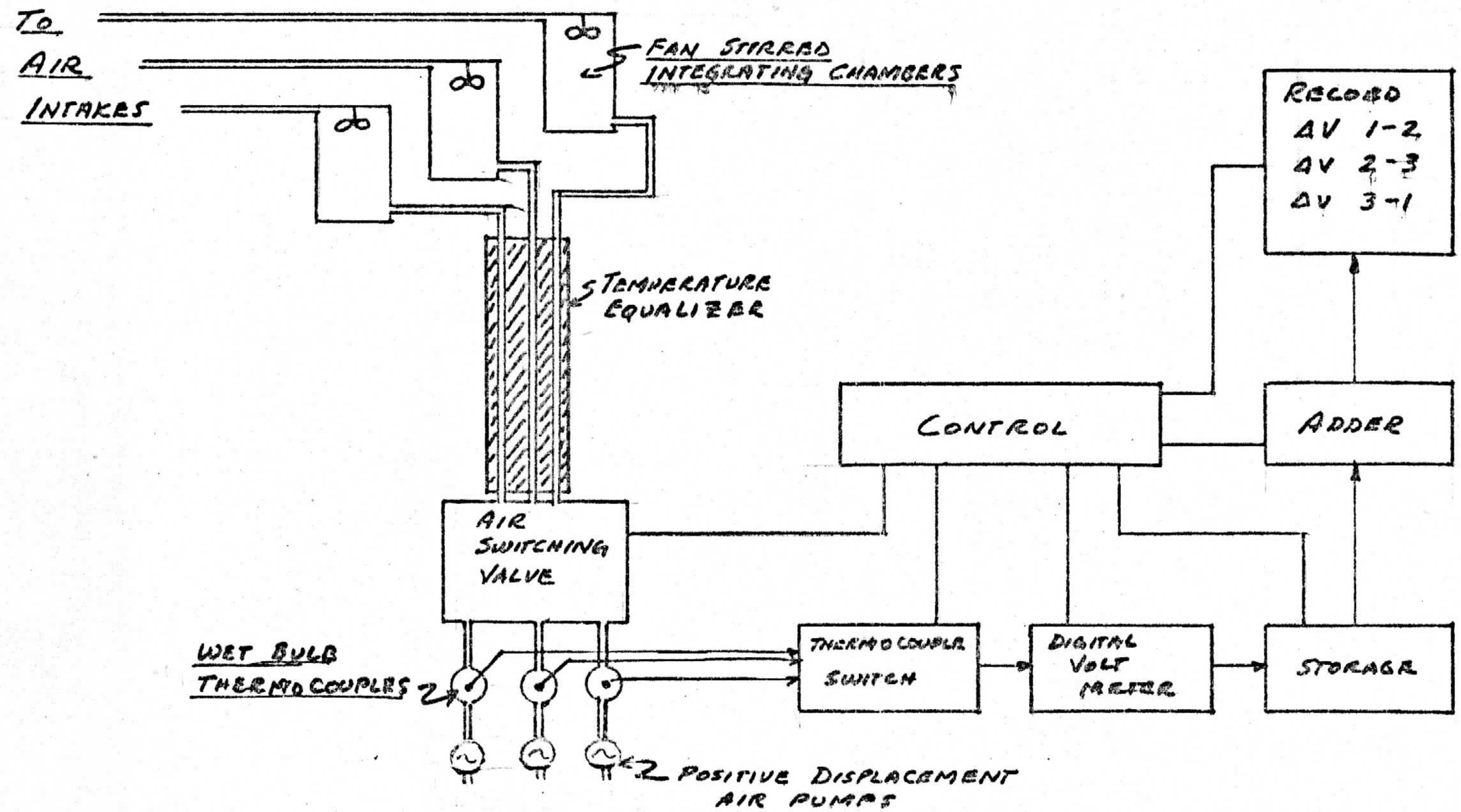


Figure 3 Humidity Gradient Measurement System

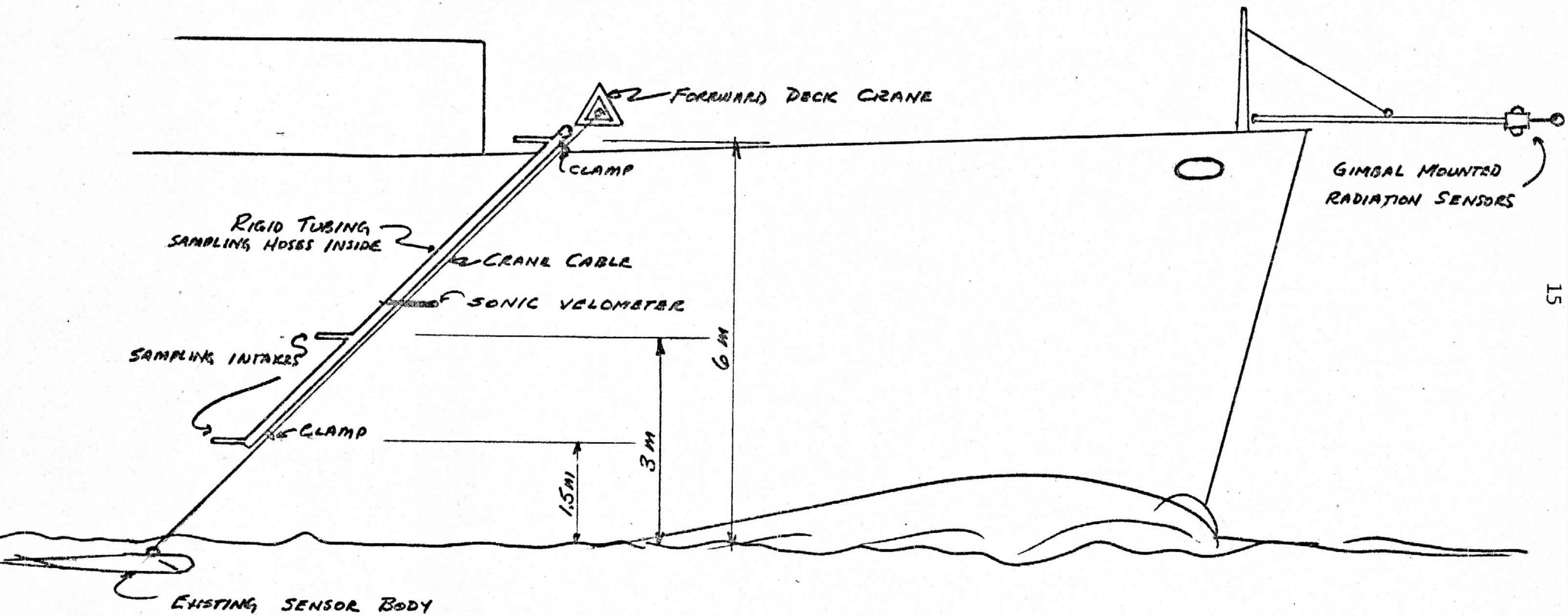


Figure 4 Air Intake Configuration for the Humidity Gradient System

air stream has been sensed, the air passes to fixed displacement rotary vane pumps.

It will now be shown that the difference between any two wet bulb temperature readings is proportional to the average moisture gradient between the corresponding two sampling levels.

For application to the Moisture Gradient Measurement Algorithm let

e = vapor pressure

T_w = wet bulb temperature

T = ambient temperature

C_A, C_B = constants determined from temperature and pressure.

Then utilizing the measurements obtained from Level 1

$$e_1 = C_A T_{w_2} - C_B (T - T_{w_1}) \quad \text{(B-1)}$$

and from Level 2

$$e_2 = C_A T_{w_2} - C_B (T - T_{w_2}). \quad \text{(B-2)}$$

Subtracting Eqn. (B-1) from Eqn. (B-2) yields the moisture gradient Δe directly from wet bulb readings.

$$e_2 - e_1 = \underline{\underline{\Delta e}} = C_A (T_{w_2} - T_{w_1}) + C_B (T_{w_2} - T_{w_1}). \quad \text{(B-3)}$$

This analysis is then continued in a similar fashion to three levels. Absolute values for dry bulb temperatures are not required for the moisture determination except for one measurement at the copper tube heat sink to define C_A and C_B.

The results of the use of this technique applied to a somewhat different problem is discussed in Reference (8).

Extreme accuracy is possible because the actual temperatures need not be known, only the temperature difference. Further, any offset errors inherent in the thermopiles themselves can be eliminated from the measurement by switching thermopiles and air streams. As indicated in Figure 3, a manifold valve air switching array permits each thermopile to be used in conjunction with any other one to sense the wet bulb temperature difference between any two air streams.

It is obvious that no spray or mist can be permitted to enter the sample collecting hoses, since this would give rise to a fictitiously high moisture indication. The danger of this is minimized by the passive mist separators at each air sample intake point. These mist separators, will have an intake orifice always directed away from the direction of the wind so that spray and mist is less likely to enter. In addition, positive intake closure valves are provided in case the inlet is submerged.

If water enters the hoses in spite of these precautions, the system will be flushed with fresh water and dry air passed through the system from the ship to thoroughly dry it before reuse.

We recognize that under conditions of heavy seas the lowest intake may be inoperative; however, useful data can still be obtained from the two higher level sensors. The simplicity and low cost of this measurement approach and the very high accuracy obtainable offset the difficulties which may be experienced in field operations.

The varying degrees of redundancy allow for the recognition and rejection of bad data which may be collected. Thus, if the Bowen ratio determined by these measurements is not nearly uniform with height, the data is suspect--or may represent a non-surface moisture source such as evaporating spray.

C. Air Temperature

We recommend that the air temperature be monitored at 1.5 m, 3 m and 6 m above the sea surface from the buoy when drifting and from the ship while steaming, using glass encased thermistors of minimum diameter in conjunction with a resistance controlled oscillator circuit. Careful insulation of all parts of this circuit is vital, since any surface leakage currents would invalidate the measurements. In addition to the sea surface temperature measurement, the dry bulb readings at the ship should be obtained at all three of the moisture gradient air inlets. A convenient way of achieving forced ventilation in the ship installation is to utilize the air intakes for the humidity gradient system.

The measurement of air temperature fluctuations near the sea surface is complicated by the occasional presence of mist or spray which can produce a wet film on the thermistor, yielding wet bulb temperatures rather than the desired values. To avoid this, a thin film of silicone wax or fluorocarbon should be applied to the thermistor to prevent adhesion of water; and, in addition, a provision to dissipate electrical heat to dry the thermistor when desired should be included.

The telemetry format for the ship and buoy temperature sensors will be compatible with the BLIS package for ease in decoding using the PODAS.

D. Sea Surface Temperature

Ideally, one should have the temperature of the uppermost film of the ocean surface since this surface temperature determines the ocean's vapor pressure and its sensible heat transfer. Such a measurement can be obtained from a ship underway using an IR radiometer of the Barnes type. When the radiometer is caused to scan across the bow of the ship at various angles to the surface, it is possible to extrapolate the radiation temperature to remove effects of water vapor in the radiometer beam. When the ship is underway, this observation not only allows a mean sea surface temperature to be determined but a variance spectrum as well.

A temperature analogous to the "bucket temperature" will be obtained at the buoy using a small float such as was used during BOMEX.

E. Radiation Measurements

A bow boom will be used for mounting the pyranometers and net radiometer on the ship. The boom should be capable of extension to 10 meters distance from the anchoring stanchion on the ship's bow. The boom must be designed so that it can be brought in for servicing the instruments and for protection of the assembly in the event of very severe sea conditions. The instrument platform at the end of the boom must be maintained at an attitude such that the average position of the radiometer sensing planes is within ± 2° of the true horoizontal.

A boom constructed of 3" diameter 1/8" wall anodized aluminum pipe with a hinged joint has been proposed by NOAA Sea-Air Interface Laboratory personnel as suitable for shipboard handling.

A Model 8-48 Eppley Black and White Pyranometer and a Model PSP Eppley Precision Spectral Pyranometer are to be used for measuring the Up Radiation and Down Radiation (short wave) respectively.

A Funk net radiometer with a polyethylene window is to be used for measuring the net radiation.

The entire assembly will be mounted in a damped gimbal configuration so as to maintain a level sensing plane. Such a proposed scheme is shown in Figure 5. The unique feature of this design, the self leveling feature, will provide for an adjustable average vertical orientation. The natural frequency of the pendulum configuration, including damping, can be described for small angular displacements by

$$f = \frac{1}{2\pi}\sqrt{\frac{mg}{\ell} - \alpha^2} \qquad \text{(E-1)}$$

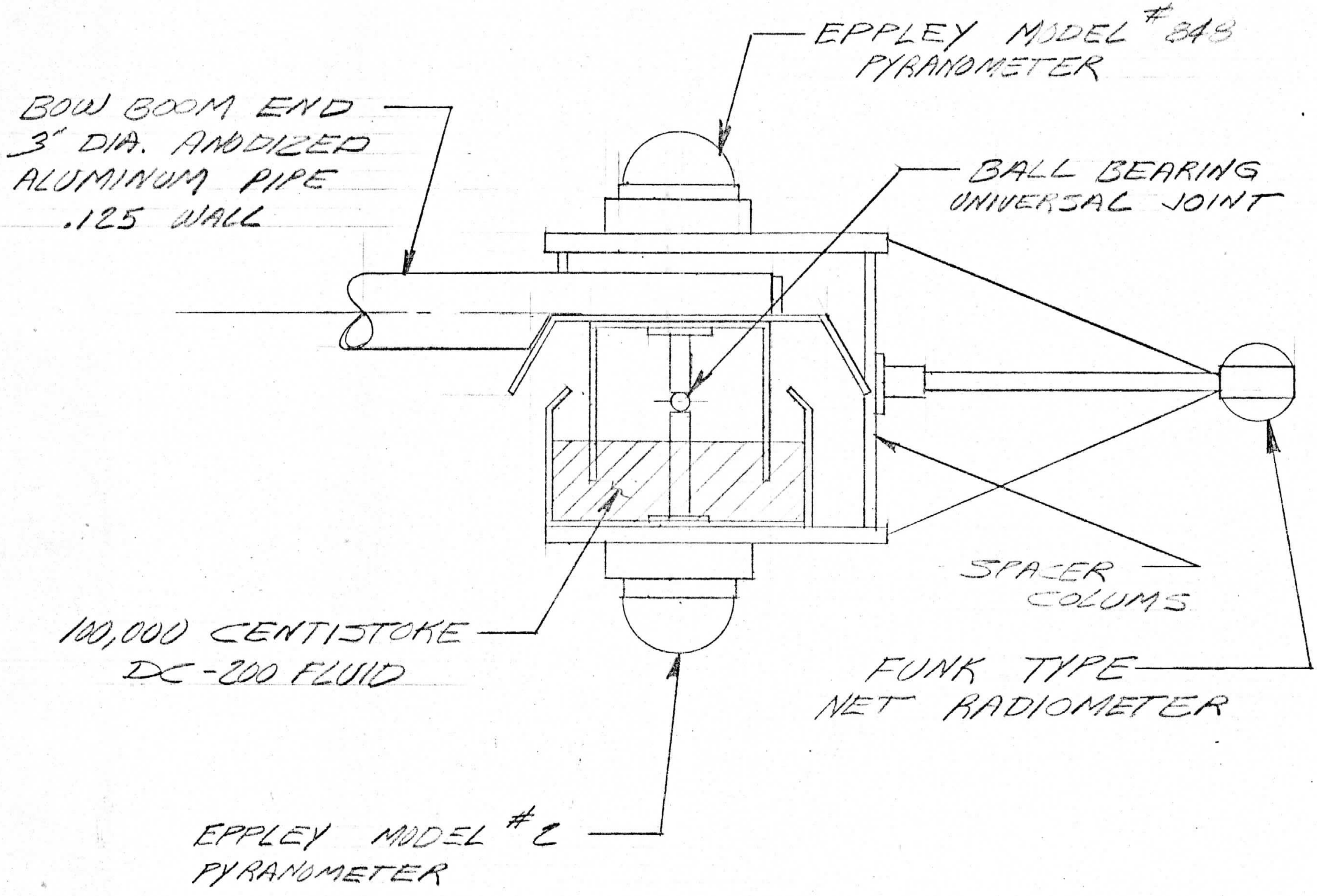


Figure 5 Radiometer Gimbal Mount

where α represents damping produced by the viscosity of the 100,000 centistoke silicone fluid. Depending upon local oscillatory conditions and ship configuration, this viscosity can be changed by using a different viscosity fluid or by changing the amount of fluid in the cannister.

This system will insure that the radiometers will always "look" in the correct average direction with up to ± 30° ship roll motion. The data from the radiometers are in analog form; however, by using a high resolution A/D converter in conjunction with previously designed BLIS electronics the data format can be arranged to be compatible with the PODAS.

F. Rain Measurement

A different technique for the shipboard and buoy mounted rain measurements is suggested.

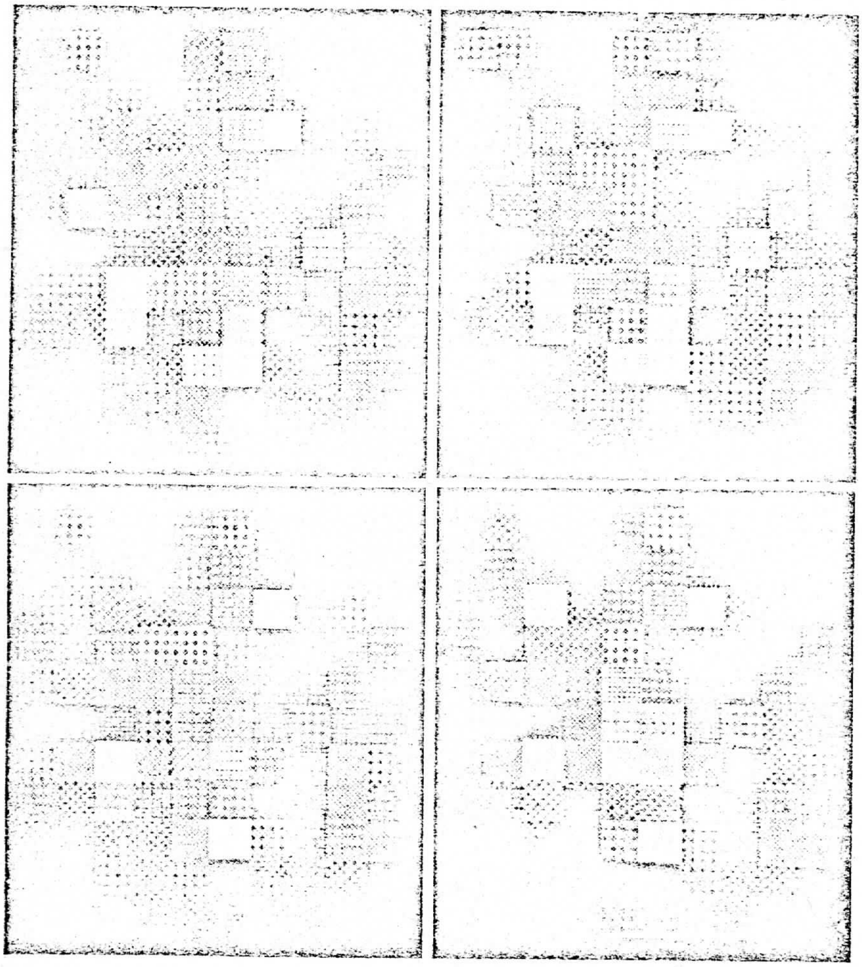
Because of the inaccuracy in any shipboard rain measurement, a commercial rain gauge, possibly gimbal mounted, located on the mast will be sufficient to obtain the required data. This rain gauge will require manual reading and dumping on a periodic schedule. A damping scheme similar to that applied to the boom radiometer mount could be used for leveling the device.

A capacitor controlled oscillator rain gauge, similar to the developed at Bell Laboratories will be used at the buoy. As shown in Figure 6, rain collected and channeled down a trough comprising a capacitor will act as a perturbation on the net capacitor dielectric constant. Since water has $\varepsilon_r = 80$, even a small quantity of rain flowing through the capacitor trough at a known rate can be detected as a frequency change in the oscillator. This oscillator could be made compatible with the pressure sensors to produce the same telemetry format.

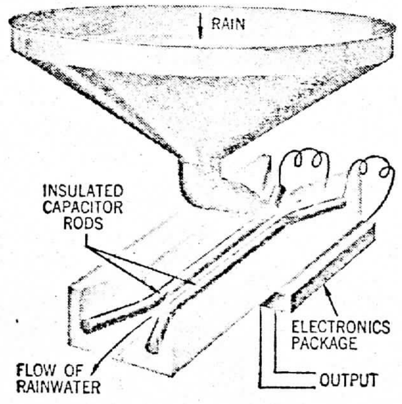
As would be expected, protection from a breaking wave or spray will be required.

Report from BELL LABORATORIES

Photos of a rainstorm



Sequence of computer-generated rainfall-rate patterns at 10-second intervals. (Order is upper left and right, then lower left and right.) Small "patches" correspond to geographic positions of 93 rain gauges. Each patch can have one of 48 computer representations of rain rate: dark for no rain, gradually brightening for increasing rainfall. Thus, each of the four frames "maps" a rainstorm in the area, and the sequence is like a motion picture. (Detailed data are recorded on magnetic tape for analysis and correlation with radio transmission characteristics, but the display gives a quick overall view.)

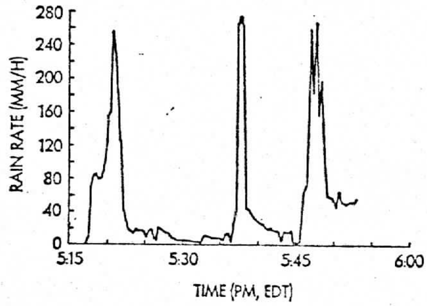


The new rain-rate gauge. Rain collected in funnel, top, flows along 45° incline between two insulated rods... the electrodes of a capacitor in an oscillator. Heavier rainfall lowers the oscillator frequency. The gauge can detect one raindrop, yet is accurate within five percent at rates of more than 10 inches per hour.

The pictures at the left represent rain on a 60-square-mile area in east-central New Jersey on November 28, 1966. Actually, they are four photos of a computer-generated display. The brightness of each little "patch" indicates the rainfall rate at each of 93 gauges spaced throughout the area.

We study rainfall because it impairs higher-frequency microwave radio transmission. But no one has had detailed data on its effects. All we had were relatively infrequent rainfall readings from a few gauges near radio paths. We needed—and now have—almost instantaneous readings of rainfall rate from closely spaced gauges over an area.

The result? We have learned a lot about rainfall—for example that heavy, small-area concentrations of rain occur and shift around within a wide-area storm. More important, we can now begin to relate rainfall patterns to specific transmission difficulties. With this information we are improving our strategies for establishing, despite the weather, more reliable radio relay paths at higher microwave frequencies.



Rainfall rate on one gauge during a storm on May 27, 1965. Note rapid response of gauge to changing intensity of rain.

Bell Telephone Laboratories
Research and Development Unit of the Bell System

G. Pressure

The scientific requirements are such that the aneroid barometer adapted to act as a pressure sensitive capacitor for an oscillator can be used for both the buoy and shipboard instrumentation. A system as described above is working well in the Boundary Layer Instrumentation Package (BLIP). The basic BLIP pressure measurement system and telemetry format can be adapted directly to the pressure measurement problem.

To obtain an accurate shipboard pressure measurement, the aneroid must be mounted in an integrating (surge) tank to minimize ship motion fluctuations. Thus this device might well be mounted in the same location as a ships' standard mercurial barometer.

The buoy mounted aneroid, although not requiring a surge tank, must be protected against the previously mentioned severe environmental conditions.

H. Upper Layer Temperature Measurement

It is very useful in studying the sea-atmosphere energy transport mechanisms to have a measure of the mean sea temperature down to a depth of about 10 meters. The temperature profile that might be expected is illustrated in Figure 7. It is proposed to measure the heat change in the layer by measuring the mean temperature in the first 10 meters. The lower limit should avoid the thermocline so that only surface effects predominate in changing the temperature. The change in heat content of a unit column in the layer can be computed from

$$\Delta H = \Delta\rho_w c_w \int_0^{10\text{ meters}} \Delta T dz \qquad \text{(H-1)}$$

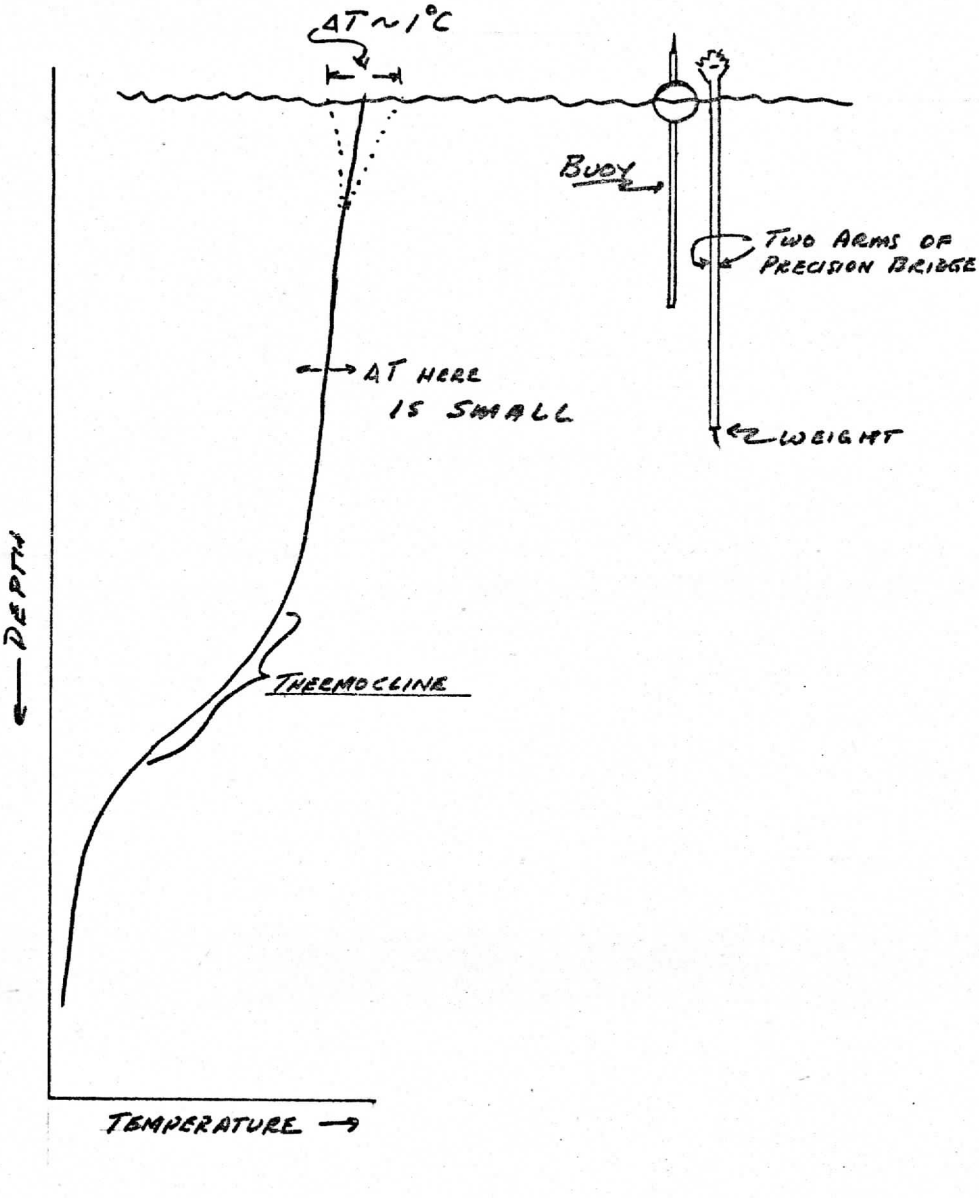


Figure 7 Schematic Representation of the Upper Layer Temperature Measurement Technique

Of course, any significant upwelling will complicate these observations; but it may be possible to separate diurnal changes due to solar input, rainfall, etc.

If 10 calories of heat were added to this layer, there would be a temperature change of 0.001°C. This would correspond to a 6 part per million change in the resistance of a length of nickel wire. While absolute values to this precision are out of the question, changes of this magnitude can be detected by using a bridge circuit as shown in Figure 7.

Since up to 300 calories can be added to a column in 1 day, highly useful measurements of this kind seem possible. Mere mixing of the surface water will not cause a temperature change but of course advection from below could.

I. Telemetry Format and Bandwidth Requirements

The present PODAS has several input channels. The total channel width assigned to BLIS has a bandwidth sufficient to acquire data from five BLIPs (15 kHz).

Each BLIP frame contains 16 words each 16 bits in length transmitted every four seconds. In the BLIP data format each pulse width is τ = 8 msec. The required bandwidth can be computed; from Schwartz (9), the bandwidth necessary to recover a recognizable pulse is given by $BW \gtrapprox 2\,(1/\tau) =$

$$\frac{2}{8 \times 10^{-3}} = 250 \text{ Hz.}$$

A 250 Hz modulating signal applied to an NBFM transmitter will result in sidebands every ± 250 Hz centered around the carrier frequency. Thus, the very minimum BLIP transmitter BW is 500 Hz for low modulation index deviations (B<<0.2). For five BLIPs, the absolute lowest bandwidth would be 5 X 500 or 2.5 kHz. Allowing for a guard band in the PODAS of at least one sideband spacing brings the minimum up to 5 kHz. The transmitter stability is good to within 10 kHz out of 400 MHz; consequently, the bandwidth for five BLIPs in the PODAS should be 5 kHz + 10 kHz or 15 kHz total. Here we assume all transmitters drift in the same direction.

The SMIS scientific requirements are such that the highest sampling rate (primarily for the wind vector) is 4 X the highest BLIP sampling rate. This implies a SMIS bandwidth using a BLIP analysis of 4 X 3 kHz BLIP of 12 kHz. To provide some margin for possible mechanically induced frequency changes due to the buoy environment and to allow for the reception of 2 pairs of sidebands, a bandwidth of 30 kHz is being specified for one SMIS channel.

It is proposed to retain the basic 16 bit/word BLIP PCM data format to allow use of BLIS compatible software in data processing and analysis. Also, the basic elements of electronic BLIS design can be retained.

J. Telemetering Link

The spar buoy will be tethered at distances on the order of one kilometer from the ship; consequently, the telemetry and power should be self-contained on the buoy. A frequency of 415 MHz has been allocated for this VHF link.

The BLIP transmitter runs 1 to 3 mW for a range of up to 2 km (line of sight). To achieve similar signal-to-noise ratios for the SMIS telemetry including the larger bandwidth requirement, the following power budget should be considered.

		Totals
1.	Heavy rain or mist attenuation at 400 MHz from a Bell Laboratory Study 10 db/km.	-15 db
2.	Bandwidth requirement as mentioned previously is X 5, or to obtain a constant $\frac{S + N}{N}$ ratio for a given power bandwidth, 7 db more signal is needed	- 7 db
3.	Assume the ship's receiver antenna gains for the BLIP and SMIS are identical	0 db
4.	Vertical colinear array to provide azimuthal symmetrical gain (over a $\frac{\lambda}{2}$ dipole)	+ 5 db
	Net decrease in power level of	-17 db

A 17 db increase in power for the transmitter of a BLIP implies a minimum power of 50 mW.

A design center of 100 mW should provide reliable data reception. This higher power will have to be considered in relation to the battery size. However, the SMIS battery constraints will be minimal compared to the BLIP.

Modulation will be pulse coded narrow band frequency modulation. However, the actual modulator design will be somewhat more involved than the BLIP transmitter because of the wider bandwidth (deviation) required. The BLIP uses a VARICAP to perturb the crystal controlled oscillator stage. This technique is limited to small deviations 1 kHz. The design of a suitable F.M. modulator to provide the larger peak phase (modulation index) deviation will not add significantly to circuit complexity or power requirements.

It is assumed that a directional antenna, will be used on the ship for both the BLIP and the SMIS buoy signals. The configuration of a spar buoy is such that a vertical colinear array should be used to provide horizontal plane power gain by compression of the high angle of radiation lobes as shown in Figure 8. Azmuthal symmetry is preserved.

In addition, because the radiation from the SMIS buoy will be vertically polarized, the ship antenna should also have the capability for a vertical plane orientation. The BLIP antennas are horizontally polarized. Thus, an added bonus is the minimization of BLIP/SMIS crosstalk because of this inherent 90° polarization rotation despite the higher radiated power from the buoy.

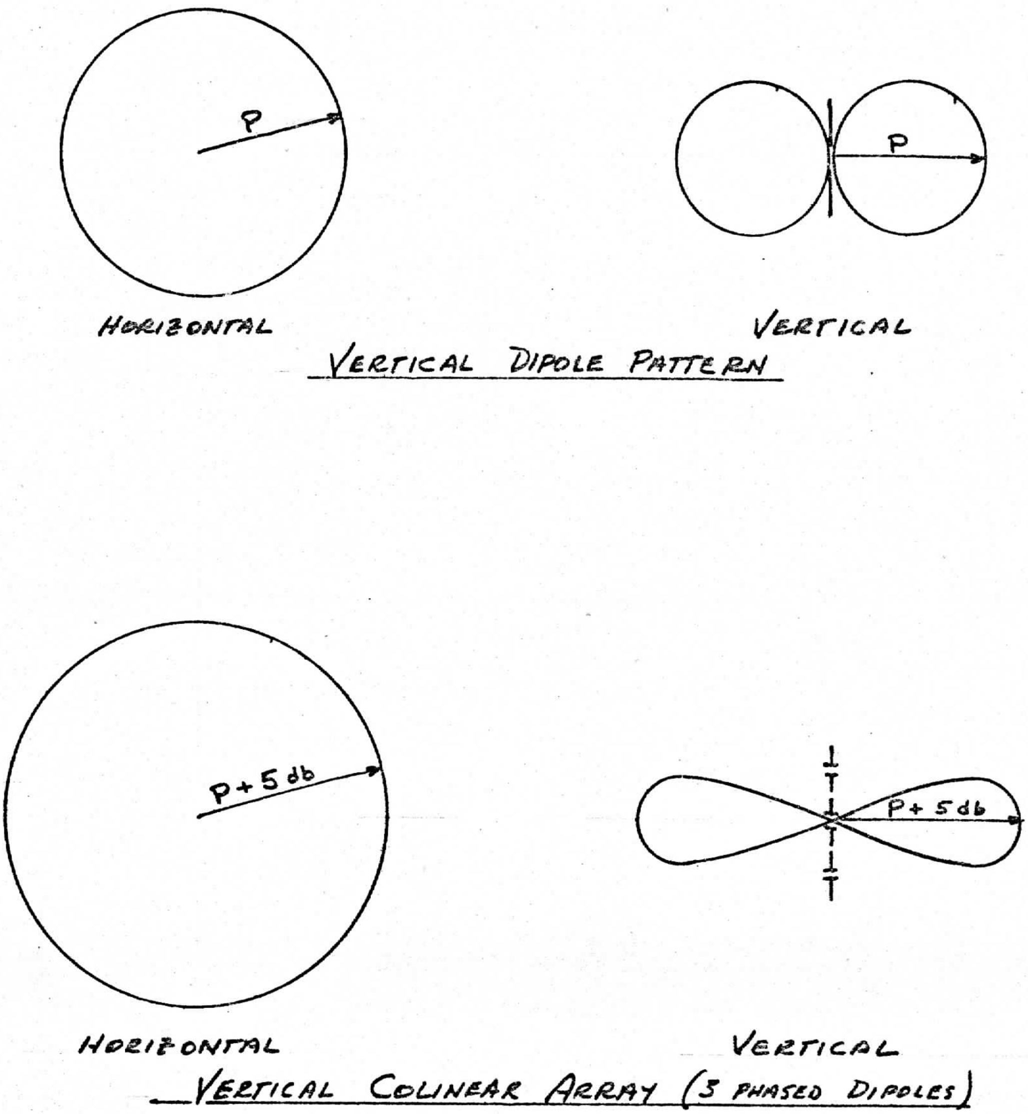


Figure 8 Buoy Antenna Radiation Pattern

VI. Summary of Recommendations

A NOAA supplied spar buoy tethered on the order of 1 km. from the ship will telemeter back in PODAS compatible format barometric pressure, dry and wet bulb temperatures at 2 or 3 levels, rainfall, the wind vector, sea surface temperature float determined, and the deep water temperature. To utilize the engineering developments obtained in the BLIS program, the basic signal processing unit on the buoy will be a ruggedized BLIP electronics pack. The above mentioned sensors will feed into the BLIP package with data being sent back to the ship via a 100 mW, 415 MHz Pulse code frequency modulated signal. It is felt that this system will allow for a great amount of flexibility in both data processing and sensor placement.

The recommended ship instrumentation will consist in part of a 10 meter bow mounted boom with three radiometers to measure up and down short wave radiation and net long plus short wave radiation. Additionally, the vapor pressure gradient and air temperature gradient will be measured by a system of three air inlets mounted on a side boom connected to a surface following float.

Using instrumentation developed for the buoy, the wind vector, air temperature (three levels), barometric pressure, and rainfall will also be measured on the ship.

By a suitable choice of sampling rates and applying sub-commutation, all of the above ship and buoy information can be accommodated in one channel of 30 kHz width.

The above described SMIS should supply useful scientific data for virtually all conditions of ship movement. These scientific requirements were given in an earlier report and have been included in the appendix.

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Appendix A

ON THE SCIENTIFIC REQUIREMENTS OF SEA SURFACE MEASUREMENTS FOR THE GARP TROPICAL EXPERIMENT

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Madison

June 1972

Interim Report on a Sea Surface Meteorological Sensing System

Task Number 2 to STAG Contract 2-35116

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SUMMARY

Sea surface measurements must serve the broad objectives of GATE - improved understanding of the role of the tropics in the global circulation and parameterization of the effects of cloud clusters in large scale numerical models - and contribute to the testing of specific hypotheses and models of disturbances: wave behavior, CISK, energy fluxes, and flux changes, parameterization of fluxes, and atmsopheric and oceanic boundary layer structure in disturbances. There is less need for accuracy in measurements than for budget studies such as BOMEX; however, measurements must be nearly continuous over periods as long as two to three weeks, and instruments and platforms must operate through some of the harshest conditions imaginable.

Fluxes of momentum, moisture, and heat are the most difficult and among the most important of measurements to be made. Based upon an intercomparison and evaluation of each of the four primary methods we recommend that fluxes be determined by the dissipation technique, with the bulk aerodynamic method used for back up and verification.

In addition to wind, temperature, and moisture, which are needed for dissipation fluxes, sea surface temperature, pressure, rainfall and radiation measurements will be made. Accuracies and sampling frequencies for all parameters except radiation are given. In addition to these core measurements we recommend that on a limited basis the spectrum of sea surface temperature should be determined by radiometric measurements from aircraft; that wave period and amplitude should be measured; and that the presence of spray should be monitored.

I. The Problem

A. Experimental objectives

Any consideration of scientific requirements for surface observations during GATE must begin with the pertinent objectives of the Experiment. J. S. Sawyer has stated these for the JOC (quoted in the Experiment Design Proposal, 1971).

> ...The primary aims of GATE are ... to extend our knowledge of those aspects of the meteorology of the equatorial belt which are essential for a proper understanding of the circulation of the Earth's atmosphere as a whole ...[and] to provide a basis upon which to develop appropriate schemes for estimating the effects of the smaller tropical weather systems on the larger scale circulations.
>
> ...[D]isturbances have important effects in producing transports of heat, momentum, and water vapor both vertically and horizontally. These must be taken into account by relating them to larger scale features of the atmospheric circulation which are adequately represented by the model. The GARP tropical Experiment has therefore been designed to provide a description of the internal structure of a number of cloud clusters, to estimate the vertical (and horizontal) transport of heat, moisture and momentum associated with the systems and to relate them to the movements of the tropical atmosphere on a larger scale. The experiment is exploratory in as much as no accepted conceptual model exists for a cloud cluster, and the experiment aims to describe the internal organization. However, the observational network in GATE will be designed to measure the bulk effects of a cloud cluster, such as the overall convergence into and divergence from it at various levels, the changes in the total vorticity of the circulation round it, the total release of latent heat and exchange of heat and water vapor between levels. An important aspect of the experiment will be the comparison of the observations with numerical calculations using dynamical models employing a fine grid. It is expected that the combined observational and theoretical approach will reveal significant aspects of the life cycle of cloud clusters with applications both to forecasting and to the understanding of the role of tropical disturbances in the general circulation of the atmosphere.
>
> The energy of tropical disturbances is largely derived from the heat input from the sea into the atmospheric boundary layer, most of it as latent heat. The energy released in a particular cloud cluster will not have been derived from the sea surface immediately beneath it, but will have been collected from a substantially wider area. Nevertheless, the effect of the cloud cluster

itself on the evaporation and heat transfer may be of significance and should be studied. Also, it is believed that the effects of frictional convergence in the atmospheric boundary play an important part in the control of the growth of organized convective systems (convective instability of the second kind - CISK) and some knowledge of the turbulent stresses in the boundary layer in different parts of the system is desirable.

Thus, although GATE is not primarily directed towards measurement of boundary-layer exchanges, measurements will be required from ships in order to establish variations in the boundary-layer fluxes of heat, water vapor and momentum which occur in association with cloud clusters - down draughts produced by the convective systems may be particularly effective in influencing the air-sea transfer processes.

Knowledge of the radiative flux divergence is of importance in the long-term control of the structure of the tropical atmosphere and may play a role in the maintenance of conditions in which convective disturbances can develop. It is therefore hoped that the GATE experiment will include sufficient radiation observations for an assessment of radiative flux divergence and its comparison with theoretical models.

B. Observational requirements

Much effort over the years has been directed toward explaining tropical weather in terms of waves. Although the focus of this wave school has recently shifted upward, there remains a good deal of interest in analyzing fluctuations of such surface parameters as pressure and wind.

In recent years several theories have been advanced to explain the existence and position of the ITCZ in terms of thermal instability related to sea surface temperature or convergence in the boundary layer related to Ekman transport, or some combination of these. The testing of these hypotheses imposes certain demands on the sea surface observational program.

The Interim Scientific and Management Group in its Experiment Design Proposal has discussed convective transport of energy in terms of four steps. It is the first of these steps - the transfer to the atmosphere of solar energy absorbed and stored in the upper layer of the sea-which concerns us here, because of reported order of magnitude increases in vertical flux within disturbances and complex interactions between the disturbance and sea surface fluxes.

Holland (1972), summarizing results from the BOMEX core experiment, argues that the observed boundary layer minimum of potential temperature, the fall off of the spectrum of temperature at frequencies below $\sim$1 cycle per 5 seconds (about 50 m wavelength) and the positive correlation of vertical fluctuations of wind with temperature and moisture - decreasing upward for temperature and increasing upward for moisture - can be explained in terms of a balance between two opposing processes. Long wave radiation, because it is controlled principally by the vertical moisture gradient, cools the boundary layer from above. This destabilization strengthens the larger scale eddies and increases the intensity of turbulence; however, the increased evaporation which results acts as a counter balance: increasing evaporation increases stability through cooling of the sea surface and the surface mixed layer of the sea. A third factor of importance in this system is the contribution of moisture to buoyancy, which up to the trade inversion typically is greater than the contribution of temperature. A too vigorous mixing may increase stability to the point where the buoyancy of moisture is suppressed.

Aircraft co-spectra of moisture and vertical wind, measured by Bean and by Miyake and Donelan (Donelan, 1970) below the trade inversion, showed a peak in the along-wind direction corresponding to wavelengths of about 1.2 to 1.9 km, changing little with height, and a sharper peak in the cross-wind direction which shifted from wavelengths of 100 to 200 m at 18 m above the sea to 500 to 1000 m at 150 m.

"The picture which emerges", Holland argues, "is one of highly elongated eddies carrying moist air up and dry air down, and having dimensions of the order of 1 to 3 km in the along-wind direction, or perhaps being even longer and oriented obliquely with respect to the wind. Their cross-wind structure seems to consist of an eddy spectrum containing a range of cross-wind scales, the scale which makes the principal contribution to the water vapor flux at each altitude increasing from about 100-200 m in the lowest 20 m to dimensions of the same order as the longitudinal wavelength as the cumulus base altitude is approached (about 500 m). These largest eddies may be in the nature of longitudinal roll vortices, with maximum energy in the cross-wind component, although the evidence on this is unclear. These eddies, in turn, contain a broad spectrum of smaller eddies, apparently in the nature of transverse vortices or plumes with predominant energy in the longitudinal direction and feeding directly on the mean shear." (Holland, 1972).

The boundary layer structure which Holland has described evidently plays an important role in determining fluxes of moisture, heat and momentum across the sea-air interface, and the redistribution of these properties within the boundary layer. Lettau (personal communication) has suggested that this boundary layer circulation of helical rolls may drive a similar circulation in the surface layer of the ocean, which, if it exists, would profoundly affect interface fluxes and the total surface heat budget. In fact, the existence of such a circulation would be confirmation of the atmospheric circulation. Lettau has suggested that precise low altitude aircraft bolometer measurements of the spectrum of sea surface temperature simultaneous with boundary layer measurements of turbulent co-spectra would constitute a sufficient test. A second matter of interest is how this model, based on measurements made in undisturbed conditions, behaves in the vicinity of a cluster. There the trade inversion is weakened or destroyed, middle and high level clouds intercept and reradiate long wave radiation, and convective downdrafts may transport large volumes of cold, dry air into the boundary layer.

An important part of the parameterization problem involves expressing near surface turbulent transport of energy in terms of synoptic scale features and the structure of the underlying surface. The observational requirements of boundary layer parameterization are stated by the ISMG (1971) as follows:

> For parameterizing the boundary layer it is necessary to obtain the measured values for vertical mass $(\overline{w'V'})$, heat $(\overline{w'T'})$ and moisture $(\overline{w'q'})$ fluxes at different heights, over sea and over land, and in different latitudes, including the equator. The vertical range should be between a level just under the surface and a height of 1 to 3 km; observations of a continuous nature or at least at two to three hour intervals, are desirable. The heat conduction of the ocean surface as well as the horizontal advection must be known. Observations of the surrounding pressure field are desirable, as well as information about insolation and long-wave radiation.
>
> The mechanisms by which the latent heat of condensation is distributed to produce overall warming of the surrounding atmosphere is one of the unsolved problems of meteorology. For its solution the vertical massflux in cumulus towers as compared to the horizontal massflux due to boundary-layer convergence must be known. This requires extremely accurate boundary-layer measurements from ships and aircraft sampling active towers. This problem is also intimately connected with the CISK hypothesis.
>
> Another sub-problem of general importance is the determination of the turbulent flux of heat and water vapor from the sea surface under conditions of disturbed weather with high winds and sea state.

C. Ground rules

Deciding what is necessary and what is merely nice becomes much easier if judgements are made on the following bases:

(1) Surface measurements support the broad objectives of GATE - they are not an end in themselves.

(2) The need for accuracy is less than for budget studies such as BOMEX.

(3) Monitoring must be nearly continuous over periods as long as two to three weeks.

(4) Instruments must operate under some of the worst conditions imaginable: salt environment, high temperature and humidity, occasional immersion, and infrequent servicing by men who in the stress of these conditions may have little skill and less motivation.

II. Parameters

The ISMG Proposal lists five basic observable quantities - wind, air temperature, relative humidity, sea surface temperature, and pressure - and accuracies of these needed for GATE (Table 6, p. 81). However, the selection of these parameters and the determination of accuracies was based upon a general atmospheric rather than a specific level point of view. As the primary reference level for GATE, the surface should be specified to at least as high a degree of accuracy and resolution as all other levels. Additionally, some of the unique and important processes occurring at the surface cannot properly be described by the Proposal measurements alone. Therefore, the measurements recommended here will be both more detailed and more stringent in accuracy and resolution requirements than those recommended in the ISMG Proposal.

The rather broadly stated experimental goals of Section I explicitly identify several parameters which must be measured, among them pressure, wind speed and direction, rainfall, air temperature and humidity, radiation, sea surface temperature, and fluxes of heat, moisture, and momentum. Because fluxes are central to the sea surface measurement program and bear heavily on measurement of the remaining parameters, the four primary methods for measuring or estimating fluxes are discussed at some length in the sections which follow.

(1) Direct eddy flux measurement. Although attractive because it avoids the theoretical complications of all other methods, direct measurement has the following shortcomings: dependence of accuracy on vertical alignment;

sensitivity to ship or buoy oscillations; sophistication of instruments and need for calibration; expense. To our knowledge no instrument is presently available which would measure dependably, continuously, and accurately in the worst of conditions likely to be encountered during GATE.

(2) Profile. The development of stabilized floating platforms has made possible fairly accurate deep water measurement of fluxes over periods as short as several minutes (Hoeber, 1969; Paulson, Leavitt, and Fleagle, 1970). Redundancy is implicit, since partial failure of the system still allows use of the bulk aerodynamic method. However, the measurement of profiles imposes severe instrumental demands. Not only are vertical gradients generally small over the sea, the layer of largest gradient adjacent to the surface must be avoided because of fluctuating, unrepresentative winds over the moving waves (Roll, 1965a) and the debilitating influence of spray and waves on instruments. Users of the profile method must therefore either carefully match and cross-calibrate multiple sensor packages, or develop a mechanism for cycling a single package through several levels. In addition to these instrumental difficulties, there remain uncertainties in profile coefficients.

(3) Bulk aerodynamic. The bulk aerodynamic method has the advantages of simplicity, familiarity, and appropriateness to tropical conditions. In its simplest form it uses standard ten meter ship observations: momentum, heat, and moisture fluxes are given by

$$\tau = \rho C_{10} U_{10}^2$$

$$H = \rho c_p C_{10} (T_o - T_{10}) U_{10} \qquad (1)$$

$$Q = \rho C_{10} (q_o - q_{10}) U_{10}$$

where C_{10} is the drag coefficient and the other variables have their conventional meaning. The bulk method is the most extensively used of all flux formulations, in numerical models of the boundary layer as well as in conventional flux studies. Garstang (1967) argues that the most restrictive of the assumptions upon which the method is based - that the turbulent exchange coefficients of momentum, heat, and water vapor are equal - are best met over the tropical oceans, particularly during disturbed weather, when the rather small departures from neutral stability which might occur are damped by the stronger turbulent mixing accompanying higher wind.

On the other hand it has been pointed out that the assumption of equivalence of eddy coefficients is invalid close to the surface where molecular transfer becomes important (Roll, 1965 b), and becomes increasingly questionable above because of buoyancy and pressure forces operating to change the scales of turbulence. (Businger, et.al., [1971] measuring fluxes and profiles over flat wheat stubble found a neutral lapse value of 1.35 for the ratio of heat to momentum eddy coefficients.) The bulk aerodynamic method also requires evaluation of the drag coefficient, about which there is a large cloud of uncertainty (Roll, 1965 b; Kraus, 1968). By definition, it depends on specification of bulk properties, and therefore may be poorly suited for revealing convective scale changes, and for accurately estimating stress when the surface wind is strong and gusty (Denman, 1972; Kraus, 1972). Wind speed, one of the most difficult measurements to make at sea, enters the bulk aerodynamic equation for stress as a squared term, and is present in all terms in any formulation where the drag coefficient is dependent on the Richardson number. This may be a critical limiting factor in an experiment such as GATE, where the ships will probably operate in a station keeping mode, adding ship motion errors to instrumental errors.

Results from BOMEX reinforce these reservations. Cain (1972) used surface winds measured by hot-film anemometers mounted on R. P. Flip to evaluate the drag coefficient. He concluded, "...due to the scatter in values of the drag coefficient obtained ... the bulk aerodynamic method should be used only as a very rough approximation to the wind stress, useful only because of its simplicity." Pond, Phelps, Paquin, McBean, and Stewart (1971) measured wind with a sonic anemometer mounted on Flip. The scatter of their drag coefficients for stress was somewhat smaller than Cain's, however, the drag coefficient computed for latent heat flux was 15% smaller than the coefficient for stress. Heat flux was so poorly related to $U\Delta T$ no estimate was made of the drag coefficient for sensible heat. Pond, et.al., concluded, "For the BOMEX data we must regard only the eddy flux values as reliable (to 10-15%) and accept the fact that the aerodynamic approach is not useful."

(4) Dissipation. In the fourteen years since it was first suggested by Deacon (1959) as a way of circumventing some of the difficulties of measuring wind at sea, the dissipation technique has rooted and flowered within a number of research groups and experimental situations. We develop the dissipation flux relations from the turbulent energy equation,

$$\frac{\tau}{\rho} \left|\frac{\partial U}{\partial z}\right| = \varepsilon + \frac{g\overline{\rho' w'}}{\rho} + \frac{1}{\rho}\frac{\partial}{\partial z} (\overline{p'w'}) + \frac{\partial}{\partial z} (\overline{Pw'}), \qquad (2)$$

which equates the turbulent energy generation from the mean shear flow $\frac{\partial U}{\partial z}$ to the dissipation per unit mass plus the buoyancy production, the transfer to waves via the Miles mechanism, and the divergence of vertical flux of turbulent kinetic energy P (Kraus, 1968). Each of the last three terms ordinarily is small. Over the tropical ocean, with lapses neutral or near neutral, the buoyancy term can be neglected and at 6 to 10 m the wave generation term can be neglected. Although little is known about the last term, it is generally considered to be minor (Kraus, 1972). Thus, with the logarithmic law the dissipation can be expressed as

$$\varepsilon = \frac{1}{z\kappa}\left(\frac{\tau}{\rho}\right)^{3/2}, \qquad (3)$$

where κ is the von Karman constant.

The Kolmogoroff law relates the spectrum of energy in the inertial subrange of isotropic turbulence to wave number k, dissipation, and a universal constant K:

$$\phi(k) = K\varepsilon^{2/3}k^{-5/3} \qquad (4)$$

Combining (3) and (4) and noting that by definition $\tau = -\rho\overline{u'w'}$, we get

$$-\rho\overline{u'w'} = \tau = \rho K^{-1}(\kappa z)^{2/3}k^{5/3}\phi(k). \qquad (5)$$

Since we seldom have the temporally and spacially continuous observations that are needed to specify the spectrum $\phi(k)$, structure functions are defined which exploit known dynamic or kinematic relationships between wave numbers and frequencies (Kraus, 1972). Cain (1971) discusses three primary structure functions which are based on differencing measurements of two sensors aligned along the mean horizontal wind, differencing measurements of two sensors aligned across the mean wind, and differencing successive measurements made by a single sensor. The latter method is based on Taylor's hypothesis, that the local frequency of turbulent eddies is equal to their streamwise wave number times the speed of the mean flow. It has the obvious advantage of requiring only one set of sensors; recent users include Cain (1971), Pond et.al., (1971), and Denman (1972).

Pond et.al., present a single sensor structure function for the down stream velocity spectrum $\phi(k)$, defined as

$$D_{uu}(r) = \overline{[u(x+r) - u(x)]^2} = 4.02K\varepsilon^{2/3}r^{2/3}, \qquad (6)$$

where $r = -Ut$, by Taylor's hypothesis. Substituting the expression for dissipation from Equation (3) and reordering gives the following expression for the horizontal stress:

$$\tau = \rho(4.02K)^{-1} (z\kappa)^{2/3} (Ut)^{-2/3} D_{uu}. \tag{7}$$

The structure function for scalar properties γ (temperature or humidity) is

$$D_{\gamma\gamma} = \overline{[\gamma(x+r) - \gamma(x)]^2} = 4.02K_\gamma N_\gamma \varepsilon^{-1/3} r^{2/3}, \tag{8}$$

with K_γ the Kolmogoroff constant for scalar fluctuations.

N_γ, the dissipation of the scalar fluxes, is set equal to production

$$-\overline{w'\gamma'} \frac{\partial\overline{\gamma}}{\partial z} = N_\gamma. \tag{9}$$

In analogy to the logarithmic law for velocity we have for the vertical gradient of the mean scalar $\overline{\gamma}$

$$\frac{\partial\overline{\gamma}}{\partial z} = \frac{\gamma^*}{z} = -\frac{\overline{w'\gamma'}}{(\kappa u^*)} \cdot \frac{1}{z} = -\frac{\overline{w'\gamma'}}{\kappa z\sqrt{\tau/\rho}}. \tag{10}$$

Combining Equations (10) and (9) gives for the dissipation of scalar fluxes N_γ

$$N_\gamma = \frac{(\overline{w'\gamma'})^2}{\kappa z\sqrt{\tau/\rho}}, \tag{11}$$

which, when combined with Equations (8) and (3) yields an expression for the scalar flux

$$\overline{w'\gamma'} = (4.02K_\gamma)^{-1/2} (\kappa z)^{1/3} (Ut)^{-1/3} D_{\gamma\gamma}^{1/2} (\frac{\tau}{\rho})^{1/2}. \tag{12}$$

The expressions (7) and (12) for fluxes of momentum, moisture, and heat have been modified by Pond et.al., (1971) to include the buoyancy term of the turbulent energy equation. Pond et.al., also discusses the Kolmogoroff constants K and K_γ, both of which seem now to be fairly well established.

The dissipation technique, and the assumptions upon which it rests, were quite extensively tested by several research groups during BOMEX. Except for temperature, spectra and cospectra generally had well defined inertial subranges. (Phelps and Pond, 1971; Pond et.al., 1971; Cain, 1971). It has been suggested by Phelps and Pond that the anomalous behavior of temperature is related to the long wave radiative influence on temperature gradients and large scale fluctuations which becomes important when moisture content is high. However, they also point out that the high frequency end of their temperature spectrum appeared to be at the edge of an inertial subrange. Gibson, Stegen, and Williams (1970) looked at this high frequency portion of the temperature spectrum, up to the viscous cut off. The shape of their spectrum indicated an inertial subrange, but anisotropy was indicated by a skewed distribution of the temperature distribution. However, Holland (1972) reports that Wyngaard has suggested the skewness resulted from an instrumental effect. Predictably, in view of this spectral behavior, the dissipation method during BOMEX compared well with eddy correlation and profile methods in estimating momentum and moisture fluxes, but stumbled on sensible heat. Holland (personal communication) has suggested that estimates of sensible heat flux might be improved if sampling occurred at ten times the "natural" frequency $\frac{U}{z}$. A second possibility for improving estimates of sensible heat flux is use of the Bowen ratio, which Pond et.al., found to be quite constant at 0.10 for their BOMEX data.

Partial results from the Bahama Banks Experiment of 1971, kindly loaned by Miyake, are, if anything, more encouraging than results from BOMEX; an inertial subrange appears to be present in spectra of moisture, temperature, and each velocity component.

III. Recommendations

The primary advantage of the dissipation technique over the bulk aerodynamic technique is its dependence on a universal constant (which is fairly well known) instead of an uncertain coefficient (which is a function of height and surface structure at least). It is far less demanding of instrumental sophistication and technique than the profile method; and more forgiving than either bulk or profile methods of errors in wind speed, which over the ocean are compounded by wobbles and unknown translational motions of the platform. We consider these advantages to be decisive, and therefore propose to estimate fluxes using the dissipation technique.

The bulk aerodynamic method will serve to back up and verify dissipation estimates of fluxes; comparisons with the dissipation technique may lead to improvements in both methods.

Besides wind, air temperature, and moisture (which are needed for dissipation fluxes) sea surface temperature, pressure, rainfall, and radiation measurements will be made. Accuracies and sampling frequencies for all parameters except radiation are given in Table 1. These accuracies and frequencies are governed by the needs of flux estimations in the case of wind, temperature, and moisture. Sea surface temperature, although not needed for dissipation estimates of the scalar fluxes, is included because of its importance to the oceanographic subprogram, and the parameterization of fluxes, its control on stability, and the need to explore interactions between sea surface temperature, boundary layer structure, and convection. Accurate surface pressure is important as a reference for soundings, but if measured to the accuracy specified it will also give insight on the response of the surface wind field to unbalanced pressure forces. With data from the Boundary Layer Instrumentation System, it is possible to vertically integrate cross-isobar flow and so arrive at an estimate of the boundary layer stress, independent of the dissipation estimate. The requirements for accuracies in estimating divergence and vorticity are noted separately in Table 1. Radiation is not considered explicitly as specifications have already been made.

For removing the effects of platform oscillation from observations of wind and rainfall and for correction of wind spectra which close to the surface may show some influence of waves we recommend monitoring wave period and amplitude. The laboratory experiments of Okuda and Hayami (1959), showing a sharp increase in evaporation rate as wind speed exceeds the threshold for spray formation, suggest that the presence of spray should also be monitored.

TABLE 1

SEA SURFACE MEASUREMENTS FOR GATE

PARAMETER	PURPOSE	ACCURACY	SAMPLING FREQUENCY	REMARKS
horizontal wind speed	fluxes	±3% (abs)	1 sec^{-1}	
	divergence	±.5m/sec (abs)*	1 hr^{-1}	
wind direction	fluxes	2-3° (abs)	1 sec^{-1}	
	divergence	3° (abs)*	1 hr^{-1}	
moisture	moisture flux	0.1°C (dewpt) (abs)	1 sec^{-1}	same level as wind
air temp	heat flux	0.1°C (abs)	∿ 10 sec^{-1}	same level as wind
		0.02°C (rel)		
sea surface temp	boundary layer dynamics	0.01°C (rel)	∿ 10 sec^{-1}	aircraft mounted radiometer; simultaneous with aircraft spectral measurements of w', T', q'; occasional basis
	fluxes; oceanographic program	0.05°C (abs)	1 sec^{-1}	
		0.02°C (rel)		
pressure	stress non-geostrophic pressure forces	.1 mb (abs)	.02-.04 sec^{-1}	long sampling frequency smooths high frequency ship-oscillations
rain	heat budget	.5 mm	8 day^{-1} or more	

*based on ship spacing of 150 km, disturbance divergence of 10^{-5} sec^{-1}, 10% accuracy in the measurement of divergence, and an error of .2 - .3 m/sec resulting from platform drift.

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