A DESIGN FOR VELOCITY MEASUREMENTS

IN THE GULF STREAM

by

DENNIS NOSON

Submitted in Partial Fulfillment

of the Requirements for the

Degree of Bachelor of Science

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June, 1968

Author . . . . . . .
Department of Geology and Geophysics
May 17, 1968

Thesis Advisor . . . . . . .

Accepted by . . . . . . .
Chairman, Departmental Committee on Theses

# TABLE OF CONTENTS

Abstract 3

Introduction
  The problem 4
  The solution 5

Review
  Gulf Stream studies 8
  Measurement techniques 12

Definition of the Problem
  Scope of the inquiry 15
  Limitations of practicality 17

Solutions
  Spatial arrangements 22
  Time sampling 31
  Some final variations 33

Conclusion
  Inadequacies 36
  Recommendations 37

Acknowledgements 39

Bibliography 40

## ABSTRACT

In consideration of the oceanographic problem of making time-dependent studies of the Gulf Stream, a system of moored current meters is developed. Restrictions imposed by costs and by the physical size of the current help to define a suitable configuration. A cross-shaped pattern of buoys is selected as the solution posessing a majority of desirable characteristics. Problems of data collection and storage are also taken into account. It is recommended that before any similar system is constructed, some preliminary needs be satisfied: a measurement of the power spectrum of the processes in the Gulf Stream and an improvement in the durability of buoys anchored in swift currents.

# INTRODUCTION

## The Problem

The efforts of oceanographers are presently turning away from synoptic surveys of ocean currents to the problem of investigating time-dependent phenomena at all possible scales of frequency, length, and amplitude. Of prime importance is the study of the velocity field in the Gulf Stream. This same study has been prominent in the past as well as the present.

Restriction of the problem to velocity measurements conducted in a strong current makes the solution more difficult, but hopefully the solution will subsequently be a generally applicable technique of analysis— one that could be expanded to considerations of the temperature, salinity, or pressure fields of the ocean.

This is not to say that the Gulf Stream is a typical and representative phenomenon; but the methods used in analyzing the problem might be a useful basis for a future, enlarged program.

The goal is a new, limited measuring system that will improve the present ability to define the velocity field and the dynamic processes in the Gulf Stream. The system must be limited by practicality to spatial scales on the order of $10^{-1}$ to $10^{-2}$ kilometers and to time scales of the order of $10^{0}$ to $10^{7}$ seconds (one year).

The limits of practicality encompass such factors as the state of instrument and equipment technology, financing, time and manpower resources, the capacity for data storage and analysis, and the type of information which is to be given priority. For example, priority might be given to data pertinent to theories predicting velocity fields.

The restriction imposed on the system by technology, money, and manpower will be treated in an idealistic and rough-mannered way; more emphasis will be placed upon the basic science involved in the solution— the theoretical and empirical character of the measuring system, the presently understood nature of the Gulf Stream, and the effect of the configuration of the system on the applicability of the data to theories of physical oceanography.

## The Solution

The problem of investigating phenomena in the Gulf Stream depends upon the selection of an instrument capable of direct, Eulerian, and automatic measurement of the velocity field without unnecessary restriction to synoptic results. The best of the currently available instruments satisfying these needs is the moored current meter, deployed in some spatial array to measure cross-stream and downstream velocities and their changes with time.

The process of refining the solution, from an initial, three-dimensional, rectangular lattice array to a more resourceful and sophisticated arrangement of current meters, results in a tentative answer to the choice of an array— a horizontal, cross-shaped pattern of buoys, each suspending a vertical line of current meters. This choice gives information about cross-stream and downstream spatial variations and correlations of horizontal velocities in space and time. It provides data of the same nature as the rectangular lattice without being nearly as large and costly.

The problem of fathoming time-dependent processes manifests itself in the new problem of determining how the velocity data can best be sampled by each current meter. Limitations imposed by the data storage and analysis capacity of the instruments eliminate collecting values at the rate of $10^{0}$ sec.$^{-1}$ for $10^{7}$ seconds; and the phenomenon of aliasing, in which the highest frequency amplitudes are added (by the nature inherent in discrete sampling) to the amplitude of the lower frequency fluctuations, prevents studying long-period processes by sampling at a lower rate, say $10^{-2}$ sec.$^{-1}$. Either a new instrument with no response to high frequency signals is required; or it is possible to use a filtering technique that collects data in bursts and averages the bursts, thus meeting the storage and handling problem— Webster (1967).

The above solution is not completely satisfactory because the rate of sampling and prevention of aliasing are dependent upon knowledge of the characteristic power spectrum of Gulf Stream processes. Until this spectrum is known, no one can be sure the information from the system is valid.

At the present time, minor difficulties (in the rough, ideal sense) concerning buoy technology and applicability of data to theories, together with the unknown spectrum problem, dictate that the program should wait until these obstacles are cleared away.

# REVIEW

## Gulf Stream Studies

In preparation for a detailed description of the proposed moored buoy system, it is helpful to see how the problem of exploring the Gulf Stream has been approached in the past and to point out the inadequacies of these efforts.

Perhaps suggesting the historical similarity of the means of investigating current velocity fields, Pillsbury (1891) launched one of the first serious efforts to gather velocity data using cross sections transverse to the Gulf Stream current axis and his own ship-supported current meter. His method is duplicated by the moored buoy system except for an added longitudinal section of buoys. However his section required nearly two years to complete— it was not even a quasi-synoptic survey. His results provided averaged transport calculations and a general indication of the transverse gradient of downstream velocity, among other things.

The first extensive surveys of the Gulf Stream were made by Iselin (1936) from the Atlantis. His sections were made from hydrocasts; he made use of the usual assumptions for calculating velocities. The width of Iselin's sections were about 500 miles and the station intervals 25 miles; they were made in the vicinity of Long Island to Bermuda. The time necessary for one of these sections was three or four days— a marked improvement over the duration of Pillsbury's measurements, but still far above the more ideal time sampling interval of the moored buoy system. Iselin's sections gave a rough, quasi-synoptic definition of the transverse temperature and salinity structure, but the sections contained only five or six stations in the Gulf Stream itself. Since the geostrophic approximation furnishes only velocity shear profiles, to obtain the absolute velocity requires assuming a level-of-no-motion (which was taken to be 2000 meters). The proposed buoy scheme would eliminate these undesirable assumptions.

A step toward describing the time-dependent nature of the Gulf Stream was taken by Iselin (1940) when a series of sections— similar to those of 1936— were made for two and one-half years. He had hoped to measure long-term fluctations of transport; but since the results were dependent upon the representativeness of the monthly sections for each particular month and since work was not possible during some winter periods, the result was inconclusive. The fluctuations of velocities and transport within any given month, he argued, were probably much larger than any annual variation; and it was pointed out by Iselin and Fuglister (1948) that any long-term averages taken in this manner would be of minimal value in terms of the understanding of the Gulf Stream's nature. Note that the proposed system is the same technique used by Iselin, differing by virtue of shrunken time and space sampling intervals. The buoy plan hopes to eliminate inconclusive results.

The multiple-ship survey, described by Fuglister and Worthington (1951), was conceived as a new plan for improvement of the synoptic picture of the Gulf Stream. With the advent of the GEK to measure surface currents and the bathythermograph to measure the temperature field to 300 meters, the ships were able to trace out the path of the main current from Cape Hatteras to the Grand Banks— 2000 miles.

Yet even with the GEK, the BT, and the new survey technique, which supplanted the old Gulf Stream picture compiled from ten years of hydrographic data, the improved synoptic map was still open to ambiguities of interpretation. Fuglister had an even harsher feeling about the validity of this method:

> Theoretical conclusions concerning downstream changes in physical characteristics of major ocean currents will frequently be erroneous as long as the present conglomeration of time and space scales is used to describe the currents.*

The problem of ambiguous spatial features and indeterminate time variations was partially solved by the ability to make detailed sections at the rate of three per day with the BT and GEK. Von Arx, Bumpus, and Richardson (1955) presented data from two week' serial sections off Onslow Bay, a region where the amplitude of Gulf Stream meanders is small. Even with its improvements, the serial section method is not sufficient; it lacks information at depths

---

* Fuglister (1955), p. 228.

below 300 meters and still depends upon the hydrographic assumptions to calculate velocities. Each section takes too much time to complete, and the sections are not done frequently enough to prevent losses of information due to the quasi-synoptic character of the data and to aliasing.

The latest large survey of the Gulf Stream added little to solving the problem of time-dependent measurements. Gulf Stream '60, as it was called by Fuglister (1963), produced a synoptic summary of the current as well as concentrated efforts on small areas. The survey again pointed out the need for less spacious separation of stations in a program of any scale— sections were 100 miles apart and stations 20-40 miles apart.

Stommel (1965b) indicated in a comparison of eight ship-survey plans that the most valuable methods were serial sections and multiple-ship mapping of a current's position. Neither of these methods provides information over a wide range of space and time scales.

Studies in the past have emphasized the transverse profile of velocity and have shown a trend toward serial sections and small-scale measurements. The buoy scheme may furnish a first culmination to these trends which eliminates the drawbacks of past investigations.

Measurement Techniques

So far consideration has been given to the use of instruments in conjunction with ship surveys and not to the instruments themselves. Chart I shows a listing of some instruments currently employed for velocity measurements, on one axis, and the characteristics most needed for a study of time-dependent processes, on the other.

The requirement that the velocities be measured in an Eulerian manner is basically derived from the inconvenience of handling Lagrangian data. Reid (1965) states that Eulerian measurements are conducive to automatic collection and storage and can be used to estimate turbulent fluxes of momentum and energy while Lagrangian data cannot.

It is necessary that measurement taken at frequent intervals for long periods be made for a valid study of Gulf Stream processes. Long-period phenomena are known to be inherent in oceanic currents; aliasing would ruin data gathered at too low a frequency. Because of this, too many men, ships, and machines and too much time would be required by manual measurement, so presumably an automatic data collection system is best.

One of the most important criteria is directness of measurement. Theoretical approximations are presently made without verification of the theory; the processes must be defined on a basic level first, then theories can be safely used.

# CHART I

## A COMPARISON OF INSTRUMENTS

| | EULERIAN | PROTRACTED MEASUREMENT | CONTINUOUS MEASUREMENT | SELF-PERFORMING | NO SHIP | DIRECTNESS | ALL-DEPTH MEASUREMENT |
|---|---|---|---|---|---|---|---|
| hydrocasts, BT | ⊕ | O | O | O | O | O | ⊕ |
| GEK | ⊕ | O | ⊕ | O | O | O | ⊕ |
| Richardson & Schmitz | ⊕ | O | O | O | ⊕ | ⊕ | ⊕ |
| LORAN: ship drift | O | O | O | O | O | ⊕ | O |
| Swallow floats | O | ⊕ | ⊕ | ⊕ | ⊕ | ⊕ | O |
| moored meters | ⊕ | ⊕ | ⊕ | ⊕ | ⊕ | ⊕ | ⊕ |
| ship-supported current meters | ⊕ | O | ⊕ | O | O | ⊕ | ⊕ |

O - Instrument system does <u>not</u> have this attribute
⊕ - Instrument system has this attribute

REFERENCES:

Von Arx (1950)
Swallow (1961)
Richardson and Schmitz (1965)
Stommel (1965a)

Finally any instrument restricted to measurements of surface variables necessarily reduces the understanding of three-dimensional processes. Hence the instrument should have the capability of measurement in the vertical.

The obvious conclusion form the chart is that moored current meters have more of the desirable attributes than any other instrument system. Although the chart exaggerates the relative value of the instruments, the result is clear. Of course some features were omitted, such as large-scale synoptic capability; but most of those omitted were essentially unnecessary to the stated purpose— understanding time-dependent phenomena.

# DEFINITION OF THE PROBLEM

## Scope of the Inquiry

How should the approach to understanding oceanic velocity fields be restricted? Stommel points out that

> ... we must propose to answer certain specific questions, and the strategy of exploration, the disposition of ships and buoys, and so on, must be designed with a view to obtaining quantitative, statistically significant answers to these questions.*

So the first general definition of the problem could be an explanation of designing the physical arrangement of the proposed system— the system which should be a catalyst for the next step in building knowledge about the ocean's currents.

It has been assumed that the velocity field is the one variable of concern. Of the possible choices of variables— salinity, pressure gradient, density, velocity, temperature, refractive index, and so forth— the decision to consider just one (velocity) was made for the following reasons: (what about pressure gradients?)

1. Dynamic processes in ocean currents are most directly related to the velocity field.

2. Techniques and information derived from the analysis of the velocity-measuring problem might be easily applied to consideration of the remaining variables.

3. The loss of generality from selecting a single

---

* Stommel (1963), p. 572.

> variable should be negligible compared with the advantage of the consequent simplification.

An argument against this choice is that the overwhelming majority of past data is in terms of temperature and salinity. But again, the necessary break with the geographic efforts of the past implies independence from older, synoptic data and a stronger tie with time-variation data. Time-dependent measurements of the past are, as was pointed out, an inadequate basis for understanding the phenomena.

The plan should be designed to evaluate suspected or known processes as well as variables. Since theories will probably be advanced for many kinds of processes, it should be assured that the information to be collected by the system is not biased or specialized by the collection technique. So the spatial and temporal limitations of the moored buoy experiment should be a matter of magnitudes rather than spatial directions or time continuity. However, mandatory qualifications will be made on this requirement in the next section.

Stommel (1963) emphasizes that we should be concerned with a non-synoptic picture of the velocity field.

> To achieve "physical understanding" we must map not only the variables but also their interactions (that is, we must map spectra of Reynolds stresses, and so on).*

In describing processes Reid (1965) suggests the data be oriented toward a determination of horizontal fluxes and temporal spectra of the variables in both downstream and

---

* Stommel (1963), p. 575.

cross-stream directions, and the departure of currents from baroclinic, geostrophic values deduced by classical methods. These parameters would be useful in the formulation and evaluation of ocean current theories.

Finally the Gulf Stream has been selected as the general phenomena under examination because it is much easier to measure variables of large amplitude and because the Gulf Stream has been the object of many earlier investigations and is an intriguing phenomenon *per se*.

To summarize, the initial problem has been defined as designing a current measuring system, modified by stipulating that the data should be oriented toward describing interactions in a generally useable manner and by choosing the Gulf Stream as the site of the proposed system.

## Limitations of Practicality

Selecting practical limitations further defining the problem is somewhat arbitrary and depends upon how close to reality the theoretical solution should be. Since the key item, the moored current meter, is already available, one would expect that the plan should be developed keeping in mind the idea of implementing the system in the near future.

The most obvious limitation is cost. Available annual support for a large oceanographic program is on the order of $10^6$ dollars. If the duration of the proposed scheme were two years, the total amount available should double.

But beyond this amount of time, it becomes questionable that more money would be forthcoming without a complete evaluation of the success of the experiment beforehand. Here is another reason for proceding with the investigation in steps, as mentioned before (p. 15).

A consequence of the finite funding of the program is a restriction on the size of the system. Since the data will be taken in the current, the first approximation to the scale of the buoy array would be the dimensions of the Gulf Stream. As will be seen later, the financial limitations dictate that the overall dimensions each be scaled down by an order of magnitude, or so. A minimum set of dimensions can be found through an argument of comprehensiveness, which is defined in terms of the magnitude of the areas mapped on a period-length diagram by the various plans.

The period-length diagram, also termed the Stommel diagram, was introduced by Stommel (1965b) to compare the areas of the oceanic velocity field mapped out by different types of ship surveys. The ordinate of the diagram is the $\log_{10}$ of the spatial scale (or wavenumber) limits, and the abscissa is the $\log_{10}$ of the time (or frequency) limits on the measurements. The size of the area thus determined is a measure of the comprehensiveness of the data collected under the given sets of spatial and temporal limitations. As shown in Fig. 1, the area mapped by four types of multiple ship surveys can cover only a small portion of the

# Ship Surveys and Hydrographic Data

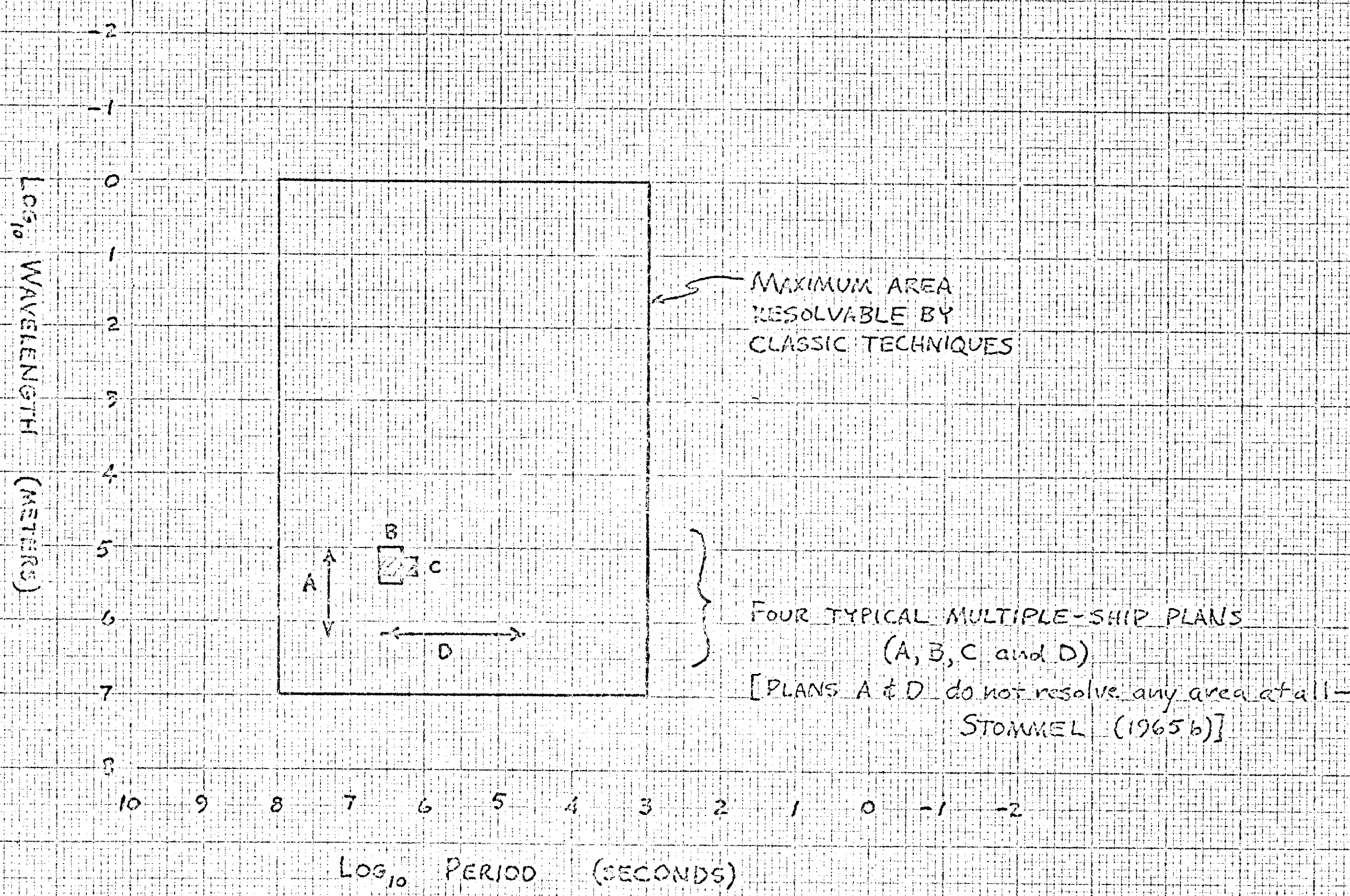



Fig. 1

total area that could possibly be mapped by means of hydrocast data. The basic limitations of hydrographic methods, which define the limits of the larger area, are the time-lag and space-average character of the reversing thermometer and the properties of geostrophic calculations.

Since one of the main objectives of developing a new system was to define dynamic processes over a maximum possible range of space and time scales, one would hope that the area mapped by the moored buoy system be significantly larger than any of the smaller areas (A, B, C, or D) in Fig. 1, say two orders of magnitude for both the space and time dimension. Therefore the spacing of data points in the cross-stream direction must have a maximum of about $10^0$ kilometers, since the Gulf Stream is approximately $10^2$ km. in width. But measuring at intervals of one km. does not determine spatial fluctuations of one km. wavelength. To eliminate underdetermination at both ends of the scale, the spatial interval mapped on the Stommel diagram must be about an order of magnitude smaller than the actual physical scale of spatial limits. For example, if data were collected at $10^0$ km. intervals over a span of $10^5$ km., then the interval mapped on the diagram would be $10^4$ km. The same argument can be applied to time limits.

The preceding reasoning shows that the size of the experiment would be much smaller than the Gulf Stream, so a site for the system must be selected. Reid (1965) chose the Blake Plateau because of its reasonable depth, nearness to land bases, and the confined meandering of the current in that location. Beyond Cape Hatteras, the range of the Gulf Stream's positions would be greater than the dimensions of a fixed system. However, the specific site on the Plateau should be far enough away from Florida, somewhere on the northern reaches, where some of the meandering character can be studied; the straits to the south are too confining. And for reasons that will be made clear, the segment of the mean Gulf Stream path occupied by the buoy system should be rectilinear. From a chart of the mean axis of the current, the only suitable location would be anywhere along a line from (31°N, 79°W) to (34°N, 76°W), approximately 200 to 300 nautical miles in length.

Finally it must also be kept in mind that the system is primarily intended to be a basis for more ambitious programs in the future and that the experiment need not delineate all scales of motion.

With the above limitations, a final statement of the problem can be phrased as follows: The problem is to design a current measuring system to be placed in the Gulf Stream over the northern Blake Plateau, to be aimed at defining interactions of various scales of motion in a generally useful way, and to be delimited in size by costs, comprehensiveness in terms of the Stommel diagram, and an awareness of the plan's preliminary nature.

## SOLUTIONS

### Spatial Arrangements

So far the need for a new technique or a new system for collecting oceanographic data has been elucidated. The development of moored current meters has been shown to be a major breakthrough toward staisfying the requirements of an ideal system. Richardson, Stimson, and Wilkins (1963) have given a comprehensive, general description of the moorings and the current meters now in use.

What must now be investigated is the spatial deployment of the stations and the current meters at the chosen site.

First consider the possible types of arrangements. The choices can be classified according to the following scheme:

I. Uneven spacing of current meters

II. Even spacing
   - A. Hexagonal pattern
   - B. Cubic lattice
   - C. Rectangular lattice

The first choice should be eliminated because uneven spacing of data points does not lend itself to any well-defined method of data analysis— Webster (1965). But there is some motivation for an extra concentration of moorings (or stations) at particular locations in the Gulf Stream. Webster (1961) has portrayed the meanders of the current off Onslow Bay, viewed along a fixed, cross-stream line, as unsteady motion. The current had a tendency to be centered at a particular point on this line for several days and then move slowly off-shore for about four days and then return quickly in about two. The cycle takes around seven days. The unevenness of the shifting mean axis of the current suggests that an unequal concentration of velocity meters might be required to give equal information about characteristic segments of the velocity field at all times.

Assuming that evenly spaced arrays have been selected, differentiation among hexagonal, cubic, and rectangular still remains. The nature of the current itself compels one to reject the hexagonal arrangement of sensors in favor of the orthogonal— the three perpendicular axes labelled downstream, cross-stream, and vertical.

Because of the essential inequality of the three axes, one would expect the spacing not to be the same in one direction as another. The natural dimensions of the current are unequal and so are the gradients of velocity in the three directions. The choice lies with the rectangular array, but what value should be given to the ratio of the total dimensions ($\frac{x}{y}$) or to the ratio of the intervals ($\frac{\Delta x}{\Delta y}$) will be at best an educated guess dependent upon practical limitations.

For purposes of comparison, postulate the following solutions to the spatial arrangement problem: a solid, rectangular lattice; a planar array; and a horizontal, cross-shaped pattern of buoys.

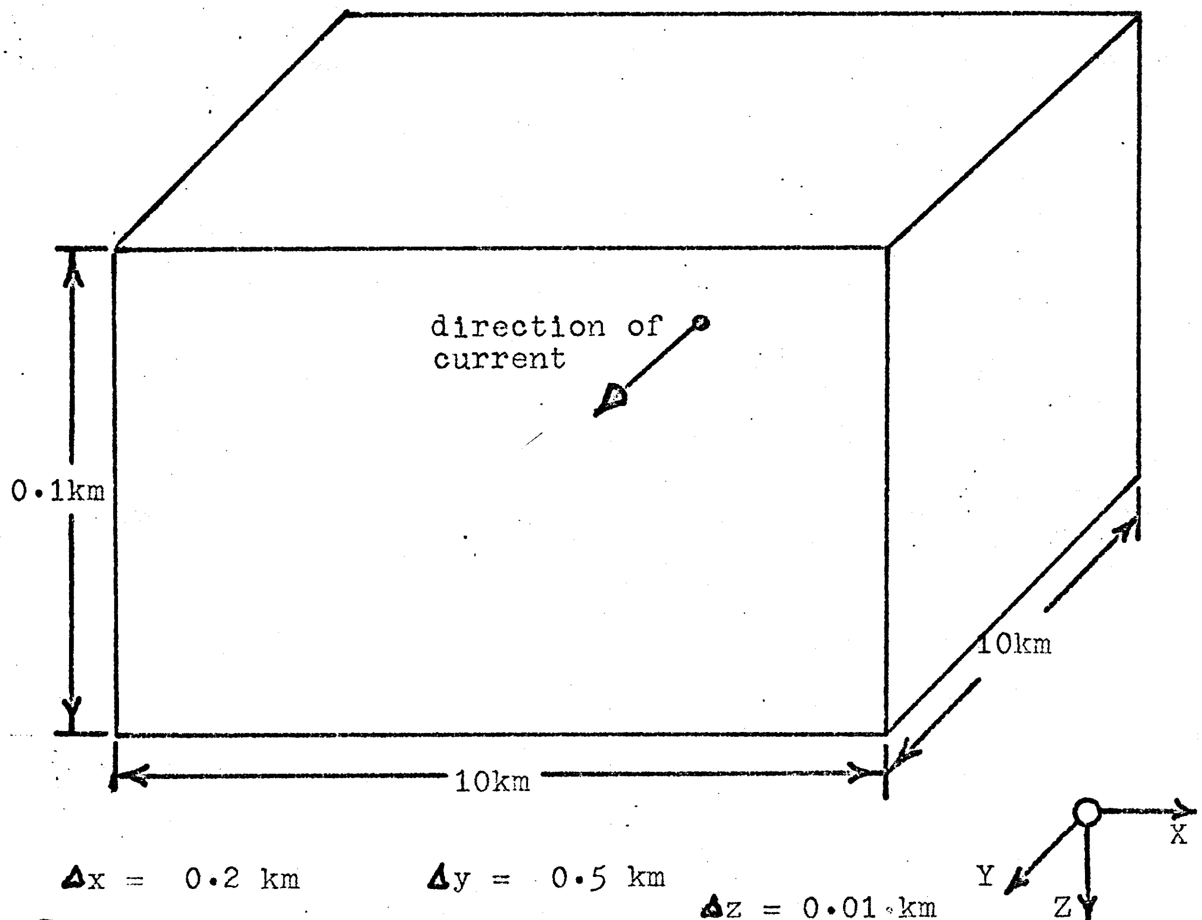
Plan A. As a beginning, make the following oversimplifications: the Gulf Stream is a uniform flow through a vertical plane ten kilometers wide and 1/10 km. deep (in the Blake Plateau), and the downstream (y) dimension is equal to the cross-stream (x) dimension. A typical number of current meters per buoy is ten. Utilizing the guidelines of physical dimensions set forth in the previous section, Plan A results in the configuration as shown in Fig. 2.

Plan B. To make a drastic contrast, exclude the y-dimension of the array, as shown in Fig. 3. This sacrifice permits more detail in the cross-stream and vertical dimensions. Note, however, that the $\Delta x$ interval is unreasonable since the range of buoy motion is probably close to 50m. and that buoy deployment from ships is inaccurate at such close intervals. Richardson and Schmitz's (1965) technique could be used to provide supplementary data on y-direction fluctuations, as suggested by Reid (1965). Improving the model of the Gulf Stream to include meandering is allowed for by increasing the x-dimension to 25 km.; the amplitude of meanders off Onslow Bay, near the site of the proposed system, is about ten kilometers— Webster (1961).

Before describing Plan C, make the following calculations on the cost of the previous pair of arrays. If the total expense of moored buoy systems is assumed to be given as $5000 per buoy and $4000 per current meter, then Plan A would cost $48.2 million and Plan B about $43.3 million. This calculation does not take into account the outlays for data analysis which could amount to a significant part

PLAN A

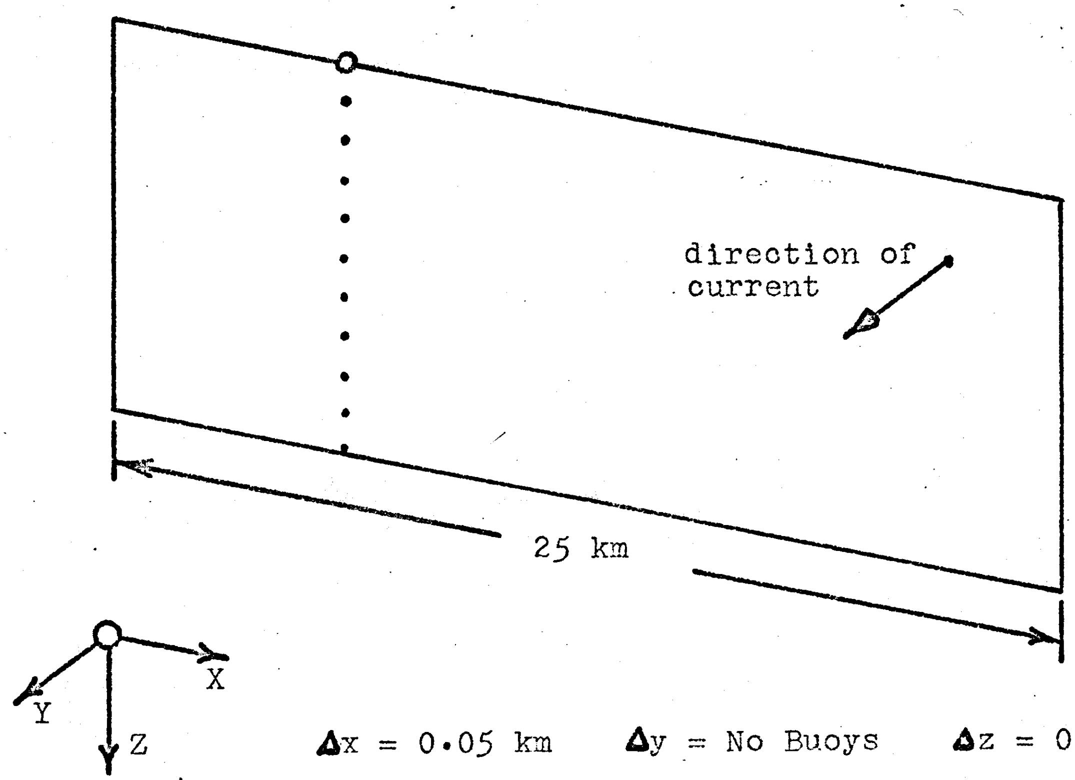
The Brute Force Method




<u>TOTALS:</u> 1071 buoys
10710 current meters

Fig. 2

PLAN B




$\Delta x = 0.05$ km $\quad \Delta y =$ No Buoys $\quad \Delta z = 0.005$ km

$\Sigma\Delta x = 25.0$ km $\quad \Sigma\Delta y = 0 \quad \Sigma\Delta z = 0.1$ km

<u>TOTALS:</u> 501 buoys
10,200 current meters

Fig. 3

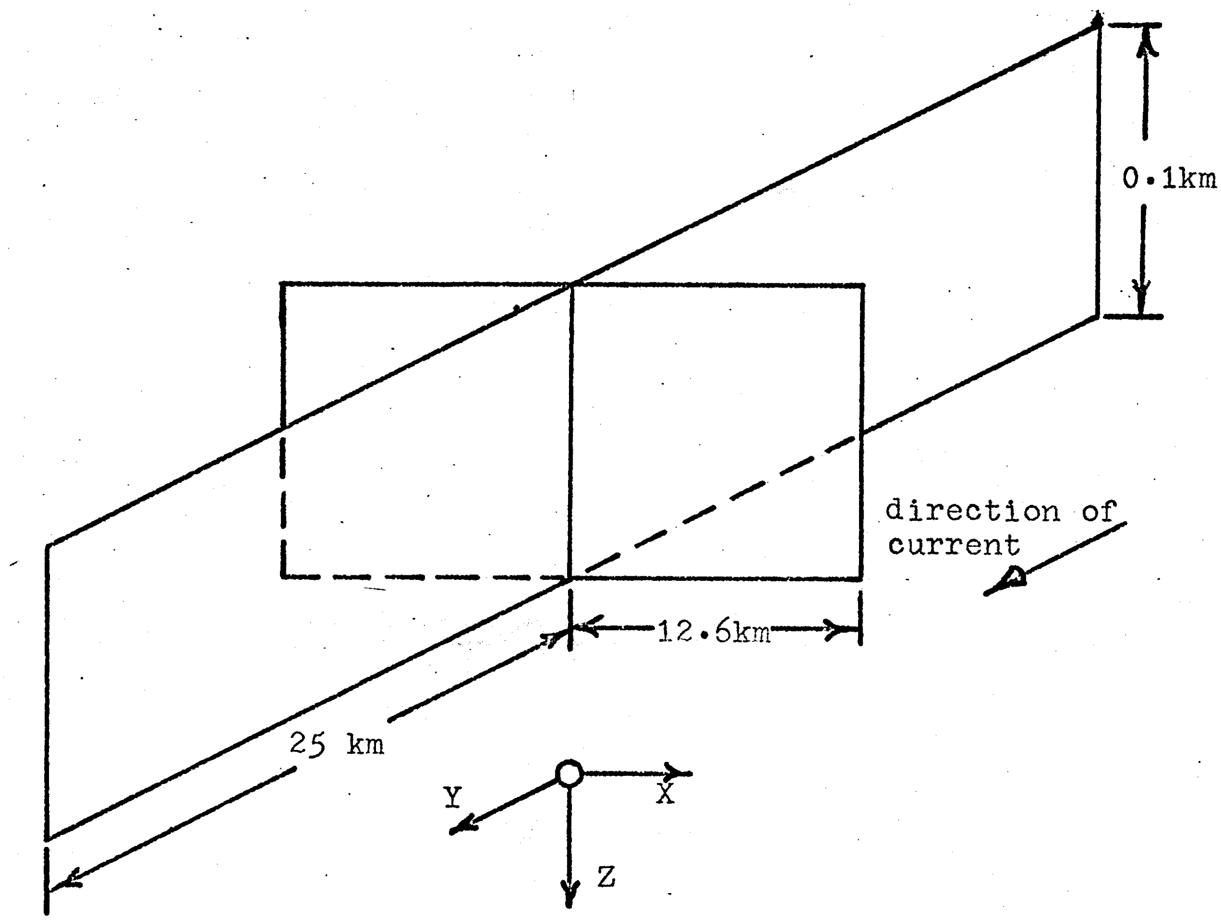
of the total. These cost figures are just being used as a rough tool for comparison.

Since it was figured that available funds were of the order of a million dollars, these two plans are unreasonable. If they were scaled down by a factor of ten, the cost of each would reach a tolerable level, but then the chances of a failure due to aliasing effects or lack of comprehensiveness would be likely.

Plan C. The compromise plan consists of two planes of current meters that intersect each other at right angles; one plane lies in the axis of the Gulf Stream, and the other is perpendicular to the current. The plan, as illustrated in Fig. 4, would cost about $6½ million.

If a comparison is made of the areas mapped out by Plans A, B, and C in a Stommel diagram, as in Figs. 5 and 6, we conclude that Plan C is commensurate with the comprehensiveness of the others, as was desired. The time limits are those for a two year experiment and a sampling rate of one per second. Reid (1965) states that a two year experiment would resolve fluctuations of six cycles per year and higher, a conservative factor of twelve rather than three, which was used here. These two factors actually should be considered as the range of the upper and lower limits on the diagram, and hence each mapped area should have fuzzy boundaries about a half order of magnitude in width.

PLAN C




$\Delta x = 0{\cdot}2$ km $\quad \Delta y = 1{\cdot}0$ km $\quad \Delta z = 0{\cdot}0125$ km

$\Sigma\Delta x = 25{\cdot}2$ km $\quad \Sigma\Delta y = 50{\cdot}0$ km $\quad \Sigma\Delta z = 0{\cdot}1$ km

<u>TOTALS</u>: 177 buoys
1426 current meters

Fig. 4

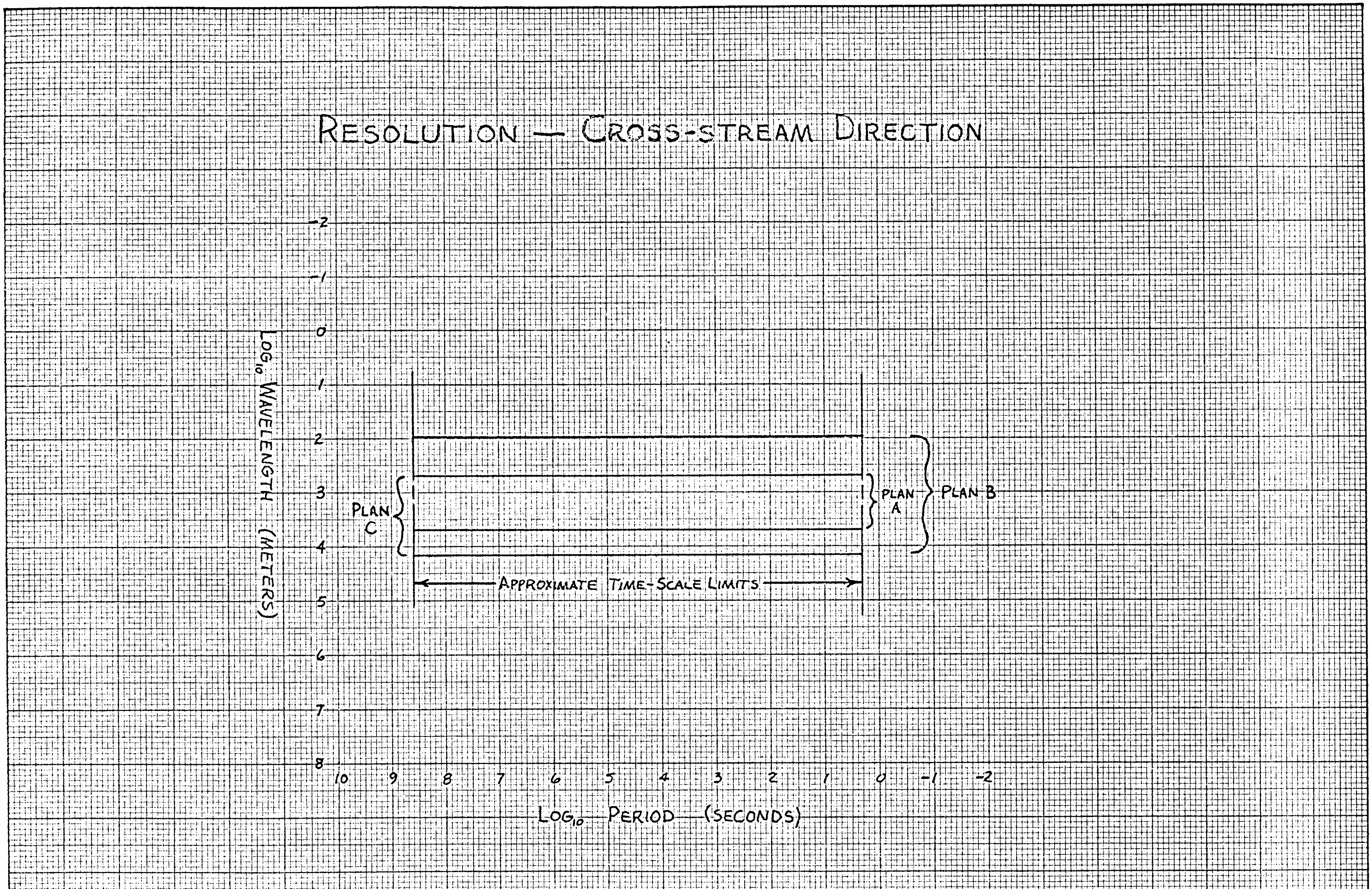

RESOLUTION — CROSS-STREAM DIRECTION
LOG10 WAVELENGTH (METERS)
-2
-1
0
1
2
3
4
5
6
7
8
PLAN C
PLAN A
PLAN B
APPROXIMATE TIME-SCALE LIMITS
10
9
8
7
6
5
4
3
2
1
0
-1
-2
LOG10 PERIOD (SECONDS)

FIG. 5

## RESOLUTION — DOWNSTREAM DIRECTION

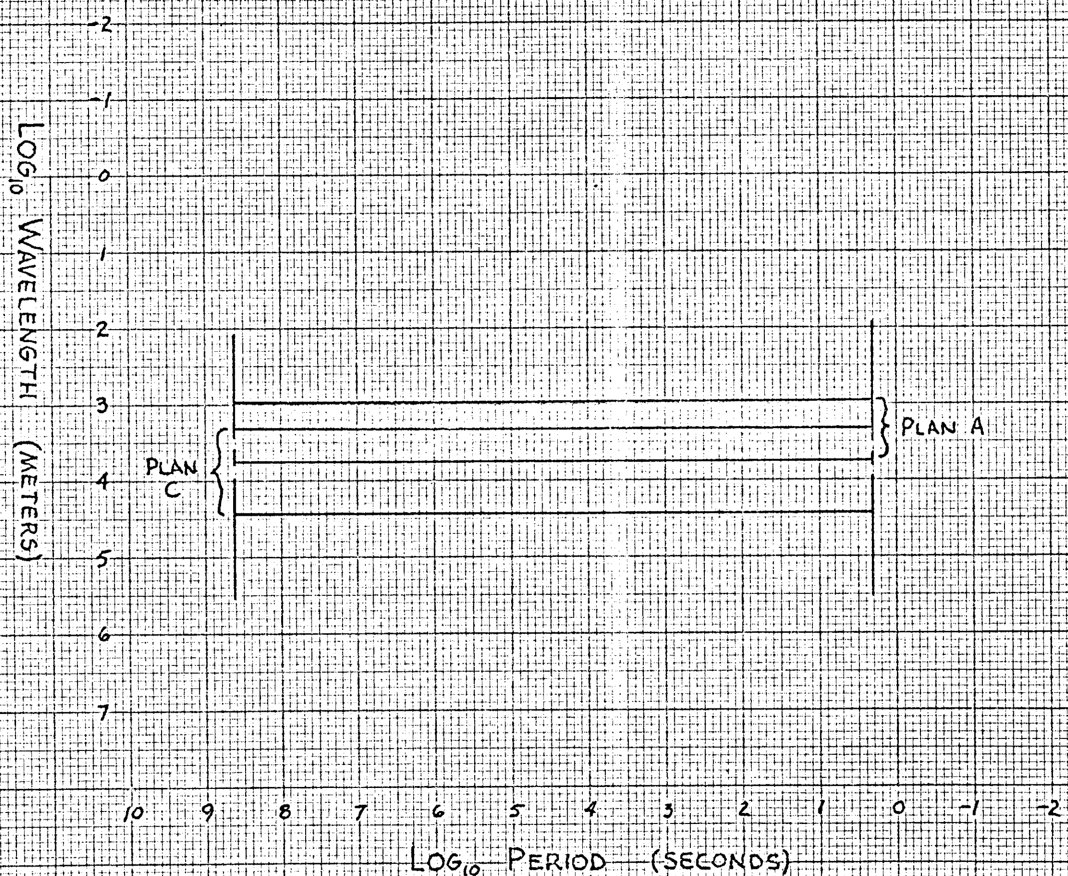



FIG. 6

When these two diagrams are compared with Fig. 1, one can see that the new program covers a sizeable portion of the total area determinable by classic methods and is a significant improvement over the multiple-ship survey.

Time Sampling

As a second consideration, one must ask how the data from the proposed system are to be sampled in time. To maintain a large area on the Stommel diagram and to permit collection of data useful for studying interactions and processes over a large range of frequencies, the scheme of buoys must assemble and store data for about a year. At the same time, aliasing must be eschewed. According to Ross (1957), if a process is sampled at a uniform rate (intervals of T seconds), the frequency of sampling will be $2\pi/T$ sec$^{-1}$; and the frequencies of processes greater than $\pi/T$ sec$^{-1}$ will not be distinguished from those in the range from zero to $\pi/T$ sec$^{-1}$. This effect is called aliasing. In the plot of a power spectrum, the values at the higher frequencies will be folded about the line of the Nyquist frequency ($f_n$, $f_n = \frac{\pi}{T}$) and added to the amplitudes at lower frequencies.

The result of this folding is the power spectrum actually observed from measurements collected every T seconds. To prevent contamination of the low frequency data, a rapid sampling rate is vital. A rate of the order of once each second is necessary because the current meter responds with a time constant of a few seconds and will physically filter out only those fluctuations below a period of one second or so— Fofonoff and Ercan (1967).

The data will total about $10^{11}$ pieces of information on velocity alone (ignoring the fact that with each velocity measurement there must be attached the spatial position of the velocity vector). It seems doubtful programmers and computers could surmount the problem of analyzing such an enormous amount of data. Since the present capacity of Richardson current meters is only a few days' worth at a one-second sampling rate, all current meters would have to be recovered every couple days; this tiring and expensive job would significantly reduce the continuity of measurements.

A solution to these two problems is possible if one is willing to surrender high-frequency information in favor of low-frequency data. If high-frequency measurements were desired, separate and short-term runs of the system could be made at the one-second sampling rate; but then determination of such things as interactions between high- and low-frequency fluctuations would not be possible. The answer is to sample in bursts at regular time intervals and average the bursts— Webster (1967). The rapid measurements (bursts) prevent aliasing, and the dormant periods between measurements allow the current meters to sustain a longer period of data collection.

This same technique could be used in spatial sampling to reduce the number of buoys and, therefore, the cost of the program. The moorings could be assembled into groups—each group far apart and the buoys within a group very closely spaced. This arrangement could become necessary if the cross-stream line of buoys in Plan C is expanded to 50 miles to encompass all of the Gulf Stream (as defined by velocity cross sections) and its meanders. Grouping would also permit the downstream dimension to be stretched—how much depending upon what small-wavelength information can be sacrificed in deference to data on large-scale, spatial fluctuations.

## Some Final Variations

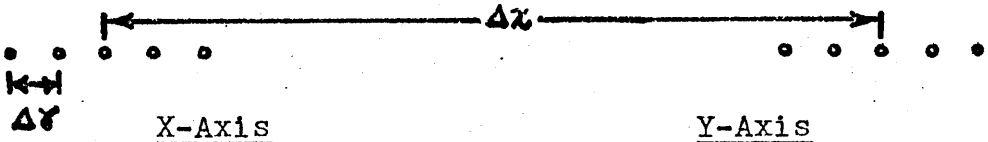
The result of the last section, Plan C, can be used as a basic framework for special refinements of the system reflecting emphasis on collecting data from a restricted range of frequencies and wavelengths in the power and spatial spectra.

The cross-stream dimension of the system in Plan C does not have data points in the main cross section of the current at all times. The axis of maximum current meanders about 20 km., so to have information on the current that is equally comprehensive at all times, the dimension should be increased to about 50 km. from 25 km. With equal spacing, the interval between buoys would change to 0.4 km. Such an arrangement would allow aliasing of the spatial fluctuations of wavelengths 0.8 km. or smaller. If one happened to know that a significant portion of the velocity spectrum was in the range of wavelengths from a half to one kilometer, then the grouping technique used by Webster (1967) could be applied to the spatial array of buoys. Chart II summarizes one possible choice of dimensions for Plan $C_1$. This alteration of Plan C lowers the "Nyquist wavelength" from 1.0 km. to about 0.2 km. The price paid by selection of this array is also shown in the comparison of the spatial spectrum segments mapped by each of the plans. A system which diminishes the Nyquist wavelength loses information from the lower wavelengths and has a smaller area mapped in the Stommel diagram.

On the other hand, if it were known that only a minor part of the wavelength spectrum was below one km., then even spacing at a half km. (Plan $C_2$) would be a better choice. In essence, the knowledge of the spectrum of velocities in space and in time would be needed to decide which area of the Stommel diagram should be mapped by the proposed buoy plan.

## CHART II

### Plan $C_1$



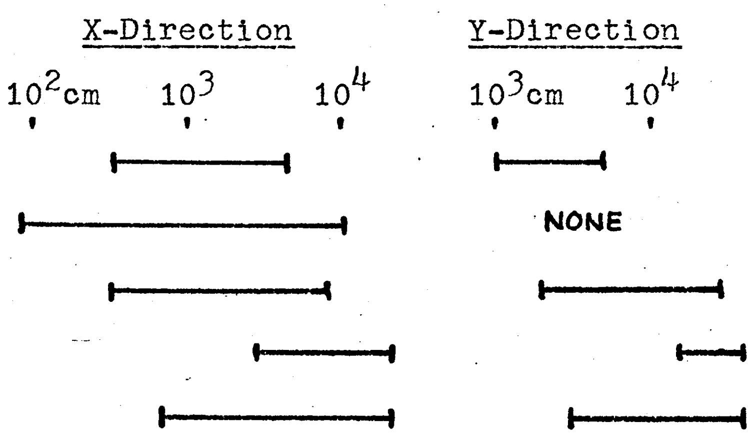

| X-Axis | | Y-Axis | |
|---|---|---|---|
| $\Delta\gamma =$ | 0.1 km | $\Delta\Gamma =$ | 0.5 km |
| $\Sigma\Delta\gamma =$ | 0.5 | $\Sigma\Delta\Gamma =$ | 2.5 |
| $\Delta x =$ | 3.0 km | $\Delta y =$ | 10.0 km |
| $\Sigma\Delta x =$ | 51.0 | $\Sigma\Delta y =$ | 100.0 |

(Z-direction same as Plan C)

### Plan $C_2$

| | | | |
|---|---|---|---|
| $\Delta x =$ | 0.4 km | $\Delta y =$ | 2.0 km |
| $\Sigma\Delta x =$ | 50.4 | $\Sigma\Delta y =$ | 100.0 |

### Summary of Plans




| Plan | #Buoys | Cost (x $10^6$) |
|---|---|---|
| A | 1071 | $48 |
| B | 251 | 43 |
| C | 177 | 7 |
| $C_1$ | 135 | 5 |
| $C_2$ | 177 | 7 |

# CONCLUSION

## Inadequacies

Although it has been possible to define a plan with several alternative configurations that satisfies the conditions and restrictions of practicality, some problems are yet to be mentioned or solved.

Perhaps it would be best to list first some of the topics not even mentioned in this paper that require similar thought. One of these is vertical velocity, which, at present, is nearly impossible to measure. It is an important factor in oceanic dynamics and requires a whole new system to evaluate it. The other is investigation of the surface processes such as waves, radiation, and mass flux.

Returning to the defined problem, one cannot know what time intervals to choose in Webster's averaging technique since there is no knowledge, at present, of the velocity spectrum in the Gulf Stream. A guess could be made on the assumption that the Gulf Stream spectrum is similar in character to spectra obtained from the Sargasso Sea; but this is too much of a risk to stake millions upon.

Likewise, the spectrum of spatial variations in the Gulf Stream is unknown. For this reason it was not possible to choose between Plans $C_1$ and $C_2$ of Chart II. The averaging method depends upon previous knowledge of the spectrum.

The option to attempt coverage of both high- and low-frequency processes does not exist because of data storage limitations which require an averaging process to solve the problem. The averaging eliminates high-frequency information. The motion of buoys also adds confusion to the high-frequency end of the spectrum. For these two reasons, one is forced to conclude that long-period studies of rapid, turbulent phenomena must be abandoned for the time being.

The meandering of the Gulf Stream, even though it is relatively confined, causes difficulties in interpreting the data that will come from a longitudinal string of buoys if the y-dimension is of the order of one meander wavelength, about 100 km. Since the meandering current axis will always be oblique to the axis of the array, data from the longitudinal string of meters will have a transverse component which will vary with time. Special handling of this information may be difficult to devise.

Finally the difficulty of maintaining an anchored buoy in the Sargasso Sea has been a very real problem for moored current meter programs in the past— Day and Webster (1965). The Gulf Stream's currents will make the problem even more severe; one can only wait until a solution is found.

## Recommendations

The system presented here (Plan C) should not be the next step in a program directed toward measuring time-dependent processes in the Gulf Stream. It should be preceded by an improvement of technology: increasing data storage and processing capability and developing a reliable buoy system for a strong current.

> We cannot plan a final network of observing points and intervals until we have mapped the spectral distribution of velocity roughly, so it is obvious this program must advance in several phases, the design of each phase depending on the nature of results obtained in previous phases.*

With the ground work laid, Plan C, in one of its appropriate configurations, might constitute the first step toward more ambitious programs of collecting data from the oceans.

---

* Stommel (1963), p. 575.

## ACKNOWLEDGEMENTS

I would like to acknowledge the inestimable help of my thesis advisor, Professor Ferris Webster.

Credit is also due to Stommel's book, The Gulf Stream, which is not directly referenced but formed the foundation for most of the understood knowledge about the Gulf Stream in this paper.

# BIBLIOGRAPHY


Day, C. G. and Ferris Webster. (1965) "Some current measurements in the Sargasso Sea". Deep-Sea Research, 12: 805-14.

Fofonoff, N. P. and Yücel Ercan. (1967) "Response characteristics of a Savonius rotor current meter". W.H.O.I. Tech. Rept. No. 67-33. unpublished manuscript

Fuglister, F. C. (1955) "Alternative analyses of current surveys". Deep-Sea Res., 2: 213-29.

Fuglister, F. C. (1963) "Gulf Stream '60". Progress In Oceanography, vol. 1, pp. 265-373.

Fuglister, F. C. and L. V. Worthington. (1951) "Some results of a multiple ship survey of the Gulf Stream". Tellus, 3: 1-14.

Iselin, C. O'D. (1936) "A study of the circulation of the North Atlantic". Papers In Physical Oceanography and Meteorology, vol. 4, no. 4.

Iselin, C. O'D. (1940) "Preliminary report on long-period variations in the transport of the Gulf Stream". Pap. Phys. Ocean. and Met., vol. 8, no. 1.

Iselin, C. O'D. and F. C. Fuglister. (1948) "Some recent developments in the study of the Gulf Stream". Journal of Marine Research, 7: 317-29.

Pillsbury, J. E. (1891) "The Gulf Stream". Rept. Supt. U.S.C.&G.S. 1890. Appdx. 10, pp. 459-620.

Reid, R. O. (1965) "Along term Gulf Stream experiment". unpublished manuscript submitted to O.N.R.

Richardson, W. S., P. B. Stimson, and C. H. Wilkins. (1963) "Current measurements from moored buoys". Deep-Sea Res., 10: 369-88.

Richardson, W. S. and W. J. Schmitz. (1965) "A technique for the direct measurement of transport with application to the Straits of Florida". J.M.R., 23: 172-85.

Ross, T. D. (1957) "Sampling and quantizing". Notes on Analog-Digital Conversion Techniques.

Stommel, H. (1963) "Varieties of oceanographic experience". Science, 139: 572-6.

Stommel, H. (1965a) The Gulf Stream.

Stommel, H. (1965b) "Some thoughts about planning the Kuroshio survey". Proc. of the Symposium on the Kuroshio, pp. 22-33.

Swallow, J. C. and L. V. Worthington. (1961) "An observation of a deep countercurrent in the Western North Atlantic". Deep-Sea Res., 8: 1-19.

Von Arx, W. S. (1950) "An electromagnetic method for measuring the velocities of ocean currents from a ship under way". Pap. Phys. Ocean. and Met., vol. 2, no. 3.

Von Arx, W. S., D. F. Bumpus, and W. S. Richardson. (1955) "On the fine structure of the Gulf Stream front". Deep-Sea Res., 3: 46-65.

Webster, F. (1961) "A description of Gulf Stream meanders off Onslow Bay". Deep-Sea Res., 8: 130-43.

Webster, F. (1965) "A draft outline of a large-scale program of oceanic observations". unpublished manuscript submitted to O.N.R.

Webster, F. (1967) "A scheme for sampling deep-sea currents from moored buoys". Trans., 2nd Internat. Buoy Symp., pp. 419-31.