APPLICATION OF REMOTE SENSING TO STUDY NEARSHORE CIRCULATION

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TABLE OF CONTENTS

ABSTRACT

Immediate use of drogued buoy tracking was made when the Virginia State Highway Department requested assistance in selecting the best route for a new bridge-tunnel complex across the James River at Newport News. Although this was not part of our original grant proposal we had the elements on hand to respond. The Virginia Institute of Marine Science (VIMS) requested help from NASA-Wallops and NASA-Langley and these three institutions combined forces to conduct a very sophisticated field study (Fang, et.al., 1972). The result was that the Highway Department acted and chose a preferred route from several alternatives.

During this same study we observed that the drogues did not follow the channel as predicted by the James River Hydraulic Model. Instead the drogues on the ebb tide drifted directly into the Norfolk Navy Base piers. This permitted us to tell the Navy why it is that part of their channel always silts up. The Navy has acted and funded a contract to study the siltation more closely in order that they might seek ways to minimize the problem.

Late in the year the Hampton Roads Sanitation District asked if our work could help them locate the best route and position of an ocean sewer outfall. In order to establish a field design for using the drogues an assessment of old field data was made. The study indicates that the proposed site is poor and alternative routes will have

to be examined. As this year ends the ocean outfall problem is unresolved but real progress has been made in that a serious problem has been brought to light.

The program received a veritable windfall when we were invited by NASA-Langley Research Center to aid in the design of field experiments using drifting buoys which are interrogated by the EOLE satellite system. Not only have we been able to assist NASA LRC in this but the information derived will be of direct benefit to the University Grant Circulation Study.

Through a series of field tests a tracking system suitable for the con-shelf has now been selected; namely, the Omega System. It should be operational by the end of the second year. All field work to this point has been done by radar drogues. Radar is very accurate but has limited range and requires extraordinary logistical support. Omega is less accurate but good enough for broad shelf work, is relatively easy to use and is compatible with satellite interrogation.

Biological activities are focused primarily on delineating biological interaction between the marsh and continental shelf waters on Virginia's Eastern Shore. The first year was devoted mainly to developing field techniques for measuring a variety of biological indices in natural waters. These measurements permit us to "characterize" the marsh and offshore waters and thereby delineate their respective movement through Wachapreague Inlet and offshore. Additionally we can determine the direction and magnitude of the flux of biologically related materials associated with these waters between the two environments. Attempts have been made with varying degrees of success to integrate the biological sampling at Wachapreague with both the drogue studies and the remote imaging of the area.

Information derived from this study is helpful in catagorizing the relative biological value of different marsh areas so that meaningful use and management decisions can be made concerning their eventual disposition. In addition, any biological interaction between the marsh and coastal environments gives rise to the possibility that with the greatly increased man-use pressures in both areas, alteration of either area could ultimately effect the ecological well-being of the adjacent environment.

Basic ecological information of the type being collected in this study is essential to enlightened use and management of these environments.

ACKNOWLEDGEMENTS

The authors wish to recognize the support of their fellow countrymen who, through willing and regular payment of taxes, financed this work. This support was ably administered by the National Aeronautics and Space Administration, Office of University Affairs through the NASA Wallops Island Station, Grant #NASA-NGL 47-022-005. In this regard, the efforts of Joe Vitale and Dave Oberholtzer are particularly appreciated. The staff of the Virginia Institute of Marine Science, particularly John Zeigler, Frank Fang, and Ken Webb, were unstinting in their support and encouragement. The field work depended on many people who showed their interest by working in uncomfortable places for long hours at low salaries. Of particular note at VIMS were Eddie Wu, Don Stauble, Dave Tyler, Bill Athearn, Jerry Sovich, and the technicians in the department of Physical Oceanography and Hydraulics. Much additional field support and technical assistance were given by Bob Long and Bob Nock of NASA Wallops Island Station, and John McFall, Leon Williams, and Jim Schwab of NASA Langley Research Center. We were aided by many other people to whom we have never been introduced. Those at NASA Houston who provided excellent aerial photography, at NASA Wallops who rescued buoys, fixed equipment, and manned the radar equipment, at NASA Langley who designed, built, and repaired the transponding buoys, and in the U. S. Coast Guard who provided shelter for our equipment and rescue in troubled waters. The rescue efforts of Joe DeAlteris and Jerry Sovich of VIMS are also acknowledged. Preparation of the report has involved Agnes Lewis, Libby Barker, Mary Jane Moncure, Ken Thornberry, Bill Jenkins and certainly not least, Shirley Crossley.

MOTIVATION

Possibly the least understood part of the ocean is the continental shelf. However, the thrust to know has changed dramatically within the past year on the Atlantic coast. Oil discoveries off Nova Scotia, the energy crisis and its handmaiden the immediate and critical need for offshore oil ports, accelerating construction of offshore sewer outfalls, offshore nuclear power plants, a national emergency regarding off shore dumping of dredge spoil and raw material shortage leading to undersea exploitation of sand, gravel, metals and so on.

Every one of these has forced itself on the Commonwealth of Virginia regulatory agencies within the past year at some level of intensity. Unless a viable spoil disposal program can be found the ports of Hampton, Norfolk, Portsmouth, and Newport News will be severely compromised. Norfolk is a major Navy base, eighty percent of exported coal leaves the United States through Newport News. Each of the above requires some kind of assessment by the Virginia Institute of Marine Science to the governor or other agencies.

In every offshore problem circulation must be considered as a major factor in design or operation. Pollutants get spread by currents, currents affect siltation, navigation, and location.

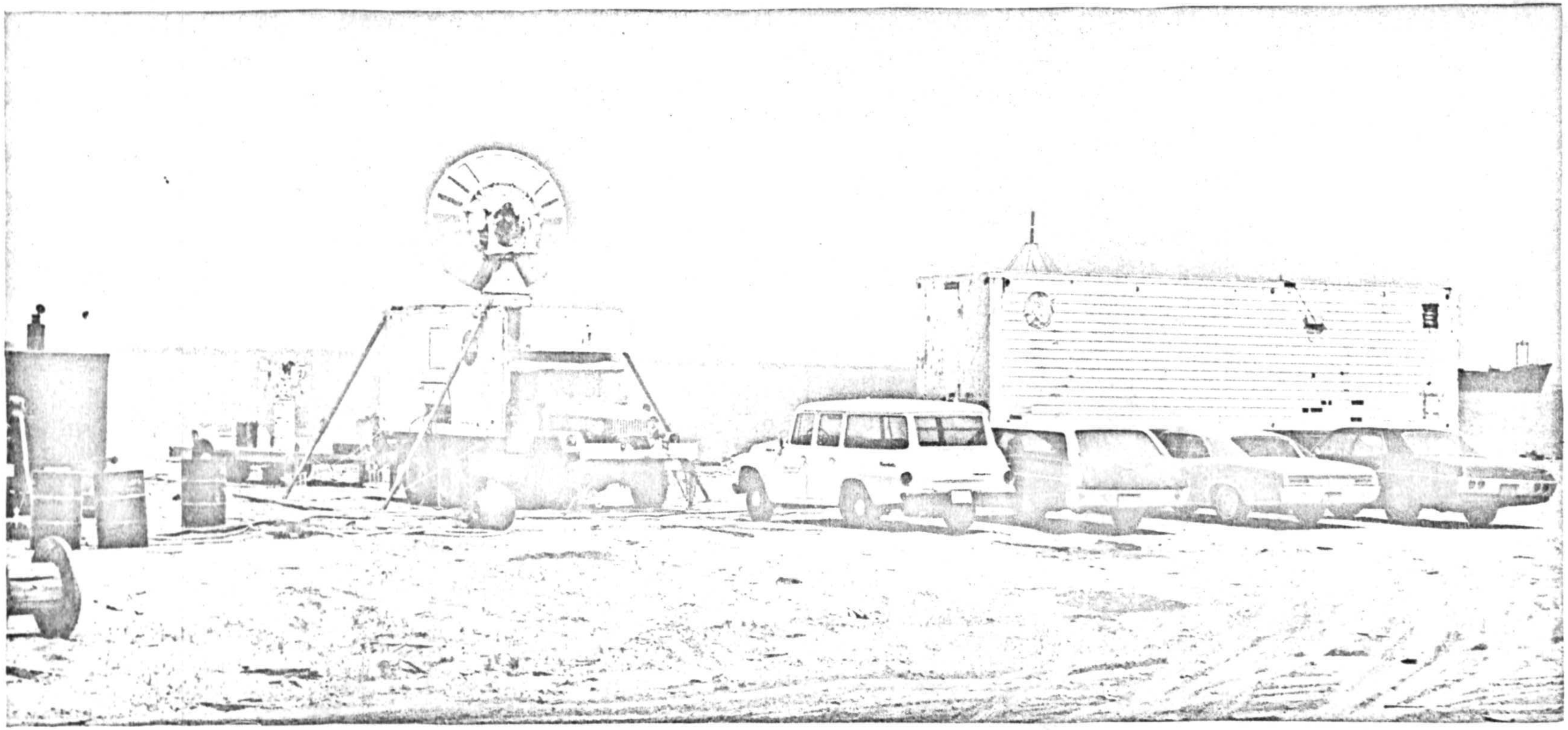
We consider ourselves very fortunate to have had the NASA Headquarters/Wallops Island Station program already underway assessing currents before the urgency became full blown. Because of the program we were able to respond to the Highway Department, the Hampton Roads Sanitation District, the United States Navy, and NASA Skylab. The applied ventures were also very useful in testing some of the field systems under development.

As this year ends we know that in addition to the research we have promised to do that we will be asked to examine a thermal plume from a power plant in the James River as well as continue to study the ocean sewer outfall.

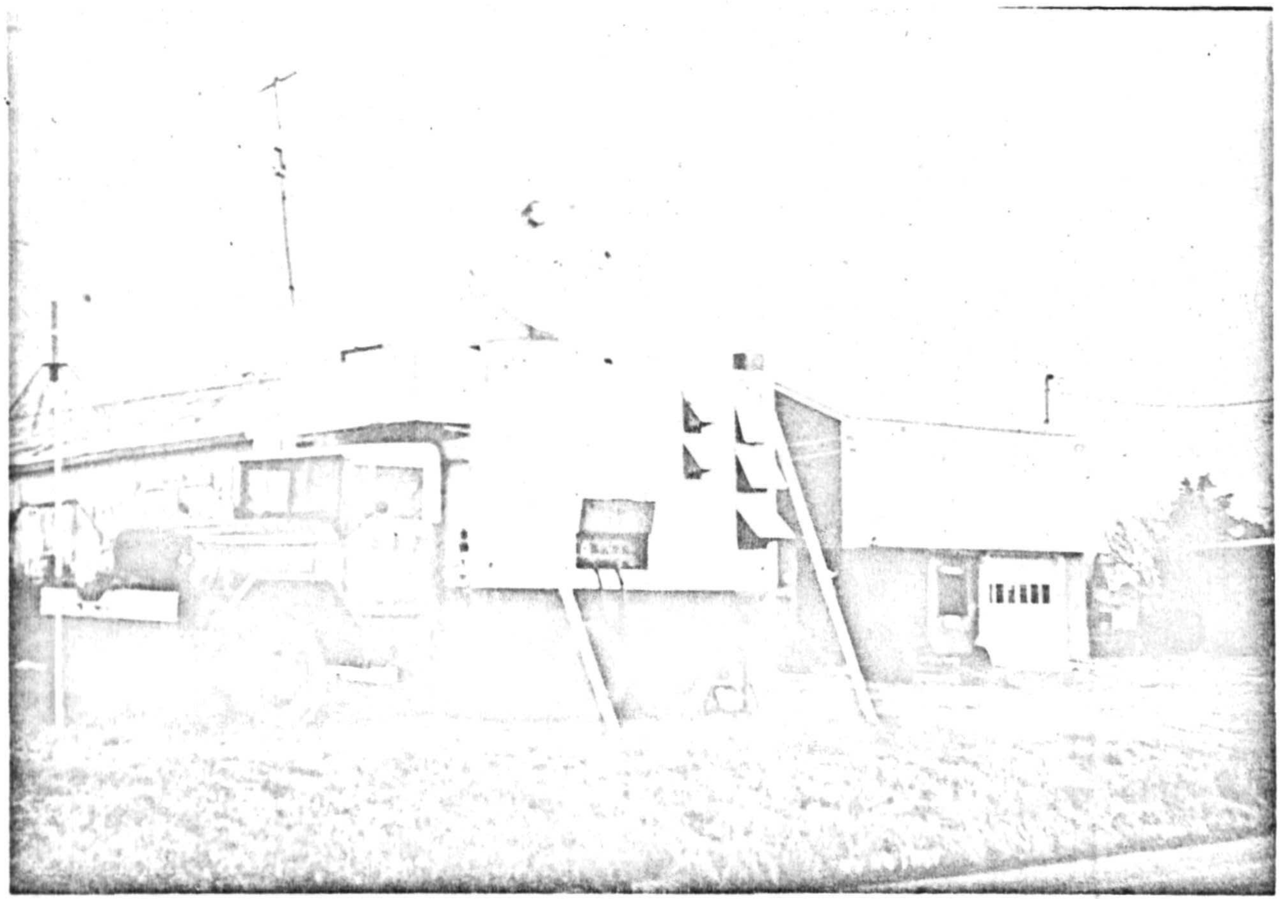
We anticipate increasing calls upon us for help with real-world applied problems. In order to be able to respond we therefore are placing high priority on development of a tracking system complementary to the radar system used this past year.

PHOTOGRAPHIC SECTION

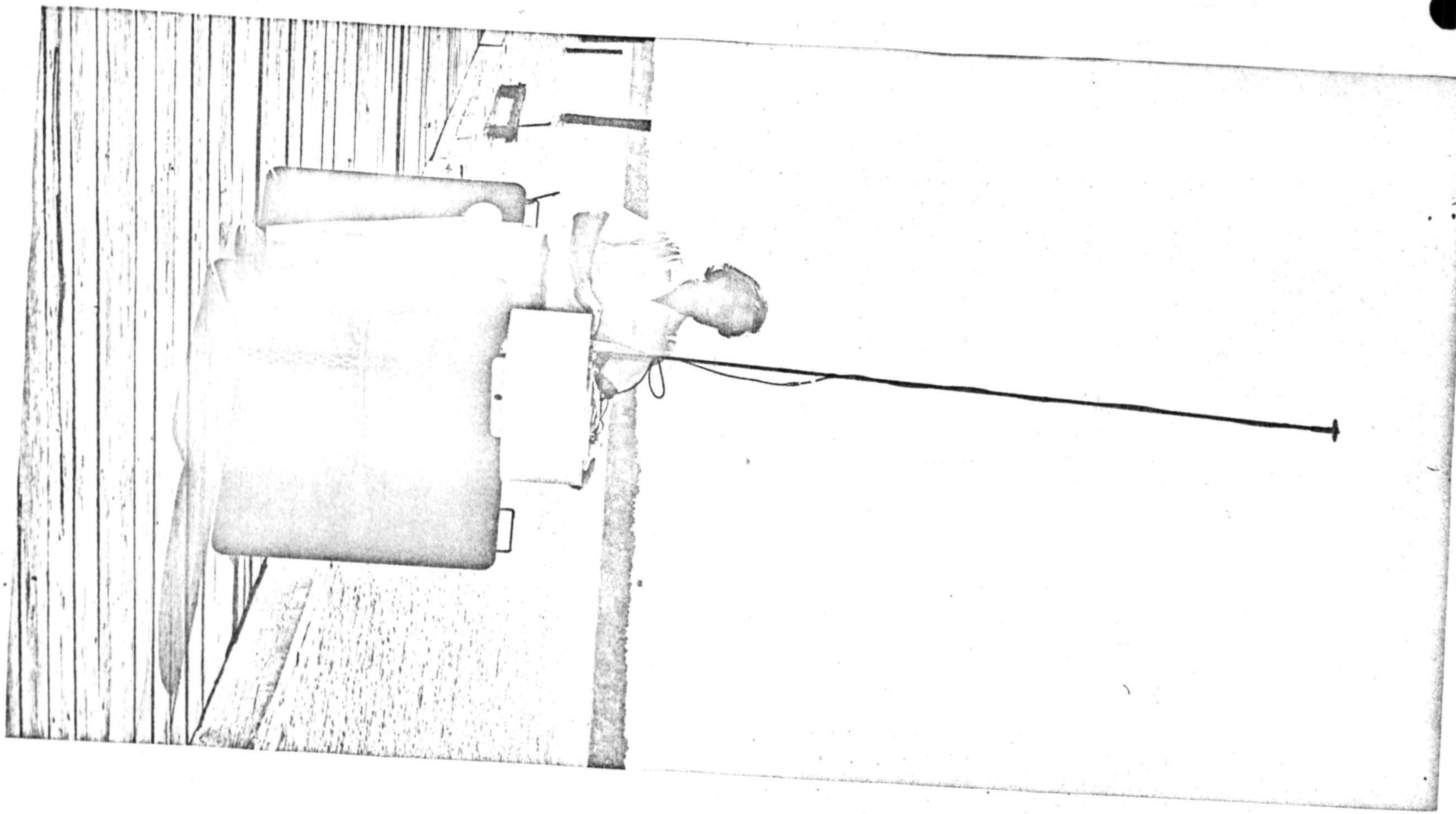
The use of drogued buoys complementing remote sensing and image analysis to describe water motion is a new and evolving art. This section of photographs is intended to convey some of the flavor of the work in the belief that a picture really is worth a thousand words. These photographs span the range from equipment and field work to data after initial processing.



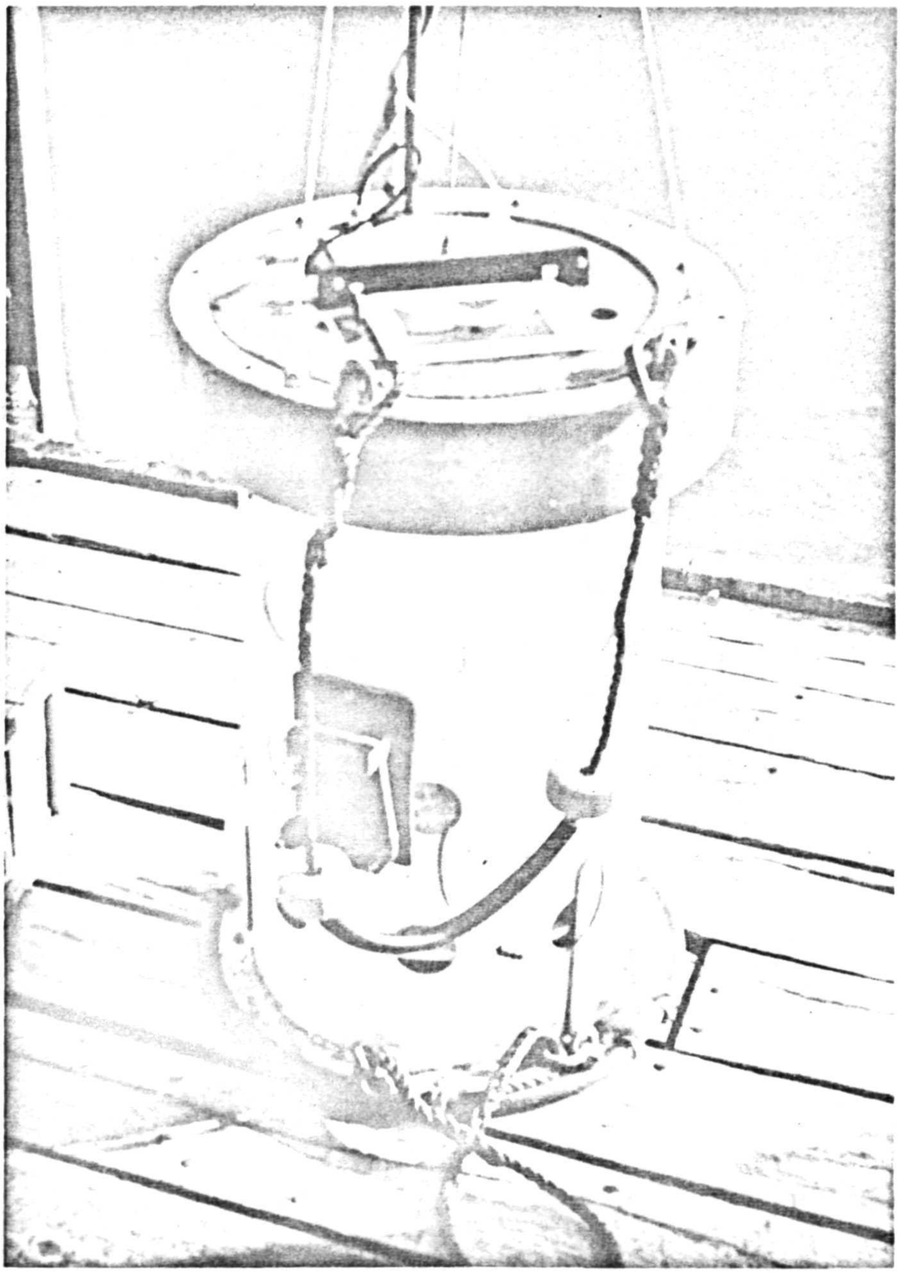
Base station setup on Craney Island during James River Drogue Study. Equipment shown is power generator, visual telescope, radar van, and central control trailer. These were all provided and manned by NASA Wallops Island Station.



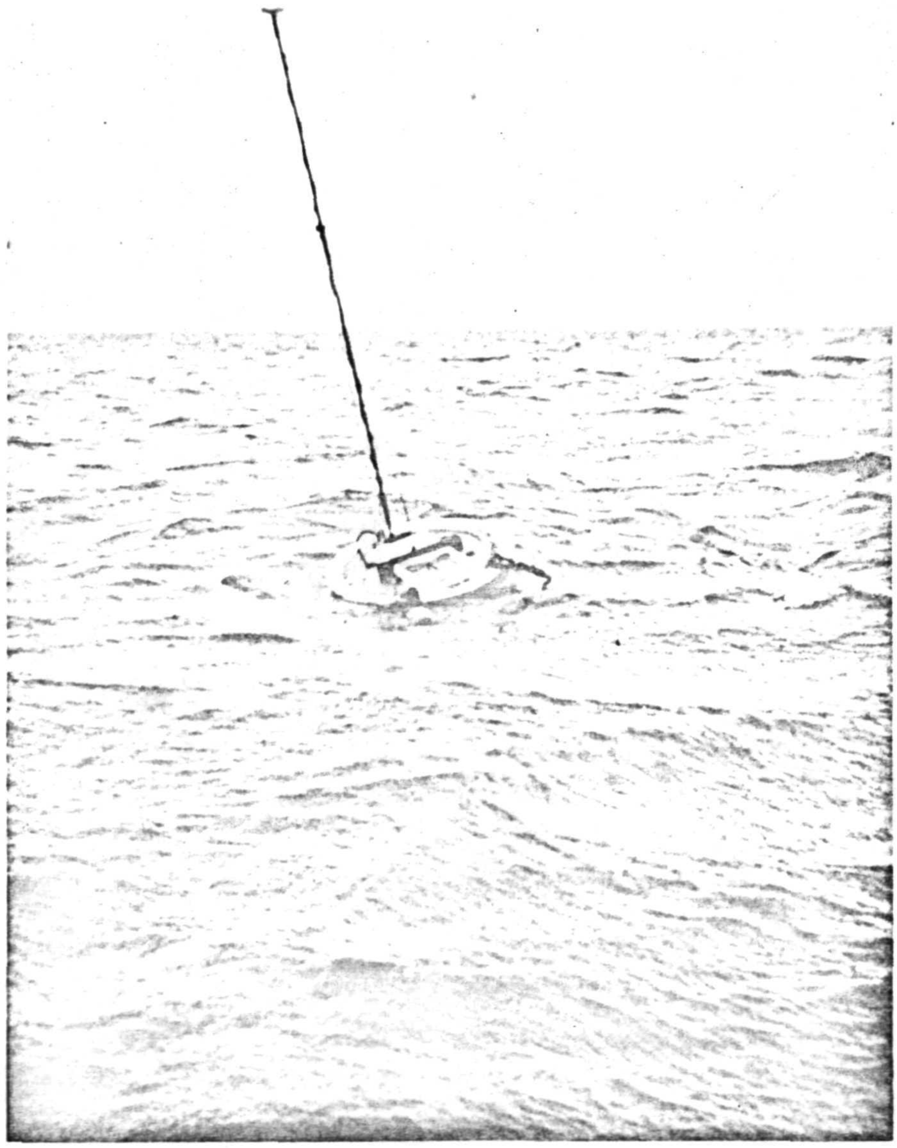
NASA Wallops Island Station radar van set up at VIMS Wachapreague Inlet Laboratory tracking buoys in an area five miles distant during the Wachapreague I experiment.



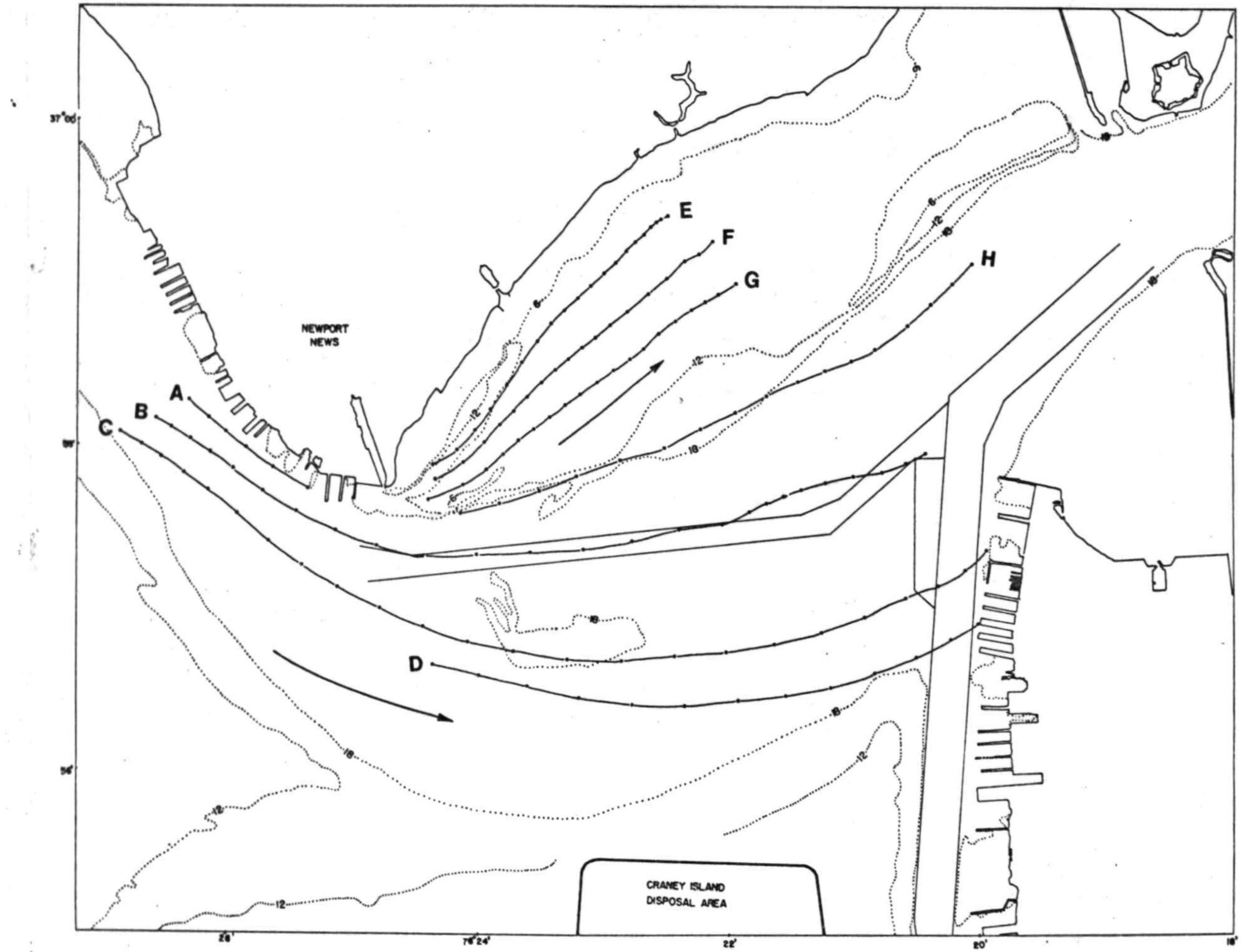
Radar buoy and drogue used in the James River Drogue Study. Buoy is white pill shaped object with mast. Transponder antenna is small button on top of mast. Drogue is aluminum current cross and can be folded for storage. Chain normally connects buoy and drogue. Entire unit was designed and fabricated by NASA Langley Research Center.



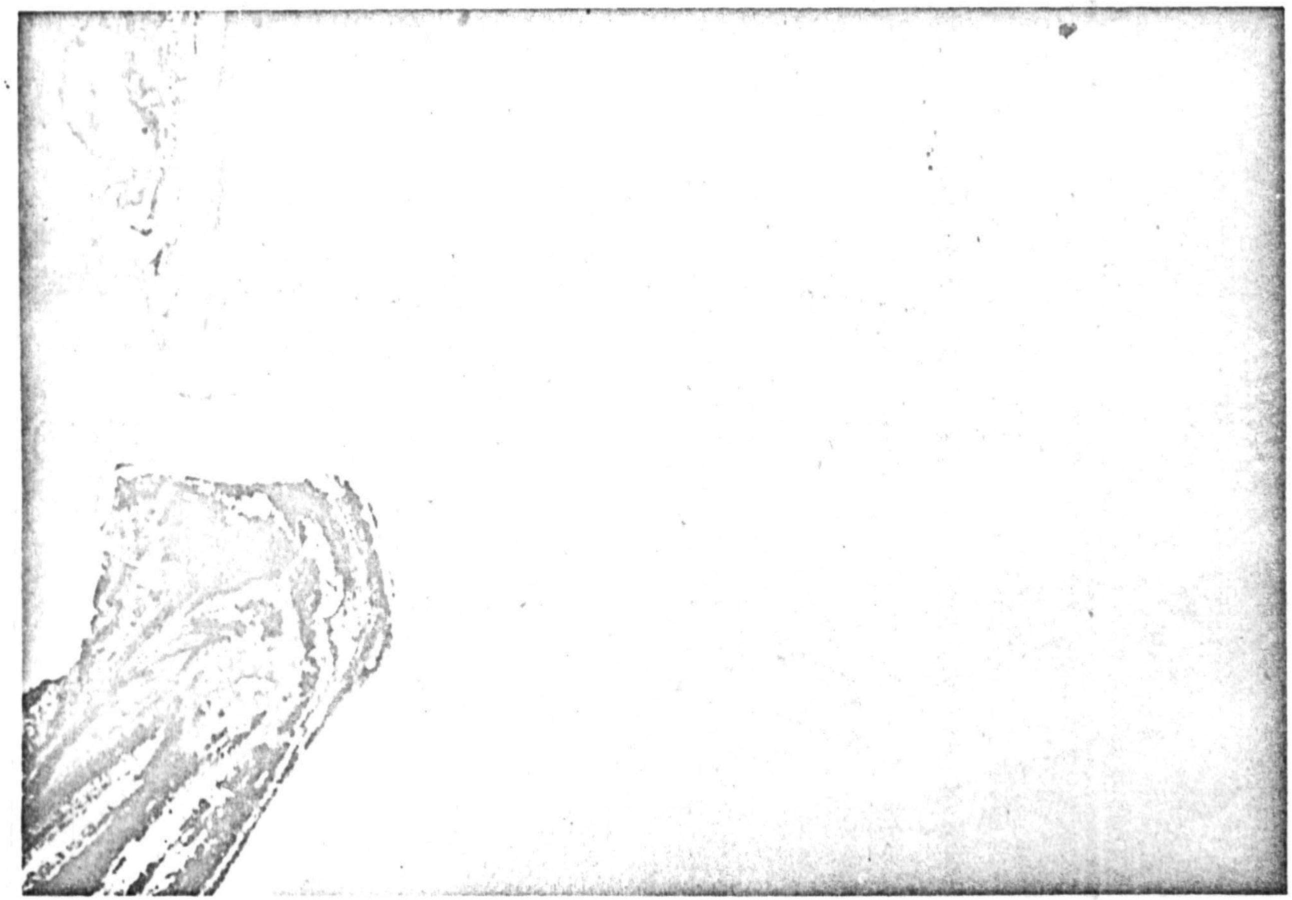
Surface drogued radar buoy used during experiments in Wachapreague Inlet. The buoy was designed to withstand passage through surf and be deployable and recoverable using helicopters. Visible are the battery pack and electronics package, launch and recovery lines, and biological sample bottle holder. Buoys were provided by NASA Langley Research Center.



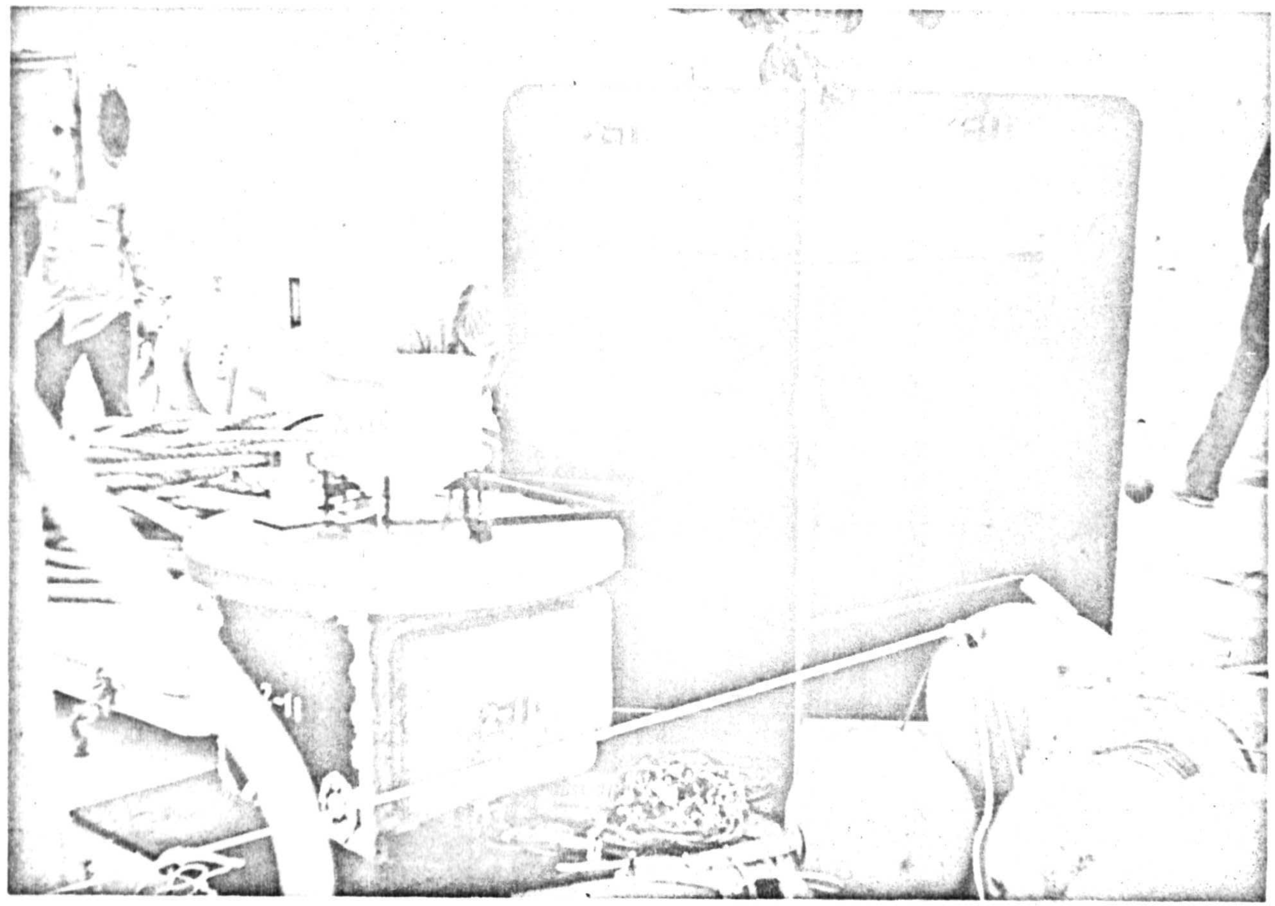
Surface drogued buoy in operation during Wachapreague II experiment. Radar transponder antenna is small button at tip of mast.



Example of drogued buoy tracks from James River Drogue Study. Dots represent ten minute intervals during ebb tide in Hampton Roads.



Sample overflight image data showing sediment plume structure outside of Wachapreague Inlet during ebb tide. Overflights were flown by NASA Houston.



Ocean-going EOLE buoy with float and fins on deck of R/V Ridgley. Warfield. Drogue is set at depth of 5 meters. Small cylinder on buoy is antenna for satellite transmission.

Application of Remote Sensing to Study Nearshore Circulation

1. Introduction

The objective of this project is to study nearshore circulation effectively using remote sensing methods and to analyze the data gathered in such a way that the results are available on a timely schedule and appropriate form that they may be effectively used in coastal management decisions. This general objective breaks down into several interdependent categories, into which the work done can conveniently be placed. These categories pertain to the gathering and analysis of data.

The first problem is to identify the types of data which would be useful for coastal managers. An example of such identification is given by Virginia Institute of Marine Science (VIMS) Special Report in Applied Marine Science and Ocean Engineering Number 12, Priority Problems and Data Needs in Coastal Zone Oceanography. In this report, currents are identified as the single most important data need for managers. The reason for this is not the direct phenomenon of currents, but the advective property of currents in transporting other fields of interest, biological, chemical, and physical, from place to place. For this reason and also because currents by themselves are being extensively studied elsewhere, the emphasis in this project is on nearshore circulation as it affects the movement of water and properties from place to place.

Given the specific circulation problem which forms the outline of the project, the next step is to identify existing techniques which can be used to study the circulation problem. In the nearshore region, the ratio of variable water motions to ship speeds makes traditional sections difficult to interpret and ambiguous. Furthermore, baroclinic motions on the continental shelf are not the greatest part of the total motions so the development of dynamic sections becomes irrelevant. Sections become useful only as tracers of properties. They can no longer be counted on to reflect circulation. Current meter stations do measure the entire current at a point, but they tend to be very expensive. In addition, they give no indication of the source or destination of the water that passes by them. Drift bottles and seabed drifter studies give the source and some of the destinations of the circulation but they provide no information between these isolated points. In addition, the ones that drift out to sea carry their information with them. They do have certain limited applications. Drogued buoys can be made to follow the circulation closely. If they are used, the primary problem is following their trajectories. Usually, a ship is used with the shipboard navigation system employed to fix positions. More recently, satellites have been used to fix some of the positions. Because of their water following nature and their compatibility with satellites, a substantial portion of the work done during the first year as well as planned is connected with the technological development of drogued buoys. An additional technique by which circulation may be partly deduced is that of remote imagery. Using images over the nearshore water, distinct patterns of color are seen as well as "tide rips" or foam lines. The regions in which these features are distinct are precisely those in which properties are varying so rapidly that conventional ship survey techniques become difficult to interpret. Thus, in the nearshore region, image gathering becomes another important technique in the determination of coastal circulation. One of the aims of this project is marrying the techniques of drogued buoy measurements with image analysis to obtain synoptic current information in the nearshore region.

Because it is the motion of advected properties that are of particular interest, a second aim of this project is to observe the changes of some specific properties. The changes in the properties are of interest, but the techniques of observing the changes and correlating them with drogued buoy data are also important. These techniques, developed for a specific property, should be easily modified to be appropriate for observations of other variables.

2. Technique Development

In order to use remote sensing to its full or even to a useful potential, new techniques must be developed and existing ones modified. There are five fields of effort in which such development is being done, to some degree, under this grant. These are platform designs, sampling techniques (in this case, biological sampling techniques), navigation and location, imagery, and data reduction. A description of the efforts in each of these fields follows.

2.1 Platform Design

The reason that drogues are preferred over current meters is that drogued buoys are thought to follow the water. The first step in designing a suitable platform is to determine the extent to which that is not so in order that the difference can be minimized for a given payload or other criterion. In order to do this, we must dissect the platform into its component parts and analyze the function of each part.

A drogued buoy system consists of four basic elements. These are a floatation package, a connecting device, a drogue, and a readout mechanism. The function of the floatation package is to provide a reference level for the assembly at the water surface. In addition, it frequently supports the readout. The connecting device transmits the level information to the drogue and maintains the drogue at constant depth. The drogue maintains as nearly as possible, a fixed position with respect to its local water, and the readout communicates information, primarily position of the drogue, to the outside world. In a special class of drogued buoys, surface drogued buoys, the floatation and the drag are connected directly and the connecting device is omitted. Frequently, the functions of floatation and drag are performed by the same body, as in a drift bottle, for instance.

The error analysis done to date is based on a force balance model of a drogued buoy system shown schemiatically in figure 1. Here, the floatation body and the drogue body are considered point drags and the connecting line inextensible, massless, and dragless.

Perhaps the most important deviation from a Lagrangian measure is in the vertical. In this axis, the ideal drogued buoy is, in fact, an Eulerian measurement device, as it stays at a fixed depth. It is this property of drogued buoys which leads to buoys being beached by "wind effect" on windy days.

The horizontal forces are considered steady and related to the local velocities by a square law drag force. If the wind force on the buoy is neglected as a first

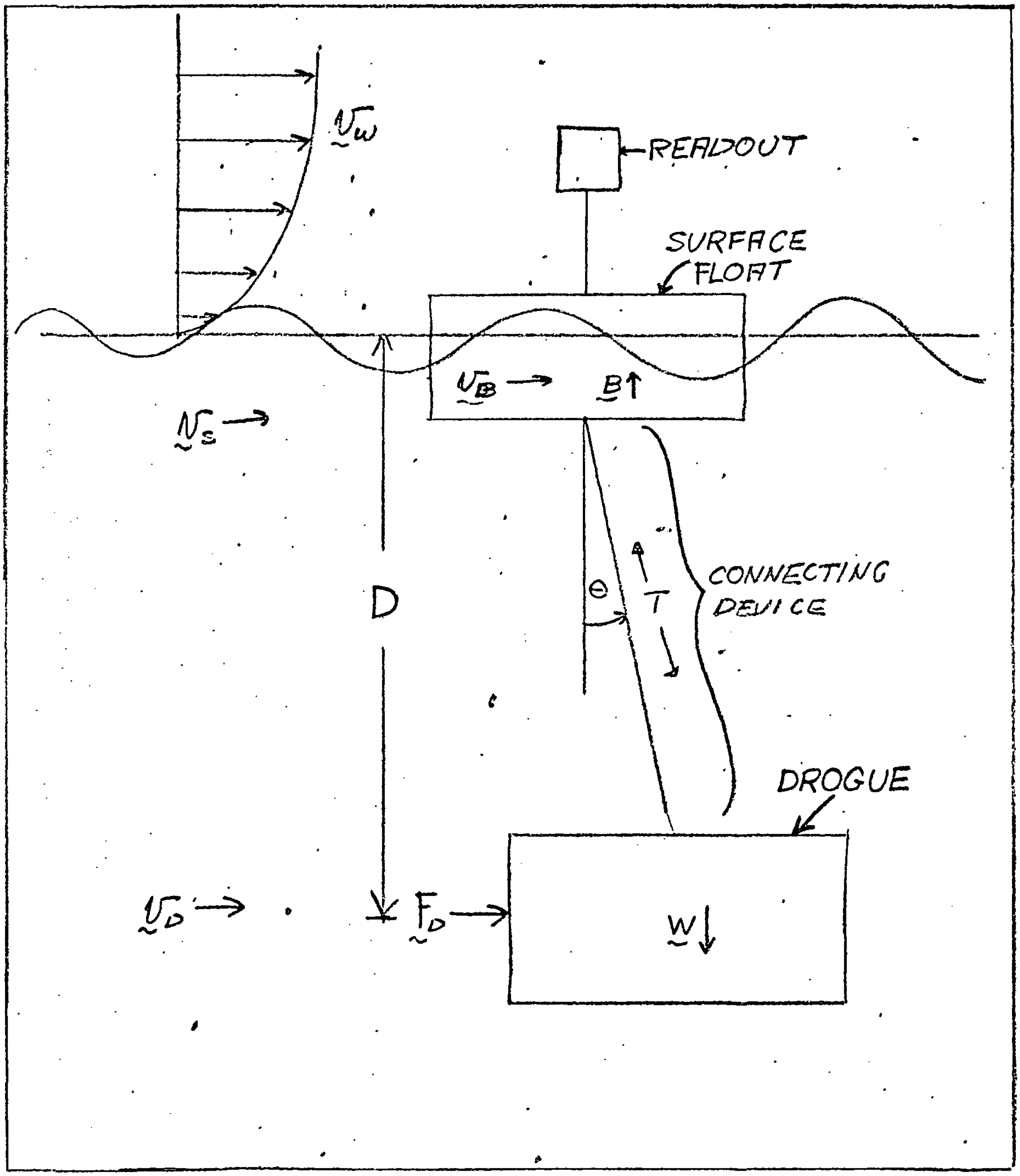


Figure 1. Schematic representation of drogued buoy with symbol definition used in analysis of inherent errors.

approximation, the force balance becomes

$$\underset{\sim}{F}_S + \underset{\sim}{F}_D = 0$$

where $$\underset{\sim}{F}_S = \rho_W C_{DS} A_S \left| (\underset{\sim}{V}_S - \underset{\sim}{V}_B) \right| (\underset{\sim}{V}_S - \underset{\sim}{V}_B)$$

and $$\underset{\sim}{F}_D = \rho_W C_{DD} A_D \left| (\underset{\sim}{V}_S - \underset{\sim}{V}_D) \right| (\underset{\sim}{V}_S - \underset{\sim}{V}_D)$$

Here ρ_W is the density of water, C_{DS} and C_{DD} are the drag coefficients for the surface float and the drogue respectively, and A_S and A_D are the respective areas projected normal to the relative velocity vectors. In this analysis, an error velocity is given as

$$\underset{\sim}{V}_E \equiv (\underset{\sim}{V}_D - \underset{\sim}{V}_B)$$

the difference between the velocity of the drogued buoy assembly and that of the water at the drogue depth. In the case described (Knauss, 1966) we have

$$\underset{\sim}{V}_E = (\underset{\sim}{V}_S - \underset{\sim}{V}_B)\left(\frac{C_{DS} A_S}{C_{DD} A_D}\right)^{1/2}$$

Two important features of drogue design are evident from this simple theory. The first is that attempts to eliminate the error by increasing the area of the drogue are going to have diminishing returns because of the square root. Thus, for equal drag coefficients, if the area of the drogue is 100 times that of the buoy, the error in the measurement is still 10% of the velocity of the surface float through the surface water. The other feature is that the error is proportional to the relative velocity of the surface float through the water. Thus, even though the drogue is not Lagrangian, an estimate of the current at drogue depth can still be made if a current meter is attached to the surface float, provided that the ratio under the square root is known.

A more complete theory for the horizontal force balance should take two further factors into account. The first (Monahan, et. al. 1973) is that many real objects do not obey a square law in their drag relations. In particular, a current cross at low speeds (2 cm/sec) may have only half of the drag that is calculated from a square law relation. Also, surface buoys at high speeds (60 cm/sec) can start to shed vortices leading to a departure from the square law with a higher than calculated force for a given speed. These two effects both tend to increase the errors in the case of large vertical shear. Even with a non-square law force vs. relative speed curve, a graphical method can be used to relate the error to the relative speed of the surface float.

The results above depend on the simplification that the forces on a drogued buoy system can be well represented by the point forces which can in turn be related to relative water velocities. These assumptions can be questioned in two important instances. The first is if the readout (e.g. flag) has a significant force acting on it from the wind. The second is if the connecting line is long enough that its projected area approaches that of the surface float. In both of these cases, the problem can no longer be reduced to a coplanar vector problem. It becomes, as a result, more complex. At some future time, we expect to investigate the fluid mechanical behavior of drogued buoy systems more completely and analyze the full problem.

2.2 Techniques

The biological techniques developed in this study serve a two-fold purpose. By measuring the magnitude of biologically related indices we hope to "characterize" certain properties of marsh and offshore waters and then use the indices to delineate the movement of these waters with respect to each other. Secondly, by measuring these same indices in water moving through Wachapreague Inlet, we anticipate being able to determine the flux of biologically related materials between the marsh and offshore. This kind of information has an important bearing on the eventual disposition of these areas for alteration of either the marsh or offshore environment by man must certainly take into account the possibility of significant biological interaction (exchange of nutrients or organisms) between the two.

A significant part of the first year of the study was devoted to developing the capability to make certain biologically related measurements in the field. The indices and methods used to measure them are described as follows:

Chlorophyll - Both the total chlorophyll content of the water and the size distribution of the chlorophyll containing organisms is measured. Total chlorophyll is determined by filtering a known volume of water through a Gelman Type A glass fiber filter then freezing the filter on dry ice for extraction and analysis in the laboratory. The size distribution of the phytoplankton chlorophyll is determined by first passing the water sample through an appropriately sized filter to retain organisms larger than the designated pore size, then passing the filtrate, theoretically containing all organisms smaller than that pore size, through a glass fiber filter to collect the total chlorophyll remaining. Millipore filters of various pore sizes were first utilized for preliminary filtering but clogged easily thereby retaining organisms that should have passed through. Consequently, we switched to Nitex nylon mesh for preliminary filtering. Ten micron mesh size is generally utilized as the dividing line, however other mesh sizes are available including 15, 20 and 35 microns.

Chlorophyll is extracted from the frozen filters utilizing a tissue grinder with 10 ml of 90% acetone. The chlorophyll content is then determined either with a Turner Fluorometer (Chl. a) or a Cary 15 recording spectrophotometer (Chl. a, b, and c). Readings on both instruments are made before and after acidification in order to correct the chlorophyll a values for the presence of phaeophytin a.

Photosynthesis - Rates of photosynthesis are determined using the C^{14} bicarbonate method with water samples kept under controlled temperature and light conditions. Consequently, the rates determined are not in situ rates. Since the light conditions utilized are saturating with respect to photosynthesis, the rates determined should reflect the potential photosynthetic capability of the phytoplankton in the water.

In addition to a total photosynthetic rate, the photosynthesis attributable to different size ranges of organisms is also determined. This is accomplished by passing the water sample through appropriately sized filters then determining the rate of photosynthesis of the organisms remaining in the filtrate. Here again millipore filters were first utilized for prefiltering but abandoned in favor of Nitex mesh filters.

Engineers at NASA Langley developed a clamp mechanism that attached to the drogues about one meter below the water surface capable of holding light and dark sample bottles. These bottles are filled with a water sample, innoculated with C^{14} bicarbonate and placed on the drogues when they are released at the point where the water sample is taken. Since the drogues should remain with the same body of water, the incubating sample is exposed to essentially natural light and temperature conditions. Therefore, the photosynthetic rates determined from this sample are comparable to in situ rates.

Unfortunately, problems associated with this procedure such as bottles lost when drogues beached and samples not fixed properly when drogues retrieved made it difficult to judge the worth of the results. With the separation of the drogue and biological programs, this technique was abandoned.

Heterotrophy - A metabolic rate attributable to the heterotrophic organisms in the water (presumably bacteria) is determined by measuring the rate of uptake of C^{14} glucose by the heterotrophic organisms is generally a hyperbolic function of the amount of glucose added. Consequently, if we assume that the leveling off in uptake at high added subtrate concentrations (>150 μgms ℓ^{-1}) is due to a saturation of the surface-bound enzyme system mediating the uptake, then the level of uptake at saturation (hereafter called V max for maximum velocity of uptake) should be a reflection of the total amount of enzyme available. Therefore, Vmax serves as a metabolic indicator of the relative levels of the biomass of the heterotrophic community.

Vmax is determined by incubating water samples at four different levels of added C^{14} glucose substrate (37.5, 75, 187.5 and 375 μgm ℓ^{-1}) for a specified period of time. The amount of glucose assimilated by the heterotrophic organisms at each concentration is determined by filtering the water samples and measuring the amount of glucose C^{14}

activity remaining on the filters utilizing a liquid scintillation counter. The value of Vmax in terms of μgms glucose assimilated per hour per liter is determined from a linear transformation of the hyperbolic relationship between assimilation and substrate concentration.

Hydrographic Data - The hydrographic data recorded when a water sample is taken includes temperature, turbidity, and samples for salinity and dissolved oxygen determination. A tide gauge located in an instrument tower just inside Wachapreague Inlet provides information on tide stage and heights with respect to time of day.

Nutrients - Water samples are preserved in the field for later analyses of the following nutrients: total kjeldahl nitrogen (TKN); dissolved kjeldahl nitrogen (DKN); ammonia (NH_3); nitrate (NO_3); nitrite (NO_2); total phosphorus (TP); total dissolved phosphorus (TDP); reactive phosphate (PO_4); inorganic carbon (IC); dissolved organic carbon (DOC); total organic carbon (TOC).

Automatic Marsh Sampler - Several days were spent at Wachapreague field testing an automatic water sampler modified by NASA Langley engineers for use in estuarine areas. This device is capable of taking 28 sequential water samples over a period of 24 hours. Presently it is adapted for deployment and retrieval via helicopter. These aspects of the field test were successful, however, the water intake port became clogged with floating debris preventing proper filling of all the sample bottles.

Modifications by NASA Langley to rectify this problem are currently underway and we anticipate that this piece of equipment will be available by July 1, 1973. Its use in the sampling program will be described in a later section.

2.3 Navigation

Perhaps the most important area of technique development where VIMS can contribute significantly is in the location of buoys remotely. This problem has occupied a large portion of the first year effort. The implementation of a particular solution to the problem will take a similar portion of the second year effort.

The navigational problem for coastal oceanography can be formulated as the location of N remote moving objects from a fixed shore station given that the remote objects are in a given area A during a time T within an area of uncertainty a. The area of uncertainty, the speed of the objects, and the sampling time should all be chosen to be within the conditions found in coastal waters. Such a set of sequential locations must be done for a period of P. In order to reduce this to an engineering problem, estimates of N, A, a, T, and P must be given and the relations, if any, between them be formulated.

In our case, on the surface, a maximum value for A is fairly easily determined by the dynamics of the shelf circulation. Its boundaries are the Gulf Stream, the continental boundary, an E-W line running approximately through Cape Hatteras, and a badly defined northern boundary. Currently, the pattern of surface flow in this area seems to be irregular with a small mean southerly transport. Surface water passes out the Cape Hatteras boundary to be entrained in the Gulf Stream system or on rare occasions to enter the shelf circulation of the North Carolina shelf water.

Within this geographical area, there seem to be several regimes of flow. The most complex is around the mouth of the Chesapeake Bay. To the north and south, several distinct areas may be present. These are sometimes referred to as gyres or gyrals. Until their dynamics are understood, we shall call them domains in analogy with ferromagnetic materials. These domains include several apparent boundary layers at the free surface and at the continental boundary.

The choice of N for a given experiment depends on the structure of the water in the A of interest and on the statistical data desired within the major structure. The choice of length and time scale boundaries, (L, τ) between "flows" and "fluctuations" is largely arbitrary. Once the boundaries have been chosen, the analysis of data and required experiment design is dependent on the choice.

To determine the flow, the drogues should be spaced closer than half the length scale. This gives $N \geq 4A/L^2$. If the drogues are to be set in a line perpendicular to a flow line, the number can be substantially reduced to

$N \geq 2\sqrt{A}/L$. For this type of experiment, the analysis assumes that fluctuating motion smaller than the length scale is random. The fluctuations can consist of either water motions or navigational errors. Thus, in the case that an area is being covered, errors up to the drogue spacing are in some sense permissible. This leads to $a = 1/4\ L^2$. That this estimate of the permissible error is much too great, in many instances, will be shown later.

If the fluctuations rather than the flow pattern are of interest, as in dispersion determinations, (Chew and Berberian, 1972), the analysis of and requirements for data are somewhat different. The area of interest is, in general, much smaller. The object is to confine the experiment to an area (L^2) small enough that the fluctuations under the area are statistically homogeneous. In this case, the statistics of interest depend on the differences in location within the area at a given time. Thus, an error of O(L) can be tolerated if the same error applies to all the positions. The differential error allowed enters into a tradeoff with the total number of buoys, the velocity scale of the motion, and the time required to locate a given buoy (assuming a single buoy is being located at a given time). If U is the velocity scale of the motion, we have

$$N U \tau = \Delta$$

as the uncertainty in positions during a scanning interval if the location error (a) can be reduced by a longer scan time per buoy $a = a(\tau)$, then the optimum tradeoff is given when $\Delta = \sqrt{a}$ or

$$N V \tau = \sqrt{a}$$

The desired number of buoys in a cluster depends on the information desired. With one buoy, an estimate can be made of the position of the parcel (L^2) of water. The position is blurred by uncertainty due to the random fluctuations within the parcel. If two buoys are used, the reliability of the position of the parcel is increased. In addition, an estimate of dispersion can be made by analyzing the rate of separation of the two buoys. With two buoys, the separation can equally be used to estimate one component of shear or conceivably, divergence. With just two buoys, the effects of these three dynamically different processes cannot be distinguished. If three buoys are used in a cluster, then shear can be distinguished from divergence, but both cannot be distinguished from random dispersion (Chew and Berberian (1972), Okubo (1970)). With four buoys in a cluster, a mean position, divergence, two components of shear, and dispersion can all be estimated, if the tracks are divided into coherent and non-coherent parts. With five buoys and more, additional degrees of freedom are obtained with a concomitant loss of resolution. Five separate buoys may be the optimum number for a two dimensional surface analysis of a small homogeneous area.

Given these preliminary remarks about experiment design with drogued buoys, various kinds of remote location schemes have been studied for suitability in terms of accuracy, cost, range and duration of operation. The systems studied include radar, microwave ranging equipment, optical direction finding equipment, existing radio navigation equipment (Loran A and C and Omega), Decca Hi-Fix and Hastings Raydist. The system that is being pursued at VIMS is one using Omega in a differential mode retransmitting the Omega signal from the remote buoy to a shore station where all the processing takes place. Multiple buoys will be followed by putting sequential transmission switches on the buoys controlled by internal clocks. This system was chosen for several reasons. The retransmission of unprocessed signals allows the buoy electronics to be very simple and inexpensive. The buoys are thus more or less expendable, a property consistent with the conditions of oceanographic research. The Omega signal format allows ease and simplicity of signal processing. The availability of an automatic Omega receiver (LITCOM ORN 101) is largely due to this simplicity and makes automatic system operation feasible. The use of the differential mode increases the accuracy of the system to a few tenths of a nautical mile even during shifts in the level of the ionosphere. The 8 mile ambiguity in Omega positions can be resolved by keeping track of phases during sequential interrogations of the remote buoy while leaving a generous amount of time for signal locking and accumulated clock errors during a track of a month. This technique also builds on some recent work done at the University of Michigan (Michelena, 1973). With the initial system, we should be able to locate 5 buoys at a 30 minute sampling period with an accuracy of .2 nautical miles for 30 days in a range of 100 miles from the base station.

2.4 Remote Sensing

Part of the object of this research is to develop techniques to use remote imagery in conjunction with buoy positioning to estimate water circulation over the continental shelf. At present, this part of the program is in its infancy. The only part of the circulation which has been considered is surface circulation.

In the nearshore region, images of the water surface show, usually, areas of constant "color" separated by well defined boundaries. The areas of constant color can be related to well mixed source regions with the boundaries being "water type" boundaries. In addition to these boundaries, there are well defined lines or streaks that appear in single water type areas. These are, on close study of verification data, usually associated with flow discontinuities. Those observed have been related to shear discontinuities, convergences, and stagnation points in the surface flow field (Kupferman, 1973).

In the specification of a flow field, sequential images can give the motion of a pattern of lines. Vertical velocities near the surface can be estimated over areas by measuring time rates of change of the area defined by closed boundaries of water types.

In addition to these features of images, there are seen glitter and streaky reflections over the water. These relate to the slope of the surface wave field and conditions at the surface. The use of these, if any, in estimating flow fields has not yet been discovered.

Horizontal velocities normal to boundary lines can be estimated from sequential images of the lines provided that a given line is recognizable from one image to the next. In circulation of less than tidal period, a maximum period between images is about six hours for analyses of this kind. Velocity estimates of this kind can be seriously in error if the boundary lines are, in fact, "flow discontinuities." The horizontal velocities measured from sequential images are thus the boundaries of flow discontinuities. In order to obtain the flow between these discontinuities, a separate determination of the strength of the discontinuity must be made.

Perhaps the most valuable use of images obtained to date is the obvious and non-numerical one. The images contain the character of the flow pattern. Knowledge of the flow character is essential to the proper formulation of a tractable mathematical problem from the equations of motion. We can expect, for example, a basic balance between the terms with higher order terms having small coefficients at the scales of the "patches" or areas of well mixed waters. The highest order terms should become important in the "flow singularities" of the basic pattern. In order to evaluate the effect of a discontinuity on the large scale flow, for instance, its dissipation of kinetic energy, the jet or boundary layer problem consistent with the singularity must be formulated. The choice of boundary layer formulation depends on the ratio of non-dimensional numbers associated with the flow. (An example is the Ekman number and the Rossby number in rotating tank flows). In the nearshore circulation problem, the non-dimensional numbers depend on characteristic velocities and length scales of the flows as well, usually, as a parameterized friction law. These quantities can only be correctly judged from the character of the flow. Thus, images can be of direct importance in the formulation of the mathematical problem which is pertinent to the continental shelf nearshore circulation as well as other circulations.

2.5 Data Analysis

Data analysis techniques are being developed in order to translate the raw data into form amenable to scientific and practical uses. To date, the analysis has been of the *ad hoc* variety with little common formatting, programming or other formal organization leading to ease of access and preliminary analysis. Data so far have been of three primary types: station sample data, relative position and time data for drogues, and two-dimensional images.

Station sample data have been entered on standard VIMS data forms and entered into the existing VIMS data systems. Plots of these data have been made and contoured by hand. Some of these plots have been compared to image data.

Position and time data for drogued buoys have been treated in several ways. Immediately on receipt during the experiment, range and azimuth from the radar are entered in a calculator-plotter and plotted on a chart of the area. This allows the experimenter to monitor the progress of the experiment. Simultaneously, the calculator computes corrections for the transponder delay times and, if necessary, for a constant azimuth error. The data are corrected for A-D converter scale factors and converted to meters. The corrected data are printed in azimuth/range and east/north forms as well as plotted on the chart. The record from the tape is used in conjunction with a separate written data log and a tape recorded record to provide redundancy to use in error checking. The azimuth/range numbers from the calculator tape are transcribed onto punched cards, which are the primary input for further data processing. Currently, they are run in a program VELBUOY which computes the velocity for each buoy as a function of time. This program, besides providing velocity information, acts as a remarkably sensitive check for many errors in position due to both radar errors and transcription errors. Currently, a buoy track is considered free of errors when the plot of speed from VELBUOY is qualitatively reasonable.

An alternative form of data reduction was applied to the data from the James River experiment. These data were received in two forms. The first was an X-Y plot of position taken directly from the operation console. These points were digitized by hand and interpolated to standard 10 minute sample intervals. Another set of programs were written for the above mentioned calculator plotter to plot any of a number of variables versus any other. The variables available were time, X and Y components of velocity, speed, X and Y components of acceleration, acceleration magnitude, position, path length, and down-stream and cross-stream acceleration for any given track. Some of these plots were used in the report to the Virginia Highway Department (Fang, et. al., 1972).

These data were also made available in the reduced data form from NASA Wallops Island Station as approximately fifty separate locations of the buoy in a ten second period. These data were averaged and variances of range and azimuth along with least count increments were calculated. These variances gave an excellent indication of the precision of the tracking system for any given point, providing an independent means for distinguishing "good" points from "bad" ones. A precision of two meters at a distance of four miles appeared to be obtainable from the system. The average positions along with the variances were placed on punched cards for further processing.

Of more complexity than the track data are the images obtained from remote sensing equipment. These images have been supplied to us by NASA Houston and NASA Wallops Island Station. The analysis of these data has not yet begun except in a qualitative way, because of that complexity. The integration of the sequential photographic data with the flow data obtainable from drogued buoys remains one of the challenges we must face. We expect the combined approach to be fruitful in specifying shelf circulation and, in particular, the important interface between the continental shelf waters and the adjacent land.

3. Field Tests and Applications

Several field programs have been run during the first year of the grant. They have been designed to achieve three objectives. These objectives are to obtain data useful to other parties, projects, and agencies concerning flow patterns, to add to our scientific understanding of hydrodynamic processes in various marsh, estuarine, and coastal situations, and to develop and test the techniques, methods and devices required to fulfill the first two objectives efficiently, inexpensively, and accurately. These programs were conducted in Hampton Roads, Mobjack Bay, and Wachapreague Inlet. The Wachapreague Inlet program had, in addition to two drogued buoy studies, a continuing biological sampling program associated with it.

3.1 James River Drogue Study

The James River Drogue Study was the first field experiment run with the joint VIMS-NASA Langley Research Center-NASA Wallops Island Station drogued buoy system. It took place between June 1 and June 14, 1972. The experiment was multipurpose, including gathering advisory data for the Virginia Highway Department I-664 river crossing study as well as various engineering and technical exercises designed to evaluate the characteristics of the radar buoy system. A total of eight types of experiments were performed. The results and status of these experiments vary considerably and will be summarized below.

Experiment: Radar Calibration and Test

This experiment consisted of placing a radar transponder in a boat and moving the boat to various points in the Hampton Roads vicinity in order to determine range and accuracy of the system. The range was shown to be greater than six miles and the accuracy at all ranges within 100 yards. These values for range and accuracy were limited by the test range and not by the radar system.

Experiment: Two Buoy Track

The MPS-19 radar used in these experiments is designed to be positioned near a moving target, lock on to the target, and follow its motion automatically. The mode of operation for the drogue work involves switching between targets with different transponder codes and obtaining essentially single positions. This mode of operation is an inconvenient and difficult one to use with the equipment. Accordingly, this experiment was designed to test the switching ability of the radar crew in this difficult mode. The results were that the equipment could be switched between buoy signals in less than 1 minute about 80% of the time. For long term work, two minute intervals between fixes were agreed upon with a complete scan of four buoys every 10 minutes. This was the criterion used in the design of additional experiments.

Experiment: Shear Calibration

This experiment was designed to verify some aspects of the simplified theory of behavior of the drogued buoys in a natural vertically sheared horizontal flow. The experiments consisted of runs of pairs of buoys one drogued at the surface and one at one of several depths past a moored current meter. The results have not yet been analyzed. The theory behind the experiment is given in Knauss (1963) while certain deviations of similar configurations from the theory are summarized in Monahan, et.al. (1973).

Experiment: Bathymetric Survey

A radar positioned bathymetric survey was conducted at the same transect as the current transect. The object was to examine the effectiveness of the radar positioning system in this mode, which involved tracking a boat and vectoring it via radio. The technique was shown to be useful, but the resulting bathymetry fit the C&GS chart best if a 5% systematic error in range was assumed.

Experiment: Channel Shear Experiment

In this experiment, the attempt was made to measure both horizontal and vertical shear in a small area using drogued buoys. The attempt was only partly successful because of several factors. What was discovered was the limits of the technique in terms of rapid deployment and retrieval of instruments in rough water conditions. The data should be good enough to obtain a few of the desired shear estimates, but they have not yet been analyzed beyond initial averaging and placing in standard format.

Experiment: Surface Current Patterns

In this experiment, the surface current patterns on the scale of the entire Hampton Roads region were measured using lines of buoys oriented roughly perpendicular to the current. The experiments in this form were particularly easy to run and largely successful. The results of these runs in pathline form for ebb and flood currents are shown in Fang, et. al. (1972) p. 236, 237. Also shown are speed versus pathlength graphs for flood and speed versus time graphs for ebb conditions.

Experiment: Hampton Flats Eddy Experiment

A particular experiment was designed during the program in the James River to test the flow in a particularly sensitive area as discovered in the associated work performed in the James River Hydraulic Model at Vicksburg, Mississippi. The model work showed that the formation of an eddy in the Hampton Flats area was critically dependent on small changes in shoreline configuration at Newport News Point (Fang, et. al., 1972). The large variation of phases noted in the river was not inconsistent with such an eddy, but the eddy did not form during the run in the model for which the shoreline was unaltered. The results of a drogue run in the Hampton Flats area agreed with the model in that no eddy was observed from the drogue tracks.

These experiments, in addition to acquainting us with the features and capabilities of the instruments and techniques, provided us with engineering data about drogued buoys and allowed us to formulate recommendations to the Virginia Department of Highways. In addition, we gained unsuspected insight into conditions near the Norfolk Navy Yard. These insights are leading to further study this summer of the conditions in the vicinity of the mouth of the Elizabeth River.

3.2 Mobjack Bay Tidal Circulation

The work in Mobjack Bay has been of a different nature. It has provided the largest part of the thesis work for a graduate student getting his Master's degree. In this work, small surface floats have been constructed with flags for location. The flags are seen with transits from shore. The resulting positions are determined using triangulation.

The surface currents measured this way are being compared with a set of current meter stations that are obtained in the area during 1970. The object of this comparison is to compare Lagrangian and Eulerian accelerations and examine the magnitude of the Stokes acceleration in Mobjack Bay. The work performed is currently being prepared for submission as a thesis this September (Wu, 1973).

3.3 Wachapreague I

The first study at Wachapreague Inlet was planned for the period between October 9 and October 27, 1972. It was run between December 4 and December 15 because of difficulty in obtaining equipment on the original schedule. The planned experiments had two primary objectives; to define surface circulation under flood and ebb tidal conditions and to obtain a modern bathymetric chart of the area. Four separate flood and three separate ebb experiments were defined to observe various aspects of the patterns from the marsh channels to the shelf water. Two bathymetric surveys using radar control of position were planned at different scales. An additional experiment was introduced into the program. This experiment consisted of using the tracking ability of the radar to follow a transponder being carried along the shoreline. This enabled us to define the position of the shoreline for several miles on either side of the inlet with respect to the VIMS Wachapreague Laboratory. As a result of the work done at Wachapreague, an outer limit of nine miles from the radar van was established for the working range of the system with the van parked near sea level.

3.4 Wachapreague II

Based partly on the results of the first Wachapreague experiment, a second field experiment was run from March 20, 1973 until April 6, 1973. This field work had, as its objective, further specification of the circulation of Wachapreague Inlet and its region of influence. In addition, several new features were added. The first addition was a field test of a "suitcase radar," a candidate system for replacement of the MPS-19 system previously described. This engineering support test occupied the first four days of the schedule. The other addition was a trial series of sequential overflights by a NASA Houston aircraft. The overflights were done with several cameras set with different pictures and an infrared scanner. The object of the simultaneity was to try to marry over flight results with drogued buoy results. Unfortunately, the buoys were unavailable on the day of the overflight. Limited hydrographic and biological sampling was done at this time, however, and the images from the overflights have direct applicability to the sampling program. The series of sequential daylight overflights is being continued in order to obtain typical images for a complete, if not single, tidal cycle.

Another cooperative effort was planned and partially run with a separate VIMS inshore circulation study using flag buoys. This ONR funded study is also a large part of a thesis for a graduate student. The cooperative phase consisted of an intercomparison between the drift of the flag buoys and the radar transponding buoy. This experiment was terminated by the capsize of the boat carrying the buoys.

The radar drogue work associated with the Wachapreague II program pointed out some other limitations of the technique. In particular, our limited ability to work in rough seas required rescue of some people by the Coast Guard and rescue of equipment; the buoys, by a NASA helicopter. If we are to achieve an operational capability in rough weather, a theoretical strong point for drogued buoys, the operation and experimental design will both have to be changed.

3.5 Biological Sampling

The sampling program associated with the biological aspects of this study went through several changes during the first year although the general objectives remained the same. Those objectives were two-fold: to sample on a transect from the marsh interior to several miles offshore in order to determine the distinguishing biological characteristics of the two areas; and to sample at some fixed point in space sequentially through time to determine the movement of biologically related materials between the two areas.

As first conceived, the biological sampling and analysis at Wachapreague was to be done on board the Boston Whaler. However, after two field trips (August and September, 1972), it became apparent that the small size and unstable working conditions of the boat made this idea untenable. We then decided to utilize a stationary platform for the analysis equipment and use the Boston Whaler to obtain the necessary water samples.

In October the field equipment was set up in a small covered scow that was anchored at the mouth of a small tidal creek sampled by station A entering into Wachapreague Channel. While water samples were taken at the mouth of this creek every 1.75 hours over a complete tidal cycle, the Boston Whaler was used to obtain samples from stations B, C and D (see chart I) at low and high slack tides. The samples from the creek were analyzed for nutrients only in an attempt to determine the net flux of these materials in or out of the marsh over a tidal cycle. Samples from stations A, B, C and D were analyzed for most of the indices mentioned under the Techniques.

In December 1972 and March 1973, biological sampling at Wachapreague was coordinated with the drogue study. We anticipated being able to determine the degree of mixing of marsh and offshore waters during ebb and flood tides by taking samples when a drogue was released and again when the drogue was retrieved. A comparison of indices (e.g. chlorophyll or heterotrophy) between these two samples should have provided insight into how water properties change as the water moves into or out of the marsh. Additionally, water samples were to be taken at stations A, B and D on slack tides and at station C sequentially over a tidal cycle. The samples from station C were to be in conjunction with sequential drogue deployment at that point.

It became apparent, however, that the logistics of drogue deployment, tracking and retrieval with the Boston Whaler was such that sufficient time was not available for the proper collection of the necessary water samples. Consequently, it was decided most efficient to separate the biological sampling program from the drogue study, a decision prompted in part by the year round nature of the former program versus the relatively short term nature of the latter.

In early April, the first opportunity arose for biological sampling independent of drogue operations. Stations were established in the two main channels forming Wachapreague Inlet (X and Y on Chart I) and samples taken there every hour for nine hours. In addition, samples were taken at stations A, B and D on the two slack tides during this time span.

A biological sampling program was initiated to accompany the NASA overflight on April 6. We anticipated that hydrographic and biological indices measured in the marsh and offshore waters would aid in interpreting the movement of water offshore as it left the marsh on the ebb tide. Boats were stationed at stations X and Y to measure water temperature, dissolved oxygen and chlorophyll content at twenty minute intervals. A single boat moving in a repeating pattern offshore measured identical indices plus heterotrophic metabolism. This boat collected a total of 32 water samples from fourteen stations during the period of the overflight (see chart II, for station designation).

3.6 EOLE

Another project has been started during the first year of this grant. An opportunity has arisen to take advantage of a system similar in many ways to the one which we wish to develop. At the least, then, we have an opportunity to obtain a presurvey of the continental shelf waters to give us an idea of the features and water movements we can expect to find when we do expand our systems to the continental shelf. This opportunity consists of the use of five channels of the EOLE satellite system. This satellite has the capability of moderately precise location (1 NM) of objects anywhere in the world during several orbits at about 1 hour intervals every 12 hours. This program is a windfall. As such, there is no estimate of the duration of the program or a follow-on program.

We have designed a series of multi-use experiments which can be performed in such a context. These experiments are being performed as opportunity permits. The experiments have consisted of sequential and group deployments of buoys near the Chesapeake Light Tower. The effort has been made to follow the movement of these buoys from deployment until they leave the shelf area, when they are picked up and renewed. This process is repeated as often as possible in order that climatology might be developed for the observed flows.

The work so far has consisted of setting the buoys and their drogues and consulting with NASA Langley Research Center about buoy design and their ongoing instrument package development. A certain amount of preliminary data analysis has been done, but final analysis and interpretation awaits the end of the field deployment stage. This data analysis and interpretation may form the heart of a separate proposal to another agency.

4. Results to Date

4.1 Physical Results

The first year of a several year project is too soon to expect results from the main stream of the project. This project is organized in a way to develop spin-off results on a short time scale. Such results have come out in the first year. They are contained in Fang, et. al., (1973), "Physical and Geological Studies of the Proposed Bridge-Tunnel Crossing of Hampton Roads Near Craney Island," a report prepared for the Virginia Department of Highways. The report was in response to a request and contract from the Department of Highways for data usable in the evaluation of environmental impact of a proposed bridge-tunnel crossing in each of several configurations. In addition to determining the minimum-effect placement and orientation for the proposed tunnel island, several other results pointing to important hydrographic and geological relationships in the Hampton Roads were obtained fortuitously. First, the complex tidal pattern points to the importance of reflected waves in the basin. Thus, there is no guarantee that a local change in configuration will not have important effects elsewhere in the basin. Also, a standing wave structure with wavelength of about 3 km was discovered in flood tide upriver from Newport News Point. Thirdly, on ebb tide, we found that Newport News Bar is directly upstream from Hampton Bar. This may indicate that the two are related in sediment transport and that alteration of one will produce a corresponding alteration in the other. In addition, on ebb tide, a flow of surface water directly into the Navy Base at Norfolk was observed under light wind conditions. This is particularly interesting in light of the fact that the water must cross the channel of the Elizabeth River in order for this pattern of flow to occur. We were surprised that the flow was not directed by the Elizabeth River channel. In contrast, on ebb tide, the surface water has a remarkable response to the presence of the main ship channel. The flow in the water over the channel (depth about 50 feet) was markably more rapid than over the natural channel (depth about 20 feet). In fact, when a single buoy drifted from the main channel to the side and back again, the speed of the buoy <u>in the same water</u> behaved accordingly. This may be because bottom friction has a strong flow determining effect in seeming contrast to the small energy withdrawing effect of friction as evidenced by the large phase differences in the tidal heights in the area. Finally, there is the result for which the study was particularly designed. That is that the small channel in Hampton Flats near Newport News Point is a flood channel and that ebb currents effectively bypass the area.

These results, besides satisfying the original request, have stimulated additional interest in the hydrodynamic behavior of Hampton Roads from several parties, who feel that knowledge of the currents in the area can help them manage their own facilities more effectively. These include the Virginia Department of Highways, who wish to access the flow around the islands and pilings of their Second Hampton Roads Bridge Tunnel Crossing now under construction and the U.S. Navy, who have been troubled for a long time by high siltation rates at their deep water piers of the Norfolk Navy Yard.

The physical results from the first James River Drogue Study are available in some detail, although not entirely, because the study was a short term study of an applied nature. The extra results are of some interest and are leading to further work in the area. The other major field work at Wachapreague Inlet has not given us many results for several reasons. First, it has been started more recently, second, it is a more comprehensive study, third, conditions are more complex in the area because part of it is over the continental shelf. The nearshore shelf region is not dominated by tidal motion the way a river is. Thus, a great simplification in experiment design is no longer available to us. Finally, the work at Wachapreague concerns more kinds of data from more disciplines under more adverse conditions than that in the James River. In spite of this, some physical results are available from the Wachapreague experiment. We have learned that the surface water exiting from the inlet takes the shape of a plume of only a few miles in extent.

This surface water does not, in general, enter the inlet.

4.2 Biological Results

The results of the slack tide transects indicate that the metabolic indices (i.e., photosynthesis, chlorophyll content and heterotrophic metabolism) are generally highest in the marsh and decrease steadily as one moves toward the offshore station. Qualitative differences between the photosynthetic organisms of the marsh and offshore environments have not at present been demonstrated. A lack of offshore samples, primarily a result of only one offshore sampling station and difficulty in always reaching this site, is the reason for this omission. We strongly suspect that the size range and pigment content of the primary photosynthetic organisms in the marsh differ significantly from those in the offshore waters. If demonstrated, these differences will be a valuable aid in distinguishing water types, for qualitative differences should be more consistent throughout the year than quantitative differences due to the seasonal nature of the magnitude of metabolic processes.

On spring tides the tidal excursion is such that the water originating in the marsh exits the inlet. Based on the aforementioned information gained from slack tide transects, we expected the magnitude of the metabolic indices of the water moving out through the inlet would increase steadily as the ebb progressed toward low slack.

However, results from April 3 (Tables 8 and 9) indicate that chlorophyll and Vmax values increase initially then decrease, apparently because decreased tidal velocities as the tide passes mid ebb and approaches low slack permit the plankton to settle out of the water column. It may be that the movement of marsh derived materials out of the inlet is a function of the tidal velocity in addition to the stage of the tide at a given time. This phenomenon will be investigated more thoroughly in the second year of field operations.

Although water moving out of the inlet obviously originates in the marsh, water entering the inlet on the flood tide may originate from several sources (e.g., offshore, the inlet up the coast, the water moved out of the inlet on the preceding ebb tide) and that source may be influenced by wind or offshore current conditions. We had hoped to be able to make some statements on the source of flood tide waters, utilizing biological and nutritional indices as "markers". However, a lack of offshore data is also hampering this analysis. As will be described subsequently, remote sensing would be a valuable aid in defining the movement of water masses outside the inlet.

A comparison of results from ground based sampling and the overflight photographs of the April 6 outwelling demonstrates the clear advantage of the latter technique in studying the behavior of this phenomenon. A correlation of plume progression (Chart II) with the times stations were sampled by the offshore vessel (Table 11) indicate that Stations 5, 6, 7, 8, 9, and 10 were probably not within the boundaries of the turbidity plume when sampled the first time. This is reflected in the generally low chlorophyll and Vmax values associated with these stations. Almost all the stations demonstrated an increase in the biological indices between the first and second sampling, presumably caused by the outward movement of the biologically more active marsh waters. It is apparent, however, that the overflight photographs far outweigh the biological sampling results in terms of adequately defining the movement of the marsh waters offshore.

Although the outwelling was readily visible in the photographs as a well defined turbidity plume increasing in size as the ebb progressed, the eventual fate of this water remains a mystery. It could have been swept back into the salt marsh on the succeeding flood tide. It could have moved along the coast and re-entered the next inlet downshore. It could have moved off the coast and gradually dissipated. Knowledge of its fate is necessary before we can attempt to determine if the organic materials associated with the outwelling constitute a significant contribution to the productivity of the receiving system. Given the difficult logistics associated with ground based sampling in this area, remote sensing is the best and perhaps only way to provide the necessary answers.

When the metabolic values obtained from Wachapreague are compared to similar values from the Chesapeake Bay and York River areas there are some interesting distinctions. The levels of chlorophyll and planktonic photosynthesis appear significantly lower in the Wachapreague marsh than in the other estuarine areas. Although this may be due to the higher salinity of the Wachapreague area, it may also be the result of altered nutrient levels, or unstable water conditions (mixing) in the marsh. The current unavailability of much of the nutrient data from Wachapreague precludes final judgment on this question.

Despite the relatively decreased levels of chlorophyll and photosynthesis, the levels of heterotrophic metabolism appear every bit as high in the Wachapreague marsh as in the Bay areas. This combination of factors may indicate a fundamental difference in energy flows through the two somewhat similar environments which could have implications for the flux of organic materials out of the two areas. The decreased productivity combined with relatively high rates of bacterial metabolism might be reflected in less organic material available for export from the high salinity Wachapreague marsh. However, more information, especially over a growing season, is necessary to substantiate this hypothesis.

The implication of these biological investigations goes beyond simply gaining understanding of salt marsh and coastal biology and interaction or lack thereof between the two. Effective and enlightened management of these environments in response to constantly increasing multiple use pressures from man is possible only if the basic underlying biological mechanisms are understood.

The results of the biological sampling completed during the first year of this study, as they are currently available, are included in tabular form at the end of this report.

5. Future Plans

Present plans for biological operations during the second year of this study center primarily on monthly field trips to Wachapreague. An effort will be made to take sequential samples at both stations X and Y every hour during a twelve hour tidal cycle as well as at stations A, B, and D at each of the three slack tides occurring during this time span. These samples will be analyzed for all of the indices described under Techniques. This type of program should be sufficient to provide information on the magnitude of biological processes both in the marsh and offshore waters, the types of organisms responsible for this activity and the flux of materials (organisms and nutrients) between the two areas.

We anticipate the use of the automatic marsh sampler provided by NASA Langley to take sequential samples every half hour for twelve hours at the mouth of the small tidal creek sampled by station A. Since the samples taken by this instrument are immediately preserved with mercuric chloride, they can be analyzed for nutrients only. However, these samples should provide an interesting comparison of the level of nutrients and their flux in a tidal stream intimately associated with the marsh as opposed to the larger order Wachapreague Inlet.

In addition to this routine sampling program, an additional day will be devoted to the investigation of special problems that arise during the course of the investigation. For example, there presently exists a need for more samples from offshore so that the differences between these waters and the marsh waters can be more accurately defined. There is also a need to determine the extent to which the waters in the main channels behind the inlet and offshore are stratified. With the very small salinity gradient exhibited between marsh and offshore waters (three parts per thousand at most) one would expect very little stratification. However, all sampling thus far has been at one meter and there is a need to know if the biological indices change drastically with depth or are generally constant from top to bottom.

The photographs from the NASA overflight on April 6 demonstrated a well defined offshore turbidity plume accompanying the ebb tide. Subsequent field investigations have confirmed that the outer edge of this plume is also readily visible from boats in the water. It appears likely that the fate of this turbid water on the subsequent flood tide could be determined utilizing a combination of an offshore boat following the outer edge of the plume, a small aircraft overhead taking color and color infra-red photographs and sequential sampling of biological indices of the water moving back into the marsh through the inlet. This type of investigation should be more flexible and hopefully as productive as the large scale overflight operation of April 6. It is our intention to institute a program of this type to determine the fate of the off-shore plume under varying tidal and wind conditions.

Despite the ongoing nature of the Wachapreague investigation, it is our intention to retain sufficient flexibility in our field operation to enable us to coordinate biological sampling with drogue experiments that develop in other locales. If the need for biological data arises, we need only a stable surface for equipment and a rapid means of transporting water samples to the work area in order to operate.

Several directions are being followed in the physical work under this grant. Small scale field experiments similar to the James River Drogue study will still be run using existing techniques. In the coming year, studies at Hampton Roads and the Elizabeth River are scheduled and one near Hog Island on the James River is planned. The first two are in support of the Virginia Department of Highways and the United States Navy. The third is in support of a project evaluating a VEPCO power station in conjunction with a study for the United States Atomic Energy Commission.

Another direction has been followed because a data search in response to a request for a proposal from the Hampton Roads Sanitation District proved particularly interesting. This had led to an analysis of existing drift bottle and seabed drifter data in the continental shelf water from the viewpoint of coastal managers. The results are currently being prepared for publication and will be included in next year's work. (Welch and Norcross, in preparation). We fully expect action to be taken by relevant agencies on the basis of the information contained in these results. A report of the actions taken and their relation to the information will be produced as part of next year's annual report or before as appropriate.

The rest of the future work is developmental in nature, although the development is towards an applications oriented system. The primary effort in physical oceanography is to design and build a retransmitting navigation system which can be used with remote expendible free-floating buoys. We expect to have five such buoys operational using Omega navigation by the end of the year. These buoys will be the heart of the ground based part of a circulation monitoring system for the continental shelf. The other major part will be images received of shelf waters from various available scanners. Techniques for using and evaluating these images will be developed along with relevant modules for analysis of these images in conjunction with the trajectories of the floating drogued buoys. These techniques are designed to be used in obtaining the answers to questions which will arise and should be answered if we are to manage our coasts effectively in the coming decade.

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APPENDIX

TABLE 1

September 11 Wachapreague Inlet

High Slack 09:47   Low Slack 16:03

Station	Time	Temp. (°C)	Salinity (0/00)	D.O. (mgl^{-1})	Total Chl. (ugl^{-1})	Vmax (ugl^{-1} hr^{-1})
B	13:07	21.6	31.24	-	-	1.13
C	10:45	22.0	31.29	9.3	6.37	.66
D	11:45	21.6	31.30	-	10.32	.78

NUTRIENTS

Station	Time	TKN	DKN	NH_3	NO_3	NO_2	TP	DP	PO_4
		(units mg l^{-1}		)	(all units	ugram-atoms liter^{-1})			
B	13:07	.672	.504	.196	1.88	.64	3.95	1.41	1.41
C	10:45	.280	.280	.056	.14	.25	1.50	1.00	.67
D	11:45	3.30	.308	.056	.81	.36	3.48	1.05	.94

TABLE 2

October 11 Wachapreague Inlet

Low Slack 05:47 High Slack 11:47

Station	Time	Temp. (°C)	Salinity (0/00)	D.O. (mgl^{-1})	Total Chl. (ugl^{-1})	Vmax ($ugl^{-1}hr^{-1}$)	Tot. Prod. ($mgCM^{3}hr^{-1}$)
A	06:30		31.66	-	13.2	4.44	4.74
B	06:37		-	-	4.0	.97	1.85
C	07.00		30.67	10.7	4.1	.22	2.09
D	07.25		30.98	10.5	5.5	.21	2.89
A	10:45		31.01	-	4.1	.90	2.81
B	10:50		-	-	4.7	.58	3.16
C	11:38		30.92	10.2	3.8	.40	3.21
D	11:15		30.99	10.54	5.2	.20	2.30

TABLE 3

October 11 Nutrients

Station	Time	TKN	DKN	NH_3	NO_3	NO_2	TP	DP	PO_4	IC	TOC
		(units mg N l^{-1})			(all units u gram-atoms $liter^{-1}$)					(ppm)	
A	06:30	.532	.420	.140	2.93	.82	4.46	2.74	2.61	25.0	38.4
B	06:37	.336	.280	.056	5.31	1.23	2.68	1.84	1.71	19.0	32.4
C	07:00	.336	.280	.056	6.61	1.20	1.82	1.48	1.38	17.6	31.2
D	07:25	.308	.224	.056	6.62	1.07	1.72	1.40	1.30	17.6	31.2
A	10:45	.700	.448	.308	2.84	1.21	3.20	.194	1.72	20.0	32.6
B	10:50	.476	.308	.196	3.03	1.29	2.49	1.72	1.58	19.8	33.6
C	11:38	.420	.252	.084	2.75	1.12	1.66	1.56	1.29	16.8	30.6
D	11:15	.448	.308	.168	3.38	1.21	2.92	1.52	1.39	17.4	30.0

TABLE 4

October 11 Tidal Creek Nutrients[1]

Station	Time	TKN	DKN	NH_3	NO_3	NO_2	TP	DP	PO_4	IC	TOC
		(units mg N l^{-1})			(all units ugram-atoms $liter^{-1}$)					(ppm	)
Tidal Creek	05:07	.536	.527	.169	6.37	1.18	1.03	1.82	3.41	17.6	32.0
Tidal Creek	06:48	.540	.390	.218	3.49	1.21	.88	1.85	1.62	17.6	31.0
Tidal Creek	08:23	.490	.340	.123	3.47	1.22	.97	1.71	1.57	17.8	31.3
Tidal Creek	10:07	.507	.425	.243	3.15	1.20	.89	1.72	1.59	17.5	31.2
Tidal Creek	11:59	-	-	.182	3.14	1.27	1.06	1.62	1.53	17.6	31.6
Tidal Creek	13:48	5.14	.430	.202	3.35	1.24	.72	1.73	1.23	17.9	32.5
Tidal Creek	15:35	.425	.355	.202	3.20	1.16	.67	1.92	1.73	18.1	32.3
Tidal Creek	17:04	.507	.430	.182	2.80	1.10	1.48	1.86	1.80	17.9	33.3

1 All nutrient values represent an average of four water samples taken on a transect across the mouth of the creek.

TABLE 5

December 6 Wachapreague Inlet

High Slack 07:46 Low Slack 14:18

Station	Time	Temp. (°C)	Salinity (o/oo)	D.O. (mgl^{-1})	Tot. Chl. (μgl^{-1})	Vmax ($\mu gl^{-1}hr^{-1}$)	Tot. Prod. ($mgCM^3hr^{-1}$)
A	07:15	9.7	30.11	9.52	5.9	.48	4.5
B	07:30	9.0	30.18	----	5.9	.21	2.4
C (Drogue I)	09:20	9.0	30.79	9.30	9.6	.15	2.1
C (Drogue II)	10:40	---	30.64	9.20	13.8	.25	6.9
C (Drogue III)	---	---	30.54	9.70	10.7	.21	8.6

TABLE 6

March 27 Wachapreague Inlet

Low Slack 07:58 High Slack 13:42

Station	Time	Temp. (°C)	Salinity (0/00)	D.O. (mg $^{-1}$)	Tot. Prod. (mg C M^3hr^{-1})	<10 u Prod. ($mgCM^3hr^{-1}$)	Vmax (ug $l^{-1}hr^{-1}$)
A	07:30	9.3	27.62	7.21	6.41	2.31	1.03
B	07:45	9.5	28.45	7.60	4.31	5.26	.95
C	08:42	7.0	28.70	7.13	4.65	2.43	.12
D	09:30	6.6	30.52	7.37	0	.97	.77
C	11:04	6.6	30.59	7.54	7.82	1.70	1.47
C	11:40	6.6	30.53	7.19	8.05	3.27	.97
C	12:50	6.7	30.58	7.27	6.04	1.67	1.24
A	13:45	9.7	28.78	8.00	5.67	7.50	.68
B	14:00	9.6	29.54	--	5.23	.62	.74
C	14:40	9.5	30.49	7.37	5.13	2.28	1.44

TABLE 7

March 27 Nutrients

Station	Time	TKN	DKN	NH_3	NO_3	NO_2	TP	DP	PO_4	IC	TOC	DOC
		(units mg l^{-1}		)	(all units microgram-atoms l^{-1})					(all units ppm)		
A	07:30	.467	.196	.014	1.93	.15	1.69	.75	.52	17.9	29.3	10.9
B	07:45	.336	.084	0	1.32	.17	1.35	.73	.51	15.6	27.8	11.2
C	08:42	.504	.112	.028	.73	.26	2.04	.98	.61	16.5	29.3	11.6
D	09:30	.280	.084	0	3.25	.17	1.47	.85	.52	6.2	14.3	1.20
C	11:04	.476	.140	0	--	.19	2.92	1.92	1.58	17.1	28.6	10.4
C	11:40	.588	.056	.014	1.92	.18	2.82	.75	.53	15.3	28.6	12.2
C	12:50	.616	.168	0	.52	.17	2.61	.75	.56	14.7	29.9	14.1
A	13:45	.280	.140	.014	2.33	.15	1.26	.75	.52	19.9	29.9	9.3
B	14:00	.476	.196	0	1.50	.18	1.22	.77	.47	15.3	28.6	12.2
C	14:40	.532	.084	0	.34	.19	2.24	.79	.47	17.4	29.3	9.4

TABLE 8

April 3 Station X

High Slack 08:30 Low Slack 14:38

Time	Temp. (°C)	Salinity (0/00)	D.O. (mgl^{-1})	Tot. Chl. (ugl^{-1})	<10u Chl. (ugl^{-1})	Vmax ($ugl^{-1}hr^{-1}$)
07:35	8.8	30.23	8.08	4.2	3.6	.46
08:28	8.5	29.94	7.98	3.4	2.8	.49
09:28	8.7	30.19	8.22	3.9	2.7	.30
10:33	10.0	29.99	--	---	---	.52
11:33	11.1	29.70	8.34	4.5	2.9	1.07
12:30	12.0	29.23	8.40	---	---	.95
13.33	12.5	29.04	8.36	3.2	2.5	.46
14:39	12.5	28.72	8.24	3.2	2.8	.41
15:35	11.4	29.65	8.38	4.4	3.2	.76[1]
16:40	8.5	30.29	8.14	5.2	3.4	.73[1]

1 These values calculated from uptake at 375 ug glucose l^{-1}.

TABLE 9

April 3 Station Y

High Slack 08:30 Low Slack 14:38

Time	Temp. (°C)	Salinity (0/00)	D.O. (mgl^{-1})	Tot. Chl. (ugl^{-1})	< 10u Chl. (ugl^{-1})	Vmax ($ugl^{-1}hr^{-1}$)
07:45	8.9	30.13	7.94	3.6	3.0	.88
08:32	8.7	30.16	7.86	2.8	1.7	.31
09:33	8.8	30.21	8.38	3.4	2.4	.42
10:39	10.4	29.77	8.28	4.8	3.4	.90
11:38	11.2	29.68	8.44	4.6	2.4	.88
12:37	12.0	29.48	8.50	3.9	3.2	.70
13:40	12.4	29.40	7.82	3.6	3.3	.15
14:45	11.8	29.49	8.32	1.7	2.9	.55
15:42	11.7	29.45	8.42	4.3	2.0	.50 [1]
16.45	10.6	29.84	8.22	4.2	2.8	.61 [1]

1 These values calculated from uptake at 375 ug glucose 1^{-1}.

TABLE 10

April 6 Station X

High Slack 09:47 Low Slack 15:51

Time	Temp. (°C)	Salinity (0/00)	D.O. (mgl^{-1})	Tot. Chl. (ugml^{-1})	<10 u Chl. (ugml^{-1})
10:00	8.0	30.22	8.62	4.8	3.0
10:30	9.5	30.19	7.96	3.9	3.1
10:40	9.2	30.27	6.83	3.1	2.7
11:00	9.5	30.20	7.90	4.1	2.9
11:20	10.0	30.21	7.78	3.1	2.5
11:40	10.0	30.21	8.50	3.7	2.9
12:20	10.5	29.94	8.14	3.7	3.0
12:40	10.5	29.92	7.98	4.0	3.0
13:00	11.0	29.71	6.93	3.9	3.6
13:20	11.0	29.54	7.84	4.4	3.3
13:40	11.5	29.45	7.96	3.1	3.1
14:00	12.0	29.32	7.33	4.7	3.4
14:20	11.8	29.30	7.03	3.7	3.3
14:40	12.2	29.22	6.53	3.7	2.6
15:00	12.2	29.15	7.19	3.5	3.0
15:20	12.5	29.09	7.84	3.5	3.2
15:40	13.0	28.95	7.78	3.6	3.0

TABLE 11

April 6 Station Y

High Slack 09:47 Low Slack 15:51

Time	Temp. (°C)	Salinity (0/00)	D.O. (mg l^{-1})	Tot. Chl. (ugm l^{-1})	<10 Chl. (ugm l^{-1})
09:40	9.0	30.18	7.03	3.8	3.1
10:00	9.0	30.14	7.43	6.7	3.1
10:20	9.2	29.88	6.75	4.1	4.0
10:40	9.8	30.03	6.45	5.3	4.1
11:00	9.3	30.04	7.84	4.1	4.3
11:20	9.3	29.92	7.33	5.4	3.8
11:40	9.6	29.80	7.56	6.0	3.4
12:00	9.8	30.19	5.99	7.1	5.5
13:20	11.0	29.60	6.63	5.3	4.2
13:40	11.2	29.12	6.83	5.3	3.9
14:00	12.0	29.55	7.78	4.9	4.5
14:20	11.9	29.58	6.81	5.6	4.7
14:40	12.0	29.52	7.37	7.1	4.7
15:00	12.1	29.52	7.80	6.1	5.2
15:20	12.2	29.52	7.82	5.4	3.9
15:40	12.4	30.18	8.04	5.1	5.3

TABLE 12

April 6 Offshore

High Slack 09:47   Low Slack 15:51

Station	Time	Temp. (°C)	Salinity (0/00)	D.O. (mg l^{-1})	Tot. Chl. (ugm l^{-1})	<10 u Chl. (ugm l^{-1})	Vmax[2] (ugm $l^{-1}hr^{-1}$)
1	09:55	9.7	30.30	8.82	4.9	2.9	.33
2	10:11	10.0	30.30	8.64	3.7	2.9	.20
3	10:38	9.5	30.34	8.86	4.3	3.3	.54
4	10.55	10.0	30.17	8.94	4.0	2.6	.36
5	11:06	9.8	30.22	8.80	2.4	2.4	.19
6	11:17	10.0	30.13	8.78	3.8	---[1]	.24
7	11:34	9.7	30.67	8.54	1.6	---	.13
8	11:53	10.5	29.42	8.60	0.8	---	.17
9	12:00	9.8	30.67	8.10	0.8	---	.12
10	12:20	9.7	30.69	8.44	1.6	---	.21
11	12:28	10.0	30.57	8.74	5.4	---	.71
12	12:40	10.5	30.37	8.16	3.7	---	.35
13	12:53	10.0	30.25	8.62	3.9	---	.51
14	13:08	10.7	30.09	8.40	5.1	---	.68
3	13:18	10.6	30.27	8.12	2.1	---	.46
4	13:23	10.0	30.03	8.20	2.1	---	.43
5	13:31	10.4	20.08	7.80	3.4	---	.46
6	13:39	10.5	30.02	8.02	3.5	---	.34
7	13:49	10.7	30.15	8.20	3.2	---	.43

TABLE 12 (Cont'd.)

Station	Time	Temp.	Salinity	D.O.	Tot. Chl.	<10 u Chl.	Vmax
8	13:58	11.0	30.24	8.24	3.9	---	.43
9	14:06	10.8	29.94	7.70	3.8	---	.50
10	14:16	11.3	30.01	7.98	4.2	---	.42
11	14:27	10.0	30.43	8.22	4.4	---	1.21
12	14:36	11.0	30.48	8.28	6.2	---	.67
13	14:45	11.2	29.80	8.26	5.8	---	.71
14	14:55	11.8	29.74	8.36	4.0	---	.74
3	15:06	12.0	29.79	8.44	3.6	---	.63
13	15:20	11.7	29.80	8.32	3.4	---	.51
2	15:35	12.5	29.48	8.20	3.8	---	.48
1	15:44	12.5	29.30	8.10	3.0	---	.51

1 Nitex prefilters malfunctioned.

2 These values calculated from uptake at 375 ug glucose liter^{-1}.

CHART I

Station Designations

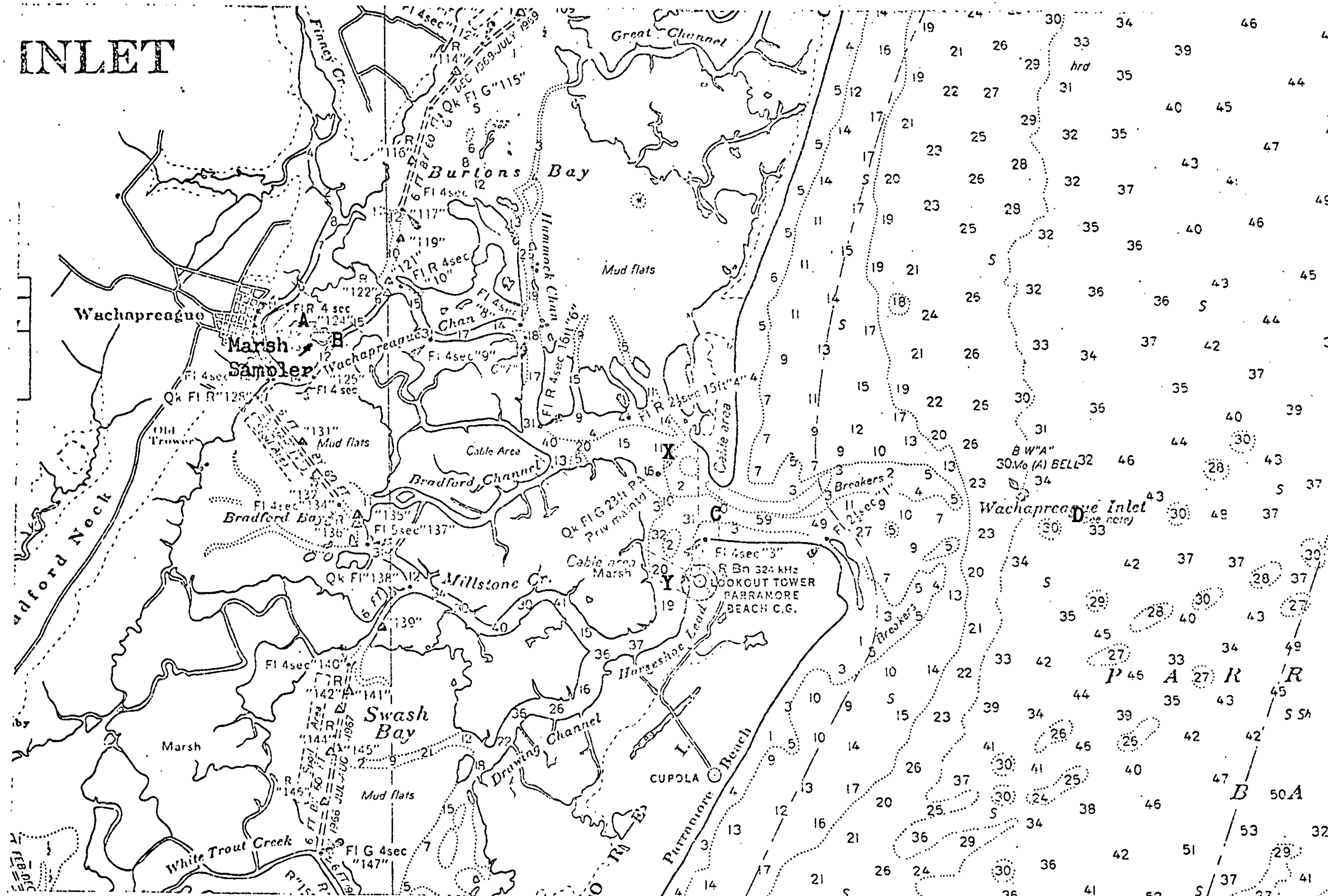
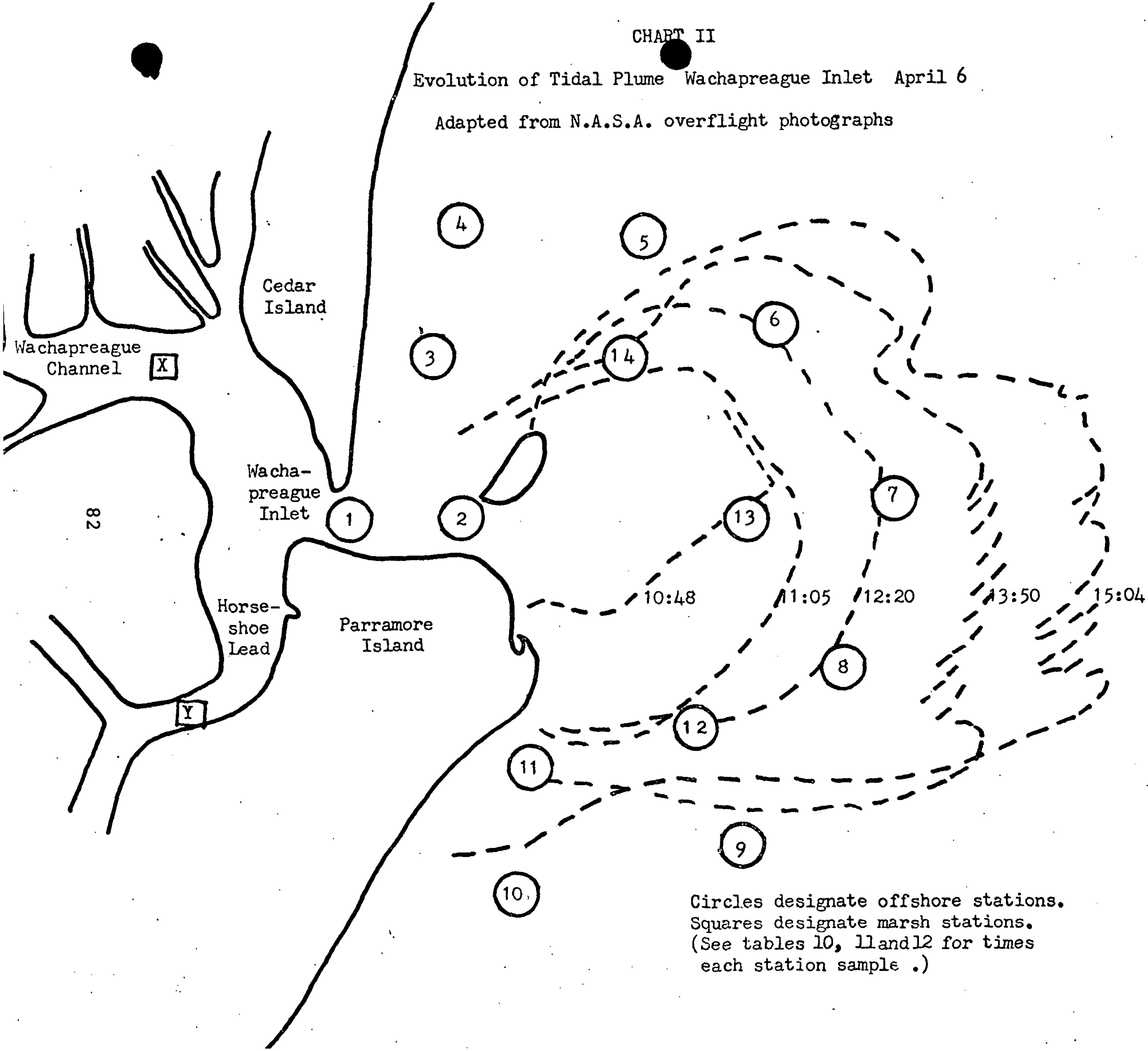


CHART II

Evolution of Tidal Plume Wachapreague Inlet April 6

Adapted from N.A.S.A. overflight photographs



Circles designate offshore stations.
Squares designate marsh stations.
(See tables 10, 11 and 12 for times each station sample .)