SECTION 112

A STUDY OF TEMPORAL ESTUARINE FLOW DYNAMICS

by

Robert L. Mairs
Naval Research Laboratory
Washington, D. C. 20390

and

Dennis K. Clark
Naval Oceanographic Office
Washington, D. C. 20390

ABSTRACT

Multispectral photography, IR imagery, image enhancements, oceanographic, radiometric, and meteorological data are used in the study of temporal estuarine flow dynamics to increase our knowledge of nearshore circulation and the resulting dispersal of suspended and dissolved substances that are introduced from the continent.

Repetitive multispectral photography, IR imagery, surface truth, i.e. total radiance and irradiance, water surface temperatures, salinity, total suspended solids, visibility, current velocity, winds, dye implants, and high contrast image enhancements are used to observe and describe water mass boundaries in the nearshore zone and to attempt to establish on what repetitive scale these coastal features would be looked at to better understand their behavior.

Water mass variability patterns seen both naturally and with the use of dyes along the North Carolina coast and in the Chesapeake Bay are being studied as synoptic data that will lead to a better understanding of the basic dynamics of circulation, flushing and mixing in our coastal waters.

INTRODUCTION

One of the most immediate problems facing the world today is the management and understanding of our coastal environment and the impact made upon it by estuarine effluents. More and more demands are being placed on this natural resource without the background material needed for its total effective use. The knowledge of nearshore circulation dynamics along the mid-Atlantic United States coasts and the resulting dispersal of suspended and dissolved substances that are naturally and culturally introduced from the continent is very fragmentary. This lack of comprehensive knowledge is proving costly in highly populated areas along our coastlines where man-introduced substances are threatening the natural utility of many coastal waterways.

With the rapid development of remote sensor technology, a new technique for ocean monitoring is developing. Remote sensors are capable of providing an overview of surface and near-surface conditions in real time over large geographical areas. This is not to suggest however, that remote sensing can replace _in situ_ measurements but quite the contrary, very stringent _in situ_ measurements must be used to fully interpret the data.

OBJECTIVES

The objectives of this nearshore remote sensing research which hopefully will lead to the solving of many of these problems are:

* attempt to describe surface and near-surface fluid flow dynamics in an estuarine environment using synoptic aerial photography and infrared imagery.

* attempt to establish the temporal characteristics of various surface and near-surface coastal features.

* correlate the spatial and temporal characteristics of estuarine effluents with other environmental parameters.

METHODS AND PROCEDURES

There are two fundamental properties of the ocean surface that require understanding when studying the ocean with electromagnetic sensors. The first property is the dynamic nature of the oceans surface; how it can change from a mirror smooth surface acting as a specular scatterer under no wind-wave conditions to white water under heavy winds. The second property is the degree to which electromagnetic energy can penetrate the water itself. Significant water penetration occurs only in two general regions of the spectrum; at very low frequencies on the order of 10^3 to 10^4Hz and at frequencies around 7×10^{14}HZ. Since it is impractical to build remote sensors at low frequencies and long wavelengths, the only portion available lies in the visible region from about 400 to 600 nanometers.

The energy source for image formation on photographic film is the sun. The amount of solar energy which is recorded by photographic film in any particular wavelength band depends upon the energy which: (1) strikes the waters surface, (2) reaches a sub-surface object, (3) is reflected by the object, (4) makes its way coherently back through the water and across the water-air interface. Much of the image formation energy that reaches the camera from below the waters surface is concentrated in a spectral region extending from about 420 to 550 nanometers. In relatively clear oceanic waters, peak transmission lies near 480 nanometers but as one moves into coastal waters that are rich in particulate matter, this transmission peak shifts towards the green. Thus, depending upon the application and the type of water, there may be a preference in the portions of the visible spectrum to be used. The response of light energy interacting with the ocean can be illustrated on a qualitative basis by using a 6-band Hasselblad camera array which records on film several discrete portions of the visible spectrum (Figure 1).

In November 1970, the North Carolina coast was the site of an Earth Resources mission utilizing the NASA MSC RB57F aircraft. The flight objective was to obtain high-altitude mosaic multispectral photography over the coastal waters at least twice during a tidal cycle. Figure 2, shows 6 simultaneous multispectral photographs of an estuarine plume front adjacent to the North Carolina coast. A qualitative comparison of the 6 filter combinations for water mass delineation can be made by examining the frames. Starting at the blue end (47-B) of the spectrum very little contrast or definition can be seen in the water but as one moves to the blue-green (2E+38), the green (58), the yellow (21+57), and the red (25-A), increasing contrast and definition of the plume front can be observed. The near IR (89-B) energy is completely absorbed at the surface so gives no information on sub-surface phenomena but shows excellent shoreline definition. The 21+57 and the 25-A filter combinations seem to give the best depth penetration, contrast and definition for these particular coastal waters.

Figure 3 is a color photograph of an estuarine plume front taken during the same mission. The film density differences across this plume front are very small thereby making it difficult to examine the plume front lineation. A number of optical and photographic enhancement techniques were utilized in an attempt to increase the delineation of this plume front. No advantages could be found by using the optical enhancers however, photographic techniques provided satisfactory contrast level information. Figure 4 is a high contrast enhancement of Figure 3 and clearly illustrates the increased plume front definition and the three separate water masses along the coastline. From water samples taken at the time of overflights, suspended particulate counts averaged approximately 8 mg/liter in this area. No correlation has yet been found between the densities of the film and the total suspended material found in the water. More research is needed on the physics of backscattered light from varying sizes, shapes, and types of particulate matter.

The plume front shown in Figure 4 was photographed three times during the day of 17 November spanning a total time of 146 minutes. The photographs were taken at 15:03, 15:26, and 17:29 GMT. High contrast enhancements were made from each of the three frames and a composite of the three enhancements was produced (Figure 5). Upon examination of this composite the movement of the plume becomes quite clear. The nearshore mass of water was moving at approximately 1.1 knot during this 146 minute period while the water mass offshore was only moving at 0.7 knot. This increased velocity (0.4 knot) in the nearshore zone is attributed to increased velocity due to the nearshore littoral current and/or increased velocity of the ebb flow discharge plume from Ocracoke Inlet as it progresses southward along the coastline.

In addition to these naturally occurring color fronts as indicators of circulation dynamics, dye tracer techniques are also being utilized to study the complex fluid flow dynamics in the estuarine system.

OBSERVATIONS AND RESULTS

During May 1971, the Naval Oceanographic Office conducted an investigation which provided simultaneous ground truth for a series of low-level overflights in the Patuxent River Estuary, Maryland. Dye tracer techniques were utilized to study the flow characteristics in an estuarine system and to aid in the interpretation of naturally occurring discontinuities detected by the remote sensors. The remote sensors operated on these missions were a CA-14 photogrammetric camera and a RECONOFAX IV infrared scanner. An extensive ground truth measurement program consisting of the following was conducted concurrently:

* Three water level stations

* Surface thermistor chain

* Surface temperature and salinity transects

* Three moored current meters

* Standard meteorological variables

* Smoke bombs for surface wind direction

* Point and continuous line dye sources

* Light penetration measurements

Although the analysis of this data resulting from this investigation is not yet complete, some of the preliminary results can be presented.

Two different observational sets will be discussed. The observations were taken on the same day at different tidal phases. The first set demonstrates a qualitative approach which is possible when flight track line spacing permits mosaics to be constructed. The second observational set, consisting of separate overflights of the same area with a short time separation, provides an example of a quantitative approach.

Mosaics constructed from the concurrent photography and IR imagery taken over the test area are presented in Figures 6 and 7. The photographic mosaic was made from Ektachrome positive transparancies and this, coupled with the reduction in size from the original mosaic, results in a very low photographic contrast level. Therefore, arrows were superimposed to indicate the direction of dye and smoke dispersal. The surface circulation within the test area is uniquely depicted in Figure 6 by the point and line dye sources. One of the areas of particular interest is the eddy which exists during flood tidal stage off Drum Point. The detail is difficult to distinguish in Figure 6 but in the original color photography, fluorescein dye from a point and a line source has been entrained into the eddy enhancing its visibility. This eddy also is observed in the IR imagery (Figure 7) where the warmer water flows out from a shallow pond just north of the Point. This outflow provides a sharp thermal contrast as this water flows around the Point into the eddy. Throughout the area the outflows of warmer water from the shallow creeks and coves provide sharp thermal discontinuities on the order of 1° to 2°C. The movements and positions of these thermal discontinuities in relation to the main stream flow provide such information as flow direction, points of flow separation, eddy size, upwelling, and lines of water mass convergence. However, the utility of the IR imagery decreases as an ebb tidal phase is impressed on the area; the warmer waters are entrained and mixed into the main stream flow and the thermal contrast is greatly diminished.

Moving further upstream the complex flow structure which occurs as the tidal current progresses through the river's successive bends can be seen more clearly in Figure 8. Here the continuous line source, which was originally generated as a line between the tip of Point Patience and the opposite bank is rotating counter clockwise as the main flow is channeled along the southeastern side of the Point. The point sources also illustrates a "choking" effect with resulting partial flow reversal occurring along the lower bank. The "choking" effect is a result of insufficient specific energy* to pass the increased discharge per unit width in this area of extreme channel contraction.

A qualitative streamline analysis based on the composite photographic and IR imagery data is shown in Figure 9 and serves to illustrate the benefit of such an approach for developing conceptual models. The boundaries of the relatively unmixed Chesapeake Bay water were derived from positions of convergent line slicks in the photography and thermal discontinuities in the IR imagery. Ground truth surface temperature and salinity transects verified the upstream limit of this surface boundary. At this boundary the flow becomes increasingly unstable and less uniform as it passes into a contracting and bending channel. The Bay water is then mixed with and overridden by the warmes and less dense waters of the river only to reappear upstream in areas of upwelling.

Figures 10 and 11 are two photographs taken 396 seconds apart during an ebb flow at the mouth of the estuary. These photographs are used to illustrate a basic quantitative approach when using short term repetitive photography of dye tracers. In Figure 10, a continuous line source is in the process of being generated between Fishing Point and Drum Point. Two point sources are dispersing dye adjacent to the line source. In addition, bayward of the new line source, the remnant of an older line source can be seen. Figure 11 shows the displacement of the line source and the movement of the point sources during the 396 second time interval. The location of the dye images (with the exception of the new line source in Figure 11) were plotted after the photographs were corrected for altitude and tilt differences and are depicted in Figure 12. The center line of the line sources was then estimated and displacement measurements along with velocity calculations were made from these positions. In Figure 12, the cross-sectional variations of the surface velocities (V_1 through V_8) clearly indicate the high velocity area at the beginning of the abrupt channel contraction. The increased velocities of the point and remnant line sources (V_9 through V_{10}) are produced by the continuation of the narrowing channel and increased convergence. This further contraction of the channel

---

* Specific energy is defined here as the energy referred to the channel bed as datum.

bathymetry is not shown on the figure.

Three current meters were taut line moored 2.6 meters below the surface, between Drum Point and Fishing Point. The data from two of these current meters is not yet available. The other meter was moored at the position shown in Figure 12 in the vicinity of maximum displacement of the line sources. This displacement occurs to the right of the channel axis. The computed velocity (V_3) has a magnitude of .6 knot and the current meter position is shown indicating approximately the same direction with a .5 knot magnitude. This reasonable correlation was obtained from the water level and current speed data compiled in Figure 13. This Figure depicts the water level fluctuation for the photographic data acquisition time and an extrapolated current speed record. The extrapolation for current speed was necessitated by instrument failure prior to the overflight. The procedure for utilizing this data was to select a period in the water level data (when the current meter was functioning properly) that had approximately the same tidal phase and amplitude. Since the amount of energy contributed by the tidal force is approximately the same and that no large variation in discharge occurred; the extrapolation should be reasonable. Completion of the data processing of the other meters will provide a better correlation base.

CONCLUDING REMARKS

As has been shown in this preliminary analysis of a continuing Navy program to better understand nearshore circulation dynamics and its impact on the environment, a new look must be taken at the temporal scale at which coastal phenomena are to be studied. Coastal features are extremely dynamic; changing rapidly on the order of minutes and hours. With the deployment of satellites that look at one point every 18 days or even on the order of 4 days in future satellites, we will not be able to statistically examine and thereby understand many of the time dependent phenomena existing in the coastal zone. A well coordinated remote sensing aircraft program capable of repeat coverages on the temporal scale mentioned above is necessary if we wish to thoroughly understand the circulation dynamics in the nearshore zone.

BIBLIOGRAPHY

1. Duntley, S. Q., 1963, "Light in the Sea," Jour. Opt. Soc. Am., Vol. 53.

2. Jerlov, N. G., 1968, _Optical Oceanography_, Elsevier, Amsterdam, 194 pp.

3. Henderson, F. M., 1966, _Open Chennel Flow_, MacMillan, New York, 522 pp.

4. Smith, J. T., editor, 1968, _Manual of Color Aerial Photography_, Am. Soc. Photo., Alexandria, Virginia, 550 pp.

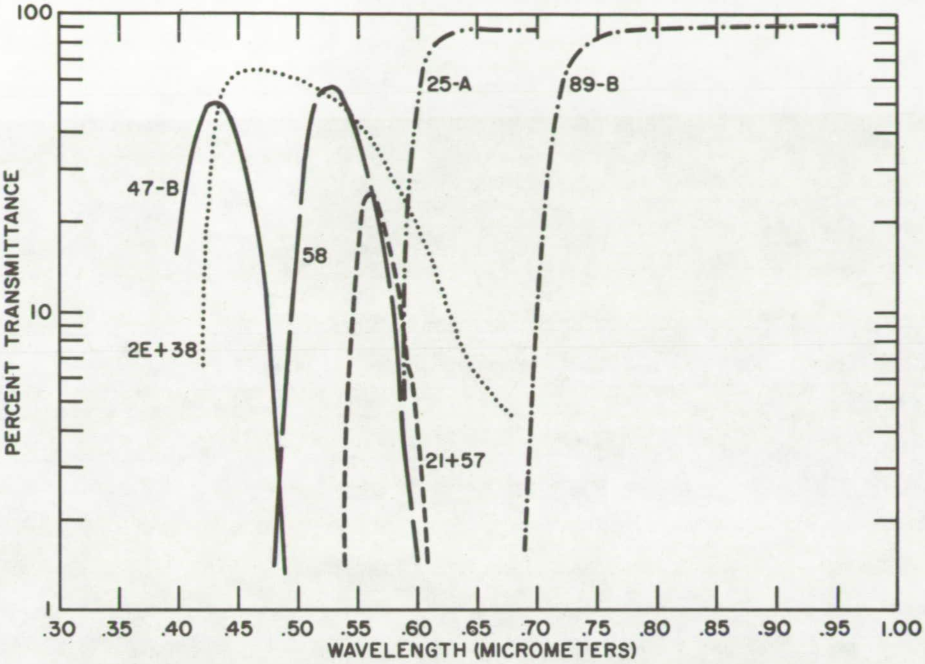
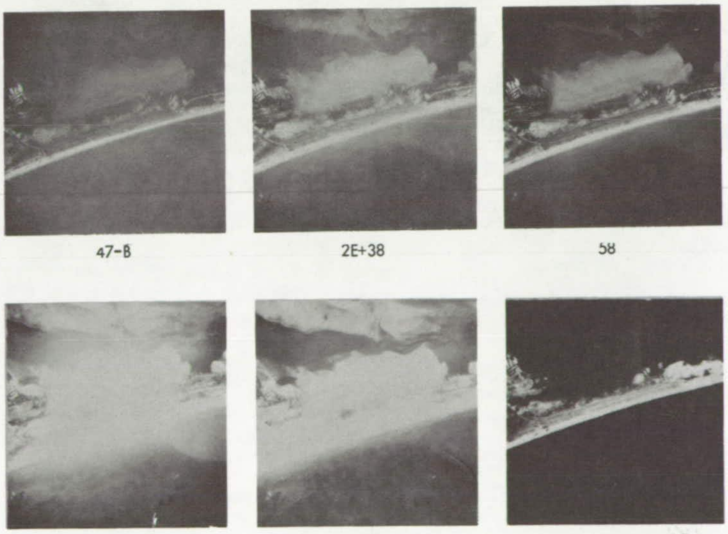


FIGURE 1. MULTISPECTRAL FILTER COMBINATION FOR NASA RB-57F HASSELBLADE ARRAY



47-B 2E+38 58

21+57 25-A 89-B

FIGURE 2. SIX SIMULTANEOUS MULTISPECTRAL PHOTOGRAPHS OF AN ESTUARINE PLUME FRONT NASA MSC MISSION NO. 147, 11-17-70

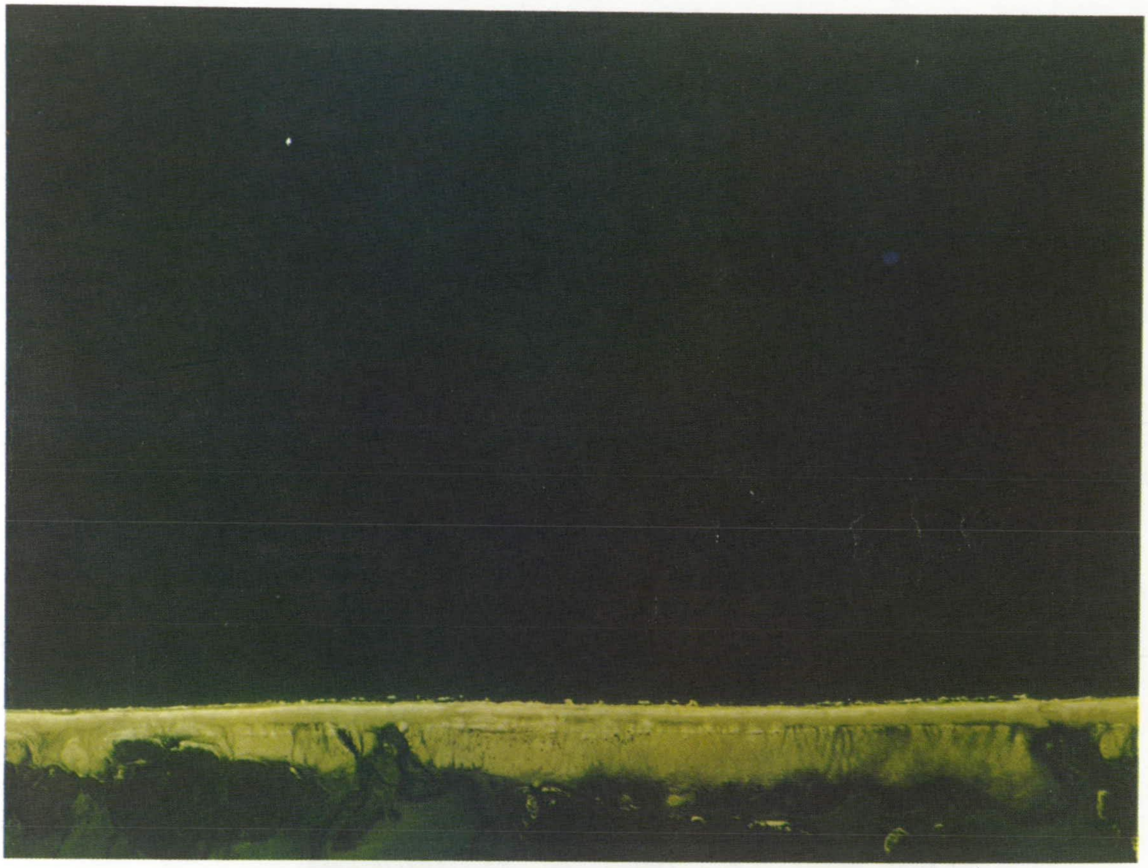


FIGURE 3. COLOR PHOTOGRAPH OF PLUME FRONT ADJACENT TO NORTH CAROLINA COAST.

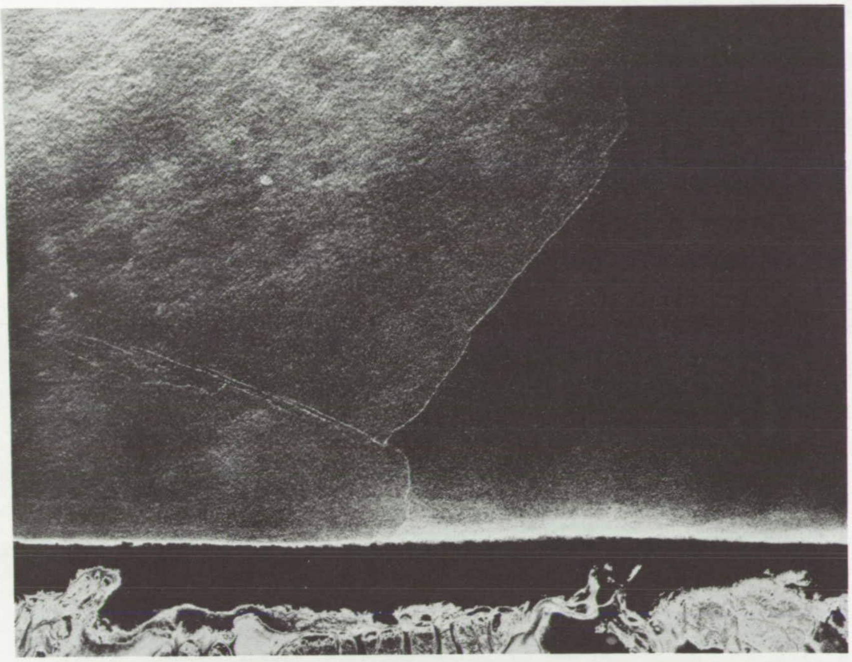


FIGURE 4. HIGH CONTRAST ENHANCEMENT FROM A COLOR PHOTOGRAPH OF AN ESTUARINE PLUME FRONT

FIGURE 5. OVERLAY OF PLUME FRONTS PHOTOGRAPHED AT 15:03, 15:26, AND 17:29 GMT

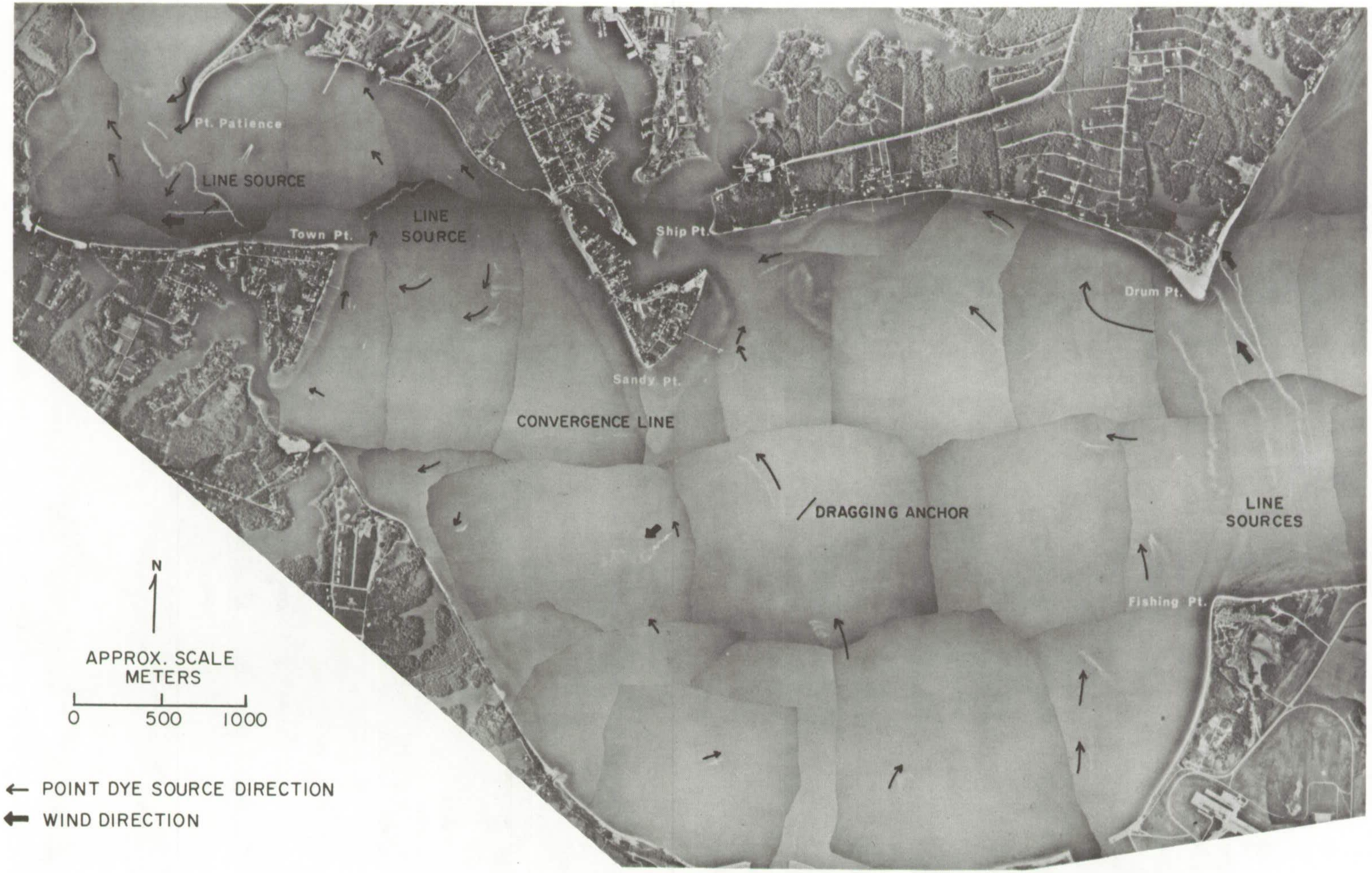


FIGURE 6. PHOTOGRAPHIC MOSAIC OF PATUXENT RIVER ESTUARY, 14 MAY 1971 (1642-1700 EDT).

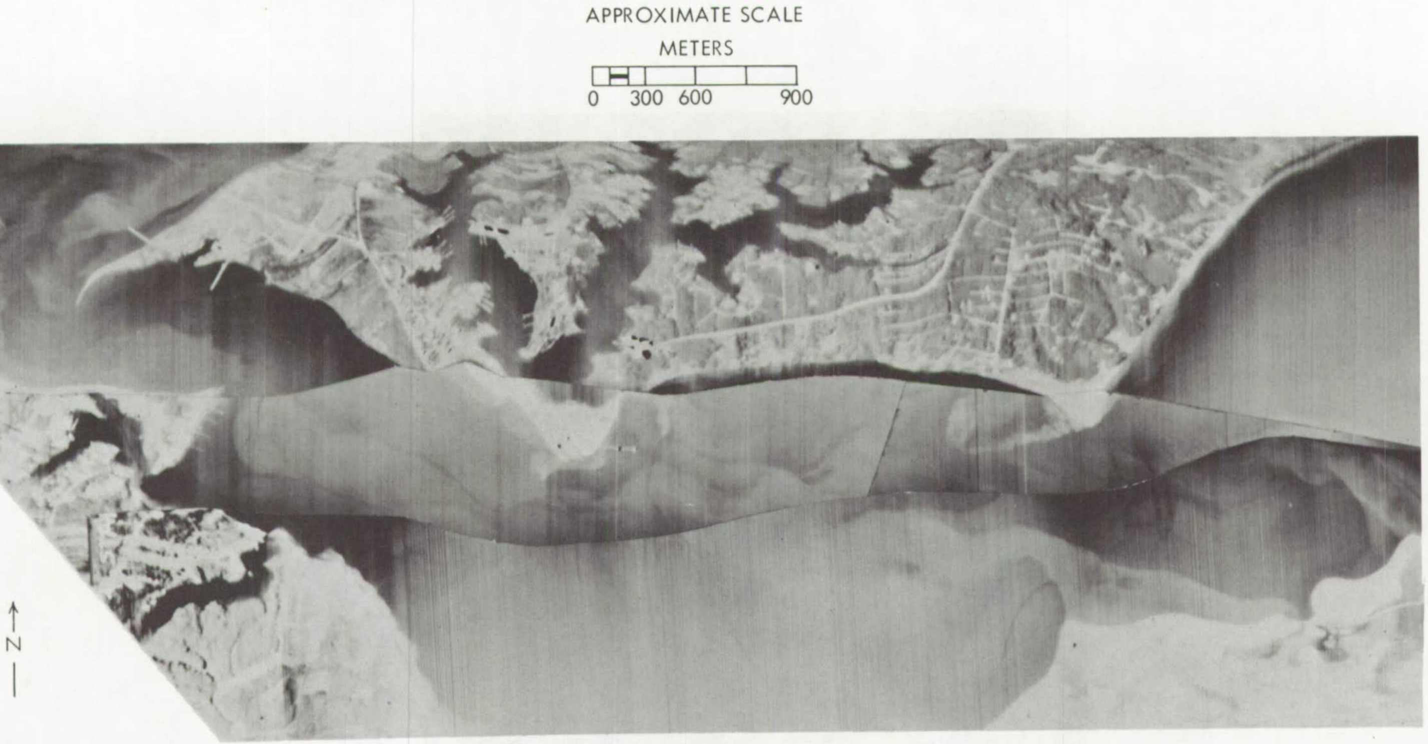


FIGURE 7. INFRARED MOSAIC (8-14 μM), 14 MAY 1971 (1642-1700 EDT).

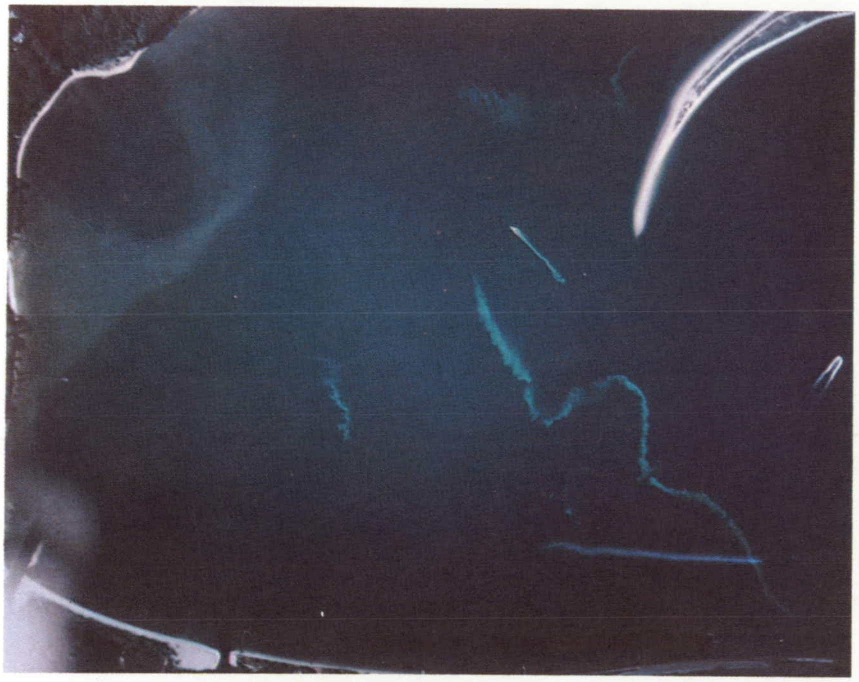


FIGURE 8. POINT AND LINE DYE SOURCES, POINT PATIENCE VICINITY, 14 MAY 1971 (1642 EDT).

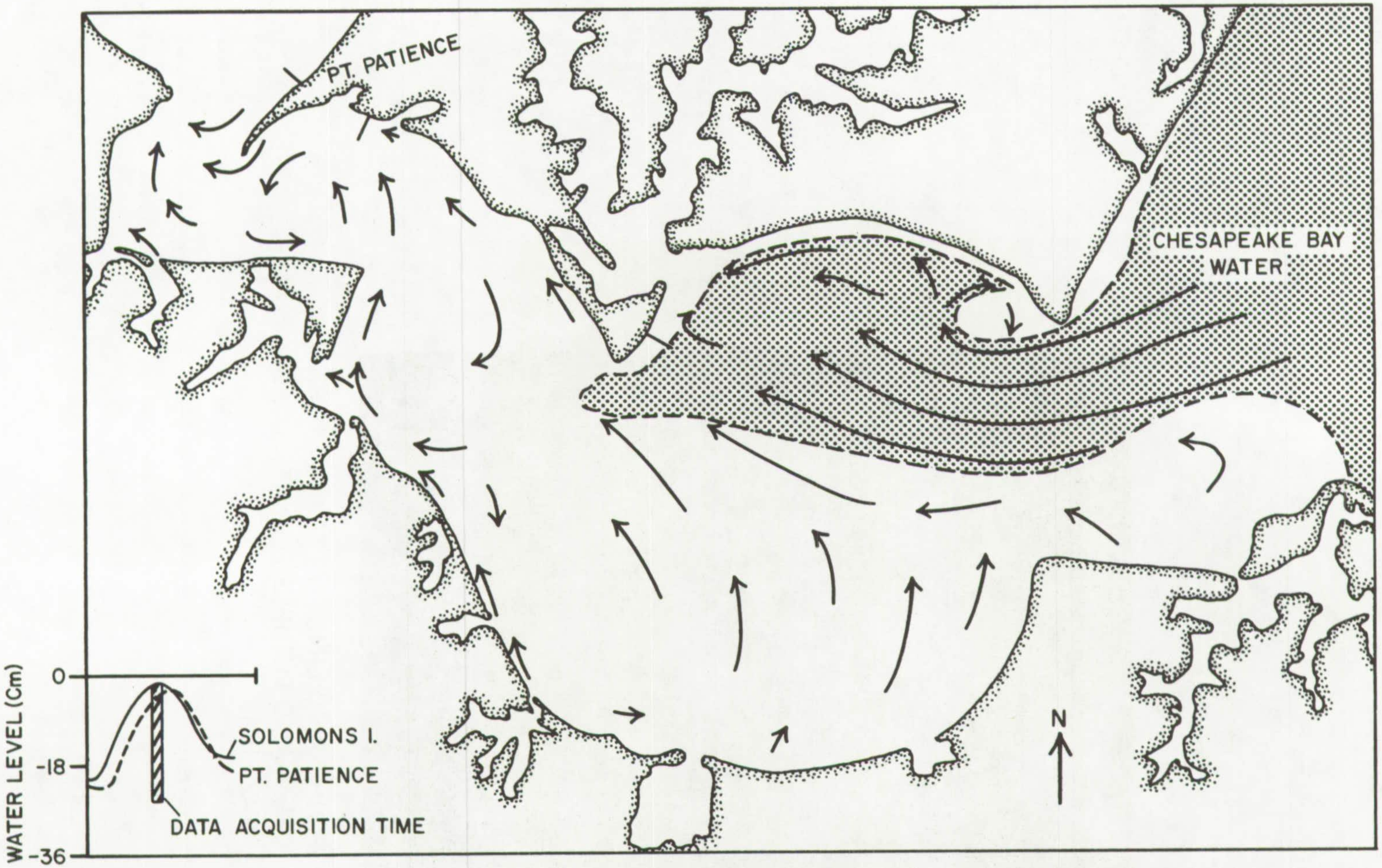


FIGURE 9. STREAMLINE ANALYSIS FROM COMPOSITE DYE TRACER AND IR IMAGERY DATA

FIGURE 10. POINT AND LINE DYE SOURCES BETWEEN DRUM AND FISHING POINTS, 14 MAY 1971 (0842 EDT).

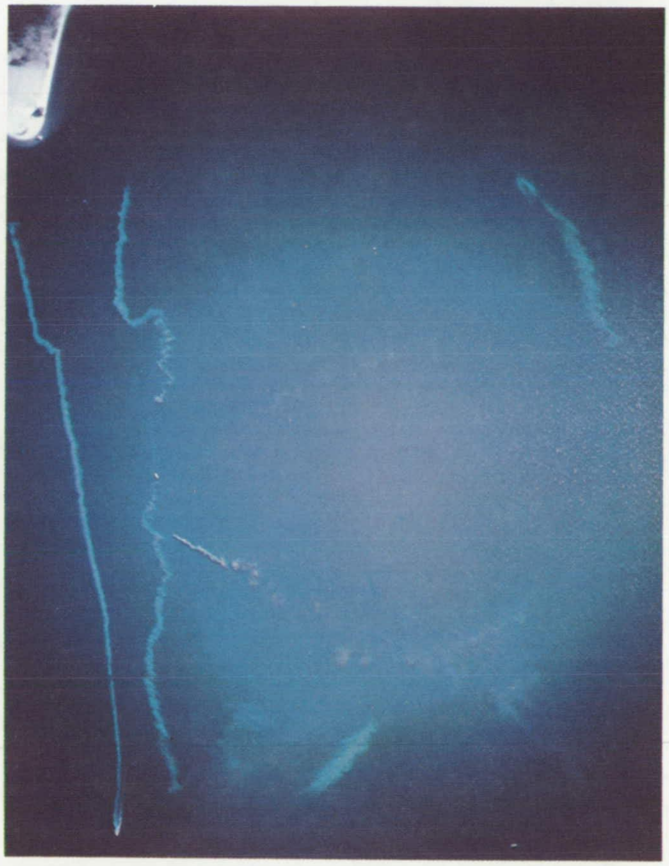


FIGURE 11. POINT AND LINE DYE SOURCES BETWEEN DRUM AND FISHING POINTS, 14 MAY 1971 (0848 EDT).

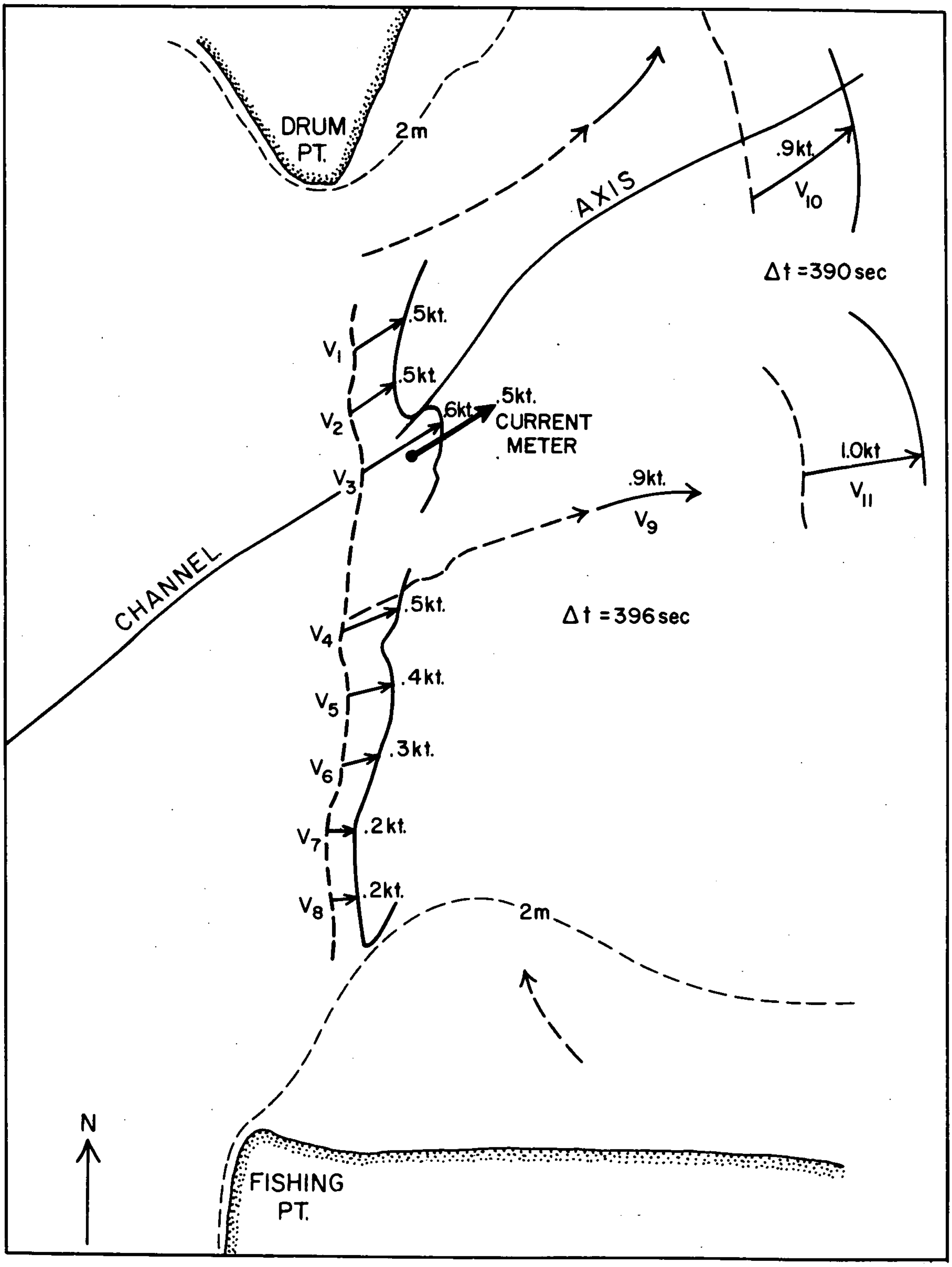


FIGURE 12. CROSS-SECTIONAL SURFACE VELOCITY CALCULATIONS FROM LINE AND POINT DYE TRACER SOURCES.

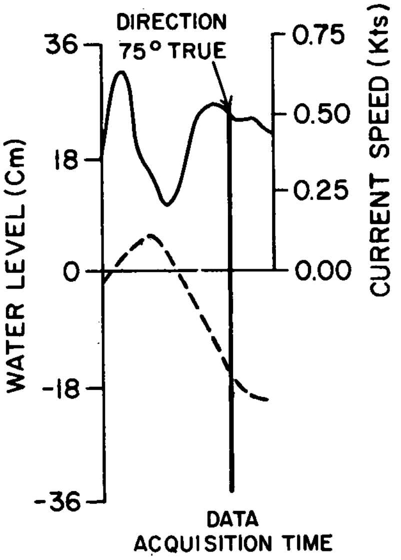


FIGURE 13. WATER LEVEL AND CURRENT SPEED DATA.