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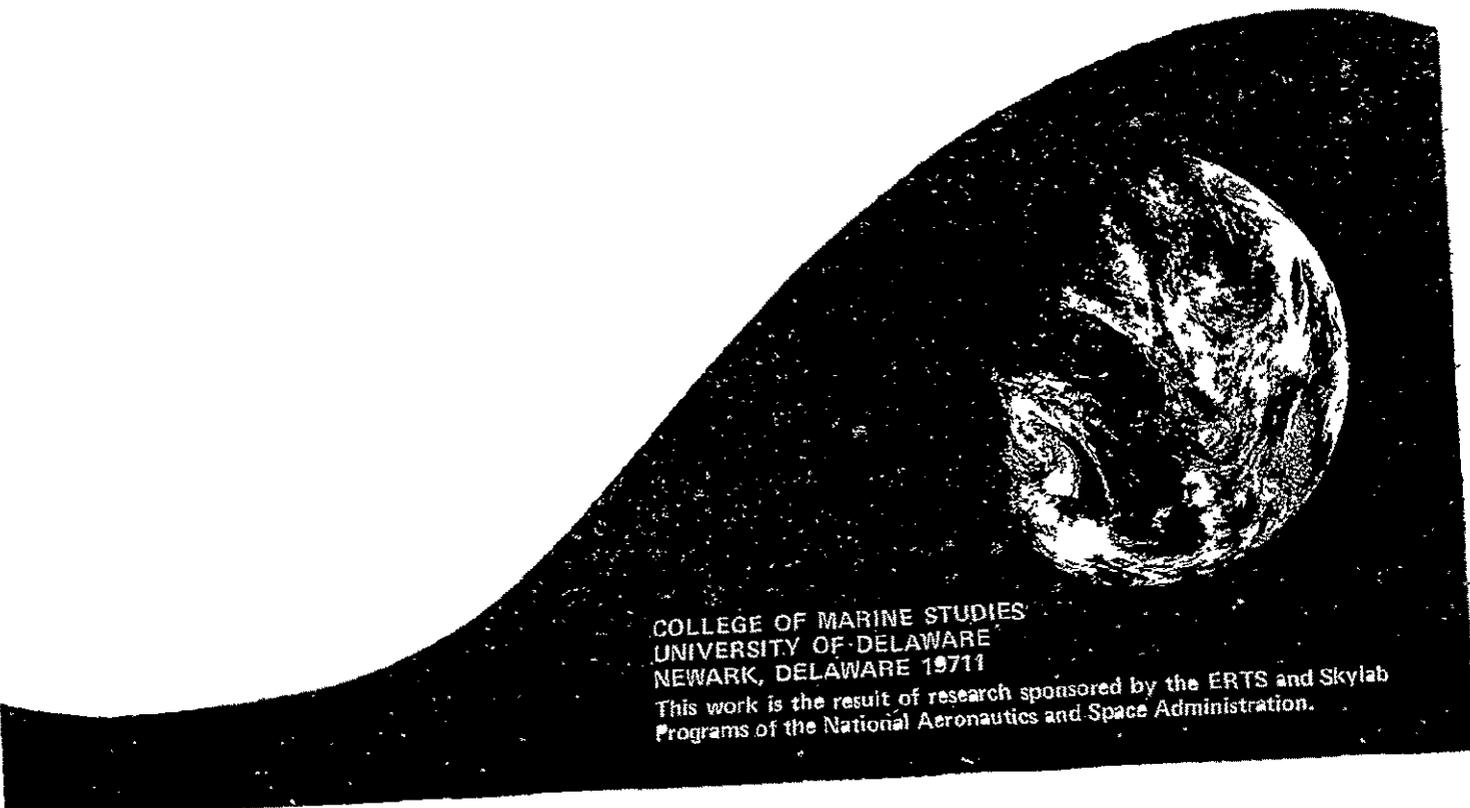
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A COST-EFFECTIVE SATELLITE-AIRCRAFT-DROGUE APPROACH
FOR STUDYING ESTUARINE CIRCULATION AND SHELF WASTE DISPERSION

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A Cost-Effective Satellite-Aircraft-Drogue Approach for Studying Estuarine Circulation and Shelf Waste Dispersion

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Abstract

The mounting economic pressure to extract oil and other resources from the Continental Shelf and to continue using it for waste disposal is creating a need for cost-effective, synoptic means of determining currents in this area. An integrated satellite-aircraft-drogue approach has been developed which employs remotely tracked expendable drogues together with satellite observations of waste plumes and natural tracers, such as suspended sediment. Tests conducted on the Continental Shelf and in Delaware Bay indicate that the system provides a cost-effective means of monitoring current circulation and ocean waste dispersion even under severe environmental conditions.

Introduction

There exists an urgent need to better understand the Continental Shelf environment because of economic pressures to extract oil and other resources, to increase the harvest of food, to continue using it for waste disposal, and to route ships or conduct small-craft rescue operations effectively. The large concentration of population in the coastal zone and the accompanying increase in utilization pressure is likely to have deleterious effects on the shelf regions. The offshore-onshore transport rates of pollutants, sediments and nutrients strongly influence the ecology of the coastal zone. In order to keep the environmental impact within acceptable levels, it is important to understand the circulation and exchange processes on the shelf.

In the last decade the data base on shelf water movement has increased significantly.¹ A large number of continuous records of variability on the shelf have been produced with self-contained current and temperature recorders and shelf-bottom pressure gauges. In addition, the use of modern instruments such as CTD's, STD's, and XBT's has increased the knowledge of water-mass structure.

The Eulerian method of measuring simultaneously the current direction and speed at preselected points in the water column requires many ships and current meters when synoptic measurements over large coastal areas are to be made. There-

fore an inexpensive, integrated satellite-aircraft-drogue approach has been developed which is based on the Lagrangian technique and employs remotely tracked drogues and dyes together with satellite observation of natural tracers, such as suspended sediment. Efforts have been initiated to employ this cost-effective technique to improve our understanding of estuarine and shelf circulation, particularly at critical sites where disturbances of shelf environment are anticipated.

Current Circulation From Satellite Imagery

Using suspended sediment as a natural tracer, it is possible to study current circulation in the surface layers of turbid estuaries and coastal waters by employing satellite imagery and a small amount of ground truth data.^{2,3,4}

Imagery and digital tapes from twelve passes of the Earth Resources Technology Satellite (ERTS-1) and one successful Skylab pass over Delaware Bay were analyzed. The ERTS-1 imagery used in our work was produced by the four-channel multispectral scanner (MSS) having the following bands:

Band 4	0 5 - 0 6 Microns
Band 5	0 6 - 0 7 Microns
Band 6	0 7 - 0 8 Microns
Band 7	0 8 - 1 1 Microns

From an altitude of 920 km each frame covered an area of 185 km by 185 km. In addition to the 9-track 800 bpi magnetic tapes, reconstructed negative and positive transparencies in 70 millimeter format and prints in 9 inch format were obtained from NASA. Before visual interpretation, some of the imagery was enhanced optically, using density slicing and color additive techniques. Annotated thematic maps were prepared by computer analysis of digital tapes and by direct photointerpretation of the transparencies reconstructed by NASA.²

Only MSS Band 5 images are shown, since the "red" band was found to give the best contrast in delineating suspended sediment concentrations in the upper one meter of the water column. Adjacent to ERTS-1 pictures, Figures 1, 2 and 3 contain tidal current maps of Delaware Bay. Each ERTS-1 picture is matched to the nearest pre-

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dicted tidal current map within \pm 30 minutes. The current charts indicate the hourly directions by arrows, and the velocities of the tidal currents in knots. The Coast and Geodetic Survey made observations of the current from the surface to a maximum depth of 6 meters in compiling these charts ^{5,6}

The satellite picture in Figure 1 was taken on October 10, 1973, two hours after maximum flood at the entrance of Delaware Bay. Masses of highly turbid water are visible around the shoals near the mouth of the bay and in the shallow areas on both sides of the bay. Since at the time flood currents were prevailing throughout the bay, some of the sediment in suspension seems to be locally generated over shoals and shallow areas resulting in a higher degree of backscatter from shallower waters. During flood tide at the mouth of the bay, considerable correlation was found between the depth profile and image radiance, even though the water depth exceeded the Secchi depth by at least a factor of three. No such correlation was found during ebb tide when silt and clay are carried down the rivers into the bay. At the time of this ERTS-1 picture, the wind velocity was 13 to 22 km per hour from the north causing surface currents in nearly the opposite direction to the tidal flow. Peak flood current velocity is occurring in the upper portion of the bay, creating sharp boundaries along the edges of the deep channels.

Boundaries or fronts (regions of high horizontal density gradient with associated horizontal convergence) are a major hydrographic feature in Delaware Bay and in other estuaries. Fronts in Delaware Bay have been investigated using STD sections, dye drops and aerial photography. Horizontal salinity gradients of 4‰ in one meter and convergence velocities of the order of 0.1 m/sec have been observed. Underwater visibility improved from 1 meter to 2 meters as certain boundaries were crossed. Several varieties of fronts have been seen. Those near the mouth of the bay are associated with the tidal intrusion of shelf water. The formation of fronts in the interior of the bay appears to be associated with velocity shears induced by differences in bottom topography with horizontal density difference across the front influenced by vertical density difference in the deep water portion of the estuary. Surface slicks and foam collected at frontal convergence zones near boundaries contained concentrations of Cr, Cu, Fe, Hg, Pb, and Zn higher by two to four orders of magnitude than concentrations in mean ocean water ⁷

By capturing and holding oil slicks, these frontal systems also significantly influence the movement and dispersion of oil slicks in Delaware Bay. Recent oil slick tracking experiments conducted by the authors to verify a predictive oil dispersion and movement model have shown that during certain parts of the tidal cycle the oil slicks tend to line up along boundaries. This results in unusual oil slick distribution patterns which even for a known oil type cannot be pre-

dicted on the basis of wind and tidal current information alone.

Figure 2 represents tidal conditions two hours before maximum flood at the mouth of the Bay observed by ERTS-1 on January 26, 1973. High water slack is occurring in the upper portion of the bay, resulting in less pronounced boundaries there as compared to Figure 1. The shelf tidal water is not rushing along the deep channel upstream anymore as in Figure 1, but is caught between incipient ebb flow coming down the upper portion of the river and the last phase of the flood currents still entering the bay. On the morning of January 26, 1973, there was a variable wind over the bay at about 9 to 11 km per hour from the south-southwest, helping tidal currents push clearer shelf water against highly turbid water masses on New Jersey's shallow flats.

The satellite overpass on February 13, 1973, occurred about one hour after maximum ebb at Cape Henlopen. The corresponding ERTS-1 image and predicted tidal currents are shown in Figure 3. Strong sediment transport out of the bay in the upper portion of the water column is clearly visible, with some of the plumes extending up to 30 km out of the bay. Small sediment plumes along New Jersey's coast clearly indicate that the direction of the nearshore current at the time was towards the north. The wind velocity at the time of the satellite overpass was about 13 km per hour from the west-northwest, reinforcing the tidal current movement out of the bay.

In addition to current circulation studies, ERTS-1 image radiance of Band 5 was correlated with suspended sediment concentration and Secchi depth data obtained from boats and helicopters during the satellite overpass ². A suspended sediment concentration map based on ERTS-1 image radiance correlation with water sample analyses is shown in Figure 4.

Satellite Observations of Ocean Waste Disposal Plumes

Approximately forty nautical miles off the Delaware coast is located the disposal site for wastes discharged from a plant processing titanium dioxide. The discharge is a greenish-brown, 15-20% acid liquid which consists primarily of iron chlorides and sulfates. The barge which transports this waste has a 1,000,000-gallon capacity and makes at least three trips to the disposal site per month.

The frequency of this dumping made it possible for the ERTS-1 satellite to photograph the acid plume in various stages of degradation, ranging from minutes to days after dump initiation. As shown in Table 1, since August 16, 1972, nine photographs were found which show water discolorations in the general vicinity of the waste dump site. The position of the discoloration, the dump pattern and the time difference between the dump and photograph give strong indications

that the discolorations are the acid plume

Table 1

List of ERTS-1 Images Containing Acid Waste Disposal Plumes and Satellite Overpass Time in Hours After Dump

<u>Date</u>	<u>I D Number</u>	<u>Time After Dump</u>
10 October 72	1079-15133	9 hrs 38 min
27 October 72	1096-15081	14 hrs 8 min
25 January 73	1186-15081	4 hrs 3 min
07 April 73	1258-15085	4 hrs 3 min
13 May 73	1294-15083	During Dump
22 October 73	1456-15055	29 hrs 25 min
23 October 74	1457-15113	53 hrs 31 min
15 December 73	1510-15052	5 hrs 45 min
26 May 74	1672-15012	21 hrs 6 min

Careful examination of the overpass of 25 January, 1973, disclosed a fishhook-shaped plume about 40 miles east of Cape Henlopen caused by a barge disposing acid wastes. The plume shows up more strongly in the green band than in the red band. Enlarged enhancements of the acid waste plumes, prepared from the ERTS-1 MSS digital tapes (Figure 5) aided considerably in studies of the dispersion of the waste plume. Currently acid dumps are being coordinated with ERTS-1 overpasses in order to determine the dispersion and movement of the waste materials along the Continental Shelf.

Sludge disposal plumes in the ocean off the Delaware coast have also been detected in ERTS-1 imagery. However they are more difficult to track due to their less frequent dump schedule and more rapid settling rate.

Drogue Design and Application

One important shortcoming of satellite investigations of coastal currents by remote sensing has been their inability to determine current magnitudes and to penetrate beyond the upper few meters of the turbid water column. These objections can be overcome by complementing the satellite observations with data from current meters and drogues capable of tracking currents at any depth encountered on the Continental Shelf.

The Eulerian method of measuring simultaneously the current direction and speed at preselected points in the water column requires many expensive current meters. If synoptic measurements over large coastal areas are to be made, considerable cost-effectiveness can be attained if Eulerian techniques are complemented by Lagrangian methods employing expendable drogues in combination with aircraft and satellite observations.

Two types of drogues are used. The first are small, compact units which can be dropped and tracked from low-flying aircraft. Their basic design does not differ significantly from that of drogues used by various investigators during the past few decades.⁸ These small drogues are

deployed whenever a detailed charting of current circulation over a relatively small area, such as four square miles, is desired. As shown in Figure 6, the drogues consist of a styrofoam float and a line to which is attached a current trap consisting of a stainless steel biplane. The length of the line determines at what depth currents will be monitored. The floats are color-coded to distinguish their movement and mark the depth of the biplanes. Packs with dyes of two different colors can be attached to the float and the biplane.^{9,10} The movement of the dye and drogues is tracked by sequential aerial photography, using fixed markers on shore or on buoys as reference points to calibrate the scale and direction of drogue movement. Results showing tracks of nearshore currents at one foot and six feet depth are shown in Figures 7 and 8.

The second type of drogue is a "radio-sonde" which can be released to track currents over large areas, such as an entire segment of the Continental Shelf. The unit was developed by the I T T Electro-Physics Laboratories with the intention of providing a free-drifting drogue which would be sufficiently economical to render it unnecessary to recover the expended hull. The sea-sonde employs a very low-powered HF radio transmitter to telemeter its position and any of several other optional variables of interest including

- a wind speed
- b water depth
- c temperature
- d conductivity

From the latter two salinity can be deduced.

The sonde consists of a ten-foot length plastic pipe somewhat less than two inches in diameter (Figure 9). Buoyancy is provided by a pair of floatation chambers so attached that when properly ballasted, the antenna position of the pipe projects approximately 39 inches above a still sea datum plane.¹¹

All necessary electronics are carried inside the pipe below the water line. Power is provided by four standard D-sized flashlight cells. A light-sensing phototransistor shuts down the system during the hours of darkness and conserves battery life. Thus, measurements of ocean drift currents are made only during daylight hours, more for system operator convenience than necessity. The sonde's operating life is selectable from one to almost six weeks through control of the transmitter power. The four units used in this test series were programmed for from ten to twelve days of operation. Range is not particularly sensitive to planned operating life.

Current sensing is achieved by the use of a current-trap or biplane which is suspended at a controllable depth beneath the sonde hull or pipe. The current intercept area is from 4 to 16 square feet and is isotropic. A ballast weight of

approximately 12 pounds is attached to the bottom of the current trap by about an eight-foot long slack line. The ballast provides a righting moment about the system's metacenter resisting heelevator under strong wind conditions and rights the sonde if it is upset by the actions of large waves.

Position-finding is normally accomplished by the use of bilateration from two (or more) shore radio direction-finding stations. In the tests described here, a single mobile DF station was used to establish the required lines of bearing by driving the appropriately selected DF stations along the Delaware-Maryland Coast.

Four radio-sondes were launched at the waste disposal site 40 miles off the Delaware coast, with current traps at depths of 10 feet and 30 feet, respectively. The sondes were tracked under severe winter Atlantic conditions including a "northeaster" storm, over a period of several weeks. As shown in Figures 10 and 11, at one point the drogues had moved 88 miles off the Delaware Coast.

The tracking accuracy depends on the distance between tracking stations and the beamwidth of the tracking antenna. During these tests the estimated position accuracy was better than ± 1.0 mile at a range of 100 miles. Since the buoy portion of the sonde is nearly awash and has only a thin radio antenna protruding above the water surface, wind drag on the sondes was not significant. A ratio in excess of 20:1 was maintained between the projected areas of the buoy exposed to surface currents and of the current trap exposed to currents at its depth. Careful hydrodynamic design of the buoy hull structure further reduced the effect of surface currents.

Compared to the \$5,000 average cost of a current meter, each radio-tracked drogue costs about \$125 and each aircraft-tracked drogue about \$20. The low cost makes the drogues expendable, i.e. usually it is less expensive to leave them in the water, than to recover them. Each radio direction-finding station onshore costs about \$1,600.

Conclusions

Satellites, such as ERTS-1, can be used to obtain a synoptic view of current circulation over large coastal areas. Since in turbid coastal regions suspended sediment acts as a natural tracer, cost is minimized by eliminating the need for expensive injections of large volumes of dye such as Rhodamine-B. One of the principal shortcomings of satellite imaging of coastal currents has been its inability to determine current magnitude and to penetrate beyond the upper few meters of the water column. These objections have been overcome by complementing satellite observations with drogues tracking currents at various selected depths. By combining the satellite's wide coverage with aircraft or shore stations capable of tracking expendable drogues,

a cost-effective, integrated system has been devised for monitoring currents over large areas, various depths and under severe environmental conditions.

Acknowledgements

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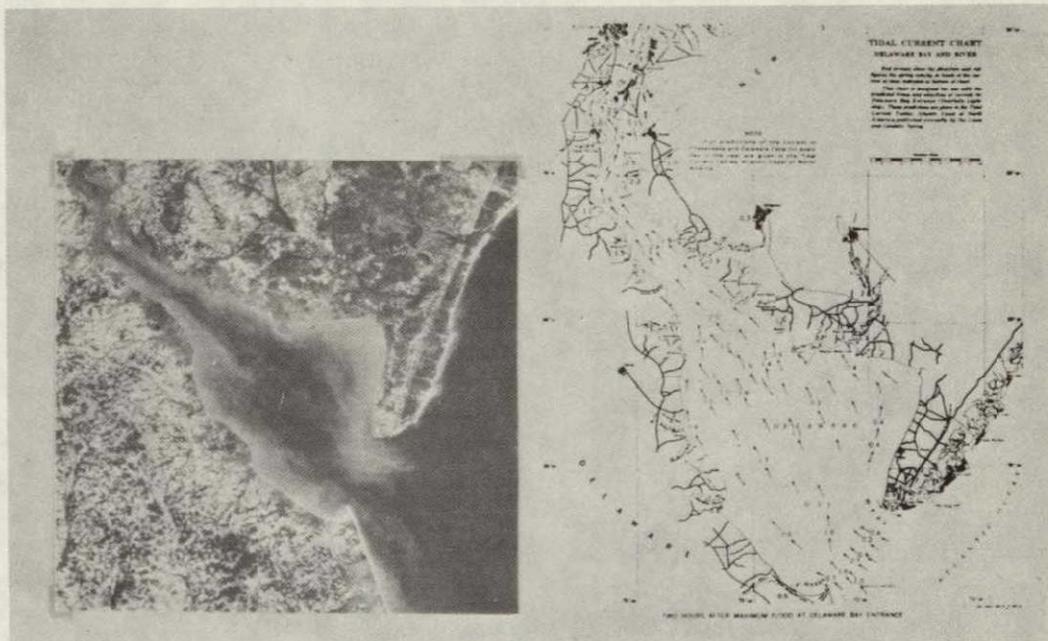


Figure 1: Predicted tidal currents and ERTS-1 MSS band 5 image of Delaware Bay obtained on October 10, 1972 (I.D. Nos. 1079-15133).

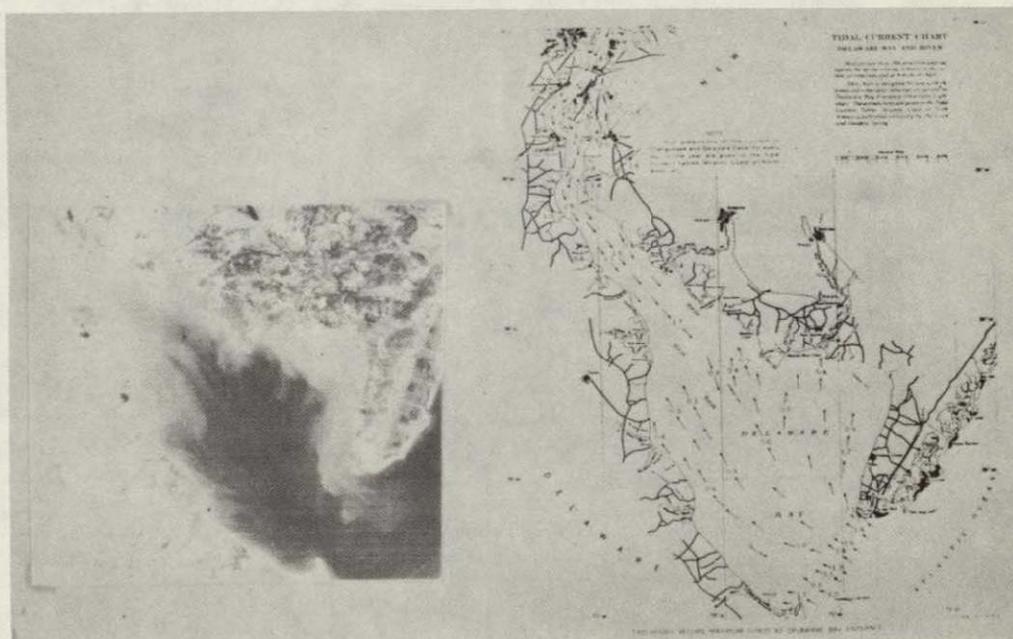


Figure 2: Predicted tidal currents and ERTS-1 MSS band 5 image of Delaware Bay obtained on January 26, 1973 (I.D. Nos. 1187-15140).

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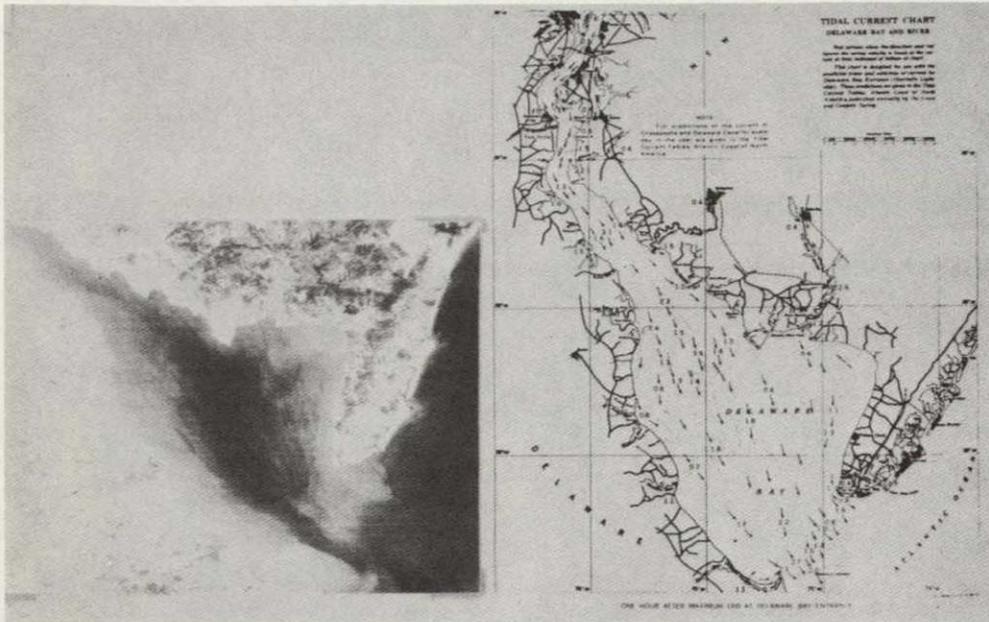


Figure 3: Predicted tidal currents and ERTS-1 MSS band 5 image of Delaware Bay taken on February 13, 1973 (I.D. No. 1205-15141).

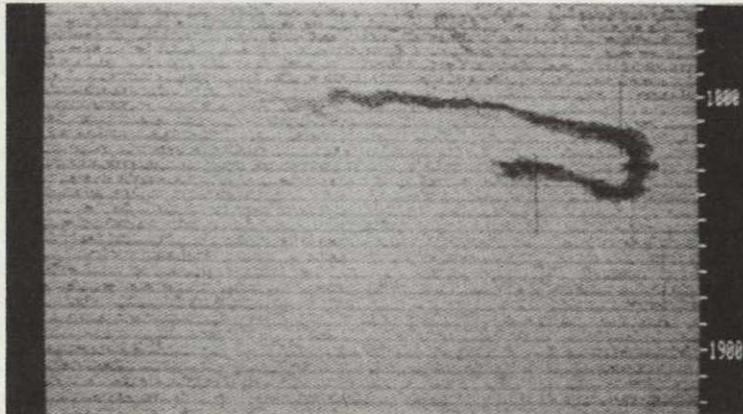
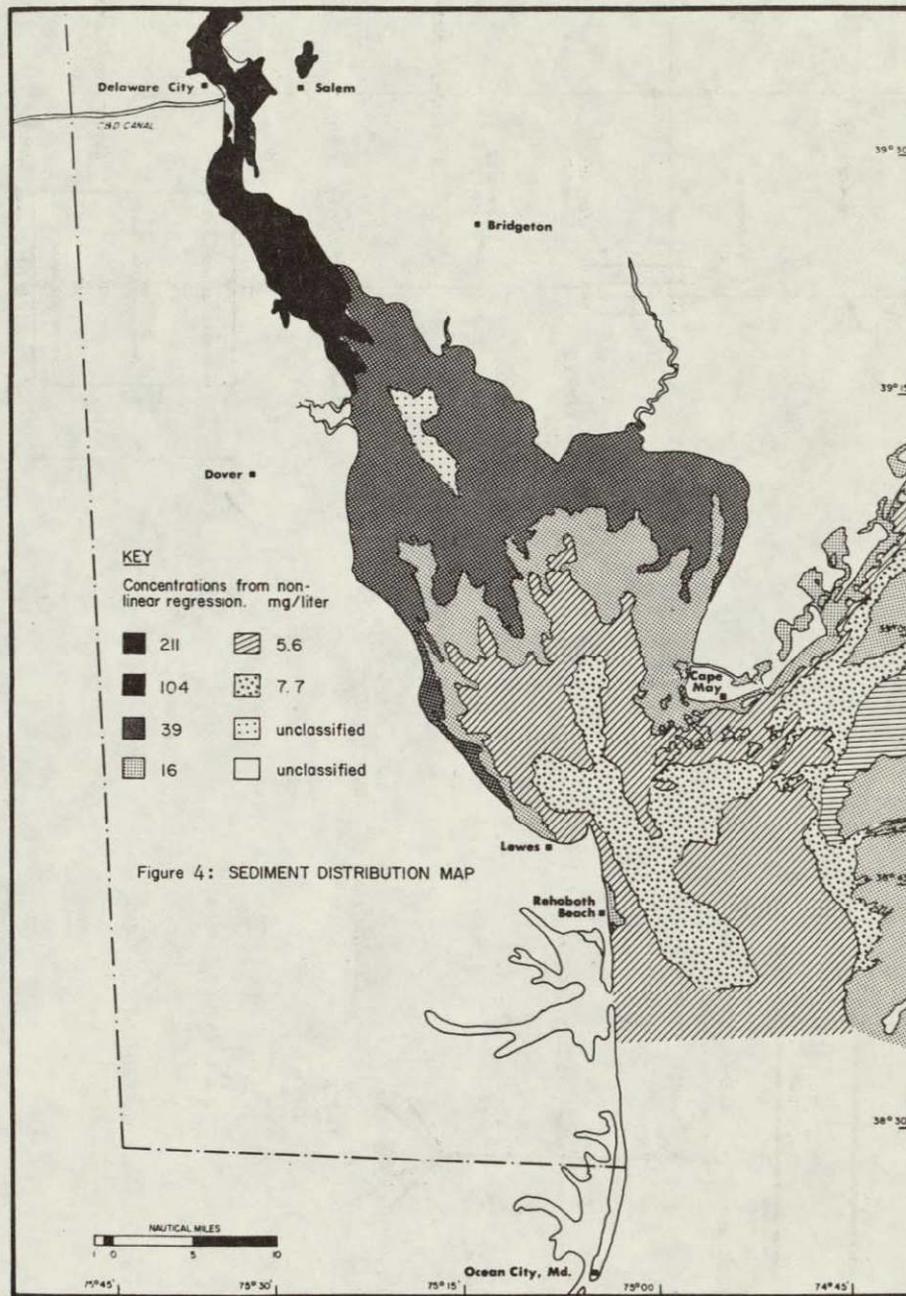


Figure 5: Enlarged digital enhancement of acid waste plume imaged by ERTS-1 on January 25, 1973.

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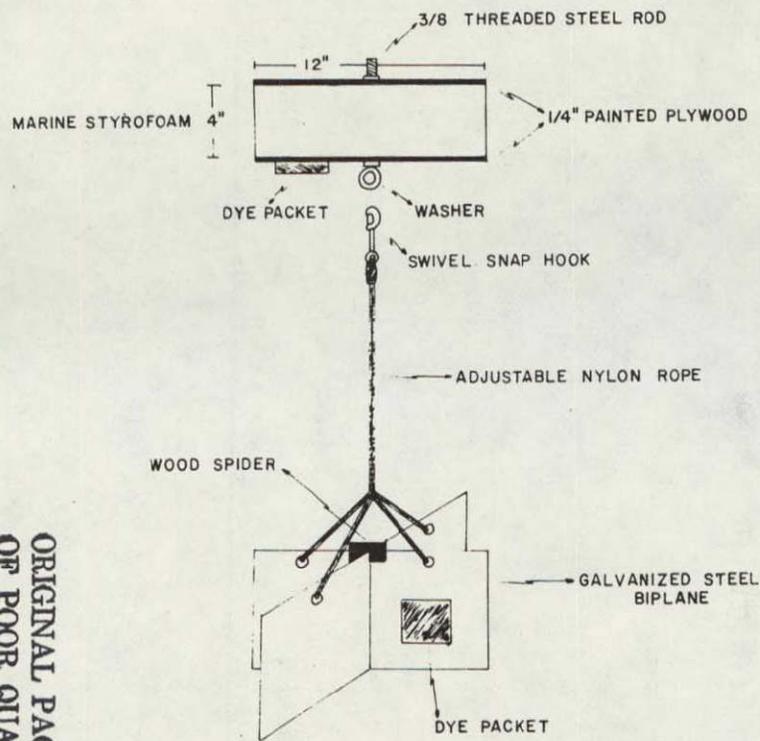


FIGURE 6 - DROGUE AND DYE EXPERIMENTAL PACKAGE

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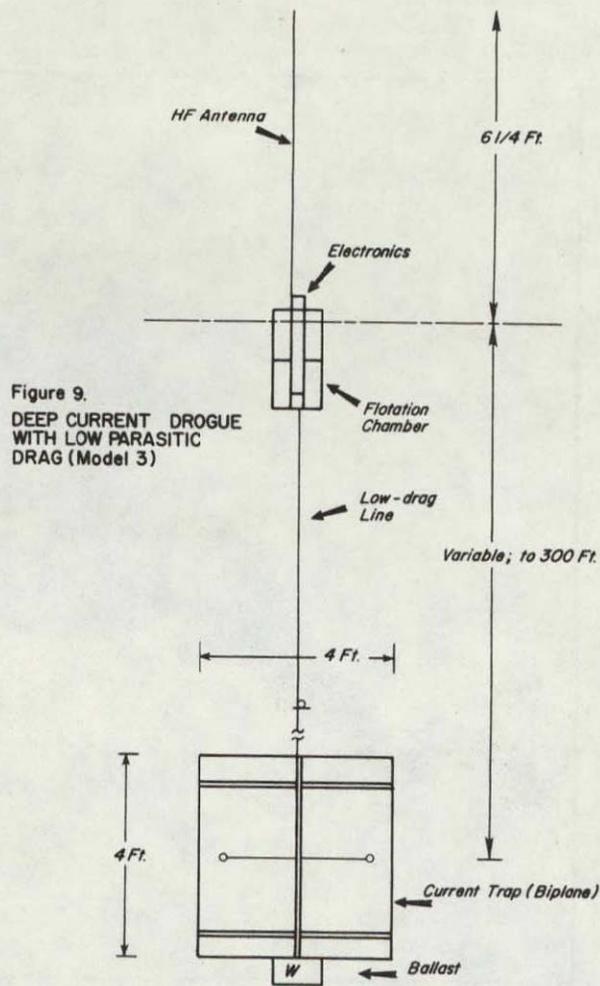


Figure 9.
DEEP CURRENT DROGUE
WITH LOW PARASITIC
DRAG (Model 3)

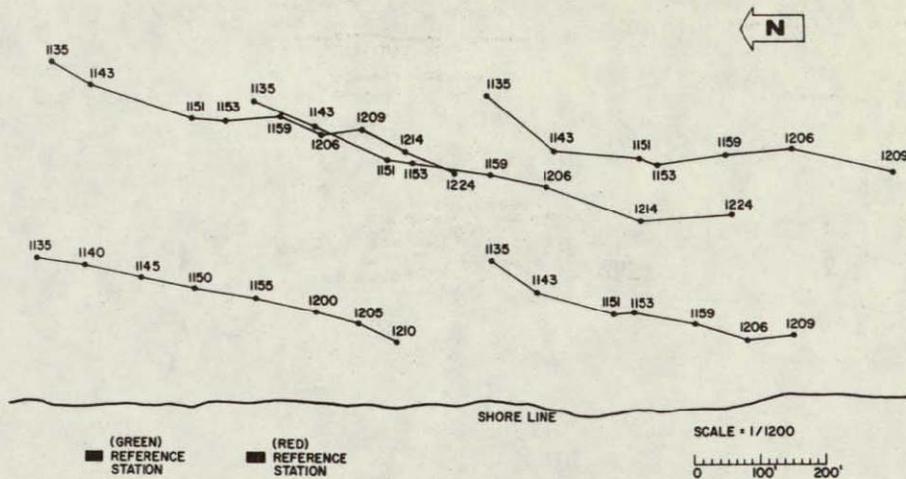


Figure 7: Trajectories of Drogues with Current Traps (Biplanes) at 6 ft. Depth. Numbers Along Trajectory Indicate Local Time (Hours).

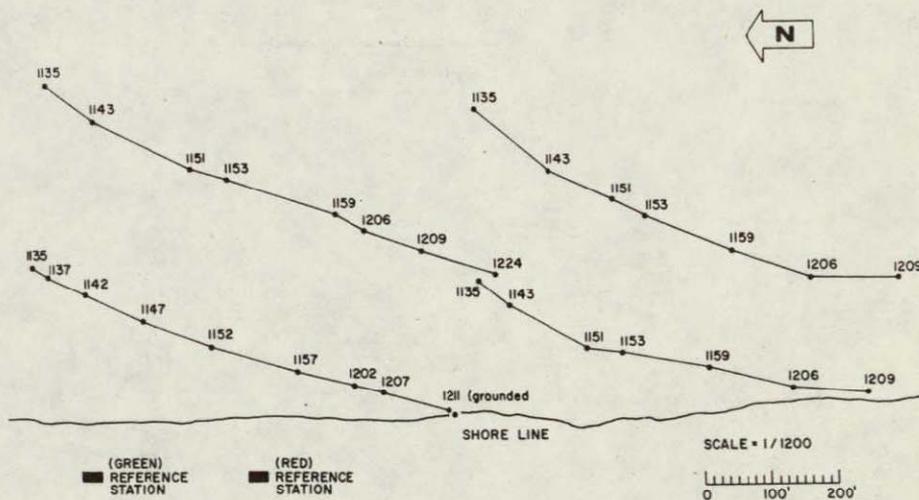


Figure 8: Trajectories of Drogues with Current Traps (Biplanes) at 1 ft. Depth. Numbers Along Trajectory Indicate Local Time (Hours).

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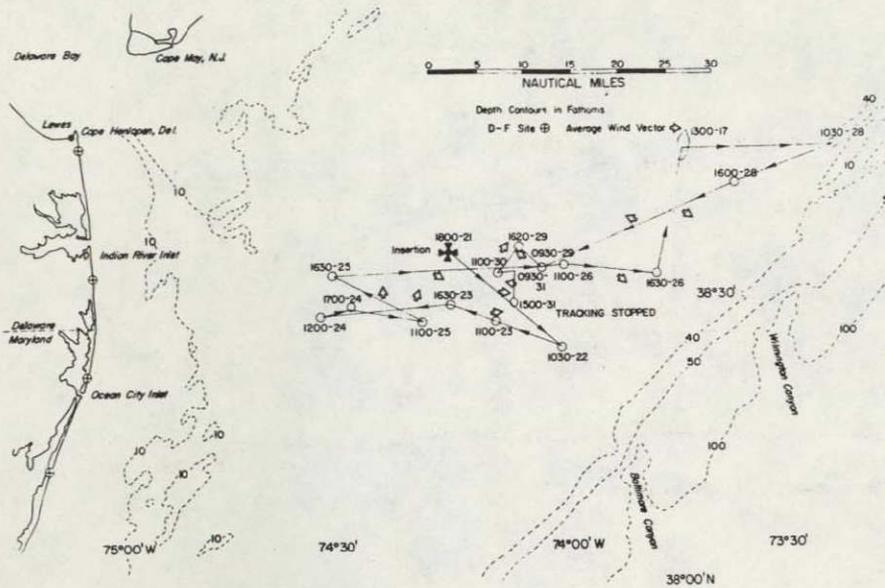


Figure 10: Trace of Sea-Sonde No. 005, Jan. 21 through Jan. 31, 1975. Current Trap Depth 30 feet.

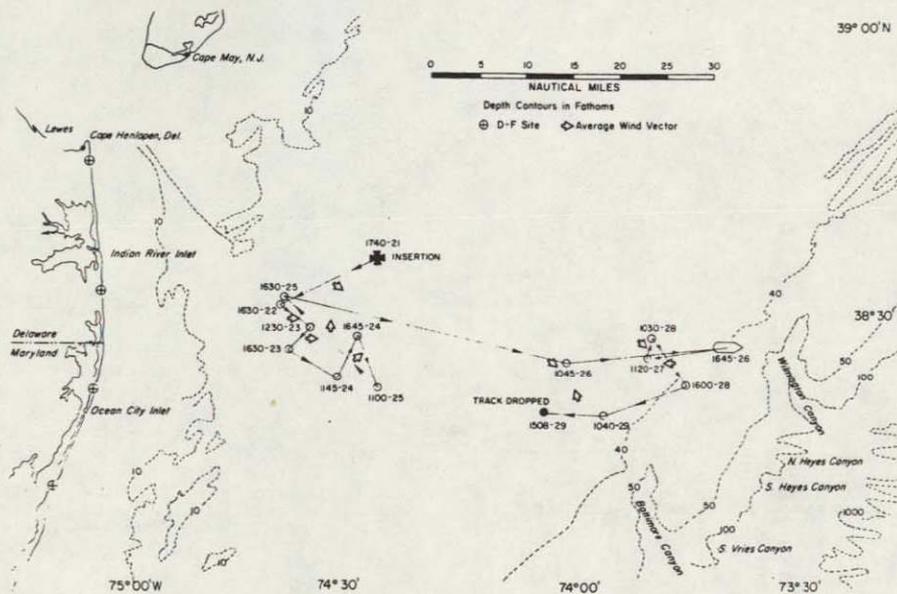


Figure 11: Trace of Sea-Sonde No. 008, Jan. 21 through Jan. 29, 1975. Current Trap Depth 10 feet.

