

## LAGRANGIAN CIRCULATION STUDY

### NEAR CAPE HENRY, VIRGINIA

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#### SUMMARY

A study of the circulation near Cape Henry, Virginia, has been made using surface and seabed drifters and radar-tracked surface buoys coupled to subsurface drag plates. Drifter releases were conducted on a line normal to the beach just south of Cape Henry. Surface drifter recoveries were few; wind effects were strongly noted. Seabed drifter recoveries all exhibited onshore motion into Chesapeake Bay. Strong winds also affected seabed recoveries, tending to move them farther before recovery. Buoy trajectories in the vicinity of Cape Henry appeared to be of an irrotational nature, showing a clockwise rotary tide motion. Nearest the cape, the buoy motion elongated to almost parallel depth contours around the cape. Buoy motion under the action of strong winds showed that currents to at least the depth of the drag plates substantially are altered from those of low wind conditions near the Bay mouth. Only partial evidence could be found to support the presence of a clockwise nontidal eddy at Virginia Beach, south of Cape Henry.

#### INTRODUCTION

This presentation is a summary review of a study funded by NASA/Langley Research Center (LaRC) (ref. 1) of the circulation along the coast in and just south of the entrance to Chesapeake Bay, Virginia. A net nontidal clockwise eddy inferred by previous investigators (ref. 2) was reinvestigated, in a limited way, by the use of surface and seabed drifters, by the use of radar-tracked floats with subsurface drag plates, and by cross-sections of the physical properties of temperature, salinity, and density. While table I lists all cruise days, locations, and the particular research method used, only the drogue data from August 8 - 9 and December 5 - 6, 1973, and the drifter data from June 22 - 23, 1974 will be discussed. (See reference 1 for the remainder of the cruise information).

#### REVIEW

##### Drogue Study

Previous investigations of the study area using current meters have primarily been associated with the Coast and Geodetic Survey (now National Ocean Survey) and have been mainly interested in tidal current predictions. Current meter stations were located at the Chesapeake Light Station,

in the entrance to the Bay, and near shore at the north and south ends of Virginia Beach. These positions were outside the present study area, except for the station near the north end of Virginia Beach, and were not useful in obtaining information about the circulation in the inferred eddy.

A search of the literature has produced only two other current studies in this area. The first and most recent current study was really a study of shelf circulation. Reference 3 tracked free drifting buoys using the French EOLE satellite in the western North Atlantic in the winter of 1973. The four buoys had drag plates at either 5 or 30 m. After initial deployment near the Chesapeake Light Tower they drifted southeasterly parallel to the coast. Upon reaching the vicinity of Cape Hatteras, the three remaining buoys were entrained in the Gulf Stream and drifted northeast. Reference 3 reports that the random error in position about the mean ranged from 1.4 to 2.3 km depending upon the transponder.

The second study, although 12 years old, did investigate the nearshore area of Cape Henry. Reference 2 made simultaneous measurements by both Eulerian and Lagrangian methods for up to 13 tidal cycles along the shore. Three Roberts Radio Current Meter Stations were occupied from Cape Henry to Rudee Inlet about 1.6 km (1 mi) offshore. A brief drogue study was conducted during one of the tidal cycles simultaneously with a dye and drifter release.

Reference 2 claims that the clockwise eddy movement is confirmed by the nontidal current values (isolated from the total current record). The station near Cape Henry shows easterly net current values at both surface and mid-depth locations (no bottom meter), while the central station, near 40th Street, indicates a net northerly current at surface, mid-depth, and bottom positions. The southern station, just south of Rudee Inlet, shows extremely small net current values (less than 2 cm/sec) in an easterly direction for surface, a southerly direction for mid-depth, and a northerly direction for the bottom meter position. The brief drogue study showed a clockwise loop of less than one nm width (normal to shore) and about three nm in length. The time of observation was slightly less than one tidal cycle. By itself, this loop could indeed be associated with the rotary tide. The results of the three current meter stations (which were averaged over 9 to 13 tidal cycles) offer the best evidence for this net motion, but do not completely cover the study area. The dye study was not conclusive in that the dye cloud was only monitored for six hours during an ebb flow situation.

#### Drifter Study

The earliest reported use of drifters to study circulation near the entrance to Chesapeake Bay suggested that the offshore shelf waters exhibited primarily southerly drift, but that the inshore waters just south of Cape Henry described a clockwise movement extending south to Rudee Inlet and to an unknown extent seaward (refs. 4 and 5).

Reference 2, besides the current meters mentioned in the previous chapter, deployed surface drift bottles from positions just south of Cape Henry and off Little Creek Harbor. While they experienced a recovery of 38.9 percent from the Cape Henry releases and 57.3 percent from the Little Creek releases, little can be learned of the inferred eddy from the recovery positions. These were mostly south of Rudee Inlet, a direct indication of the net nontidal surface outflow from the Bay and of the general southerly flow of the shelf waters.

A number of seabed drifters of the plastic umbrella-shaped variety (Woodhead-Bumpus seabed drifters) were released at a single point on a separate occasion in connection with a brief dye and current meter study at the tip of Cape Henry. These were released at slack water before ebb. A recovery of 80 percent of the drifters was made a few hours later up to 2.7 nm (5 km) south of the release point. Most of the seabed drifters were recovered at the south end of Virginia Beach and probably were carried by shelf current around the eddy area.

Reference 6 released vast numbers of seabed and surface drifters off the Chesapeake bight during 1963-1964. The recovery of large numbers of seabed drifters in or near Chesapeake Bay from releases to the north and east indicated net bottom inflow into the bay as well as the expected southerly drift. Apparently the inflow was related to changes in river discharge and seasonal prevailing winds. The general trend of the surface waters as determined by drift bottle recoveries was also southerly, but highly dependent upon the prevailing wind direction. Most recoveries were made during periods of onshore winds. No mention is made of the inferred clockwise eddy south of Cape Henry. However, reference 7 placed generalized flow pattern arrows on figure 15 of reference 6 which indicate a possible clockwise circulation of the bottom currents inferred from winter releases of seabed drifters. The size of the cell, however, is quite large in comparison to the Virginia Beach study area.

Brehmer (ref. 8) specifically studied the problem of nearshore bottom currents off Virginia Beach. His approach was to release seabed drifters along a transect parallel to and approximately 5.6 km (3.5 mi) offshore from Cape Henry to False Cape. His results indicated that during the fall and winter months recoveries suggest northerly nearshore nontidal bottom drift from Rudee Inlet to Cape Henry. South of Rudee Inlet the drift was southerly. During the summer months, however, the recoveries inferred that the nontidal drift patterns were primarily inshore and slightly northerly as far south as False Cape. No attempt was made to establish the seaward extent of the circulation, but Brehmer states that his data "appear to confirm the presence of the clockwise eddy in the Atlantic Ocean south of Cape Henry."

## METHODS

### Drogue Study

The buoy-tracking phase of this study utilized up to 4 surface buoys with drag plates centered at 6.1 m (20 ft). The steel plates are crosses, 0.9 m (3 ft) high by 1.5 m (5 ft) wide. S-band radar was used to interrogate each buoy in turn, taking approximately 5 to 20 min to locate and position all 4 buoys. The radar operates in the 2700 to 2900 MHz range and is limited to line-of-sight operation. Each buoy is "told" to turn on and become an active target for the radar by a double pulse from the radar unit. The pulse widths vary from 2 to 12 msec. Each buoy receives on the same frequency but "senses" from the width of the time delay between pulses when it is its turn to be interrogated.

The MPS-19 S-band radar was housed in a mobile tracking van provided and operated by personnel from Wallops Station, NASA, located at Wallops Island, Virginia. The four buoys were provided by the Sensor Development Section (SDS), NASA/LaRC. In addition, the SDS also provided the rechargeable batteries for the floats (up to 40 hr transmitting life) and the small trailer used to record and plot the buoy trajectories. Ship communication was through portable FM units supplied by the Wallops Station crew. The Department of Oceanography, Old Dominion University (ODU), provided the R/V *Linwood Holton* for release and recovery of the buoy/drogue plate combinations and personnel for data recording and plotting. Power for the shore operation of the radar van and data-recording trailer was obtained from a Wallops-Station-supplied 50-kW diesel-powered generator.

In the attached figures, the initial position of each buoy is indicated by "S," the final position at pickup by "F." The numbers and associated tick marks indicate the sequence number and location of tidal current reversal. Appendix A, tables A1 through A4 of reference 1, contains the tabulated data for each buoy and each day of tracking. The tables contain sequential data point number, local time, range from radar vans, and azimuth. The individual buoy's initial and final position latitude and longitude are given, as well as the position of the radar van. The position fixes are accurate to within 5 m (5.5 yd) to a distance of 28 km (15 nmi). The position error of the location of the radar van must be added to the buoy position error. Horizontal sextant angles are used to determine van position. The accuracy depends upon chart position of the sextant targets, distance to the targets, sextant error, and operator error. These errors have been estimated to be  $\pm 9$  m ( $\pm 10$  yd).

### Drifter Study

The drifter program used both surface and seabed drifters. The surface drifters were made of weighted heat-sealed plastic pouches containing sand to allow the bags to float with a minimum of surface area above the water. The sand forced the bag into a near vertical position so that the water motion effect on the bags of the surface of "skin" layer would be minimized. Each

pouch contained a red postcard with identifying information and requested the finder to give the data and time found as well as the actual location. Return information could be provided as to when and where released if the finder so desired.

The seabed drifters were of the Woodhead-Bumpus type. These were slightly negatively buoyant, plastic, umbrella-shaped floats. Each had a plasticized postcard attached under the umbrella with the same request for information.

The surface drifter envelopes were thrown individually into the water at each station. The number thrown varied from 7 to 10, depending upon availability for that particular cruise. All stations during a cruise had the same number released, however.

The seabed drifters had to be weighted so that sinking time to the bottom would be as short as possible, otherwise the drifters would behave partially as surface and intermediate layer drifters as well as seabed. Salt spools of 76-cm (3-in.) diameter about 2.5 cm (1 in.) thick, were used for the weight. Each cluster of 5 to 10 seabed umbrellas was fastened to a salt spool with a small rubber band. The spool and rubber band were attached in such a way that when the spool dissolved the rubber band released the drifters. The sinking and release of the drifters was observed to take about 45 min to 1 hr in 15 m (50 ft) of water. Water temperature was near 15.6° C (60° F).

The groups of drifters, both surface and seabed, were assembled and identified prior to each cruise. Before throwing them overboard all numbers were checked as to release date, time, and location. Upon recovery, the shortest distance between release and recovery was used to determine travel distance and speed, and direction was then calculated. All data for surface and seabed drifters are tabulated in Appendix B of reference 1.

## DISCUSSION

### Drogue Study

August 8-9, 1973.— The buoy-tracking runs of August 8-9 were an attempt to look at the flow around the "corner" of Cape Henry. Permission was obtained from the U.S. Army to allow placement of the radar tracking van within Fort Story. This position, near the tip of Cape Henry, allows line-of-sight tracking for several miles within the bay as well as along the coastline of Virginia Beach.

Figure 1 shows the radar van position as well as the trajectories of each of the buoys. Only three buoys were deployed during this tracking operation. Buoy 3 was in a nonoperating condition at the time scheduled. Unfortunately, the strong net seaward flow during this tracking operation caused the buoys to be carried from the line of sight much sooner than expected; only intermittent fixes were obtained after data point 73 (buoy 1), data point 76 (buoy 2), and data point 69 (buoy 4). Final positions were obtained from the R/V *Linwood Holton* at time of recovery: data points

76, 77, and 71 for buoys 1, 2, and 4, respectively. No information was obtained concerning flow reversals between the last radar position and ship recovery position. In addition, a malfunction in the automatic range determination unit required manual determination of range from 1233 to 1717 EDT on August 8. Several ranges prior to this are in possible error due to malfunction prior to 1233 EDT. Both sets of observations have been marked and footnoted (see ref. 1, Appendix A).

The clockwise motion of the three buoys is evident, but the proximity to the Cape Henry "corner" causes the buoy tracks to become more elliptical in shape. Except for the reversal, this pattern is quite similar to standard frictionless flow around a corner, or one side of flow from an orifice. Notice that each buoy system moves parallel to the 9-m (30-ft) depth contour during the strength of the ebb and flood cycles and moves approximately perpendicular to the contour during the slack times. The rotary nature of the tidal currents on the shelf prevents a pure reversal in direction.

Speeds for the buoy's drag plate stems exceeded 1.4 m/sec (2.7 kn) during the ebb cycle in the channel just north of Cape Henry and exceeded 0.7 m/sec (1.4 kn) during the next ebb off Virginia Beach. The flood strength was only 0.3 m/sec (0.5 kn).

December 5-6, 1973.— An attempt was made to restudy the flow around the top of Cape Henry by moving the radar tracking van "around the corner." This would result in improved line-of-sight fixes. The new position is shown in figure 2 along with the tracks of the two operational buoy-drogue systems.

Shortly after deployment of the two buoys, the wind increased from under 5 m/sec (10 kn) from the south to over 12.9 m/sec (25 kn) from the southeast (average wind December 5 was 20 kn). This caused a rather sudden change in surface currents to occur. The initial effect was to cause ocean water to be moved into the Bay on a flood cycle lasting nearly 12 hr, starting at approximately 0900 EST and terminating at about 1900 EST on the fifth. The duration of flooding predicted by the U.S. National Ocean Survey (1972) was for only 2.5 hr (approximately 1400 to 1630 EST). The maximum flood current was computed to be approximately 1.0 m/sec (1.9 kn) compared to the predicted maximum of 0.4 m/sec (0.7 kn).

The net drift was northeasterly during the day of December 5 and started to show signs of returning to a southwesterly direction on December 6, the winds having shifted around to the north with an average speed of 5.7 m/sec (11 kn) on December 6. The net drift, computed from the track of buoy 3, was approximately 20.4 km (11 nmi) for an average speed of 0.2 m/sec (0.4 kn). The Ekman wind-driven current speed was obtained from figure 5 of reference 9 as 0.10 m/sec for an average depth of 9 m (30 ft) and wind speed of 12.8 m/sec (25 kn). This large contribution to the net motion reinforces the need for continual observation of wind conditions during all circulation studies. No calculation of wind wave currents was made, but these were probably less than 25 percent of the direct wind-driven current during the time.

## Drifter Study

The stage of the tide could not be observed to have any influence on the recovery of drifters for the previous four drifter releases (ref. 1). This was, at least in part, due to the one-time release of drifters along the line of stations. An attempt was made during the cruise of June 22, 1974 to investigate this effect by the release of drifters along the line of stations four times over a tidal cycle.

The nearest tidal current prediction station is number 4475, Virginia Beach, north end,  $36^{\circ}52'N$  and  $75^{\circ}58'W$ . This is about 1.9 km (1 nmi) south and shoreward of station one. The times of release for the four sets at station one corresponded well with the predicted tidal current information as follows (U.S. National Ocean Survey, 1973):

Station One Release Time	Tidal Condition
1. 1038 EDT	Maximum Flood
2. 1423 EDT	Slack Before Ebb
3. 1700 EDT	Maximum Ebb
4. 1932 EDT	Slack Before Flood

It must be noted here that the tide at stations seaward of number one does not behave as it does at the predictor station.

The winds during the two days prior to and during the day of release were generally from the south at less than 7.7 m/sec (15 kn) average; however, for the next week, winds were northerly, averaging just under 7.7 m/sec (15 kn).

The recovery positions for the seabed drifters are presented in figures 3 through 6 and for surface drifters in figures 7 through 10. Table II presents a summary of recovery information for the four release runs.

An inspection of the seabed drifter information from table II and figures 3 through 6 does not show any obvious connection to stage of tidal current near station one. Over 56.4 percent of all released seabed drifters were recovered, mostly north of the release line, indicating onshore northerly (into the Bay) flow. Further inspection suggests that the more easterly station releases were recovered to the south. The surface drifter information is even more widely scattered. It appears that the northerly wind affected the seaward released drifters more than the shoreward only for the first release set. Returns were either from near Cape Henry or from North Carolina. Only 31.0 percent of all surface drifters were recovered, indicative of either seaward surface flow or pouches that leaked and sank. Hence visual inspection of the data is not conclusive.

A statistical study of drifter returns was then implemented by Mr. Richard Philips, Ph.D. student within the ODU Department of Oceanography. Unfortunately, the data were not analyzed comparing each run, but only as to significance of north or south recovery positions for each station. This resulted because of insufficient data in adding the four additional classifications and also because less than nine percent of the drifters were recovered within two days. Drifters in circulation for more than two or three semidiurnal cycles tend to lose their original tidal identity.

The surface and bottom data were analyzed separately. The surface circulation is quite different from that near bottom due to the presence of the Bay mouth and wind effects. The data were analyzed using the one-way analysis of variance approach and with a modified Duncan multiple-range test. All analyses were performed at the 95 percent confidence level.

The bottom drifter data results suggest the presence of the inferred eddy. Stations one through four all had net northerly drift, while stations five through seven all had southerly drift. The surface study was inconclusive; no trends appeared to indicate northerly flow, only southerly flow: a consequence of wind shift part way through the drift? Again, it was noted that a bimodal distribution existed with one group clustered in North Carolina and the other group centered near the release position. This possibly can be explained by the relative densities of people along the beaches. The two major recovery areas are prime resort areas and could account for the few recoveries between them.

#### SUMMARY AND CONCLUSIONS

The investigation of the nearshore circulation in the vicinity of Cape Henry was undertaken to extend the current knowledge of the inferred net nontidal eddy reported in the literature. Establishment of this feature, of course, would greatly aid the understanding of the circulation along Virginia Beach and, hence, the erosive problem faced by that city.

Lagrangian methods were employed. The seabed and surface drifters duplicated, but also extended, earlier work. Release transects across the inferred eddy center of rotation were made. Radar-tracked drogues were used for the first time. Four separate cruises were made, lasting from 8 to over 30 hr of tracking time. A combination of factors, including weather, ship and manpower availability, and insufficient subsurface tidal information, prevented the deployment and tracking of the buoys exactly in or near the inferred eddy location. The size and scope of the original grant also precluded making more data collection runs.

The drogue studies support the concept of onshore and clockwise motion during at least part of a tidal cycle. The individual buoy/drag plate assembly motion seemed to follow an irrotational pattern, however, rather than the rotational one expected from motion associated with an eddy.



The drogoue study of August 8-9, 1973 was slightly north of the inferred eddy, located at the entrance to the bay. This series was partially interrupted by loss of line-of-sight contact with the surface buoy; however, the described trajectories closely resemble the flow pattern found around theoretical, frictionless corners. The path closely followed the bottom contours, again turning in a clockwise fashion through flood, ebb, etc. The orbit was reduced to almost linear proportions on the buoy closest to shore. All three buoy tracks appeared to be merging to the same flow line after 10 hr or so.

The study of December 5-6, 1973 was affected by a rather intense south to southwest wind shortly after buoy deployment that quickly altered the long-term surface current on the shelf. The buoy paths, while retaining tidal characteristics, showed a northeasterly trend counter to that previously noted. This, of course, suggests that any nontidal eddy located along Virginia Beach near Cape Henry could be hidden or "washed out" for long periods at a time.

The summer drifter release of June 22, 1974 was an attempt to study the stage of the tide vs. time of drifter release. This could not be done due to insufficient returns. One result that did emerge, however, showed that the seabed drifters from stations one through four had a net northerly drift, while those from stations five through seven had a net southerly drift. The surface study was inconclusive.

As yet no positive determination of the presence of a nontidal clockwise eddy has been shown. The present data collection more clearly shows the response of the nearshore regime under the action of wind. However, not enough long-term studies have been made to subtract the wind and other currents from the record, leaving the residual. This sort of analysis requires the use of 30-day or longer drogoue studies, anchored current meters, or both.

## REFERENCES

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TABLE I.-DATA ACQUISITION INFORMATION

Cruise Date	Location	Methods
3 Apr 1973	Virginia Beach	Drifter
10 May 1973	Virginia Beach	Drogue
11 May 1973	Virginia Beach	Drogue
22-23 May 1973	Thimble Shoal Channel	Drogue
8 Jun 1973	Virginia Beach	Drifter
26 Jul 1973	Virginia Beach	Drifter
8-9 Aug 1973	Cape Henry	Drogue
5-6 Dec 1973	Cape Henry	Drifter/Drogue
22-23 Jun 1974	Virginia Beach	Drifter/Thermohaline

TABLE II.-DRIFTER RECOVERY SUMMARY FOR JUNE 22, 1974

Time EDT	Drifter	Drifter Release per Station	Recovery per Station							Recovered
			Station							
			<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>	
1038-1117	Seabed	5	4	5	4	5	2	1	0	60.0
	Surface	9	6	2	0	5	7	3	4	42.9
1473-1500	Seabed	5	4	4	4	2	2	2	4	62.9
	Surface	9	2	2	1	3	3	1	3	23.8
1700-1733	Seabed	5	4	3	3	5	0	1	2	51.4
	Surface	9	2	3	7	1	1	2	4	31.8
1932-2014	Seabed	5	4	4	3	3	2	2	0	51.4
	Surface	9	3	1	2	1	3	2	4	25.4

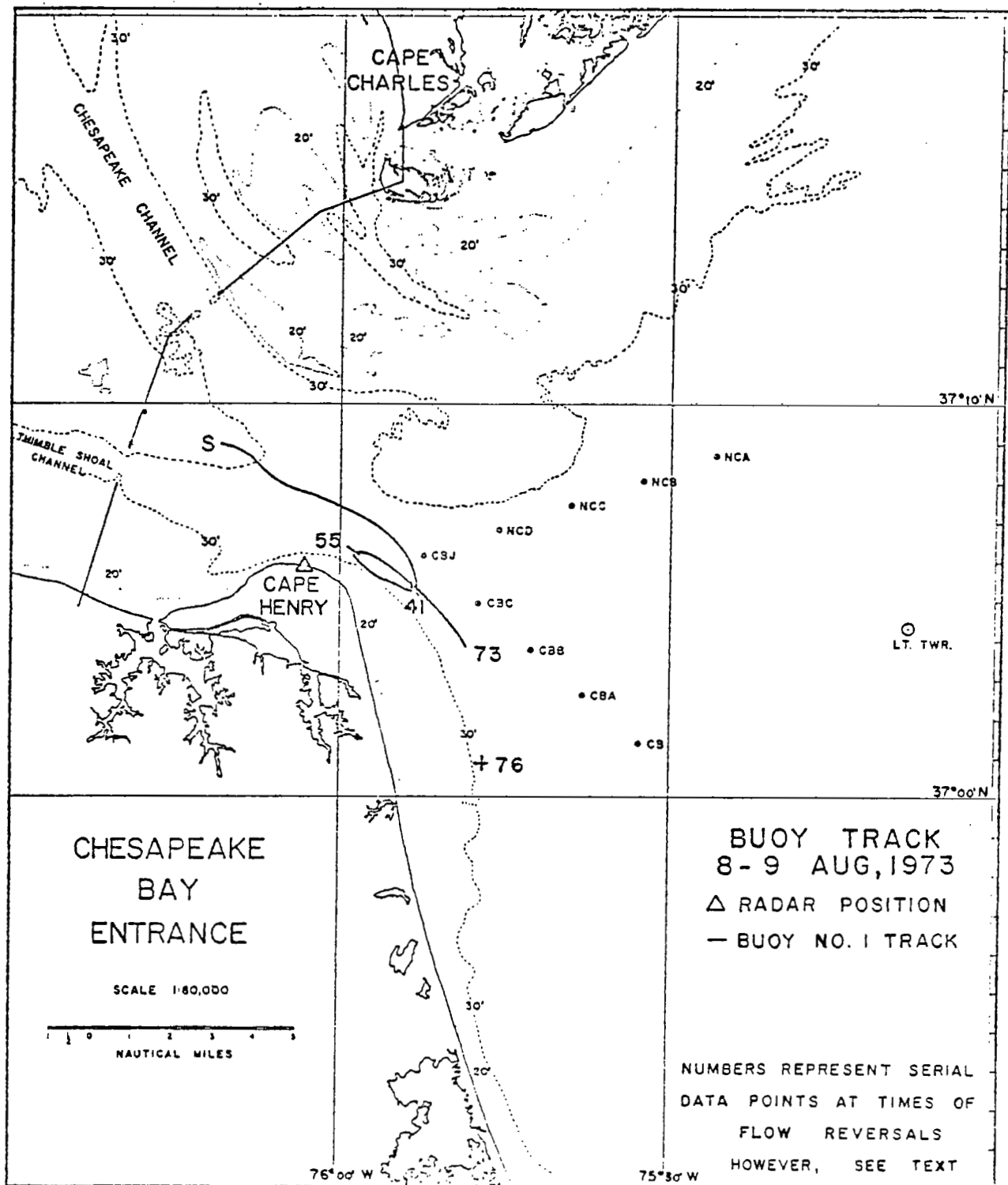


Figure 1.- Trajectories of radar-tracked buoys for 24 hours on August 8-9, 1973.

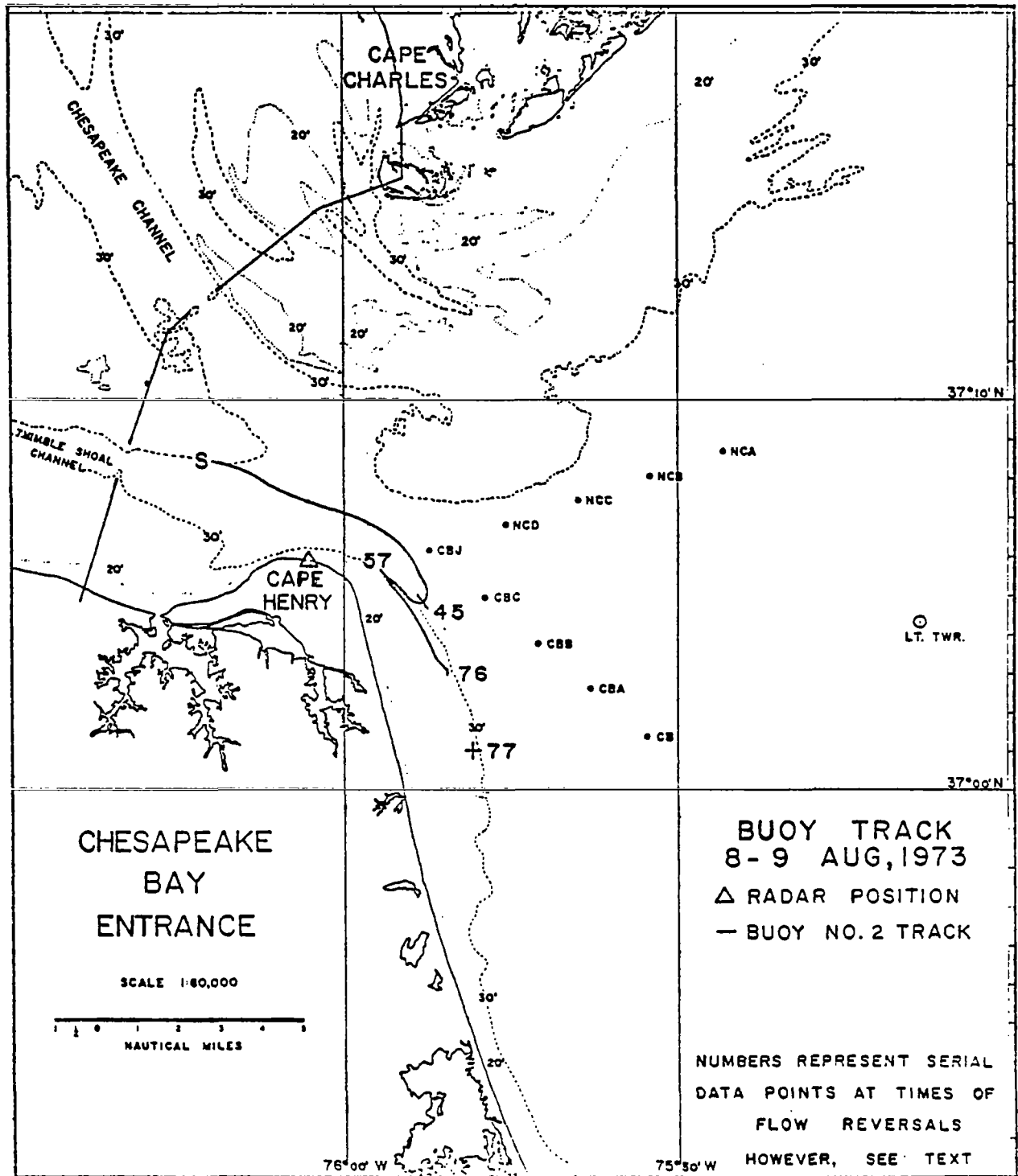


Figure 1.- Continued.

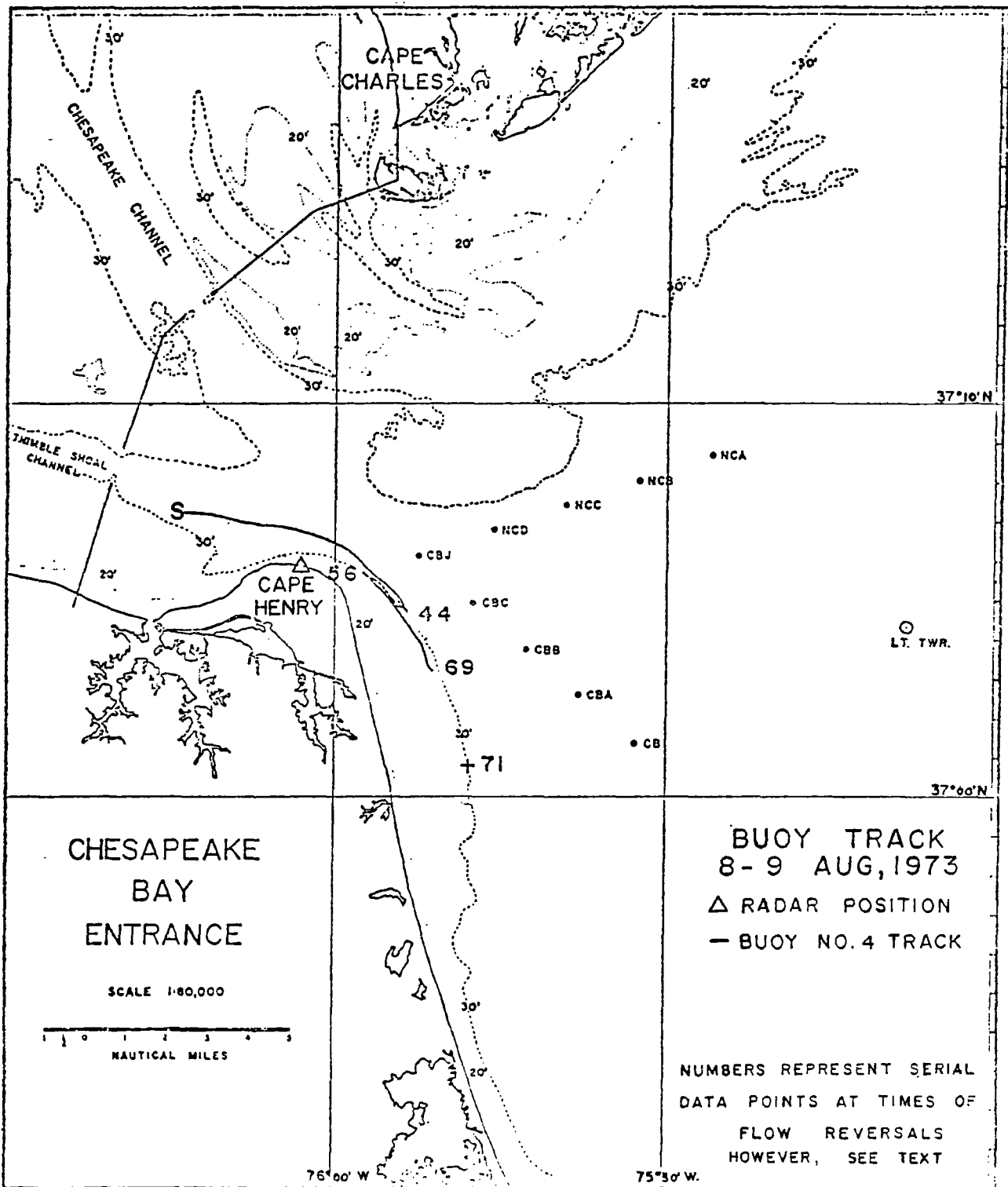


Figure 1.- Concluded.

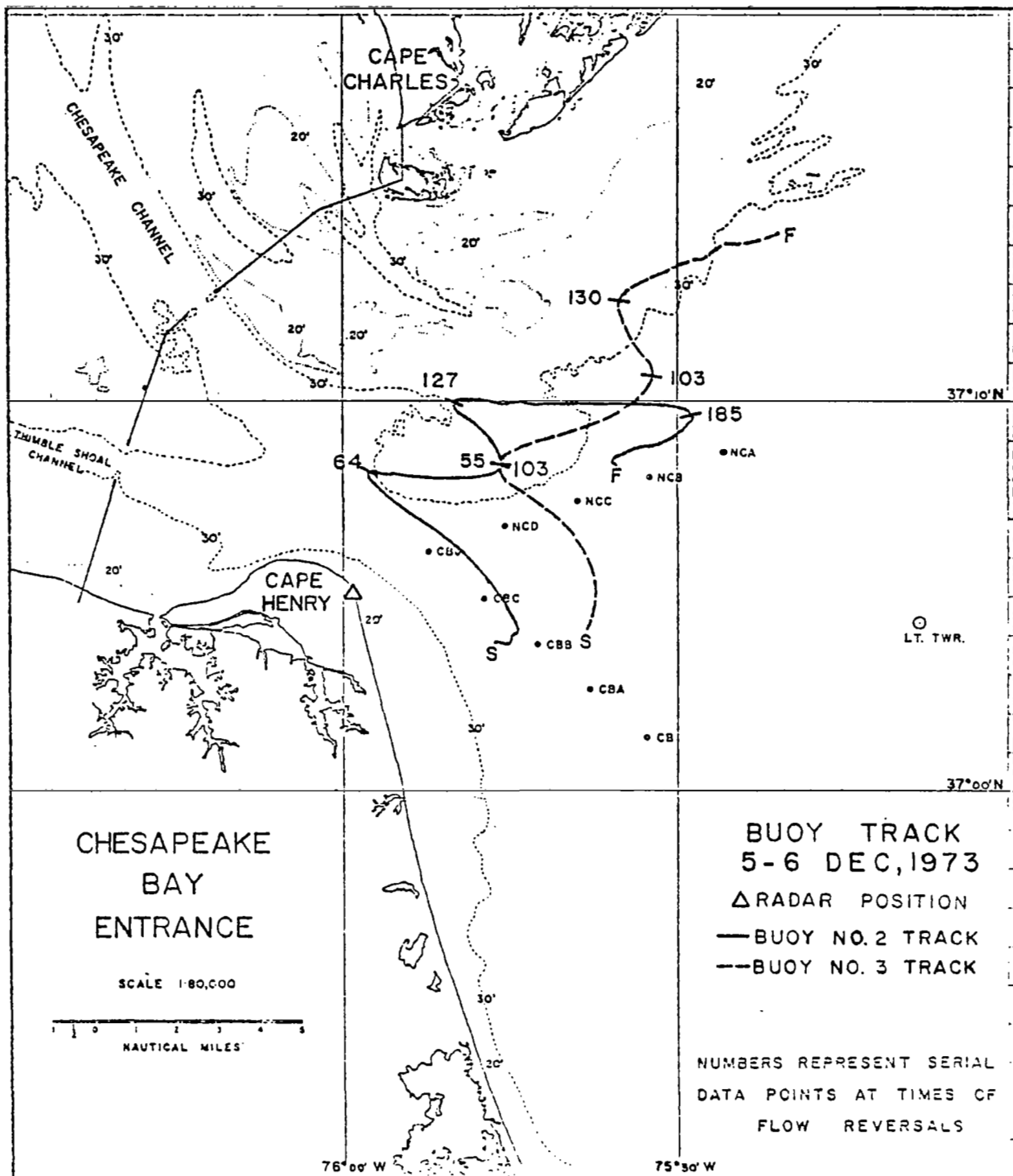


Figure 2.- Trajectories of radar-tracked buoys for 34 hours on December 5-6, 1973.

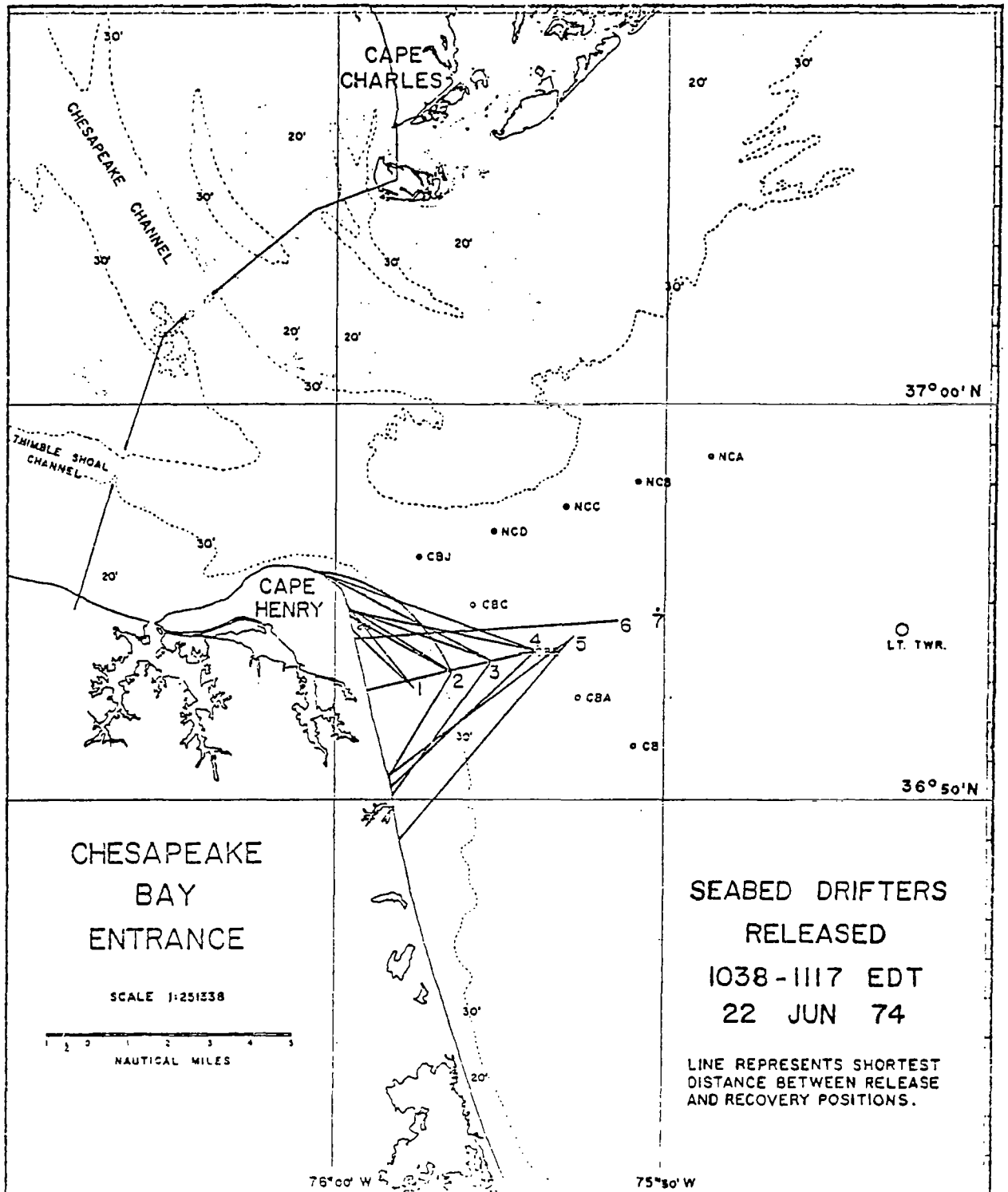


Figure 3.- Recovery positions for seabed drifters released 1038-1117 EDT, June 22, 1974.





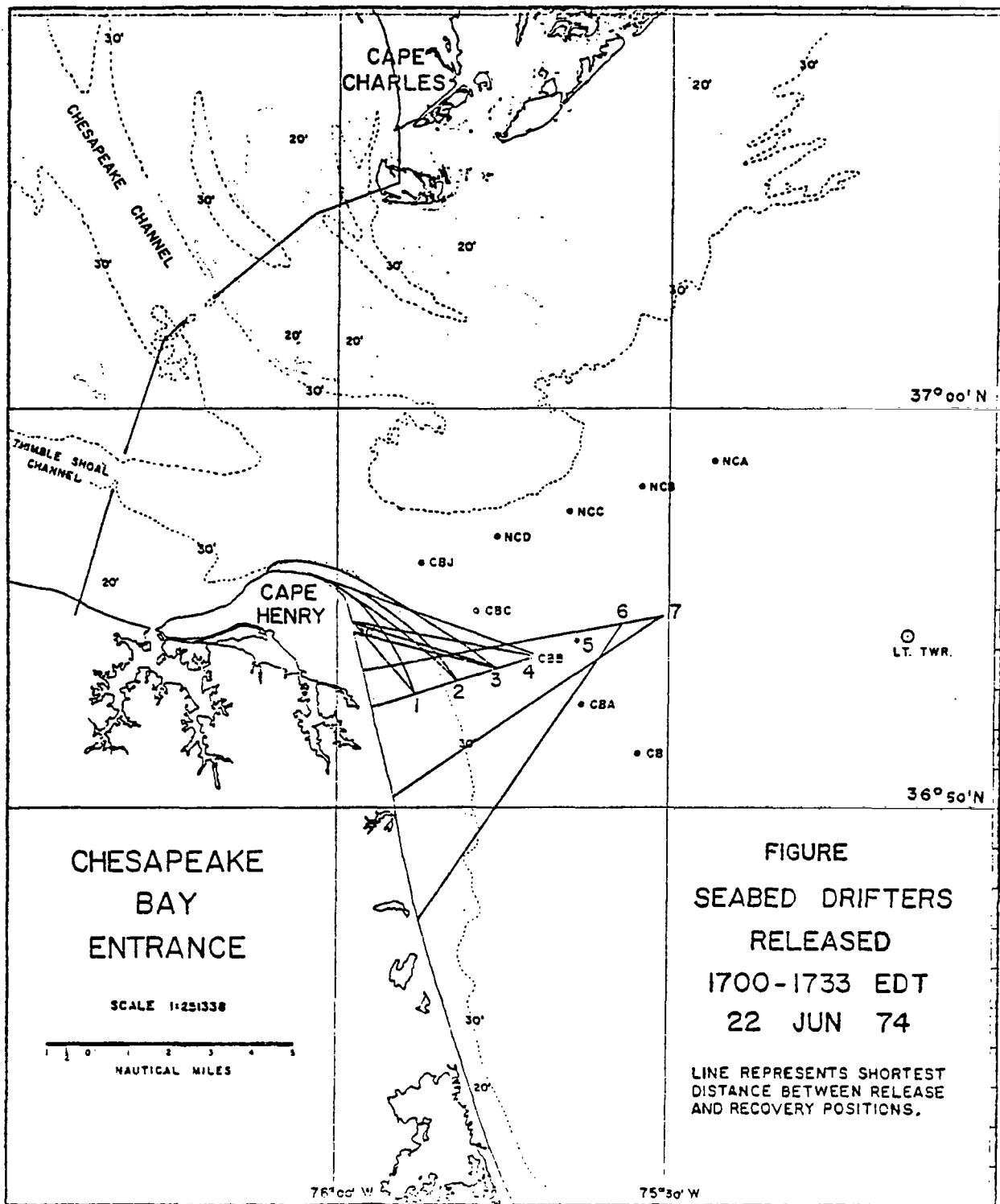


Figure 5.- Recovery positions for seabed drifters released 1700-1733 EDT, June 22, 1974.

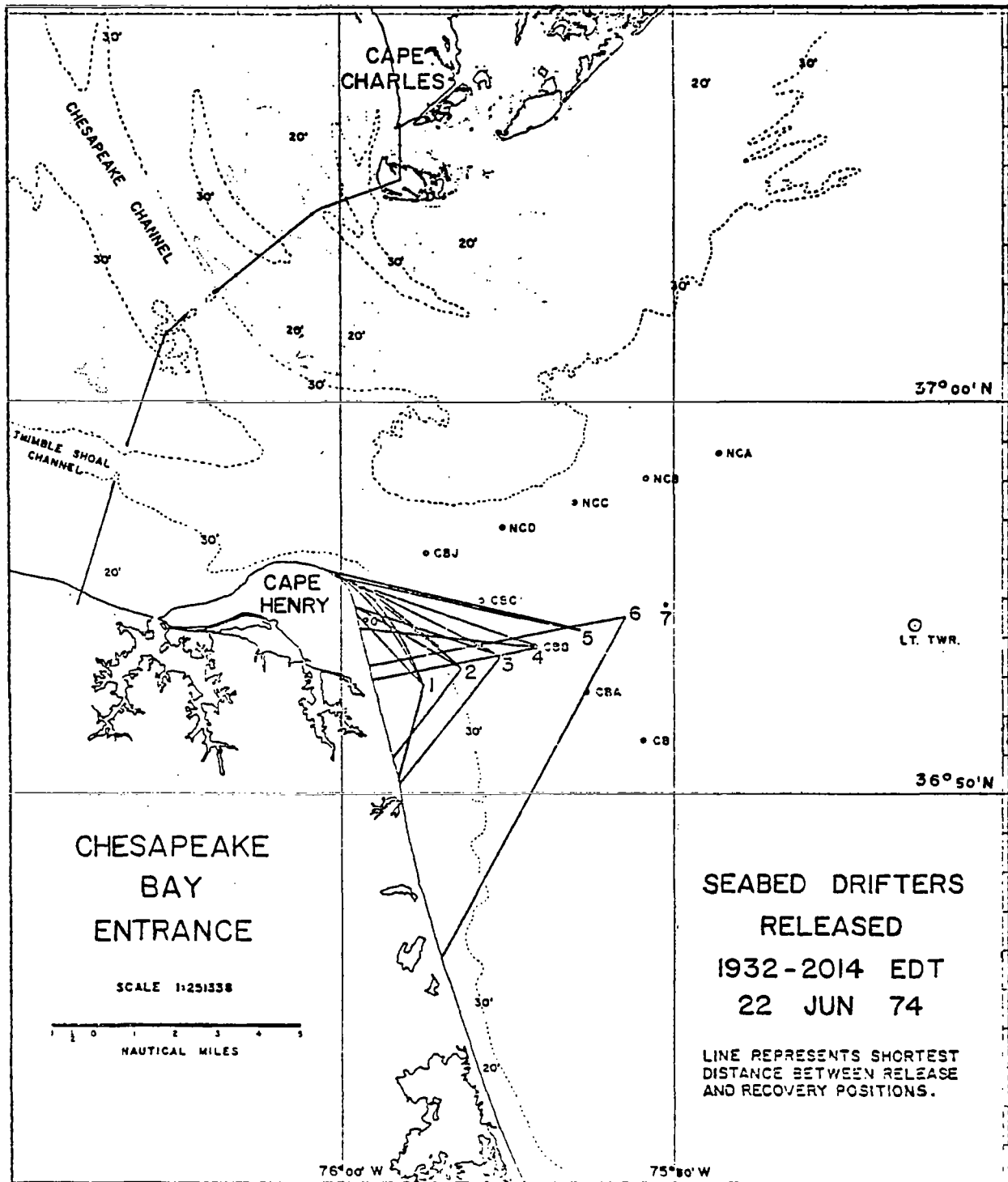


Figure 6.- Recovery positions for seabed drifters released 1932-2014 EDT, June 22, 1974.

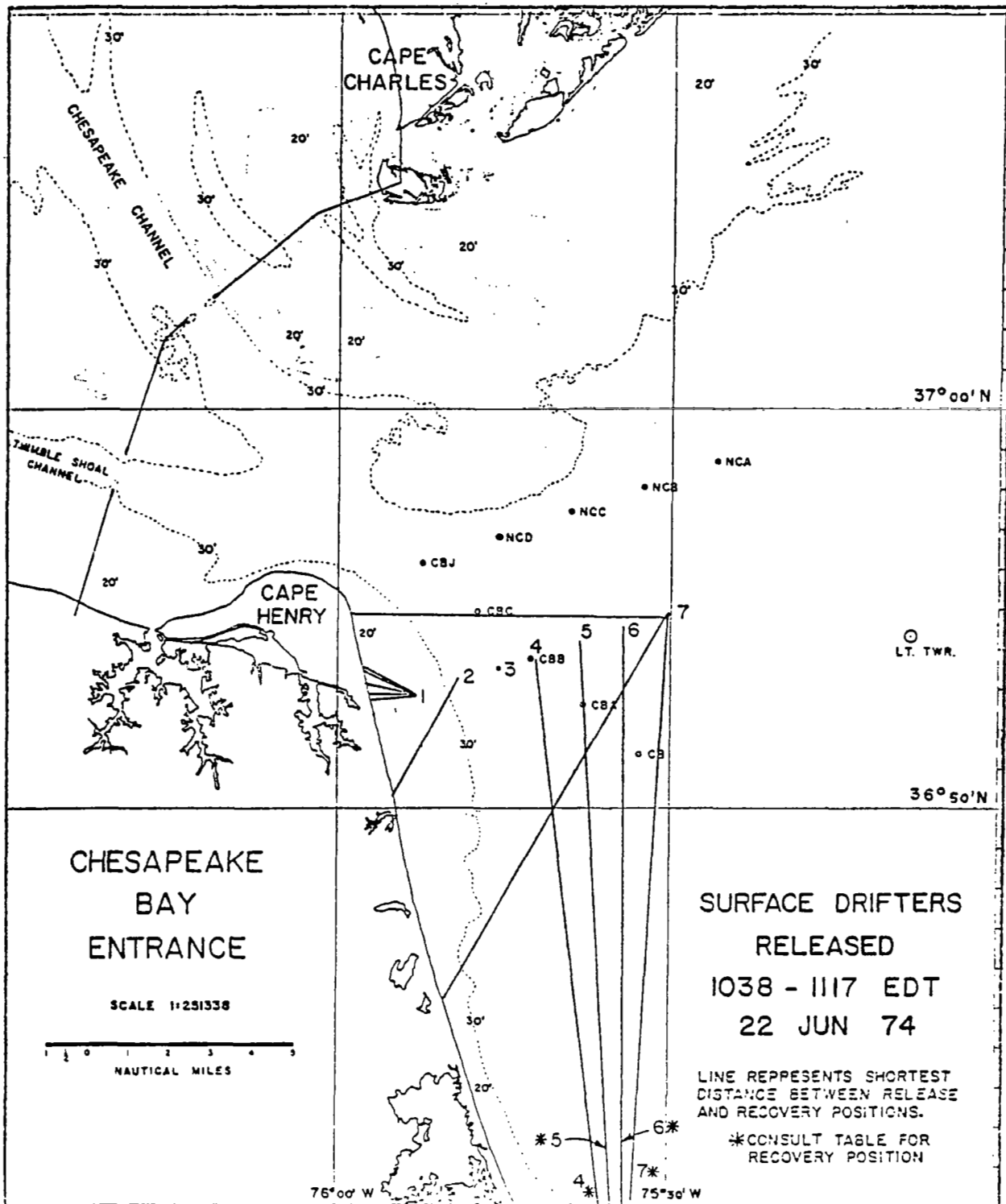


Figure 7.- Recovery positions for surface drifters released 1038-1117 EDT, June 22, 1974.

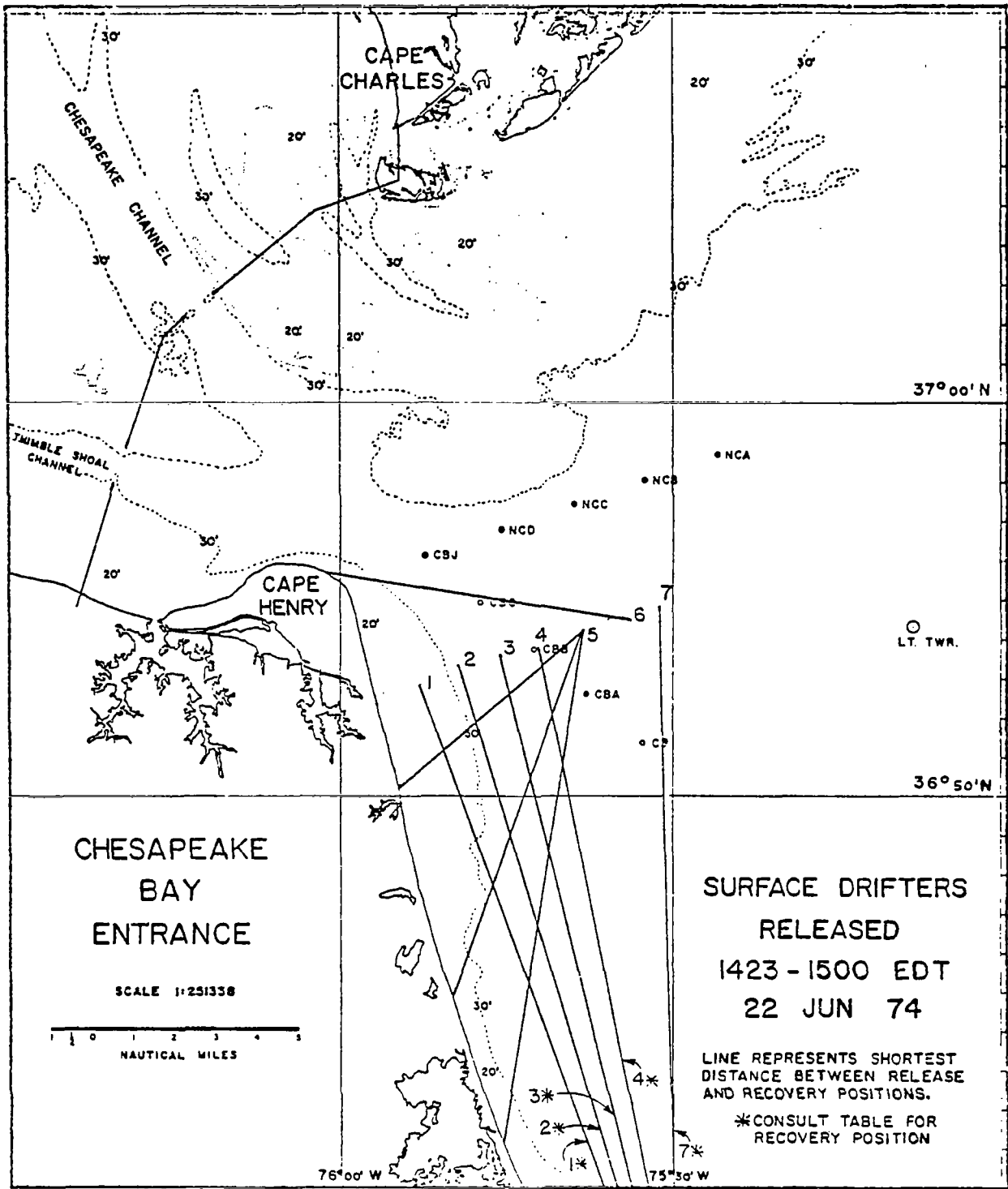


Figure 8.- Recovery positions for surface drifters released 1423-1500 EDT, June 22, 1974.

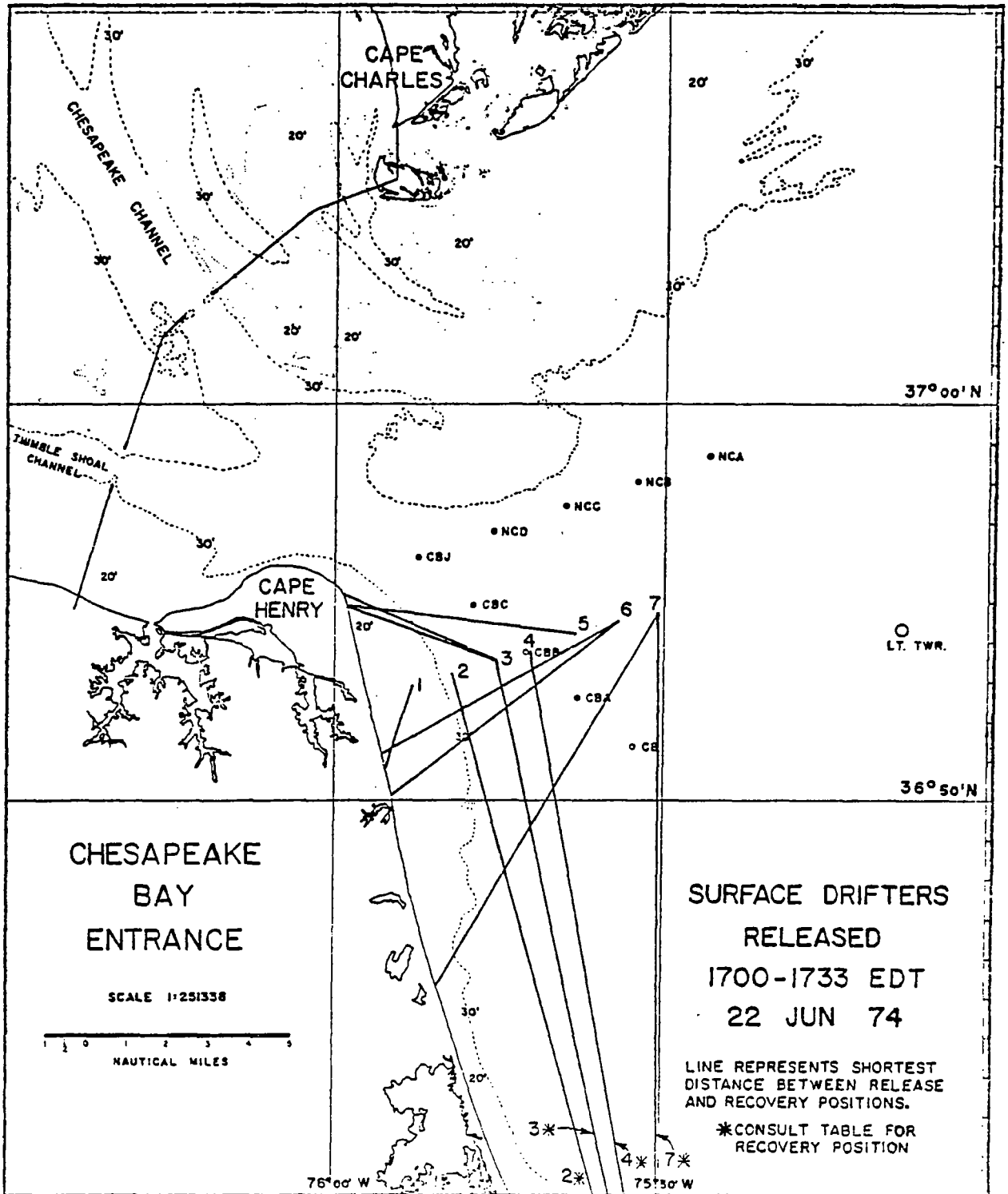


Figure 9.- Recovery positions for surface drifters released 1700-1733 EDT, June 22, 1974.

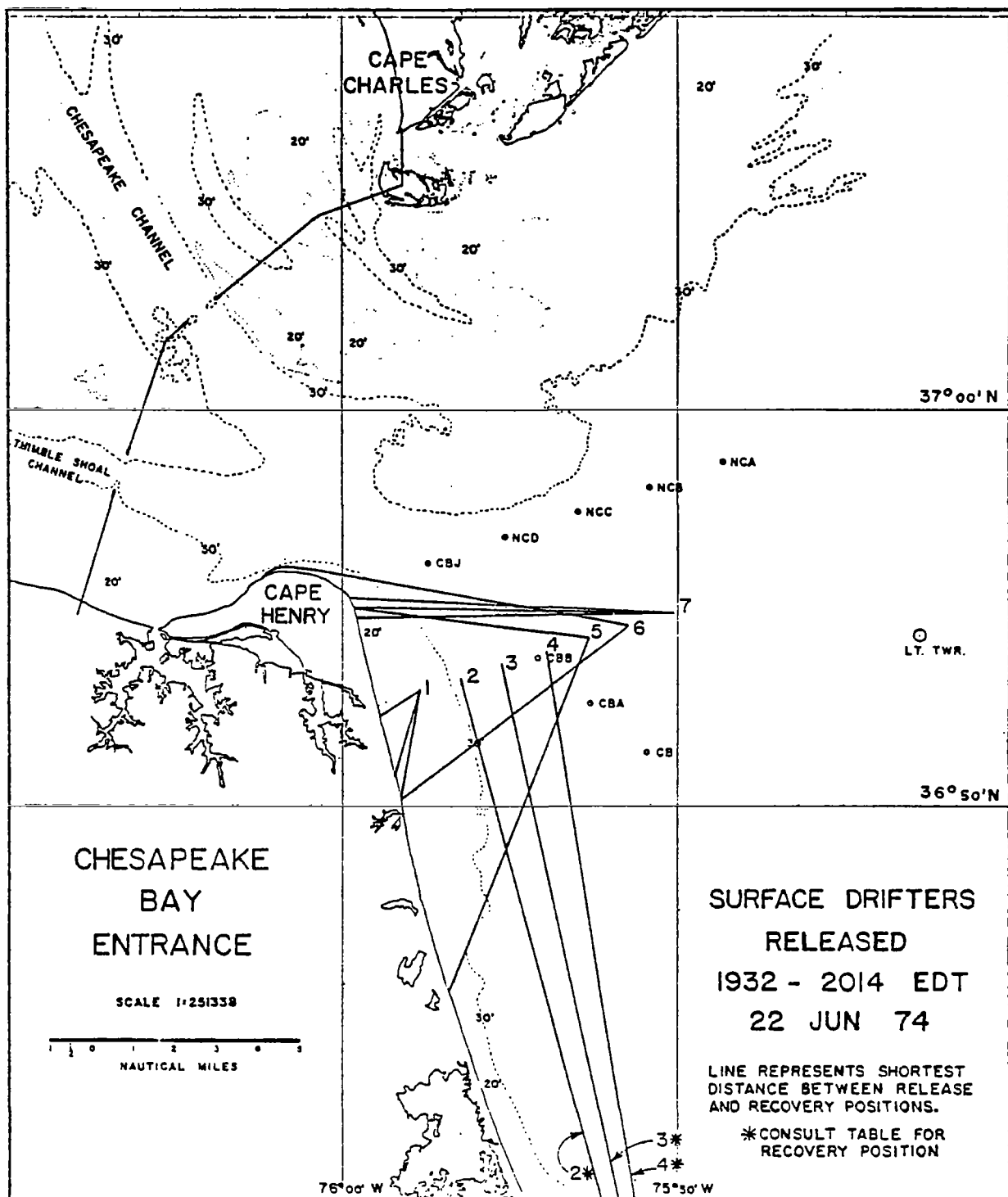


Figure 10.- Recovery positions for surface drifters released 1932-2014 EDT, June 22, 1974.