REMOTE SENSING OF THE CHESAPEAKE BAY PLUME SALINITY VIA MICROWAVE RADIOMETRY

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SUMMARY

The NASA-Langley-developed L-Band microwave radiometer was used to remotely measure sea surface salinity during the March 1980 (Superflux I) and June 1980 (Superflux II) Chesapeake Bay Plume Studies. Obtained measurements of microwave brightness temperatures of the sea surface were combined with measurements of sea surface temperature obtained with an infrared radiometer and inverted to produce corresponding values of sea surface salinity. Results from the plume measurements, which indicate the southward extent of the plume along the Virginia-North Carolina coast, are presented and discussed. Additional measurements obtained for the Delaware Bay Mouth flight on June 17, 1980, and the James River-Shelf flight on June 20, 1980, are also discussed.

INTRODUCTION

The results of several aircraft programs have demonstrated that geophysical parameters such as temperatures, salinity, and thickness of oil spills can be derived from passive microwave measurements with an accuracy that satisfies most user applications (ref. 1). In particular, a technique was demonstrated to remotely measure sea-surface temperature and salinity with a dual-frequency microwave radiometer system (ref. 2). Accuracies in temperature of 1° C and in salinity of 1 part per thousand ($^{0}/00$) for salinity greater than 5 $^{0}/00$ were attained after correcting for the influence of extraterrestrial background radiation, atmospheric radiation and attenuation, sea-surface roughness, and antenna beamwidth. The radiometers, operating at 1.43 and 2.65 GHz, comprise a third-generation system using null balancing and feedback noise injection. This dual-frequency microwave radiometer system was developed at the NASA Langley Research Center for the purpose of obtaining sea-surface temperature and salinity maps of coastal and estuarine areas. As the objectives of the joint NASA-NOAA (NMF) Chesapeake Bay Plume studies were to determine surface extent and concentration of various water quality parameters using synoptic data obtained by remote sensors which could be compared with in-situ-measured sea truth samples, the NASA-Langley microwave radiometer system was flown on-board the NASA-Wallops Flight Center P-3 aircraft during the March 1980 (Superflux I) and June 1980 (Superflux II) experiments to study the Chesapeake Bay Plume surface characteristics. Salinity mappings of the lower Bay area and southward along the Virginia and North Carolina coast were performed to measure the plume extent and movement. These measurements were performed using the L-Band (1.43 GHz) radiometer to measure salinity and an infrared radiometer to measure sea surface temperature. The S-Band (2.65 GHz) radiometer was not used because of the increased amount of radio interference from coastal radar installations at its frequency.

This paper will describe the theory of the radiometric measurement of salinity and the results of the June 1980 measurements. The results of the March 1980 measurement are not available at this time as a data recording problem with the infrared radiometer precludes a timely reduction of that data.

THEORY AND DATA REDUCTION

The measurement technique is based on the principle that matter, when heated to an equilibrium temperature T, will emit electromagnetic radiation, whose spectral dependency is governed by the Planck radiation law.

It has long been known that Earth's atmosphere is essentially transparent to transmission of electromagnetic radiation at frequencies of 1 to 3 GHz. Extensive work over the years on microwave signal propagation through the atmosphere at centimeter wavelengths has indicated that the influence of clouds is small at these frequencies except under very severe storm conditions. An added factor for consideration is that the background galactic noise tends to decrease substantially as frequencies increase beyond about 1 GHz. Therefore, the frequency regime from 1 to 3 GHz is a well-suited choice for minimizing the effects of extraterrestrial background radiation and atmospheric interference.

Despite these advantages, accurate surface temperature measurement by airborne radiometers in this microwave region requires detailed knowledge of these effects for correcting the instrumental observations. The corrections to the measured brightness temperature of the ocean surface can still be on the order of a few kelvins and therefore, must be taken into account. The apparent temperature T_R (which may also be called the equivalent radiometric temperature of the complete set of received radiations) is calculated from the equation of radiative transfer by making use of the Rayleigh-Jeans approximation to the Planck law (as explained in ref. 2) for a measurement in nadir direction.

$$T_R = T_B[1 - \tau(h)] + (1 - e)[1 - \tau(h)][(T_{cos} + T_{gal})(1 - \tau_o) + T_{atm}] + \tau(h)\langle T\rangle + \Delta T_w + \Delta T_p \qquad (1)$$

The first term accounts for the attenuated $[1 - \tau(h)]$ emission (T_B) from the ocean surface. The second term in equation (1) comprises the temperature of the downward radiation of the extraterrestrial noise $(T_{cos} + T_{gal})$ attenuated $(1 - \tau_o)$ by the entire atmosphere, and the downward radiation T_{atm} of the atmosphere itself, reflected $(1 - e)$ by the ocean surface and in turn attenuated $[1 - \tau(h)]$ by the intervening atmosphere between the ocean and radiometer. The term $\langle T\rangle \tau(h)$ is the averaged physical temperature of the intervening atmosphere between the radiometer and the sea surface times the atmospheric opacity $\tau(h)$ for the instrument altitude H. The next term ΔT_w is the apparent temperature contribution due to the sea surface roughness generated by shear forces of the surface winds. The last term ΔT_p is due to the antenna pattern deviating from the ideal "pencil" beam shape.

The brightness temperature T_B is related to the molecular temperature of a radiating surface via the emissivity of the surface. The emissivity of a dielectric surface at a particular wavelength is determined by its complex dielectric constant which for calm seawater is a function only of temperature and salinity. Therefore, the brightness temperature of the sea surface is given by

$$T_B(\lambda) = e_\lambda(T_s,S)T_s \qquad (2)$$

where the emissivity e at the wavelength λ is expressed in terms of surface temperature T_s and salinity S. Plots of brightness temperature as a function of salinity and surface temperature at 1.43 GHz are given in figure 1. The inversion of microwave (L-Band) brightness temperature using the infrared radiometer measurement of surface temperature to salinity is shown graphically in figure 1 and is obtained using derived regression equations.

Although the demonstrated absolute accuracy of the radiometer system is 1 $^0/00$ for salinity (>5 $^0/00$) and 1° C for temperature, the relative accuracy within a given data set is better than 0.5 $^0/00$ and 0.5° C. The spatial resolution of these measurements is given by the antenna beam "footprint" and is one-third of the measurement altitude.

The output data of both radiometers are converted to digital form by a data processor developed at the NASA Langley Research Center. The processor also conditions and formats the housekeeping data from other sources that are necessary for the reduction of the radiometric data, such as flight parameters, time, latitude, and longitude. The data processor is capable of adjusting measurement integration times independent of the radiometer settings. This capability provides an efficient way to adapt the overall integration time to the aircraft altitude and measurement spatial resolution (antenna half-power footprint size).

RESULTS

All the radiometer flight measurements during the June 1980 Superflux II program were made on-board the NASA-Wallops Flight Center P-3 aircraft at an altitude of 152 m and an aircraft speed of 190 knots. As the radiometer antenna footprint or surface resolution cell was 51 m (one-third of the measurement altitude), the resulting measurement time to advance one resolution cell was 0.5 seconds. However, the position data of latitude and longitude which was being recorded from the aircraft inertial navigation system (INS) was up-dated only once every 2 seconds. Therefore, the radiometer measurement data during these series of flights were only sampled and recorded every 2 seconds. The L-Band microwave radiometer had a one-second integration time for the measured data so that the output data was integrated over two resolution cells. With a two-second sampling rate, only every other integrated measurement was sampled. This fact coupled with the wide spacing between flight lines dictated by flight time restraints resulted in a little less than desirable conditions for the radiometric salinity mapping of a geographical area. However, the obtained data did allow for contour mapping of the measured areas as discussed in the following sections of this paper. The experience obtained during these measurements led to the use of a 0.3-second sampling rate for a series of flight measurements which were later made over the fronts of the Chesapeake Bay Mouth area. This faster sampling rate allows for a much finer scale measurement of salinity which can be seen by using time plots of individual flight lines. This removes the restrictions of the up-date time of latitude and longitude from the data reduction. Although the parameters of latitude and longitude were recorded from the aircraft INS, the resulting long term drifts during the 3-hour flights were prohibitive for the accurate mapping of salinity. Errors as large as 2 nautical miles near the end of a particular flight were experienced. Therefore, the obtained salinity data positions were corrected using data as recorded from the on-board Loran-C system. The following is a discussion, in chronological order, of the radiometric flight measurements made during the June 1980 Superflux II missions.

On June 17, 1980, the radiometric measurement of salinity was performed on several flight lines across the mouth of the Delaware Bay between the hours of 6:37 and 7:40 EDT. Also a few lines were flown from the Bay mouth out over the open ocean. The results of these measurements are shown in figure 2 where salinity contours are shown as a function of latitude and longitude. While the amount of data obtained was limited in terms of geographic area size, the obtained contours are sufficient to show that the Bay mouth during this time period (mid flood tide cycle) has lower salinity waters at the southwestern end and higher salinity waters toward the northeastern end. Figure 2 also shows the gradual increase in salinity as you progress outward from the Bay mouth over the open ocean. Also indicated in figure 2 are the locations of several oil spills that were detected by the L-Band radiometer along the open ocean flight lines. These detections were indicated by a sharp step-function type decrease in the L-Band radiometer measured brightness temperature of several degrees Kelvin.

The next mission was flown on June 20, 1980, between 06:04 and 07:42 EDT which was near the end of the ebb tidal cycle. This flight consisted of a flight line down the James River, across the Chesapeake Bay mouth and out over the open ocean to the continental shelf break and return. The results of this mission are shown in figure 3 where representative salinity numbers are shown along the measurement flight line. This figure shows the general increase in salinity as you progress down the James River toward the saltier Bay waters; the salinity increasing across the Bay entrance toward the open ocean with some variations due to the mixing action of the Bay waters; and then the gradual further increase in salinity outward over the open ocean to the continental shelf break.

The overflight radiometer measurements for the Chesapeake Bay Plume were performed on June 23, 25, and 27, 1980. The approximate locations of the flight lines are shown in figure 4. The measurements of June 23, 1980, were performed between the hours of 06:00 and 08:33 EDT which was at the middle of the ebb tidal cycle. The obtained salinity contour lines for this measurement are shown in figure 5. In constructing the salinity contours shown in figure 5 from the measured data some liberty had to be taken in contouring between the flight lines (fig. 4) due to their wide spacing. However, the amount of data obtained was sufficient to allow line-to-line contouring that was representative of the general changes in the surface water salinity and thus outline the Chesapeake Bay Plume extent. As seen in figure 5, the lower salinity Chesapeake Bay water flows out, during ebb tidal cycle, through the lower part of the Bay entrance and southward along the Virginia and North Carolina coast to its southernmost extreme. This body of lower salinity Bay water could be described as a salinity plume by the isohalines of figure 5. Also seen in figure 5 are the higher salinity ocean waters being swept into the Bay entrance at the northern end, due to Coriolis forces, but not extending very far up the inside of the Delmarva peninsula as had been previously measured (ref. 2) as the low salinity waters are seen to extend across the entire Bay mouth.

The measurements made on June 25, 1980 were performed between the hours of 05:53 and 08:51 EDT which occurred at the beginning of an ebb tidal cycle. The results of these measurements are shown in figure 6. The most obvious feature of the salinity contours in this figure is the compression of the lower salinity waters inward at the Chesapeake Bay mouth and the narrow width of the plume along the coast. Evidently this was the result of having just undergone a complete flood tidal cycle. This observation can be seen even more clearly if figure 6 is compared with figure 5 which shows the outflowing of the Bay waters during mid ebb tidal cycle.

The last flight measurement of this area was made on June 27, 1980 between 09:34 and 11:38 EDT which was at mid tidal cycle. This mission, however, did not cover the complete area shown in figure 4 as the most southern flight line for this day was line No. 5. The results of these measurements are shown in figure 7. Because of the shorter area of coverage, only the upper portion of the Bay plume is seen in figure 7 as the lower salinity waters exit the Bay entrance. The southern extent of the plume along the coast was beyond the area of measurement.

CONCLUDING REMARKS

The extent of the Chesapeake Bay Plume was mapped by remote measurement of its surface salinity using an L-Band microwave radiometer during the June 1980 Chesapeake Bay Plume Studies (Superflux II). The obtained measurements of microwave brightness temperature of the sea surface were combined with measurements of the sea surface temperature obtained with an infrared radiometer and inverted using a regression analysis to produce corresponding values of sea surface salinity. The results of these measurements demonstrate the utility of using surface salinity as a descriptive feature for the extent of the Chesapeake Bay Plume and one that can be timely measured by a remote sensor. While it would be desirable to have obtained many more measurements over several tidal cycles and for the different seasons of the year to form a complete data bank of surface salinity measurements for the Chesapeake Bay Plume area, the results obtained, to date, are representative of the Plume and because of the "first time" nature thereby form a benchmark of information which other work or measurements can reference.

REFERENCES

1. Swift, C. T.: Passive Microwave Remote Sensing of the Ocean - A Review. Boundary-Layer Meteorology, vol. 18, 1980, pp. 25-54.

2. Blume, H-J. C.; Kendall, B. M.; and Fedors, J. C.: Sea-Surface Temperature and Salinity Mapping From Remote Microwave Radiometric Measurements of Brightness Temperature. NASA TP-1077, Dec. 1977.

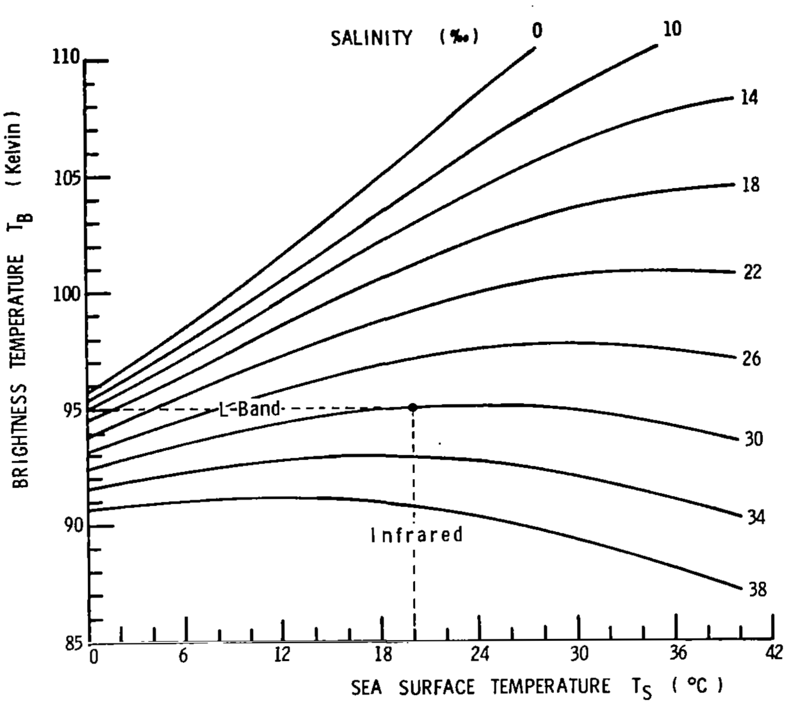

Figure 1.- Brightness temperature at normal incidence versus molecular sea-surface temperature for smooth sea at 1.43 GHz.

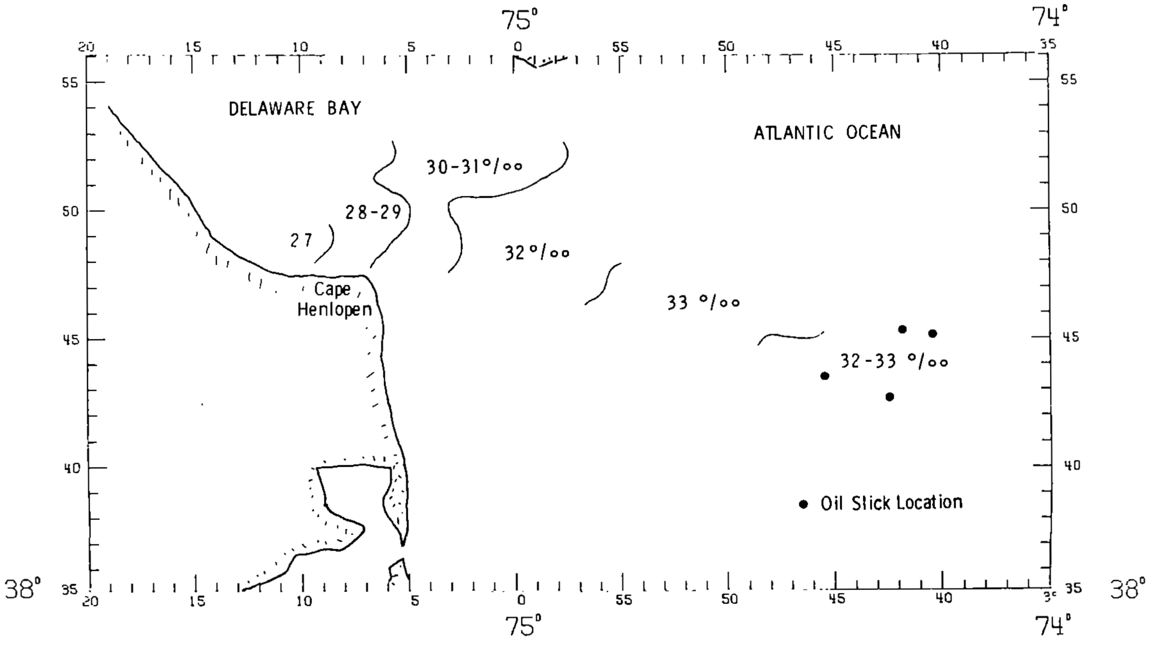

Figure 2.- Salinity map of Delaware Bay Mouth on June 17, 1980 (06:37-07:40 EDT).

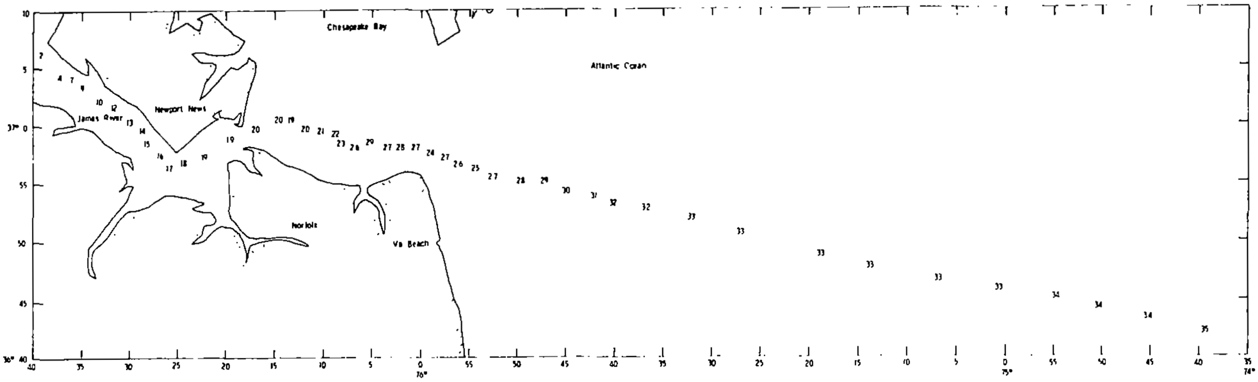

Figure 3.- Average salinity values ($^0/00$) for James River-Continental Shelf Break on June 20, 1980 (06:04-07:42 EDT).

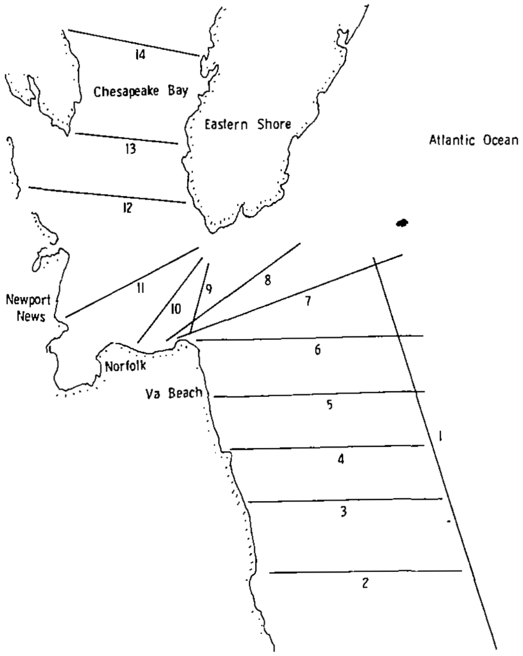

Figure 4.- Flight lines for June 1980 Chesapeake Bay Plume measurements.

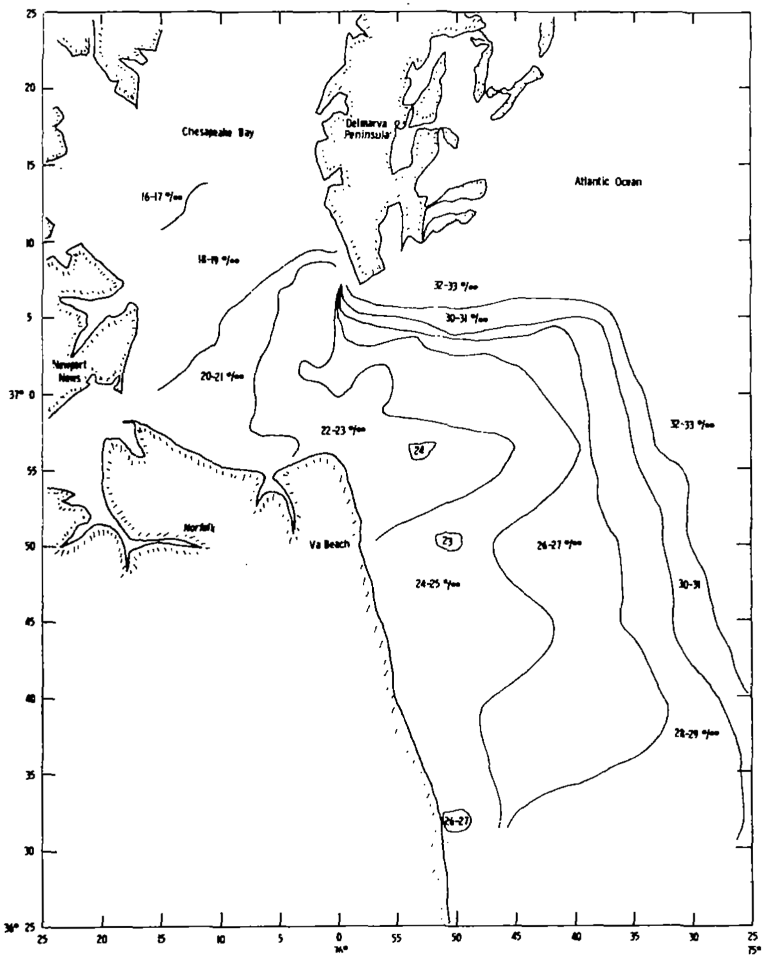

Figure 5.- Salinity map of Chesapeake Bay Plume on June 23, 1980 (06:66-08:33 EDT).

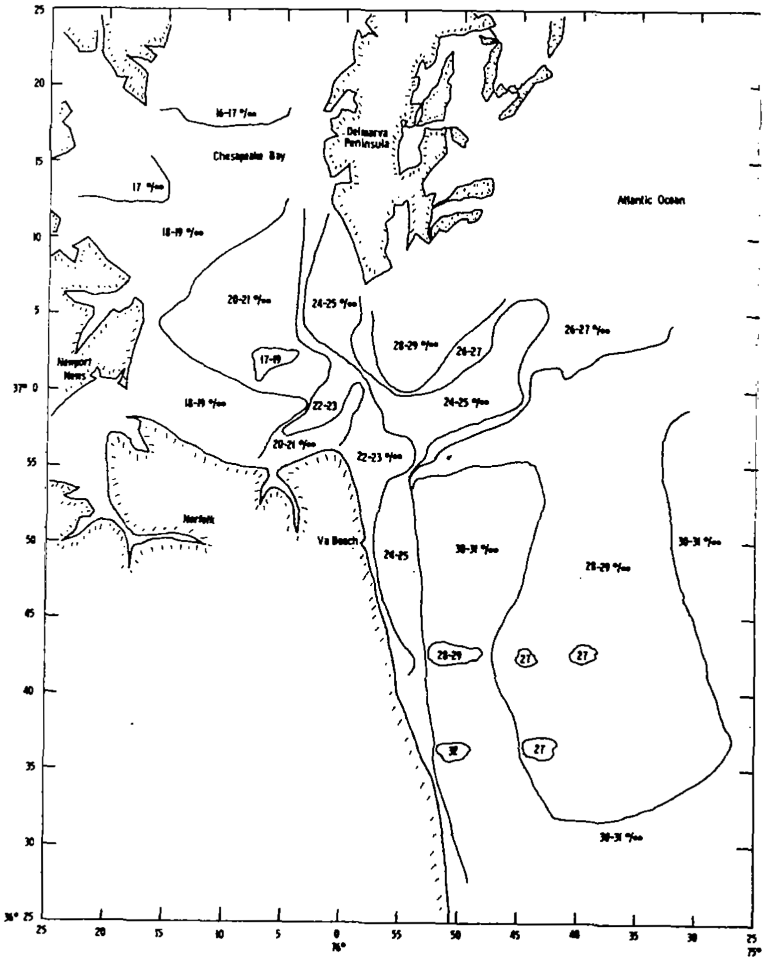

Figure 6.- Salinity map of Chesapeake Bay Plume on June 25, 1980 (05:53-08:51 EDT).

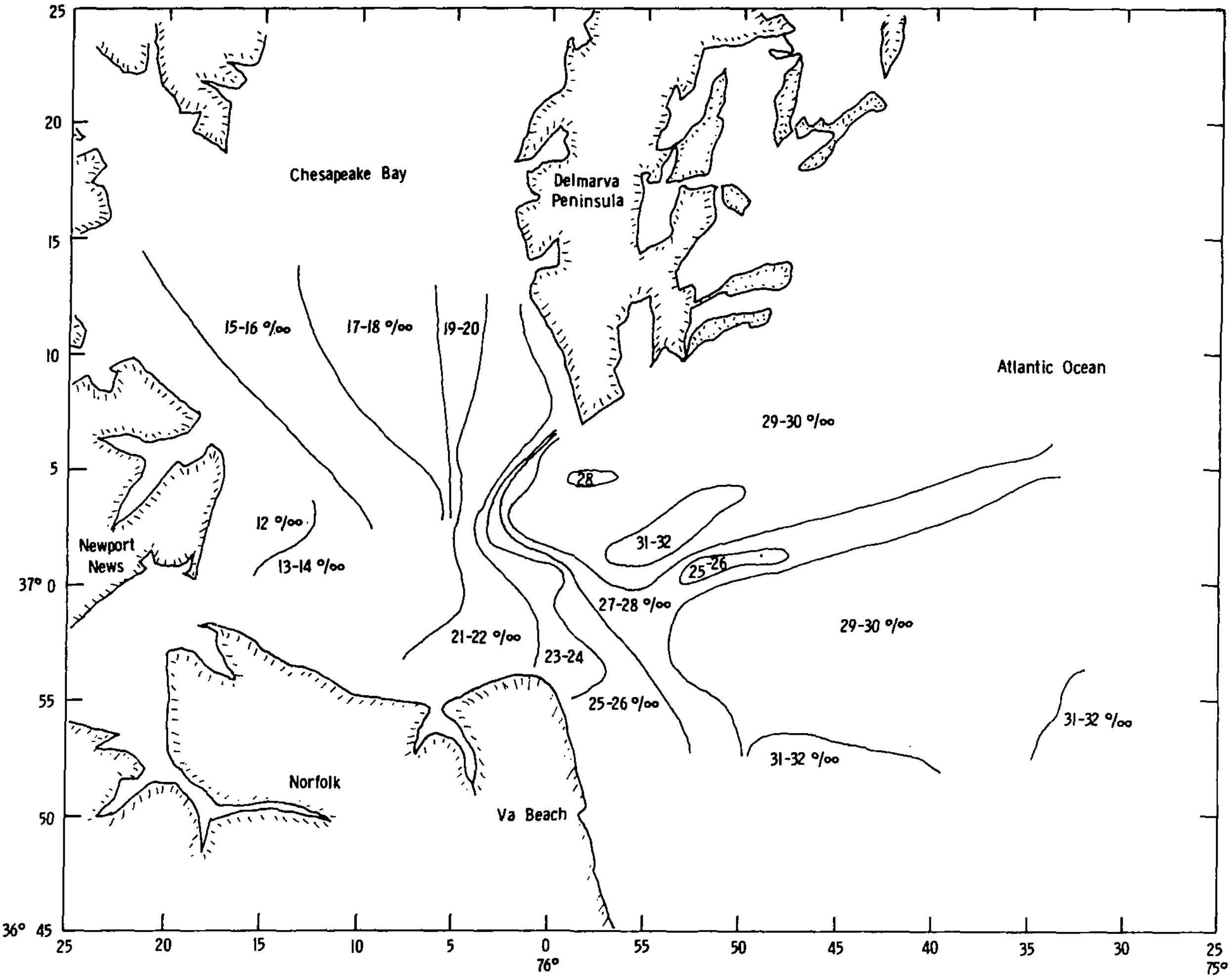

Figure 7.- Salinity map of Chesapeake Bay Plume on June 27, 1980 (09:34-11:38 EDT).