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Use of Aerial Photography with Loran C Positioning to Map Offshore Surface Currents

Dye-emitting tracers were located with an accuracy of ±114 m at distances as great as 300 km from shore

Abstract: *Techniques have been developed for mapping surface currents in the offshore zone using aerial photography. Dye-emitting tracers, resembling spar buoys with color-coded arms and a radio transmitter, are used to track surface currents in the upper metre of the water column. The tracers are relocated by homing on the radio signal and looking for the dye patch, then are photographed using Loran C as the aircraft position reference. Photographic tracer data are digitized and computer-processed to make photogrammetric corrections and display tracer locations in tabular and graphic formats. The total error of tracer locations determined by these techniques is ±114 m. The method has been used to study both large- and small-scale Lagrangian circulation phenomena on the outer continental shelf.*

Introduction

As the outer continental shelf region is increasingly used for oil and gas recovery and remains a viable location for waste disposal, the need to predict the transport of oil spills and floatable wastes becomes more important. These predictions require a knowledge of surface currents, defined as currents in the upper metre of the water column. Surface currents are heavily influenced by wind and frequently decoupled from the flow of underlying water. Because surface currents cannot be accurately measured with moored instrumentation, remote sensing techniques have been applied to their investigation.

Surface currents have been extrapolated from satellite imagery (Klemas *et al.*, 1974) and aircraft imagery and photography (Mairs and Clark, 1973) using turbidity and dye as tracers. Instantaneous velocities have been measured in lakes and the coastal zone by the parallax method (Cameron, 1952; Keller, 1963) involving stereoscopic analysis of floating targets appearing in overlapping aerial photographs. Time lapse aerial photography has also been used to track rafts (Duxbury, 1967), plywood floats (Ramey, 1968), shallow drogues (Cook, 1971), and dye buoys (Munday *et al.*, 1978). Small buoys equipped with radio transmitters have been tracked from shore with direction finding equipment (Whelan *et al.*, 1975), and in a recent development, radar has been used to map surface currents out to 70 km from shore (Barrick *et al.*, 1977).

Difficulties arise in extending these techologies to the outer continental shelf region, which is more than 100 km offshore in many regions. The natural turbidity variations of the coastal zone

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are generally absent offshore, limiting the usefulness of this parameter as a tracer in images or photographs. Both the parallax method and time-lapse photography of floating objects require the presence of fixed reference points, which are plentiful along the coast but not offshore. Ramey (1968) addressed this problem by using a boat, whose position was determined with an electronic navigation system, as a reference point in photographic frames. Aside from requiring a boat, which is expensive to place in the offshore zone, this approach limits the study area to the vessel's immediate vicinity. The use of radio-tracked buoy systems enables synoptic measurement of surface currents over large areas. However, the accuracy of locating a free drifting buoy by this method decreases with distance from shore to about ±1.7 km at a range of 100 km. This accuracy is insufficient to resolve small scale (2 to 5 km) circulation features which may be important near frontal zones.

This paper describes a technique developed to overcome the limitations of previous methods for measuring surface currents in the offshore zone. The technique involves aerial photographic tracking of small dye-emitting, radio-equipped tracers by using Loran C for positioning. From 60 to 100 aircraft-deployed tracers can be tracked for several days in a 25,000 km^2 area, with tracer positions determined to an accuracy of ±114 m. Associated data processing includes digitizing the photographic tracer information and using a computer to make photogrammetric corrections and display the results in various graphical and tabular formats.

The paper is organized to address the basic problem areas inherent in an offshore surface current tracking study, namely tracer relocation, positioning, logistics, and data processing. These sections are followed by an evaluation of system performance to data.

Tracer Design and Relocation

Any surface current tracer must respond to currents in the upper metre of the water column and have a minimal exposure in order to limit effects of direct wind stress. To enable aerial photographic tracking in the offshore zone, tracers must be relocatable at one- to three-day intervals and be uniquely identifiable in the photographs. The need to rapidly distribute the tracers over broad areas in order to initiate a study requires that they be aircraft-deployable.

The surface current tracer developed to meet these requirements, shown in Figure 1, consists of a 132-cm long, 9-cm diameter polyethylene cylinder with four radiating flat arms. The cylinder floats vertically like a spar buoy and is ballasted such that the 20- to 60-cm arms are located a few cm below the water surface. The polyethylene arms function as a rotochute during aerial deployment, which slows descent and orients the tracer, and they are color coded to provide each tracer with a unique identification.

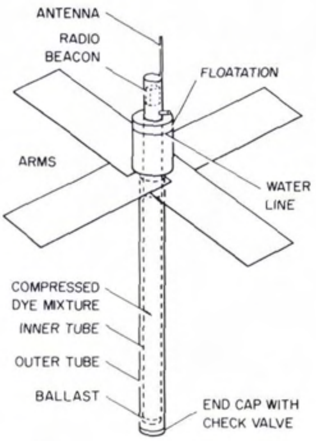

FIG. 1. The Lagrangian tracer developed for the offshore surface current studies.

Housed inside the outer cylinder is an inner tube filled with a mixture of fluorescein dye, polyethylene glycol, and oleic acid. A check valve, activated by wave action, creates a flow of water from the tracer bottom upward between the two cylinders. As the water flows upward, it dissolves the semi-solid dye mixture exposed by slits in the inner cylinder. The water with entrained dye exits just below the arms and creates a green patch surrounding the tracer, which aids in aerial relocation. The tracers are packed with sufficient dye mixture to last three to seven days depending on sea conditions. The proportions of fluorescein dye, polyethylene glycol, and oleic acid are adjusted to provide a uniform rate of dissolution at different water temperature ranges.

The primary aid to tracer relocation is a VHF radio beacon housed in the uppermost part of the tracer body. These beacons, similar to emergency location transmitters used by aircraft, can use one of six different frequencies, with one of six audio codes available with each frequency. Different frequency-code combinations provide up to 36 unique signals. The beacons will operate for up to two weeks and can be detected from distances of 30 to 80 km, depending on aircraft altitude.

Field tests were performed to determine the tracer leeway, defined as tracer motion caused by direct wind stress on the upper 20 cm of the cylinder exposed to air. The tests demonstrated that the tracers slip downwind through the water at 0.5 percent of the wind speed. This is comparable to the leeway of other surface current tracking devices such as drogued buoys. In the absence of strong winds, the tracers follow surface currents with reasonable accuracy.

Additional information on tracer design is given by Cook *et al.* (1980).

Positioning

Positioning of the survey aircraft used for tracer tracking is accomplished by using the Loran C system. The U.S. Coast Guard-operated Loran C network provides good groundwave coverage off the eastern coast of North American, including the Georges Bank area off New England where the surface current measuring system described in this paper has been used. Loran C has a nominal accuracy of ±1 m per kilometre range in the groundwave region, which is superior to accuracies presently attainable with the Loran A and Omega marine navigation systems.

Two aircraft-mounted units have been used to sense the Loran C signals and compute positions: the Internav Model 123 and Teledyne TDL711.

The Internav system, originally designed for marine use, was converted for aircraft by making some minor changes, resulting in an increased tracking speed and an improved signal-to-noise ratio. The Internav has the capability of tracking up to four secondary stations while displaying any two of them. A coordinate converter can be integrated with the system, which converts the time delay data into latitude and longitude. However, the converter was not used because the raw time delay data provided more accurate positions and the unit took up valuable space in the air craft. A problem encountered with the Internav was the loss of tracking during tight circling maneuvers. When this occurred, the aircraft was flown slowly in a straight line until the signal was regained.

The Teledyne TDL711 is a new system designed for aircraft use. It tracks two secondary stations, displays position as latitude-longitude or time delay data, and updates once a second. Because the TDL711 was designed for aircraft, it is small, lighter, and does not lose track of the Loran C signal during tight maneuvers. Additionally, it has the capability to store up to nine predetermined waypoints and make navigational computations. These computations include the course between two waypoints; distance from the predetermined course and heading to intercept the course; ground speed; and estimated time to the next waypoint.

Both the Internav and Teledyne systems are checked during each data collection flight by using any object plotted on a nautical chart and easily identifiable from an aircraft. As the aircraft passes over the object, the time delays are recorded and plotted to ensure that the system is tracking the Loran C signal properly.

Logistics

A Cessna Skymaster Model 337-G aircraft has been used for tracer tracking. The Skymaster is a high wing monoplane with engines at the forward and aft ends of the fuselage and a twin boom-type tail. It has a cruise speed of 313 km/h, a range of 2200 km, and is equipped with full civilian navigation and communication equipment. This includes a homing system keyed to the tracer radio beacons. In the survey configuration, the aircraft can accommodate a maximum crew of four. Advantages of the Skymaster for tracer tracking include excellent visibility to the sides and downward coupled with the speed and range.

In addition to the previously-described Loran C positioning system, survey equipment includes aerial cameras and a data panel. Tracer positions are recorded with two vertically mounted Hasselblad MK-70 photogrammetric reseau cameras. One camera is loaded with Kodak 2448 color positive film and the other is loaded with Kodak 2445 color negative film. This not only provides a back-up, but aids in tracer identification because certain color codes may be more distinguishable on one or the other film types.

The MK-70 cameras have a distortion-free 70-mm lens and a reseau plate with a 1 cm by 1 cm grid calibrated to within a few micrometres. Bulk film magazines have been adapted to the cameras to provide about 500 exposures without reloading. The panel contains a gyro-horizon for vertical reference, a direction gyro, a wet compass, a magnesyn compass, a pressure altimeter, a Loran C display, and a clock with a digital second counter. Synchronous with firing of the vertical cameras, the data panel is photographed with a Hasselblad 500-EL camera.

Tracer tracking is accomplished by initially homing on the radio beacon in order to bring the aircraft to the immediate vicinity of the tracer. The tracer location as marked by the dye patch is then identified visibly by the aircraft crew. Once located, the aircraft flies over and photographs the tracer to record its position. The photographer uses a drift sight affording both forward and vertical visibility to guide the pilot and ensure that the tracer is within the field of view before triggering the vertical cameras. Plate 1 shows an example of a set of photographs documenting a tracer sighting. Deployment of tracers has been accomplished using planes ranging in size from a Cessna Skywagon to a Douglas DC-3.

The offshore surface current studies performed to date have included long-term investigations of local circulation near frontal zones and longer studies of regional circulation. The short term investigations have involved deploying about a dozen tracers across a frontal zone and recording tracer locations at 15 to 30 minute intervals for a few hours. Processes of interest include convergence, shearing, and Langmuir circulation. The longer studies have been directed at evaluating non-tidal circulation over areas as large as 160

(a) (b) (c)

PLATE 1. Photographs used to document tracer locations: (a) vertical photograph of tracer on color positive film, (b) the same tracer on color negative film, and, (c) the data panel photographed synchronously with the tracers.

by 160 km. In these, 60 to 180 tracers have been distributed in up to six lines or L-shaped patterns 20 to 30 km long. Relocation flights have then been scheduled daily for the first few days and then on alternate days. About 80 to 90 percent of the beaconed tracers deployed have been relocated on the first few days of a regional study, after which the relocation rate drops off as the tracers disperse and beacon batteries weaken. These studies usually last seven to eight days.

Additional information on survey logistics is given in Flynn and Cook (1978).

DATA PROCESSING

With the data acquisition system described above, tracer information is contained on photographic film recorded by the aerial and data panel cameras. After developing this film, the aircraft flight track is plotted from the Loran C data in order to ensure that the indicated positions are consistent. The films are then placed on a light table and, for each set of synchronous frames, the following information is digitized: tracer positions (relative to key reseau marks) and identifications, aircraft flight data (roll, pitch, heading, and altitude), time, and latitude-longitude coordinates (converted from Loran C data with a minicomputer). The digitized data, contained on punched paper tape, are processed on a CDC Cyber 174 computer which calculates actual tracer positions. These calculations are made using geometric relationships to first determine photograph scale and orientation, and then adjust for displacement of the tracer from the recorded Loran C position as projected on the water surface. Potential error sources associated with the computed tracer positions and the resulting position uncertainties include the following:

• Resolution of heading indicator	±	3m
• Resolution of aircraft pitch-roll indicator	±	5m
• Resoluton of aircraft altimeter	±	20m
• Camera film distortion	±	<1m
• Lack of synchronization between triggering cameras and Loran C position updating	±	51m
• Loran C accuracy	±	100m

These errors are estimated based upon the survey aircraft operating at a speed of 51 m/sec and an altitude of 305 m, and the Loran C system updating at once per second.

The Loran C error varies depending on the geographic area and distance from shore; the value of 100 m is typical for the Georges Bank area where the surface current studies have been performed. With these accuracies, the total error (Fisher, 1915) of the system is ±114 m and thus is dominated by the Loran C error.

Outputs of the computer processing include the following three data products:

- A listing is generated for each individual tracer showing the date, time, position, photographic frame, and extropolated speed (since the last observation) associated with each sighting.
- A plot is made of tracer trajectories with individual tracer positions connected by straight lines and annotated with dates and times of, and extrapolated speeds between, sightings.
- When creation of a photo-mosaic is desired, a plot is produced showing the margins of the area covered by each photograph annotated with the frame identification number.

An example of the trajectory plot appears in Figure 2, and Figures 3 to 5 demonstrate how the tracer data can be used to illustrate circulation phenomena of interest.

Figure 3 shows tracer trajectories observed over Georges Bank during two large-scale studies in the winter of 1978. The trajectories reflect a general southeast wind drift superimposed on a flow directed clockwise around the north, east, and south sides of the Bank. The opposing trajectories on the southwestern portion of the Bank appear to

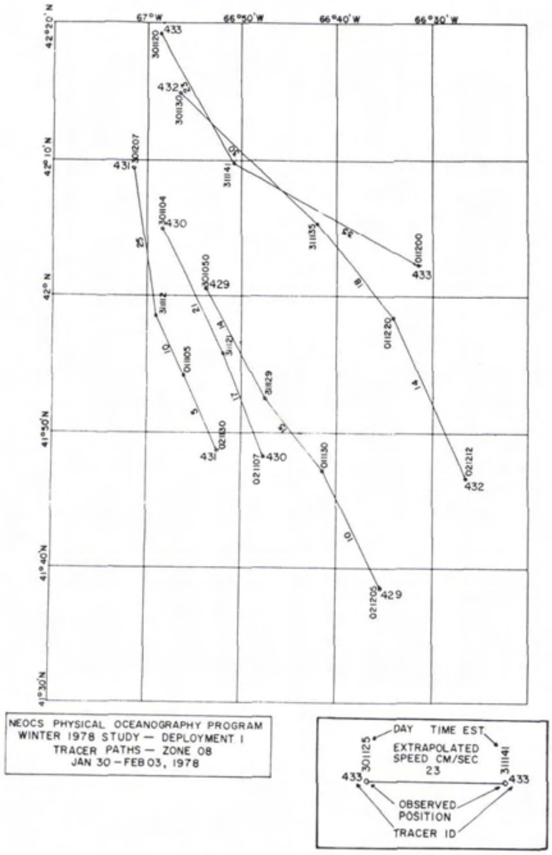

FIG. 2. Example of a tracer trajectory plot.

be real and result from a local intrusion of slope water. This figure demonstrates the large geographic area which can be examined with the surface current technology described in this paper.

Figure 4 illustrates tracer trajectories observed when a Gulf stream eddy was impinging on the southwestern flank of Georges Bank. Tracers within the eddy rotated clockwise up to 90 km in a day, whereas those beyond the eddy margin moved at much lower speeds. These warm-core eddies may contribute significantly to the exchange between shelf and slope waters off the northeastern United States.

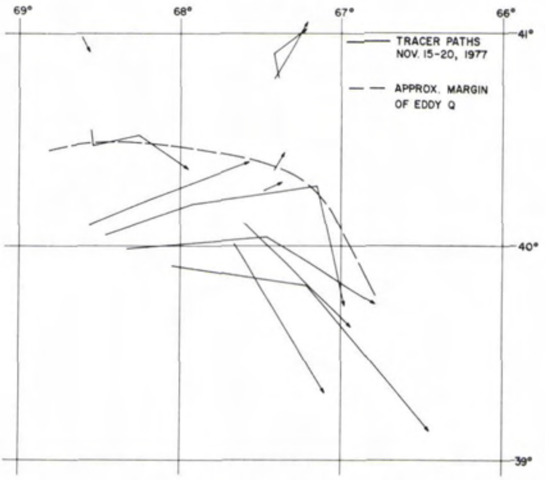

FIG. 4. Tracer trajectories at Gulf Stream eddy Q from 15 to 20 November 1977.

Figure 5 demonstrates small-scale tracer motion in the presence of a shear along the northern flank of Georges Bank. Tracers deployed towards the northwest, in deeper water, were carried northeast to east by a non-tidal current flowing parallel to isobaths. Those deployed towards the southeast, on the bank margin, underwent clockwise transport by rotary tidal currents. Such shear zones frequently delineate water mass boundaries and areas of upwelling or downwelling.

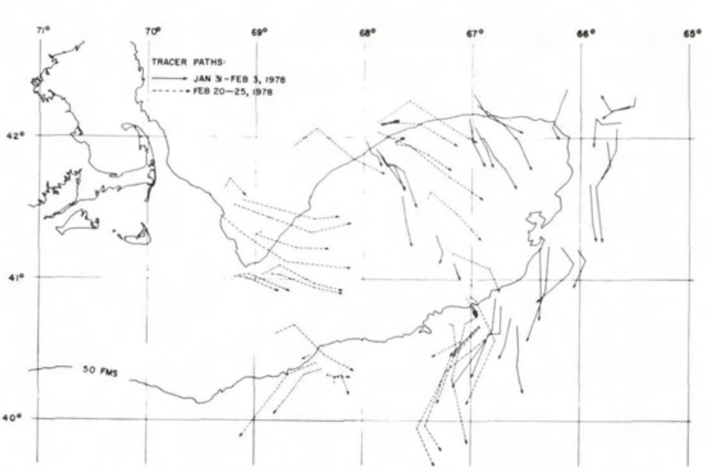

FIG. 3. Tracer trajectories observed over Georges Bank during 31 January to 3 February and 20 to 25 February 1978.

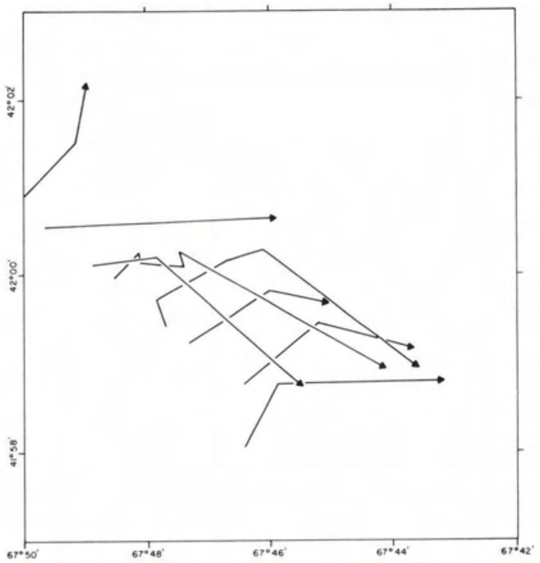

FIG. 5. Tracer trajectories in the presence of a shear zone along the northern flank of Georges Bank on 9 February 1978.

CONCLUSION

The aerial photographic techniques described in this paper represent a viable approach to the previously unresolved problem of collecting synoptic and accurate surface current data over large areas of the continental shelf at distances from shore exceeding 100 km. Collection of comparable data using surface vessels would involve a large number of ships and an inordinate expenditure of funds. By comparison, aerial methods allow tracking of dozens of Lagrangian tracers over areas exceeding 25,000 km^2 for up to several days, using one aircraft for tracking and a second only for initial deployment.

The surface current circulation data can be applied to practical problems such as prediction of spilled oil or other pollutant transport. Thus, the mapping techniques are potentially important to long-term management of outer continental shelf resource development. Also, the aerial techniques can be used for basic research on mixing across frontal zones and other physical processes with a surface expression in shelf waters.

ACKNOWLEDGMENTS

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REFERENCES

Barrick, D. E., M. W. Evans, and B. L. Weber, 1977. Ocean surface currents mapped by radar. *Science* 198:138-144.

Cameron, H. L., 1952. The measurement of water current velocities by parallax methods. *Photogramm. Eng.* 18:138-163.

Cook, D. O., 1971. Evaluation of estuarine circulation by aerial photography of current drogues. *Proc. 7th Mar. Technol. Soc. Conf.* pp. 663-670.

Cook, D. O., J. W. Richardson, T. L. Flynn, and K. J. Berger, 1980. Design of Lagrangian surface current tracer. *Limnol. Oceanogr.* 25:1123-1127.

Fisher, A., 1915. *The mathematical theory of probabilities and its application to frequency curves and statistical methods:* McMillan Company, New York, N.Y.

Flynn, T. L., and D. O. Cook, 1978. Charting of outer continental shelf surface currents by aerial tracking of tracers. *Proc. Oceans '78 Conf.*, MTS-IEEE, pp. 315-320.

Keller, M., 1963, *Tidal current survey by photogrammetric methods.* U.S. Coast Geodetic Surv. Tech. Bull. 22, 20p.

Klemas, V., M. Otley, W. Philpot, C. Wethe, R. Rogers, and N. Shah, 1974. Correlation of coastal water turbidity and current circulation with ERTS-1 and Skylab imagery. *Proc. 9th International Symposium on Remote Sensing of the Environment*, pp. 1289-1317.

Klemas, V., G. Davis, H. Huang, W. Whelan, and G. Tornatore, 1975. A cost-effective satellite-aircraft-drogue approach for studying estuarine circulation and shelf waste dispersion. *Proc. Oceans '75 Conf.*, IEEE, p. 751-759.

Mairs, R. L., and D. K. Clark, 1973. Remote Sensing of estuarine circulation dynamics. *Photogramm. Eng.* 39:927-938.

Munday, J. C., Jr., C. S. Welch, and H. H. Gordon, 1978. Outfall siting with dye-buoy remote sensing of coastal circulation. *Photogramm. Eng. and Remote Sensing* 44:87-96.

Ramey, E. H., 1968. *Measurement of ocean currents by photogrammetric methods.* U.S. Coast Geodetic Surv. Tech. Memo. C & GSTM-5, 18p.

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