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CODAR in the Straits of Florida: Final Report

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ABSTRACT. The Atlantic Oceanographic and Meteorological Laboratory (AOML) operated a Coastal Ocean Dynamics Applications Radar (CODAR) from 1986 through 1988 in a project to measure ocean surface currents near Miami and produce a series of maps of ocean surface current vectors. The project, CODAR in the Straits of Florida, also evaluated the feasibility and value of routine operational use of this HF radar system. The CODAR system produced many excellent maps that showed the west and central portions of the Florida Current. The core speed of this rapid flow, its distance offshore, and the often sharp decrease in speed nearshore were apparent. In addition, the maps showed at times a band of water nearshore that was moving slowly southward along the coast, and sometimes a cyclonic eddy about 15 km in diameter that was centered in a nearly fixed location 20 km northeast of Miami. However, on the whole this CODAR system could not be used as the project planned. The system required excessively frequent maintenance to remain on line. More significantly, the maps produced were inadequate for the intended uses, and too many maps were missing. The maps frequently contained too few current vectors, and, without further computer editing, many of the vectors that did appear were grossly incorrect. With added direction editing, major features of the circulation were omitted, and even fewer vectors remained on the maps. Examination of several CODAR maps and the calculated data from which they were produced showed certain limitations of the contractor-supplied data analysis procedure. Various interferences in the antenna voltage readings led to erratic radial velocity readings. In addition, the type of radial velocity combining procedure used was inaccurate with the sometimes erratic data. The concept of a fully automatic system to produce valid CODAR results was not realized in the version of the CODAR system that the project evaluated. In a suggested alternative calculation technique, the assimilation of CODAR data into a numerical model should result in many more maps with few missing data points in the coverage area. This CODAR system might then furnish results equivalent to those from several previous studies that gave valuable information on ocean circulations.

1. INTRODUCTION

1.1. CODAR Overview

CODAR, an acronym for Coastal Ocean Dynamics Application Radar, produces radar measurements of ocean surface currents. A radio transmitter sends pulses of HF radio waves over the ocean surface, and a portion of the radio energy is reflected to the radar by a particular ocean wave component, the Bragg wave, having a wavelength one-half that of the radio waves and oriented perpendicular to the direction of radio wave propagation. The Doppler shift of the returned radio signal indicates the speed of the ocean wave form. When the readily calculated (deep water) phase velocity of those ocean waves is subtracted, the radial component of the ocean current at the location of radio wave reflection remains. Combination of radial components from two separated CODAR stations gives the total surface current field.

In a narrow-beam radar system, the signal is calculated as having arrived from a particular direction, and the radial component of the ocean current is calculated directly from the radar Doppler shift, whereas in a broad-beam system (CODAR) the direction of signal at each Doppler shift is deduced from the signals on different antennas. In either case, the entire area within radar range can be covered at one time. The radial components and spectra of the original measurements may be retained for performance evaluation.

Ground-based HF radars are usable for nearshore ocean current monitoring over significant areas, since the HF radio waves, properly transmitted, can follow a curved surface duct in the lower atmosphere over the ocean and attain ranges of 30–100 km. These ranges are much greater than the ranges of radio waves that propagate nearly in the line of sight, as do those from microwave radars. On the other hand, HF radars cannot be used from space, partly because their radio waves often cannot penetrate the ionosphere at useful angles of incidence, whereas microwave radars are recognized as having the potential to measure ocean currents from space.

A CODAR system produces maps of ocean surface currents said to contain as many as 500 vectors in 100 x 100 km^2 areas within 60 km of the stations (Barrick et al., 1985). It gives simultaneous measurements of water speed and direction in the many locations at an effective depth in the water of 1/2 m (Barrick, 1986). New maps can be produced at intervals of $\geq$1 hour.

These radar current maps are particularly useful in measuring surface currents and their changes with time at desired remote locations. They also identify locations with distinctive features of the surface current patterns. By showing the full current field, the maps depict entire current structures and follow their development. These maps help one to understand causes of the observed currents and their variations at the specified locations.

1.2. CODAR and This Project

A NOAA scientist, Donald Barrick, acted on earlier clues from the reflection of radio waves by the ocean and became the primary developer of an operating system to make HF radar measurements of the ocean (Barrick and Evans, 1976; Barrick and Lipa, 1979; Lipa and Barrick, 1983; Georges, 1984). Several studies demonstrated the accuracy and coverage of such HF broad-beam systems (Barrick and Lipa, 1983; Frisch and Weber, 1982; Janopaul et al., 1982). By 1984, the CODAR technique had been well established. A 1985 workshop of the American Radio Science Meeting led to a special issue of the *IEEE Journal of Oceanic Engineering* (IEEE, 1986) in which several studies of HF radio measurements of the ocean were reported. These articles showed that not only was the United States making major progress, but also several other countries had active and successful HF radar programs for ocean measurements.

The CODAR technique seemed ready for routine operational use, but its use needed to be demonstrated. The project CODAR in the Straits of Florida was developed to test the feasibility of its operation and to evaluate the value of the maps to routine users. The principal objective of the project was "to establish a demonstrational CODAR measurement capability on the southeast Florida coast which will enable NOAA to generate and disseminate specific sea surface measurement products on a routine and continuing basis."

This report describes the 3-year (1986–1988) experiment and presents its basic results. Most of the CODAR maps were produced by a system provided by CODAR Ocean Sensors Ltd. (COS); the operating group at the Atlantic Oceanographic and Meteorological Laboratory (AOML) had neither a capability to modify the performance of the system nor complete information on how the system functioned. After the experiment the AOML group reprocessed the radial velocity data into a modified map product; this product and the comparison with the original product were analyzed to show several aspects of the CODAR system performance. This report evaluates maps from the CODAR system as it was provided and compares the performance of CODAR with that of other such systems. The possibility is discussed of producing improved surface current maps from CODAR if the system were modified.

2. PERFORMANCE

2.1. Project Organization

The CODAR in the Straits of Florida project called for the collaboration of several groups. AOML was to assist in the equipment installation and operate the CODAR system in the planned first phase of the experiment. AOML would then use the CODAR current measurements for ocean research. The Miami Weather Service Forecast Office (WSFO) was to disseminate the ocean current maps and their information as well as sea state data. The U.S. Coast Guard (USCG), 7th District, was to use the ocean current data in a USCG computer for search-and-rescue (SAR) planning. The National Ocean Service (NOS) was to manage a contract with an outside contractor to refurbish, set up, make operational, and maintain the total system. The Wave Propagation Laboratory (WPL) also contributed to this experiment.

The CODAR product was to consist of ocean surface current maps and ocean wave parameters at 3-hourly intervals in real time through telephone transmission of the remote-site radar data to a CODAR computer at the central site at AOML. The contractor would set up the system at designated remote sites and operate it for 2 months. Then the system would be operated by the National Weather Service (NWS) at the Miami WSFO office for another 10 months. If deemed successful, a permanent arrangement for continued operation would be made at that time. Tests with drifting transponders would evaluate the accuracy of the radar current measurements.

The north CODAR site was on Naval Surface Warfare Center (NSWC) ocean-front property at Ft. Lauderdale. The south site was on USCG property on Fisher Island in Miami. USCG provided the site and electricity for the south-site system. The antenna there was on the south jetty of the entrance to the Miami harbor. The jetty was owned by the U.S. Army Corps of Engineers, which allowed our temporary installation of an antenna. Access to that site was through private property owned by Island Developers, Ltd., which provided regular ferry service and allowed our passage through its property.

The contract was let to CODAR Systems Inc. (CSI) in 1985 to set up the CODAR system and maintain it for 1 year. Specifications for measurements of currents and waves, and provision for transponders was included in the contract. The wave values specified were the minimum accuracies for the wave product to be of use.

2.2. System Installation

Although the two remote-site locations had been selected in earlier planning, CSI chose the exact positions of the antennas at those sites for suitable radio transmission characteristics. CSI refurbished the existing electronics and replaced the existing four-element antennas with CSI-designed crossed-loop antennas (Fig. 1). CSI replaced the computer programs throughout the CODAR system with programs applicable to the new type of operation that differed significantly from the previous one. CSI installed programs so that the remote computers transmitted the results of each CODAR run by telephone to the central-site computer. AOML supplied an equipment van at each of the two remote sites and the auxiliary equipment. After installing the electronic equipment, CSI calibrated the antenna patterns at each remote site. Finally, it ensured that the total system functioned as planned.

The new programs for crossed-loop operation were proprietary to CSI, and in general only their overall operation could be known by us. However, CSI freely made some of these programs available to us so that we could investigate certain aspects of the system operation.

2.3. System Operation

Progress Report No. 1, *Site Reconnaissance and Minutes of First Project Meeting*, dated December 1985 (available from the authors of the current report), was furnished by CSI. In March 1986, CSI began operation of the newly installed CODAR system with computer programs that had been modified for the high speeds of the Florida Current. These programs had not been fully debugged, and the

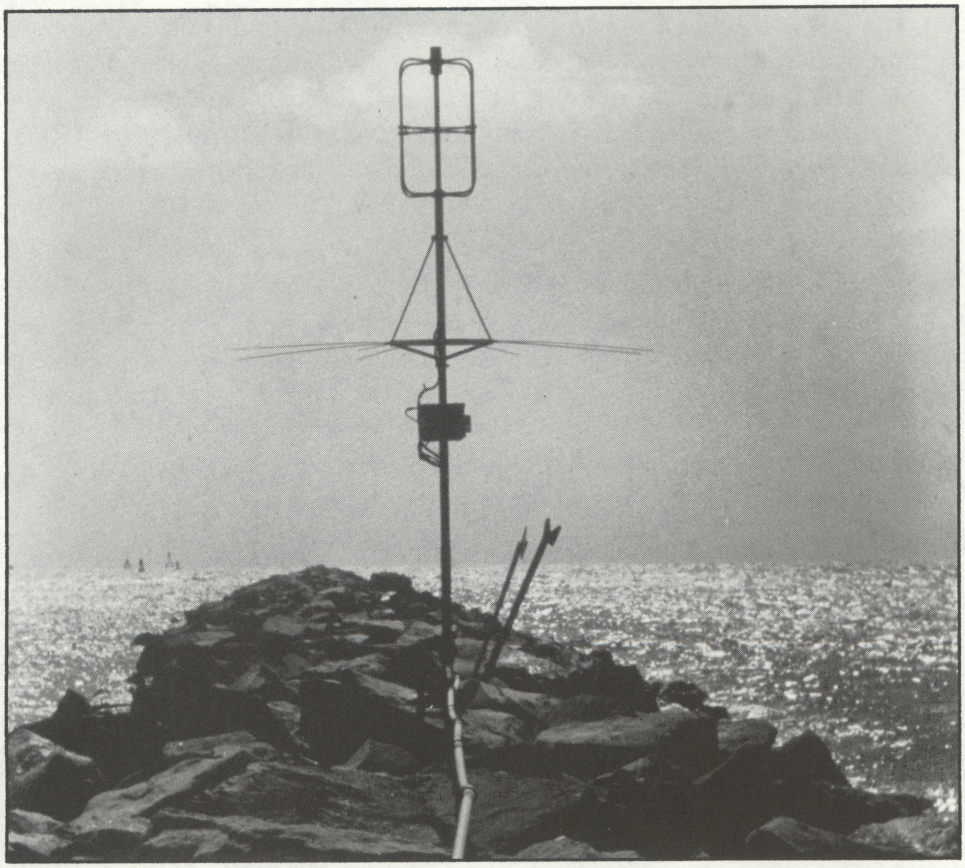


Fig. 1. Crossed–loop CODAR antenna on the south jetty, Fisher Island, Miami.

resulting maps were labeled "Preliminary Results." Progress Report No. 2, *Status of Site Preparation and Equipment Installation*, dated April 23, 1986 (also available from the authors), was furnished by CSI. In June 1986, CSI installed new programs to measure ocean currents stronger than had been anticipated. At that time CSI informed the user group that it would not be able to furnish wave measurements with this system.

In August 1986, CSI was dissolved and its responsibilities on this project were canceled. A new corporation, CODAR Ocean Sensors Ltd. (COS), was formed with several of the same people and with the proprietary rights to the software. Attempts to write a new contract to complete the system programming were begun. The north–site CODAR station became inoperative December 2, 1986, and AOML personnel were unable to repair it.

In May 1987, COS provided *The CODAR Handbook* that describes many features of how to operate its system. COS also advised that the CSI software that had replaced the WPL software could not be used for the WPL–designed transponders. In June 1987, COS repaired and retuned the system in preparation for a loran buoy experiment in which ocean currents were measured concurrently by buoy and CODAR. In July 1987, AOML turned off the CODAR system, awaiting completion of the final programs to operate the system.

In March 1988, a meeting was held between representatives of AOML, the National Hurricane Center (NHC), USCG, and NSWC (the Navy station where the north remote CODAR station was situated). A new contract to finish the CODAR computer programs had not been written, and completion of the CODAR programs seemed unlikely. The group decided to terminate the project "CODAR in the Straits of Florida," and the equipment was to be disassembled within a few weeks and removed from the operating sites.

However, in April 1988, a purchase order with COS was agreed on, and the project continued. Also in April 1988, COS installed the final, debugged software, and the maps were no longer labeled Preliminary Results. This software edited the current measurements to avoid erratic vectors that had appeared on the maps. The radial vector files and the total vector files could be recorded on tape. COS personnel were continually available by telephone for advice on keeping the system operating. The revised operating schedule and the COS responsibilities under the purchase order allowed operation through June 1988.

In June 1988, WPL provided funds to extend the COS maintenance agreement in the contract another 6 months, and AOML continued paying personnel, electrical, and telephone expenses. USCG and NSWC allowed the equipment to remain on their property, and therefore a significant body of data collected from the CODAR system. Also at that time, AOML reprocessed the spectra collected in June 1987 during the loran buoy experiment into the final form provided by COS.

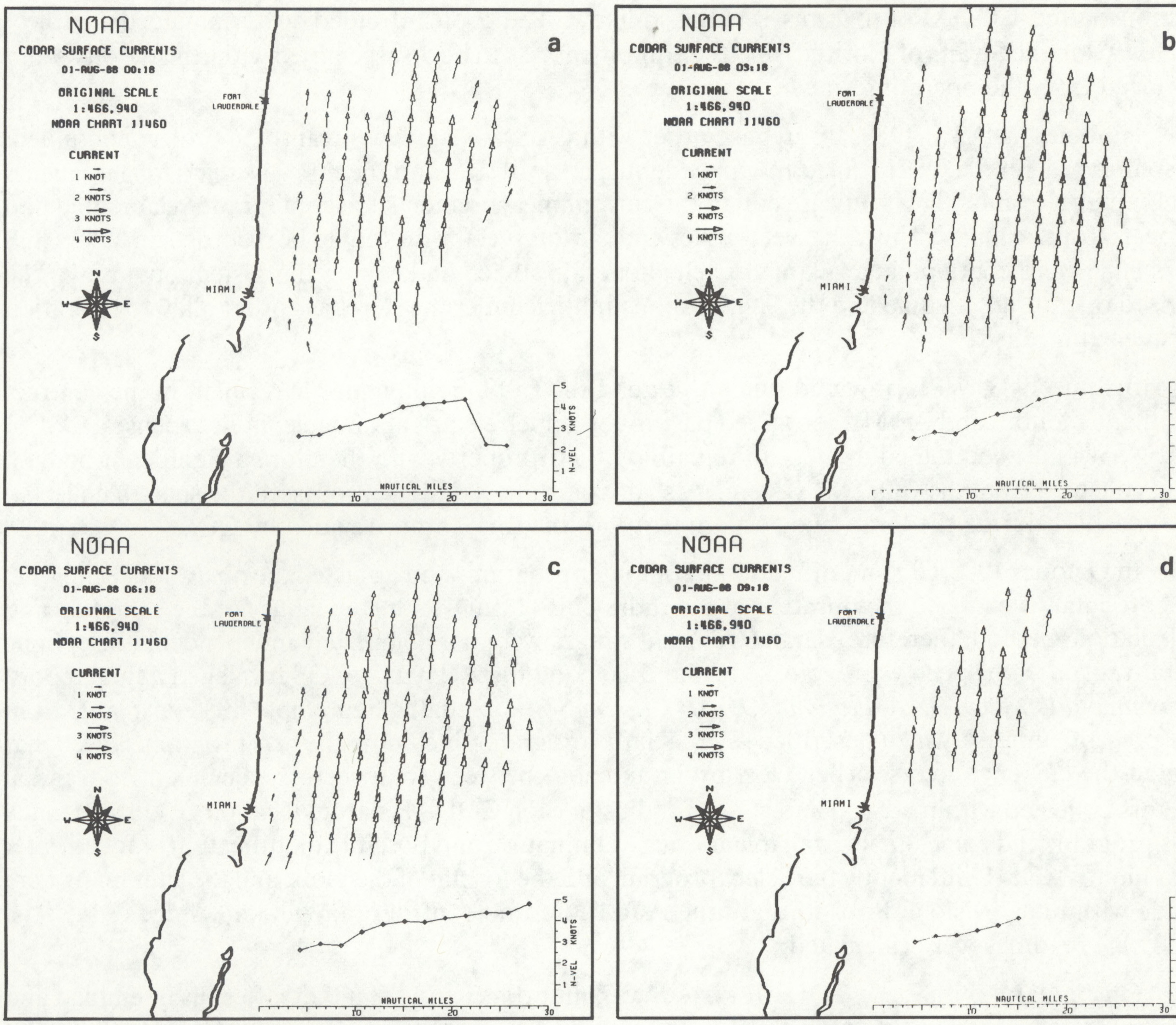
In October 1988, COS modified some computer programs and adjusted the operation technique. In particular, it changed the duration of the radio pulse from 8 μs to 16 μs but not the sampling and calculation method; therefore, data at adjacent ranges were not completely independent. Telephone data transmission speed was decreased from 2400 baud to 1200 baud. COS furnished a final report, *Documentation for NOAA–Florida CODAR Current Software*, dated September 1988 (available from the present authors), which described several of the programs, including the new program, Select, that edited the current vectors. The Select program chose between total vectors calculated from radial vectors collected within a 2-km and a 3-km radius of each CODAR datum location. COS also made this program and some others available for our examination and possible modification. Indeed, later that month AOML did modify the Select program and the format of the plots, and the later maps were made with that revision. Prior to that time AOML had no control of or full knowledge of how the CODAR readings were calculated.

On January 2, 1989, the CODAR system was shut down and soon thereafter disassembled and removed from the operating sites. In February 1989, COS wrote a new program, Conv, that allowed AOML to reprocess radial vector files previously collected, using different analysis programs as desired. Then AOML reprocessed all the CODAR radial vector files collected since April 1988 and the 1987 loran buoy experiment CODAR files, all without the Select program. A 4-km radius of acceptance was chosen for the recalculations in part so that the newly reprocessed CODAR current maps could be compared with the early Preliminary Results maps that also used that radius. The increased (4 km) radius acceptance area exposed the total current calculations to more erratic radial current values and allowed more errors from current shear, as described in Secs. 3.3.2 and 3.3.3.3.

3. DATA EXAMINATION

3.1. Product Quality

During a run, each of the two CODAR stations transmitted pulses of HF radio waves in all directions. At times corresponding to a series of ranges, voltages were read on the two crossed-loop antennas and on the mast itself, referred to as the "monopole" antenna. The three sets of voltage readings were transformed into a set of five auto- and cross-spectra. The spectrum estimate with zero Doppler shift, corresponding to stationary objects, was set to zero. A direction-finding algorithm at each site examined the first-order spectrum values at each range and frequency, and determined the

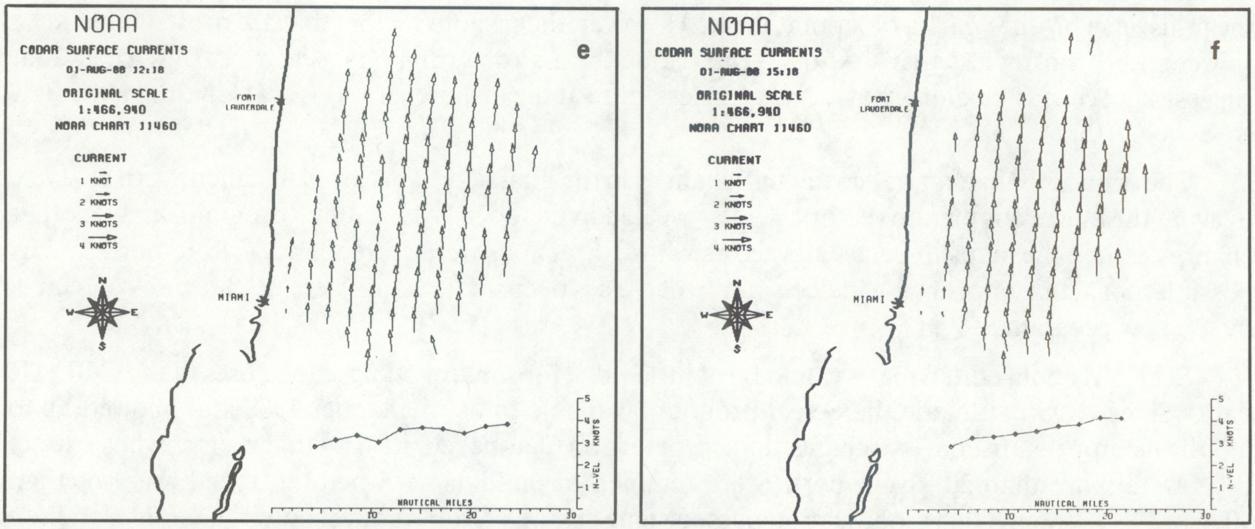


directions of one or two radial vectors representing ocean currents. Their speeds were derived from the frequencies. The degree to which a radial vector fit the spectrum readings from which it was derived was tested by the uncertainty, or standard deviation (SD), of each.

Radial vectors from the two sites within an accepted distance of each location on a CODAR map were combined into one total vector by means of an rms best-fit technique. Again the product value was tested by its SD value.

3.1.1. Differently calculated products

The initial, Preliminary Results maps represent calculations using computer programs that were not debugged, and thus the maps carry no claim to be accurate. Such maps from June to December 1986 and from June and July 1987 are retained in storage; they show ocean surface current patterns comparable with those of later maps and have about as much areal coverage as do the more recent ones edited by uncertainty only. The preliminary maps indicate that some of the distinctive current patterns in the later affirmed maps had been observed earlier.



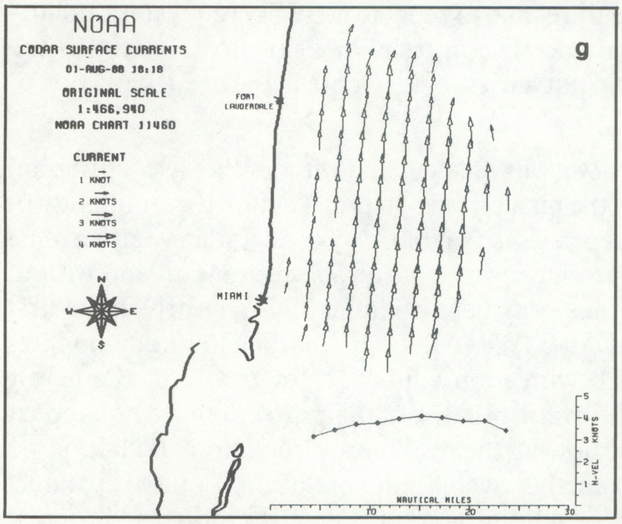


Fig. 2. CODAR maps from August 1, 1988. Maps were produced every 3 hours daily; the 2100 LT map for this day was not generated. The transverse profile is the average of the middle three rows.

The Preliminary Results maps show a number of erratic vectors, surface current readings that are much different from their neighbors or that indicate ocean surface flow patterns not consistent with physical reasoning. Although direct data are generally not available to demonstrate whether a particular suspected vector in this data set is incorrect, such readings are not accepted as valid. In the final version of the computer programs written by COS, ocean current vectors on the maps were processed with the Select program to remove such problem data. The final-product maps without modification were generated from April 28, 1988, to October 20, 1988. In addition, we reprocessed spectra collected from the two remote stations during June 1987 into this format.

Figure 2 shows the seven CODAR maps produced during one day, August 1, 1988 (the eighth map was not produced). CODAR map locations are identified by row from the north and column from the west, i.e. (row, column); Miami is between rows 15 and 16. Each map in Fig. 2 contains vectors in many locations, but there are also gaps within the covered areas and major sections sometimes unfilled. The flow is continuously northward; direction changes are small and confined to local areas. The speed changes only smoothly, increasing gradually offshore with a steady shear and changing from 2–3 knots inshore to nearly 5 knots offshore. The vectors along the coast, 4 km offshore, are mostly missing, and the transverse profiles miss a plot point there. However, the inshore vectors that are present indicate a slower speed, mostly less than 2 knots. There must be a strong transverse shear near the coast that suggests an ocean front alongshore. Nevertheless, even at the inshore locations that have data, the flow is to the north.

The contractor had made "cosmetic" changes in the final output program installed April 28, 1988, to avoid the numerous erratic vectors. COS revealed in October 1988 that this program, among other changes, edited the maps to delete all vectors whose directions were more than 20° from north. Thus possible, not actual or probable, defects in a broad class of current vectors were deleted, not corrected, by the new program.

Such direction-edited maps would be of little value for some of our intended uses of the CODAR data. Since COS had made the Select program available to us in October 1988 and allowed us to modify its proprietary code, we changed the program on October 20, 1988, so that vectors whose directions were more than 20° from north were retained in the data set when the speed was less than 100 cm s^{-1}. Although this modification passed some erratic vectors, it did show circulation nearshore having flows in various directions. As one result, we were able to reply to a USCG request for up-to-date ocean current information for an SAR operation. The current was slow to the west in the requested area, and the original Select program would not have provided data in the needed portion of the maps.

The entire data set from April 1988 to January 1989 was recalculated without the Select program so that we could examine the effect of that editing on the results and perform a detailed examination of the data. The original spectra from June 1987 were reprocessed in both ways. As a somewhat extreme example, Fig. 3 shows a CODAR map for one run produced without the Select program and with it. The SD test of 10 cm s^{-1} was used as before. A surface eddy near Miami is shown clearly in the first map but does not appear in the second. A number of other CODAR maps recorded this eddy, and it is an intermittent feature of the circulation there. The direction editing removed all but the nearly parallel vectors, and therefore vectors assumed to be erratic because of their directions do not appear on the maps, but it also deleted many valid vectors showing the nearshore circulation and left only a portion of the coverage otherwise produced. Most further evaluation here of the CODAR product uses both types of product: the final form with direction editing using or simulating the Select program and the form with corrected programs but without direction editing.

3.1.2. Completeness of the product

The system was scheduled to produce a map every 3 hours, i.e., eight maps per day. There were, however, extended periods when the system was inoperative and times when maps were not plotted for other reasons. The quickness with which a failure in the system could be corrected depended on the availability of personnel to correct it. Maintenance was performed mostly during regular office hours. Map and vector counts were derived from the files collected while the CODAR system was operating. A total of 1248 maps containing at least one current vector were produced out of about 2000 that had been scheduled during the 250 days from April 28, 1988, to January 2, 1989, a production rate of 63%. The lowness of this value does not represent entirely a limitation of the CODAR system itself, since personnel were not always available for maintenance when needed.

The top graph in Fig. 4 shows the number of maps per day produced by the system for each day of the year (DOY) in 1988 that the system was operated. Major gaps occurred when the system was inoperative awaiting repair. Gaps of 10 days, 22 days, and 19 days are seen. In addition, the plot shows a number of shorter gaps. A number of maps were recovered a day late when an operator returned after a weekend; such delays are not indicated in the plot. On nearly all days when the system was

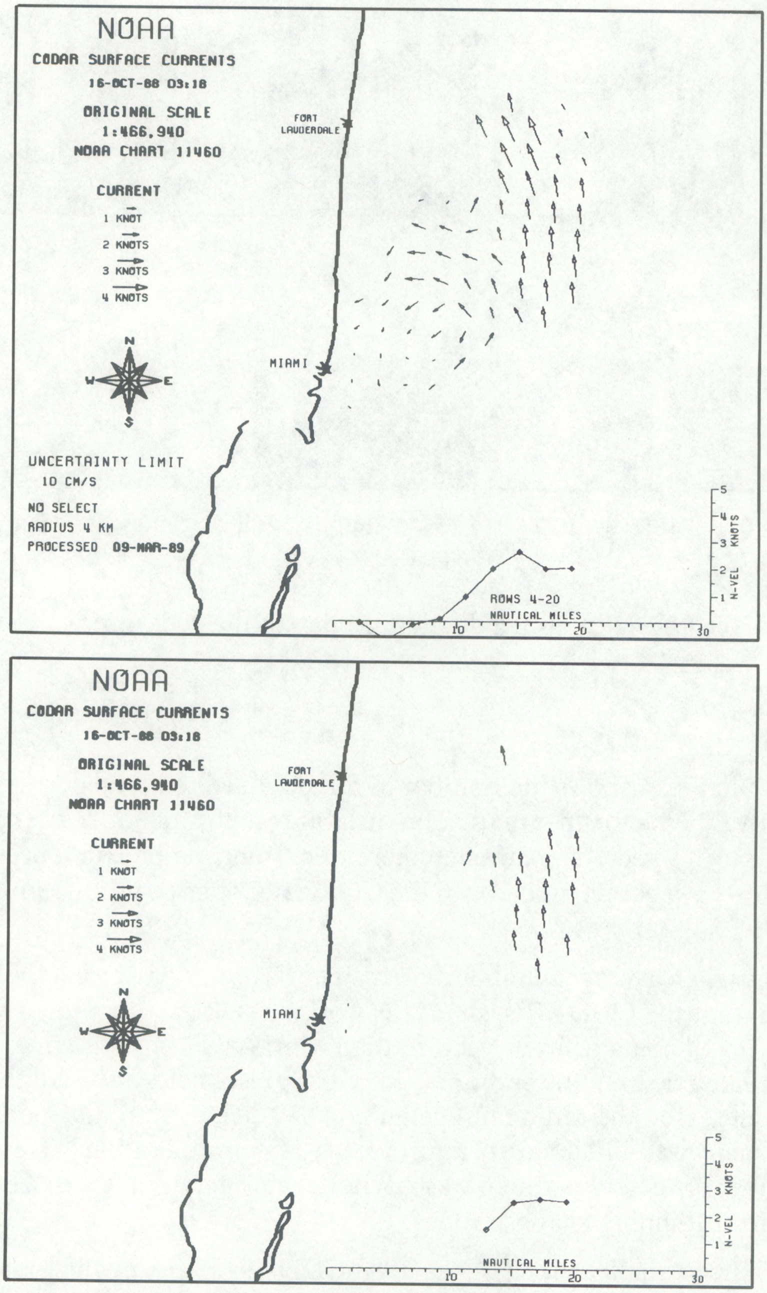


Fig. 3. CODAR maps produced for one run on October 16, 1988. Top: Map without direction editing, i.e., without the Select program; the transverse profile is the average of rows 4–20. Bottom: Map with direction editing; the transverse profile is the average of the middle three rows.

operating, it produced seven or eight maps; the average map production of only 63% results largely from the periods when it was not operating. To be included in the count for the top graph in Fig. 4, a map needed to contain only a single vector; such sparse maps are in fact of little use. Counting only maps with at least 50 vectors that pass the direction editing test reduces the average production rate to 40% and perhaps better represents the useful map productivity of the system.

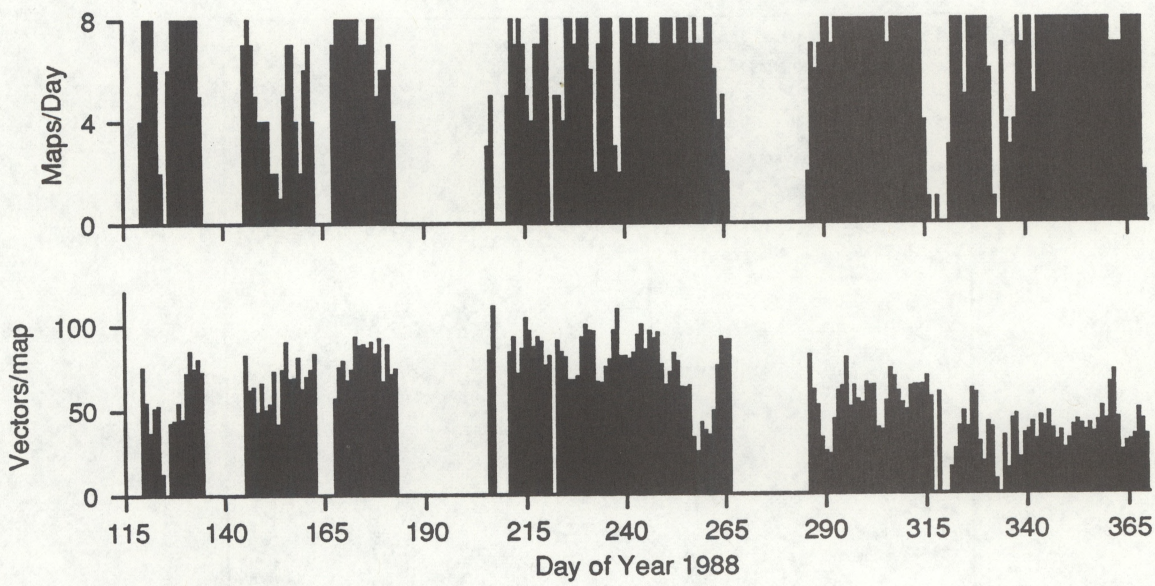


Fig. 4. CODAR map production vs. day of the year during 1988.

The bottom graph in Fig. 4 shows the number of direction–edited total current vectors per map vs. DOY. The average was 62 vectors per map. The variability in this quantity was considerable; daily averages ranged from 8 to 109 vectors. Although there were some major differences between successive days, the graph shows a general tendency for the CODAR system to produce more vectors during the warmer months.

There were a larger than average number of maps per day after day 285 in the upper graph; this might be an indication that the CODAR system was working well at that time. However, the lower graph shows that the maps contain fewer vectors than average during this time, and therefore, in general, they were less valuable than the earlier maps. COS personnel readjusted the radio system on days 117 and 285 and increased the radio pulse length on day 285. Electronic operation had deteriorated, and the adjustment was intended to improve the system operation. This graph indicates, however, that the number of vectors per map was not noticeably greater after those dates, nor did the number drift downward beginning at those times.

Smoothed Fig. 5 shows the fractions of the 1988 CODAR maps in which there was a current reading at each location. Data edited solely by the variability of each radial vector, i.e., the SD values, are shown on the right. Direction–edited data are shown on the left. There is a small area in the fast current offshore where current readings are regularly obtained by either method of vector editing. The direction editing removed a major fraction of the data on the shoreward side of the Florida Current, and the difference between these two plots is greatest there. This figure shows that in only a limited area are the currents measured regularly. When a map contains only a few vectors, they are frequently in the high–density location shown in the figure. Ocean current measurements were obtained at only 73 locations (with SD editing only) or 58 locations (with direction editing) on more than one–half of the successfully generated maps. Nearly 200 locations might be expected from a CODAR range of 60 km and a datum location spacing of 4 km.

The actual radar range achieved by this CODAR system was examined by averaging the data in Fig. 5 at different distances from the farthest CODAR station. With either method of current vector

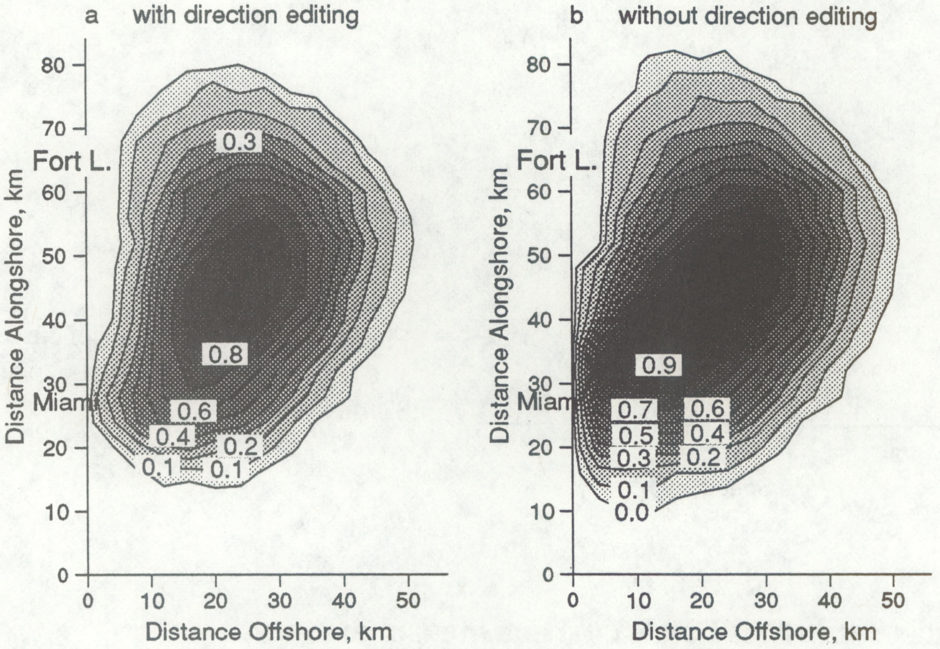


Fig. 5. Fraction of CODAR maps in 1988 containing a current vector in a location.

editing, the fraction of maps with data in a range band decreased to one-half of its maximum at a farthest distance of 45 km. The fraction decreased to one-fourth at 50 km, a rather sharp cutoff. Had the CODAR maps been constructed for a maximum range of 45 km instead of the 60 km specified in the CODAR proposal, the average number of vectors per map would have been 51% or 63% of the scheduled maximum with the two types of editing.

The number of vectors per reprocessed map during a period of 82 days was calculated for different wind speeds at the same hour that the speeds were measured at AOML, a distance of 4 km from the Miami CODAR station and 50 km farther from some vector locations. Because the wind at some observation locations may be significantly different from that at AOML, a close relationship between CODAR performance and AOML wind speed need not exist. The mean number of vectors per map at different wind speeds is plotted vs. wind speed in Fig. 6. At most of the wind speeds, 90% of the values are within about 5 counts from the mean number of vectors per map, although the plot range is 29 counts; the change in the mean is much greater than the variability about that mean. When only maps with wind speeds greater than 2.5 m s^{-1} were used, the number of vectors per map had a weak negative linear correlation with wind speed ($r = -0.23$), a correlation significant at the 99% level according to a statistical t-test. The most vectors per map were produced at a wind speed of 2-3 m s^{-1}. A sea state generated by a continuing wind of this speed would have the ocean wave spectrum peak frequency near 0.5 Hz ($f_m = 0.14g/U$, where f_m is peak frequency, g is acceleration of gravity, and U is wind speed), which is the ocean Bragg wave frequency for the radio frequency used. This observation is in accord with the suggestion of LeBlond (1985) that CODAR current measurements would be most accurate under moderate sea states when the wavelength of the peak of the spectrum is near that for first-order Bragg scattering of the radar signal. However, the analysis of Barrick (1986) reveals a measurement difficulty in this portion of the ocean wave spectrum. Complete studies extending this limited effort are needed to show the dependence of the success of a CODAR run on various properties of the environment, but clearly there is some wind dependence.

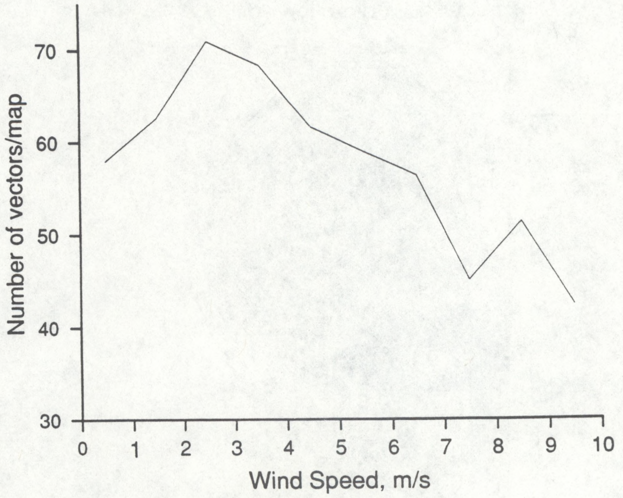


Fig. 6. Average number of current vectors on a CODAR map vs. wind speed during an 82–day period.

3.1.3. Accuracy of CODAR current measurements

3.1.3.1. *Loran buoy comparisons*

In a series of experiments in June 1987, groups of free–floating buoys with sea anchors extending to 1–m depth were released to drift through the CODAR measurement area. The buoys reported their positions obtained from loran–C readings at 20–min intervals. Location accuracies were estimated from buoy readings at known locations (near a pier, passing an offshore tower, and when next to a sea buoy) to be 1–2 km and precision (from three loran buoys on the same ship at sea) to be about 200 m. On one day, current measurements from two offshore drifting buoys contained $\pm 10\%$ speed variations that showed a correlation of $r = 0.72$ between them when the time offset calculated for the different distance along the flow was used, illustrating the precision of the buoy data and the steadiness of the flow during a few hours.

After the 1987 experiments were performed, some loran buoy data were compared with the Preliminary Results maps from the CODAR system. It appeared at the time that only the nearshore, possibly erratic data were in question and that the regular offshore data were valid. Comparisons of these CODAR and buoy data showed good fits in the offshore areas (McLeish et al., 1987). Later, it was recognized that even these values could be in question, and the comparison now has been reexamined with reprocessed CODAR data.

The buoy surface current measurements were compared with corresponding CODAR current measurements calculated without direction editing. The two types of measurements are not fully the same. The buoy measurements represented mean currents along the lines traversed by the buoys, whereas CODAR measurements were calculated from whatever radial vectors fell within 4–km–radius areas. This difference must be considered in evaluating comparisons between the two types of measurement. CODAR values for a buoy location were interpolated from those at fixed locations, allowing further inaccuracies. Detailed comparison between these two types of data is not warranted. Three buoys released June 18 gave mean velocities that when compared with averages of direction–edited CODAR maps differed by 9 ± 4 cm s^{-1} and $8° \pm 4°$. This is considered a good validation of the CODAR data being compared.

On June 26, 1987, two buoys placed 12 km offshore traveled steadily north (Fig. 7). One buoy off Miami (which is between CODAR rows 15 and 16) traveled past CODAR locations (17,3) through (13,3). The directions of this buoy agreed well with the CODAR data, but the CODAR speed was low,

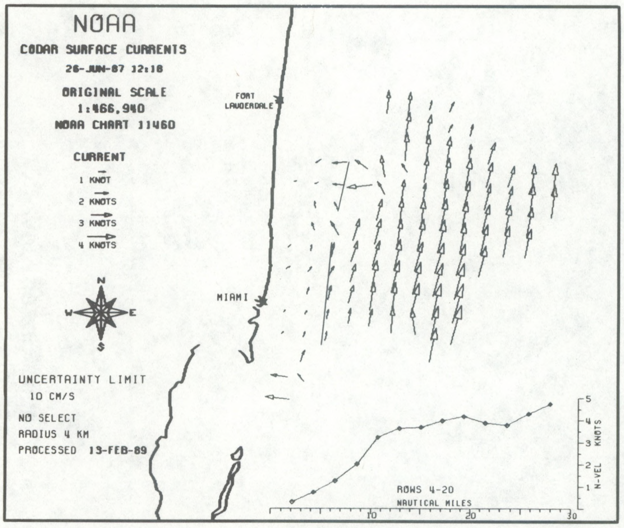


Fig. 7. CODAR map for June 26, 1987, showing tracks of two loran buoys that measured surface currents.

possibly a result of CODAR uncertainties in the shear zone at the edge of the Florida Current (see discussion of Fig. 23). On this date the buoy reported an increased speed of 2 cm s^{-1} km^{-1} of travel downstream, and so did the CODAR data. The parallel small speed changes in the different types of measurements emphasize the accuracy of some CODAR data. The different current directions shown by CODAR and by the second buoy are discussed in Sec. 3.3.2.

3.1.3.2. *Changes in speed over several days*

CODAR data that passed the direction–editing test in each map over an area of 12 x 24 km, 30–42 km offshore, were combined, and daily averages of these were calculated. Figure 8 shows how the 10–day smoothed mean speed from the CODAR varied over the 250 days of the operation. Significant speed changes occurred; the minimum plotted speed was 60% of the maximum. For comparison, mean surface speeds across the Straits of Florida deduced from tide gauges at Haulover Beach in the CODAR area near Miami and at Lake Worth north of the CODAR area (Maul et al., 1985; Maul et al., 1987) are plotted on a scale selected so that the curves will be similar. The two tide gauge lines mostly parallel each other, and most of the variations in the CODAR speeds closely parallel those of the tide gauges. In particular, the major drop in current speed during days 250–285 in the CODAR curve is also seen in the tide gauge data, and the subsequent return to the previous values by day 360 occurs in all three surface data sets. The CODAR speeds dip much below the tide gauge values between days 167 and 170. The CODAR maps show that on these days the entire flow within the CODAR measurement area decreased appreciably; it was not a fluctuation of only a small area of the maps. The reason for this temporary difference between the two types of measurements is not known. Examination of the series of CODAR maps for that time period did not reveal a distinctive feature of the circulation; the CODAR–derived speeds were simply lower than at other times. In general, however, major changes in the surface flow of the entire Florida Current were followed closely by CODAR observations that extended only part way across the Straits.

Voltages from an electrical cable across the Straits 60 km north of the north CODAR site are interpreted as volume transport through that channel (Larsen and Sanford, 1985). Selected values of offset and proportionality factor allow these data to be plotted on the same graph. The overall shape of the curve is similar to that given by Rosenfeld et al. (1989). Although the lesser variations in transport do not follow well the lesser changes in indicated surface speed, the major decrease at day 250 in the other plots occurs also in the cable data. The transport scale was chosen so that the major cable

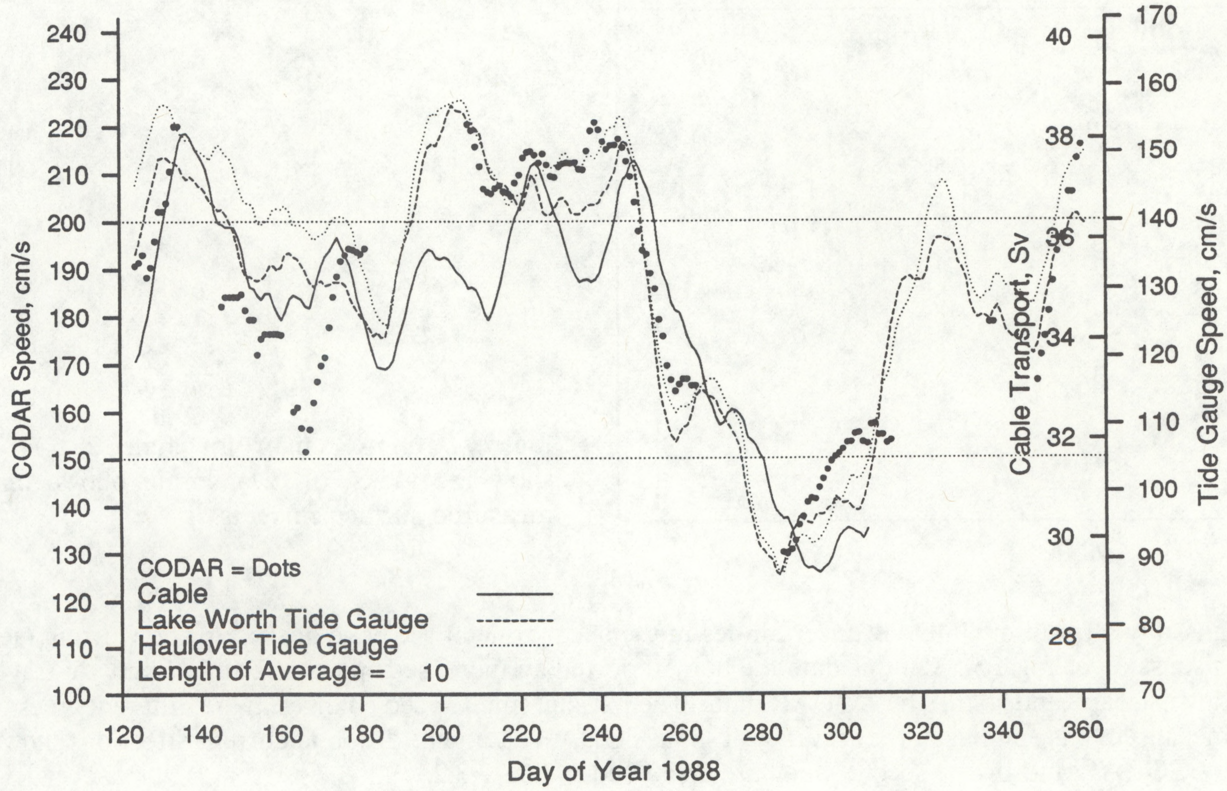


Fig. 8. Speed of the Florida Current vs. day of the year during 1988.

change appeared to be similar to those of the others; however, the change in transport over the entire depth (–22%) was less in proportion to the total than the relative change in surface current speed (–40%). The changes in the upper flow were not all accompanied by proportional changes in the flow at greater depths.

3.1.3.3. *Variations in speed with location*

The two plots in Fig. 9 show the average during the 1988 data collection period of the north component of surface velocity at each CODAR location, calculated with and without direction editing. In the direction–edited plot, there is an increase in speed offshore, but otherwise the mean flow is nearly uniform. A low–speed region in the southern portion of the nearshore region may result from a weak eddy sometimes found there. The uniformity of the indicated offshore speeds in the direction–edited plot is evidence that except at the range limits there are not noticeable biases in the CODAR speed measurements in different portions of that area.

Without the direction editing, the low–speed flow region nearshore appears more pronounced, probably a result of the eddying flow. In addition, there are low–speed zones at the greatest ranges, along the northeast and southeast sides of the area. A similar speed decrease was reported by Schott et al. (1985) from CODAR data farther north in the Straits of Florida. In some respects, those data of Schott et al. may be more comparable with the present non–direction–edited data than with the final product here.

In the data set as a whole, the SD's of the northward components in the two plots in Fig. 10 are distinctly different in places. In the direction–edited plot, there is an irregular region nearshore, but

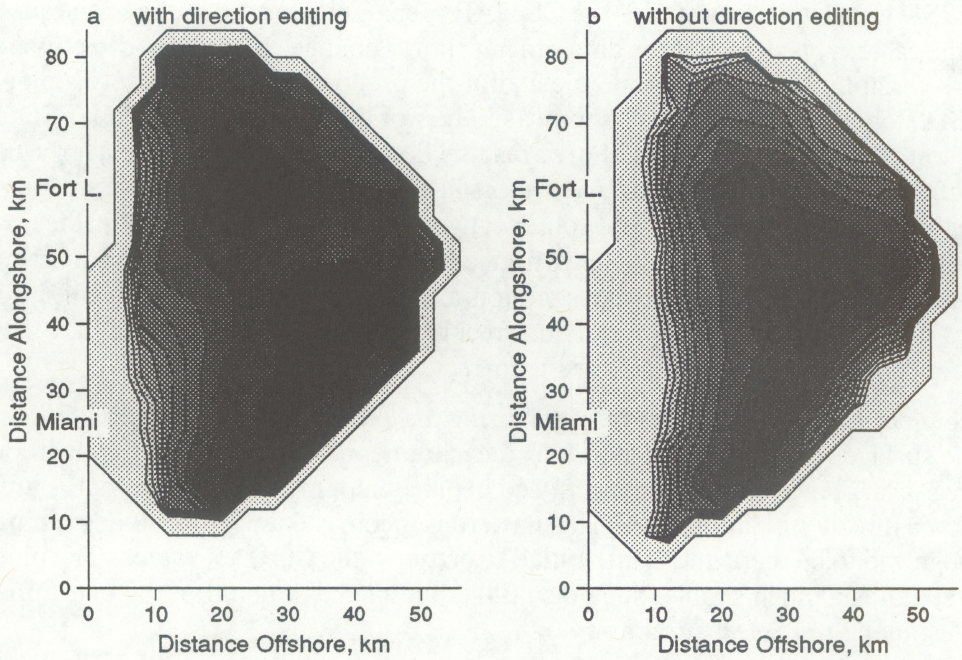


Fig. 9. Average northward speed for the CODAR area during 1988. The innermost contours represent 180 cm s^{-1}, and the contour interval is 10 cm s^{-1}. Darker shades are higher speeds.

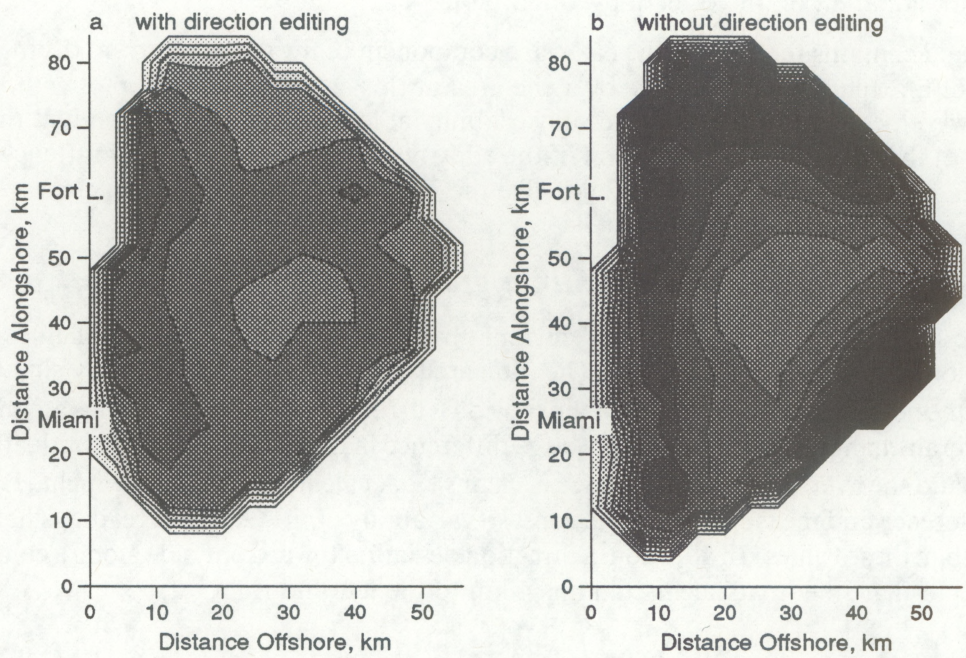


Fig. 10. Standard deviation of northward speed for the CODAR area during 1988. The innermost contours represent 40 cm s^{-1} (left plot) and 50 cm s^{-1} (right plot), and the contour interval is 10 cm s^{-1}. Darker shades are higher standard deviations.

otherwise the SD is nearly constant over the CODAR area. The plotting routine generated low–value contours at the eastern borders; but the data did not show a change. In the non–direction–edited data, the nearshore variability was more pronounced, but the predominant feature of this plot is the large increase in SD along the northeast and southeast edges of the map area. A similar SD pattern was shown by Schott et al. (1985). In this offshore area, the flow has been found to be nearly uniform. The indicated increase there represents CODAR vectors in irregular directions. These erratic vectors were produced in the weak–signal regions at the outer ranges of the system. In addition, the erratic vectors may account for the decreased mean northward speeds in that portion of the non–edited map in Fig. 9. Because of this difference between the types of plots and because of the uniformity of the current flow offshore (e.g., as shown by some of the loran buoy records), it appears that many of the offshore vectors that the Select program removes are indeed incorrect.

The two plots in Fig. 11 show the average during the 1988 data collection period of the east component of the surface velocity at each CODAR measurement location. In the plot without direction editing, there is a large increase in eastward speed in places along the outer edges of the area. Schott et al. (1985) show a mostly similar pattern. This pattern is inconsistent with the uniform northward flow patterns recognized to be there and is attributed to errors in the CODAR values. The plot with direction editing contains a much smaller such deviation, but a small amount of the bias appears to have passed the testing by the Select program.

The time–averaged plot in Fig. 11 without direction editing also contains a marked anomaly nearshore. A positive peak in eastward component centered 8 km offshore and 35–40 km alongshore, between Miami and Fort Lauderdale, is not consistent with the concept of a northward flow offshore, slower near the coast. Furthermore, a roughly circular area at an alongshore distance of 50–55 km contains westward flows seen from the original data to be up to 30 cm s^{-1}. These features of the plot reveal a mean disturbance to the circulation in that location. The surface eddy in Fig. 3 was observed repeatedly between Miami and Fort Lauderdale. The midpoint of these two east component features is 20 km farther north than Miami and must represent the center of a mean eddy near the shore. This feature is not apparent on the direction–edited plot.

Figure 12 contains the SD's of the eastward component of the surface current during 1988. With direction editing, there is little change over the area at this speed scale. The plot without direction editing, however, contains large increases in variability at locations nearshore, both at the north and south ends of the area and at the location of the eddy north of Miami. An intermittency of the eddy between Miami and Fort Lauderdale could give the increased variability.

3.1.3.4. *Individual directions within a group*

Figure 13 shows the direction–edited current directions along five north–south lines of measurement locations from one CODAR run. The indicated directions mostly vary only slightly from one location to the next, indicating that within the Florida Current the direction readings are highly consistent and overall changes are small. The average difference in directions at north–south adjacent locations is 2°, and the average speed difference is 7 cm s^{-1}. A calculated difference includes both actual current difference and measurement variations, so variability of the CODAR readings here should be no greater than these values. In addition, a direction deviation toward one side along a column tends to appear also to that side in adjacent columns 4 km to the left and right.

3.1.3.5. *Deceleration with latitude*

The 1988 average direction–edited speed plot vs. distance along the flow in Fig. 14 shows a definite slowing in the section north of Miami. Since, by continuity, the speed through the channel should

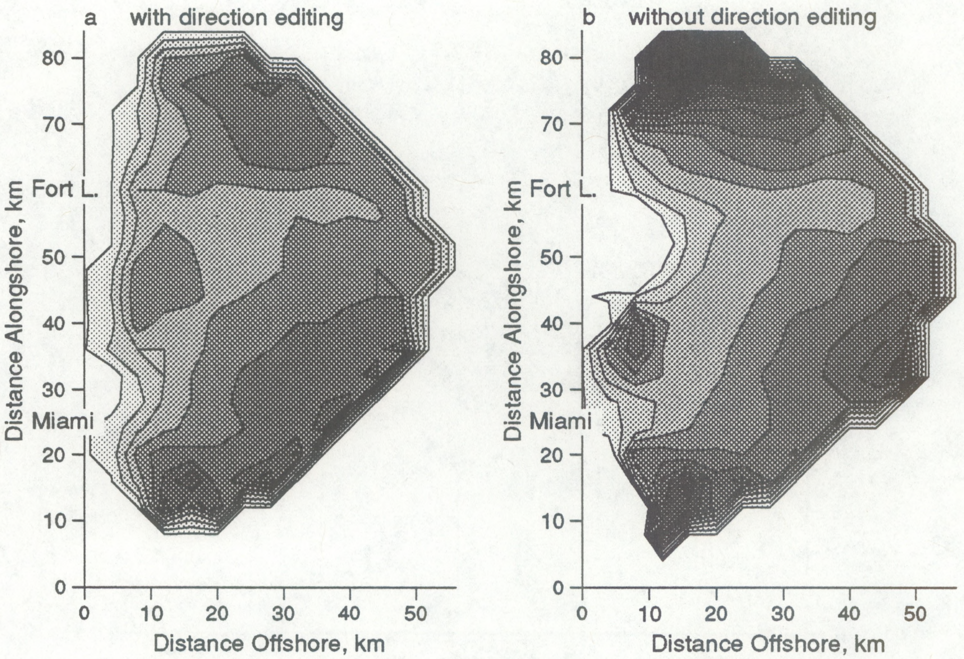


Fig. 11. Average eastward speed for the CODAR area during 1988. The outermost contour represents zero speed, and the contour interval is 5 cm s^{-1}. Darker shades are higher speeds.

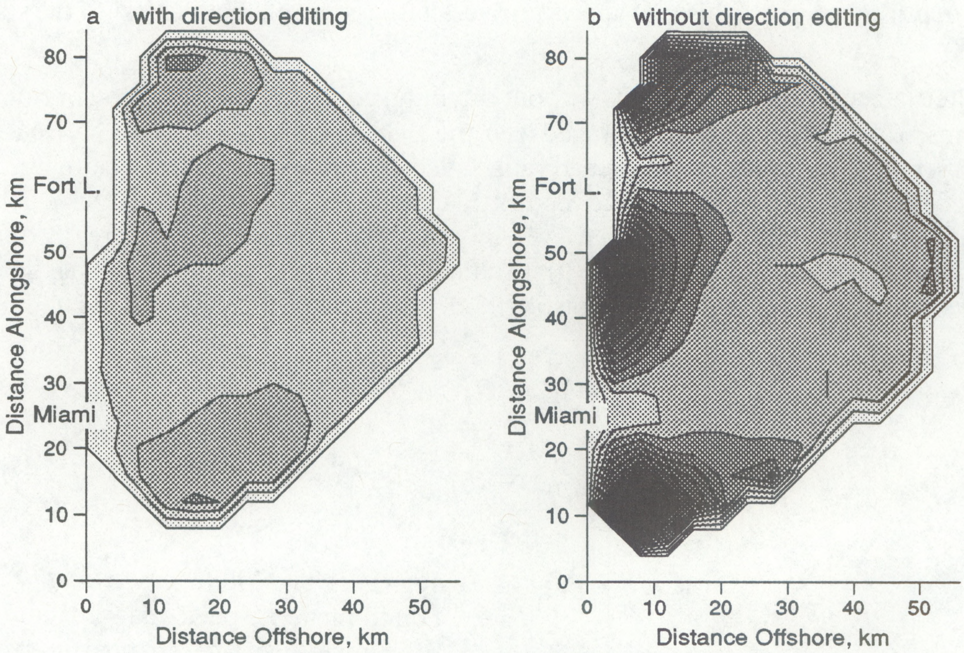


Fig. 12. Standard deviation of eastward speed for the CODAR area during 1988. The outermost contour represents zero deviation, and the contour interval is 10 cm s^{-1}. Darker shades are higher standard deviations.

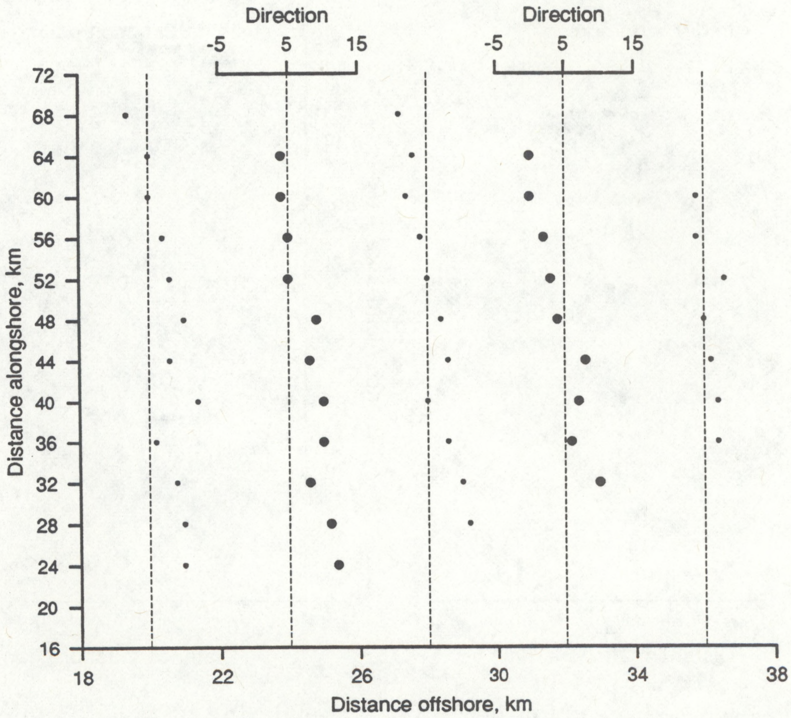


Fig. 13. Direction–edited current directions along five north–south lines of CODAR vectors from one CODAR run.

be inversely related to the cross–sectional area of the flow, this deceleration might result from the widening of the upper portion of the Straits of Florida. The reciprocal of the width between the 100–fathom depth contours on this plot shows an overall fractional change similar to the speed change (0.70 vs. 0.78).

In an alternate approach, the speeds without direction editing at each location in column 8 of the CODAR maps, 32 km offshore, were averaged over the 1988 reprocessed data set. A frequency histogram of number of occurrences in each speed range at each location on a north–south line is shown in Fig. 15. This data set contains some erratic vectors that the direction editing would have deleted. Their influence was removed in this approach, however, by placing the values that were greatly different from most of the others, less than 94 cm s^{-1}, in the first column of the histogram and ignoring that column. A dashed line connecting the peaks of the plots is tilted. The decrease in speed indicated by this tilt is

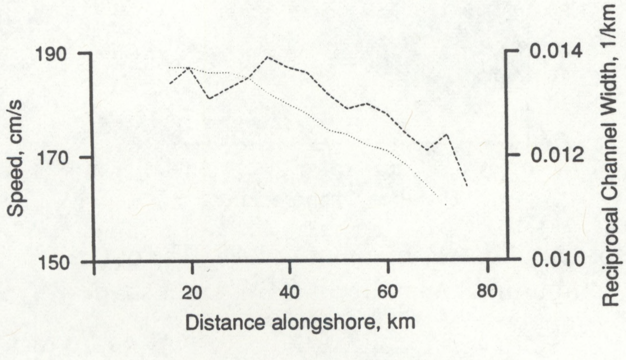


Fig. 14. The 1988 average offshore direction–edited current speed (dashed) and reciprocal of the width of the channel in the Straits of Florida (dotted) vs. distance along the flow.

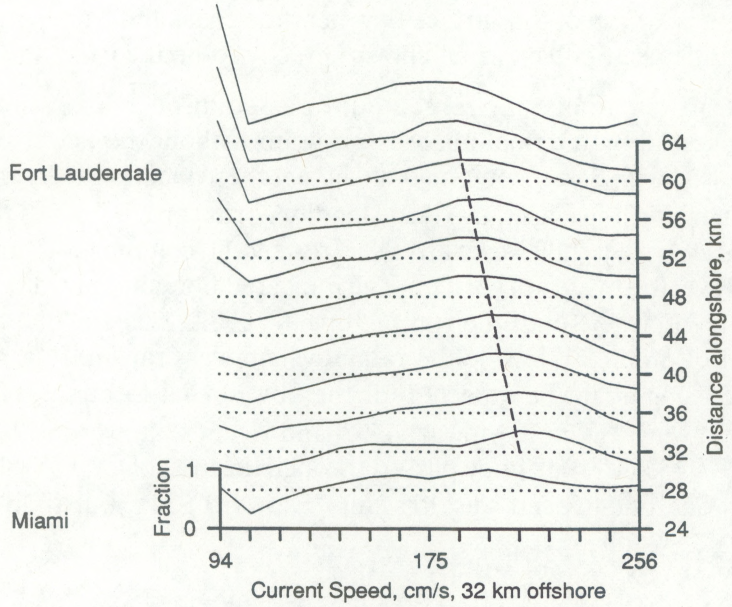


Fig. 15. Frequency of occurrence of current speeds without direction editing along one line of longitude at different latitudes. The dashed line connects the peaks of the plots.

0.73 cm s^{-1} km^{-1} distance north. In comparison, the speed data in Fig. 14 give a decrease rate of 0.76 cm s^{-1} km^{-1}. This tilt is another representation of the overall speed decrease of 30 cm s^{-1} in a 40–km distance downstream. Thus, data sets both with and without direction editing showed similar slowing with distance downstream.

An earlier CODAR study near Palm Beach, Florida (Schott et al., 1985), reported an indicated increase in speed of the Florida Current that the authors later suggested might have resulted from changes in the underwater topography (Schott et al., 1986). Although several factors could have caused the change, it is noted that the speed increase of 9% was not greatly different from the narrowing of the distance between the 100–fathom contours of 13% in that area.

3.1.3.6. *Tidal current coefficients*

Average central current speeds from the CODAR system during November and December 1988 gave tidal amplitude coefficients of surface currents O1, K1, and M2 of 9.4, 9.8, and 6.8 cm s^{-1}. In comparison, Smith et al. (1969) analyzed surface current values to obtain 5.6, 5.7, and 3.4 cm s^{-1}, respectively. Zetler and Hansen (1970) reported the M2 value to be 9.2 cm s^{-1} at a location 50 km south. The CODAR values are in the same range as those reported previously. There was instrument noise in these CODAR data (plots of the Fourier coefficients vs. frequency showed adjacent minima about one–third of the peaks), and Leaman et al. (1987) noted intermittent baroclinic tidal currents, which would give significant differences in the coefficients. As a result of these comparisons, the present CODAR surface tidal current coefficients may be consistent with the previous results.

3.1.4. Demonstration that some total vectors are erroneous

Most CODAR maps produced without direction editing by this system during the 1988 operation contained at least a few surface current vectors that were considered "erratic" because they differed significantly from what is known of the surface flow near the coast and from surrounding current vectors. Some of the erratic vectors have been shown directly to be incorrect.

On occasion during the loran buoy runs, a buoy passed through a location where the CODAR vectors that were processed by the final analysis program without the Select program were erratic. CODAR maps processed with Select contained no data at these locations. As an example, the second buoy, which was farther north in Fig. 7, traveled steadily northward (9° ± 5°) through a region indicated by the CODAR to have a fully westward flow (rows 9–11, columns 3–4) and demonstrated that those erratic CODAR vectors were not correct. The indicated flow anomaly did not appear in the next CODAR map 3 hours later. Also, in the run of June 17, 1987, 1200 LT, one buoy passed between CODAR locations (18,1) and (18,2) while the radar system was transmitting. The buoy speed was 143 cm s^{-1} toward 354°, as might be expected for the flow at that location. However, the CODAR readings without Select were 173 cm s^{-1} toward 271° and 96 cm s^{-1} toward 319°. In addition, during the run of June 18, 1987, 1500 LT, one buoy passed through the area of CODAR location (11,1), during radar transmission. The buoy speed was 155 cm s^{-1} toward 354°, but the CODAR reading was 280 cm s^{-1} toward 82°.

3.2. Causes of Incompleteness of the Product

Although sometimes the causes were not known, missing maps generally resulted from equipment failure somewhere in the system, often telephone faults. Missing total vectors commonly resulted from missing radial vectors, those not produced in the direction–finding calculation, or those with SD values greater than the SD threshold. In addition, the uncertainty of some total vectors caused their deletion.

3.3. Causes of Erratic Total Vectors

Whether a particular total vector is incorrect generally is not known, and only some of the possible causes of erratic total vectors may be discussed.

3.3.1. Incorrect direction editing

It should first be noted that not all total vectors at an angle to the coast are incorrect, as is considered in the Select program. The CODAR map without direction editing in Fig. 3 shows both the Florida Current offshore and an eddy nearshore. Nearly all of the 10 CODAR maps produced just before this one and the next 15 maps after it gave evidence of the eddy in this location. Some of the radial vector speeds from which it was generated are plotted in Fig. 16. These radial vector speeds do not at all follow the pattern commonly seen from these stations, i.e., a strong inflow component in the southeast changing smoothly to a strong outflow component in the northeast with small speeds near the coast (such as in the plots in Figs. 20, 21, 24, and 26). Instead the radial velocity vs. direction plots from the north site (Fort Lauderdale) show unusually low–speed radial velocities in all directions within 45° from south; in fact, some are negative, indicating a southward flow nearshore. Plots from the south site (Miami) in the directions between 45° (northeast) and 70° (east–northeast) normally show negative values, i.e., water departing to the north. However, in this case there is a variable positive radial velocity representing the return flow in the eddy. Radial vector plots from both sites confirm the unique flow patterns through several values both adjacent in direction and at independent ranges. In this case, a pattern indicating flow in directions other than northward and parallel to the coast must be correct.

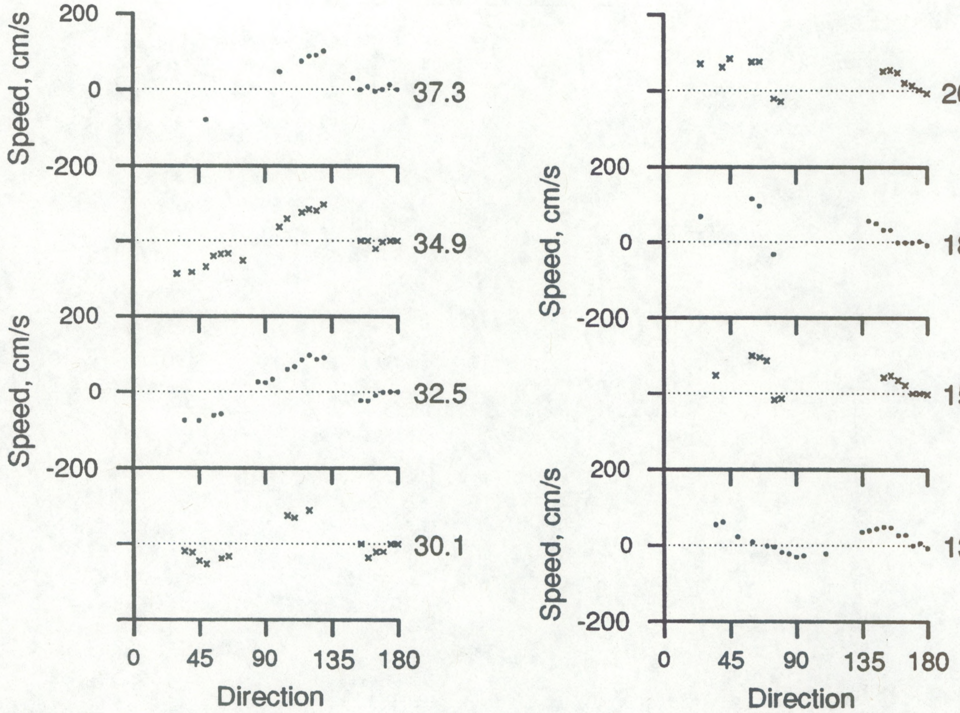


Fig. 16. Radial velocity vs. direction at different ranges (km). Left: Recorded from Fort Lauderdale. Right: Recorded from Miami. Negative values indicate flow away from the radar. The values shown here were among those used to generate the maps in Fig. 3.

3.3.2. Incorrect total vectors from incorrect radial velocities

The reprocessed CODAR map for 0900 LT on June 14, 1987, in Fig. 17 shows the generally smooth flow of the Florida Current offshore, weak irregular flow near the coast, and some erratic current vectors. Four vectors at locations (9,3), (9,4), (10,3), and (10,4) indicate a flow of more than 100 cm s^{-1} to the west instead of the flow to the north indicated by several nearby vectors, and these cannot be accepted as correct.

Figure 17 also shows the radial velocities observed from the two CODAR sites that led to the CODAR map in that figure. The many missing radial vectors leave a fractional coverage of the 60–km–radius area, as often observed from CODAR runs. Most data that do exist, however, fit into a general pattern of radial velocities similar to that in Fig. 18, discussed further in Sec. 3.4.1.1, which represents the calculated result of a northward–flowing Florida Current, with incoming flow from the southeast and outgoing flow to the northeast. However, the patch with a positive radial velocity (about + 130 cm s^{-1}, incoming) in the south radial vector plot of Fig. 17, 28 km from Miami, bearing 25°–30°, is in a region with otherwise negative radial velocities (about –100 cm s^{-1}, outgoing) and represents two radial velocity values much out of accord with their neighbors. The total vectors were generated from the radial vectors shown. This figure provides an example of erratic total vectors caused by erratic radial vectors.

The erratic values from the south site had small SD values and passed the SD quality test, but what caused the readings and how they received their small SD values cannot be specified. The source is not obvious from the map. The velocity profile does not show a marked velocity shear zone at these

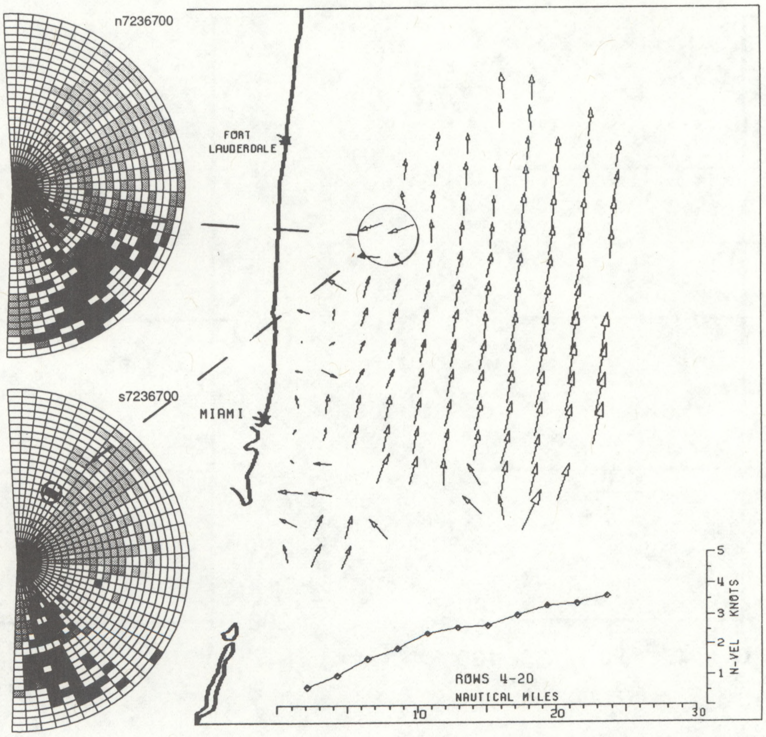


Fig. 17. Radial velocities recorded from Fort Lauderdale (top left) and Miami (bottom left), and the CODAR map (right), June 14, 1987, 0900 LT. More positive radial velocities are shaded darker. The blank blocks within the 60-km range limit represent areas with no data during this run from this site. Some radial velocities contributing to the circled total vectors on the map are also circled.

vectors. The view angle (Sec. 3.3.3.1) was nearly a right angle, and baseline instability would not have been a factor here. In contrast to the radial vectors from Miami, those from Fort Lauderdale for that ocean location were about +60 cm s^{-1}, which might be expected for a flow to the north with that angle to the current and probable speed there, and do not indicate that the current there was unusual.

As another example, the CODAR map in Fig. 19 shows two vectors in locations (12,4) and (12,5) directed toward 105° even though surrounding vectors are to the north. These erratic vectors were derived from radial vector files from the two remote sites (Fig. 20). The two plots in Fig. 20 show a characteristic low speed to the south rapidly becoming positive, then smoothly becoming negative. Data from the south site in the direction of 50° show nearly uniform values at the different ranges. Data from the north site are near the sharp speed–change zone to the south, but again most are of similar values. However, the north plot at 30.1 km contains two points at 135°–140° with values of -190 cm s^{-1} instead of about +100 cm s^{-1} nearby. One radial vector is just within the acceptance region for total vectors. The rms best–fit method allows even a single value, distant and with a small weight, to influence greatly the result if it is greatly different from the others being fitted. Thus, this one erratic radial vector appears to have caused the total vectors to be eastward instead of northward.

Furthermore, the loran buoys demonstrated that some CODAR vectors are incorrect. The four westward–directed vectors in Fig. 7, at locations (9,3), (9,4), (10,3), and (10,4), contrast with the north-

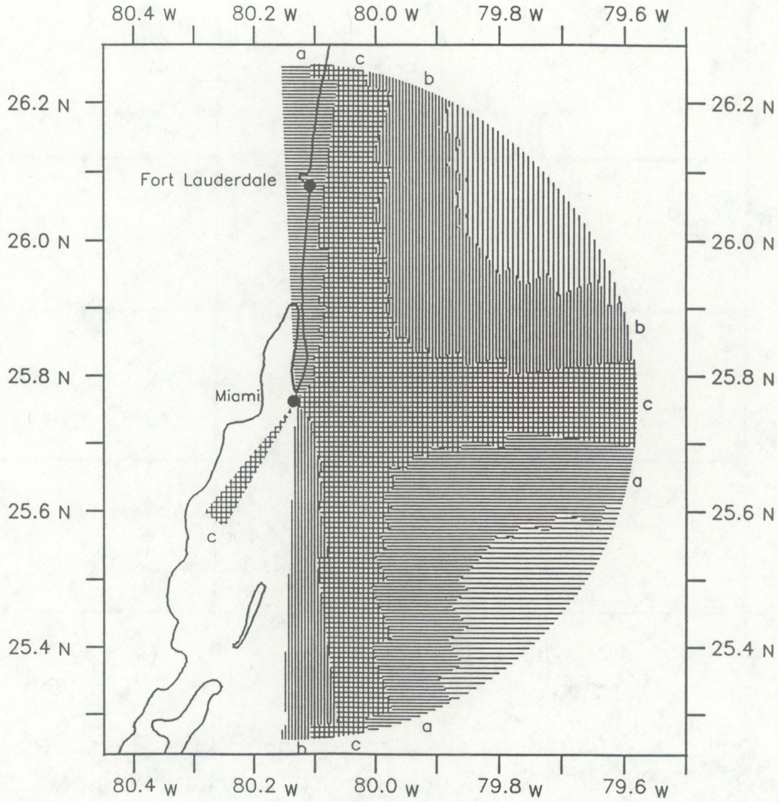


Fig. 18. Predicted radial velocities expected at Miami from an assumed flow offshore and near-zero current in Biscayne Bay. Horizontal shading represents incoming flow, vertical shading represents outgoing flow, and cross hatching represents flow near zero speed. Letters along the border indicate particular speeds discussed in Sec. 3.4.1.1. The unlettered horizontal and vertical shaded areas contain maximum incoming and outgoing flow, respectively.

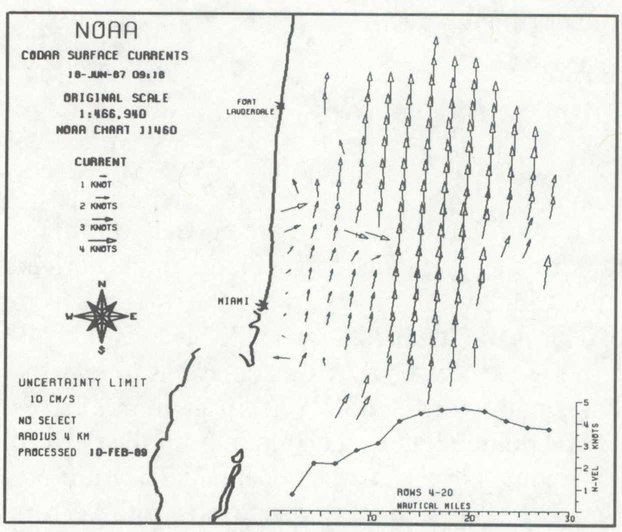


Fig. 19. CODAR map with erratic vectors within the Florida Current.

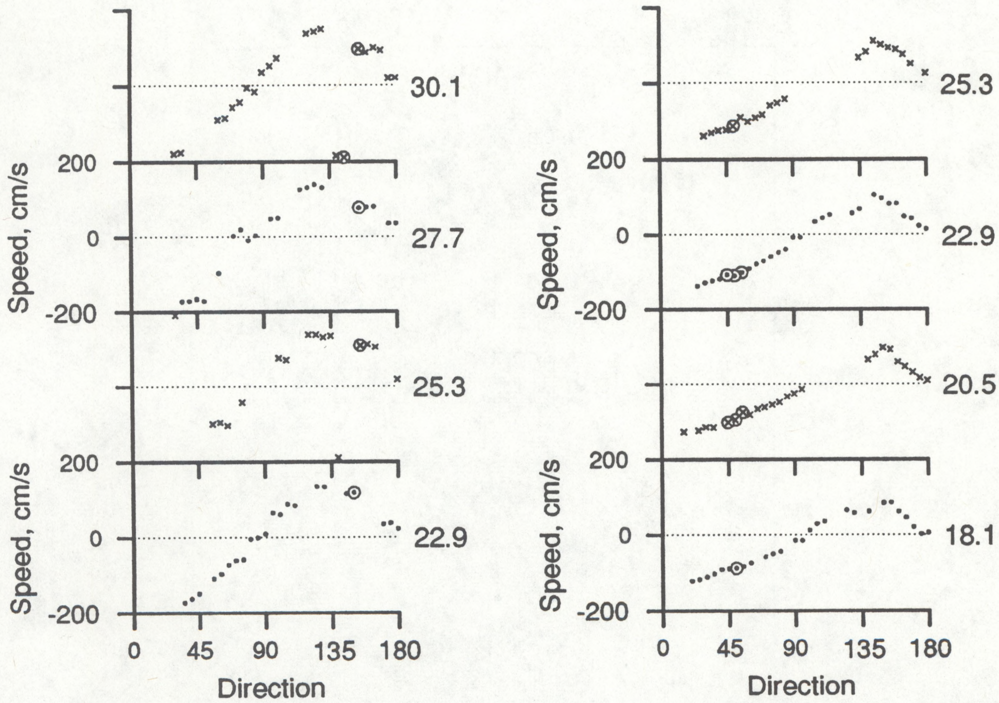


Fig. 20. Radial velocity vs. direction at different ranges (km). Left: Recorded from Fort Lauderdale. Right: Recorded from Miami. Circled values are within 4 km of the offshore erratic vectors on the map in Fig. 19.

ward currents with directions of $12° \pm 6°$ found by the loran buoy that passed through that area. The erratic vectors at locations (9,3) and (10,3) are found to have resulted from radial vectors at three ranges from the south site (Fig. 21) that had values of about $+20$ cm s^{-1} instead of values of about -100 cm s^{-1} that might be expected (see Figs. 20 and 26 for common radial vector patterns in this region). The radial vectors from the north site were in accord with other such data. Notably, there were no radial vectors from the south site within 4 km of locations (9,4) and (10,4) and the CODAR map vectors must have been calculated with data from the north site only.

3.3.3. Incorrect total vectors from accepted radial vectors

3.3.3.1. *Baseline instability*

When the two lines from a measurement location to the CODAR stations are in nearly the same or opposite directions, small errors in the radial vector speed lead to much larger errors in the derived total vectors. The degree of this baseline instability is indicated by the angle between the two lines from a location to the two CODAR stations, the view angle. This is the "triangulation angle" of Leise (1984). Figure 22 shows the angles from the locations used in the present CODAR calculations. Near the baseline, between and beyond the two CODAR stations, small errors in radial velocity give large errors in the total vectors (Leise, 1984). Lipa and Barrick (1983) pointed out that errors in both the derived total vectors and their associated uncertainties (SD) become large near the baseline. They did not discuss the fit error, but its effect will also become large. The SD test will then delete most total vectors with baseline errors, but not all.

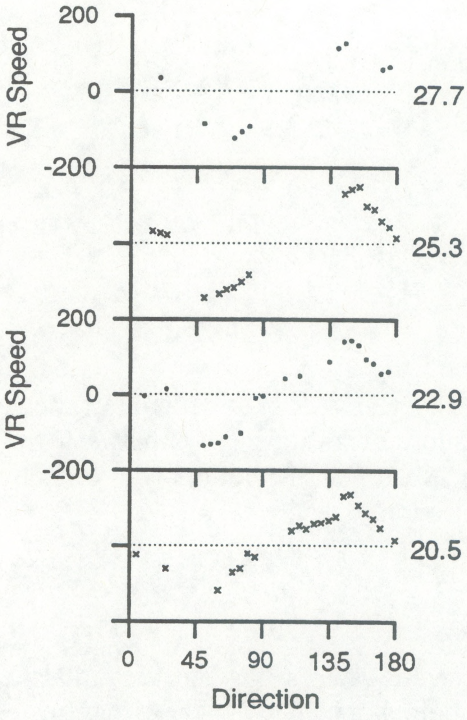


Fig. 21. Radial velocity vs. direction at different ranges (km), recorded from Miami. Several of these values in the northern directions could have contributed to the incorrect total vectors on the CODAR map in Fig. 7 near the north loran buoy.

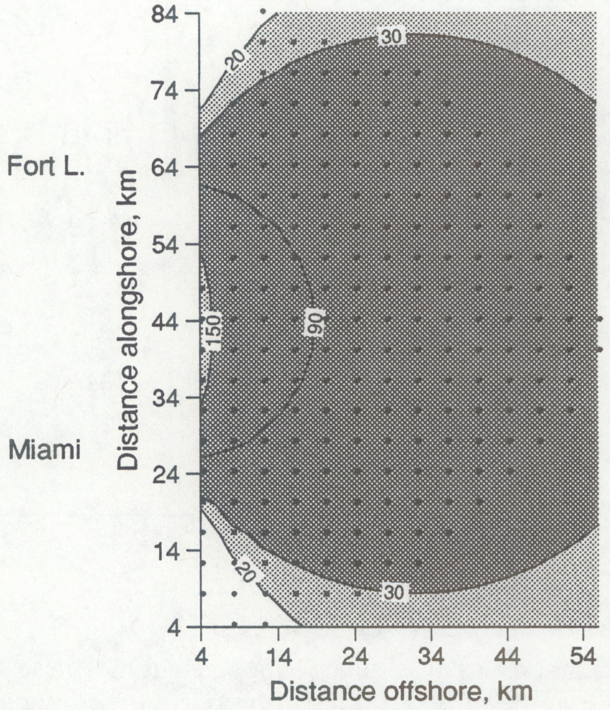


Fig. 22. View angles between the two CODAR stations from different CODAR measurement locations. View angles between 20° and 160° are shaded and between 30° and 150° are shaded darker. Angles less than 20° are not shaded.

This consideration limits the range of locations to be calculated. Lawrence and Smith (1986) showed a maximum view angle of 145° (or 35°), and Prandle (1987) used 160° (or 20°). In defining the locations of the present observations, CSI deleted 12 locations within 15° of north from the Miami station because of obstruction or interference by the bulge in the shoreline north of Miami plus one location in the southwest corner of the array. It is seen using Fig. 22 that five datum locations nearshore between Miami and Fort Lauderdale have view angles of 150° or more, and several in the nearshore areas north and south of the CODAR stations have view angles less than 20°. All the locations with these extreme view angles frequently show erratic current vectors, and their data appear to be degraded by this factor. A large fraction of the erratic current vectors in the SD–edited data set occurred at these locations. At times the westernmost locations also experience strong current shear nearshore. Comparison of this figure with Fig. 5 shows that the nearshore region of extreme view angles also generally has fewer current vectors. The CODAR coverage area does not extend far enough offshore for the view angles to become small.

3.3.3.2. *Incorrect fit*

The CODAR map in Fig. 23 depicts a strong flow to the east at the nearshore location (10,1), which is inconsistent with the known range of circulations there. The view angle at that location from Fig. 22 is 159°, 21° from a straight line. In contrast, the radial vectors in Fig. 24 that could form this

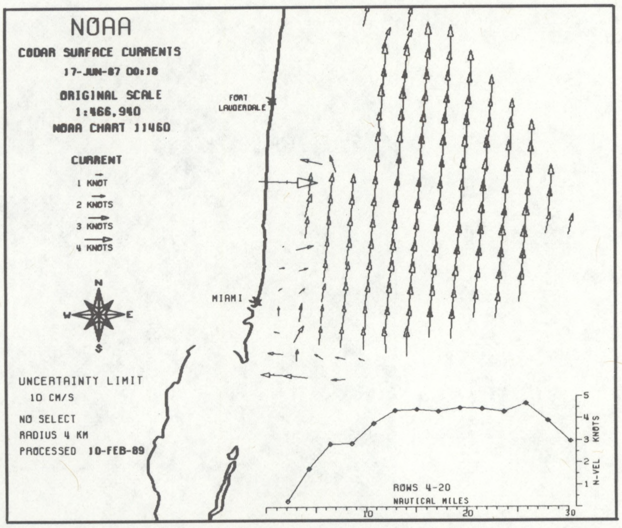


Fig. 23. CODAR map with an erratic vector nearshore at location (10,1) between the stations. Vectors in the bottom two rows also are in question.

total vector are similar to their neighbors; these need not be erratic vectors. Instead, the radial vectors may describe accurately the current components at the points specified by the programs. The CODAR map indicates that the radial velocities producing the total vector at location (10,1) were -80 cm s^{-1} and -100 cm s^{-1}, whereas the effective radial velocities in Fig. 24 were about -10 cm s^{-1} and -170 cm s^{-1}, a poor fit, although even a good fit would not have given a credible total vector.

Barrick has indicated that, where there was large shear in the water, the CODAR combining calculation routine could go astray and give results grossly in error. In such a case, the SD value would be acceptable, even though the result was in error. This bad fit could have occurred here. In addition, the discussion of errors at small or large view angles indicated possible large errors in total vectors from small errors in radial vectors. Here the view angle is only 21° from a straight line, and baseline instability could be significant. The lack of fit between radial and total vectors could not be ascribed directly to this effect, but the baseline errors would also increase the fit errors, and this might contribute some of the discrepancy. In either case, an accepted SD value neither proves that the radial velocities are correct nor that they were correctly combined.

3.3.3.3. *Incompatible radial vectors*

The CODAR map in Fig. 25 shows noncredible, strong eastward flow very close to shore at locations (11,1) and (12,1). The plots of radial velocity vs. direction in Fig. 26 show no grossly erratic values. However, the north site recorded a slow flow very close to the coast near there, whereas the south station, with the nearshore area shadowed from the radar by land, recorded a fast northward-moving flow somewhat farther offshore. The two observations, of different flows, are not compatible. However, the CODAR combining program found all the vectors within a distance of 4 km of the measurement location and combined them. The erratic vectors resulted. This difference in currents within the area about a single location could account for many of the erratic total vectors found at the edge of the Florida Current. With an acceptance distance less than 4 km, fewer such cases would occur. These observations affirm that erratic CODAR radial velocities, ones that seem in question but have passed the CODAR quality test, may in fact be unsuitable to be combined.

Vectors at locations (4,4) and (5,4) in Fig. 25 had no radial vectors from the south station within 4 km and must have been calculated from the north station data alone.

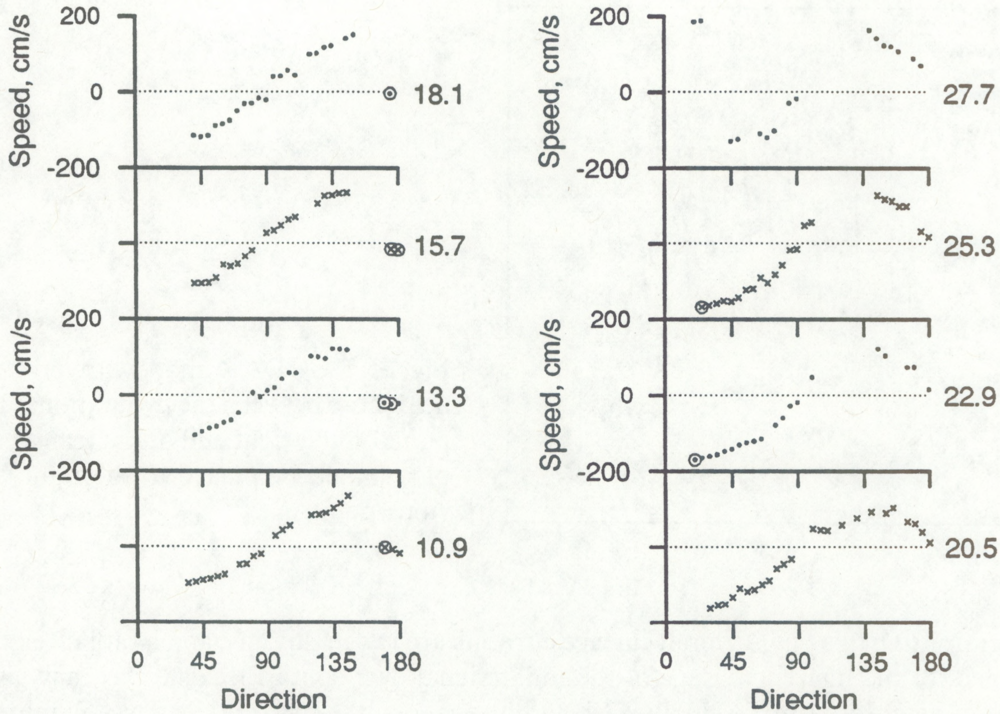


Fig. 24. Radial velocity vs. direction at different ranges (km). Left: Recorded from Fort Lauderdale. Right: Recorded from Miami. Circled values are within 4 km of the erratic vector in Fig. 23.

3.4. Causes of Erratic and Missing Radial Vectors

3.4.1. Signal from the ocean

3.4.1.1. *Signal from more than two directions*

CODAR calculations of the directions from which a particular reflection arrives all assume that the signal at one frequency (or radial velocity) and one range arrives from only one or two directions. In the uniform flow offshore in this area, that assumption is mostly correct. Under such conditions the CODAR calculations can give correct results. Figure 18 shows the radial velocities expected from a single CODAR station over a 60–km–radius area with an alongshore flow. The northward ocean current speed increases steadily with distance from shore, but a weak countercurrent nearshore was included in the calculation. Of course, the strongest inflow component is in about the southeast direction and the strongest outflow in about the northeast. On either side of the maximum inflow and maximum outflow, a particular lesser speed is found in two directions (e.g., the two a's in the southeast quadrant and the two b's in the northeast quadrant). However, with zero radial velocity there can be frequencies with three directions in one range cell (the three c's in the ocean), and the calculation of radial velocity may fail. Furthermore, with a counterflow parallel to shore as shown, there may be an additional direction from which signal returns for a number of other speeds (the third a and b near shore), giving a larger group of possible failed calculations.

The estimated area of possible radar signal return from south Biscayne Bay is also represented in Fig. 18. Although the radar signal would have to travel over 4 km of a low–lying island before beginning to pass over water, such distances have been observed with HF radar energy traveling over land (Marex Technology, Ltd., personal communications, 1989). Other islands not shown restrict the possible area

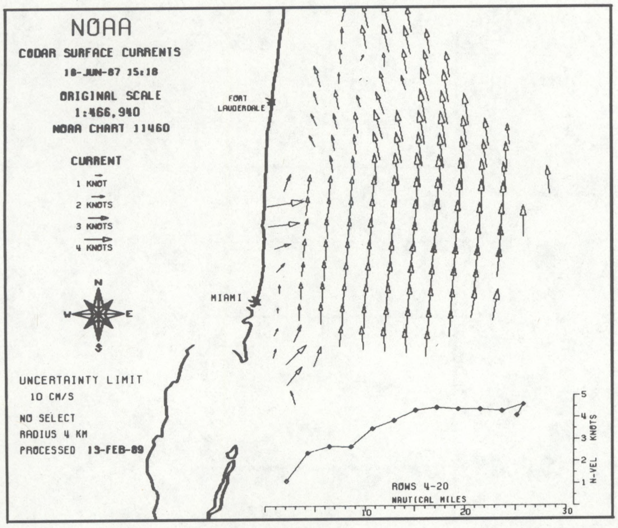


Fig. 25. CODAR map with erratic vectors nearshore between the two stations. The erratic point on the right end of the transverse profile plot should be placed to the right of the previous point.

of radar return from this bay. Overall surface currents are low in this bay, and a radial velocity of zero was assumed for the figure. Passage of the radar signal over south Biscayne Bay may give an even larger area of near-zero radial velocities (the additional c in the bay) and lead to still more incorrect direction calculations with signal from possibly four directions. More complex surface flows offshore can lead to different cases of signal at a frequency arriving from more than two directions.

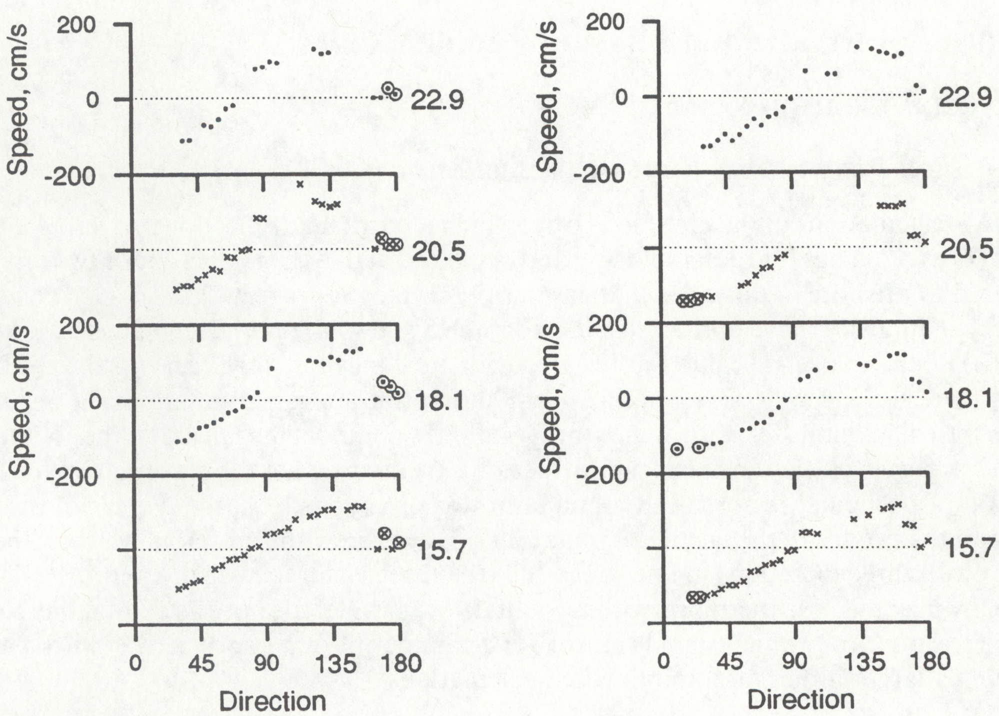


Fig. 26. Radial velocity vs. direction at different ranges (km). Left: Recorded from Fort Lauderdale. Right: Recorded from Miami. Circled values are within 4 km of the erratic vectors between the CODAR stations in Fig. 25.

3.4.1.2. *Insufficient radar signal*

The fraction of the CODAR runs in which there is a radial vector at a scheduled location is plotted both vs. range and vs. direction in Fig. 27 for each CODAR station. The range dependence from the two stations is similar. The low fraction values at small range must result from the geometry near the stations and do not indicate decreased CODAR performance in that area. The coverage is nearly uniform to a range of 40 km, then it decreases steadily to a range of 60 km. Only at the outer portions of the CODAR area need the limited range of a CODAR signal restrict the total current coverage by the system.

The direction dependence of the radar signal shows shadowing in the northernmost directions, as expected from the presence of large buildings across the shipping channel from the north station and a slight outward bulge of the coastline north of the south station. The plot in Fig. 27 for the station at Fort Lauderdale showed nearly uniform coverage in the other directions, but that for the station at Miami contained a deep trough in directions near 120°. The major difference between the plots from the two stations must result from the locations of the antennas. A rubble jetty extends into the ocean about one-half kilometer beyond the CODAR antenna at Miami (see Fig. 1), and that electrically complex structure (a pile of rocks wetted with salt water) appears to have produced this major defect in the CODAR signal passing over it. A smaller amplitude of the signal in that direction was not reported from the antenna calibration that was conducted when the CODAR station was installed.

The effect of this trough at the south site on the distribution of total vectors may be seen, sometimes only as a cutoff to the south, in many CODAR maps, including those shown in this report. Figures 7 and 17 provide good examples.

3.4.2. Signal from ship echoes

Nearby thunderstorms and possibly radio radiation from electrical equipment must have interfered with the CODAR signal at times, and several other causes seem possible, but their effects on the present data were not investigated. This section discusses only ship echoes in the CODAR spectra.

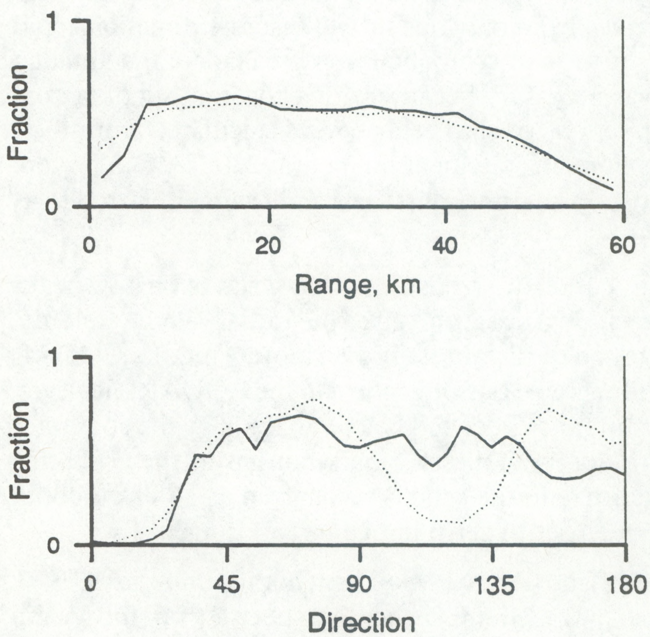


Fig. 27. Averaged fraction of CODAR runs that had radial vectors at a location vs. range and vs. direction, at Fort Lauderdale (solid) and Miami (dotted).

3.4.2.1. *Identification of ship echoes*

The set of spectra from one CODAR run (Fig. 28) is representative of the initial results from Miami. Each spectrum is dominated by two increasingly broad first-order peaks located 0.5 Hz on either side of the zero Doppler frequency center of the plot. All ocean current data are derived from these two peaks. The amplitudes of the spectrum estimates within the first-order Bragg wave peaks are highly variable, dependent on several varying factors. Interference by buildings near shore and by land removes some segments of the azimuthal coverage from the spectra, giving a dip in the peaks at particular frequencies. In addition, a trough is often seen in spectra from the Miami station at frequencies representing radial velocities in the direction of the Miami jetty, whose interference to the radar waves is discussed with Fig. 27 in Sec. 3.4.1.2. Also, a peak at a Doppler frequency representing near-zero current might result from an additional area of low-speed currents in Biscayne Bay, as described in Fig. 18 in Sec. 3.4.1.1.

In addition, a number of narrow peaks are seen in Fig. 28 outside the first-order regions. Peaks at a Doppler frequency near + 1.5 Hz are seen at eight ranges between 15.7 and 32.5 km. Another series of peaks occurs near frequencies of -1.5 Hz at ranges between 20.5 and 30.1 km. Barrick found that ship echoes could cause erratic radial vector values, and this possibility has been investigated (McLeish and Maul, 1988). Spectrum variance resulting from the echo from a ship will occur at the range and at the frequency within a spectrum that corresponds to the ship radial velocity. If the echo occurs within a first-order peak, it could destroy the calculation of radial vector direction at the ranges and frequencies where it occurs. In the present examination, it is not possible to detect ship echo energy in these regions. If, on the other hand, the echo occurs outside the first-order peaks, it will not affect the ocean current calculations from that spectrum, but its presence and amplitude within the spectrum can be evaluated. After being identified, ship echo peaks in spectra were examined in this study in an effort to estimate the frequency of occurrence and amplitudes of these possible interferences to the calculation of CODAR radial vectors.

The correctness of identification of ship echoes in CODAR spectra was demonstrated in part through correlating the echoes with directly observed ship positions and in part through comparison with known ship speeds and directions of travel. The calculations with the first-order regions of CODAR spectra that lead to the radial vectors also can give the directions of any sufficiently well-defined and unique echo in other frequency ranges. After all, the CODAR assumption is that at a single frequency and distance the radio return arrives from only one or two discrete directions, and that is what a ship echo does. CSI provided the software in symbolic form to calculate the antenna calibration factors for the individual runs. This was necessary because with a constant set of factors the results were inaccurate and variable. The directions of ship echoes were calculated from their amplitudes on the crossed-loop antennas with the Fortran statement dir = atan2d(C23, C13), where C23 and C13 are the cross spectra between the two loop antennas and the overall signal referred to as the monopole antenna voltage.

Ships moving toward or away from a CODAR station are recognized by a series of narrow peaks in adjacent range cells. The frequency of the peak within a spectrum gives the radial velocity, and the set of range cells containing the peaks gives the range of distances to the ship during the CODAR transmission time. Motionless objects such as buildings give a strong return to the CODAR; however, the return appears in the spectra at zero Doppler shift and is deleted before analysis by the computer program. Anchored ships, on the other hand, are not motionless. Small motions of these floating bodies give small Doppler shifts to some of the return, and the echo is recognized as a peak on both sides of zero frequency (where the spectrum has been set to zero) in one or two range cells.

The aircraft carrier U.S.S. *Saratoga* anchored offshore in the Miami anchorage on April 4, 1987, for a weekend visit to Miami. While the carrier was in the Miami anchorage, spectra from the Miami

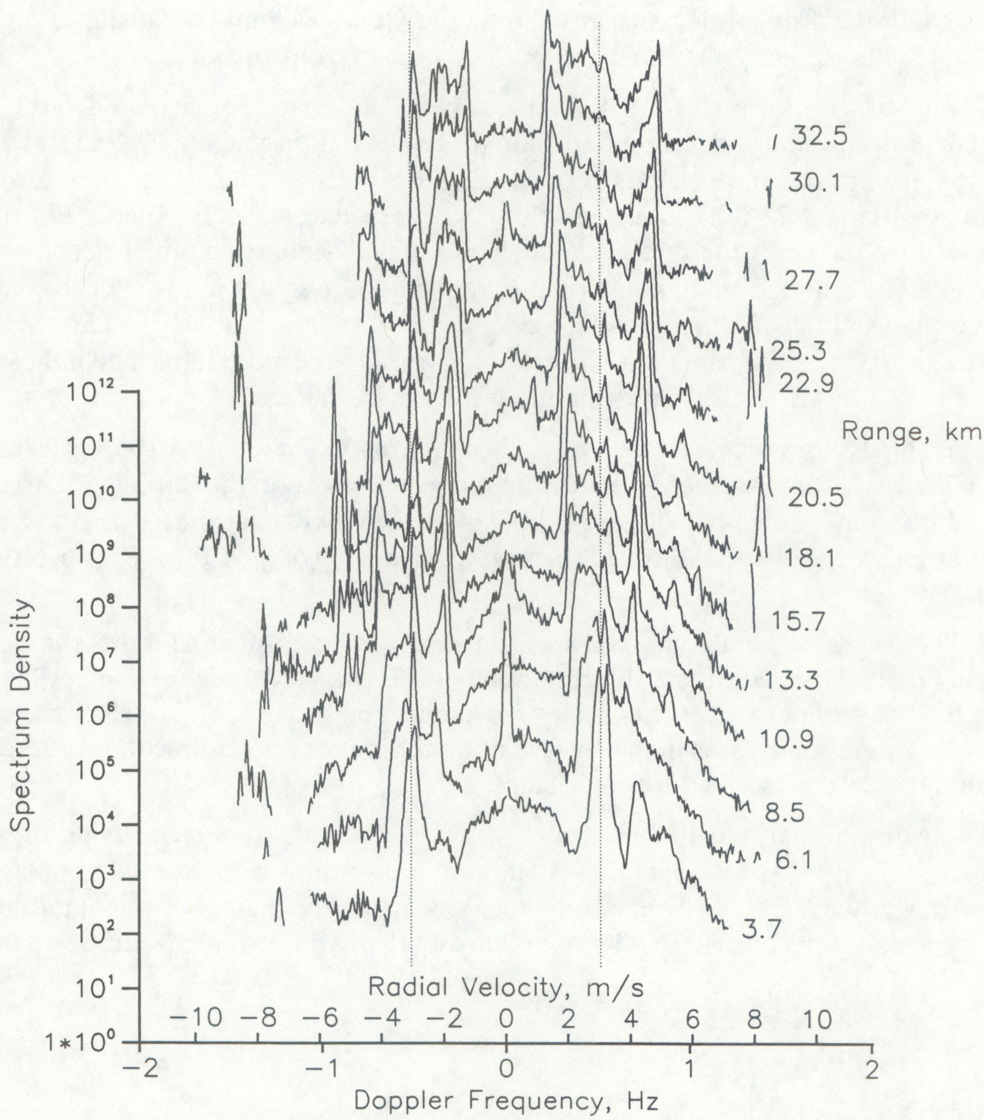


Fig. 28. Series of spectra of input voltages at Miami at consecutive ranges. Doppler frequency is the difference from the transmitted frequency. Radial velocity is inferred from the frequency.

CODAR station were recorded regularly on magnetic tape. The anchored ship could be seen by eye from the top of that CODAR van, and its direction was measured to be 70°. The echo from the anchored ship appeared regularly in the spectra in the first and second range bins. It was only through small motions of the ship that it was detectable to CODAR. An average of the 25 CODAR readings of the ship direction was 72°. The SD of 2.8° included both CODAR variability and swinging of the ship about its anchor. Thus the CODAR observations recorded the direction of that anchored ship with only small errors.

Anchored ship positions in a series of six CODAR runs on June 13–14, 1987, were 6.1 km at 75° from Miami and 33.7 km at 174° from Fort Lauderdale. A pair of CODAR runs on June 25, 1987, gave positions of 6.1 km at 44° from Miami and 32.5 km at 178° from Fort Lauderdale. These values give differences between the location readings from the two sites of 1 km and 2 km, whereas the spacing between range cells is 2.4 km. By locating an echo source within one range cell distance with two separated CODAR stations, the system further identified echoes from anchored ships.

The Miami–based cruise ship SS *Scandinavian Sun* operated for a period on a fixed daily schedule. It departed Miami and passed the Miami CODAR station at about 0900 LT, then proceeded at 10 m s^{-1} to Freeport, Bahamas Islands, on a heading of 60°. It returned from there, also rapidly, to arrive at Miami at about 2200 LT. Because of the ship's regular schedule, speed, and route, it was possible to identify and study the ship's echoes. The CODAR–indicated radial velocities and directions of three sets of echoes from this ship on different dates are shown in Fig. 29. The outgoing ship track showed changes in direction and radial velocity at near ranges, but the irregular variations were only about 2° and 0.2 m s^{-1}. Farther out, the incoming tracks were more stable and indicated that the variability of the CODAR readings was not more than these values.

When the ship RV *Researcher* departed Miami on March 23, 1987, the CODAR tracked it through five to six range cells, and its positions were compared with those from the ship's log. Directions averaged 3° different from those in the log, about 1 SD of the CODAR values. Speeds averaged 0.4 m s^{-1} greater than from the log of speed through the water, again 1 SD of the CODAR values, or 5% of the total speed.

Figure 30 shows the indicated ship tracks during the 36 minutes of the CODAR run that also gave the spectra in Fig. 28. Some latitude in interpretation of the echoes exists, in particular whether a chain of peaks in the spectrum at successive ranges represents one ship or two at nearly the same radial velocities. There were some cases in the spectra of double peaks whose directions differed by only a small amount; these were ascribed to single ships.

The ship with a radial velocity of +8.4 m s^{-1} in Fig. 30 was probably arriving from Freeport, Grand Bahama Island (60°), a frequent destination of cruise ships from Miami. Similarly, the ship with a radial velocity of -7.9 m s^{-1} may have been departing for there, but the outermost location plotted on the figure seems inaccurate. The two ships south of Miami were moving down the Straits of

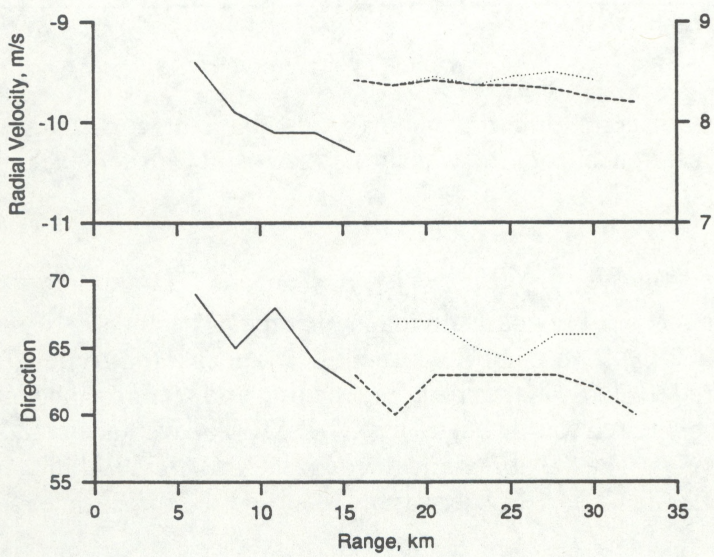


Fig. 29. Readings of a ship recorded by the station at Miami during three CODAR runs. Top: Radial velocity vs. range. Bottom: Direction vs. range. Readings of the ship while it departed (left) are given by solid lines, and those while it arrived (right) are given by dotted and dashed lines.

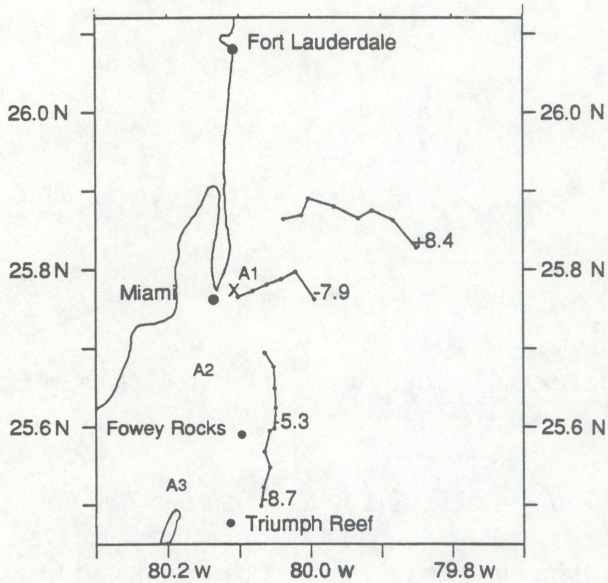


Fig. 30. Tracks of four ships calculated from CODAR radial velocity readings during one run (that gave the series of spectra in Fig. 28) at the CODAR station at Miami. Radial velocity (m s^{-1}) accompanies each track line. Possible anchored ship locations indicated by echoes are denoted by A1–A3 and X.

Florida toward the Caribbean Sea. The ship with a radial velocity of –8.7 m s^{-1} was represented in the spectra by some double peaks in slightly different directions. Ships moving south in the Straits remain close to shore to avoid the strong oncoming Florida Current but must remain outside the shallow water at the reef offshore, whose edge is marked by the Fowey Rocks and Triumph Reef light towers.

An anchored ship northeast of Miami (A1) is in the same location in Fig. 30 as one recorded from Fort Lauderdale (X), within a difference of about one range cell. There is a 180° ambiguity in each direction calculation. Commonly, it is obvious which direction to a ship is the correct one to use, since the other is on land. However, sometimes in the vicinity of the Miami CODAR station, both directions may be possible. Two other anchored-ship locations determined from echoes in the Miami CODAR spectra were plotted in south Biscayne Bay (A2, A3); less probable alternative locations were to the north, but the actual location is not known. These data suggest that a radar echo could come from the bay and thus signals could arrive from an additional direction, a situation in which the CODAR direction-finding algorithm will yield either incorrect or no values.

Ship echo locations in a ship track show mostly close fits to straight lines. The individual direction readings are indeed highly precise. It appears that accuracy of the technique of measuring single directions from crossed loops might be determined with echoes of ships moving toward or away from the station. Since direction calculations are based on values of gain and phase shifts for each of the crossed loops, recalculated for each CODAR run, comparisons of ship echo directions could also constitute a validation of these electronic performance parameters. How often the amplifier values must be recalibrated is not known, but successive calibrations at 3–h intervals varied greatly.

3.4.2.2. *Properties of ship echoes*

From a set of 64 CODAR runs in 1988 from the two sites, 513 moving–ship echoes were identified in the spectra. Echoes from ships moving so that their reflections either fell within a first–order region or varied significantly in frequency were not identified or included. Figure 31 shows the frequency of echoes from moving ships identified in the spectra at each range extending to 40 km. This figure shows that many range cells of a spectrum contained at least one moving–ship echo. Smaller frequencies of identified echoes at small ranges may result from a ship maneuvering near the harbor entrance and so

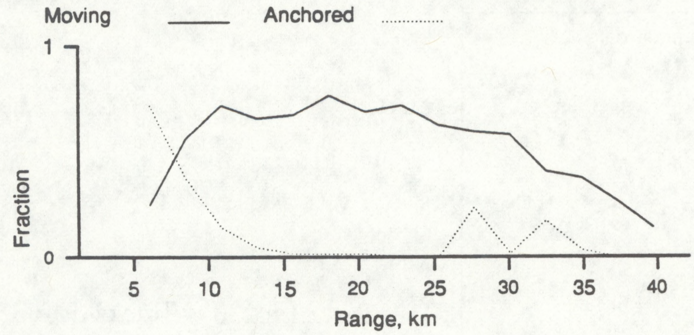


Fig. 31. Fraction of the set of spectra containing recognized ship echoes at different ranges.

not being identified, and the decrease at large ranges may result from weak signal near the noise threshold at the outer limit of CODAR coverage. The frequency of anchored-ship echoes observed from Miami is also included in the plot. Most anchored ships were in the Miami anchorage; some were recorded from Fort Lauderdale, about 35 km distant. Ship echo contamination, then, can occur not only near a station but probably also throughout the entire CODAR coverage area.

The amplitude of moving-ship echoes relative to the peak in the first-order regions was not seen to change with range. Readings of the relative echo amplitudes in 80 ship tracks that were recognized in at least four consecutive range cells from the 64 CODAR runs gave an average decrease of 0.16 dB per range cell with an SD of 1.6 dB. Thus, no trend was evident. Naturally, ship echo amplitudes decrease with range, but so do ocean echoes, and in fact all radar signal often is lost in noise near the range limit.

The spectrum amplitudes of moving-ship echoes were clearly smaller than the peaks in the first-order regions of the spectra, an average of 27 dB less. However, the ship echoes often were not small in comparison with the minimum values within the first-order regions, and these too were used to calculate radial velocities. A count of 247 echoes gave an average of 4.7 dB less and an SD of the differences of 12.4 dB, not a major difference. In addition, however, nearly one-half of these ship echoes were at least as great as the smallest ocean echoes in the adjacent first-order region. As a consequence, many of those ship echoes that fall within the first-order regions of a spectrum will surely interfere with the CODAR direction calculations.

The ship echoes examined here did not lead to incorrect CODAR readings, since they altered only the second-order region of the spectrum and the CODAR calculations obtain ocean current speeds from values in the first-order portion of the spectrum. Other ship echoes with radial velocities of about $\pm$(2–4) m s^{-1} could, however, lead to incorrect CODAR values. In addition, the moving-ship echoes could contribute a large part of the measured noise level of the system and cause weaker portions of the first-order region to be omitted. These observations of ship echoes in the radar spectra show that such effects can give both gaps and errors in the calculated currents on CODAR maps.

4. DISCUSSION

4.1. Variability of the Quality of CODAR Maps

Some of the present CODAR maps are of impressive high quality, as, for example, in Fig. 2. They have good coverage of a significant area, nearly all of the vectors appear consistent with each other, and the flow patterns are credible. Many other maps, however, have much less coverage, gaps within some sections that do have data, and a number of vectors that are wildly different from their neighbors. A few apparent causes of these discrepancies were discussed in Sec. 3.

4.2. Properties of the Radio Signal

4.2.1. Signal from other than the water

Inherent in CODAR calculations is the assumption that the signal to be processed was reflected from the water; all other is noise. Yet a significant amount of extraneous signal energy apparently enters the calculation procedure and has not been separated from the data. The signal reflected from ships was examined in Sec. 3.4.2, but there was also electrical noise from the atmosphere (several thunderstorms occurred close to the stations), the sky (solar and galactic radio noise), and radio interference. Although much of the noise will be removed by the filtering, the observations in Sec. 3.4.2 show that ship echo was not removed by this means. In addition, a 0.1–Hz noise beat component could be seen in earlier spectra from the filtered signal, although its origin was not found.

4.2.2. Signal directions

As noted in Sec. 3.4.1.1, the radial vector direction–finding calculation is based on the assumptions that at a single range all of the returned signal was reflected from the ocean in only one or two directions (delta–functions) and that signal arrived from within a specified direction range covering 180°. The considerations in Sec. 3.4, however, show that signal reflected from the ocean could arrive from more than two directions, and echoes of anchored ships were identified from both within and outside the 180° direction range that the computer programs were designed to use. Many of the observed erratic current vectors may have resulted from these assumptions not having been satisfied.

Furthermore, of necessity, CODAR transmitter sites generally will have some limitations on the possible radar coverage of the ocean. In the case presented here, both sites had some obstacles to the north and therefore limited coverage in that area. However, in some cases, the calculations found radial vectors in the obscured regions where they could not actually be. As noted in Sec. 3.4.1.2, the south site had decreased signal strength in the direction of the jetty. These factors were not taken into account in the computer programs, and additional missing and erratic radial vectors must have resulted.

Finally, several measurement locations on the calculation schedule had extreme view angles to the two sites, and ocean current vectors should not be calculated there. These limitations led to some poor CODAR vectors.

4.2.3. Signal from nonuniform ocean currents

The program that forms total vectors from radial vectors from each site first collects all accepted vectors within a defined circle about the total vector location to be analyzed. The calculation assumes that all vectors within that circle apply to a single current speed and direction or that radial vectors from the two sites represent to proportional extents the different currents within the circle. If different currents occur within one resolution cell, it must be assumed that the amount of signal returned from the ocean toward either site is the same in the different currents. Furthermore, each radial vector that has passed the SD test is assumed to be accurate.

In actuality, these assumptions need not be correct. Drastic differences in radial velocity exist between locations on opposite sides of an ocean front extending along the inshore edge of the Florida Current. Because ocean waves of the Bragg frequency crossing an oceanic current shear zone may be refracted, sometimes greatly, the reflectivity of the ocean to the CODAR radio waves must at times be very much different on the two sides. The differences will not be the same toward CODAR stations in different directions. This leads to combining radial vectors that do not all represent the same locations; to combine them is meaningless.

4.3. Calculation Procedure

4.3.1. General method

The general procedures by which CODAR measures ocean surface currents were described by Georges (1984). A mathematical analysis applicable to the crossed–loop amplitude–measuring antenna supplied for this project was described by Lipa and Barrick (1983), and the general plan of the calculation procedure is included there. An outline of the computer program set was given by COS (1987); the specific computer programs that processed the CODAR readings are proprietary to COS.

The voltage readings collected during a CODAR run at one station are sorted, filtered, and transformed to spectra. A set of radial vectors and their SD values is calculated at each site. Data from the two sites are combined into total vectors that are plotted on a CODAR map.

4.3.2. Initial corrections

During a 34–min run scheduled every 3 hours, one CODAR station makes more than 100 million voltage readings. The very heavy filtering in the calculation procedure removes large amounts of radio noise and allows for high accuracy of most current vectors. However, this step is entirely a smoothing, with no deletion of errors in the data; grossly incorrect voltage readings will still influence the product, although to a diminished degree. Identification and replacement of large noise values is not attempted in this program, although such a procedure would eliminate the effects of the erratic voltage readings that were obtained.

4.3.3. Least–squares fitting

A maximum–likelihood procedure is considered the optimum method of extraction of parameters from signals containing statistical fluctuations (Lipa and Barrick, 1983). Indeed, when the data fluctuations are Gaussian, the least–squares method accomplishes this. Through an iterative search routine, the calculation procedure used in this study found the vector whose rms difference from the data leading to it was a minimum. Each calculation minimized the sum of the squares of the differences between the input parameters and those of the calculated value.

In the present data sets, the voltage readings appear to contain a significant number of grossly incorrect values. With this calculation procedure the incorrect input values have an increased deleterious influence on the product. As a result, some incorrect values were produced and were applied in the further calculations.

In addition, these fits were found with an iterative procedure. Under some circumstances, such as with a very large view angle, the highest accuracy is required, but the iteration procedure stops at a predetermined stage.

4.3.4. Standard deviation acceptance tests

In the present program, each calculated vector was subjected to the SD test, an acceptance test that judged how well the derived value fitted the filtered data. A certain poorest–fitting fraction of the values were deleted. The SD test was intended to reject extraneous radial vectors, those with signal from more than two directions or with excessive noise and those that did not fit into the conceptual model. However, the statistical variability in the initial voltage readings led to a statistical variability in the SD values. Most decisions based on SD are correct, but because of this variability not only were some correct values deleted but also some incorrect ones were accepted. Some of the missing data on CODAR maps and some grossly erratic vectors that appear on them are attributed to this factor.

For this project, the SD acceptance tests for total vectors were based on the individual radial vector values only. Some CODAR programs in other projects apparently smoothed the calculated values so that they were altered toward some preconceived notion of the actual flow, but the CSI/COS writers of the present CODAR programs rejected that approach except in the Select program. The present test used only the data from which a value was derived to test that result. There was no test with other CODAR readings, such as those in adjacent ranges or in nearby directions, which would compare differences with what might be expected for this section of the ocean. Also, except with the Select program, there was no comparison of the derived total vector values or their differences with assumed limits for the ocean surface currents or their rates of change at each location. As a result, some of the current vectors produced can be seen directly to be impossible. For example, a current speed of 4 m s^{-1} directly away from shore at location (10,1) in Fig. 23 with an average distance from shore of 4 km is not a realistic result. Inclusion of further constraints would be expected to improve the CODAR maps.

The Select program itself removes an entire group of surface current values, some of which must be wrong but many of which must be correct. This removal of correct data leads to deletion of important features of the surface circulation and to an even smaller data coverage of the area intended. Such loss of real circulation features cannot be accepted for many purposes.

4.3.5. Possible remaining computer program errors

The computer programs might still contain errors. One error was detected during examination of the early preliminary data at AOML, another was corrected by COS in preparing the final version of the programs, and two others were found in the added Select program. The limited quality of the CODAR maps, with the many missing and erratic vectors, does not have to be ascribed solely to the external factors already discussed or to the inadequacies in the calculation procedure described here, but some poor results might result from undetected computer program errors. For example, it is not apparent how observed features of some maps, such as entire bands of erratic total vectors in an arc, could have resulted solely from the physical factors discussed here.

4.3.6. Postulated calculation instability

Barrick suggested that, in certain special cases, an iteration procedure might not settle on a nearly correct result from a set of input parameters but might gravitate instead toward a wildly different result. This effect might be similar to the varying results in unstable iterative calculations. The instability would occur in regions where other measurement problems also are found, and the erratic values studied here could have resulted from other causes.

4.3.7. Departure of ocean wave phase speed from linear dispersion theory

Since the CODAR current measurements subtract ocean Bragg phase speed from the total radial speeds, they are dependent on accurate knowledge of this phase speed. The accuracy has been questioned (LeBlond, 1985). Barrick (1986) examined the conditions under which higher-order terms in the wave equation would change the phase speed and found that this error is small when the Bragg waves have a much higher frequency than the peak of the ocean wave spectrum. This was normally the case in the present observations, but an error from this source is possible.

4.4. Recommended Operating Changes

Examination of the CODAR data collected during the measurement period suggests that some changes to the CODAR system could provide better results. The performance of electronic components and certain aspects of the system operation are here assumed to be optimum, but other functions did not seem to be suitable for the conditions encountered.

In further studies, the remote CODAR sites should be on the shore of a straight coast, as was assumed when the software was written. They should not be on an island with an appreciable extent of water behind it, near the base of a jetty, or blocked from portions of the ocean by buildings. CODAR total current vectors should be calculated only at usable locations: those with extreme view angles or shadowed from a transmitter should not be calculated.

In the original voltage readings, erratic readings possibly recognized by their large values (ship echo), or by their differences from readings at the same range in previous or later pulses (radio noise) should be replaced with appropriate substitutes.

To avoid many erratic vectors, initial datum values possibly contaminated by ship echoes might be removed before the spectrum analysis by deleting anomalously high voltage readings. Although some incorrect and missing values would be recovered by this change, it would not be expected to correct all erratic CODAR vectors, partly because the CODAR return supplemented by ship echo will not always be readily detectable, and partly because there are other probable causes of some erratic CODAR vectors.

To reduce the effect of greatly erratic radial vectors when a total vector is calculated, each fitted total vector could be tested with the first instead of the second power of its differences from the radial vectors. For example, a mean absolute deviation (MAD) approach could be used. Alternatively, instead of a best-fit calculation, a median filter approach could be used to reduce the effect of greatly erratic input data. In another apparently well-used approach, when radial vectors are combined into a total vector, a program could average the accepted radial vectors from each CODAR station, then solve for the total vector analytically instead of finding a best fit for the entire set of radial vectors. Each output vector should be tested with information about possible circulations in the sea. A program would specify what velocities are possible at each location. Limits on differences between adjacent locations could be set. Limits on the amount of change at a location from its value on the previous map could be chosen based on earlier direct studies of the currents in the locations.

Possibly the best technique would compare each new set of total vectors from a CODAR run with a routinely running numerical model covering the area to be studied. When a fresh data set arrived, it would be integrated with the existing circulation pattern into a new pattern. After some time with a series of CODAR maps, a good representation of the current pattern would be expected to develop. Data from locations missing on one map would be available from previous times, and erratic CODAR total current values would have been removed. By using an entire series of CODAR maps to develop the latest map, one could expect an improved real-time surface circulation pattern. A dynamic model would give the best results, but even a program that simply retained the accepted vectors from a few previous maps would be useful. That model need represent only the surface flow pattern.

5. EVALUATION

5.1. Character of This Project

All previous operations with CODAR were temporary, short–term data collection periods, often less than 1 month. The systems were operated by those who designed and built them, and the CODAR products were examined and evaluated by the operators. It appears possible that in some cases additional data processing or selection had been performed before publication. The earlier projects were performed in order to develop the radar and calculation techniques, to conduct research on the ocean, and to demonstrate what the system could furnish.

For this operation, the CODAR system was a long–term operational installation that could have been made permanent. The equipment was designed by CSI to operate autonomously, but it was to be monitored and occasional equipment maintenance provided. CSI provided frequent advice on maintaining the system, but most details of its operation were not available to the operators. Except for the overlap between the areas contributing to adjacent vectors, each of these current readings was derived without reference to the others. The CODAR products were to be examined by groups other than the developers, and results were to be evaluated by these others for their various purposes.

According to the proposal for this project, our study was to test the readiness of the CODAR system for routine operational use. Thus we evaluated the CODAR for operability of the system, the quality of the product, and the usefulness of the results.

5.2. Operability of the CODAR System

5.2.1. Equipment

Most of the electronics equipment consisted of components from previous four–element antenna CODAR systems, and were of older design and construction. Before installing the new system in the Miami area, the contractor, CSI, refurbished the electronics, provided new front–end electronics and crossed–loop antennas, and installed into the three computers almost entirely new software to control the revised mode of operation of the system. The electronics of the refurbished system performed during the CODAR operation period for the most part as had been designed.

The equipment at the remote sites was installed in portable vans during the operation period. Neither the vans nor the antennas suffered any vandalism during the nearly 3 years that they were in place nor were they damaged by major natural hazards, such as lightning or large ocean waves. The vans were both air conditioned and dehumidified to protect the electronics. The high salt content of the air at the shore probably caused the repeated failures of the air conditioners; during a period when one van was open to repair an air conditioner, moisture entered and damaged some electronic equipment. Power failures in the van led to a few equipment problems, and the aged computers failed a few times.

A daily log was kept of the system operation during weekdays. At irregular intervals, the CODAR system ceased producing the 3–hourly current maps and required maintenance. The central–site computer at AOML was used to diagnose the problem, and sometimes, about once a week on the average, the system could be reinstated solely through computer operations from AOML. Frequently only the telephone linkage sections in the computers needed to be reset. When repairs from the central site were not successful, a trip to the remote site was required, at irregular intervals again averaging about once a week, to reinstate the system. Frequently only the computer there needed to be rebooted or the modem reset. Repeated efforts were made to avoid the computer problem, but it recurred.

5.2.2. Instruction manual

Operating instructions and a partial description of the CODAR system were provided by CSI in their manual, *The CODAR Handbook*, dated May 1987. This Handbook was not written directly for the existing CODAR setup; it contained extensive sections of information that did not apply to the present system. The manual did describe some tests of the system performance, but did not give the criteria for an accepted test. Three contract reports were also furnished to AOML during the project. Maintenance manuals for the different items of electronic equipment had been obtained by NOAA with most of the equipment, and instructions for the new front-end electronics were not needed by AOML.

Review of *The CODAR Handbook* demonstrates that the present CODAR system is not a routine and autonomous operational tool. Instead, it can be understood only by someone familiar with computer programming and requires detailed knowledge of several specific features of the programs in the system.

5.2.3. Personnel required

As the system was configured, a computer operator and an electronics technician were required to be on call. Unless extended equipment outages were acceptable, the people needed to be available whenever the CODAR equipment malfunctioned. A range of skills is needed for routine and minor maintenance of the electronics, but major equipment failures require factory repair.

5.3. Product Quality

5.3.1. Current maps from other projects

Literature reports of previous ocean current radar operations can provide a standard against which the present CODAR maps may be compared.

The CODAR equipment used in this project had been used in a four-element-antenna configuration in the Palm Beach area of the Straits of Florida in 1983 and 1984. Schott et al. (1985, 1986) analyzed the results, but the articles did not present current vectors. Good results were generally indicated, but some problems were reported. A crossed-loop antenna system was used later in Delaware Bay (Barrick et al., 1985; Porter et al., 1986). In the calculations for that experiment, the radial vectors from each site were averaged before they were combined into total vectors. In contrast, the present calculation combined all radial vectors in the accepted region into one total vector without differentiating the source of the radial vectors. This calculation is considered to be a further development of the analysis technique. Current maps that were shown from the Delaware Bay experiment contain about 140 vectors, often with only 2 or so vectors that were not consistent with their neighbors.

CODAR maps from four-element-array HF experiments in Germany (Gurgel et al., 1986; Essen et al., 1989) contain about 125 current vectors, each consistent with its neighbors. A British narrow-beam HF radar system, the Ocean Surface Current Radar (OSCR), has shown repeated good results. Prandle (1987), Matthews (1988), and Matthews et al. (1988) presented maps with about 100 vectors, only a few of which were inconsistent with their neighbors, and Hammond et al. (1987) presented maps with about 35 vectors that appeared regularly.

5.3.2. Current maps from this project

Although when the CODAR was running it normally gave a sufficient number of maps in a day for the present use, the overall map success rate was modest (see Sec. 3). Major gaps in the map series resulted from equipment failures. Had these gaps been reduced by more aggressive maintenance, the map production rate might have risen from 63% to an estimated 80%.

In addition, the average map contained many fewer current vectors than had been expected; some maps had nearly none. In comparison with the maps produced in other projects (Sec. 5.3.1) and the potential for nearly 200 vectors/map from this system, the direction–edited CODAR maps from the present study contain an average of 62 vectors. The maximum daily average (of seven or eight maps) is 109 vectors (the day of Fig. 2). In one respect, the SD–edited CODAR maps for 1988 in this report are an unrepresentative sample of the coverage in the total 1988 set of CODAR maps. The average number of vectors in the SD–edited maps that are shown in this report is 123, not 62. Although the map coverage is a function of the wind speed, that speed was rarely extreme enough over a sufficient time period and area to preclude CODAR operation.

CODAR current vectors representing the strong northward flow in the Florida Current showed good accuracy. Comparison with drifting buoy measurements generally gave differences less than the uncertainties in the buoy data and in the degree to which those data represented the area–averaged flow reported by CODAR. Averaged CODAR current speeds varied during the year in a manner parallel to changes in the Florida Current indicated by tide gauge and electromagnetic cable measurements. Even coefficients of the small tidal currents in deep water from the different instruments were similar. Comparisons between CODAR readings at neighboring locations during a single run showed close consistency, and mean speed differences in the offshore flow were small. Small changes in the mean flow of the Florida Current downstream were consistent with each other and with the shape of the channel through which the current flowed.

However, not all vectors on the CODAR maps were accurate. Those locations at the outer edges of the range limits of the system showed much greater variability of the SD–edited data than did the central region (Figs. 9–12), yet actual variability of the currents is not believed to have been greater there. Also, locations near shore, close to the baseline between radar stations, had many erratic vectors. Some were shown to be incorrect by comparison with drifting buoy measurements, and many indicated ocean currents that were very improbably in their particular locations.

The original plans to tailor the initial CODAR map format to improve the value of the maps to NWS users and to interface the digital data files with the USCG SAR computer program were not implemented because of the large number of missing or erratic vectors on the CODAR maps. The format provided with the system is considered suitable for general use.

The contract with CSI specified that the CODAR system would provide wave parameters that were to be used for NWS forecasting and dissemination. This feature of the system was never implemented, and the value of the CODAR product to that group was greatly decreased (Hebert, Miami WSFO, personal communication, 1989). In addition, the contract specified transponder operability so that the accuracy of this CODAR system could be evaluated. The use of transponders also was not available. The nearly 2–year delay between the cancellation by the original contractor, CSI, and completion of the system by the new contractor, COS, led to an aging of equipment and a loss of personnel.

5.4. Usefulness

The valuable potential of CODAR for producing valid maps of surface currents repeatedly on a routine basis without operator intervention has been partially realized. This system generated a number of maps with a moderate number of accurate vectors. Had the maps been generated more regularly, had nearly all of the maps contained as many vectors as did the fuller ones, and had nearly all the vectors on the maps been correct or as nearly correct as could be judged by eye, the CODAR maps from this project would have been considered very valuable.

As it occurred, however, many of the scheduled maps were missing. For many purposes, an up-to-date map is not necessary if recent ones are available, but maps more than a day old normally would be of little value to operational users. In particular, these many missing maps seriously decreased the value of the present data set for the purposes of this project. In addition, most maps contained only a fraction of the number of vectors that had been planned. This frequently small coverage also seriously decreased the usefulness of the set of CODAR maps, and the many erratic ocean current vectors on the CODAR maps greatly decreased the credibility of the entire CODAR product. Therefore, the CODAR results came to be considered by some to be of little value.

As a result of these inadequacies, the CODAR maps could not be applied to their operations by the different users as planned when this project was instituted. In particular, NWS plans suffered from the beginning from the lack of wave data, and the CODAR maps that did appear were not usable for NWS operations (Hebert, WSFO, Miami, personal communication, 1989). More complete, accurate, and regularly appearing maps would have been used and disseminated from NWS, but the product that was obtained was not included in the WSFO daily operations.

Similarly, the product was inadequate for USCG use. The digital data were to be integrated with the SAR planning computer program. Results from the CODAR discouraged such efforts. The Florida Current profile and the distance of fronts offshore were available on the maps but were not used.

Section 3.1.3 shows that in some respects the data were very good and usable in a number of research investigations. The many missing and erratic data, including groups of several questionable vectors, however, cause major portions of the present CODAR map set to be of little value for research. Examination of particular aspects of the present CODAR data, however, allows some properties of the nearshore circulation to be followed. Figure 8 shows the capability of this system to provide long-term monitoring of major currents in an area; large changes in the flow of the Florida Current were followed by the CODAR system. Smaller changes, although real, have not been related to the overall flow of the current. The pattern in Fig. 9 with direction editing shows that the mean transverse profile of the north component of velocity in this portion of the Straits of Florida does not change significantly between distances of 16 and 44 km offshore; the 8-month mean profile is nearly flat in distinction from single time measurements of a velocity maximum and steady decrease offshore beyond it. Similarly the variability of the flow (Fig. 10) does not change significantly over this area. In the central portion of the current, small changes in direction of about 5° represent minor meanders having a scale of about 10 km. Two types of CODAR evidence indicate that the mean surface Florida Current slows by about 15% in a section where the upper portion of the channel of the Straits of Florida widens by about that amount.

6. CONCLUSIONS

6.1. Operation of the CODAR System

This system needs a regularly assigned operator to keep it operating and an electronic technician to be available to repair components. Although the equipment could be operated with the facilities of AOML, it would not be possible to operate a system such as this from an office dedicated to other efforts without personnel specifically assigned to operate it.

With the personnel assigned to the CODAR project, the system furnished about two-thirds of the scheduled maps. A map edited by the Select program provided by COS often contained about one-third of the ocean surface current vectors scheduled to be calculated in the designed area. This reduced coverage limited the value of the CODAR to the intended users. In addition, without editing by the Select program, the maps commonly contained some current vectors that could not be believed to be correct. Even though the great majority of vectors are believed to be accurate, the presence of even a few erratic ones caused all vectors to be questioned by some map users.

Comparison of the results of this project with CODAR maps produced from other projects and with surface current maps produced by other radar systems shows that the present data are of lower quality than data from several previous studies. Similar interferences must have existed in some of the other cases, but the published results showed few missing vectors and nearly none that were seen to be erratic. The causes of this decreased performance relative to that of others are not known.

6.2. Value of the Present Product for Operational use

The intended use of the CODAR product by NWS for providing information to the public concerning the ocean currents and waves offshore was not implemented because of the decreased quality of the ocean current maps and the lack of wave product. The plan to use the data in SAR planning in the USCG SAR computer program was not implemented after the 2–year delay in beginning the system operation, but the data generated by the CODAR, with the many gaps and the erratic vectors, could not easily have been applied to the USCG problem. Potential for ocean research with the current product remains (McLeish and Maul, 1991), but the data will have to be examined carefully before use.

6.3. Value of the Product for Other Uses

CODAR data demonstrate a capability to monitor nearshore ocean circulations. In the present case the data allow monitoring of the speed of the Florida Current, of the transverse surface profiles, both transient and the mean, and of north–south variations, minor meanders, and the change in speed with latitude. In addition, the CODAR data show at times a countercurrent at the coast or a small eddy nearshore.

Ocean current maps produced from radar data have shown great potential for ocean pollution control. Routine monitoring of the water around sewer outfalls should allow for better management, examining the currents at an ocean dump site should lead to safer performance of such operations, and radar measurements could assist in responding to oil spills and in planning protective measures. The availability of ocean surface current patterns over complete areas should be of great value for ocean research. For example, nearshore circulations in different areas could be much better understood with ocean radar measurements.

6.4. Potential for Improvement of the CODAR Results in This Location

Several changes in the installation and operation of the CODAR system suggested here would give greatly improved CODAR maps. At least a few erratic vectors and blank spaces will remain in the product. However, if the vectors from each CODAR run were assimilated into a routinely updated numerical model of the circulation of the Straits of Florida, a much more complete product without the observable erratic vectors would be expected.

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