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The RAFOS System

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ABSTRACT

The RAFOS float is a small neutrally buoyant subsurface drifter, which, like its big brother the SOFAR float, uses the deep sound (or SOFAR) channel to determine its position as a function of time. Whereas the SOFAR float transmits to moored receivers, the ~12 kg glass pipe RAFOS float listens for accurately timed signals from moored sound sources to determine its position. The acoustic signal detection and storage of data are all handled by a CMOS microprocessor in the float. The data are recovered at the end of its mission when the float surfaces and telemeters its memory contents to Systeme Argos, a satellite-borne platform location and data collection system. Just a few sound sources provide navigation for an arbitrary number of floats.

1. Introduction

Since the MODE experiment in spring 1973, SOFAR (Sound Fixing and Ranging) floats have been regularly used as Lagrangian drifters to study subsurface currents in the western North Atlantic. The floats are tracked acoustically by means of the deep sound or SOFAR channel. By emitting acoustic signals on a regular schedule, their positions can be determined as a function of time at ranges in excess of 2000 km, depending on acoustic propagation considerations, source power level and ambient noise conditions. Initially, the use of SOFAR floats was restricted to areas of the western North Atlantic within reach of shore-based SOFAR hydrophones at Bermuda, Eleuthera (Bahamas), Grand Turk Island and Puerto Rico. Later, as part of the POLYMODE program, the autonomous listening station (ALS) was developed for moored applications. Today SOFAR floats can be used worldwide. They are presently in extensive use in the eastern North Atlantic in U.S., British, and French oceanographic programs.

In this paper we report on the development and use of a new float, the RAFOS float, and its operating system as we are using it for studies in the Gulf Stream (Rossby et al., 1985a). Conceptually, the RAFOS and SOFAR floats serve identical purposes. The technical difference is that whereas the SOFAR float transmits to moored receivers, the RAFOS float listens to moored sound sources. The word RAFOS (SOFAR spelled backwards) refers to the use of the SOFAR channel for a system of acoustic navigation (Bowditch, 1962).

There were two reasons for developing the RAFOS system. First, for the studies we had in mind we needed a low-cost, lightweight Lagrangian drifter. The SOFAR float, to be cost-effective, has to be used in large numbers since the listening stations are rather expensive and require a ship for replacement and final recovery. Second, because of their size and weight the SOFAR floats require specialized launching equipment. For large dedicated studies this is not a serious problem; for studies of the kind we illustrate here it becomes a serious handicap.

We begin with a technical description of the RAFOS float: its mechnical and electrical characteristics. This is followed by a discussion of float ballasting for isopycnal (and isobaric) operation. We then summarize the acoustical aspects of float tracking, the data recovery and final processing.

2. The RAFOS float

a. Mechanical characteristics

Physically, the RAFOS float is nearly identical to the previously developed deep drifter (Rossby and Dorson, 1983). It consists of an 8.6 cm by 1.52 m glass pipe, which provides the flotation and housing of all electronics. The upper end of the pipe, which floats vertically, is rounded off and the lower end is sealed with a flat aluminum endplate where all electrical and mechanical penetrators are located (Fig. 1). The glass wall thickness is ~5 mm giving these pipes a theoretical maximum depth (length/diameter $\gg$ 1) of ~2700 m (Gray and Stachiw, 1969).

The internal mechanical assembly is very simple. A single PVC spar runs the length of the pipe. Mounted on it from top to bottom are the radio antenna, the Argos transmitter, the microprocessor and memory circuit board, the analog circuit board (pressure, temperature and acoustic filtering circuits) and at the bot-

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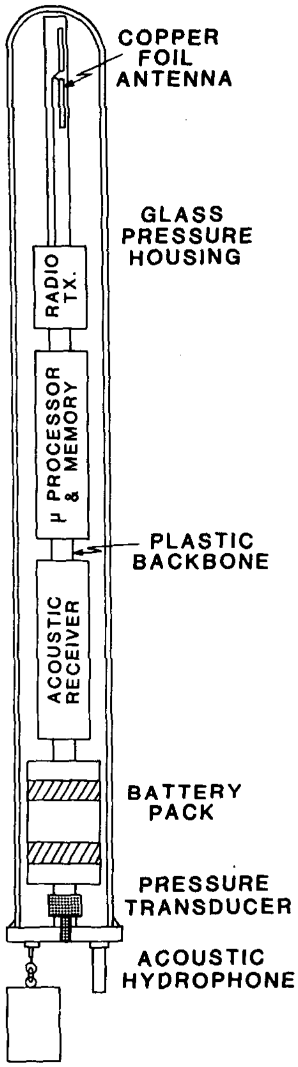

FIG. 1. The mechanical arrangement of the RAFOS float. A glass pipe, rounded at the upper end, is closed at the lower end with an aluminum endplate. All of the components–antenna, radio transmitter, microprocessor, acoustic receiver and battery–are mounted on a PVC spar prior to insertion in the pipe.

tom, for vertical stability, the battery pack. The pressure gauge is rigidly threaded to the endplate and the thermistor is attached to the inside surface.

The attachment of the endplate to the glass pipe is very simple: a bead of silicone rubber is applied around the perimeter where the plate is pressed against the pipe (Fig. 2). This is a change from the glass flange and clamp arrangement we had used earlier (Rossby and Dorson, 1983), which was both more expensive and probably less reliable at high pressures. Between the flat-ground end surface of the pipe and the endplate, a thin (~0.025 cm) sheet of teflon is inserted to permit the glass pipe to compress radially under pressure without spalling against the metal surface. (From recent experimental work there are indications that this is an unnecessary precaution.) For short pipe samples (15 cm long) the straight (flangeless) pipe termination has worked repeatedly to pressures greater than 3000 db. We are confident the termination of the pipes is not a depth-limiting factor. The pipe itself is made of standard Number 7740 borosilicate glass—widely used in various lengths and diameters in the pharmaceutical, chemical and food processing industries.

The hard-coat anodized aluminum endplate supports the penetrators for the hydrophone, the ballast release wire and hole for the pressure gauge. The hydrophone is a single ceramic element and is rigidly potted onto a standard three-pin connector using a two-component polyurethane resin compound. The external ballast (for return to the surface) is suspended by a short piece of Inconel wire chosen for its resistance to saltwater corrosion. By dissolving it electrolytically (2 min at 0.3 amp) the approximately 1-kg ballast is released.

b. Electrical characteristics

The RAFOS electronics consist of four main parts: a set of sensors for collecting temperature, pressure and tracking information; an ARGOS compatible transmitter to relay the collected data after surfacing; a clock for time reference; and a microprocessor (CPU) to control the sensors, store the data, and format the data for the transmitter (Fig. 3).

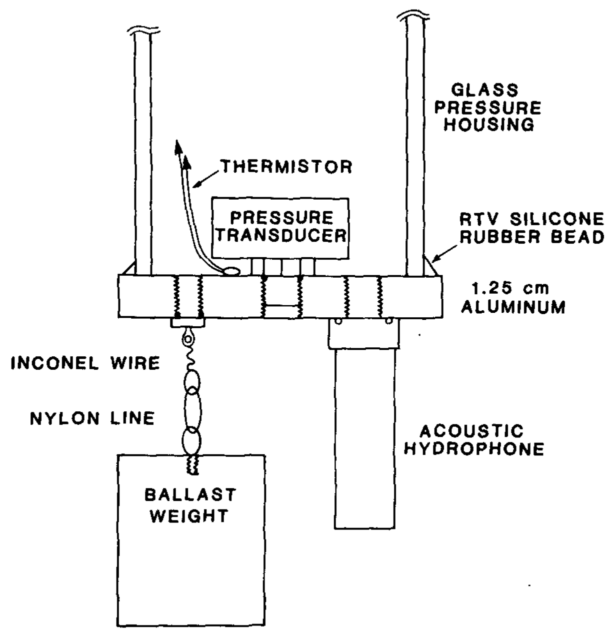

FIG. 2. Detailed drawing of the endplate arrangement. The endplate is bonded to the glass pipe by means of a bead of silicone (RTV) around the perimeter. A thin sheet of teflon between the glass and aluminum is intended to allow slippage of the glass under compression.

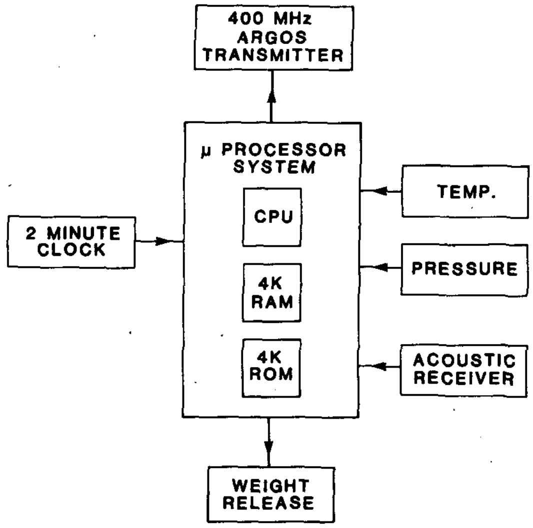

FIG. 3. Functional block diagram of the RAFOS float electronics. Under software control and the precision 2-min clock the microprocessor (Motorola 6805) controls the timing of all functions.

A thermistor with an accuracy of 0.1°C is used to measure temperature. The thermistor controls the frequency of an RC oscillator. A multiple-period technique is used to measure the oscillator frequency. Twelve bits of data are stored for each temperature measurement. This provides a resolution of 10 m deg.

Pressure is measured with a strain gauge having a frequency-modulated output. This frequency is measured in a manner similar to the temperature system. Twelve data bits are also stored for each pressure measurement for a resolution of 1.0 db. The accuracy of the transducer is ±0.5%.

Tracking information is obtained by detecting the time of arrival of SOFAR signals from moored sound sources at the RAFOS float. The acoustic signals consist of an 80-sec CW pulse centered near 260 Hz during which time the frequency increases linearly 1.523 Hz. The acoustic receiver is dual conversion with a first intermediate frequency of 38.5 Hz. This provides good image rejection and bandpass filtering. The signal is then converted to 1.5 Hz, filtered to 1.5 Hz bandwidth and hard limited. The CPU samples this signal at a 10-Hz rate and performs an 800-bit quadrature correlation on it. The limiter removes any amplitude variations from the signal so only phase information is used in the correlation process. With the present sound sources south of the Gulf Stream (Rossby et al., 1985a), usable signals are obtained to at least a 1200-km range.

The ARGOS transmitter receives stored data via a synchronous serial interface. Each time the CPU transfers a data block, the transmitter automatically generates the necessary unmodulated carrier and time and phase modulates the appropriate synchronization, identification and data bits.

The clock, which maintains synchronization with the moored sound sources schedule, is based on an AT cut crystal in the 4-MHz range. The crystal oscillator has its own battery and requires about 100 μW. The oscillator output is divided down to a period of two minutes. This 2-min signal "wakes" the CPU. The CPU checks its schedule, performs any pending task and returns to a "sleep" mode. The microprocessor controls power to all subsystems except the clock. The sequence of events needed to collect and store the various data is all done with software.

A typical 45-day mission will collect 2835 bytes of data. The RAFOS float listens for three different sources every 8 hours with a 20-min offset for each source. The time of arrival for the two largest signals heard in an 820-sec window corresponding to a maximum range of 1230 km are stored for each source. Sixteen bits of time information (0.1-sec resolution) and eight bits of correlation height information is stored for each signal. Pressure and temperature are measured every 8 hours.

At trip end the CPU activates a release circuit which drops a ballast weight and returns to the surface. Exactly 30 min after release initiation the ARGOS transmitter is turned on. Approximately every 43 sec thereafter, an ARGOS format message with 32 data bytes is transmitted. The first byte of each message is a check byte to detect any data errors introduced during transmission and data transfer. The second byte is a message number to keep track of each data block. The remaining 30 bytes are the collected data sequentially transmitted in the order they were stored.

A satellite pass is within range for less than 15 min so a number of orbits are required to successfully transfer the complete dataset. Typically, at least three days are required to transfer the 2835 bytes of data.

c. Ballasting

Ballasting a float means adjusting its weight to neutral buoyancy to a certain depth or for a certain density (σ_t) surface (i.e., isobaric or isopycnal operation). Isobaric floats have been in common use since the pioneering development by John Swallow in the 1950s (Swallow, 1955). Isopycnal studies have been initiated in the last few years (Rossby et al., 1985b).

In classic isobaric operation the compressibility of the float must be significantly less than seawater. In this case, if a float is displaced upwards from its equilibrium surface, it will expand less than the water around it. The resulting density difference will force it back to its equilibrium depth.

To achieve isopycnal operation, it is necessary to match the compressibility of the float to that of seawater so that pressure-induced restoring forces are removed. This is accomplished by adding a compressible element, or compressee as it is called, consisting of a spring-backed piston in a cylinder so that an appropriate volume loss is achieved as a function of pressure. Additionally, however, for constant density operation the float's density must be independent of temperature (T) since variations in salinity (S) obviously cannot affect it. If this can be arranged, it follows that once a float is neutrally buoyant on a certain density surface, it will remain there regardless of variations in T and S. The simplest way to make a float insensitive to temperature is to make it out of borosilicate glass which has a volume coefficient of thermal expansion ~20× less than seawater. Rossby et al. (1985b) discuss the requirements for isopycnal operation in detail. In that paper it is noted that the restoring forces for isopycnal neutral buoyancy are substantially smaller than for isobaric operation in the main thermocline. Thus the accuracy requirements for ballasting a float to a given σ_t surface are much more stringent. To illustrate, the volume of the RAFOS float is approximately 10^4 cm^3. If we want to target a float to within $\pm 0.1\sigma_t$ units, the weight must be correct to 1 g. Note that $0.1\sigma_t$ units corresponds to a change of 1°C or to a vertical displacement of 30–40 m in the main thermocline in the Gulf Stream.

The compressee is not linear at low pressures due to the difficulty of loading or seating the spring until it is sufficiently compressed. This nonlinearity can give rise to several grams' error at very low pressures. Also, bubbles can be difficult to eliminate at atmospheric pressure. Thus, we have found it essential to ballast the floats at elevated pressures; preferably pressures comparable to where they will be operating. We are fortunate to have such a facility.

The pressure vessel is over 2 m deep and 70 cm wide so two floats can be ballasted simultaneously. They are made a few grams light in fresh water. A light chain (0.4 gm cm^{-1}) is hung underneath such that the float becomes neutrally buoyant at a certain height. Neutral buoyancy of the float at pressure in fresh water is given by the amount of suspended chain, which can be observed by the elevation of the float through a window in the side of the tank.

The weight correction for tank to in situ seawater can be expressed as follows (Rossby et al., 1985b):

$$\Delta m = V[(\rho_i - \rho_t) - \rho_i \gamma (p_i - p_t) + \rho_i \alpha (T_i - T_t)]$$

where ρ, p and T are the density, pressure and temperature; γ is the float's compressibility, α the volume coefficient of thermal expansion of glass pipe, the subscripts t and i refer to tank and in situ; V is the volume of the float. Thus, by ballasting the float at the same pressure for which it is targeted, it is not necessary to know the exact compressibility of the float, since the second term on the right-hand side of the above expression is identically zero. If the compressibility differs from seawater it will, of course, not remain isopycnal if the density surfaces change depth.

Another source of error is the presence of dissolved minerals in tank water. These can increase the density by about one part in 10^4 over distilled water for the same temperature. We have subsequently installed a demineralizer to remove this uncertainty.

d. *The acoustics of float tracking*

The use of the SOFAR channel for tracking floats is quite straightforward, but there are several acoustic considerations that should be kept in mind in order to maximize the area of coverage or insonification. These include

(i) acoustic source level,
(ii) ambient noise conditions, and
(iii) the depth of the float in relation to the sound channel axis.

In our work we have used essentially standard SOFAR floats as acoustic beacons (Webb, 1977). They are buoyed up from the bottom at the depth of the sound channel axis (1300–1400 m in the western North Atlantic). These provide a CW acoustic source level of about 175 dB relative to 1 μPa. The ambient noise conditions are a strong function of weather and shipping. In the Gulf Stream, where we have been working, it appears to be quite high due to a combination of heavy shipping and strong winds.

If we assume a horizontally uniform SOFAR channel, the propagation loss (PL) between source and receiver ($r > r_0$) can be written

$$PL = 10 \log r_0 + 10 \log r + \alpha r$$

where r_0 is the transition distance from spherical to cylindrical spreading and α is the attenuation coefficient. Webb and Tucker (1970) estimated the transition distance r_0 to be about 3 km and α to be 2.9×10^{-5} dB m^{-1} at 778 Hz. At our operating frequency, 260 Hz, α is approximately 1.0×10^{-5} dB m^{-1}. A maximum operating distance can now be estimated. We assume a noise level (NL) = 65 dB re 1 μPa in a 1-Hz band (corresponding to the combination of heavy shipping and 10-kt winds). This gives an effective noise level of 68 dB re 1 μPa since the equivalent noise bandwidth of the RAFOS float receiver is more like 2 Hz. The signal processor or correlator provides a gain (PG) of 17 dB [=10 log(80 sec × 1.5 Hz) − 3 dB due to use of phase information only]. The signal-to-noise ratio (S/N) should therefore be

$$S/N = 175 - PL - NL + PG.$$

The following table shows S/N as a function of distance in km:

Distance	500	1000	1500	2000	2500
S/N	27	19	12	6	0

These numbers suggest that useful detection ranges might be as great as 2000 km, say. Unlike the SOFAR float system, however, where continuous signal monitoring was possible at land-based stations, the RAFOS floats are limited to storing only the two largest correlations per expected signal. Thus, we judged it necessary to require a large S/N for positive signal detection. At greater ranges and hence weaker S/N, the longer listening period will also increase the chance of a spurious correlation reaching larger values. For these reasons we felt that listening beyond 1500 km would be of little value. The actual operating range was set at 1230 km (=820 sec × 1.5 km s^{-1}). There is considerable uncertainty in the above calculations. On the one hand, the attenuation coefficient may be smaller than the assumed value; on the other hand, the assumption of a horizontally uniform sound channel is definitely not valid in the region of the Gulf Stream.

If either the float or transmitter is offaxis, then the useful operating range is reduced due to the loss of the rays that propagate close to the sound channel axis. For moderate offaxis distances the losses are not severe. Figure 4 shows the fraction of transmitted signals from two different sound sources detected by two float groups: one about 300–400 m (solid line) and one about 500–600 m (dashed line) above the sound channel axis. Clearly the shallower floats show somewhat poorer performance than the deep floats, but both groups work over the entire listening range of 1230 km (820 sec × 1.5 km s^{-1}). The fraction of detected signals is greater from sound sources 2 and 3 (bottom panel of Fig. 4). This may be because they are louder, but we suspect that oblique propagation paths from sound source 1

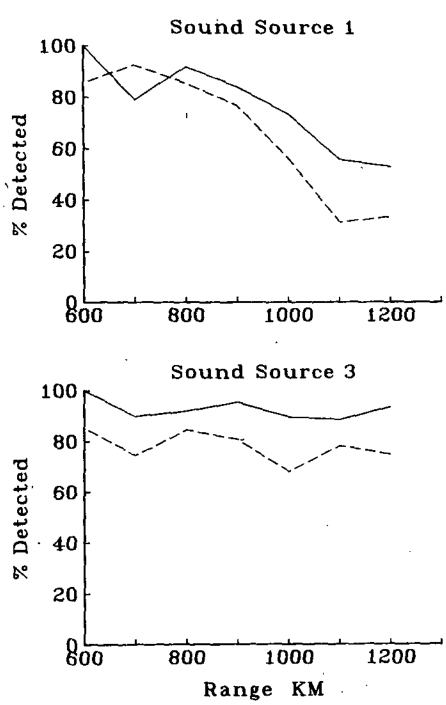

FIG. 4. The fraction of signals detected as a function of distance from sound source 1 (top panel) and from sound source 3 (bottom panel) for two groups of floats: 7°–10°C, solid line, and 11°–14°C, dashed line.

through cyclonic meanders of the Gulf Stream and/or cold core rings may cause additional losses. In any event the performance of the system is better than we expected. It is clear that the window of listening should be extended. The reader should consult one of several books for a thorough discussion of long-range sound propagation (e.g., Urick, 1975).

e. *Data flow and processing*

At the end of a float's mission underwater it is programmed to drop its ballast and return to the surface. Under control of the master clock, the float starts transmitting to Systeme Argos the contents of its memory repeatedly until its battery is exhausted, a duration of about two weeks. Systeme Argos is a satellite-borne platform location and data collection system. All data collected from each 100-min polar orbit are processed at Argos headquarters in Toulouse, France, where a few hours later it can be examined by telephone. The data are also forwarded by mail on a regular basis.

The first step in data processing is to group the data messages according to instrument (platform ID) and to check that each message has not been corrupted during transmission. Each data message consists of 32 bytes. As we pointed out earlier, the first byte is a check-sum byte, the second byte is the message number and the remaining 30 bytes contain the data. The check-sum byte is constructed from the following 31 bytes. After each message is received, this byte is reconstructed from the data bytes and compared to the original. The message is accepted only if the check-sum bytes agree. On average we have found three or four messages to be correct. On calm days at sea we can obtain 90% error-free data transfers; in severe weather (heavy sea states) this can drop to ~50%. If necessary, the rejected messages could be examined more closely for salvagable data.

The transfer of data from floats takes time. Even though the float sends a message of 32 bytes approximately every 43 sec, a satellite (there are two) is above the float's horizon less than 10% of the time. Typically 60%–80% of the data is received the first day but several days are usually required before the data transfer is complete.

The procedures for editing and processing the acoustic travel-time data to reconstruct the float trajectories are very similar to those for SOFAR float tracking (Spain et al., 1980). To compute the position of the float the following information is needed:

(i) the time of signal transmission,
(ii) the time of arrival of signal at float,
(iii) the average speed of sound, and
(iv) a Doppler correction.

(i) The time of transmission is known from the preset transmission schedule for each sound source. Errors in their transmission times are monitored over a constant path to a hydrophone at Bermuda (see below).

(ii) The time of signal arrival is determined relative to the float's clock. The float clock is set "on time" and verified (to within a second) at launch and the accumulated error at the end of its submergence is indicated by the error in radio transmission schedule, which can be determined to a fraction of a second.

(iii) The path averaged speed of sound is known to within 2–3‰, i.e., $1.496 \pm .003$ km s^{-1} for floats in the main thermocline. There are two sources of uncertainty. The biggest one is that the received signal is really a complex signal of many path arrivals spread out over several seconds (Spiesberger et al., 1983). Each one of these has a different average speed of sound. The correlator will pick out the combination of rays that has the greatest phase stability. We have no way of knowing which ray or set of rays it is without resorting to a vastly more sophisticated signal identification analysis (i.e., acoustic tomography). The other uncertainty is due to low frequency changes (i.e., weeks) in the thermocline depth along the path between transmitter and receiver.

These two uncertainties can be seen in Fig. 5 which shows the arrival times at Bermuda of signals transmitted from a sound source south of Cape Hatteras. The scatter envelope of 2–3 sec is due to the uncertainty in which ray (or rays) has the greatest phase stability at that time. The lack of straightness over weeks and months reflects mesoscale changes in thermocline depth. The slope reflects the clock drift at the transmitter and is the primary reason for monitoring the transmissions, as mentioned above. Finally, should a float escape far into the Slope Waters north of the Gulf Stream, it may be necessary to correct the travel times for the fraction of time the signal is passing through the Slope Water region. Figure 6 shows the sound velocity field in relation to the density field of the frontal region. Notice how the sound channel axis shoals to the north and the minimum speed of sound decreases (due to decreased pressure).

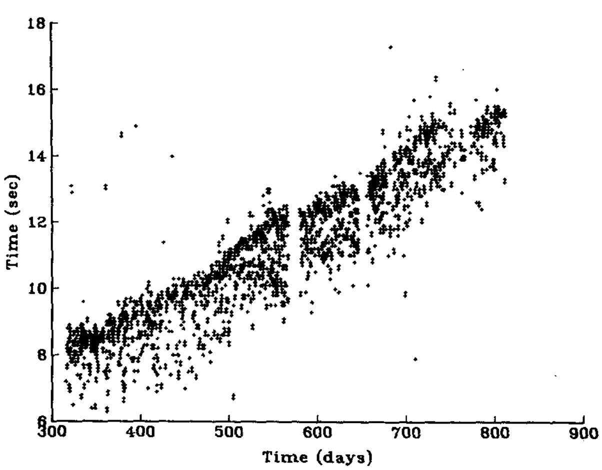

FIG. 5. Plot of arrival time variations at a hydrophone near Bermuda from sound source 1. The short-term fluctuations (scatter) are due to arrivals along different ray paths. The low frequency (weeks to months) variations are due to depth changes of the main thermocline along the path. The slope of the line represents the clock drift in the sound source and is the primary information of interest here.

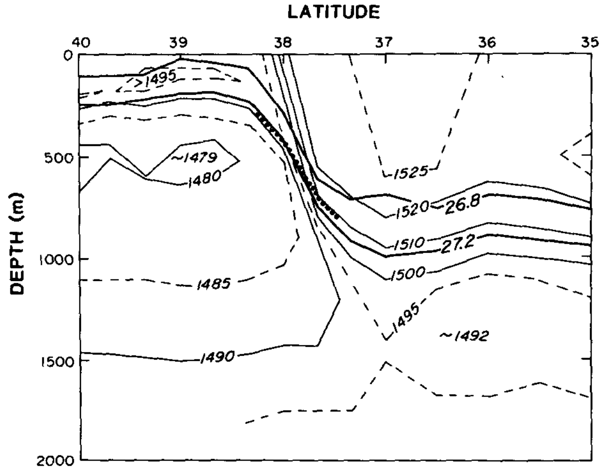

FIG. 6. Isopleths of sound velocity across the Gulf Stream and their relationship to the cross-stream density field as indicated by the 26.8 and 27.2 sigma-t surfaces (corresponding to about 14°C and 10°C, respectively.) Note the shoaling of the sound channel axis to the north and the attendant decrease in sound velocity minimum. The data are taken from Section I in Gulf Stream '60 (Fuglister, 1963). See text for a discussion of the dotted line.

(iv) The Doppler correction due to the float's motion is more subtle, since we do not know its speed at the instant its position is to be determined. Instead, the range rate or closing speed is estimated from the rate of change in time of arrival of one transmission to another as a centered first difference. The Doppler shift in frequency, Δf, is

$$\Delta f = \frac{v}{c - v} f_0$$

where f_0 is the transmitted frequency, c is the speed of sound, and v is positive for closing motion. Since the transmitted signal is a linearly ascending CW tone, the shift in time of arrival becomes

$$\Delta t = f_0 \frac{v}{c - v} \cdot \frac{80\ [\text{sec}]}{1.523\ [\text{Hz}]}$$

or about 4.4 sec kt^{-1}. Clearly the Doppler correction is a significant improvement to the accuracy of float tracking in regions of strong currents.

After these corrections have been applied, the float tracking can be completed. There are two modes: range or circular tracking and hyperbolic tracking. The hyperbolic mode has the advantage that it is independent of any clock errors in the float since it depends only on travel time differences from pairs of sound sources. Circular tracking has the advantage of requiring only two measurements. In the Gulf Stream study (Rossby et al., 1985a) the area of coverage by three sound sources is so limited that the float tracking is done exclusively in the range mode.

The tracking procedure is iterative; a position is assumed (initially, the launch position) and distances to the sound sources are computed. The difference between these and the measured values are used to improve the initial guess. This process is repeated until the absolute sum of the differences is less than 1 km. This position is then used as the initial guess for the next position in time, and so on. The reader is refered to Spain et al. (1980) for a detailed discussion of the SOFAR float tracking system from which the RAFOS system is adapted.

3. An example of a float track

More than 40 RAFOS floats have been launched in the Gulf Stream since the beginning of 1983. An early report on this research was published in the *Bulletin of the American Meteorological Society* (Rossby et al., 1985a). Here we illustrate the RAFOS system by following one float from the time it was launched 200 km NE of Cape Hatteras in the center of the current. It was ballasted to become neutrally buoyant at $\sigma_t = 27.0$, but equilibrated at $\sigma_t = 27.1$. This means the float was about 1.3 g heavy. Part of this is probably due to the dissolved mineral content in the ballasting which rendered it denser than we thought. In terms of depth the float was about 50 m deeper than intended.

The trajectory of the float is shown in Fig. 7. The three sound sources, indicated by the numerals 1, 2 and 3, are located south of Cape Hatteras, on the northern slope of the Bermuda Seamount and on top of one of the Southern New England seamounts. The trajectory of the float was determined with sound sources 1 and 2 until yearday 74 and with sound sources 2 and 3 thereafter. It exhibits the characteristic wavy character of the meandering Gulf Stream. There is a dominant wavelength of about 450 km and a peak-to-trough meander amplitude growing from 100 to 200 km from west to east. The mean speed of the float, i.e., the traveled distance divided by the elapsed time, is 55 cm s^{-1}. The pressure and temperature records, Fig. 8, are an important part of the story. The near constancy of temperature tells us that to a first approximation the float remained on the same σ_t surface regardless of depth. From the pressure record we can learn much about the lateral displacements of fluid within the current. Thus, for the first three days after launch the float rapidly shoals from 570 to 330 m. For the next 15 days it remains between 300 and 400 m and then sinks to 600 m and deeper for the remainder of the trip. The slow speeds, as evidenced by the close dot spacing between days 65 and 70, and the shallow depth suggest that the float was very close to escaping to the north. A striking aspect of this and all other float tracks is the

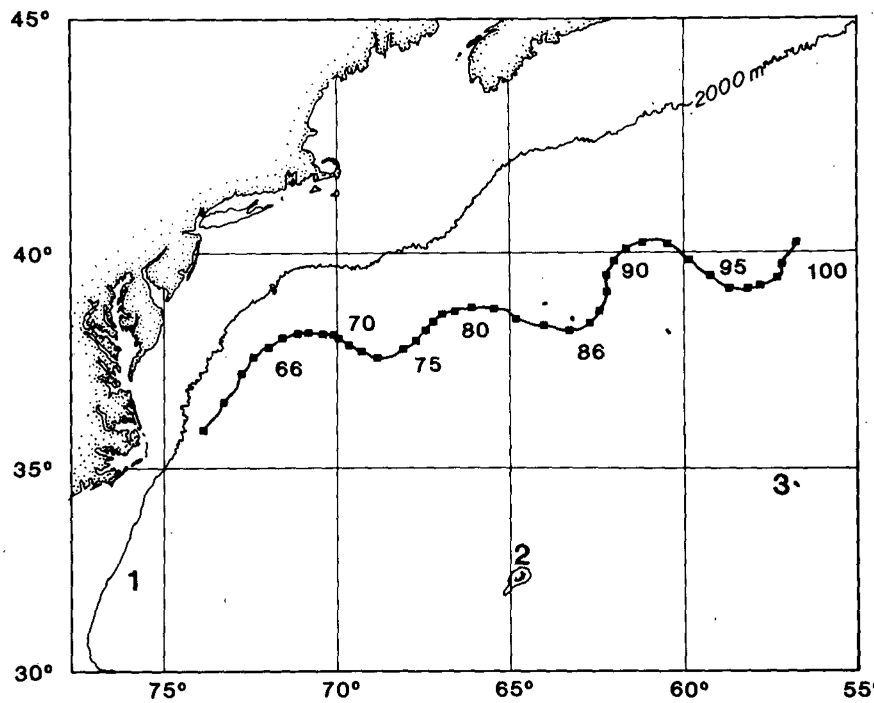

FIG. 7. The 45-day trajectory of RAFOS float 29. Elapsed time in yeardays (1985) is indicated with one dot per day. The trajectory has not been smoothed. The numbers 1, 2 and 3 indicate the locations of the three sound sources.

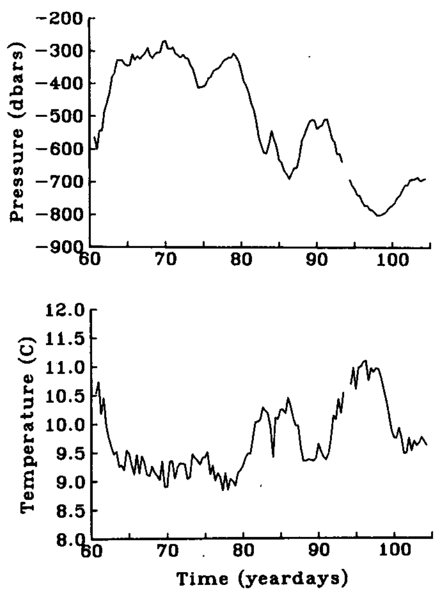

FIG. 8. Plots of pressure (top panel) and temperature (bottom panel) as a function of yearday (1985). For an ideal float the temperature record should be constant (except for adiabatic effects) regardless of float depth, unless there is mixing into a new water mass. The correlation between temperature and pressure is due to the fact that the float compressibility is not perfectly matched to that of seawater.

tendency for floats to shoal from meander trough to crest and to deepen from a meander crest to the next trough. This is evident in the pressure record which shows pressure maxima on days 86 and 97 and minima on days 79 and 90. The temperature record is correlated with pressure because the float is not perfectly isopycnal; it is slightly less compressible than seawater so that when there is upwelling the float lags behind and becomes neutrally buoyant in denser or colder water. The lateral and vertical movement within the current is indicated by the dotted line in Fig. 6.

Thus we see that during the float's 2100 km journey to the east, its lateral displacements relative to the current are less than 100 km. And from the pressure record it is clear that these motions are not random, but clearly a result of the dynamics of curvilinear motion.

4. Summary

The RAFOS system provides a straightforward means for studying oceanic variability over a wide range of spatial and temporal scales. Sequentially launched in the Gulf Stream, we are using the floats to study the space–time evolution of the meandering current. Other applications suggest themselves. For short periods of time (days to weeks) dense clusters of floats can be employed to study dispersive processes. With minor change the RAFOS float can be programmed to remain submerged in excess of a year. Deployed in large numbers over wide areas, they can be used effectively to estimate mean flows.

The instruments are lightweight making deployment a simple hand operation, and, in fact, there is no reason why they could not be adapted for launch from aircraft at a future time.

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