ACOUSTIC TELEMETRY SYSTEM FOR REAL-TIME MONITORING OF THE GULF STREAM PATH

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ABSTRACT

An acoustic telemetry system is now in place to monitor and predict the meandering movements of the Gulf Stream. Five inverted echo sounders (IES), bottom-moored under the stream near Cape Hatteras, compute daily averages of the overhead thermocline depth. The processed value is encoded as a single, variable time-delayed acoustic pulse which is simultaneously repeated and frequency down-shifted by the telemetry system. The telemetered information is contained in the delay of the transmission from a reference time determined by the IES clock. The acoustic link to Bermuda uses the 260 Hz SOFAR swept signal.

This system has been operational since October 1989. A sample of the collected data is included.

THE NEED

The Inverted Echo Sounder (IES)[1] is being used to determine thermocline depth[2,3] by measuring changes in the time-of-flight of surface reflected acoustic pulses. Arrays of IESs are being used[4] to determine the position and direction of Gulf Stream flow. Typically the data have been recorded internally and processed only after IES retrieval (12-14 months). A record is then constructed of the meandering movements of the Stream[5].

Physical oceanographers conducting mesoscale ocean monitoring and prognostic studies have been challenged to implement the data collection and observation systems necessary to provide the data base in real time. In the case of Gulf Stream studies[6,7], a variety of data acquisition components are being used. Satellite IR imagery has the advantage of real-time monitoring but cannot "see" the vertical structure of the stream. Inverted Echo Sounders can measure the average vertical temperature profile but have not been able to report the data real-time. RAFOS float trajectories, XBTs and AXBTs are being used for near real-time work, but do not provide the synoptic view that an array of IESs can provide.

For the SYNOP program, a large array (33 ea.) of IESs are deployed to record Gulf Stream movements in the western North Atlantic. A subset array of IESs is deployed off Cape Hatteras and referred to as the "Inlet Conditions Experiment". The "inlet" of the Gulf Stream is generally considered to be the point off Cape Hatteras where the stream turns east into the Atlantic basin; see figure 1. Predictive modeling of Gulf Stream meanders require information on the conditions at this point of current inflow, e.g., stream position, angle and curvature.

The challenge became how to have real, or near-real-time access to inlet conditions, as measured by the IES array, so that downstream conditions could be predicted.

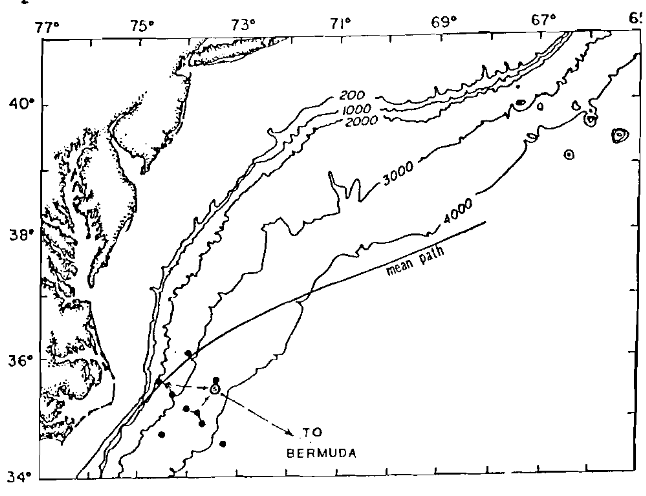

Figure 1 The IESs are located at sites shown as solid circles. The overhead transponders (OT) are shown as (X). The central transponder (CT) is shown as (S). The solid line through the area shows the historical mean path of the Gulf Stream.

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CH2858-9/90/0000-0046 $1.00 © 1990 IEEE

THE SOLUTION

A simple solution was proposed by Dr. Tom Rossby and Dr. Randy Watts of the University of Rhode Island Graduate School of Oceanography (URI-GSO). Since the latest version of the Pacer Systems, Inc. Model 1665 Inverted Echo Sounder is microprocessor controlled and has the pre-requisite memory, it can process its own data, in situ. Besides recording the raw data on tape, it computes a 24 hour average of the 12 degree thermocline depth. This daily average is encoded as a single time-delayed acoustic pulse whose delay from a time reference (IES clock) is proportional to the value of the data word. The time delay IS the information. Since there is a listening station on Bermuda used to monitor the moored SOFAR sound sources used in the RAFOS float program, a system was proposed to transpose the delay-encoded 10 kHz pulse, produced by the IES on the ocean bottom, to a 260 Hz signal (SOFAR) in the main sound channel that could be received at Bermuda.

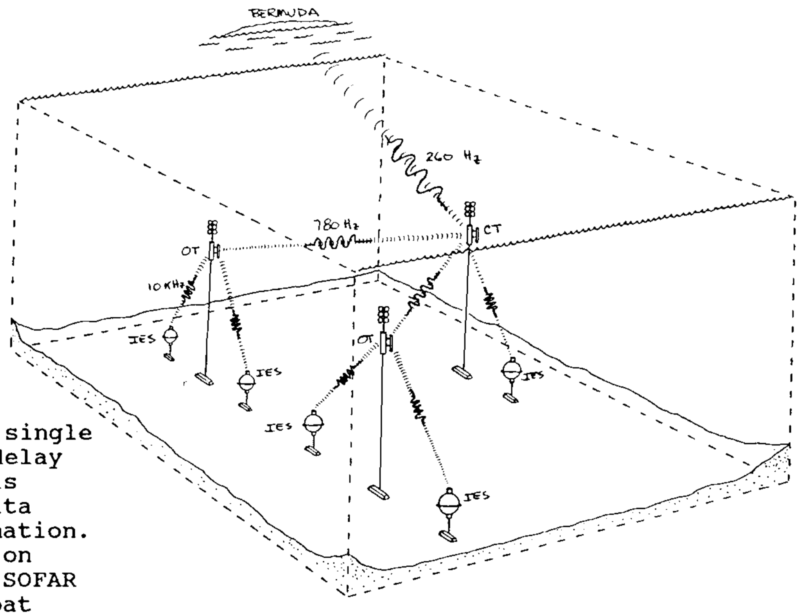

Figure 2 Two-stage telemetry link from IES array to Bermuda.

Rossby and Watts proposed a two-stage transponding system; see figure 2. At each IES site a lightweight mooring floats up in the deep sound channel axis (1450 m depth). This overhead transponder (OT) will transmit an intermediate frequency (IF) chirp centered at 780 Hz when it detects a special (extra long, 50 msec.) 10 kHz CW pulse from the IES below. The rebroadcast of the detected signal has a fixed delay so the information that is carried in the timing of the pulse is not lost. The 780 Hz chirp is received at a central transponder (CT) mooring placed down stream at another IES site and is similarly rebroadcast as a SOFAR (260 hZ sweep) signal to the shore station at Bermuda. Once again, the signal is shifted down in frequency but its timing, i.e., the telemetered information, is preserved. As figure 2 shows, two OTs serve four IESs and one CT serves two OTs and an IES, for a total of five IESs reporting. It was thought that the cost of the CTs would be significantly more than that of OTs, hence the two stage acoustic link. This turned out not to be the case. In future systems all repeater/transponders will be identical, one-step units, i.e., 10 kHz signals will be rebroadcast as 260 Hz SOFAR signals directly to Bermuda without the intermediate 780 Hz step.

The elegance of this solution is not only its functional simplicity but the fact that very little development work was necessary for its implementation. The receiving station at Bermuda had time available in its schedule for more listening intervals. The data processing algorithm, already developed at URI-GSO, was easily adapted to operate in the IES. Using available options, the Pacer Systems, Inc. IES was configured for the task. With slight modifications, off-the-shelf SOFAR source floats from Webb Research Inc. were configured as repeater/transponders. The only development effort was the receiver installed in the transponders to detect the 10 kHz signal from the IESs.

SYSTEM REQUIREMENTS

Acoustics:

The acoustic field model is diagrammed in Figure 3. Note that given the 4 Km depth and the mean sound speed profile shown, the maximum horizontal distance between an IES and its receptor OT is about 20 km. Average distances between IESs in the "inlet array" experiment are 26 km so that a single OT, centered between IES sites can serve both instruments. Also note that the IES must have a wide beam (hemispherical) output (see equipment modifications). From previous field work the range of the OTs 780 Hz link to the CT was known to be reliable to 200 km. In this system the OT-CT distances are less than 60 km.

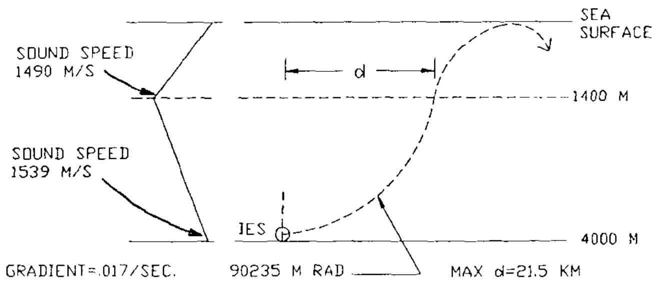

FIGURE 3 ACOUSTIC FIELD RAY DIAGRAM

IES acoustic source level in the horizontal direction was measured at 180 dB re 1 uPa.m. The ambient noise (sea state 6) is about 53 dB re 1 uPa, 1 Hz band @ 10kHz. If the overhead transponder (OT) is centered between IESs, the propagation losses for 15 km are: 84.5 dB (geometric spreading) + 13.5 dB (attenuation) = 98 dB. The 10 kHz receiver has a bandwidth of 38 Hz so the signal-to-noise ratio will be better than 13 dB under most conditions for the IES-to-OT 10 kHz link.

Timing:

Consider the timing diagram of Figure 4. The reference time Tr which is known and set for each IES is the time from which the variable time ΔT is measured. The delay varies between 0 and 8.5 minutes as an analog measure of the IES information to be transmitted, i.e., the median value of the previous days measurements. Once the overhead transponder (OT) has detected the 50 millisecond, 10 kHz CW pulse from the IES, it transmits a 780 Hz chirp pulse which is detected ΔToc seconds later at the central transponder (CT). The CT, in turn, transmits a standard RAFOS/SOFAR signal which is finally received ΔTcs seconds later at the RAFOS navigation system monitor at Tudor Hill, Bermuda. Since the delays in the transponders and the acoustic travel times Δ Toc and ΔTcs are fixed, variations in the arrival time at Bermuda reflect variations in transmission time at the IES, i.e., changes in the thermocline depth.

There are uncertainties introduced. These are: (1) clock drift in the IES, estimated to be <10-7 or less than 1 second/100 days, and (2) multipath ambiguities in ΔTcs, which amount to about 2 seconds (see figure 5). Since the total range in delay time is 0-8.5 minutes and the uncertainty in the estimate of ΔT is of order 3-6 seconds, we have a useful dynamic range of 85:1. The more serious of these uncertainties, the clock error, will, in future systems, be monitored by inserting infrequent timing signals.

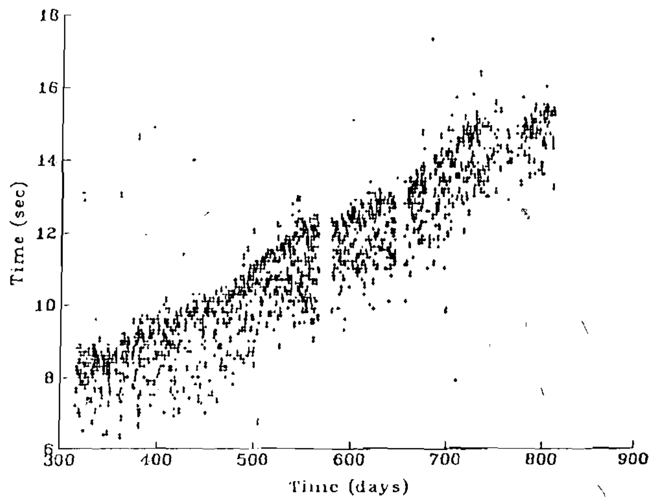

Figure 5 Scatter in time-of-arrivals of signals at Bermuda from a moored SOFAR source south of Cape Hatteras 100 Km away. It shows that uncertainties in travel times are less than 2 seconds. The slope represents the linear clock drift in the sound source. The record spans 500 days.

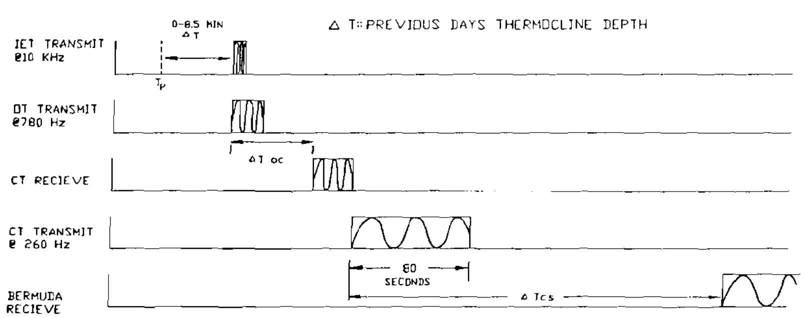

FIGURE 4 TIMING DIAGRAM SHOWING THE PROGRESSION OF THE 'SIGNAL' FROM THE IES TO THE SHORE STATION

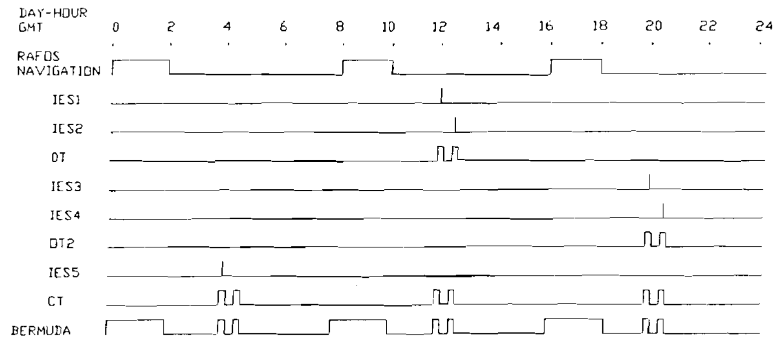

FIGURE 6 DAILY SCHEDULE OF IES/RAFOS/SOFAR/TIMESHARING

To insure that the SOFAR source (CT) does not interfere with the RAFOS navigation system, that the OTs do not respond to normal IES 10kHz transmissions and to conserve battery power, the OTs and CT are only powered up for short periods corresponding to IES/SOFAR transmission windows. Figure 6 shows how a staggered schedule allows information to be obtained from all five IESs without compromising the RAFOS navigation system.

EQUIPMENT MODIFICATIONS

IES Software:

An algorithm developed at URI-GSO[8] for processing IES data in real time was used to compute a 24 hour average of 12 degree thermocline depth.

The normal IES measurement scheme is to burst-sample 24 times, at a 10 second rate every 30 minutes. The telemetry processing routine composes and saves a sorted and windowed median of each burst. When the IES has collected all 48 medians from one days measurements, it again sorts and windows to get the 24 hour median. This 24 hour low-pass filtering removes the tide signal.

After processing, the normal 18-bit data word is truncated to an 8-bit word (bits 4-11) that represent a full scale change in acoustic travel time of 100 milliseconds (.39 msec resolution). Each count corresponds to a 7.8 meter change in thermocline depth and is encoded as a 2 second delay in transmission time from a specified clock time. Hence the full scale delay (8 bit word) is 255 x 2 seconds = 8.5 minutes = 1997 meter change in 12 degree isotherm depth.

The algorithm was validated by processing some earlier, noisy IES data records and comparing the results with the normal URI-GSO in-house processing routines. The comparison is shown in Figure 7.

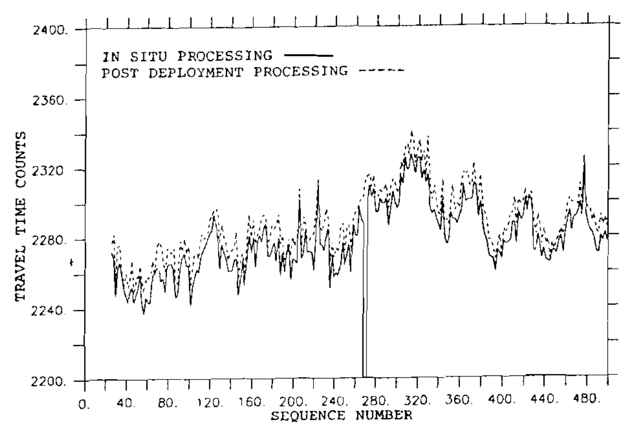

Figure 7 Results comparison of in situ processing algorithm and in-house processing routines.

IES Hardware:

Besides the addition of the in situ processing code, some options on the Pacer Systems IESs had to be carefully chosen.

The Pacer Model 1665 IES offers a high power output driver and transducer option. The standard transducer has a null in the output beam near 90 degrees so cannot be used in this application (see acoustic requirements, above). The output of the high power transducer is down -20 dB @ 90 degrees, but this is adequate for the distances involved.

To maintain IES acoustic output as high as possible for the entire 50 msec. transmission, the large (50,000 ufd.) output capacitor option and high current capacity lithium batteries were used.

A super-stable clock crystal was used. This is a standard feature of the Pacer Inverted Echo Sounder. Clock stability with temperature is .02ppm/C°, and stability with time is .03ppm/mo. after 3 months.

SOFAR Software:

The operating code for the Webb SOFAR sound sources was modified to provide power switching for the receive and transmit circuits. A receiver lockout was also provided to prevent multiple transmissions.

SOFAR Hardware:

To keep the 10 kHz link simple, (i.e, CW pulse transmission and analog detection), and still provide narrow bandwidth for high signal-to-noise ratio, switched capacitor filters were used in the 10 kHz receiver. The single heterodyned receiver has a bandwidth of 38 Hz at 10 kHz and a threshold S/N ratio of +3 dB.

THE DEPLOYMENT

The transponder (OT & CT) mooring is outlined in figure 8. EG&G model 8242 acoustic releases and Benthos flotation spheres were used. The mooring cables and hardware were assembled by the Buoy Group at Woods Hole Oceanographic Institution. The moorings were deployed during Randy Watts SYNOP cruise from the R/V Oceanus in October 1989.

The staggered timing schedule prescribed careful synchronization of each instrument clock before deployment. The SAIL communications system in the Webb Research instruments allowed a last minute check of SOFAR source time and watertight seal integrity.

To verify that each acoustic link was operating properly without waiting to complete a verification loop from Bermuda to URI and back to the ship, surplus sonobuoys from WHOI were used to eavesdrop in the main sound channel after deployment. The wideband receivers were able to detect all telemetered signals.

Calibration XBTs were dropped after deployment to determine the depth of the 12 degree isotherm and, hence, calibrate the IES.

THE DATA

The data from IES #5, the downstream instrument, was noisy and not usable. Hence, the lateral movement of the stream could be observed but not the change in flow angle. Figure 9 shows data typical of the four remaining data links. The 12 degree isotherm ranged over 200 meters for this instrument. Figure 10 is a compilation of all IES data showing the lateral displacement of the stream referenced to an arbitrary axis through the IES array. This lateral movement is overlayed with data hand-digitized from NOAA satellite images. The correlation of the trends is evident.

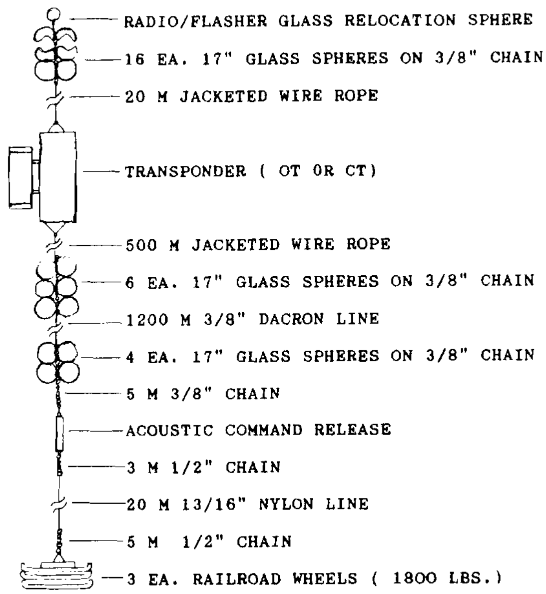

Figure 8 SOFAR sound source mooring

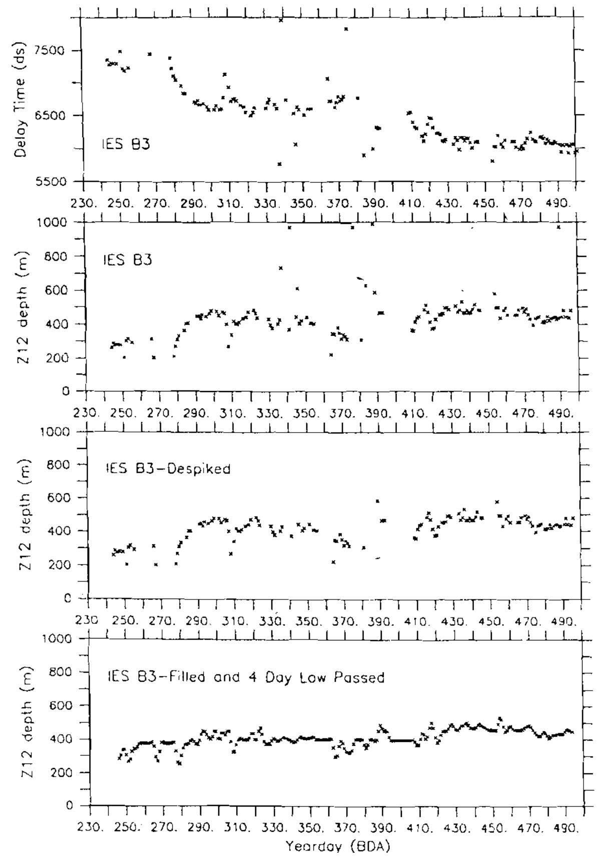

Figure 9 Typical data from a single IES. From the top: delay time-of-arrival at Bermuda, 12^{o} isotherm; raw data, despiked, filled and low-pass filtered.

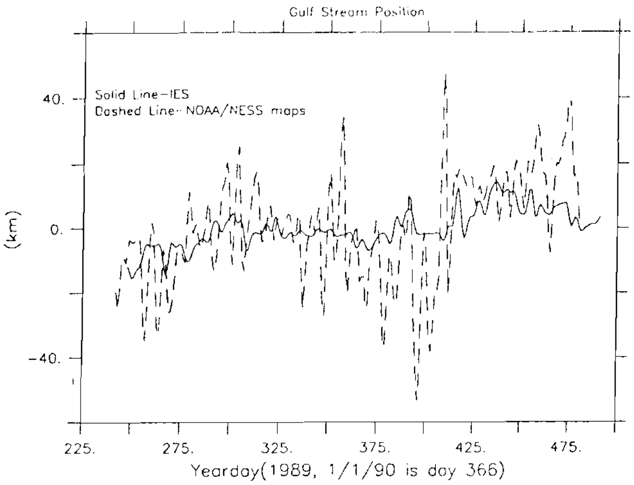

Figure 10 Gulf Stream position from mid-array axis. IES data compared to NOAA satellite images.

SUMMARY

Recent Inverted Echo Sounder developments have shown the instrument to be a valuable research tool. Echo detector improvements, new data processing techniques and intercomparison studies with drifters and satellite imagery have demonstrated its effectiveness. The long range telemetry system outlined in this report further expands the capabilities of the IES to near real-time reporting.

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