THE FLYING FISH: AN UNTETHERED SENSOR PLATFORM WITH ACOUSTIC HOMING CAPABILITY, ITS ROLE IN GLOBAL SCALE HYDROGRAPHIC SURVEYS

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ABSTRACT

A free-fall vehicle developed as a platform for a suite of oceanographic sensors is described. The vehicle's principal attributes are portability, speed, and acoustic homing. The vehicle architecture promotes the use of automated diagnostics and data collection. Concurrent with the vehicle development program at Woods Hole, several manufacturers are designing sensors which can be interfaced both mechanically and electronically with the fish. Intercomparison tests with the conventional CTD sensors are planned for late 1985 and early 1986. This paper presents the basic specifications of the Flying Fish to assist in the planning of experiments based on this instrument system. We also present some suggestions for the infrastructure required to support global scale hydrographic surveys.

INTRODUCTION

The Flying Fish is an autonomous, streamlined, gravity driven vehicle designed for high speed (15 knots) return trips to depths of 6,000 meters (see Figure 1). In addition, the fish is capable of guiding itself back to an acoustic beacon at the surface. The principal parameters to be measured during this vertical excursion include conductivity and temperature as functions of depth. These parameters are used as water mass tracers. They can also be used in the equation of state of seawater to calculate the density field and the total transport of large scale circulation patterns.

In addition to the operational specifications of the fish (see Table 1), this paper describes the vehicle architecture as it relates to maintenance requirements, self-test diagnostics, and failure isolation capability. From deployment to data archiving, the design allows for substantial automation. Some of this capability has already been developed. Beyond the question of technical feasibility, however, are the issues of logistics, sensor calibration, data handling, and data quality control. Sensor evaluation and intercomparisons with present techniques are scheduled for 1985-86. The goal is to have routine measurement capability in time for the global scale surveys that are being designed to coincide with oceanographic satellites scheduled to be launched in the early 1990's.

BACKGROUND: A SHORT PRIMER ON HYDROGRAPHIC SURVEYS

One of the fundamental limitations of present meteorological models used for weather prediction is the unknown boundary condition imposed by the world ocean. Despite advances in understanding the basic physics of the ocean, there is a dearth of field data that covers the spatial and temporal scales required by the models. A complete study of an entire oceanic basin was done only once, and the time scale spread over two years (1957-58) using discrete water samples (Fugister, 1970). Large scale monitoring programs to study the global atmospheric weather patterns have, at present, no counterpart within the oceanographic community.

There are three basic approaches in physical oceanography to measuring the circulation patterns of the world oceans. One approach uses direct measurements of fluid velocity and direction at discrete points. (e.g. current meters) These instruments have a limited on site endurance and cannot measure the low frequency seasonal and interannual scale variability. Drifters, a second class of instruments, make Lagrangian measurements. When used in large numbers and studied statistically, they give good measurements of fluid velocity but not of total transport. They are excellent for flow visualization studies. The last method for calculating circulation patterns is based on measurements of salinity and temperature as functions of depth. From these quantities, one can calculate the density field. Geostrophy (the study of potential flow fields on rotating reference frames) exploits knowledge of the density field to determine the dynamic head driving large scale circulation patterns. The primary contributors to density field variability are salinity and temperature. Historically these quantities have been measured from water samples taken at discreet locations. More recently the density field has been calculated in situ from conductivity, temperature, and pressure measurements. Thus the CTD (conductivity, and temperature as functions of depth) sensor is the backbone of large scale circulation and global heat budget studies.

Despite many advances in sensor technology, most sections of the world ocean are still undersampled. This undersampling is directly attributable to the prohibitive cost of mounting large scale ocean monitoring programs using present day technology. The Flying Fish was designed to break this cost bottleneck by increasing sampling speeds by a factor of between three and six (depending on sampling density and ship speed; see Figure 2). The development of a small streamlined free-fall sensor platform with acoustic homing capability has several tangible benefits:

1. Faster deployment times shorten the time between first and last profiles of a trans-oceanic section to dramatically improve the synopticity of the observation and reduce ship operating costs.

2. Decoupling the ship motion from the sensor platform improves the flow around the sensors.

3. Elimination of the electromechanical winch increases the number of ships capable of collecting data.

VEHICLE ARCHITECTURE IN THE CONTEXT OF REDUCED MAINTENANCE AND ENHANCED SELF TEST CAPABILITY

Both the mechanical and electronic architecture of the fish are based on the need for low shipboard maintenance requirements. Any scientist/graduate student team should be able to use a personal computer of convenience to control the measurement system and to collect data of known quality. The design philosophy is one of minimizing human involvement in order to (1) reduce operating/labor costs, and (2) achieve some acceptable standard in data quality. Each vehicle sub-assembly is built around a microprocessor that can be queried and exercised by the on deck computer. All sub-assemblies communicate using the IEEE 997-1985 SAIL protocol. Such a modular architecture and standard interface promotes automated check out and testing. Figure 3 describes the major sea-going system components. At present, the cradle (with battery charger, air circulationn pump, and hydrophone test fixture) homing beacon, and tracking hydrophone exist as separate entities and have not been integrated into the shipboard computer. The launch and recovery fixtures exist in simplified form while the telemetry terminal and calibration fixture are hypothetical.

Beyond the simple questions of the technical feasibility of speeding up the data collection process are the questions of suitability of the instrument to widespread use. These additional issues include (1) cost (both initial outlay and ongoing maintenance) and (2) required infrastructure (e.g. logistics of calibration, data handling, and quality control). The following scenario is intended to give some insight into the operational requirements.

The Operational Scenario

Prior to a deployment, the main shipboard computer prompts the user to connect the fish to (1) the four conductor cable, (2) the hydrophone test jig, and (3) the air circulation pump (see Figure 3). If the fish has just finished a profile, the batteries are recharged and the data is transferred to the main computer for archiving. Otherwise, testing of the fish sub-assemblies begins. The hydrophone and receivers are tested throughout their operating range by capacitively coupling a reference signal into the hydrophone array and comparing this with the receiver output monitored through the SAIL interface. Any offsets are recorded as a way of monitoring long term trends in hydrophone degradation. The strobes, pinger and motors are then exercised. A shuttle valve built into the fore endcap of the electronics pressure housing is opened by the test fixture. While the batteries are being recharged through the umbilical, dry air is forced to circulate through the electronics housing to prevent the concentration of volatiles that are outgassed by the secondary cells. Prior to deployment, the main housing is evacuated to half an atmosphere to help seat the O rings. If any seal fails, the internal vacuum cannot be maintained and the main computer is alerted.

If all systems are "GO", the operator inputs the expected bottom depth (Note that this can also be automated by querying a depth sounder through shipboard SAIL) and removes the umbilical. All steps are initiated by prompts generated by the main computer.

As soon as the fish is over the side, the ship should slow down, loop back to the approximate deployment location, and energize the homing beacon. The maximum glide angle of the fish is about ten degrees. Thus, for a 5,000 meter deployment, the ship can be as much as 1 km off station.

As the fish ascends, it emits a double ping. The first ping is repeated regularly on a time base while the second is delayed proportional to depth. Thus, the operator knows the slant range at all times and can anticipate the arrival of the fish at the surface. By manuevering the fish to the ship and by knowing the ETA of the fish, the ship's crew need not get involved in the recovery operation. Total deployment time, including recovery, should be about forty minutes.

Failure Modes

Failures can take many forms, from shorted windings in the fin actuator motors to bad hydrophones to hardware and software glitches.

Further, they may occur when the fish is on deck or when it is at depth. In the event of a failure on deck, several levels of debugging and fault isolation can be employed. Those uninitiated in fault finding or unfamiliar with the inner workings of the instrument can rely on a simple "All OK" or "Don't Use Me" output from the self-test routines. In the event of a negative response, the fish is put aside and a new one is put in its place. A "school" of fish provides true redundancy in data collection capability. If there are no spare fish available, the deck computer can utilize the test capability of the deck stand to invoke test routines built into the sub-assemblies to isolate the fault and instruct the operator to replace the appropriate sub-assembly. More difficult problems which cannot be found by this automated procedure require the instrument to be sent to a central repair station.

The second class of failure modes center on those which occur during deployment. To address this issue, the vehicle has an established internal communication protocol between the master controller and each sub-assembly which insures that each processor is running correctly. Figure 4 shows the hierarchical structure of the processors. Any communication breakdown triggers the abort of a dive. This can result from (1) bad signal to noise ration at the receiver, to (2) change in internal pressure, to (3) a short in the motor or motor driver, to (4) a processor based module failing to respond when queried. An abort causes all or some of the following chain of events: (1) drop the ballast; (2) a change in the ping rate to notify the support vessel that a problem exists; (3) an attempt to straighten all fins.

INFRASTRUCTURE REQUIREMENTS

Data Handling, Quality Control, and Satellite Telemetry

Quality control is a serious issue when one is looking for 0.001°C variability in the deep ocean over time scales of ten years. In the IGY "all data...were collected under the personal supervision of L. V. Worthington, W. G. Metcalf, A. R. Miller, and F. C. Fuglister." This level of supervision aboard each vessel working in a global scale survey contradicts the initial premise that these measurements would be taken by operational groups with minimal training. One option is to have a centralized quality control center which, in near real time can decide whether or not to re-survey an area where the data is suspect.

A second argument for telemetry to a central clearing house is based not on logistical arguments but on scientific need. For those interested in predicting oceanic weather patterns, it is important to collect, digest, and assimilate the hydrographic data on the same time scale as the satellite data (i.e. near real time). Two types of data are collected by the fish: the first is the raw scientific data, the second is engineering data. The former consists of (typically) one meter averages of conductivity, temperature, and depth and totals about 100 KBytes/cast. At six casts a day the scientific data alone is over 0.5 MBytes/day. the engineering data is used to monitor the health of the fish and consists of pitch, yaw, control effort, and key battery and system voltages. This data set may be collected between, as well as during, deployments and has the potential to outstrip the volume of scientific data. However, it may be sufficient to archive this data locally. This data can then be accessed by the on deck computer to plot the long term behavior of a fish as its floatation material degrades or batteries cease to take a charge.

The telemetry requirements are based, at a minimum, on data that is required in near real time. Table 2 outlines several telemetry schemes which have varying capacities. The only alternative, even using the conservative estimate for data volume of 0.5 MBytes/day, that has sufficient capacity is MARISAT. If one assumes that actual data volume will grow as other measurements are desired then serious consideration should be given to outfitting the oceanographic fleet with MARISAT terminals (at $100,000 each) since this is the only system that could accommodate such growth.

By automating the data collection, archiving, and telemetry, human intervention can be kept to a minimum and some standardization among data sets (format etc.) can be achieved. The complexity and the sophistication must be transparent to the operations group. A central clearing house reviews the data in near real time, maintains strict quality control, and should be able to redirect a vessel to intensely survey a specific feature as the need arises.

Sensor Calibration

Though the actual sensor suite to be carried aboard the fish has yet to be selected or tested, it is not premature to consider what sensor attributes are conducive to routine hydrographic measurements. The precision, accuracy, temporal and spatial scales of the measurements are dictated by the science. The long and short term drift characteristics are dictated by the physics of the sensor.

Successful ocean surveys are characterized by careful and continuous attention to sensor accuracy and stability. This is especially true in light of the high precision sought. Any questions in the data quality that cannot be answered by careful calibration records diminishes the scientific value of the data set. Historically, the art of reducing Nansen water samples to salinity and temperature measurements was a technique that required patience, care, and training. Few people were trusted to execute the procedure correctly and many data sets were summarily discarded due to suspect techniques. With present CTDs, the care must go into calibrating the sensors and monitoring the drift characteristics. At present, this calibration is extremely costly in terms of both money and man-hours.

If the Flying Fish CTD is to become the backbone of future large scale hydrographic surveys, and if the calibration costs are to be contained, an effective automated calibration program with strict quality controls must be designed as an integral system component. We propose that, at a minimum, the sensor electronics be self-calibrating, with any drift in calibration constants monitored and recorded by the shipboard computer. Each sensor should have an ID and a known history. This ID may be in the form of a bar code which is read and appended to the data from each profile. Further, the sensor pods should be designed to be replaced in the field without major disassembly of the fish.

Several simple but high accuracy portable salinometers suitable for shipboard use are now available commercially. Consequently, the notion of shipboard calibration is not completely out of place. The need for such support facilities depends directly on the long and short term drift characteristics of the sensor suite. As shown in Figure 5, it is important to know not only the rate of drift but the nature of the drift, in order to determine how often to calibrate the sensors. If the drift is episodic, then simple interpolation between end points may not be sufficient. Shipboard calibration may be the only way to maintain confidence in intercomparisons made between data sets collected by different instruments in different oceans several years apart.

CONCLUSION

The first steps to carry the Flying Fish from novel prototype to operational hydrographic tool are being undertaken at present. These steps include (1) involving the commercial sector, and (2) making intercomparisons with present techniques. In addition to generating confidence in this new tool, the scientific community must come to grips with the costs and organizational burdens that are necessary if global scale observations are to become routine. Specifically, the community must be prepared to set up calibration, telemetry, and quality control facilities as part of a planned multi-year program.

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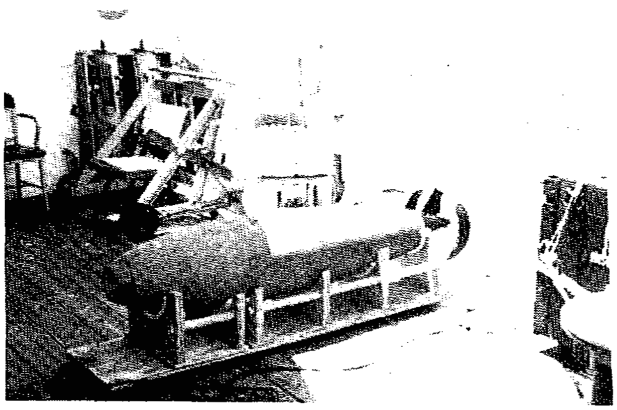

FIGURE 1. THE FLYING FISH

Deployment Time	40 min/station (based on 6,000 m water depth)
Vertical Speed	6 meters/second (down and up)
Maximum Operating Depth	6,000 meters
Vehicle Air Weight	120 kg.
Expendable Ballast	45 kg.iron
Sensor Suite	(1) state of the art CTD (2) 2,100 ml. water samples
Data Volume	0.5 MByte/Deployment
Turn Around Time	15 minutes (to transfer data and recharge batteries)

TABLE 1. **VEHICLE OPERATIONAL SPECIFICATIONS**

1. Flying Fish with CTD.
2. Cradle with battery charger, air circulation pump, SAIL interface, and hydrophone test fixture.
3. Launch and recovery fixture.
4. Homing beacon and tracking hydrophone.
5. Shipboard computer with mass storage and data archiving.
6. Telemetry terminal?
7. CTD calibration fixture?
8. Expendable ballast storage boxes.

TABLE 2. **SEAGOING SYSTEM COMPONENTS**

TELEMETRY MEDIUM	COVERAGE	NOMINAL THRU-PUT	ENERGY (J/BIT)	POWER	COST
ARGOS	Global	1 KBIT/Day	1	10 W	$2K + $6/day
GOES	Lat$\leq$ 70	10 KBIT/Day	1	100 W	$3K
MARISAT	Lat$\leq$ 70	1 GBIT/Day	.01	250 W	$70K + $10/min
METEOR BURST	2000 KM	10 KBIT/Day	.03	300 W	$60K base + $6k remote
VHF/UHF	Line of sight	10 MBIT/Day	.001	10 W	$2K

TABLE 3. INTERCOMPARISON OF VARIOUS APPROACHES TO TELEMETRY
(after E. Mellinger unpublished data)

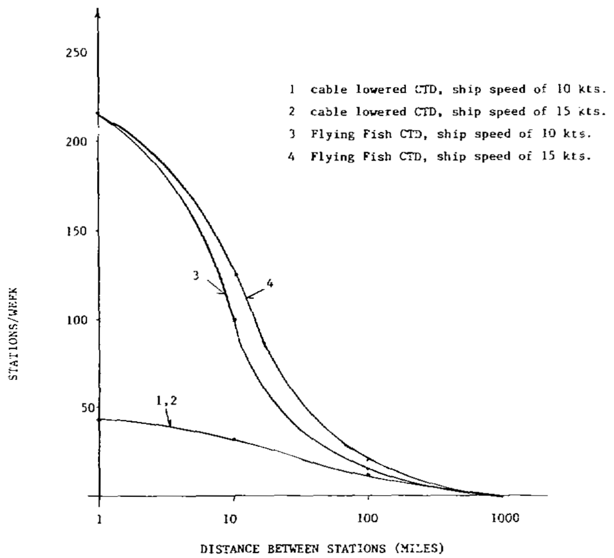

Figure 2. Intercomparison of Flying Fish and cable lowered CTD. Performance based on 40 minute and 4 hour deployments to full ocean depth.

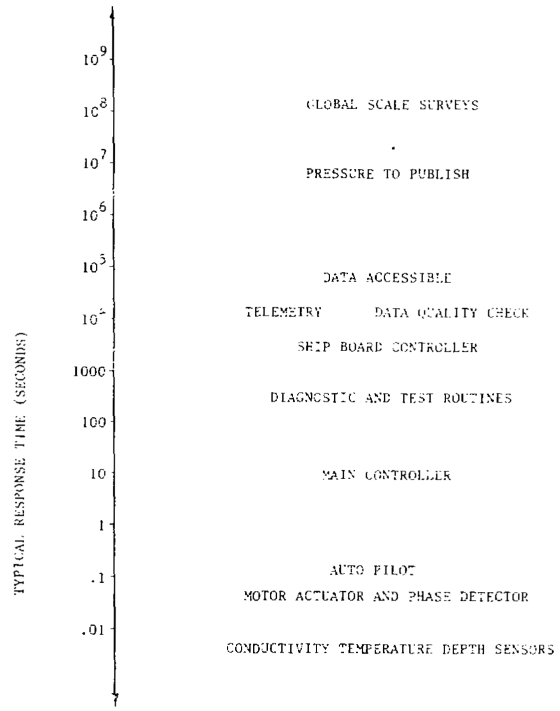

Figure 4. Hierarchical structure of the Flying Fish system components.

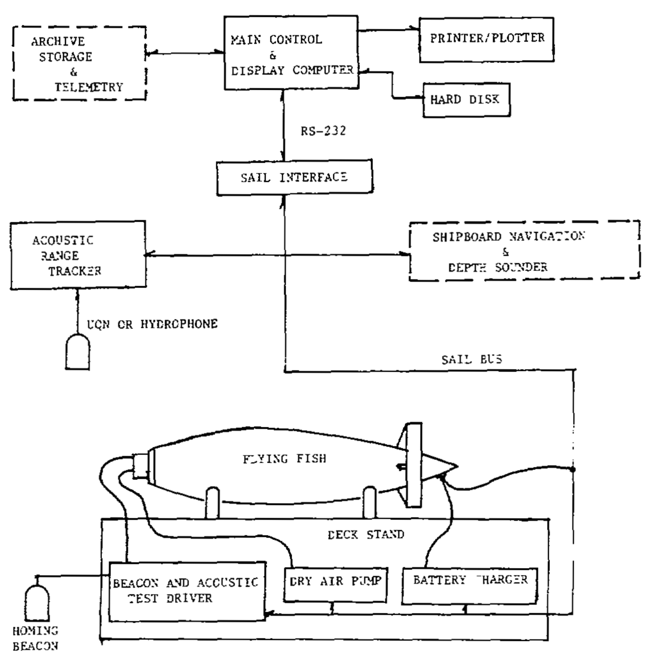

Figure 3. Schematic of major shipboard system components.

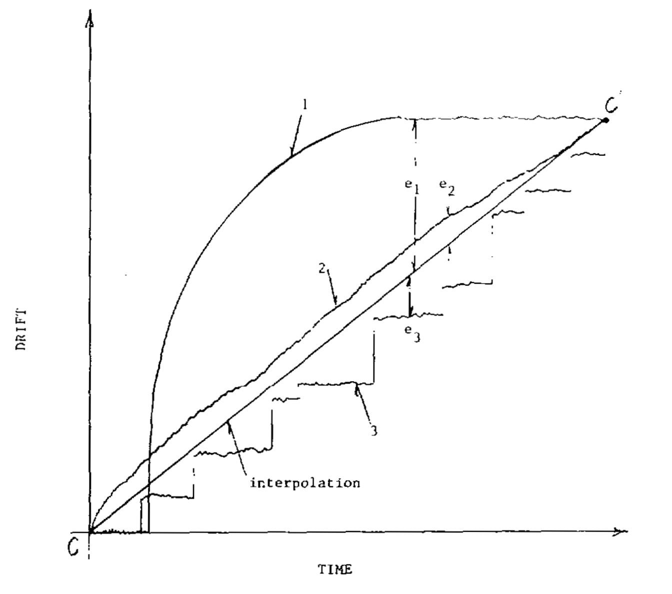

Figure 5. Schematic depicting three types of drift and their respective errors when subject to endpoint calibration:
(1) Burn in; (2) continuous; (3) episodic.